PB-249 616

USER'S MANUAL FOR RELAP 3B-MOD 101. A REACTOR SYSTEM TRANSIENT CODE

Nuclear Regulatory Commission
Washington, D. C.

January 1976

8005220357

NUREG-0004

USER'S MANUAL FOR RELAP 3B-MOD 101

A Reactor System Transient Code

January 1976

Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission

113

SHEET	NUREG-0094	NUREG/CR-0150

4. Title and Subtitle	5. Report Date
"User's Manual for RELAP3B-MOD 101 A Reactor Systems Transient Code"	January 1976
	6.
7. Author(s)	8. Performing Organization Rept. No.
9. Performing Organization Name and Address Division of Systems Safety Nuclear Regulatory Commission Washington, D.C. 20555	10. Project/Task/Work Unit No.
	11. Contract/Grant No.
12. Sponsoring Organization Name and Address	13. Type of Report & Period Covered
	14.

15. Supplementary Notes

16. Abstracts

The RELAP3B computer program describes the behavior of water cooled reactors during postulated accidents or power transients, such as large reactivity excursions, coolant loss transient, steam line break accident and the class of transients called ATWS. The program calculates flows, mass and energy inventories, pressures, temperatures and steam qualities along with variables associated with reactor power, reactor heat transfer or control systems.

17. Key Words and Document Analysis. 17a. Descriptors

Nuclear Reactors

Thermal Hydraulic Analysis

Transient Analysis

Blowdown

ATWS

Reactor Transients

Reactor Accidents

17b. Identifiers/Open-Ended Terms

RELAP 3B

PRICES SUBJECT TO CHANGE

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 113
Release unlimited	20. Security Class (This Page) UNCLASSIFIED	22. Price $4.55

USER'S MANUAL FOR RELAP3B-MOD 101

A REACTOR SYSTEM TRANSIENT CODE

JANUARY 1976

DIVISION OF SYSTEM SAFETY

OFFICE OF NUCLEAR REACTOR REGULATION

NUCLEAR REGULATORY COMMISSION

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ACKNOWLEDGMENTS

The RELAP3B computer program was developed as a joint effort between Brookhaven National Laboratory and the NRC staff. The NRC would like to thank the BNL personnel that worked on this program. These people have given freely of personal time and have worked after normal working hours. Without this effort, the computer program could not have been produced in a timely manner.

FOREWORD

The RELAP3B computer program has been developed to improve the Nuclear Regulatory Commission (NRC) staff's capability to perform independent audits of vendor and applicant analyses of light water reactor transients. MOD 101 is the first version of the program. It is expected that as the program is developed further, new versions will be published. The computer program can be used for both boiling and pressurized water reactors.

The program is designed to analyze the ATWS and Chapter 15 SAR transients and it is based on the RELAP3 MOD 62 computer program which was developed to analyze loss-of-coolant accident. Because the program contains the main features of the RELAP3 MOD 62 code, the running time is long compared to other transient codes which are used by the vendors. This computer program contains the flexibility to perform other than ATWS analyses. Therefore, if it is used by an applicant for a specific plant license application, further justification may be required to demonstrate that the application of this program in specific cases is acceptable.

The technology presented in this report represents the current status of this transient code. It is expected that new versions will be issued in the future. These new versions will contain new improvements, such as a non-equilibrium pressurizer model, or new capabilities, such as boron injection required in many SAR transients. At present the computer program is being used for the independent ATWS analyses and to audit the vendor calculation results. Where there are uncertainties in the models, conservative values are chosen for independent audit calculations. Updates to the computer program are made to evaluate special vendor models and audit calculational results. These updates are presented in Appendix D.

While we believe that the present computer analysis techniques presented in this document are adequate and conservative for the purpose of ATWS analysis, we wish to encourage and emphasize the need for additional work in this area. We anticipate that improved computer codes will be available in several years as a result of continuing research and development activity.

CONTENTS

I. INTRODUCTION

In support of the Loss of Fluid Test (LOFT) safety analysis effort, the RELAP series of computer programs [1,2] has been developed to predict hydrodynamic conditions inside a reactor primary system. This manual describes a new version, designated RELAP3B, which has been developed at Brookhaven National Laboratory under the auspices of the NRC* staff for NRC independent calculations of light water reactor transients. RELAP 3B is a modification of the RELAP3 MOD 62 code developed by the Aerojet Nuclear Company for use on an IBM 360 computer. The MOD 62 version of RELAP3 contains two features not included in the earlier MOD 36 version, viz., the implicit time step techniques of FLASH-4 [22] and the homologous pump model. Many sections of this manual are taken directly from the RELAP3 MOD 36 manual [1].

RELAP3B describes the behavior of water-cooled nuclear reactors during postulated accidents or power transients, such as large reactivity excursions, coolant losses or pump failures. The program calculates flows, mass and energy inventories, pressures, temperatures, and steam qualities along with variables associated with reactor power, reactor heat transfer or control systems. Its versatility allows one to describe simple hydraulic systems as well as complex reactor systems.

The additions to and/or modifications of RELAP3 MOD 62 that are contained in RELAP3B are

1) Doppler feedback dependence on moderator density
2) Extended restart capability
3) Capability to trip individual pumps on independent signals
4) Automatic time-step selection

*Previously the AEC Regulatory staff

5) Improved definition of the average fuel temperature

6) Option to allow the fuel-rod gap size to vary during a transient

7) Capability to modify the steam table mesh

8) Inclusion of realistic steam generator models

9) Calculation of reactivity weight factors

10) Option to specify new fill curves at restart

11) Option to specify new feedback coefficients at restart.

As with the earlier RELAP versions, the RELAP3B user must specify both the geometric description of the system to be analyzed and the initial conditions. The geometrical description consists of the definition of a set of control volumes joined by a set of junctions or flow paths.

RELAP3B is written in FORTRAN IV for the CDC 7600 computer with 65_{10}^{k} central memory words but has been made operational on the IBM 360 without extensive programming changes. The use of systems dependent programming has been avoided whenever possible. One exception is in the use of the automatic time step selection option where the CDC 7600 LCM is used.

In RELAP3B, the reactor system is represented as a set of arbitrarily connected fluid volumes that describe the plenums, piping, reactor core, and heat exchangers. Any volume may be chosen independently as a core region, heat exchanger, or pump. Fluid compressibility in all volumes (including core regions) is taken into account in predicting the course of the transient. Each connection between volumes may be specified as a normal junction, a leak junction, or a fill water source. A normal

junction may also include a valve. The transient is calculated in time-steps. By the end of each step the volume masses, energies, and bubble contents are advanced, new junction conditions are obtained, and flows recomputed. Reactor conditions may be used to provide reactivity feedback.

The body of this manual is divided into two parts. The first part (Sec. II) contains a description of RELAP3B features. The second part (Sec. III) is a summary of the basic equations underlying the RELAP3B program. In addition, three appendices are included.

II. RELAP3B FEATURES

RELAP 3B is an extension of RELAP3 which is itself an extension of the previous version (RELAP2). The physical models of RELAP3 vary little from those used in RELAP 2, but the logic requires almost completely new programming. RELAP3 was designed so that changes could be made in the physical models without major reprogramming, whereas previous versions were too interlocked in structure for such changes to be made easily.

For added generality, no constraints were included in RELAP3 on the nature of a specific volume or junction. For instance, any volume may be selected to represent any core region or heat exchanger, or pump. Likewise, any junction may represent a leak out of the system with no restrictions as to which or how many junctions must be so used. Thus, multiple breaks may be treated directly by specifying several leak junctions in the input.

1. GEOMETRIC DETAIL

In RELAP3B the terms "volumes" and "junctions" have the following meanings: volumes specify a region of fluid within a given set of fixed

boundaries; junctions are the common flow areas of connected volumes. Calculated results are limited in geometric detail by the size of each volume.

RELAP3B allows a maximum of 75 volumes connected by a maximum of 100 junctions, with no restrictions as to the order of these connections. The maximum number of volumes and junctions, 75 and 100, respectively are arbitrary and can be increased to far greater limits on a large computer. The changes required consist almost entirely of increasing the array sizes given in the COMMON statements.

2. GRAVITY HEAD

In RELAP3B junctions connect volumes directly and thus contain no elevation changes. To account for gravity terms, the pressure calculated within a volume from thermodynamic relationships is assumed to exist at the center of gravity of the volume. Positive or negative gravity heads may then be found by integration of the fluid density from the center of gravity to the level of the junction connected to the volume.

3. CONTROL OPTIONS

Control parameters are generalized in RELAP3B. For instance, reactor scram may be initiated by the first condition detected among high power level, short period, fuel temperature, high pressure in any volume, low pressure in any volume, and so on. Opening the leaks (staggered leak openings might be accomplished through the individual opening-time curves), tripping the pumps, starting the fill systems, controlling up to five

valves separately, or ending the problem also may be put under the control of many different conditions.

4. STEAM SEPARATION

One of several sets of coefficients (input) for the steam separation calculation may be chosen for each volume. Part of the required volume data is a bubble set index which determines, for each volume, the set of coefficients to be used. The zeroth set (a uniform liquid-steam mixture) is built-in; others must be supplied as input.

5. PUMP CHARACTERISTICS

The centrifugal pumps are described by a so-called homologous model, which specifies relations connecting head, torque, flow rate, and rotational speed. The location of a pump is defined by the volume in which it resides and by the junctions which provide the pump inlet and outlet. A given set of pump characteristics may appear in more than one volume. In order to handle system transients in which one pump is tripped while the others continue to operate, an option was programmed into RELAP3B permitting the independent tripping (on independent signals) of each pump in the system.

6. FRICTION COEFFICIENTS

An option which eliminates some input is the implicit calculation of friction coefficients. When the friction coefficient is left out of the data for a junction, RELAP3B will calculate a value which establishes steady state flow. This calculation, which is based on initial pressures including gravitational heads, can yield a negative friction coefficient that

would cause numeric instabilities. If a negative friction coefficient is found after the input is processed, the RELAP3B run will be aborted to avoid lost computer time. Initial pressures must be readjusted by the user.

7. RESTART CAPABILITY

At user designated times during a RELAP3B run, information is saved which then allows the computation to be re-started. The purpose of this feature is two-fold: (1) The run may have ended prematurely due to unexpectedly large running time, or to some error in machine operation or input and (2) It may be desirable to alter some of the basic input data at some time after the beginning of the problem. The restart can be activated at a specified time step anywhere in the course of a previous run or automatically at the last step of a previous run.

8. PLOTTING AND EDITING OPTIONS

The data tape used for storing the information required for restarting or plotting is also used for storing the editable variables at designated intervals. RELAP3B can process this tape to obtain additional edits as required. The plotting program in use at BNL is adapted only to a CDC 7600 with LCM, but is available as a separate package for those who want to convert it. The original plotting program distributed by ANC was intended for use on an IBM 360 computer.

9. AUTOMATIC TIME-STEP VARIATION

In RELAP3B full advantage can be taken of the implicit differencing technique through a feature which allows the time-step size to be increased automatically during slowly varying portions of a run. Similarly, automatic time step decreases are also possible.

10. OPTIONAL CALCULATION OF WATER PROPERTIES AT RUN TIME

An option has been included to allow the user to change the pressure mesh in the steam tables or to extend the tables of thermodynamic properties above the critical pressure. This option calculates thermodynamic property tables from the "1967 IFC Formulation for Industrial Use", the basis of the 1967 ASME Steam Tables.

III. EQUATIONS SOLVED

RELAP3B obtains a time-dependent thermal and hydraulic description of a reactor by integrating a set of differential equations subject to certain algebraic relationships. These equations and relationships are presented in the following sections.

A mass and energy balance is obtained from junction conditions, heat output of reactor regions, heat removed by heat exchanger regions and heat added by pumping power. By using the equation-of-state for water (in the form of tables) a pressure and a quality are obtained for each volume. Assumption of a linear density model for steam separation within each volume allows fluid conditions to be determined for each junction. A one-dimensional momentum balance (flow calculation) is then obtained for each junction. The fluid conditions within a volume, the flow through a volume, and the reactor power level are then used to establish the reactor heat flux and the fuel element temperatures. By the use of reactivity feedback from reactor conditions, the space-independent reactor kinetics equations are then advanced to determine a new reactor power level. A new cycle is then begun with a new mass and energy balance.

1. MASS AND ENERGY BALANCES

As demonstrated in Appendix A, the mass and energy stored in each volume are calculated from the basic conservation equations by assuming constant flow and fluid properties during any given time step. The conservation equations are in the form of ordinary time-dependent differential equations describing the behavior within a fixed control volume, illustrated in Figure 1. The mass and energy equations are

$$\frac{dM_i}{dt} = \sum_{j=1}^{N} W_{ij} \tag{1}$$

and

$$\frac{dU_i}{dt} = \sum_{j=1}^{N} W_{ij} \; h_{ij} + Q_i \tag{2}$$

where

M_i = total mass in volume i

W_{ij} = flow rate into volume i through junction j

U_i = energy in volume i

h_{ij} = enthalpy of flowing fluid

Q_i = heat input to volume i.

Kinetic energies and frictional heat sources are neglected in Equation (2).

For an energy balance in each volume, the correct enthalpy must be determined for all incoming and exiting flows. In RELAP3B, the exit state of the fluid in a junction is defined by the state of the fluid entering the junction. If the mixture level of liquid and entrained steam bubbles is below a junction, the flow is assumed to be steam. Conversely, if

the mixture level is above the junction, the flow is determined by the bubble gradient equations described in Section III-10.

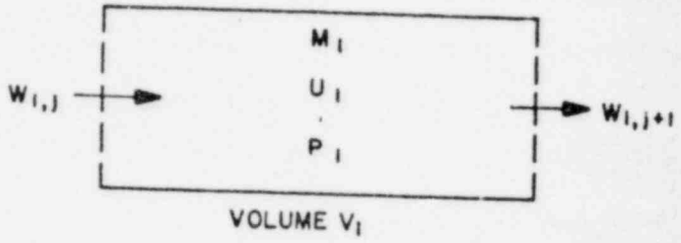

FIG. 1 CONTROL VOLUME.

2. THERMODYNAMIC PRESSURE

Pressure, P_i, in each volume is determined implicitly by requiring the mass of fluid, M_i, with internal energy, U_i, to fill control volume V_i. The enthalpy, h_i, of volume i is calculated by the equation

$$h_i = \frac{U_i}{M_i} + P_i \frac{V_i}{M_i} \quad . \tag{3}$$

Through use of this enthalpy, along with an estimated pressure, the specific volume of the fluid is calculated from the available physical property tables. An iterative process of matching the specific volume from the steam tables with known specific volume V_i/M_i is used to determine the volume pressure. The built-in property tables for water cover the range of $0.1 \leq P \leq 3206.2$ psi, and $32 \leq T \leq 5600°F$.

The values in the built in thermodynamic property tables were calculated from the 1967 ASME Steam Formulae[3]. For each pressure, P_j, the tables of water density, ρ, and steam specific volume, v, are arranged as follows:

liquid

$h_{j,1}$	$\rho_{j,1}$	$T_{j,1}$
$h_{j,2}$	$\rho_{j,2}$	$T_{j,2}$
.		
.		
.		
.		
.		
$h_{j,13}$	$\rho_{j,13}$	$T_{j,13}$

steam

$h_{j,1s}$	$v_{j,1s}$	$T_{j,1s}$
.		
. steam		
.		
.		
$h_{j,6s}$	$v_{j,6s}$	$T_{j,6s}$

where

$T_{j,1} = 32°F$

$T_{j,13} = T_{j,1s} = T_{sat}(P_j)$

$T_{j,5s} = 1600°F$

$T_{j,6s} = 5600°F$

and P_j = 0.1, 0.3, 1.0, 5.0, 14.7, 30., 100., 200., 400., 600., ...
3000., 3206.2 psi

In the low-pressure (<50 psi) liquid range of the tables, entries are arranged along equal temperature lines for all pressures, as shown in Figure 2.

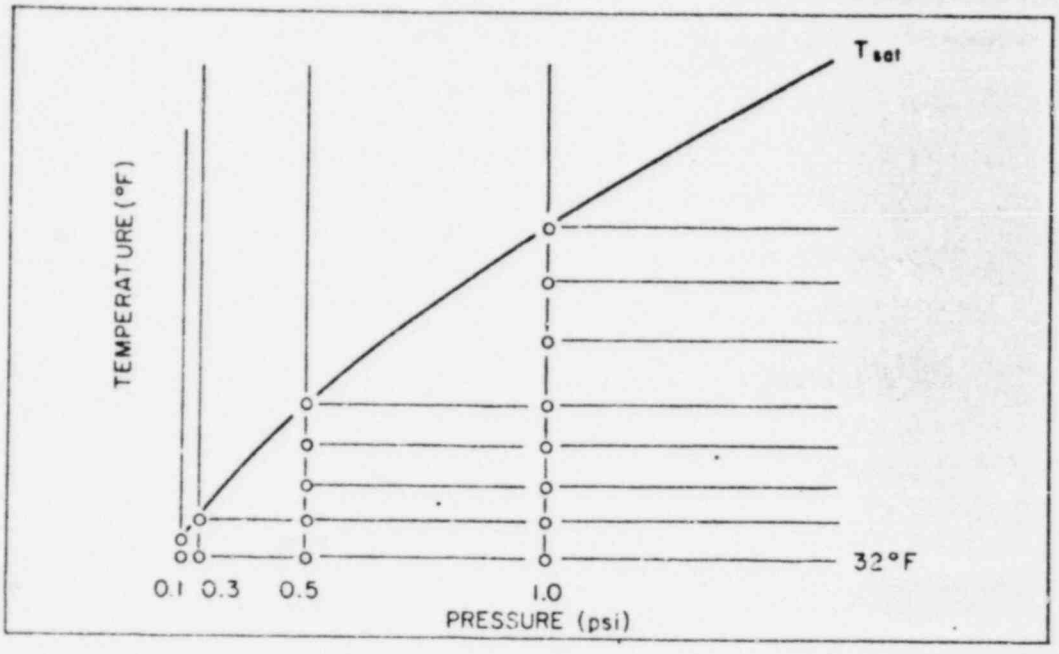

FIG. 2 LOW PRESSURE TABLE STRUCTURE.

For pressures > 100 psi, the liquid entries for a given pressure are at equally spaced temperature intervals from 32°F to T_{sat}. The entries for a given pressure in the steam region are equally spaced between T_{sat} and 1600°F with a final point at 5600°F.

In the liquid region, at high pressure (>2200 psi) and within a few degrees of saturation temperature, the tables have proven inadequate. This deficiency was noticed especially in BWR calculations where it was found that when the boiling boundary left (or entered) a volume, pressure oscillations were introduced that could not be diminished by reducing the

time step size. The oscillations were diminished by using a finer pressure mesh near the saturation line in the steam tables, as well as a finer temperature mesh.

Furthermore, the calculation of over-pressure transients in PWR's require thermodynamic properties above the critical pressure of 3208.23 psia (PCRIT). Consequently, an input option is included in RELAP3B which allows the user to change the steam table entries at run time. When this option is used a table of pressures (maximum allowable pressure is 7000 psia) is input and the following changes are made in the liquid region temperature mesh:

The number of liquid temperatures at any pressure is forced to equal 13.

First temperature entry = 32.0°F

Eighth temperature entry = 0.8 $T_{sat}(P_j)$

Thirteenth temperature entry = $T_{sat}(P_j)$

The other entries are at equally spaced temperature intervals between these entries.

In the steam region the number of temperature entries at any pressure is forced to equal 6 and the table entires are devided into equally spaced temperature intervals between T_{sat} and 1000°F.

The steam tables and the physical property tables are replaced with data generated using the 1967 ASME Steam Formulae [21] and the temperature and pressure mesh described above.

3. MOMENTUM BALANCE

The control volume used for the flow calculation is shifted to a mid-position between the two adjacent mass-energy control volumes, as shown in Figure 3. This shifting of the two types of control volumes has the advantage of minimizing the extrapolation of boundary conditions. The mass-energy calculations require a junction flow as a boundary condition, which, with the shifted flow volume, is approximately the average flow as given by Equation (4). Likewise, the flow volume calculation requires, as a boundary condition, the pressure which is available as the average thermodynamic pressure in a mass-energy volume, adjusted for gravity effects.

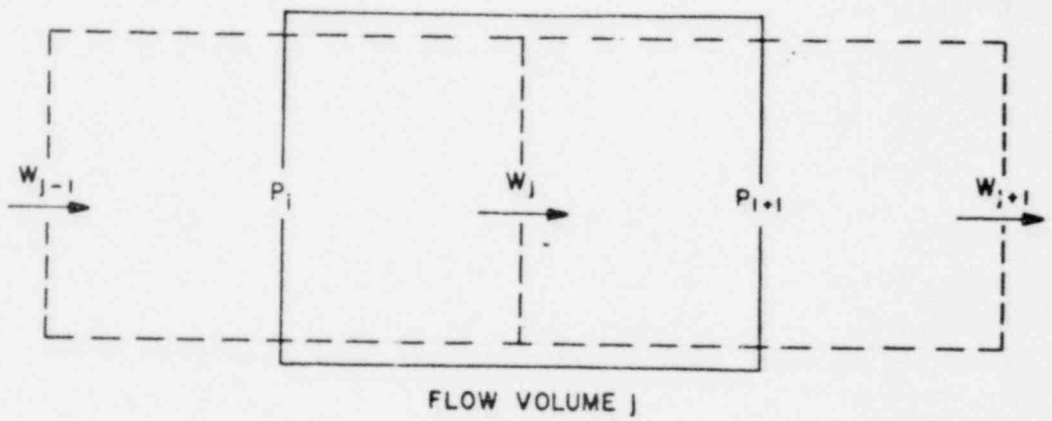

FIG. 3 FLOW VOLUME.

Junction flows are calculated from the one-dimensional momentum equation which in English units is:

$$\frac{1}{144 g_c}\left(\frac{\ell}{A}\right)\frac{dW_j}{dt} = P_i - P_{i+1} + \Delta P_p + \int_{V_j} \frac{\rho dz}{144} - \frac{K_j W_j |W_j|}{\rho_j} \quad (4)$$

where

g_c = gravitational conversion constant

$\frac{\ell}{A}$ = junction inertia

W_j = average flow from volume i to volume i+1

$P_i - P_{i+1}$ = thermodynamic pressure differential across the fluid contained in the flow volume

ΔP_p = pump head

$\int_{V_j} \rho dz$ = gravitational head across fluid column

K_j = net friction coefficient including normal friction losses (See Appendix A)

ρ_j = fluid density in junction j.

The fluid contained within the flow volume has an associated inertia which depends on the actual shape of the volume. The junction inertia for a homogeneous volume is

$$\left(\frac{\ell}{A}\right)_j = \int_{V_j} \frac{d\ell}{A} \tag{5}$$

where

ℓ = the length of the flow path

A = cross-sectional area for the flow.

In the simple example shown in Figure 3,

$$\left(\frac{\ell}{A}\right)_j = \frac{1}{2}\left(\frac{\ell_i + \ell_{i+1}}{A_i}\right) \tag{6}$$

The normal friction coefficients should initially balance with the input pressure distributions for flowing systems. If initial flow exists between two volumes, RELAP3B can calculate the appropriate friction coefficient to produce this balance. For junctions with no initial flow, the user must supply a value for K_j.

Elevation heads, which are included in Equation (4), are calculated by integrating the density distribution as defined by the steam separation model.

4. CHOKED FLOW

At the user's option normal junction flow can be tested for choking and can also include the effects of a two-phase friction pressure drop multiplier for the junction friction coefficient. When the proper conditions exist, leak junction flow is automatically limited by choking. The limiting mass flow is defined by Moody's two-phase choked flow model[4],

$$W_{choke} = A_{choke} \; f_n(P_o, h_o) \tag{7}$$

where

W_{choke} = maximum junction flow

A_{choke} = minimum area in junction

f_n = mass flux as a function of stagnation pressure, P_o, and enthalpy, h_o.

The stagnation conditions are assumed to be the thermodynamic conditions within the volume feeding the junction and at the junction height. The flow through a junction is chosen as the smaller of the inertial flow or the choked flow.

Moody's model also gives the throat pressure, P_{th}, as a function of P_o and h_o. In RELAP3B, the sink pressure must be less than the throat pressure for choking to occur in a leak junction.

5. ENERGY REMOVAL

5.1 MOD 0 HEAT EXCHANGER

Energy removal by a heat exchanger is calculated from an input table or by the following flow-dependent equation:

$$Q_i = -Q_{HE} = -\frac{W(t)}{W_o} H_{HE}(T_{pri}(t) - T_{Sec}) \qquad (8)$$

where

Q_i = rate of heat addition to volume i

Q_{HE} = heat removal rate of the heat exchanger

$W(t)$ = flow of the primary coolant through volume i, time dependent

W_o = initial coolant flow through volume i

H_{HE} = effective heat transfer coefficient during steady state full power operation, constant at initial value

$T_{Pri}(t)$ = temperature of primary coolant in the heat exchanger, time dependent

T_{Sec} = temperature of secondary coolant in the heat exchanger, constant.

The flow rates, $W(t)$ and W_o are taken to be one half the sum of the inlet and outlet junction flow rates for the heat exchanger volume. It is assumed there are only one inlet junction and one outlet junction for this volume.

The term representing the heat transfer coefficient H_{HE} is determined internally in the code from initial steady state conditions:

$$H_{HE} = -\frac{Q_i}{(T_{Pri} - T_{Sec})} \quad . \qquad (9)$$

Since heat exchangers are independent of each other, the choice of a flow-dependent model for one does not eliminate the possibility of using an input table for another.

5.2 MOD 1 HEAT EXCHANGER

In this version, the equation solved is

$$Q(t) = H_{HE} \left(T_{pri}(t) - T_{sec}(t)\right) \tag{10}$$

where H_{HE} is a constant and the secondary temperature is allowed to vary in time. This permits an entire time-varying secondary loop to be calculated as part of the transient. Each primary heat exchanger volume must be connected to a single secondary heat exchanger volume.

5.3 MOD 2 HEAT EXCHANGER: U-Tube Steam Generator Model

In the RELAP3B U-tube steam generator model, the primary-to-secondary heat transfer rate and the temperature distribution within the tube metal are determined by solving the following non-steady-state conduction equation for the heat exchanger U tubes:

$$\rho C_v \frac{\partial T}{\partial t} = k \left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right] \tag{11}$$

Equation (11) is solved numerically under the following initial condition and the boundary conditions of variable wall heat fluxes.

For $t = 0$, $T = f(r)$ = steady-state temperature distribution

For $t > 0$,

$$\text{at } r = R_1 \text{ , } -k\frac{\partial T}{\partial r} = q_{W_1}(t) = U_p \left[T_{pri} - T_{W_1} \right] \cdots \tag{12}$$

$$\text{at } r = R_2 \text{ , } -k \frac{\partial T}{\partial r} = q_{w_2}(t) = U_b \left[T_{w_2} - T_{sat} \right] \cdots \qquad (13)$$

where

$$\frac{1}{U_p} = \frac{1}{h_p} + R_{fp} \text{ and } \frac{1}{U_b} = \frac{1}{h_b} + R_{fb}$$

In the above equations:

T	= temperature, °F
t	= time, hr
q_{w_1} , q_{w_2}	= inner and outer surface heat flux of the heat exchanger tubes, Btu/ft^2 hr
U_p, U_b	= over-all heat transfer coefficients for the primary and secondary sides respectively, Btu/hr ft^2 °F
ρ , C_v , k	= density (lb_m/ft^3), heat capacity (Btu/lb_m °F) and thermal conductivity (Btu/ft °F hr), respectively of the tube metal.
R_1 , R_2	= inner and outer radius of the heat exchanger tubes, ft
h_p , h_b	= heat transfer coefficients for the primary and secondary sides, respectively, Btu/hr ft^2 °F
T_{pri}	= primary side fluid temperature, °F
T_{w_1} , T_{w_2}	= inner and outer wall temperatures of the tube, °F
T_{sat}	= saturation temperature corresponding to the pressure in the secondary-side volume, °F
R_{fp}, R_{fb}	= fouling factors for the primary and secondary sides respectively, [Btu/ft^2 hr °F]$^{-1}$

The steady-state temperature distribution is obtained by solving Eq. (11) with $\frac{\partial T}{\partial t} = 0$, and T_{pri} is defined for each volume using the logarithmic mean temperature difference at the inlet and exit of the heat exchanger volume. At each time step, h_p and h_b are recalculated based on the thermal and hydraulic

conditions prevailing in the primary and secondary side volumes, respectively. The primary side heat transfer coefficient, h_p, is computed by using the Dittus-Boelter [9] correlation:

$$Nu = 0.023\ Re^{0.8}\ Pr^{0.4} \tag{14}$$

For water, when the combined allowance for the variation in physical properties with temperature is made, the above equation reduces to [19]

$$h_p = 0.148\ (1+10^{-2}\ \tilde{T} - 10^{-5}\ \tilde{T}^2)\ \frac{v^{0.8}}{D^{0.2}} \qquad \text{Btu/hr ft}^2\ ^\circ\text{F} \tag{15}$$

where $\tilde{T}(^\circ F)$ is the bulk temperature, v (ft/hr) is coolant velocity and D (ft) is the tube diameter.

The temperature, $\tilde{T}$, and coolant velocity, v, appearing in Equation (15) are taken to be one half the sum of the inlet and outlet junction values. It is assumed there are only one inlet junction and one outlet junction for a primary heat exchanger volume. The average temperature and coolant velocity do not need to be computed for the secondary side.

For the secondary side heat transfer coefficient, h_b, the following Jens-Lottes [20] correlation for nucleate boiling is used:

$$\Delta T = T_{W_2} - T_{sat} = 60\ e^{-\frac{P}{900}} \left(\frac{q''}{10^6}\right)^{0.25} \tag{16}$$

$$h_b = \frac{q''}{T_{W_2} - T_{sat}} \tag{17}$$

p = pressure, psia

q" = boiling heat flux, Btu/ft^2 hr

Tube uncovery is simulated by using a multiplier, ψ_s, such that $q_{w2} = \psi_s\ q''$. When the steam quality in the secondary side volume reaches 1.0,

ψ_s is taken to be zero, $\psi_s = 1$ otherwise. The thermal conductivity of the tube metal (assumed to be Inconel) is calculated from:

$$k = 8.0 + 0.0051 \left(\frac{T_{W_1} + T_{W_2}}{2} \right) \quad \text{Btu/°F ft hr} \tag{18}$$

To develop numerical schemes, the tube wall is radially divided into N increments of equal width, Δr, such that $(R_2 - R_1) = N\Delta r$. Eq. (11) is then expressed in a finite difference form by using the standard formulae, such as,

$$\frac{\partial T}{\partial \tau} = \frac{T_{m,n+1} - T_{m,n}}{\Delta t}, \quad \frac{\partial^2 T}{\partial r^2} = \frac{T_{m+1,n} - 2T_{m,n} + T_{m-1,n}}{(\Delta r)^2} \quad \text{etc.}$$

where Δt denotes the time increment and the subscripts, m and n, refer, respectively, to the radial node number and the time step. With the choice of N = 5, m takes the values of 1 through 6, and the following set of equations finally results. It should be pointed out that, for transient calculations, the surface heat fluxes at a new time step, $q_{W_{i,n+1}}$ are taken to be $\frac{1}{2}\left[q_{W_{i,n}} + q_{W_{i,n+1}} \right]$ where i = 1 or 2.

(i) For m = 1 (i.e., wall surface at the primary side)

$$T_{1,n+1} = \frac{1}{1+A'\gamma_{n+1}} \left[(1 - \frac{2}{M} - A'\gamma_n) \; T_{1,n} + \frac{2}{M} T_{2,n} \right.$$

$$\left. + A'(\gamma_n \bar{T}_n + \gamma_{n+1} \bar{T}_{n+1}) \right] ,$$

where

$$M = \frac{\rho C_v (\Delta r)^2}{k \, \Delta t} , \quad B = R_1/\Delta r$$

$$A' = \frac{1}{M}(1 - \frac{1}{2B}), \quad \gamma_n = \left(\frac{\Delta r}{k} \right) U_{p,n}$$

$U_{p,n}$ = the primary side over-all heat transfer coefficient at time step, n.

(ii) For m = 2 to 5 (i.e., inner nodes)

$$T_{m,n+1} = \frac{1}{M}\left[\left\{1 + \frac{1}{2(B+m-1)}\right\} T_{m+1,n} + (M-2)T_{m,n} + \left\{1 - \frac{1}{2(B+m-1)}\right\} T_{m-1,n}\right]$$

Because of the explicit numerical scheme used, Δt must be chosen so that both $M \geq 2$ and $M \geq \frac{2}{1-A^{*}\gamma_n}$ are satisfied for stable solutions. To improve the probability that these conditions are met, Δt of this numerical scheme is taken to be 1/4 of the time step size specified in the RELAP3B input. Consequently, for each RELAP3B time step, the calculation involved in this numerical scheme is repeated four times.

(iii) For m = 6 (i.e., wall surface at the secondary side.)

$$T_{6,n+1} = T_{6,n} + \frac{2}{M}\ (T_{5,n} - T_{6,n}) - \frac{\alpha}{2}\ (q_{w_{2,n}} + q_{w_{2,n+1}})$$

where $q_{w_{2,n+1}}$ is the root of the following equation:

$$\left(R_{fb} + \frac{\alpha}{2}\right) q_{w_{2,n+1}} + 1.89753 \left(e^{-\frac{P_{n+1}}{900}}\right)\left(q_{w_{2,n+1}}\right)^{1/4} + \left\{T_{sat,n+1} + \frac{\alpha}{2}\, q_{w_{2,n}} - (1-\frac{2}{M})T_{6,n} - \frac{2}{M}\, T_{5,n}\right\} = 0$$

and $\alpha = \frac{\Delta r}{kM}\ (2 + \frac{1}{B+5})$.

5.4 MOD 2 HEAT EXCHANGER: Once-through Steam Generator Model

This model differs from the U-tube model in two respects: (a) different heat transfer modes can be used to compute either the primary or

the secondary-side heat transfer coefficient, and (b) an implicit finite-difference scheme is used to solve the tube wall conduction equation, thus relaxing the limitation on the time-step size.

The heat transfer modes provided are those represented by MODE 1 through MODE 6 of the heat transfer correlations shown in Section 6 of this manual. The effect of baffling on the secondary-side heat transfer may be taken into account by specifying a proper baffle factor for each heat transfer mode. The thermodynamic state of fluid in the primary- or the secondary-side of the heat exchanger volume is determined by the pressure and the average fluid enthalpy in the volume with the latter computed by taking the arithmetic average of the fluid enthalpies entering and leaving the volume. The implicit numerical scheme used in solving the wall conduction equation essentially follows that given in the Heat 1 code [5].

The non-steady state conduction equation written in cylindrical coordinates:

$$\rho C_v \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[kr \frac{\partial T}{\partial r} \right]$$

is solved subject to the following initial and boundary conditions.

For $t = 0$, $T = f(r)$ = steady-state temperature distribution.

For $t > 0$,

at $r = R_1$, $$-k \frac{\partial T}{\partial r} = q_{w_1}(t) = U_p(t) \left[T_{pri}(t) - T_{w_1}(t) \right]$$

at $r = R_2$, $$-k \frac{\partial T}{\partial r} = q_{w_2}(t) = U_s(t) \left[T_{w_2}(t) - T_{sec}(t) \right]$$

where $\frac{1}{U_s} = \frac{1}{h_s} + R_{fs}$, and

U_s = overall heat transfer coefficient for the secondary-side, Btu/hr ft^2 °F

h_s = heat transfer coefficient for the secondary-side, Btu/hr ft^2 °F

T_{sec} = secondary-side fluid temperature, °F

R_{fs} = fouling factor for the secondary-side, $[Btu/ft^2\ hr\ °F]^{-1}$

Other symbols have the same meanings as in Section 5.3.

The primary- or the secondary-side fluid temperature is defined as the arithmetic average of the temperatures of the fluid entering and leaving the volume. The implicit finite-difference equations are derived by dividing the tube wall radially into five increments of equal width. This gives rise to a set of six simultaneous equations which can be solved for the two wall temperatures (the primary- and the secondary-side walls) and the four inner-node temperatures. The (6 x 6) matrix equation is solved by using the Gauss elimination method.

6. ENERGY ADDITION

Energy addition to the fluid occurs in the core volumes[a]. The rate of heat addition is calculated using a multinode pin conduction subroutine and a subroutine for predicting the heat transfer coefficients for the various modes of heat transfer.

An iterative process alternately calls the subroutine which calculates the heat transfer coefficient and the conduction subroutine, which calculates the temperatures. The latter subroutine requires as input the heat transfer coefficient, the bulk fluid temperature, the surface flux (from the previous time step), the time step size, and the heat generation rates. Convergence of the heat transfer coefficient terminates the iteration; that is, if after two successive iterations the change in the heat transfer coefficient is less than a specified tolerance, the calculation is terminated.

Flows, pressures, and densities of the coolant fluid are assumed constant during a single time step. The flow through a given core volume is obtained by averaging the flow through all the inlet and outlet junctions of the volume.

Heat generation in the fuel pins is determined by reactor kinetics routines or by table look up of power versus time. Assuming a uniform heat flux and an average temperature defined by

$$\bar{T} = \frac{\int_V C_p T dV}{\int_V C_p dV} \simeq \frac{\sum_{n=1}^{N} (\rho V)_n C_n T_n}{\sum_{n=1}^{N} (\rho V)_n C_n} , \qquad (19)$$

[a] The steam generator volumes can also be used as an energy source through the use of a negative heat removal curve.

the overall energy balance for the pin is

$$V\bar{\rho}\bar{C}\frac{d\bar{T}}{dt} = Q + S_N k_N \frac{dT_N}{dR} \qquad (20)$$

where

V = fuel pin volume

$\bar{\rho}$ = average density

$\bar{C}$ = average specific heat

t = time

$\bar{T}$ = average pin temperature

Q = heat generation rate in fuel pin

S_N = pin surface area

k_N = thermal conductivity at surface of pin

R = radius

T_N = surface temperature

N = total number of annuli in the fuel pellet (excluding the annuli in the gap and clad)

n = fuel pin annulus number.

6.1 Conduction Model

The pin conduction model solves the one-dimensional heat conduction equation in cylindrical geometry. The pin conduction model and the method of solution are patterned after the model and method used in the HEATI code [5]. Currently, the model can accommodate up to 31 radial nodes, six different concentric regions, and six different materials. Core volumes can be stacked vertically to achieve axial definition. The model geometry is illustrated in Fig. 4.

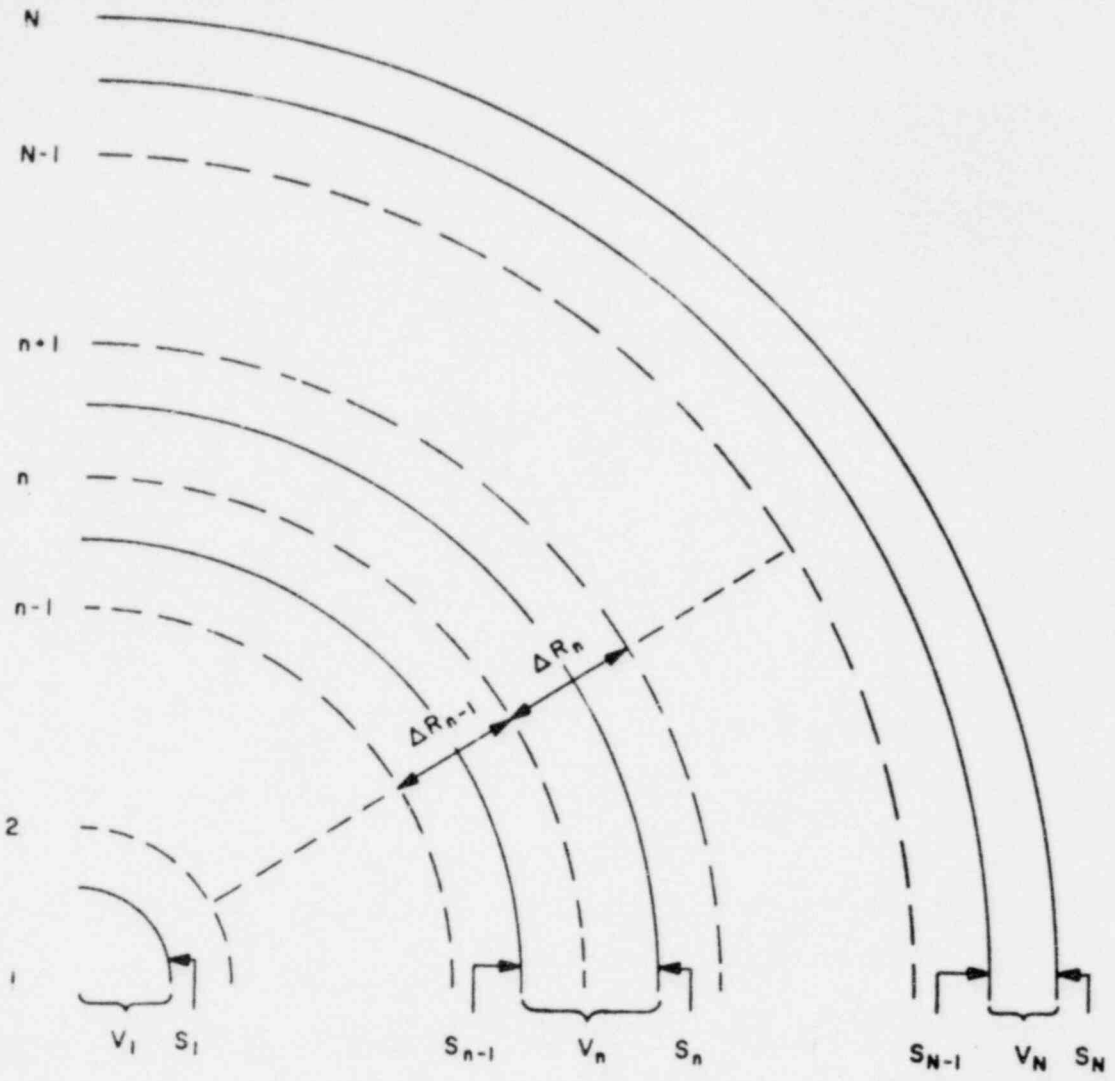

FIG. 4 FUEL ROD HEAT CONDUCTION MODEL.

For annulus n shown in Fig. 4, the conduction equation is

$$V_n \bar{\rho}_n \bar{C}_n \frac{d\bar{T}_n}{dt} = Q_n + S_n k_n \frac{dT_n}{dR} - S_{n-1} k_{n-1} \frac{dT_{n-1}}{dR} \tag{21}$$

where

S = annulus surface area.

Equation (21) is approximated numerically by

$$V_n \bar{\rho}_n \bar{C}_n \frac{(T'_n - T_n)}{\Delta t} = Q'_n + \frac{S_n}{2\Delta R_n} \left[\bar{k}_{n,n+1} (T_{n+1} - T_n) + \bar{k}'_{n,n+1} (T'_{n+1} - T'_n) \right]$$

$$- \frac{S_{n-1}}{2\Delta R_{n-1}} \left[\bar{k}_{n-1,n} (T_n - T_{n-1}) + \bar{k}'_{n-1,n} (T'_n - T'_{n-1}) \right] \tag{22}$$

where

$$\bar{k}_{n,n+1} = \frac{k_n + k_{n+1}}{2} \tag{23}$$

and prime (') designates the current iteration.

The boundary conditions are

$$\left. \frac{dT'}{dR} \right|_{R=0} = 0 \tag{24}$$

and

$$\frac{dT'_N}{dR} = \frac{h(T'_N - T'_w)}{-k'_N} \tag{25}$$

where

T'_w = coolant temperature

h = heat transfer coefficient.

N simultaneous equations of the form

$$a_n T'_{n-1} + b_n T'_n + g_n T'_{n+1} = d_n$$

are obtained by writing Equation (22) for each of the N regions where a, b, g, and d are constants for a given iteration.

The N equations form a matrix equation which is solved by the method described in Reference 5 for the temperatures at each node.

6.2 Variable Gap Model (to allow for variation of gap conductance during a transient)

Gap conductance, h, can be expressed as $k/\Delta G$, where k is the gap thermal conductivity and ΔG is the gap thickness.

RELAP3B allows for a variable gap width. The formulation used is essentially that of GAPCON[16], namely:

$$\Delta G = \Delta G_o - (a+b\bar{T}_f)\bar{T}_f + c\,\bar{T}_{cl} + \Delta G_{min} \quad , \qquad (26)$$

where ΔG_o is the nominal room temperature gap width, $\bar{T}_f$ and $\bar{T}_{cl}$ are the average fuel and clad temperatures and ΔG_{min} accounts for the effect of asperities and the temperature jump distances. Asperities are deviations from the normal dimensions, and temperature jump distances represent the temperature discontinuities that occur at the cladding and fuel surfaces as a result of incomplete energy interchange between the surfaces and the gas. (Fig. 5). In equation (26) the product of the nominal fuel radius and the linear part of the fuel expansion coefficient is denoted by a; similarly the product of the nominal fuel radius and the quadratic part of the fuel expansion coefficient is denoted by b. The product of the mean clad radius

and clad expansion coefficient is given by c. The gap thickness is limited by the requirement $\Delta G \geq \Delta G_{min}$; no pressure collapse of the asperities is considered.

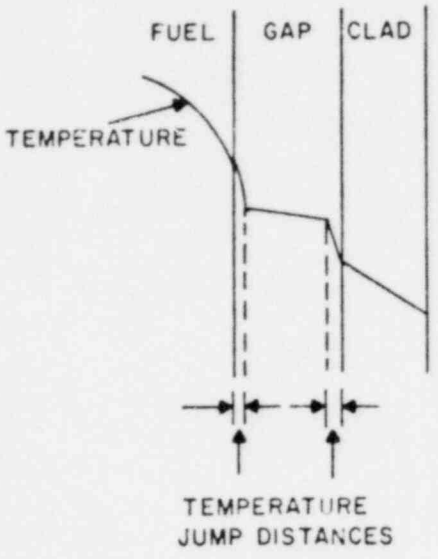

FIG. 5 VARIABLE GAP MODEL FOR FUEL PIN HEAT CONDUCTION.

6.3 Heat Transfer Correlations

Correlations for predicting heat transfer coefficients for seven different modes of heat transfer are provided. The correlations and conditions for which they are used are given below. In PWR cases for pressures greater than 3208.2347 psia the quality is set to 0.0.

Mode 1 -- Subcooled Forced Convection: $X \leq 0.0$, $T_s < T_{NB}$

Sieder-Tate correlation[6]

$$h = \frac{0.023k_f(T_w)}{D}\left[\frac{DG}{\mu_f(T_w)}\right]^{0.8}\left[Pr(T_w)\right]^{1/3}\left[\frac{\mu_f(T_w)}{\mu_f(T_s)}\right]^{0.14} \quad (27)$$

h = heat transfer coefficient, Btu/ft^2 hr °F

X = mass fraction of steam (quality)

T_{NB} = minimum surface temperature for nucleate boiling as defined by Equation (28), °F

$k_f(T_w)$ = saturated liquid thermal conductivity evaluated at T_w, Btu/ft hr °F

T_w = temperature of coolant, °F

D = hydraulic diameter of flow channel, ft

G = mass flux of coolant, lb/ft^2 hr

$\mu_f(T_w)$ = saturated liquid viscosity evaluated at T_w, lb/ft hr

$Pr(T_w)$ = Prandtl number for coolant

$\mu_f(T_s)$ = saturated liquid viscosity evaluated at T_s, lb/ft hr

T_s = fuel pin surface temperature, °F

subscript f indicates saturated liquid property

subscript g indicates vapor property.

Mode 2 -- Subcooled Nucleate Boiling: $X \leq 0.0$, $T_s \geq T_{NB}$

Thom correlation[7]

$$T_S = T_{sat} + 0.072\, e^{-P/1260}\, \phi_S^{0.5} \qquad (28)$$

$$h = \frac{\phi_S}{T_s - T_w} \qquad (29)$$

where

T_{sat} = saturation temperature, °F

P = pressure, psi

ϕ_S = surface flux, Btu/hr ft^2.

Mode 3 -- Nucleate Boiling: $0 < X < 0.1$

The heat transfer coefficient is calculated by interpolating with respect to quality between Equations (29) and (30).

Mode 4 -- Forced Convection Boiling: $0.1 \leq X < 0.6$

Schrock and Grossman correlation with Wright constants[8]

$$h = 6700 \left[\frac{\Phi_S}{GH_{fg}} + 0.00035 \left\{ \left(\frac{X}{1-X} \right)^{0.9} \left(\frac{\rho_f}{\rho_g} \right)^{0.5} \left(\frac{\mu_g}{\mu_f} \right)^{0.1} \right\}^{0.66} \right]$$

$$\left[\left(\frac{0.023 k_f}{D} \right) \left(\frac{DG(1-X)}{\mu_f} \right)^{0.8} \left(P_r \right)^{0.4} \right] \qquad (30)$$

The physical properties are evaluated at saturation conditions where

H_{fg} = heat of vaporization, Btu/lb

ρ = density, lb/ft^3

k = thermal conductivity, Btu/hr-ft-°F

Mode 5 -- Forced Convection Boiling: $0.6 \leq X < 1.0$

The heat transfer coefficient is calculated by interpolating with respect to quality between Equations (30) and (31).

Mode 6 -- Single Phase Steam: $X \geq 1.0$

Dittus-Boelter correlation[9]

$$h = 0.023 \frac{k_g}{D} \left(\frac{DG}{\mu_g} \right)^{0.8} \left(Pr_g \right)^{0.4} \qquad (31)$$

Physical properties are evaluated at $\frac{T_W + T_S}{2}$.

Mode 7 -- Stable Film Boiling: ϕ_S has exceeded the critical heat flux.

Dougall-Rohsenow correlation[10]

$$h = 0.023 \frac{k_g}{D}\left[\left(\frac{DG}{\mu_g}\right)\left(\frac{\rho_f}{\rho_g}(1-X) + X\right)\right]^{0.8}\left[Pr_g\right]^{0.4} \qquad (32)$$

The physical properties are evaluated at saturation conditions. If $X \leq 0.0$, the term $[\frac{\mu_g}{\mu_f}(1-X) + X]$ is set equal to 1.0, which reduces Equation (32) to Equation (31).

Once the heat transfer goes into Mode 7 in any volume it remains in Mode 7 regardless of the tests cited above.

7. CRITICAL HEAT FLUX

The choice of a correlation for predicting the critical heat flux depends upon the pressure and mass flux. If the surface flux exceeds the predicted critical heat flux, stable film boiling is assumed to occur.

The correlations and the conditions under which they are used are as follows:

Range 1 — P < 725 psi: Modified Barnett correlation[a]

$$\frac{\phi_{CHF}}{10^6} = \frac{B + E\,(H_f - H_{in})}{F + L} \tag{33}$$

where

$$B = [73.71\, D_{HE}{}^{0.0523} G^{0.663} (1.0 - 0.315e^{-11.34 D_{HY} G'}) 888.6][H_{fg}]^{-1} \tag{34}$$

$$E = 0.104\, D_{HE}^{1.445}\, G^{0.691} \tag{35}$$

and

$$F = 45.55 D_{HY}{}^{0.0817} G^{0.587} \tag{36}$$

P = pressure, psi

ϕ_{CHF} = critical heat flux, Btu/hr ft^2

H_f = saturated liquid enthalpy, Btu/lb

[a] New constants were derived for the Barnett[11] correlation for low pressure rod bundle data by Idaho Nuclear Corporation.

H_{in} = inlet enthalpy, Btu/lb

L = channel length, in.

D_{HE} = heated equivalent diameter, in.

G' = mass flux, 10^6 lb/hr ft^2

D_{HY} = $[Dr(Dr + D_{HE})]^{1/2}$ - Dr, in. (Dr = pin diameter)

H_{fg} = heat of vaporization, Btu/lb

Range 2 -- 725 psi $\leq$ P < 1000 psi

The critical heat flux is calculated by linear interpolation with respect to pressure between Equations (33) and (37).

Range 3 -- 1000 psi $\leq$ P < 1500 psi: Barnett correlation[11]

$$\frac{\phi_{CHF}}{10^6} = \frac{J + M\,(H_f - H_{in})}{R + L} \tag{37}$$

where

$$J = 67.45\, D_{HE}^{0.68} (G')^{0.192}\, [1.0 - 0.744 \exp(-6.512\, D_{HY}\, G')] \tag{38}$$

$$M = 0.2587\, D_{He}^{1.261} (G')^{0.817} \tag{39}$$

$$R = 185.0\, D_{HY}^{1.415} (G')^{0.212}. \tag{40}$$

Range 4 -- 1500 psi $\leq$ P < 1800 psi

The critical heat flux is calculated by linear interpolation with respect to pressure between Equations (37) and (41).

Range 5 -- P $\geq$ 1800 psi, G > 0.5 x 10^6 lb/hr ft^2

B&W-2 correlation[12]

$$q''_{CHF} = \frac{S[3.702 \times 10^{7} W^{Z} - 0.15208 G H_{fg} X]}{12.71 Y^{N}} \quad (41)$$

where

$$S = [1.15509 - 0.40703 D_{hY}] \quad (42)$$

$$W = (5.9137 \times 10^{-7} G) \quad (43)$$

$$Z = [0.8304 + 6.8479 X 10^{-4}(P - 2000)] \quad (44)$$

$$Y = (3.0545 \times 10^{-6} G) \quad (45)$$

and

$$N = [0.71186 + 0.00020729 (P - 2000)] \quad (46)$$

where

G = mass flux, lb/hr ft^2

X = quality.

Range 6 -- P $\geq$ 1800 psi: G $\leq 0.5 \times 10^{6}$ lb/hr ft^2

The critical heat flux is calculated by using the average value between Equations (37) and (41).

The inlet enthalpy used in the critical heat flux correlations is defined as the flow weighted enthalpy from all junctions connected to the volume. That is, inlet junctions with positive flow and outlet junctions with negative flow.

8. POWER GENERATION

Power generation is determined by either a reactor kinetics calculation or by a tabular input of power versus time. The reactor kinetics equations are solved by a method similar to that used in the IREKIN program [13]. The standard reactor kinetics equations are

$$\frac{dn}{dt} = \frac{\beta}{\Lambda} [(\rho/\beta) - 1] n + \sum_{i=1}^{6} \lambda_i C_i + S \qquad (47)$$

$$\frac{dC_i}{dt} + \lambda_i C_i = \frac{\beta_i}{\Lambda} n, \quad i=1, 2 \ldots 6 \qquad (48)$$

$$\beta = \sum_{i=1}^{6} \beta_i \qquad (49)$$

where

n = reactor fission power

β = effective delayed neutron fraction

Λ = neutron generation time

ρ = reactivity

λ_i = decay constant of delayed neutron group i

C_i = concentration of delayed neutron group i

S = neutron source

β_i = effective fraction for delayed neutron group i.

Also included as an option in the reactor kinetics subroutine are 11 groups of radioactive gamma heat sources:

$$\frac{d\gamma_j}{dt} + \lambda_j \gamma_j = E_j n, \quad j=1, 2, \ldots 11 \qquad (50)$$

where

γ_j = concentration of delayed gamma group j

λ_j = decay constant of delayed gamma group j

E_j = yield fraction of delayed gamma group j.

The total power is a sum of the direct fission power and the instantaneous gamma heating. All power is assumed to be generated in the fuel elements, direct gamma heating of the coolant not being considered. The inclusion of the gamma terms gives a more realistic shutdown transient. The total power, P, is

$$P = n E_f + \sum_{j=1}^{11} \lambda_j \gamma_j \tag{51}$$

where

E_f = fraction of power produced in steady state by fission

If the gamma heating option is not used, then $E_f = 1$; otherwise, $E_f = 0.93$ and $E_j = 0.07$.

9. REACTIVITY

As input to the reactor kinetics calculations, reactivity is developed explicitly as a known function of time and implicitly through core feedback mechanisms. The explicit input reactivity is calculated from a table of ρ/β versus time, and feedback reactivity is determined from coolant density, coolant temperature, and fuel temperature for each reactor volume.

The void reactivity is calculated by density changes in the coolant:

$$(\rho/\beta)_v = \sum_i 100 a_{vi} \left(1 - \frac{\rho_i}{\rho_{io}}\right) \tag{52}$$

where

$(\rho/\beta)_v$ = void reactivity

α_{vi} = void reactivity coefficient of core region i

ρ_i = coolant density in core region i

ρ_{io} = initial coolant density in core region i.

Likewise, the temperature-dependent reactivities are

$$(\rho/\beta)_{WT} = \sum_i \alpha_{WT_i} \Delta T_{bc_i} \tag{53}$$

$$(\rho/\beta)_{FT} = \sum_i \alpha_{FT_i} \Delta T_{f_i} \tag{54}$$

$$(\rho/\beta)_{DOP} = \sum_i \lambda_{DOP_i} \left[\frac{f(\rho_i(0)) + f(\rho_i(t))}{2}\right]\left[(T_{f_i}(t)+459.69)^P-(T_{f_i}(0) + 459.69)^P\right] \tag{55}$$

where

$(\rho/\beta)_{WT}$ = coolant temperature reactivity

α_{WT_i} = coolant temperature reactivity coefficient of core region i

ΔT_{bc_i} = change in bulk coolant temperature in core region i

$(\rho/\beta)_{FT}$ = fuel element temperature reactivity

α_{FT_i} = fuel element temperature reactivity coefficient of core region i

ΔT_{f_i} = change in fuel element temperature in core region i

$(\rho/\beta)_{DOP}$ = Doppler reactivity

λ_{DOP_i} = Doppler reactivity feedback coefficient evaluated at the core inlet coolant density

$f(\rho_{coolant})$ = variation of Doppler reactivity feedback coefficient with coolant density.

T_{fi} = fuel element temperature in core region i.

p = constant used to fit Doppler reactivity variation with fuel temperature. (Usually $\sim$ 0.5)

$\rho_i(0)$ = the initial average coolant density in core region i

$\rho_i(t)$ = the average coolant density in core region i at time t

In the input data $f(\rho_{coolant})$ is entered as the Doppler Multiplier-Coolant Density Curve. Since only the product $\alpha_{DOP_i} \cdot f(\rho_{coolant})$ is of importance, and not the separate quantities, it is convenient (but not required) to define α_{DOP_i} and $f(\rho_{coolant})$ in such a way that $f(\rho_{inlet}) = 1.0$, where ρ_{inlet} is the initial core inlet coolant density.

The total reactivity is obtained by summing the contributions from control rods, water void, water temperature, fuel temperature, and Doppler effects.

10. TWO-PHASE SEPARATION MODEL

The two-phase separation model used in RELAP3B is a semiempirical fit to a number of experimental, high pressure blowdowns[14].

The quantities necessary to describe the separation of steam bubbles into a gas dome are the partial density of the bubbles and the local bubble velocity at the steam-dome mixture interface. Physically, during a continuous decompression of a large stagnant volume, the density of bubbles is expected to be least near the bottom of the volume. This distribution is reasonable because the static pressure will be highest near the bottom

and because the bubbles tend to accumulate as they rise through the mixture. The first order approximation is one in which the density of bubbles increases linearly as a functior of height within the two-phase mixture. A limitation of this model is its inability to describe bubble distributions arising from complicated physical conditions, such as oscillating pressures or oscillating flows.

The assumed bubble distribution is

$$\rho_{gb} = m \frac{z}{Z_m} + b \tag{56}$$

where

ρ_{gb} = partial steam density within the mixture

m,b = time-dependent slope and intercept

z = height above the bottom of the volume

Z_m = time-dependent height of mixture interface.

The slope and intercept of the assumed bubble distributions are evaluated by applying conservation of mass. Integrating the partial bubble density over the volume of the mixture gives the instantaneous mass of steam within the mixture. For an average void fraction less than 0.5, that is

$$0 \leq \frac{M_{gb}}{\rho_g V_m} \leq \frac{1}{2} \tag{57}$$

where

M_{gb} = mass of steam entrained in the mixture

ρ_g = density of saturated steam

V_m = volume of the mixture,

the slope and intercept are

$$m = 2C_o \frac{M_{gb}}{V_m} \tag{58}$$

$$b = (1-C_o) \frac{M_{gb}}{V_m} . \tag{59}$$

For average void fractions between 0.5 and 1,

$$\frac{1}{2} \leq \frac{M_{gb}}{\rho_g V_m} \leq 1 , \tag{60}$$

the slope and intercept are

$$m = 2C_o \left(\rho_g - \frac{M_{gb}}{V_m} \right) \tag{61}$$

$$b = (1+C_o) \frac{M_{gb}}{V_m} - C_o \rho_g . \tag{62}$$

To generalize this model, an arbitrary constant, C_o, is included. This constant (which must be limited to values between zero and one) determines the maximum bubble gradient at any instant. If the constant is chosen as zero, the mixture is homogeneous; if chosen as one, the bubble gradient is always maximum within the permissible physical constraints. Values outside this range may give negative values for the partial bubble density and so are not allowed. Within RELAP3B, each

volume can have an individual C_o chosen by the user. Small volumes with high mass flux such as core channels or pipe sections are best described by a homogeneous model where $C_o = 0$. In plenums and tanks where the homogeneous model is not desirable, a value of $C_o = 0.8$ is recommended. This value was determined as a best choice for a one-volume description of experimental vessel blowdowns[15].

The velocity of steam bubbles relative to the mixture interface is another input quantity which can be different for each volume. In the preceeding referenced model test, a value of three feet per second was used. If the velocity is zero, no separation occurs although a bubble density gradient may still exist.

By using Equation (56), the local fluid quality is determined for each junction at its connection to a volume. The partial steam density at the surface of the mixture (needed to calculate the rate at which bubbles cross the interface) is also obtained from Equation (56).

To determine the mass and quality of the mixture, a balance for the entrained steam must be performed. Steam can be added to a volume either through a junction or by flashing of liquid within the mixture. The differential equation describing the bubble mass balance within a given volume is

$$\frac{dM_{gb}}{dt} = \frac{dM_s}{dt} - \Sigma \varphi_i X_i W_i - A v_{bub} \rho_{gb}\Big|_{Z_m} \tag{63}$$

where

M_{gb} = mass of steam (gas bubbles) entrained in the mixture

M_s = total mass of steam within the volume

v_i = fraction of steam flowing at the junction and originating within the steam dome

X_i = quality of junction flow

W_i = flow into or out of the volume at junction i

A = cross-sectional area of the volume

$_{bub}$ = bubble velocity at mixture surface

$\rho_{gb}|_{Z_m}$ = partial steam density at the mixture surface.

II. JUNCTION QUALITIES

Since junctions at control volume boundaries are treated as points rather than distributed areas (so far as fluid properties within the volume are concerned), qualities at these points can oscillate between zero and one. Also, when junctions are near the top or the bottom of a volume, more gas or liquid can be extracted than really exists within the volume. If during a blowdown, the mixture level falls to a junction, then during one time step the flow will be two phase and then change to pure steam the following time step. Under these conditions the flow can be large enough to extract more steam than is physically present. To eliminate these difficulties, the flow during any single time step is assumed to be composed of a combination of steam and mixture when the mixture level is adjacent to the junction location. This modification smooths the time step variation of junction quality and virtually eliminates the time step size instability associated with oscillating mixture levels.

12. FILL SYSTEMS

Fluid may be injected into any volume by means of fill junctions. The junction flows are obtained by interpolating tabular input of flow versus either time or pressure. Several fill junctions may connect to the same volume if desired. Initiation of flow through fill junctions may be controlled by many different trip signals. No cut-off is allowed except implicitly through the flow versus time table. For positive fill rate values the fluid has the properties of the fill reservoir; for negative fill rate values the fluid has the properties of the volume from which it is flowing.

13. SYSTEM BALANCES

An overall mass balance is performed:

$$M_B = \sum_i M_i + \int \sum_j W_j dt - \int \sum_k W_k dt \qquad (64)$$

where

M_B = mass balance

M_i = mass in volume i

W_j = flow in leak junction j

W_k = flow in fill junction k.

Energy within the system described by RELAP3B can be stored, injected, or removed by several mechanisms. In general, the total energy at any time within the reactor system is

$$E_T = E_f + \Sigma E_i \qquad (65)$$

where

E_T = total energy stored

E_f = energy stored within fuel elements

E_i = internal energy of water in volume i.

The energy stored within the fuel elements is

$$E_f = \sum_m \left[\sum_n (\rho V)_n C_n T_n \right]_m \tag{66}$$

where

m = core region number

n = node number

ρ = density

V = node volume

C = specific heat capacity

T = temperature.

Energy can be extracted from the system through leaks or heat exchangers, respectively, as

$$E_\ell = \int_0^t \sum_j W_j h_j dt \tag{67}$$

and

$$E_{HE} = \int_0^t \sum_m Q_{HE_m} dt \tag{68}$$

where

E_ℓ = energy lost through leakage

W_j = flow through leak j

h_j = enthalpy of fluid flowing through leak j

E_{HE} = heat removed by heat exchangers

Q_{HE_m} = rate of heat loss through heat exchanger m.

Energy can be added to the system by the reactor power and the fill water injection, respectively, as

$$E_{RP} = \int_0^t \sum_m Q_{RP_m} dt \tag{69}$$

and

$$E_F = \int_0^t \sum_k W_k h_k dt \tag{70}$$

where

E_{RP} = heat added through nuclear fission

Q_{RP_m} = rate of heat addition in core region m

E_F = heat added through fill water injection

W_k = flow through fill junction k

h_k = enthalpy of fluid flowing through fill k.

Applying the conservation of energy principle to the system gives

$$E_{initial} = E_{stored} + E_{extracted} - E_{injected} \tag{71}$$

or

$$\text{Energy Balance} = \sum E_i + E_f + E_\ell + E_{HE} - E_{RP} - E_F \; . \tag{72}$$

This energy balance is computed and available in the minor edit list. The first time step edit gives the initial energy inventory because the time integral terms are zero.

14. CHECK VALVES

Check valves may be placed, at the users option, in any RELAP3B junction. Three pressure loss coefficients, C_i, and the back pressure necessary to close the valve, P_{cv}, are user supplied input constants. The user also has a choice of valve type: Type 1 without a hysteresis loop in the characteristic flow versus pressure curve and Type 2 with the hysteresis loop. The characteristic curves for these two types are shown in Figure 6. Both types of check valves are controlled by flow dependent pressure losses of the form $C_i W|W|/\rho$.

Three regions of operation are defined for each valve:

(1) C_1 is used for positive flow with the valve open

(2) C_2 is used for negative flow with the valve open

(3) C_3 is used for negative flow with the valve almost closed.

For all positive flow, the valve remains open and sustains a pressure loss proportional to C_1. For negative flow, the valve remains open if the pressure loss, which is proportional to C_2, is less then the back pressure required to close the valve.

After the valve closes, the pressure loss is proportional to C_3 for small leakage flows. The hysteresis difference between Type 1 and Type 2 check valves is apparent in Figure 6. Type 1 check valves open in exactly the reverse procedure of the closing sequence. A Type 1 valve opens when negative flow has decreased to a value such that the pressure loss for the open phase is less than the loss required to keep the valve closed. A Type 2 valve reopens only when the pressure loss developed in the closed position is less than the required back pressure.

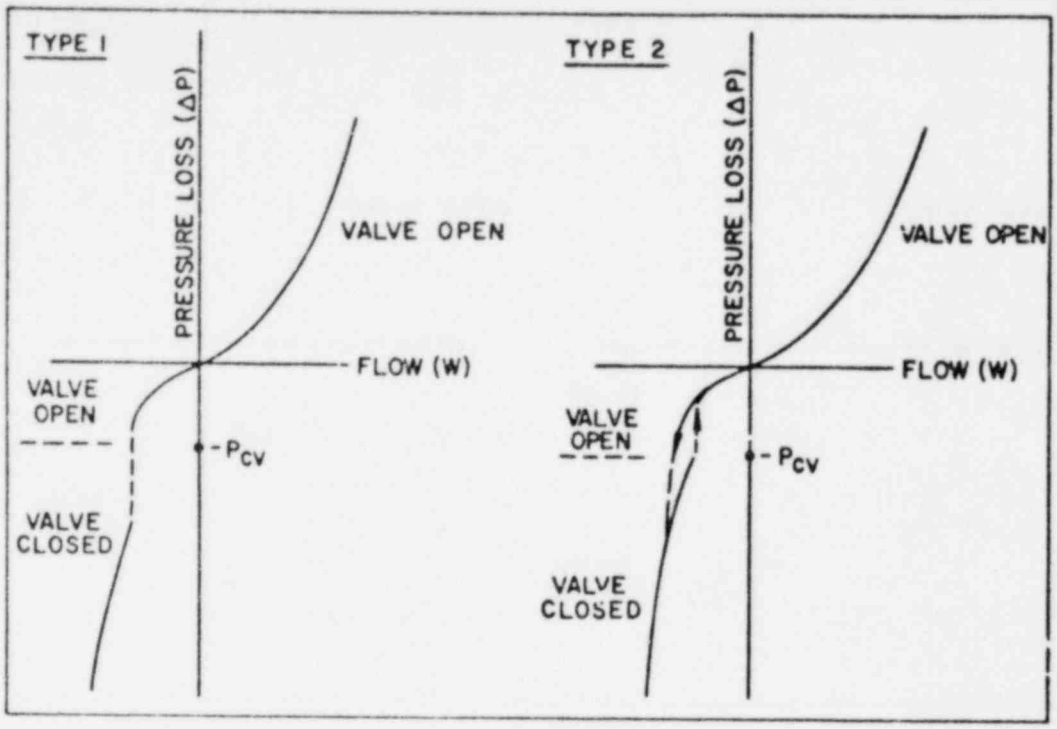

FIG. 6 CHECK VALVE CHARACTERISTIC CURVES.

15. CALCULATION OF WEIGHT FACTORS AND POWER FRACTIONS

RELAP3B uses point reactor kinetics, but even in this simple formulation some of the effects of space dependence can be included by means of reactivity weight factors. The reactivity weight factor model takes a specified steady state axial power distribution and determines associated fuel, gap, clad, and moderator temperatures, along with coolant voidage (if any). The model [17] is based on the temperature model used in NØAH and TWIGL-BNL (one- and two-dimensional transient neutronics codes in use at BNL). Several options are allowed when using the weight factor model. Subcooled voidage and variable slip (based on a modified Bankoff-Jones model) are the normal options, but constant slip (of any specified value) and a thermodynamic heating model (no subcooled voidage) are also allowed. After the calculation of the temperature and void distributions,

Average weight factors and average feedback coefficients are defined in core region I by the following relations:

Average Axial Doppler Weight Factor,

$$D.W.F. = \frac{\int_I P^2(z)\ \ (T_f{}^p(z) - T_{in}{}^p)\ \ dz}{\left(\sum_I \int_I P^2(z)dz\right)\left[\left(\left(\int_I T_f(z)dz\right) \Big/ \int_I dz\right)^p - T_{in}{}^p\right]} \qquad (73)$$

where T_f and T_{in} are in ^oR, T_f is the fuel temperature, T_{in} is the coolant inlet temperature, p is the Doppler exponent (usually 1/2), and P is the specified steady state axial power distribution.

Average Moderator Temperature Feedback Coefficient of Reactivity,

$$M.F.C. = \frac{\int_I \alpha_m\ (T_m(z))P^2(z)\ T_m(z)dz}{\left(\sum_I \int_I P^2(z)\ dz\right)\ \left(\int_I T_m(z)\ dz\right) \Big/ \int_I dz} \qquad (74)$$

Here T_m is the moderator temperature <u>increase</u> above the inlet value and α_m may be a function of T_m.

Average Moderator Void Feedback Coefficient of Reactivity,

$$V.F.C. = \frac{\int_I \alpha_v(V(z))\ P^2(z)V(z)dz}{\left(\sum_I \int_I P^2(z)dz\right)\left(\int_I V(z)dz\right) \Big/ \int_I dz} \qquad (75)$$

Here V(z) is the local void fraction and α_v may be a function of void fraction.

α_m = the moderator temperature feedback coefficient.

α_v = the homogeneous void feedback coefficient.

Because RELAP3B defines exit and average moderator properties to be the same while the weight factor model defines the coefficients in terms of average values, corrections must be made to M.F.C. and V.F.C. These corrections are

$$\text{M.F.C.}_{\text{corrected}} = \text{M.F.C.} \int_I T_m(z)dz / (T_I \int_I dz) \tag{76}$$

where T_I is the value of $T_m(z)$ at the end of region I, and

$$\text{V.F.C.}_{\text{corrected}} = \text{V.F.C.} \left(-V_I + \rho_\ell / (\rho_\ell - \rho_g) \right) \left(\frac{\int_I V(z)dz}{V_I \int_I dz} \right)^2 \frac{X_I}{\bar{X}_I} \tag{77}$$

where V_I is the end of region value of V(z), X_I is the end of region value of the quality, $\bar{X}_I$ is the region I average quality, and ρ_ℓ and ρ_g are the saturated liquid and vapor densities.

The power fractions QFRAC(I) in the core regions are given by

$$\text{QFRAC(I)} = \frac{\int_I P(z)dz}{\sum_I \int_I P(z)dz} \tag{78}$$

16. IMPLICIT NUMERICAL MODEL AND AUTOMATIC TIME-STEP VARIATION

Implicit Numerical Model

RELAP3B, based on RELAP3-Mod 62, uses an implicit scheme for advancing the time. However, the scheme used in MOD 62 is not fully implicit. Three important explicit factors remain: first, the fuel-gap-clad temperatures are calculated from the coolant temperature at the previous time step; second, the coolant enthalpies in the transport term of the energy equation are taken at the previous time step; and

third, the point kinetics equations are solved by Runge-Kutta. The model is thus a mixed one with the major effect of the current implicit structure being the elimination of the effect of the velocity of sound in the limitation on the time step size.

Besides the fact that h_{ij} (the junction enthalpy) is taken at the previous time step, the calculation of h_{ij} from h_i (the volume average enthalpy) is done by assuming $h_{ij} = h_i$ (exit enthalpy = average enthalpy). While such an approximation is not unreasonable if the space increment is small (not only small volume, but small flow distance), it is not clear how valid it is for large volumes. A corollary is that average temperatures, void fractions and heat transfer coefficients and modes are not completely accurate.

Automatic Time-Step Variation

Full advantage can be taken of the implicit differencing technique if one can automatically increase the computation time-step size during the slowly varying portions of a transient. At every time step RELAP3B can test the percentage change in each of several edited variables, e.g. EV, from a criterion value, CRIT(EV). Thus, for normalized power, NQ, the test is

$$\frac{NQ(t+\Delta t)-NQ(t)}{NQ(t)} \leq \text{CRIT (NQ)}$$

If the test fails, the time step size, Δt, is automatically halved and the time step repeated. Otherwise, the calculation continues. After every 40 consecutive time steps in which the step size was not changed the time-step size is automatically doubled. An input item allows the specification of both a minimum and a maximum time-step size. Informative statements on the time-step status are printed out between major edits.

17. PUMPS

The pumps are described by a so-called homologous model [18]. The model gives relations among the variables Head (H), Torque (T), flow rate (Q), and rotational speed (ω). First these variables are normalized by dividing each one by its value at rated conditions. Thus the new variables are

$h = H/H_r$

$\beta = T/T_r$

$v = Q/Q_r$

$\alpha = \omega/\omega_r$.

The four quantities H_r, T_r, ω_r, and Q_r are required in the input, where they are called PHEADR, PTORKR, POMGAR, and PFLOWR.

The homologous modelling relates h, v, and α (fig. 7) by tabulating

h/v^2 vs α/v when $|\alpha/v|$ is between 0 and 1

and

h/α^2 vs v/α when $|v/\alpha|$ is between 0 and 1.

It relates β, v, and α (fig. 8) by tabulating

β/v^2 vs α/v when $|\alpha/v|$ is between 0 and 1

and

β/α^2 vs $v/\alpha|$ when $|v/\alpha|$ is between 0 and 1.

The pressure differential Δp through the pump is given by

$\Delta p = \rho H$

where ρ is the average fluid density in the pump, and H is the pump head defined in the foregoing paragraphs.

During a coast-down, the rotor acceleration is related to the net torque through

$$I \frac{d\omega}{dt} = -T_{HY}\left(\rho/\rho_r\right) - T_{frict}\left(\omega|\omega|\right)/\omega_r^2 \qquad (79)$$

Here I is the moment of inertia, T_{HY} is the hydraulic torque described in the previous paragraphs, and T_{frict} is the frictional torque at rated conditions. The moment of inertia and the frictional torque at rated conditions are required input, where they are called respectively PINRTA and TORFR. The density at rated conditions ρ_r is required in the input where it is called VRHOI. The input parameter PSRAT is the ratio, Initial Speed/Rated Speed.

The code has head and torque tabulations for two pumps already built in. The first set is described as "Bingham Pump with NS=4200." The second set is described as "Westinghouse Pump with NS=5200," NS being the "specific speed." A calculation may use up to four different head/torque tabulations. When a set of head/torque values is to be read in, they appear in eight segments depending on whether α is positive or negative, β is positive or negative and α/v is between 0 and 1 or v/α is between 0 and 1. For each segment the appropriate head or torque data is read in as a table of values vs. the appropriate independent variable v/α or α/v.

The location of a pump is defined by the volume in which it resides and the junctions which provide the pump inlet and outlet. A given set of pump characteristics may appear in more than one volume; this corresponds to having identical pumps in those volumes. A pump volume is specified by setting the parameter IPUMP on the junction card to a negative pump number for the suction side junction and a positive pump number for the discharge side junction. The output listed as SPEED for the outlet junction is NORMALIZED TORQUE. Half of the pump head is assigned to the junction at the inlet to the volume containing the pump and half to that at the outlet.

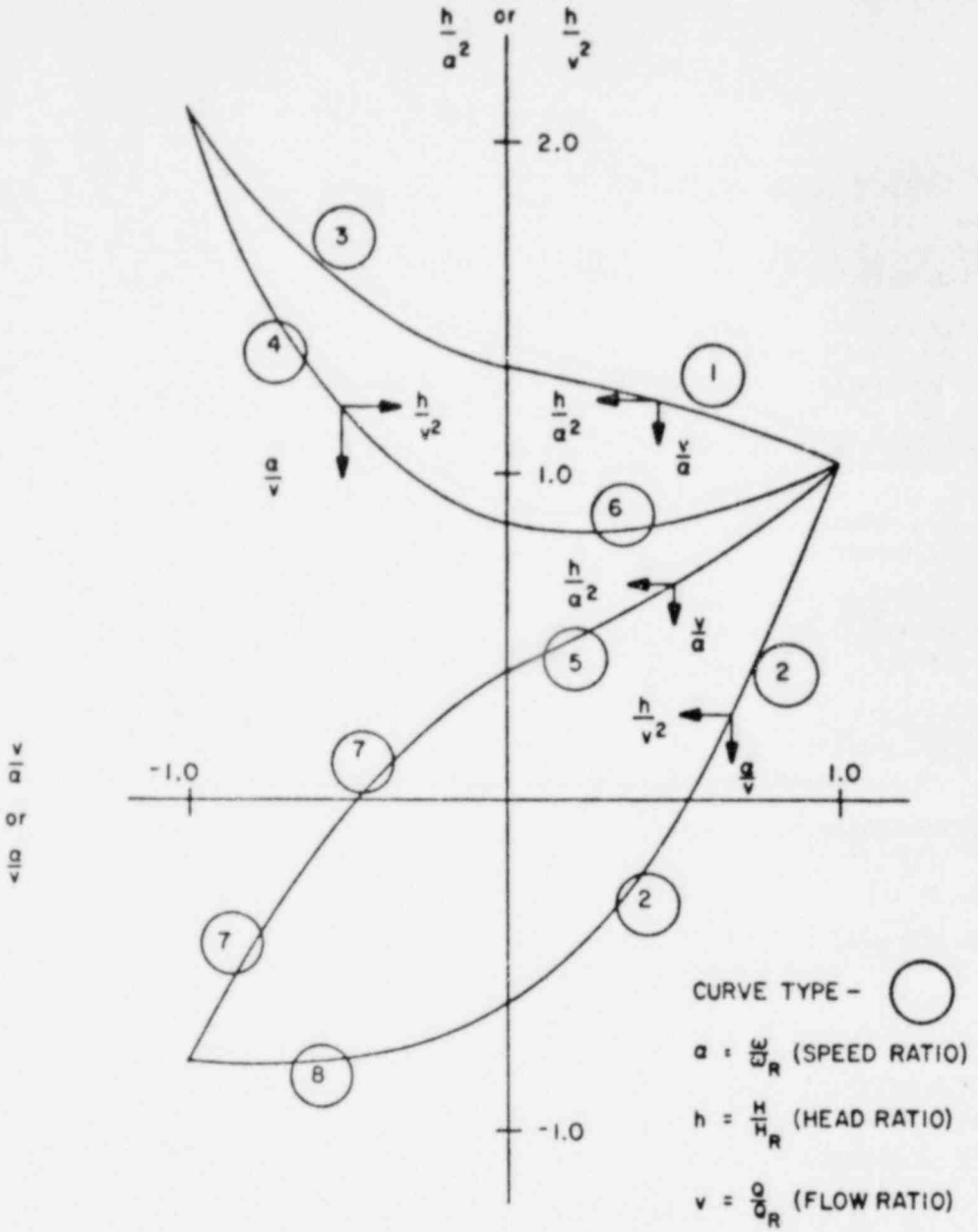

FIG. 7 PUMP HEAD CURVES - REDUCED FORM OF PUMP CHARACTERISTICS.

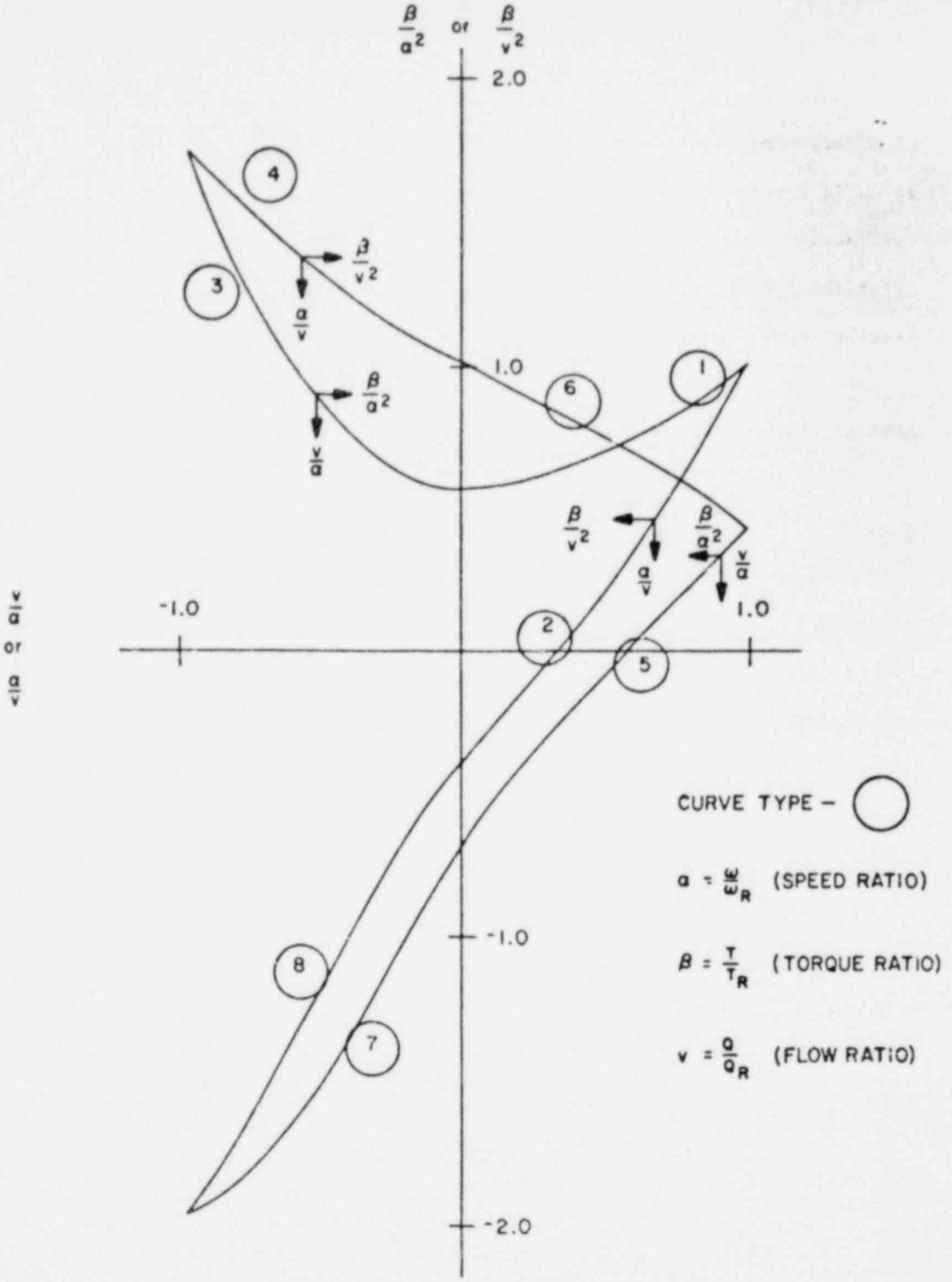

FIG. 8 PUMP TORQUE CURVES - REDUCED FORM OF PUMP CHARACTERISTICS.

18. LEAKS

Leaks are described by a constant sink pressure and a leak area vs. time curve that is activated by a trip signal. The leak area (L) is given in square feet by L = AJUN x CONCO x AREA(t) where CONCO is the contraction coefficient (dimensionless), AREA(t) is the area at time t after the leak trip signal has been activated and AJUN is the minimum flow area for choked flow calculations.

In the input to RELAP3B if AJUN is specified in ft^2 ($|AJUN|>0$) AREA(t) must be dimensionless. If AJUN is specified as zero, AJUN is set to 1.0 in the program and treated as a dimensionless multiplier. In this case AREA(t) must be entered in units of ft^2.

Using the constant sink pressure an initial flow is computed with the junction friction coefficient optionally multiplied by a two-phase friction pressure drop multiplier. The choked flow is computed if suitable conditions exist and the flow is chosen as the smaller of the inertial flow and the choked flow.

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APPENDIX A

APPROXIMATIONS TO THE CONSERVATION EQUATIONS

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APPROXIMATIONS TO THE CONSERVATION EQUATIONS

The following brief description of the fluid equations used in RELAP3B is based upon the fundamental mass, energy, and momentum conservation equations[a].

These equations are

(a) Mass conservation

$$\frac{\partial \rho}{\partial t} = - \vec{\nabla} \cdot (\rho \vec{v}) \qquad \text{(A-1)}$$

where

ρ = fluid density

and

$\vec{v}$ = local fluid velocity.

(b) Energy conservation

$$\frac{\partial (\rho e)}{\partial t} = - \vec{\nabla} \cdot (\rho e \vec{v}) - \vec{\nabla} \cdot \vec{q} - \vec{\nabla} \cdot (p \vec{v}) - \vec{\nabla} \cdot (\vec{\tau} \cdot \vec{v}) \qquad \text{(A-2)}$$

where

e = total specific energy = $u + \frac{v^2}{2} + \phi$

q = heat flux

p = pressure

τ = viscous stress tensor

u = thermodynamic internal energy

ϕ = potential energy function.

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[a] Several excellent references are available on thermal hydraulics; one being by R.B. Bird, W.E. Stewart, and E.N. Lightfoot, Transport Phenomena, John Wiley and Sons, Inc., New York, 1960.

(c) Momentum conservation

$$\frac{\partial(\rho\vec{v})}{\partial t} = -\vec{\nabla}\cdot(\rho\vec{v}\vec{v}) - \vec{\nabla}p - \vec{\nabla}\cdot\vec{\tau} + \rho\vec{g} \qquad \text{(A-3)}$$

where

g = gravitional acceleration constant.

General assumptions include

(a) Stationary control volumes

(b) Axisymmetric, one-dimensional flow

(c) Negligible body forces (except gravity).

Integrating the mass equation over a fixed volume and applying the divergence theorem gives

$$\frac{d}{dt}\int_{v}\rho dv = -\int_{s}\rho\vec{v}\cdot d\vec{s} \qquad \text{(A-4)}$$

or

$$\frac{dM_i}{dt} = \sum W_{ij} \qquad \text{(A-5)}$$

where

M_i = total mass in volume i

and

W_{ij} = mass flow rate into volume i through junction j (surface area j).

In the energy equation, frictional, kinetic, and potential energy effects are assumed negligible. Hence (A-2) becomes

$$\frac{\partial(\rho u)}{\partial t} = -\vec{\nabla}\cdot(\rho h\vec{v} - \vec{q}) \qquad \text{(A-6)}$$

where

h = enthalpy

Integrating (A-6) over volume v_i gives

$$\frac{dU_i}{dt} = \sum W_{ij} h_{ij} + Q_i \qquad \text{(A-7)}$$

where

U_i = thermodynamic energy in volume v_i

h_{ij} = enthalpy content of fluid moving into volume i through junction j

Q_i = rate of energy transferred through surface s_i.

Restricting the momentum equation to one-dimensional flow and integrating over flow volume v_i gives

$$\frac{d}{dt}\int_{v_i} \rho\vec{v}dv = -\int_{s_i} \vec{v}(\rho\vec{v}\cdot d\vec{s}) - \int_{s_i} \vec{\tau}\cdot d\vec{s} - \int_{s_i} p d\vec{s} + \int_{v_i} \rho\vec{g}dv \qquad \text{(A-8)}$$

For the friction term, the pressure losses are assumed proportional to v^2. If the volume v_i is a simple tube with no area changes, then in English units we have, neglecting the momentum flux term,

$$\frac{1}{144 g_c}\left(\frac{\ell_i}{A_i}\right)\frac{d\bar{W}_i}{dt} = -\frac{k_i \bar{W}_i |\bar{W}_i|}{\rho_i} + P_{ij} - P_{ik} - \frac{g}{144 g_c}\int_{Z_{cm1}}^{Z_{cm2}} \rho dz \qquad \text{(A-9)}$$

where

g_c = gravitational conversion constant

ℓ_i = length of pipe in flow volume i

A_i = pipe cross-sectional area in flow volume i

$\bar{W}_i$ = average flow in flow volume i

k_i = RELAP3B friction coefficient for flow volume i

P_{ij} = inlet pressure for flow volume i

P_{ik} = outlet pressure for flow volume i

$Z_{cm1,2}$ = the elevation of the center of mass in each adjacent mass-energy control volume.

The density ρ is determined by the distribution described in III.10.

For a straight section of pipe, the friction term k is directly related to the Fanning friction factor for a single pipe:

$$k = \frac{fA_w}{2(144g_c)A^3} \quad \text{(single pipe)} \tag{A-10}$$

where

f = Fanning friction factor

A_w = wetted wall area

A = cross-sectional area for flow.

For a single flow path with several area changes, the ratio of control volume length to flow area is

$$\frac{\ell}{A} = \sum_{i=1}^{N} \frac{\ell_i}{A_i} \tag{A-11}$$

and momentum flux terms are included as a part of the friction term k. This last simplification is correct only when the flow is unidirectional during the transient. In complex loop systems, the best way to define k is from a steady state condition i.e. from Eq. (A-9) with $d\bar{W}_i/dt = 0$. Noting that $\bar{W}_i$ is by definition positive in a steady state condition, we find

$$k_i = \frac{\left(P_{ik} - P_{ij} - \frac{g}{144g_c}\int_{Z_{cm1}}^{Z_{cm2}} \rho\, dz\right)\rho_i}{\bar{W}_i^2} \tag{A-12}$$

APPENDIX B

OPTIONAL TWO-PHASE FRICTIONAL PRESSURE DROP CORRELATION

APPENDIX B

DEVELOPMENT OF THE OPTIONAL TWO-PHASE FRICTIONAL PRESSURE DROP CORRELATION FOR USE IN RELAP3 AND INCLUDED IN RELAP3B

Based on evaluation of existing correlations, modification of the Baroczy[1] model was undertaken to provide a better fit to experimental data. After considerable trial and error, two fundamental changes to the Baroczy model were selected. First, the method for obtaining the mass flux correction (MFC) for mass fluxes greater than 3×10^6 lb/hr-ft^2 was changed from linear extrapolation to use of the equation:

$$\text{Mass Flux Correction} = \text{MFC} = \frac{(\text{Correction at } G = 3)^{(G-2)}}{(\text{Correction at } G = 2)^{(G-3)}}, \quad \text{for } (G > 3) \qquad \text{(B-1)}$$

where G is the mass flux in millions of lb/hr-ft^2. The method for obtaining mass flux corrections for mass fluxes below 3.0×10^6 lb/hr-ft^2 was not changed, linear interpolations being used for intermediate values in the mass flux correction tables produced from Baroczy's mass velocity correction plots.

The second major change from the Baroczy method is that instead of multiplying the mass flux correction by the two-phase multiplier obtained from a basic graph for a mass flux of 1.0×10^6 lb/hr-ft^2, the final two-phase frictional pressure drop multiplier is obtained from the equation:

$$\text{TPF} = 1.0 + [\text{BM} - 1.0]\ (\text{MFC}) \qquad \text{(B-2)}$$

where TPF is the final two-phase frictional multiplier, and BM is the

basic multiplier obtained from a basic graph for a mass flux of 1.0×10^6 lb/hr-ft^2. This basic plot is modified from Baroczy's basic plot by increasing the multipliers for qualities greater than 40%.

Although there is very little experimental data for mass fluxes greater than 3×10^6 lb/hr-ft^2, the experimental data indicate that the final two-phase frictional multiplier for higher mass flux rates will be correspondingly lower, but still greater than the 1.0 for single-phase liquid flow. Since the new correlation produces only positive values for the mass flux corrections, the second major change from the method of Baroczy, Equation (B-2) combined with Equation (B-1), ensures that the final two-phase frictional multiplier will always be greater than or equal to the 1.0 for single-phase liquid flow, and that an increase in mass flux will produce a corresponding decrease in the final two-phase frictional multiplier. Thus, the new correlation is bounded.

The new correlation was compared with the 590 to 1200 psia CISE[2,3,4] data and the 50 bar ($\approx$ 725 psia) FRIGG-1[5] and FRIGG-2[6] data, indicating satisfactory agreement over the ranges of pressure and mass flux given. However, loss-of-coolant accident may produce pressures outside the 590 to 1200 psia range, and may produce mass flux rates much greater than those present for the CISE and FRIGG data. Therefore, comparisons were made with the 2000 psia data of Sher and Green[7], and with the data of Isbin[8], et al. These additional data extend the pressure range to apply to all of the two-phase portion of the typical loss-of-coolant accident.

A scarcity of frictional pressure drop data for mass flux rates greater than 3×10^6 lb/hr-ft^2 seriously handicaps evaluation of the correlation at high mass flux rates. However, the fact that the correlation is bounded at high mass flux rates is apparent.

To increase the usefulness of the correlation, further refinement has included generation of tables of multipliers for values of pressure and quality to eliminate using the awkward tables of multipliers for values of property index and quality.

The new two-phase frictional pressure drop correlation has been incorporated into the current version of RELAP3B. This version uses, as block data, tables of multipliers as functions of pressure and quality, rather than Baroczy's property index and quality.

This correlation is used in RELAP3B when AJUN, in the junction input data, is greater than zero.

REFERENCES - APPENDIX B

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2. L. Berkowitz et al; "Results of Wet Stream Cooling Experiments: Pressure Drop, Heat Transfer, and Burnout Measurements with Round Tubes," CISE Report, R27 (October 1960).

3. N. Adorni et al; "Results of Wet Steam Cooling Experiments: Pressure Drop, Heat Transfer, and Burnout Measurements in Annular Tubes with Internal and Bilateral Heating," CISE Report, R31 (January 1961).

4. N. Adorni et al; "Design and Construction of Facility for Heat Transfer Experiments with Wet Steam," CISE Report, R23 (July 1960).

5. O. Nylund et al; "Measurements of Hydrodynamic Characteristics, Instability Thresholds, and Burnout Limits for 6-Rod Clusters in Natural and Forced Circulation," FRIGG-1, R4-422/RTL-194, AB ATOM ENERGI STOCKHOLM (1967).

6. O. Nylund et al; "Hydrodynamic and Heat Transfer Measurements on a Full-Scale Simulated 36-Rod Marviken Fuel Element with Uniform Heat Flux Distribution," FRIGG-2, R4-447/RTL-1007 (1968).

7. N. C. Sher and S. J. Green, "Boiling Pressure Drop in Thin Rectangular Channels," Chem. Engr. Symposium Series, No. 23, 55 (1959).

8. H. S. Isbin et al; "Two-Phase Steam-Water Pressure Drops," Chem. Engr. Progr., Symposium Series No. 23, 55 (1959) pp 75-84.

APPENDIX C

INPUT DEFINITIONS

RELAP3B INPUT DEFINITIONS

(1) Title (one card)

FORMAT: 18A4, 2A4

At least one nonblank character must appear somewhere in columns 1-72.

(2) Problem Dimensions (one card)

FORMAT: 15I3, E10.6, 14X, I1, 1X, I1, 2A4

N1	LDMP	=	Tape control (only one tape may be generated during a job) (0 = no tape used) (-1 = store restart information on FORTRAN Unit 4) (-2 = store restart and plot information on FORTRAN Unit 4) (-3 = edit the tape on FORTRAN Unit 3) (N = restart at page number N using the tape on FORTRAN Unit 3) (999 = read last page number from FORTRAN unit 2 and restart at last page of initial run using the tape on FORTRAN unit 3) ($-3 \leq$ LDMP ≤ 999)
N2	NEDI	=	Number of minor edit variables desired ($0 \leq$ NEDI ≤ 9)
N3	NTC	=	Time Step Control $1 \leq$ NTC ≤ 20: time steps are not under automatic control; NTC = number of time step cards. $-9 \leq$ NTC ≤ -1: time steps are under automatic control; the first $\lvert$NTC$\rvert$ variables on the edit variable card will be tested.
N4	NTR	=	Number of trip control cards ($1 \leq$ NTR ≤ 20)
N5	NVOL	=	Number of control volumes ($1 \leq$ NVOL ≤ 75)
N6	NBUB	=	Number of bubble parameter sets to be read in. A set may be used in several volumes ($0 \leq$ NBUB ≤ 25)
N7	NJUN	=	Number of junctions or flow paths ($1 \leq$ NJUN ≤ 100)
N8	NPMPC	=	Number of centrifugal pump types. A pump type may be used in more than 1 volume. ($0 \leq$ NPMPC ≤ 10)

N9	NCKV	=	Number of check valve types. A parameter set may be used for several junctions ($0 \leq NCKV \leq 5$)
N10	NLK	=	Number of normalized-area vs time curves for leak junctions. May be used many times ($0 \leq NLK \leq 5$)
N11	NFLL	=	Number of fill system curves. May be used many times ($0 \leq NFLL \leq 15$)
N12	NOCOR	=	Number of core regions ($0 \leq NOCOR \leq 20$)
N13	NMTL	=	Number of sets of rod geometry ($1 \leq NMTL \leq 20$) if $NOCOR \geq 1$, ($0 \leq NMTL \leq 20$) if $NOCOR = 0$,
N14	NHTX	=	Number of heat exchanger data sets ($0 \leq NHTX \leq 51$)(See item 7, page C-9)
N15	NKC	=	Number of thermal property tables ($NKC \leq 6$)
X1	POWER	=	Reactor thermal power in megawatts ($0. \leq POWER$)
NX1	IFLAG		Applicable to restart runs only If IFLAG = 1, Option to read in reactivity coefficients at restart If IFLAG = 0, Null option
NX2	IMPWR	0	BWR calculation - uses the standard steam tables of RELAP 3B.
		1	PWR calculation (pressure table input required) MOD 2 heat exchanger is U-tube steam generator model.
		2	BWR calculation - rewrite the steam tables. (pressure table input required)
		3	PWR calculation (pressure table input required) MOD 2 heat exchanger is once-through steam generator model.
	ID		Card identification

3. Optional Pressure Table Input (when IMPWR >0)

Limits are 25 pressures/13 liquid temperatures/6 gas temperatures. The input is

Card 1 FORMAT: (4I5)

	ILST = 0	Do not list the tables
or	ILST = 1	list the tables

NPRESS	number of pressures ($\leq$ 25)
NTEMPL	number of liquid temperatures per presssure ($\leq$ 13)
NTEMPG	number of gas temperatures per pressure ($\leq$ 6)

Additional Cards FORMAT: (7E10.5)

Values of pressure for pressure table input - 7 values per card
(0 < P $\leq$ 7000.0 psia)
The current version of RELAP3B defines NTEMPL = 13 and NTEMPG = 6 and disregards the input values.

4. Edit Variable Cards (one card if NEDI >0)

FORMAT: 9(1X, A2, 1X, I2), 18X, 2A4

1	2	4	5	7	8	10	11	13	6I-4	6I+1	73
	X1		N1		X2		N2	------	NI	-BLANK-	ID

(I=NEDI, number of minor edit variables desired)

XI = Minor edit variable symbol

NI = Volume or Junction number of variable desired

Symbols of available minor edit variables

Symbol	Variable (with reference to volume)
AP	Average pressure
TM	Total mass
TE	Total energy
AT	Average temperature
AR	Average density
AH	Average enthalpy
AX	Average quality
BM	Bubble mass
ML	Mixture level
VF	Specific volume of fluid
VG	Specific volume of gas
HF	Specific enthalpy of fluid
HG	Specific enthalpy of gas

TS	Saturation temperature
PS	Saturation pressure
WM	Liquid mass

(for these variables, NI is volume number $1 \leq NI \leq 75$)

Symbol	Variable (with reference to volumes which are core volumes only)
WQ	Power into coolant
DF	DNB heat flux
SF	Surface heat flux
HC	Surface heat transfer coefficient
FT	Fuel element temperature
CT	Center-line temperature
ST	Surface temperature
FQ	Power generated in fuel

(for these variables, NI is volume number $1 \leq NI \leq 75$)

Symbol	Variable (with reference to junctions)
JW	Junction flow
JH	Junction enthalpy
JX	Junction quality
LF	Leak force
TD	Total pressure differential
FD	Pressure differential due to friction
ED	Pressure differential due to elevation
PD	Pressure differential due to pump
AD	Pressure differential due to acceleration

(for these variables, NI is junction number $1 \leq NI \leq 100$)

Symbol	Variable (with reference to the system)
NQ	Normalized power
AE	Total energy added during transient
FE	Energy stored in fuel pin
LE	Total energy leaked
HE	Total energy removed by heat exchangers
EB	Energy balance term
LM	Total mass leaked
MB	Mass balance
TR	Total reactivity
RV	Reactivity due to coolant voids
RW	Reactivity due to temperature changes in coolant
RF	Reactivity due to temperature changes in fuel
RC	Reactivity due to control rod changes
RD	Reactivity due to Doppler effect
PO	Power
HL	Total heat removed
RP	Reactor period

(these variables are system variables, NI = 0)

UNLESS OTHERWISE STATED

ALL THE FOLLOWING CARDS USE THIS FORMAT: 4I3, 6E10.6, 2A4

```
 1    4    7    10    13    23          63    73
| N1 |  N2| N3 | N4  | X1  | .......   | X6  | ID|
```

In all cases ID is any legitimate BCD field. If fewer than four integers are required, the remaining integer fields are left blank. If more cards

are required to fill the tables, a similar format is used:

```
 1    4    7    10    13    23          63    73
 |    |    |    |     | X7  | ....... | X12 | ID|
```

etc.

Tabular data of the form $y_n(x_n)$ is entered for |N| data points. If N>0 the code performs linear interpolation between points; if N<0 the code performs linear extrapolation beyond the range of the table.

5. Time Step Data (5 (a) or 5 (b))

(5-a) Time Step Cards (NTC Cards) If NTC > 0

N1 Number of time steps per minor edit
(0 is interpreted as 1)

N2 Number of minor edits per major edit
(0 is interpreted as 50)

N3 Number of major edits per restart tape edit
(0 is interpreted as 20)

N4 Number of time steps per plot tape edit
(0 is interpreted as N1)

X1 DELTM = Time step size (sec)
(0 < DELTM)

X2 TLAST = End of current time step data (sec)
($TLAST_{i-1}$ < $TLAST_i$)

(5-b) 3 Cards If NTC < 0 (Automatic time-step option)

First Card FORMAT (4I3, 6E10.6, 2A4)

N1 Number of time steps per minor edit
(0 is interpreted as 1)

N2 Number of minor edits per major edit
(0 is interpreted as 50)

N3 Number of major edits per restart tape edit
(0 is interpreted as 20)

N4 Number of time steps per plot tape edit
(0 is interpreted as N1)

X1 DELTM = Initial time step size (sec)
(0 < DELTM)

X2 TLAST = End of problem time (sec)

Second Card FORMAT (9E8.4)

X(I) = percentage criteria applied to variables in same order as on the edit variable card (item (4) above).
$1 \leq I \leq |NTC|$

Third Card FORMAT (9E8.4)

DTMIN = Minimum time-step size (sec)

DTMAX = Maximum time-step size (sec)

(6) Trip Controls (NTR Cards)

N1 IDTRP = Action to be taken
($1 \leq$ IDTRP ≤ 10)
1 = End of problem
2 = Open all leaks
3 = Reactor scram and MOD 0 heat exchanger coast down
4 = Trip all pumps with the same signal*
5 = Start all fills
6 - 10 = Open (or close) all valves

N2 IDSIG = Signal being compared
($1 \leq |$ IDSIG $| \leq 9$)

1 = Elapsed time	+ = HIGH, - = HIGH
2 = Normalized reactor power	+ = HIGH, - = LOW
3 = Reactor period	+ = LOW, - = LOW
4 = Pressure (Vol. N3)	+ = HIGH, - = LOW
5 = Mixture level (Vol. N3)	+ = HIGH, - = LOW
6 = Liquid Level (Vol. N3)	+ = HIGH, - = LOW
7 = Water temperature (Vol. N3)	+ = HIGH, - = LOW
8 = Metal temperature (Vol. N3-core volumes only)	+ = HIGH, - = LOW
9 = Flow (JUNC N3)	+ = HIGH, - = LOW

N3 IX1 = Volume or Junction Index

N4 IX2 = Optional volume index
If IX2 > 0 a high ΔP or ΔT test is used for IDSIG = 4,-4,7,-7. $\Delta P = P(IX1) - P(IX2)$; $\Delta T = T(IX1) - T(IX2)$

X1 SETPT = Signal setpoint

X2 DELAY = Delay time for initiation of action after reaching setpoint.

NOTE: On first trip card, N1 = N2 = 1

*To trip individual pumps with independently specified signals see Sec. (6-a).

(6-a) Option to Trip Pumps Separately

One of the trip actions can be for tripping the pumps under separate controls. The input for this action consists of a set of 3 or more cards which replace the single trip control card of type IDTR = 4.

First Card

N1A IDTRA (cols. 1 and 2) Total number of individual pumps in the system

N1B IDTRB (column 3) The number 4. (i.e. trip pumps signal)

The remainder of this card is blank and the card is followed by trip controls for each pump in the system in the format (4I3, 6E10.6, 2A4).

Second (and following) Cards (N1A cards)

N1 Volume number in which pump is located

N2 IDSIG = Signal being compared
($1 \leq |IDSIG| \leq 9$)

1 = Elapsed time	+ = HIGH, - = HIGH
2 = Normalized reactor power	+ = HIGH, - = LOW
3 = Reactor period	+ = LOW, - = LOW
4 = Pressure (Vol. N3)	+ = HIGH, - = LOW
5 = Mixture level (Vol. N3)	+ = HIGH, - = LOW
6 = Liquid Level (Vol. N3)	+ = HIGH, - = LOW
7 = Water temperature (Vol. N3)	+ = HIGH, - = LOW
8 = Metal temperature (Core N3)	+ = HIGH, - = LOW
9 = Flow (JUNC N3)	+ = HIGH, - = LOW

N3 IX1 = Volume, or Junction Index

N4 IX2 = Optional volume index
If IX2 > 0 a high ΔP or ΔT test is used
(for IDSIG = 4, -4, 7, -7)

X1 SETPT = Signal setpoint

X2 DELAY = Delay time for initiation of action after reaching setpoint.

(7) Volume Data (NVOL cards)

N1 IBUB = Bubble data index
($0 \leq IBUB \leq NBUB$)

N2 IQIN = Heat generation index
($-NHTX \leq IQIN \leq NOCOR$)

IQIN<0 = Heat exchanger region (for a MØD 0 heat exchanger the same index may be repeated only if it refers to a time dependent heat exchanger.)

$-1 \geq$ IQIN ≥ -10 MOD 0 Heat Exchanger

$-11 \geq$ IQIN ≥ -20 MOD 1 Heat Exchanger

$-21 \geq$ IQIN ≥ -51 MOD 2 Heat Exchanger

IQIN>0 = Core region (same index may not be repeated)

X1 P = Pressure (psi)
($0.1 \leq P \leq 3206.2$ unless table input option is used)

X2 TEMP = Temperature (or quality of mixture)
(°F or dimensionless)
($0. \leq$ TEMP $\leq 1.$ or $32. \leq$ TEMP $\leq 5600.$)

X3 V = Volume (ft^3)
$0. < V$)

X4 ZVOL = Volume height, bottom to top (ft)
($0. <$ ZVOL)

X5 ZM = Mixture level (from bottom) (ft)
$0. \leq$ ZM $\leq$ ZVOL)
Liquid phase: ZM = 0. is interpreted as ZM = ZVOL
Liquid phase: 0. <ZM <ZVOL implies an air head over the liquid (if $T_{input} < T_{sat}$)

X6 ELEV = Elevation at the bottom of the volume (ft)

(8) Bubble Data (NBUB cards)

X1 ALPH = Bubble gradient parameter
($0. \leq$ ALPH)

X2 VBUB = Bubble velocity (ft/sec)
($0. \leq$ VBUB)

NOTE: Set number 0

(ALPHA = 0., VBUB = 0.) is built-in.

(9) Junction Data (NJUN cards)

N1 IW1 = Volume index at junction inlet
($0 \leq IW1 \leq NVOL$)

N2 IW2 = Volume index at junction exit
($0 \leq IW2 \leq NVOL$)

N3 IPUMP = *(a) 0 — Normal Junction
($IW1>0$, $IW2>0$)
**(b) $1 \leq |IPUMP| \leq NPMPC$ — Pump Index
($IW1>0$, $IW2>0$)
(c) $1 \leq IPUMP \leq NLK$ — Leak Index
($IW1>0$, $IW2 = 0$)
(d) $1 \leq IPUMP \leq NFLL$ — Fill Index
($IW1 = 0$, $IW2>0$)
(e) 0 — Null Junction
($IW1 = 0$, $IW2 = 0$)

* Normal junctions must precede the leak and fill junctions

** $|IPUMP|$ refers to the pump type and is specified as negative for the junction which is inlet to the pump volume and positive for the junction which is outlet from the pump volume.

N4 IVALVE = Valve index
($0 \leq |IVALVE| \leq NCKV$ or $6 \leq |IVALVE| \leq 10$)
(a) IVALVE = 0, No valve
(b) $1 \leq IVALVE \leq NCKV$, Type 1 check valve
(c) $-NCKV \leq IVALVE \leq -1$, Type 2 check valve
(d) $6 \leq IVALVE \leq 10$, Initially open valve which closes under trip control (IDTRP = IVALVE)
(e) $-10 \leq IVALVE \leq -6$, Initially closed valve which opens trip control (IDTRP = IVALVE)

X1 WP = Flow (lb/sec)

X2 AJUN = Minimum flow area for choked flow calculation (ft^2)
(a) If AJUN<0, use the homogeneous friction model limited by choked flow based on |AJUN|.
(b) If AJUN=0, use the homogeneous friction model and skip the choked-flow calculation.
(c) If AJUN>0, use the two-phase friction model limited by choked flow. (See Appendix B)
(d) If IW1>0, IW2=0 (a leak) AJUN is set equal to one if entered as zero.
If AJUN>0 use the two phase friction model limited by choked flow. If AJUN≤0 use the homogeneous friction model limited by choked flow.
(e) If IW1=0, IW2>0 (a fill) AJUN is set equal to one if entered as zero.
(f) If IW1≤0, IW2≤0, then AJUN is ignored.

X3 ZJUN = Junction elevation (ft)
(a) IW1 > 0, IW2 > 0
ZJUN must lie between bottom and top of both inlet and exit volumes
(b) IW1 > 0, IW2 = 0
ZJUN must lie between bottom and top of inlet volume
(c) IW1 = 0, IW2>0
ZJUN must lie between bottom and top of exit volume
(d) IW1 = 0, IW2 = 0
ZJUN is ignored

X4 INERTA = Junction effective L/A (ft^{-1})
(0. $\leq$ INERTA)
(a) IW1 > 0, IW2 > 0
INERTA > 0
(b) IW1 = 0 or IW2 = 0
INERTA $\geq$ 0

X5 KJUN = Friction coefficient (lb_f-sec^2/lb_m-ft^3-$in.^2$)
(0. $\leq$ KJUN)
(a) IW1 > 0, IW2 > 0
KJUN = 0. implies value computed from pressure drop data. Must give positive answer.
(b) IW1 $\leq$ 0
KJUN ignored beyond this print
(c) IW2 $\leq$ 0. If KJUN $\leq$ 0, then KJUN is calculated internally from the orifice equation, which is

$$KJUN = \frac{1}{144 g_c (2A^2)} ,$$

where A is the effective leak area, including a contraction coefficient.

(10) Homologous Pump Data

(10-a) Pump Curve Input Indicator Data. Format (4I3)

This card is entered if NPMPC > 0

NC(1), ..., NC(4) = Numbers of pump curves to be read into curve sets 1, 2, 3, and 4, respectively. (For each set, $0 \leq NC \leq 16$)

NC(1) and NC(2) must always be 0.

(10-b) Pump Curve Print Indicator Data. Format (4I3)

This card is entered if NPMPC > 0

KW(1), ..., KW(4) = 0 or $\neq$ 0. If KW(1) $\neq$ 0, then pump curves for set I will be printed.

(10-c) Pump Description Data.

NPMPC sets of cards must be entered. Each set consists of two cards.

I. Format 2I3, 6X, 6E10.6

IPC = Curve set
($1 \leq IPC \leq 4$)

IRP = Reverse indicator
0 = no reverse allowed
1 = reverse allowed

POMGAR = Rated speed (rev/min), ω_R

PSRAT = Pump speed ratio of initial speed-to-rated speed, ω_o/ω_R

PFLOWR = Rated flow (gal/min), Q_R

PHEADR = Rated head(ft), H_R

PTORKR = Rate torque (lb_f-ft), T_R

PINERTA = Moment of inertia (lb_m-ft^2), I

II. Format 42X, 2E10.0

VRHOI = Rated or initial density (lb_m/ft^3), ρ_R

TORFK = Frictional torque (lb_fft), T_{frict}

(10-d) Pump Head and Torque Data. Format (4I3, 6E10.6)

Required if NC(3) or NC(4) is > 0.

KR, $3 \leq KR \leq 4$, indicates the curve set number.

NC (KR) total curves must be read for each set.

Curves for the following pumps are already built in:

Curve set 1 - Bingham Pump Company pump, N_S = 4200

Curve set 2 - Westinghouse Electric Corporation pump, N_S = 5200

KR = Curve set number ($3 \leq KR \leq 4$)

IT = Head or torque indicator
1 = head
2 = torque

IC = Curve type
$(1 \leq IC \leq 8)$

N = Number of data point pairs. Each data point is defined by a pair of numbers.
$(1 \leq |N| \leq 20)$
Positive value indicates no extrapolation; negative value permits extrapolation.

INDEP(I) = Independent Variable of the pair (v/α for IC odd; α/v for IC even). $1 \leq I \leq N$

DEP(I) = Dependent Variable of the pair (h/α^2, or β/α^2, for IC odd) (h/v^2, or β/v^2, for IC even). $1 \leq I \leq N$

Independent Variable 2 and Dependent Variable 2, ..., until N pairs are entered, where Independent Variable j < Independent Variable j+1. v, h, α and β are ratios of performance parameters to the rated parameters, where v = flow ratio, h = head ratio, α = speed ratio, and β = torque ratio.

α = speed/rated speed

v = flow/rated flow

h = head/rated head

β = torque/rated torque

There is an h curve and a β curve for each of the eight curve types.

For odd types, h/α^2 (or β/α^2) = F (v/α)

For even types, h/v^2 (or β/v^2) = F (α/v)

Type		Type	
1	α>0, v>0, v/α<1	2	α>0, v>0, v/α>1
3	α>0, v<0, v/α>-1	4	α>0, v<0, v/α<-1
5	α<0, v<0, v/α<1	6	α<0, v<0, v/α>1
7	α<0, v>0, v/α>-1	8	α<0, v>0, v/α<-1

(11) Check Valves (NCKV cards)

X1 PCV = Back pressure for closure ($lb/in.^2$)

X2 CV1 = Forward flow friction coefficient ($lb_f\text{-}sec^2 lb_m\text{-}ft^3\text{-}in.^2$)

X3 CV2 = Reverse flow friction coefficient, valve open ($lb_f\text{-}sec^2/lb_m\text{-}ft^3\text{-}in.^2$)

X4 CV3 = Reverse flow friction coefficient, valve closed ($lb_f\text{-}sec^2/lb_m\text{-}ft^3\text{-}in.^2$)

(12) Leak Sets (NLK curves)

N1 NAREA = Number of data points
($2 < NAREA < 20$)

X1 SINK = Sink pressure ($lb/in.^2$)

X2 CONCO = Contraction coefficient (dimensionless)

X3 $TIME_1$ (sec)

X4 $AREA_1$ (ft^2 if AJUN (X2-(d) in item 9) is entered as 0, dimensionless if $|AJUN| > 0$)

X5 $TIME_2$

X6 $AREA_2$

etc

where $TIME_1 < TIME_2 < \ldots$

(13) Fill Sets (NFLL curves)

N1 NFILL = Number of data points
($2 < NFILL < 20$)

N2 IX Independent variable
IX = 0, time
IX > 0, pressure ($P_{vol} + P_{grav}$)
IX < 0, differential pressure ($P_{vol} + P_{grav} - P_{fill}$)

N3 IY = Flow type
IY $\leq$ 0, flow in pounds per second per square foot
IY > 0, flow in gallons per minute per square foot

X1 FILPRS = pressure in fill reservoir

X2 FILTEM = Temperature (or quality) in fill reservoir (°F)

X3 $TIME_1$ or $PRESSURE_1$ (sec or $lb/in.^2$)

X4 $FLOW_1$ ($lb/sec/ft^2$ or $gal/min/ft^2$)

X5 $TIME_2$ or $PRESSURE_2$

X6 $FLOW_2$

etc

where $TIME_1 < TIME_2 < \ldots$

or $PRESSURE_1 < PRESSURE_2 \ldots$.

(14) Kinetics Constants. (One card if NOCOR > 0)

N1 NODEL = Number of delayed groups
NODEL $\leq$ 0, explicit time-power curve
NODEL = 7, one prompt neutron group plus six groups of delayed neutrons
NODEL = 18, one prompt neutron group plus six groups of delayed neutrons plus eleven delayed gamma emitters

X1 BOVL = β/L = Effective delayed neutron fraction over mean lifetime (sec^{-1})

X2 RHOIN = Initial reactivity ($)

(15) Scram Curve (One curve if NOCOR >0)

N1 NSCR = Number of data points
($2 \leq NSCR \leq 20$)

X1 $TIME_1$ (sec)

X2 $REACTIVITY_1$ (if NODEL > 0) or $NORMALIZED\ POWER_1$ (if NODEL $\leq$ 0)
($ or dimensionless)

X3 $TIME_2$

X4 $REACTIVITY_2$ or $NORMALIZED\ POWER_2$

etc

where $TIME_1 < TIME_2 < \ldots$

(16) Doppler Data

(16-a) Doppler Multiplier - Coolant Density Curve Format (I3,9X,6E10.6,2A4)

(One Curve if NOCOR > 0 and NODEL > 0)

N1 NDOP = Number of data points
($2 \leq NDOP \leq 20$)

X1 Coolant Density$_1$ (lb/ft^3)

X2 Doppler Reactivity Feedback Coefficient Multiplier$_1$ (dimensionless)

X3 Coolant Density$_2$

X4 Doppler Reactivity Feedback Coefficient Multiplier$_2$

etc.

where Coolant Density$_1$ < Coolant Density$_2$ < .....

(16-b) Doppler Parameters Format (12X, 2E10.6, 40X, 2A4)

X1 p = Doppler Reactivity Fitting Constant

X2 T_{in} = Initial Core Inlet Coolant Temperature (°F)

(17) Reactivity Coefficients (NOCOR cards if NODEL > 0)

X1 ALPHVW = Water void coefficient ($/ % density change)

X2 ALPHTW = Water temperature coefficient ($/°F)

X3 ALPHTM = Metal temperature coefficient ($/°F)

X4 DOPWT = Doppler Reactivity feedback coefficient ($/$\Delta T^p$)

(18) Channel Data (NOCOR cards)

N1 IMTL = Rod geometry index ($1 \leq IMTL \leq NMTL$)

N2 NODT$_1$
N3 NODT$_2$
N4 NODT$_3$
} = radial point numbers at which temperatures are to be printed

(note: radial point number 1 is at center of rod)

X1 QFRAC = Fraction of total power generated in core volume
or
= -1.0 Implies use of core weight factor calculation option (item 19).

X2 ARHT = Total heat transfer area in core volume (ft^2)

X3 CHNL = Channel length (ft)

X4 HDIAM = Hydraulic diameter (ft)

X5 HEDIAM = Heated equivalent diameter (ft)

(19) OPTIONAL CORE WEIGHT FACTOR INPUT (entered if QFRAC in item (18) = -1.0)

(19-a) FORMAT (I3, 9X, 4E10.6)

IMAX The number of core volumes in the average channel.

H1(I) 4 miscellaneous constants or indicators are entered in this array.
H1(1) is the exponent of Doppler Feedback. recommended: 0.5
H1(2) > 0.0 means the voidage starts when the coolant reaches saturation. This yields a thermodynamic model. recommended: 0.5
H1(3) ≠ 0.0 means a constant slip model is desired. recommended: 1.0
H1(4) the reciprocal of the constant value of the slip ratio. recommended: 1.0

(19-b) FORMAT (22I3)

FICE(1) (IMAX+1) Integer values are entered into the FICE array. These values define the spatial mesh points (recommended total number of points is 25) at the interface between core volumes in the average channel.
e.g. FICE(1) = 1, ... FICE(4) = 12, ... FICE(IMAX+1) = 25

(19-c) HO(I) 11 miscellaneous constants are entered in this array. FORMAT 12X, 6E10.6/12X, 6E10.6)

HO(1) The clad inside radius at room temperature (ft)

HO(2) The nominal radial gap at room temperature (ft)

HO(3) The clad nominal radial half thickness (ft)

HO(4) The product of the fuel expansion coefficient and the fuel radius (ft/°F)

HO(5) The system inlet pressure (psia)

HO(6) The core inlet flow rate ($lb/sec/ft^2$)

HO(7) Not used

HO(8) The cell (i.e. pin) pitch (ft)

HO(9) The fraction of the core not in the unit cell. (recommended values: PWR: 0.01, BWR: 0.19)

HO(10) Not used

HO(11) The product of the clad expansion coefficient and the clad radius (ft/°F)

(19-d) FORMAT (12X, 6E10.6)

P(I) FICE(IMAX+1) values of power ($BTU/(FT^3-SEC)$ (This array defines the input value of the power for each spatial mesh point in the core volumes)

(19-e) FORMAT (12X, 5E10.6)

C The fraction of power going directly into the coolant

CR The fraction of power going directly into the clad

DX The value of the space increment between spatial mesh points in the core volumes (ft)

BETA The delayed neutron fraction

HTCHFR The fraction of power in the hot channel if there is a hot channel

If there is no hot channel skip to item 19-g

(19-f) Spatial mesh points at the interface between core volumes in the hot channel. FORMAT (22I3)

FICE(J) Integer values defining the interface points in the hot channel volumes (as in item 19-b for the average channel). If there are N core volumes in the hot channel enter N+1 values.

Tabular Values for Moderator Temperature Feedback Coefficient Data

(19-g) FORMAT (12X, 6E10.6)

VD(I) Moderator temperature (°F)
enter 21 values

(19-h) FORMAT (12X, 6E10.6)

VDCF(I) Moderator temperature feedback coefficient (/°F)
enter 21 values corresponding to the temperatures entered in item 19-g

Tabular Values for Moderator Void Feedback Coefficient Data

(19-i) FORMAT (12X, 6E10.6)

VDA(I) Void fraction
enter 21 values

(19-j) FORMAT (12X, 6E10.6)

VDCFA(I) Homogeneous moderator void feedback coefficient (/%void)
enter 21 values corresponding to the void fractions entered in item 19-i

(20) Rod Geometry Constants (NMTL sets) Format (4I3, 3E10.6, 2I10, 10X, 2A4)

(20-a) First card in a set:

N1 NR = Number of regions in rod and number of cards in this set ($1 \leq |NR| \leq 6$) -NR implies variable gap option

N2 IKCW = Thermal property table index for region ($1 \leq IKCW \leq NKC$)

N3 NDRW = Number of spatial mesh intervals in region

N4 IMREG Region identification tag
= 1 fuel region
= 2 gap region
= 3 clad region

X1 DRW = Region spatial mesh interval size (ft)

X2 RHOIW = Region material density (lb/ft^3)

X3 POFRW = Power fraction for region

IX4 ANNW1 = inner radial point number for region average temperature

IX5 ANNW2 = outer radial point number for region average temperature

(note: radial point number 1 is at center of rod; radial mesh interval number 1 is between radial point numbers 1 and 2)

(20-b) Second Card (required only if variable gap option is chosen, i.e. NR < 0) Format (12X, 5E10.6, 10X, 2A4)

X1 GAPMNW = sum of asperities + temperature jump distances (ft)

X2 GAPZW = Nominal room temperature gap (ft)

X3 ACLDW = Product of mean clad radius and clad expansion coefficient (ft/°F)

X4 AFULAW = Product of nominal fuel radius and fuel expansion coefficient, linear part (ft/°F)

X5 AFULBW = Product of nominal fuel radius and fuel expansion coefficient, quadratic part ($ft/°F^2$)

Successive cards in the set are one type (20-a) card for each additional region in the set. On these cards:
N1 = NR = blank or 0
All other fields are the same as in the first card of the set.
For each set, ZNDRW < 31.

(21) Thermal Property Tables (NKC sets)

One set:

N1 NKP = Number of points in thermal conductivity table ($2 \leq NKP \leq 20$)

X1 = $Temperature_1$ (°F)

X2 = $Thermal\ Conductivity_1$ (Btu/ft^2-hr-°F)

X3 = $Temperature_2$

X4 = $Thermal\ Conductivity_2$
etc, until NKP points are read,
where $Temperature_1 < Temperature_2 < ....$

N1 NCP = Number of points in heat capacity table ($2 \leq NCP \leq 20$)

X1 = $Temperature_1$ (°F)

X2 = $Heat\ capacity_1$ (Btu/lb-°F)

X3 = $Temperature_2$

X4 = $Heat\ capacity_2$
etc, until NCP points are read,
where $Temperature_1 < Temperature_2 < ...$

(22) Heat Exchanger Data (NHTX sets)

Heat exchangers must be input in this order:

MOD 0

MOD 1

MOD 2

(22-a) MOD 0 Input

N1 IHTX = Number of data points, 0 meaning flow and temperature dependent.
(IHTX = 0 or $2 \leq$ IHTX ≤ 20)

(A) IHTX = 0

X1 PFRAC = Fraction of initial reactor power removed by heat exchanger

X2 TSEC = Secondary side temperature (°F)

X3 HTXCO = Heat Exchanger Coefficient
(Btu-sec/hr-°F-lbm)
If HTXCO is entered as zero, then the program calculates the value of HTXCO = Heat Removal Rate/(Initial Flow x Temperature difference between fluid and secondary side).

If initial flow is zero, the user must put in a nonzero value for HTXCO.

Note: The program will always use the input value of HTXCO if it is nonzero.

(B) IHTX > 0 (used only after a type "3" trip)

X1 $TIME_1$ (sec)

X2 $NORMALIZED\ POWER_1$ (Fraction of initial reactor power removed by this heat exchanger)

X3 $TIME_2$

X4 $NORMALIZED\ POWER_2$

etc

where $TIME_1 < TIME_2 < \ldots$

(22-b) MOD 1 Input FORMAT (3I3, 3X, 2E10.3, 51X, 2A4)

INUM — Heat exchanger number (-IQIN in volume input)

IPRI — Volume number of the primary volume

ISE — Volume number of the secondary volume

HTXCO — = 0. Heat transfer coefficient is computed and is equal to:

$$\frac{Q\ (0)}{T_{pri}(0) - T_{sec}(0)} \quad ,Q(0) = \text{POWER} \times \text{PFRAC}$$

or

HTXCO — > 0. Heat transfer coefficient = HTXCO

PFRAC — Fraction of power removed by heat exchanger

Either HTXCO or PFRAC must be > 0.

(22-c) MOD 2 Input U-tube steam generator model (IMPWR = 1)

2 cards/MOD 2 "Heat Exchanger"

Card 1 Format (3I3, 3X, 4E10.3, 20X, 2A4)

INUM — Heat exchanger number (-IQIN in volume input)

IPRI — Volume number - primary volume

ISE — Volume number - secondary volume

PFRAC — Fraction of power removed at t = 0 by heat exchanger

ASGN — Inner surface area of the tubes (Ft^2)

RISGN — Inner radius of the heat exchanger tubes (Ft)

THIK — Tube wall thickness (Ft)

CARD ID

Card 2 Format (12X, 5E10.3)

RFPSGN — Fouling factor on primary side $(Btu/Ft^2/hr/°F)^{-1}$

RFBSGN — Fouling factor on secondary side $(Btu/Ft^2/hr/°F)^{-1}$

SSGN — Cross sectional flow area on primary side (Ft^2)

RHOSGN Density of Heat exchanger tube material (Lbm/Ft^3)

CVSGN Specific heat of tube material (Btu/Lbm/°F)

(22-d) MOD 2 INPUT Once-through steam generator model (IMPWR = 3)

2 cards/MOD 2 "Heat Exchanger" plus 1 card for baffle factors

Card 1 FORMAT (3I3, 3X, 6E10.3, 2A4)

INUM Heat exchanger number (-IQIN in volume input)

IPRI Volume number - primary volume

ISE Volume number - secondary volume

PFRAC Fraction of power removed at t = 0 by heat exchanger

ASGN Inner surface area of the tubes (Ft^2)

RISGN Inner radius of the heat exchanger tubes (Ft)

THIK Tube wall thickness (Ft)

RFPSGN Fouling factor on primary side ($Btu/Ft^2/hr/°F)^{-1}$

RFBSGN Fouling factor on secondary side ($Btu/Ft^2/hr/°F)^{-1}$

CARD ID

Card 2 FORMAT (12X, 6E10.3)

SSGN Cross sectional flow area on primary side (Ft^2)

SSG2N Cross sectional flow area on secondary side (Ft^2)

HEDSN Heated equivalent diameter on secondary side (Ft)

RHOSGN Density of heat exchanger tube material (Lbm/Ft^3)

CVSGN Specific heat of tube material (Btu/Lbm/°F)

SGKN Thermal conductivity of tube material (Btu/Ft/hr/°F)

Baffle factors FORMAT (12X, 6E10.3, 2A4)

BAF(I) 6 baffle factors for heat transfer modes in the order mode 1 to mode 6

(23) End Card (1 card, optional)

Columns 1 through 72 blank

Omit this card if another problem follows.

INPUT FOR RESTARTING

An old restart data tape to be used must be mounted on FORTRAN Unit 3 and a blank tape must be mounted on Unit 4. The normal RELAP3B program is used with the following input definitions.

(1) Title (one card)

FORMAT: 18A4, 2A4

The first 12 characters of the new title must be identical to the title of the problem which is to be restarted.

(2) Problem Dimensions (one card)

FORMAT: 1513, E10.6, 14X, I1, 1X, I1, 2A4

N1 LDMP = N, the page number of the old problem where restart is to begin
($1 \leq LDMP \leq 999$)
N = 999 will cause restart to begin at the last page number of the initial problem

N2 NEDI = Number of minor edit variables
($0 \leq NEDI \leq 9$)

N3 NTC = time step control
$1 \leq NTC \leq 20$: time steps are not under automatic control; NTC = number of time step cards.
$-9 \leq NTC \leq -1$: time steps are under automatic control; the first $|NTC|$ variables on the edit variable card will be tested.

N4 NTR = Number of trip control cards
($0 \leq NTR \leq 20$)
NTR = 0 will cause the trip control values on the restart tape to be used, assuming chronological consistency.

N5 NVOL = ignored

N6 NBUB = ignored

N7 NJUN = ignored

N8 NPMPC = ignored

N9 NCKV = ignored

N10 NLK = ignored

N11 NFLL = Number of fill system curves. May be used many times ($0 \leq NFLL \leq 5$)
NFLL = 0 will cause the fill curves on the restart tape to be used.

N12 NOCOR = ignored

N13 NMTL = ignored

N14 NHTX = ignored

N15 NKC = ignored

X1 POWER = ignored

NX1 IFLAG
If IFLAG = 1, read in reactivity coefficients at restart
If IFLAG = 0, Null option

NX2 IMPWR
0 BWR calculation - uses the standard steam tables of RELAP3B
1 PWR calculation (pressure table input required) MOD 2 heat exchanger is U-tube steam generator model
2 BWR calculation - rewrite the steam tables. (pressure table input required)
3 PWR calculation (pressure table input required) MOD 2 heat exchanger is once-through steam generator model

ID Card identification

(3) Optional Pressure Table Input [IMPWR > 0]

Item (3) must be the same at restart as for the original problem. This is required in order to keep the same pressure mesh as the initial problem.

(4) Edit Variable Cards (one card if NEDI > 0)

The same rules apply as for the original problem. The quantities being edited on the new run need not have any relation to those of the original run.

(5) Time Step Cards

The same rules apply as for the original problem. The time step sequence, or the automatic time step tests and criteria, on the new run need not have any relation to that of the old run. No cards referring to p .em times previous to the point of restart will be used.

(6) Trip Controls (NTR cards)

The same rules apply as for the initial problem.

(7) Fill Sets (NFLL curves)

A new set of fill curves can be read in at restart. The same rules apply as for item (13) for the initial problem.

(8) REACTIVITY COEFFICIENTS (IFLAG = 1)

Data must be entered for all items in (8) even if some data are unchanged from the initial values.

(8-a) Variables for initialization at restart FORMAT (22X, 5E10.3, 2A4)

X1 RHOIN = Initial reactivity at restart ($)

X2 RDCAL = Initialization used to evaluate the contribution to reactivity from the Doppler effect.

X3 RFCAL = Initialization used to evaluate the contribution to reactivity from fuel temperature changes.

X4 RVCAL = Initialization used to evaluate the contribution to reactivity from coolant density changes.

X5 RWCAL = Initialization used to evaluate the contribution to reactivity from coolant temperature changes.

(8-b) Reactivity Coefficients (NOCOR cards)
Format (12X, 4E10.3, 20X, 2A4)

X1 ALPHVW = Water void coefficient ($/% density change)

X2 ALPHTW = Water temperature coefficient ($/°F)

X3 ALPHTM = Metal temperature coefficient ($/°F)

X4 DOPWT = Doppler coefficient for reference coolant density.

(8-c) Power Fractions (NOCOR cards)
Format (12X, E10.3, 50X, 2A4)

X1 QFRAC = Fraction of total power generated in each core volume.

RDCAL, RFCAL, RVCAL, and RWCAL are computed and printed out together with the input data.

(9) End Card
FORMAT: 20A4

Columns 1 through 72 are blank.

This card is omitted if another problem follows. A following problem must not use or generate a tape.

INPUT FOR TAPE EDITING

An old plot tape must be mounted on FORTRAN Unit 3. The normal RELAP3B program is used with the following input definitions.

(1) Title (one card)
FORMAT: 18A4, 2A4

The first 12 characters of the new title must be identical to the title of the problem which is to be edited.

(2) Problem Dimensions (one card)
FORMAT: 15I3, E10.6, 17X, 2A4

N1 LDMP = -3

N2 NEDI = Number of minor edit variables
($0 \leq NEDI \leq 9$)

N3 NTC = Edit frequency control card count
($1 \leq NTC \leq 20$)

These are the only control integers required for a tape edit. The others will not be checked because the information will be retrieved from tape.

(3) Edit Variable Cards (one card if NEDI > 0)

The same rules apply as for the original problem. The quantities being edited need not have any relation to those of the original run.

(4) Edit Frequency Control Cards (NTC cards)
FORMAT: 2I3, 6X, 2E10.6, 40X, 2A4

N1 Number of plot tape edits in original run for each currently desired minor edit. Plot tape edits in the original run were generated every N4 time steps. Refer to input in item (5-b) of original run.
(0 is interpreted as 1)

N2 Number of minor edits per major edit
(0 is interpreted as 50)

X1 DELTM = Time step size (sec)
(0 < DELTM)

X2 TLAST = End of current edit frequency control data
($TLAST_{i-1} < TLAST_i$)

(5) End Card (one card)
FORMAT: 20A4

Columns 1 through 72 are blank.

This card is omitted if another problem follows. A following problem cannot use a different input tape.

APPENDIX D

SPECIAL UPDATES MADE IN SIMULATING VENDORS MODELS

A. Updates for Westinghouse Model

In order to verify Westinghouse calculational methods and codes, and to simulate generic Westinghouse plant behavior, the following updates are made:

1. Moderator Reactivity Coefficient

In the RELAP computer program the moderator reactivity is calculated from the product of coolant temperature reactivity coefficient and the change in the bulk coolant temperature. Westinghouse has calculated the moderator density coefficient using three dimensional diffusion theory in order to accurately calculate the effect of large enthalpy increases. The moderator density coefficient includes the effects of power level and boron concentration. This coefficient is plotted in Figure 2-2 of Reference D-1. Westinghouse uses the coefficient calculated for 50% of the power. This coefficient is less negative than that for 100% power. The staff approximated the moderator density coefficient curve for 50% of the power to a polynomial and updated the reactivity subroutine in the RELAP3B computer program. Total moderator reactivity is then calculated using this curve and linear flux weighting of the reactivity at each core node. The necessary coding modifications are presented in Reference D-2.

2. Doppler Reactivity Coefficient

In Reference D-1, Westinghouse presents a Doppler Temperature Coefficient versus Effective Fuel temperature curve, Figure 2-6. Effective fuel temperature is related to the volumetric fuel temperature by a Westinghouse proprietary formula. Thus, a relationship between the Doppler Temperature Coefficient and Volumetric Fuel Temperature is obtained. This relationship is curve-fitted by using the proper "p" value in the equation for Doppler Reactivity (Equation 55). Total reactivity is then calculated by linear flux weighting at each core node.

Since Westinghouse uses the Doppler power defect method, a separate update was made in the program to check whether the two methods would give similar results. These coding modifications are presented in Reference D-2. The program is updated to insert the Doppler reactivity using the curve in Figure 2-5 in Reference D-1. These two different methods gave almost identical results for the loss of feedwater ATWS transient.

3. Steam Generator Model

The tube uncovery is simulated in the RELAP3B computer program using a heat transfer multiplier which assumes values of either zero or one. The multiplier is set to zero (heat transfer becomes zero) for a volume if the quality in the secondary side volume reaches 1.0. This is nonconservative because in actual conditions there is a degradation in heat transfer at CHF. This occurs before quality reaches 1.0. Hence, the model in the RELAP3B computer program was changed to a conservative model.

In the new model, the heat transfer to a volume is set to zero when the average volume quality reaches 0.9. Check calculations made using the Macbeth CHF Correlation indicated that CHF does not occur at this quality.

Therefore, this assumption is conservative. In order to avoid abrupt changes in heat transfer and avoid any possible nonconservatism (quality at top of the volume may reach 1.0 although the average quality is 0.9), heat is transferred into the secondary volume based on steady state relationships after the quality at the top of the volume reaches 0.9. The heat transfer is continued until the average quality reaches 0.9 ... then the heat transfer is set to zero. The coding modifications ... sary to perform the calcualtion are presented in Reference D-2.

B. UPDATES FOR THE COMBUSTION ENGINEERING MODEL

In order to verify Combustion Engineering's calculational methods and codes, and to simulate the generic Combustion Engineering plant behavior, the following updates are made:

1. Moderator Reactivity Coefficient

In the RELAP3B computer program the moderator reactivity is calculated from the product of the coolant temperature reactivity coefficient and the change in the bulk coolant temperature. For Combustion Engineering the moderator reactivity is obtained from both changes in the bulk coolant temperature and changes in the bulk coolant density. The moderator temperature coefficient is evaluated as described in Section 9 of this report. The moderator density coefficient versus density data supplied by Combustion Engineering was fit to a polynominal expression. The reactivity subroutine was then updated to evaluate this data. A linear flux weighting was used for both of these term, their sum being the total moderator reactivity. The coding modifications for this model are presented in Reference D-3.

2. Doppler Reactivity Coefficient

In Reference D-4, Figure 1.5-1, Combustion Engineering presents a Doppler Reactivity Coefficient versus Average Fuel Temperature curve This relationship is curve-fitted by using the proper "p" value in the equation for Doppler Reactivity (Section 9, equation 55). The Doppler reactivity is linear flux weighted for each core region.

3. Steam Generator Model

See Section A-3 of Appendix D.

C. UPDATES FOR GENERAL ELECTRIC MODEL

In order to verify the General Electric calculational methods and codes, and to simulate generic General Electric plant behavior, the following updates are made:

1. Reactivity vs Void Fraction

The relationship between reactivity and void fraction is non-linear. The general form of the relationship was developed from curves submitted by General Electric (Reference D-5). This modification now permits the study of transients where the axial distribution of void fraction and quality can vary significantly. These coding changes required for the model are presented in Reference D-2.

In order to audit and evaluate critical heat flux transients, the Hench Levy Critical Heat Flux Correlation has been inserted into the program (proprietary).

REFERENCES - APPENDIX D

D-1. Westinghouse Anticipated Transients Without Trip Analysis, WCAP-8330, August 1974.

D-2. Brookhaven National Laboratory Technical Assistance Progress to USNRC Directorate of Licensing, dated January 31, 1975.

D-3. Brookhaven National Laboratory Technical Assistance Progress Report to USNRC Directorate of Licensing, dated March 17, 1975.

D-4. Combustion Engineering Anticipated Transients Without Reactor Trip, CENPD-158, October 1974.

D-5. Letter to V. Stello, Jr., USNRC, from J. L. Benson, General Electric, dated July 24, 1974.