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IDAHO NATIONAL ENGINEERING LABORATORY

RELAP4/MOD5
A COMPUTER PROGRAM FOR TRANSIENT THERMAL-HYDRAULIC ANALYSIS OF NUCLEAR REACTORS AND RELATED SYSTEMS
USER'S MANUAL

VOLUME I
RELAP4/MOD5 DESCRIPTION

EB

PREPARED BY AEROJET NUCLEAR COMPANY FOR
U. S. NUCLEAR REGULATORY COMMISSION
AND
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
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ABSTRACT

RELAP4 is a computer program written in FORTRAN IV for the digital computer analysis of nuclear reactors and related systems. It is primarily applied in the study of system transient response to postulated perturbations such as coolant loop rupture, circulation pump failure, power excursions, etc. The program was written to be used for water-cooled (PWR and BWR) reactors and can be used for scale models such as LOFT and SEMISCALE. Additional versatility extends its usefulness to related applications, such as ice condenser and containment subcompartment analysis. Specific options are available for reflood (FLOOD) analysis and for the NRC Evaluation Model.

RELAP4 models system fluid conditions including flow, pressure, mass inventory, fluid quality, and heat transfer. A subroutine provides water property tables. Component thermal conditions and energy transfers are modeled. The reactor system is subdivided into discrete volumes which, with interconnecting junctions (flow paths), are treated as one dimensional homogeneous elements. RELAP4 solves an integral form of fluid conservation and state equations for each user defined volume and generates a time history of system conditions. Data are recorded for volume fluid, component heat, and junction flow characteristics. The output is in the form of printed tabular digital data. Available subroutines also allow output to be plotted as a function of time. Provision is made for selectively stopping the program at any point for data edits. The program can be restarted for problem continuation.

RELAP4 is available from the Argonne Code Center in both double precision IBM and CDC 7600 version source decks accommodating up to 75 volumes and 100 junctions. Eight checkout problems covering a wide variety of reactors and scale models have been run on a Control Data Corporation Model 7600 computer. These problem runs are illustrated in

Volume III. Thirty additional short problems were run. These were designed to check out a broad spectrum of RELAP4 features. This was to help prevent coding additions to one part of the program from adversely affecting other parts of the program and to insure an essentially identical comparison of results between the IBM and the CDC versions of the code. Central processing unit time varied from 8 to 78 minutes. RELAP4 is also operational on the IBM model 360 computer.

This manual describes RELAP4/MOD5, Update 2. The results of the eight runs reported in Volume III were made to check out Update 1. The version of the code released is Update 2. The differences between the two versions are minor. Update 2 checkout problems have also been run and are discussed in Volume III, Appendix I.

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VOLUME I

RELAP4/MOD5 DESCRIPTION

1. INTRODUCTION

RELAP4 is a computer program, written in FORTRAN IV, that was developed primarily to describe the thermal-hydraulic transient behavior of water-cooled nuclear reactors subjected to postulated accidents such as those resulting from loss of coolant, pump failure, or nuclear power excursions. Fundamental assumptions inherent in the thermal-hydraulic equations are that a two-phase fluid is homogeneous and that the phases are in thermal equilibrium. Models are available in the code to modify these homogeneous assumptions. The program is sufficiently general to be applied to experimental water reactor simulators and many other hydrodynamic experiments.

The program requires numerical input data that completely describe the inital conditions and geometry of the system being analyzed. The input data include physical characteristics such as fluid volume geometry, pump characteristics, power generation, heat exchanger properties, and material composition. Starting with system initial flow, pressure, temperature, and power level boundary conditions, transients can be initiated by the control action inputs to the program. These can describe breaks in fluid piping, valve actions, pump changes, and core power level variations. The program computes (for each time advancement) fluid conditions such as flow, pressure, mass inventory, and quality. Also computed are thermal conditions within the solid materials such as temperature profiles and power, and the fluid-solid interface conditions such as heat flux and surface temperature.

The degree of detail to which the system is described is specified by the program user. This includes nodalization of fluid flow paths within the piping, vessels, and reactor core as well as heat transfer modeling within solids such as the fuel rods, piping, and vessel walls. Both the reactor primary and secondary flow systems can be modeled. The permitted system detail is limited by the maximum dimensions within RELAP4. These dimensions can be adjusted to fit a particular computer. From a practical viewpoint, the detail is most generally limited by computer time costs. Computer running time increases rapidly with increasing detail of system modeling.

The definition of the thermal-hydraulic system is also completely specified by the user. A portion of a system, such as a single reactor channel, can be analyzed by supplying appropriate time-dependent boundary conditions. The boundary conditions can be defined by the user if known, or they can be obtained from a previous RELAP4 analysis. For example, analysis of a reactor blowdown transient may be performed using a RELAP4 integral system that describes the entire primary flow loop, the upper and lower plenums, and a simple nodalization of the total reactor core. A second RELAP4 calculation that uses the previously computed fluid conditions in the upper and lower plenums as a boundary condition can be performed for a hot channel analysis.

RELAP4/MOD5 was intended primarily as a blowdown code. It will calculate system phenomena from initial operating conditions at the time of pipe rupture through system decompression up to the beginning of core recovering with emergency core coolant. RELAP4/MOD5 is capable of calculating this core recovering within the limitations of the MOD5 models. These models will not adequately calculate all the reflood phenomena. RELAP4/MOD6 will be designed to address the PWR reflood problem.

RELAP4-EM (Evaluation Model) is available on an optional basis as a part of the RELAP4/MOD5 program. RELAP4-EM is a part of the Nuclear Regulatory Commission (NRC) Water Reactor Evaluation Model (WREM). The

WREM[1] package consists of several computer programs developed to evaluate the transient behavior following a postulated Loss of Coolant Accident (LOCA) in a light-water-cooled power reactor. RELAP4 does not fully comply however, with the requirements set forth in Appendix K to 10 CFR Part 50[2] and thus is not a stand alone code for licensing purposes. (See Section 3.10).

A serious attempt has been made to orient this user's manual to the user by providing an indepth treatment of the many included subjects. Space limitations, however, have required that equations be stated in some cases rather than be fully derived. Some assumptions and approximations are stated without full justification, also due to space limitations.

The manual is comprised of three volumes. Volume I describes the models included in MOD5. Volume II is directed toward the use of the Code, including application and programming information, and a sample problem. These two volumes are cross-referenced to aid the program user. Volume III presents the results of eight computer runs used in checking out RELAP4/MOD5. These are furnished with interpretation of results for illustration purposes and represent the actual use of RELAP4/MOD5 to investigate real or hypothesized situations. These should not, however, be considered as an in depth study of the reactor plants modeled or of the postulated accidents. The input data for the checkout problems only generally relate to the identified plants.

RELAP4/MOD5 represents a current state of the art calculation method for estimating the transient thermal-hydraulic phenomena in light water reactors and reactor simulators. RELAP4 is currently undergoing modification and extension. Modifications of RELAP4 along with updated documentation will be released in the future. MOD6, which will include a PWR Reflood Model, will be released in 1977. MOD7 will include a BWR Reflood Model and is expected to be released at a later date. Additional modifications are also planned.

This User's Manual describes RELAP4/MOD5, Update 2. Volume III provides a detailed description of eight checkout runs made using RELAP4/MOD5, Update 1. Six months of extensive use of Update 1 led to the identification and correction of a number of errors in the code as well as some logic changes, additional Evaluation Model (EM) checks, and one model revision. These changes culminated in the development of an improved code identified as RELAP4/MOD5, Update 2. Appendix I of Volume III presents the significant differences between Updates 1 and 2, as well as the checkout of Update 2.

2. PROGRAM SUMMARY DESCRIPTION

RELAP4 is a computer program that was developed to describe the thermal-hydraulic behavior of light-water reactor systems subjected to postulated transients such as those resulting from loss-of-coolant, pump failure, or nuclear power excursions. RELAP4 can also be used to calculate the behavior of a part of a system provided the appropriate thermal-hydraulic boundary condition inputs are made to the program. RELAP4 is comprehensive and predicts the interrelated effects of coolant thermal-hydraulics, system heat transfer, and core neutronics. Because the program was developed to solve a large variety of problems, the user must specify the applicable program options and the system to be analyzed.

2.1 Major Parts

The RELAP4 program controls are used to specify the problem dimensions and constants, time step size, trip controls for reactor system transient behavior, and output. Controls are also provided for restarting a problem and producing a plotting tape. There are four basic options in the RELAP4 code that can be selected by input. These are Standard RELAP4, RELAP4-EM, RELAP4-FLOOD, and RELAP4 CONTAINMENT.

The major parts of the RELAP4 program are the fluid equations (Section 3.3), heat transfer (Section 3.4) and reactor kinetics (Section 3.5). These are outlined as follows:

The fluid dynamics portion of RELAP4 solves the fluid mass, energy, and flow equations for the system being modeled. In order to provide a reasonable degree of versatility, a choice of the following five basic forms of the flow equation is provided:

(1) Compressible single-stream flow with momentum flux,

(2) Compressible two-stream flow with one-dimensional momentum mixing

(3) Incompressible single-stream flow without momentum flux

(4) Compressible integral momentum

(5) Incompressible mechanical energy balance.

The compressible two-stream flow equation has four sub-forms to represent different stream flow patterns.

The fluid system to be analyzed by RELAP4 must be specified by the user. It must be modeled by fluid volumes and by fluid junctions (flow paths) between the volumes. User specified fluid volumes (control volumes) are used to represent the fluid in the system piping, plenums, reactor core, pressurizer, and heat exchangers. Any fluid volume may be chosen independently to represent a region of the system associated with a heat sink or source, such as fuel rods or a heat exchanger. The fluid volumes are connected by junctions which are used to transfer fluid into and out of fluid volumes. Junctions are of three types:

(1) Normal (connects fluid volumes)

(2) Leak (system fluid loss point)

(3) Fill (system fluid gain point).

A junction must be located within the elevations specified for the fluid volumes that are connected to the junction because the fluid path is physically continuous. A normal junction connects two adjacent fluid volumes.

A heat conductor model is used to transfer heat to or from the fluid in a volume. The geometry and conditions of the heat conductor are specified by the user. This model may be used to describe the thermal behavior and effects of fuel rods, pipes, and plates. The program contains correlations for calculating the critical heat flux (CHF), pre-CHF heat transfer, and post-CHF heat transfer. Several

options are also available for describing heat exchangers.

Program options are available for describing the power internally generated in system components such as fuel rods or electric heaters. These options include user-supplied normalized power versus time curves and program solution of the space-independent reactor kinetics equations with or without radioactive decay heat.

2.2 Programming

The RELAP4 program is written in FORTRAN IV and is operable on both the IBM 360 and CDC 7600 computers.

Two computer programs used in conjunction with RELAP4 are (a) the PLOTR4M program (Section 3.14) which produces both Calcomp and microfilm plots of appropriate variables-versus-time from a RELAP4 data tape, and (b) the STH2OG (Section 3.13) which generates tables of water properties in the proper format to be used in RELAP4.

The running time of a RELAP4 loss-of-coolant problem can vary from minutes to hours, depending primarily upon the number of fluid volumes used, the coolant break size, and the number of heat conduction nodes for slabs used throughout a given system representation. For a PWR modeled with 30 to 40 fluid volumes, running time through refill may range from 15 to 60 min or more on the CDC-7600 and from 2 to 8 hr or more on the IBM-360/75. The time requirement for BWR analysis is roughly the same for a corresponding degree of detail in system representation.

Although RELAP4 is a comprehensive program, it has approximations which must be recognized. The approximations include the use of:

(1) Point reactor kinetics model

(2) Homogeneous fluid equations with the phases in thermodynamic equilibrium

(3) Air volumes to provide work without allowing the air to mix or flow (This assumption does not apply for the containment option.)

(4) One-dimensional fluid and heat conduction equations

(5) Steady state empirical correlations to estimate heat transfer coefficients, critical heat fluxes, two-phase friction factors, and critical mass fluxes.

2.3 MOD5 Improvements

RELAP4/MOD5 is the most recent in a series of computer programs[3,4,5] developed to describe the thermal-hydraulic conditions attendant to postulated transients in light-water-reactor systems. RELAP4/MOD5 incorporates various improvements and modifications made to RELAP4 since its original publication[5]. These modifications and improvements include the following:

(1) Critical Flow Models added - Subsection 3.6.8

- Modified Burnell/Homogeneous Equilibrium Model (HEM)
- Henry Fauske/HEM

(2) Stagnation Pressure Calculation (For use with the Critical Flow Calculation) - Subsection 3.6.9

(3) Downcomer Penetration (Flooding) Models - Subsection 3.6.4

- Wallis and Wallis-Crowley
- Model based on Battelle-Columbus 1/15th Scale Glass Vessel Tests

(4) Lower Plenum Entrainment Model - Subsection 3.6.5

(5) Heat transfer - Subsections 3.4.1 and 3.4.6

- Modified Bromley Correlation (low quality, low flow, post CHF)
- Free Convection and Radiation Correlation (high quality, low flow, post CHF)
- Berenson pool film boiling correlation and transition pool film boiling deleted
- Multiple heat slabs per fluid volume permitted

(6) Vertical and Horizontal Slip Models - Subsections 3.6.2 and 3.6.3

(7) Air Flow Model (Containment Option) - Subsection 3.12.1

(8) Ice Chest Model (Containment Option) - Subsection 3.12.3

(9) Improvements in code running capabilities - Subsection 3.6.7

- Improved operability under water packing conditions
- Junction smoothing option (for mixture level crossing vertical slip junction from above)
- Choking - smoothing option.

Each of these improvements and modifications is discussed in detail.

2.4 Evaluation (EM), FLOOD, and Containment Models

RELAP4-EM (Evaluation Model) is available on an optional basis as a part of the RELAP4/MOD5 program and represents a conservative approach to modeling. As mentioned, RELAP4-EM is a part of NRC WREM. The WREM[1] package consists of several computer programs developed to evaluate the behavior of light-water-cooled nuclear power reactors when subjected to a postulated LOCA with Emergency Core Cooling (ECC) injection. RELAP4 by itself does not meet the current NRC acceptance criteria[2]. RELAP4-EM calculations are performed using certain specified EM options within the basic RELAP4 program.

RELAP4-EM is used to perform system thermal-hydraulic decompression analysis and detailed fuel rod thermal behavior calculations for both Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR). For PWR systems, the RELAP4-EM blowdown analysis provides a calculation model of the reactor primary and secondary systems, including the hot fuel assembly or assemblies in the core, the remainder of the core, the reactor vessel downcomer, the upper head, the upper plenum regions, the secondary coolant systems, and emergency core coolant injection. The RELAP4-EM analysis begins from steady-state or assumed initial operating conditions. The analysis continues through pipe rupture and system decompression to the onset of the reactor core recovering with emergency coolant. RELAP4-EM computes the space and time variations of the primary and secondary coolant system thermal-hydraulic conditions. Included in the calculation are coolant flows between regions, heat transfer between the primary and secondary coolant system, and heat transfer from system metal surfaces and the core to the coolant. Also included are: the hydraulic effects of system components such as pumps, valves, and the core; the temperature of the hot fuel assembly and the remainder of the core; the fuel rod swelling and rupture; and the ECC bypass.

The RELAP4-FLOOD program (Section 3.11) performs essentially a continuation of the PWR system blowdown calculation through the period of ECC reflood of the reactor core. The program itself is a special

version of the RELAP4-EM program with modifications, primarily in the core region, to calculate reflooding rates and fluid conditions.

The RELAP4-EM program is used for BWR systems to model the hot fuel assembly and the remainder of the core, the fluid system within the reactor vessel, and the recirculating loops. The analysis begins with steady-state operating conditions and is usually terminated at the end of lower plenum flashing unless further calculations are desired. The RELAP4-EM system analysis computes the space and time variation of thermal-hydraulic conditions of the fluid within the reactor vessel and recirculating loops. Also computed are flows between system regions, heat transferred from system components and the core to the coolant, hydraulic effects of the pumps, fuel rod swelling and rupture, and the power and temperature of the core and the hot fuel rod assembly.

The RELAP4 Containment Program (Section 3.12) contains options that are specific to calculating the transient response of a nuclear reactor containment during postulated accidents[6]. Included in RELAP4/MOD5 is an option which can be used for containment air flow. Also included is an ice condenser containment system analytical model. The latter represents inertial door opening, ice melt, and heat transfer between ice and a flowing fluid.

3. MODEL DESCRIPTION

RELAP4 considers a thermal and hydraulic system as a series of interconnecting user defined (control) volumes. The RELAP4 program (code) solves the mass and energy balances for volumes assumed to contain one-dimensional homogeneous fluid with the vapor and liquid phases in thermodynamic equilibrium. RELAP4 solves the momentum balance at the interfaces or junctions between control volumes. In some instances, options are available to modify the code predictions when these basic assumptions are not appropriate. RELAP4 requires specific input in order to solve the governing equations for both the modeled volume contents and the connecting junctions. Specific input is also required to describe additional component models which affect the mass, momentum, and energy balances. These latter models include pumps, metal surfaces, and power sources.

The purpose of this introduction to Section 3 is to present a general picture of what follows so that a reading of the section can be in a total context of the working of RELAP4. Items to be covered in turn are:

(1) One dimensional model characteristics

(2) Modeling guidelines

(3) Control volumes

(4) Flow areas

(5) Initial conditions

(6) Conservation equations

(7) Junction inertias, frictional form loss, and residuals

(8) Conductive heat transfer

(9) Pump modeling

(10) Steam generator modeling

(11) Break modeling.

RELAP4 regards all fluid volumes as generalized right cylinders with fluid conditions defined at the geometric center. Radial variations are ignored. The modeler must determine a basic system breakdown which will adequately predict transient system phenomena within an acceptable computation time frame. In general, complex geometries require a finer degree of nodalization than does straight piping.

Some general modeling guidelines that should be considered are:

(1) Components with dissimilar thermal and/or hydraulic characteristics should not be lumped together into a common control volume

(2) Detailed modeling of passive components does not appear necessary for the saturated portion of blowdown

(3) Components in which energy is transferred across the system boundary, such as steam generators, require detailed model description

(4) Junctions should be defined at locations of geometric change such as orifices, nozzles, etc.

(5) An effort should be made to preserve system elevations (by defining junctions at minimum and maximum elevations) if possible, in order to properly model gravity head.

Primary emphasis should be placed on preserving system volume when the system geometric description inputs are made. In addition, thermodynamic condition input should be reasonably consistent with the actual initial system conditions to provide realistic initial mass and energy inventories. The data for the initial pressures, temperatures, and velocities are usually insufficient to uniquely determine these values for all locations and some extrapolation becomes necessary. Care should be exercised as different investigators might perform this function in ways that would produce different initial conditions and thus different results.

The user must define a flow area input for each volume. The flow length is calculated by the code using this area, the volume, and the assumption of a right cylinder. Since computer costs and storage availability limit the number of volumes in any model (usually less than 75), various components in a given region may have to be combined into a single volume. A representative area must be chosen to use with this combined volume model. In general, an area which preserves flow length is used if the volume represents components where Fanning friction losses dominate. In addition, a model volume equivalent (or hydraulic diameter), which may be inconsistent with a circular flow area, must be introduced to account for Fanning losses in non-circular geometry. The program will calculate a diameter consistent with the actual or equivilent circular flow area whenever the diameter input is entered as zero. If the volume represents a component that has a relatively large cross-sectional area, such as a plenum, the predominant cross-sectional flow area input should be made. For example, the pressure vessel inner diameter might be used for the upper plenum.

The Mach numbers calculated at junctions and downstream points (assuming isentropic compression) are functions of the flow areas. Consequently, unrealistic system parameters, such as extremely small specific volumes, may be predicted if the junction area exceeds the smallest connected volume flow area. If a larger flow area is used, care must be taken to ensure that the connecting junction area is not greater than the flow area of either volume that it connects.

The RELAP4 code requires both the initial pressure and mass flow rate distribution throughout the system. For a transient situation, specification of both of the quantities is theoretically acceptable. In practice this can result in large initial non-physical accelerations. These accelerations will not occur if true steady state initial conditions are prescribed. The input distributions will not, in general, be consistent with the steady state version of the momentum equation. In order to balance this equation at steady state, a residual friction coefficient is calculated by RELAP4 to make the velocity and pressure distributions consistent with the steady state momentum equation. This is to eliminate the large accelerations. The residual friction is added to the friction throughout the computer run. This residual friction coefficient is an expedient that will bias the results. The favored procedure to eliminate this problem is to provide a pressure and flow distribution input which is consistent with the steady state form of the momentum equation and thus yield a zero (or negligible) residual friction. Consistent pressure and flow distribution data are sometimes not available for reactors and associated experimental systems. Care should be taken as significantly varying input may be provided by different modelers. The total friction coefficient at a junction is obtained by summing the Fanning friction factor, form loss coefficients, and residual coefficients. If this sum is negative at any point, the calculation is aborted and adjustments must be made to the input distributions before the program will run. Section 4.3 of Volume II will aid the user in setting up a RELAP4 problem initialization.

The steady state form of the energy equation might not be satisfied by the input. No provision is made in RELAP4 to force this. Thus, the modeler may find it desirable to solve the steady state energy equation and use the results as input. The technique used to satisfy the steady state form of the momentum and energy equations is one of trial and error using the code to determine if input conditions result in a transient.

The assumption of homogeneous fluid conditions is inappropriate in some reactor components. A bubble rise model is available in RELAP4 as a correction for non-homogeneity, however.

The momentum equation, as included in RELAP4, is an approximation of one dimensional flow in a variable area stream tube. The momentum equation applies to flow through a junction from one volume to another with no provision for cross flow. The continuity and energy equations on the other hand are applied over a control volume which can have more than two junctions. In a sense these equations are multi-dimensional. A single junction can connect only two modeled volumes, but a single control volume may interface with many junctions.

RELAP4 has five basic forms of the one-dimensional fluid flow (momentum) equation available. The equations assume either compressible flow or incompressible flow with various momenta considerations. In general, the compressible form of the momentum equation should be used at each junction. The exception occurs at volumes which interface with more than two junctions. This is where one dimensional flow representation is not applicable such as volumes which interface with more than two junctions. The compressible form of the momentum equations should be used at the two junctions which form a one-dimensional primary flow path. Judgement must be exercised as to which form of the momentum equation should be used at the remaining junctions. If a one dimensional approximation is valid, then the compressible form of the equation should be used. If, on the other hand, the approximation is definitely not one dimensional, the incompressible form should be used.

The exception to the multi-junction rule is the BWR jet pump model described in Subsection 3.6.11. In this model, the compressible form should be used at the outlet. The mixing form of the momentum equation should be used at the drive and induced-flow junctions.

The inputs required to specify the fluid flow (momentum) equation information at a junction include:

(1) Inertia

(2) Flow area

(3) Elevation

(4) Form loss coefficient (forward and reverse)

(5) Equivalent diameter

(6) Fluid flow equation desired form.

The flow area, elevation and diameter are basic geometric descriptions of the flow path between two control volumes. The inertia, loss coefficients, and form of the fluid flow equation require a fundamental understanding of the predominant local phenomena and component functions.

The junction inertia term is a relative measure of the response of junction flow to system forces, essentially being representative of the amount of fluid that must be moved to allow acceleration of the junction flow. In some junctions, transient effects are not important so that it is not necessary to accurately determine the inertia for these junctions. In junctions where the flow is primarily in one direction with little change in magnitude, transient effects are small. In junctions where the flow changes direction, the inertia will have a significant effect.

RELAP4 has the option of accounting for frictional form losses due to obstructions and form changes with theoretical equations for sharp edged expansions and contractions. These losses can result from expansions, contractions, orifices, instrumentation, etc. The theoretical formulae in RELAP4 can be used, but should be applied with caution since the assumptions inherent in these equations often may not apply to the element selected for modeling. Smooth expansions and contractions cannot be represented by these equations. Similarly, the plenums on the steam generators cannot be represented with these equations. The safest

procedure is to model these components with experimental data. The data most readily available may be the experimentally measured pressure distribution in the reactor loop. The experimental pressure and velocity distributions can usually be assumed to be more correct than the theoretical loss coefficients built into the code. Generally speaking, the form loss should be entered as input data if it can be determined from available information.

RELAP4 assumes that the functional form loss coefficients are constant. Idelchik[7] indicates that these coefficients are constant at steady state for large Reynolds numbers (greater than 10^4) but are a function of the Reynolds numbers in the laminar and transition regions. Use of actually measured form loss coefficients in the turbulent range is recommended.

As mentioned previously, RELAP4 assumes initial steady state conditions. It will calculate a residual friction loss coefficient based on the input pressure distribution which does not necessarily agree with the steady state momentum equation. This residual coefficient is assumed to be constant and equal in either direction, which may not be the actual case. It is added to the input, or RELAP4 calculated, frictional form loss coefficient at that junction. The problem should generally be initialized to minimize the absolute value of the residual.

The form loss coefficient can be entered for forward and reverse flows or can be treated as a constant. If the latter is elected, the coefficient is neither a true Fanning friction factor (since it does not vary with Reynolds number) nor a directional form loss coefficient (since it does not change with direction). The best input procedure therefore, is to select Fanning, directional form loss, and bidirectional form loss coefficient inputs which agree with the pressure distribution input. If an initial steady state pressure profile is known, a trial run is made to determine the size of the residual coefficients. Adjustments are then made to the input until a satisfactory value is achieved. The residual coefficients can be negative. Accordingly, RELAP4 checks on the total friction coefficient (Fanning plus

form loss plus residual) to determine that it is positive. This procedure does allow a negative residual coefficient, but RELAP4 will abort if the total coefficient is negative.

Conduction heat transfer within solids is described in RELAP4 with the finite difference equation for heat conduction in both one dimensional rectangular and cylindrical geometries. The input for a heat slab must describe the material it is composed of, the thicknesses of the material (in the direction of heat flow), and the area available for heat transfer to the fluid. The material description must include conductivity, density, and specific heat.

The effects due to material thermal expansion can be described by an expansion model in RELAP4. The model requires that the expanding region be enclosed by two nonexpanding regions. The expansion model is useful when describing heat conduction across the gap that exists in a nuclear fuel rod.

RELAP4 utilizes a volume pump model. Items such as internal choking, average fluid conditions, etc. can be calculated in determining pump performance. Volume should be preserved when modeling a pump. The flow area can be determined in at least three different ways:

(1) Setting the pump flow area equal to the arithmetic average of the area of the pump discharge and suction pipe

(2) Establishing some "average" flow length through the pump and equating the flow area to the ratio of pump volume to pump flow length

(3) Using the minimum flow area within the pump.

Internal choking can then be modeled by putting a frictionless orifice at the pump discharge junction.

Pump characteristic inputs are usually made from curves based on the tested performance of a similar pump. The pump model for a conglomerate loop represents all the pumps in the combined loops. The homologous curves for the combined pump are the same for the one pump of the group; however, the rated torque and flow must be multiplied by the number of pumps being combined.

Gravity head can result in being poorly defined due to the assumption that fluid properties are homogeneous and calculated at the geometric center of the volume. This is especially true in pump suction lines which have a U-tube configuration. The suction line should be modeled in sufficient detail to properly account for the effect of gravity on pump inlet conditions. RELAP4 has the capability of calculating two-phase degradation of the pump head. Incorrectly predicting pump inlet conditions will result in an incorrect prediction of cavitation and the accompanying pump head degradation.

The secondary and the primary sides of a steam generator can both be modeled using RELAP4. The U-tube and the single pass steam generator configurations are modeled in the same manner. Experience with the checkout problems indicated that seven nodes (which includes one node in each plenum) for the primary side of the U-tube generator and four nodes for the primary side of the single pass generator both gave good results. A lesser number may be adequate. Sensitivity studies using a lesser number can be performed for new systems to establish the appropriate number for convergence. One node may even be adequate to describe the secondary side of the steam generators. Three to six heat slabs are normally required to represent the secondary heat transfer media.

The primary side is divided into passive (no heat removal) inlet and outlet plenums and active (heat removal) heat transferring volumes. The enthalpy transport option should ordinarily be used at the active volume junctions. Enthalpy transport generally is not recommended for use during low flow periods. If problems are encountered with low flow use, it is recommended that enthalpy transport be turned off and the

problem restarted. The intact loop steam generator is a "lumped" configuration and differs from the blowdown loop generator in volume and flow area. Total volume and flow length must be conserved.

Use of the bubble rise model is recommended on the secondary side of a steam generator with a gradient value of 0.8. A sufficient bubble velocity to support the outlet vapor flow rate must be used. Secondary flow is induced with a positive fill junction inlet and a negative fill junction outlet both having equal magnitude. The junction momentum equation option must be properly selected for a negative fill juction so that an average velocity and not a zero velocity is used.

Two types of breaks are normally modeled in predicting the transient behavior of a reactor during a loss-of-coolant accident (LOCA). These breaks are a split break and a guillotine break (double-ended offset shear). The RELAP4 program has several critical flow options which may be selected for breaks. The user also has the choice of modeling a break with a connection to a containment volume (using a junction connecting two modeled volumes) or by the use of a leak junction where the state of the downstream volume (null volume) does not affect the critical flow calculation.

3.1 Problem Dimensions

RELAP4/MOD5 is primarily a fixed dimension program. This is to say that the total number of most input variables must fit between an upper and a lower limit. This is based on program design and is related to computer capacity. These limits are detailed in Volume II, Subsection 4.2.2 (2) for input on the Problem Dimension Data Card.

Some variables are dynamically dimensioned and as such are limited only by the capability of the computer core memory. These include:

(1) Fill data

(2) Ice condenser data

(3) Core memory scratch areas for data input, heat transfer calculation, and conservation equation matrix solution.

Core availability within a given computer installation, may limit the use of junctions to less than the maximum of 100 listed in Volume II, Subsection 4.2.2 (2). Section 5.2 of Volume II should be consulted for adapting the junction number limit to the computer to be used.

3.2 Program Options

The RELAP4/MOD5 code has four general program options that have the effect of appearing to the user as four separate codes. These are:

(1) RELAP4/MOD5 with minimum controls (standard RELAP4)

(2) RELAP4-EM (Evaluation Model)

(3) RELAP4-FLOOD

(4) RELAP4-Containment.

3.2.1 RELAP4/MOD5 with Minmum Controls. The user can select the RELAP4/MOD5 with minimum controls option by entering 0 for ISPROG on the Problems Dimensions Data Card, Volume II, Subsection 4.2.2 (2). This option results in the most general form of the RELAP4 code and allows maximum flexibility both in configuring the code and in selecting input options. Entering 1 on the Program Options Card, Volume II, Subsection 4.2.2 (4) also allows access to the options in the code designed for the evaluation model (EM) without the EM controls. The code output will be labeled RELAP4/MOD5 when the minimum controls option is selected.

3.2.2 RELAP4-EM. The user may select the Evaluation Model configuration. This is accomplished by entering 1 for ISPROG on the Problem Dimensions Data Card. A very restricted set of input data is required when this option is selected. The requirements for the EM program runs are explained in Section 3.10. The output will contain a heading indicating that the RELAP4 Evaluation Model was used when the EM option has been selected.

3.2.3 RELAP4-FLOOD. The RELAP4-FLOOD option requires a special configuration for the reactor core to model reflood phenomena. This option is a part of the NRC WREM.[1] RELAP4-FLOOD is accessed by entering a "2" for ISPROG on the Problem Dimensions Data Card and by use of the data cards outlined in Volume II, Subsections 4.2.2 (66) through (72). Details for the RELAP4-FLOOD models and their uses are contained in Section 3.11.

3.2.4 RELAP4-CONTAINMENT. The RELAP4-CONTAINMENT option gives the user access to additional special use models in the code. The containment option is selected by entering "3" for ISPROG on the Problem Dimensions Data Card. This option allows air flow and activates the Ice Condenser Model for use in the containment analysis. This is further described in Section 3.12.

3.3 Fluid Equations, Fluid Dynamics, and Related Input Data

This section of the RELAP4/MOD5 User's Manual presents the fluid equations used in the program. Also presented are the fluid dynamics options and the input data requirements for the proper use of these equations in modeling plants to be studied by the code.

Derivation of the fluid equations starts with the classical conservation equations for fluid mass, energy, and flow in differential form. These are integrated to produce stream-tube equations. The foregoing are subjected to mathematical development into a range of five separate fluid flow forms. One of the foregoing five is comprised of four sub-

forms. Thus eight distinct fluid flow equations give RELAP4 wide versatility.

The eight fluid flow equations are used by RELAP4 in conjunction with the thermodynamic properties of water along with user specified options and input data. The latter options and input data describe the system dynamics, the static components, and the effects of active system hardware such as pumps, valves, etc. A fluid volume is described by specifying the geometry of the volume and the fluid conditions within the volume. The program will either calculate the time-dependent fluid conditions within a volume or the user can enter the fluid conditions as special boundary conditions. A junction is described by specifying geometry, type, friction loss, inertia, choking conditions and flow equation form.

3.3.1 Fluid Equations. This subsection presents the differential equation form of the fluid mass, energy, and flow equations. These are integrated and developed into specific application equations for the RELAP4 program options.

(1) Stream-Tube Fluid Equations. The conservation equations for fluid mass, energy, and flow along with the fluid state-property relations give a complete solution to fluid-flow phenomena. RELAP4 solves a particluar set of fluid equations in the stream-tube form that is based on the assumptions of one-dimensional, homogeneous, thermal-equilibrium flow. Although RELAP4 does not prohibit the use of connected multiple-flow paths, a multidimensional flow path is approximated with one-dimensional equations.

The stream-tube fluid equations are derivable from the conservation equations given in standard texts on fluid flow [8]. These equations are as follows:

(1) Fluid Mass Equation

$$A \frac{\partial \rho}{\partial t} = - \frac{\partial W}{\partial x} \tag{1}$$

(2) Fluid Energy Equation

$$A \frac{\partial (\rho e)}{\partial t} = - \frac{\partial}{\partial x} \left[W \left(h + \frac{v^2}{2} + \Phi \right) \right] + q_w \frac{\partial A_w}{\partial x} \tag{2}$$

(3) Fluid Flow Equation

$$A \frac{\partial (\rho v)}{\partial t} = - \frac{\partial (vW)}{\partial x} - A \frac{\partial P}{\partial x} - \rho g A \frac{\partial z}{\partial x} - \frac{\partial F_k}{\partial x} \tag{3}$$

where $q_w \frac{\partial A_w}{\partial x}$ represents the rate of heat transfer per unit path length through the wall surface area that bounds the control volume.

The symbol definitions for the foregoing are as follows:

W = mass flow rate

ρ = fluid density

A = flow area

v = fluid velocity

P = thermodynamic pressure

F_k = frictional force

e = total fluid specific energy $(u + \frac{v^2}{2} + \Phi)$

u = fluid specific internal energy

h = fluid enthalpy $(h = u + \frac{P}{\rho})$

Φ = gravity potential function $(g = \frac{\partial \Phi}{\partial z})$

g = gravitational acceleration constant

q_w = wall heat flux

A_w = wall area for heat transfer

t = time coordinate value

x = path length coordinate value

z = elevation coordinate value.

Basically, RELAP4 allows fluid volumes (referred to as control volumes) to be arbitrarily connected by multiple flow paths (junctions) where the actual arrangement must be completely defined by the user. This versatility is desirable for a general purpose program; however, it must be viewed in terms of the inherent assumptions discussed previously.

To obtain mass, energy, and flow values, the conservation equations are integrated over mathematically defined control volumes. The thermodynamic pressure is defined by the state-property relations in terms of specific internal energy and density. The resulting set of simultaneous equations is linearized and advanced for a small time increment by a fully implicit numerical technique. The control volumes for the mass and energy equations are the fluid volumes required as user-defined input (Volume Data Cards outlined in Volume II, Subsection 4.2.2 (11)). The junction control volume describes the flow paths in the composite volume between the centers of adjacent fluid volumes. This flow path is

referred to as a junction and the user should not be mislead by an implication that junctions are point entities.

The quantities known (within any volume after the mass and energy equations have been integrated over a time step) are the total water mass, the total air mass, and the combined internal energy of both water and air. From these variables, the specific thermodynamic states of the water and air are determined in a fluid property subroutine. Water properties are obtained from the steam tables as functions of temperature and specific volume (Section 3.13). The air is assumed to be a perfect gas with a constant specific heat. The fluid property routine iterates over the temperature by using the Newton-Raphson Method until the computed internal energy converges to the value obtained from integrating the energy equation.

(2) Integrated Stream-Tube Fluid Equations. The actual fluid equations used in RELAP4 can be obtained by integrating the stream-tube equations over a fixed volume, V. The fluid mass and energy equations are developed for the generalized i^{th} fluid volume that connects to j flow paths (junctions), connecting volumes K and L. The results of integrating the stream-tube equations are presented in the following subsections.

(3) Fluid Mass Equations. The mass equation is:

$$\frac{dM_i}{dt} = \Sigma_j W_{ij} \tag{4}$$

where

M_i = mass in volume V_i

W_{ij} = flow into volume V_i from junction j.

(4) Fluid Energy Equation. The energy equation for homogenous flow is:

$$\frac{dU_i}{dt} = -\frac{\ell_i}{2A_i}\frac{d}{dt}\left(\frac{\bar{W}_i^2}{\bar{\rho}_i}\right) + \sum_j W_{ij}\left(h_{ij} + \frac{v_{ij}^2}{2} + z_{ij} - \bar{z}_i\right) + Q_i \qquad (5)$$

where

U_i = total fluid internal energy within volume V_i

ℓ_i = flow length of volume V_i

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

$\bar{\rho}_i$ = average fluid density in volume V_i

A_i = flow area of volume V_i

h_{ij} = local enthalpy at junction j of the fluid entering or leaving volume V_i

v_{ij} = local fluid velocity at junction j of the fluid entering or leaving volume V_i

$z_{ij} - \bar{z}_i$ = elevation change from the center of mass of volume V_i at $\bar{z}_i$ to junction j

Q_i = rate of heat energy transferred into volume V_i

The specific internal energy u is, by definition, the ratio of the total internal energy U to the total mass M as follows:

$$u = \frac{U}{M} \tag{6}$$

and the average fluid density is:

$$\bar{\rho} = \frac{M}{V}. \tag{7}$$

To evaluate the kinetic energy term involving the volume average flow rate $\bar{W}_i$, the volume V_i is assumed to have a constant flow area A_i at both inlet and outlet sides. This assumed volume geometry is also required for the following flow equations. With this geometry definition, the volume average mass flow is then assumed to be the average of the inlet flows and the outlet flows:

$$\bar{W}_i = \frac{\left(\sum_{j,in} W_{ij}\right)\left(\sum_{j,in} v_j A_j\right) - \left(\sum_{j,out} W_{ij}\right)\left(\sum_{j,out} v_j A_j\right)}{\sum_{j,in} v_j A_j - \sum_{j,out} v_j A_j + \frac{\sum_{j,in} W_{ij} - \sum_{j,out} W_{ij}}{\bar{\rho}_i}} \tag{8}$$

where W_{ij} is the mass flow entering or mass flow leaving (negative) volume V_i through junction area A_j with a junction velocity v_j.

The junction enthalpy, h_{ij}, and the junction velocity, v_{ij}, are evaluated immediately upstream of the actual junction flow area, A_j, that connects a volume to another volume or flow source. By definition, the junction enthaply and kinetic energy are determined by the fluid properties of the source of flow, W_{ij}. For example, if W_{ij} is negative; that is, if W_{ij} is a flow out of volume V_i, then h_{ij} and v_{ij} are determined by the properties of V_i. Hence, the junction enthalpy with respect to the source volume is:

$$h_{ij} = \bar{h}_i + \frac{\bar{v}_i^2}{2} - \frac{v_{ij}^2}{2} + (\Delta h_i)_q + (\Delta h_{ij})_s \qquad (9)$$

where

$\bar{h}_i$ = average enthalpy of source volume V_i

$\frac{\bar{v}_i^2}{2}$ = average kinetic energy of source volume V_i

$\frac{\bar{v}_{ij}^2}{2}$ = kinetic energy of flow W_{ij} immediately upstream of the junction area A_j

$(\Delta h_i)_q$ = junction enthalpy change from center of volume to junction due to heating within the source volume V_i

$(\Delta h_{ij})_s$ = enthalpy change due to phase separation at junction j within the source volume V_i.

The rate of enthalpy increase due to heating within volume V_i at junction j is described in Subsection 3.6.14.

(5) Fluid Flow Equation. Five basic forms of the fluid flow equation are provided in RELAP4. Each form contains a particular set of assumptions and one form is comprised of four subforms. The user should choose the form most appropriate for a particular junction. This choice is accessed by the MVMIX index on the Junction Data Card as defined in Volume II, Subsection 4.2.2 (21), with one form being organic to the Evaluation Model.

Specifically the five basic forms are:

(1) Form 1 - Compressible Single-Stream Flow with Momentum Flux - MVMIX = 0 (defaults to forms with table choking)

(2) Form 2 - Compressible Two-Stream Flow with One-Dimensional Momentum Mixing (comprised of four subforms) - MVMIX = 1 or 2

(3) Form 3 - Incompressible Single-Stream Flow without Momentum Flux - MVMIX = 3

(4) Form 4 - Compressible Single Stream Integral Momentum Equation - MVMIX = 4

(5) Form 5 - Incompressible Mechanical Energy Balance Equation (used in EM option).

The choice of the form of the flow equation depends upon the purpose and detail of the desired calculation. The forms for compressible single-stream flow with momentum flux (Form 1) and for compressible two-stream flow with one-dimensional momentum mixing (Form 2) both include a one-dimensional momentum flux term. These are applicable when the control volumes represent a one-dimensional stream-tube. The form for compressible two-stream flow with momentum mixing should be used only when two streams can combine and exchange momenta on a one-dimensional basis. The basic momentum mixing form (Form 2) has four subforms that represent four different flow patterns of the streams. The incompressible single stream flow without the momentum flux term (Form 3) provides an alternate to the compressible flow equation with the momentum flux term for modeling multi-dimensional geometries. An alternate form of the momentum equation developed by Zuber[9] is obtained by using a different user-modeled volume approach yielding the Compressible Integral Momentum Equation (Form 4). The incompressible Mechanical Energy Balance Equation (Form 5) is required by the Nuclear Regulatory Commission for the Evaluation Model.

General, two or three dimensional flow problems are modeled using a one-dimensional approximation of the momentum flux term. The user must recognize this RELAP4 approximation when geometries containing predominantly multi-dimensional flows are modeled.

The general flow equation applicable to all forms is first developed by referring to Figure 1, which is a general description of a flow path connecting volumes K and L. The different flow equation forms are then developed as extensions of the generalized flow equations.

The flow equation for path j is defined from the center of volume K to the center of volume L, as shown in Figure 1. Both control volumes are identical to the volumes defined for the mass and energy balance equations. Hence, the thermodynamic pressures, P_K and P_L, and the average volume flows, W_K and W_L, are known and are assumed to exist at the center of the respective volumes. These pressures and average flows thus form the boundary conditions for the flow path j. Volumes K and L also have unique flow areas, A_K and A_L, respectively, and path lengths, ℓ_K and ℓ_L, respectively. Flow area changes are permitted at the junctions between control volumes.

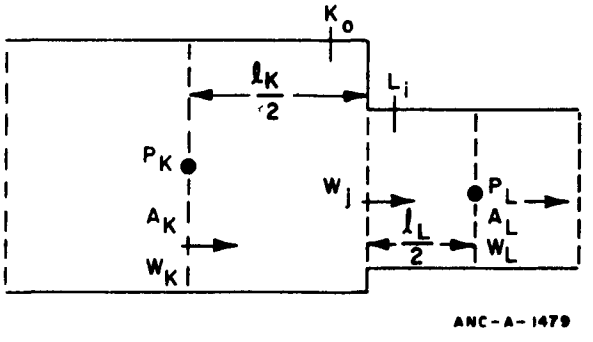


Fig. 1 Flow path control volume.

A direction coordinate is implicit in the flow path definitions. For path j, the user must define the volume from which the flow originates, volume K, and the volume to which the flow is going, volume L. Hence, junction j represents the outlet side of volume K and the inlet side of volume L.

The general integral of the stream-tube equation for path j from the center of volume K to the center of volume L is:

$$I_j \frac{dW_j}{dt} = (P_K + P_{Kgj}) - (P_L + P_{Lgj}) - F_{f_K} - F_{f_L} - F_{fr} - \int_{K_o}^{L_i} dF - \int_K^L \frac{d(vW)}{A} \tag{10}$$

where

K_o refers to the outlet side of volume K adjacent to the junction area A_j

L_i refers to the inlet side of volume L adjacent to junction area A_j

and where

P_K, P_L = thermodynamic pressure at volume centers

P_{Kgj} = gravity pressure differential from the center of volume K to junction j

P_{Lgj} = gravity pressure differential from junction j to the center of volume L

F_{f_k}, F_{f_L} = Fanning friction pressure loss within each half-volume or

$$= 4\ f\ \left(\frac{\ell}{2D_h}\right)\quad\left(\frac{\rho\bar{v}|\bar{v}|}{2}\right)\quad \Phi_{2p}$$

F_{fr} = residual friction term defined by steady state conditions

$\int_{L_o^K}^{L_i} dF$ = expansion or contraction friction between volumes K and L

$\int_{L_K}^{L} \frac{d(vW)}{A}$ = momentum flux terms for area and density changes between volumes K and L

f = Fanning friction factor

ℓ = volume length

A = volume flow area

D_h = hydraulic flow diameter

ρ = fluid density

v = fluid velocity

K = subscript referring to volume K

L = subscript referring to volume L

j = subscript referring to junction j

Φ_{2p} = multiplier for increased friction when flow is two-phase fluid

I_j = geometric inertia for junction j or

$$= \frac{\ell_K}{2A_K} + \frac{\ell_L}{2A_L}$$

W_j = mass flow at junction.

The Fanning friction factor for turbulent flow in smooth pipes based on the Karman-Nikuradse equation[10,11] is:

$$\frac{1}{\sqrt{f}} = -0.4 + 4 \log_{10} (Re\sqrt{f}) \tag{11}$$

with

$$0.002 \leq f \leq f_e$$

and for laminar flow is:

$$f = \frac{16}{Re} \tag{12}$$

with

$$f > f_e$$

where

Re = Reynolds number

f_e = cross-over Fanning value between turbulent and laminar equations.

In RELAP4, the intersection of the turbulent and laminar equations defines the cross-over Fanning value f_e. This intersection occurs when Re $\simeq$ 1000 and $f_e \simeq 0.012$. The Reynolds number in RELAP4 is is based on saturated liquid viscosity for subcooled fluid and saturated gas viscosity for superheated gas. For two-phase fluid, the viscosity is a quality weighted value of the saturation values.

The two-phase friction multiplier, ϕ_{2p}, is an optional correction factor used to increase the wall friction loss for two-phase fluid flow. The two-phase friction multiplier is calculated as a function of mass flux, pressure, and quality through use of a modification of the Baroczy[12] correlation. The modification allows the final two-phase friction multiplier to always be greater than or equal to 1.0 which corresponds to single-phase liquid flow.

The junction flow, W_j, is defined as the volume-average inertial-weighted flow between the centers of volumes K and L as follows:

$$W_j = \frac{\int_K^j \frac{Wdx}{A_K} + \int_j^L \frac{Wdx}{A_L}}{I_j} . \tag{13}$$

The other terms in Equation (10) represent the friction loss pressure change across the junction and the momentum flux effects within the flow paths. These terms are evaluated in the following presentation for the previously described forms of the flow equations.

(a) Compressible Single-Stream Flow with Momentum Flux (Form 1). The Compressible Single-Stream Flow (Form 1) Equation derivation begins by assuming compressible flow across junction j from Ko to L;[13]. Equation (10) then becomes:

$$\begin{aligned} I_j \frac{dW_j}{dt} = {} & \left(P_K + \frac{\bar{v}_K \bar{W}_K}{A_K} + P_{Kgj}\right) - \left(P_L + \frac{\bar{v}_L \bar{W}_L}{A_L} + P_{Lgj}\right) \\ & + \rho_{Li} \left(v_{Li}^2 + C_j^2\right) - \rho_{Ko} \left(v_{Ko}^2 + C_j^2\right) \\ & - F_{f_K} - F_{f_L} - F_{K,j,L} \end{aligned} \tag{14}$$

where

$\overline{W}$ = volume average mass flow as previously defined for the energy equation

$\overline{v}$ = volume average velocity

ρ_{Li}, ρ_{Ko} = fluid density at the inlet side of volume L and the outlet side of volume K, respectively

v_{Li}, v_{Ko} = fluid velocity at the inlet side of volume L and the outlet side of volume K, respectively

C_j = fluid sonic velocity or

$$\sqrt{\left(\frac{\partial P}{\partial \rho}\right)_s}$$

F_{f_K}, F_{f_L} = Fanning friction pressure loss as previously defined

$F_{K,j,L}$ = frictional pressure loss from the outlet side of volume K through junction j into the inlet side of volume L

s = subscript referring to constant entropy.

The junction sonic velocity, C_j, is determined from the source volume. Thus, for positive flow, the junction sonic velocity is the sonic velocity at the outlet side of volume K, C_{Ko}, and for negative flow it is the sonic velocity at the inlet side of volume L, C_{Li}.

In general, the frictional pressure loss through junction j is defined in terms of a form-loss coefficient:

$$F_{K,j,L} = K_f \frac{\rho_j v_j |v_j|}{2} \tag{15}$$

where the form loss coefficient K_f is dimensionless. It is based on the junction area A_j and the upstream and downstream areas, A_K and A_L. RELAP4 provides the user with the option of calculating special form loss coefficients based on sharp-edged area changes from A_K to A_j and then from A_j to A_L. This combination of a sharp-edged contraction and expansion also permits an approximation of an orifice loss coefficient. The form loss coefficient for expansions or contractions is dependent on the flow direction and is defined for both positive and negative flows. For complex geometries or smooth area changes, the user must supply the form loss coefficients. Tables of form loss coefficients are available [7,10].

The downstream junction density and velocities are calculated from the isentropic constant-sonic-velocity equation:

$$\frac{\rho}{\rho_o} = e - \frac{(M^2 - M_o^2)}{2} \tag{16}$$

where

- o = subscript referring to junction inlet conditions (outlet of upstream volume)
- ρ = density
- M = Mach number, v/C
- C = sonic velocity.

The equation is solved in RELAP4 by computing the intermediate Mach number within the junction area A_j. If the Mach number is less than unity throughout the area change across the junction, the flow is continuous and unchoked. If the calculated Mach number exceeds unity within the area change, the flow is assumed to be choked and the flow

equation is redefined such that no force remains to accelerate the stream; that is, $I \frac{dW}{dt}$ is set to zero. An optional critical flow calculation is available from tables of critical mass flux versus source pressure and enthalpy (Subsection 3.6.8). When critical flows are calculated from both the flow equations and the table correlations, the accepted value is the minimum of the two flows.

(b) Compressible Two-Stream Flow with One-Dimensional Momentum Mixing (Form 2). The same equation as given for the single-stream flow is used as the basis for the two-stream mixing equation (Form 2), with several modifications. This form of the flow solution equation is restricted to the mixing of two streams, either on the inlet (or "to") side of a volume (MVMIX=2), or on the outlet (or "from") side of a volume (MVMIX=1). The following forms of the flow equations developed for the flow W_{ji}, are presented for the cases in which the two streams, W_{j1} and W_{j2}, are located on the outlet side of volume K (MVMIX=1). Flow solutions for mixing at the inlet side of volume L can be obtained by appropriate changes in the subscripts. The general geometry assumed for mixing streams is shown in Figure 2. In the vicinity of the multiple junctions, the net flow at the outlet side (K_o) of volume K is labeled W_m. The area A_m for this net flow is the sum of the individual junction areas ($A_{j1} + A_{j2}$) and forms a constant area "mixing" section. Mass storage effects are neglected within the mixing section and hence the flow and mass continuity equations for this section have no time derivatives.

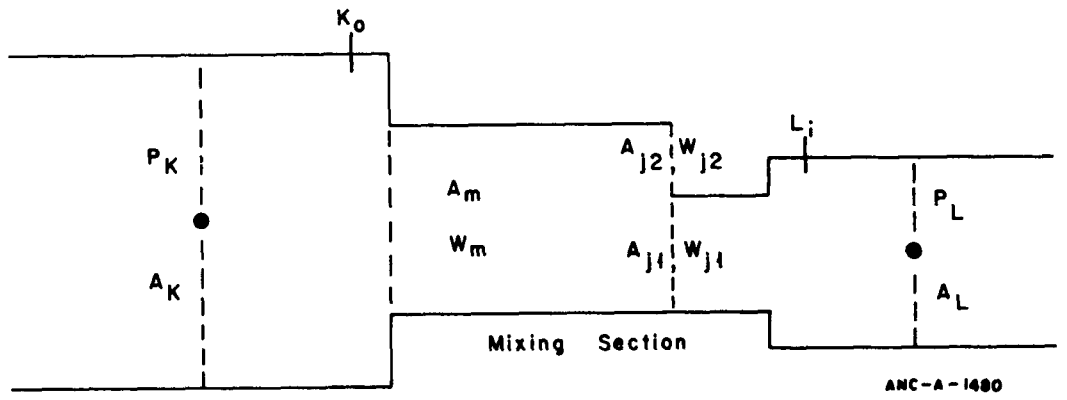


Fig. 2 General multiple junction geometry.

In RELAP4, the flow can be mixed on only one side of the junction. That is, for a given junction, the flow can be mixed with another stream in either the volume "to" which the flow is going or the volume "from" which the flow is coming. The basic assumptions for the mixing model as used in RELAP4 are essentially the same as used in the BRUJET computer program[14]. The fluids from the two streams are required to have the same velocities in the mixing section; furthermore, a frictional effect that is not optional is calculated to ensure that the resulting mixed streams lose kinetic energy.

Four subforms of the Form 2 (two-stream) flow equations will be used to represent various flow patterns of the streams. These will be referred to as Subforms 2a, 2b, 2c, and 2d respectively. All four subforms for the two-stream flow equations can be expressed with variation only in the ΔP_{j1} term of the following:

$$I_{j1}\frac{dW_{j1}}{dt} = -I'_{j2}\frac{dW_{j2}}{dt} + \left(P_K + \frac{\bar{v}_K\bar{W}_K}{A_K} + P_{Kgj1}\right) - \left(P_L + \frac{\bar{v}_L\bar{W}_L}{A_L} + P_{Lgj1}\right) - F_{f_K} - F_{f_L} - F_{Kj1,j1,Lj1} + \Delta P_{j1} \tag{17}$$

where

W_{j1} = flow from volume K through junction j1 to Volume L

W_{j2} = flow through junction j2 that is mixed with W_{j1}

I_{j1} = inertia for flow W_{j1}

I'_{j2} = half-volume inertia for flow W_{j2} in the volume common to flow W_{j1}

$F_{Kj1,j1,Lj1}$	=	friction loss for the flow through junction j1
ΔP_{j1}	=	pressure change effect in the vicinity of the multiple junctions that is dependent on the flow pattern
F_{f_K}, F_{f_L}	=	Fanning friction pressure loss in volumes K and L, respectively
P_{Kgj1}, P_{Lgj1}	=	elevation pressures for flow W_{j1} in volumes K and L, respectively.

The following four subforms for the mixing section pressure change ΔP_{j1} depend on the particular flow pattern in the mixing section and are automatically selected by the operation of the program.

For Subform 2a, both flows, W_{j1} and W_{j2}, are in the same direction and they exit from volume V_K as shown in Figure 3. In this case, the pressure at the outlet section of volume K is assumed to be uniform across both junctions, A_{j1} and A_{j2}. Also, the flows, W_{j1} and W_{j2} are required to have the same velocities in the mixing section. "Unmixing" with a subsequent exchange in stream momentum is not allowed once it would yield a net increase in total stream energy.

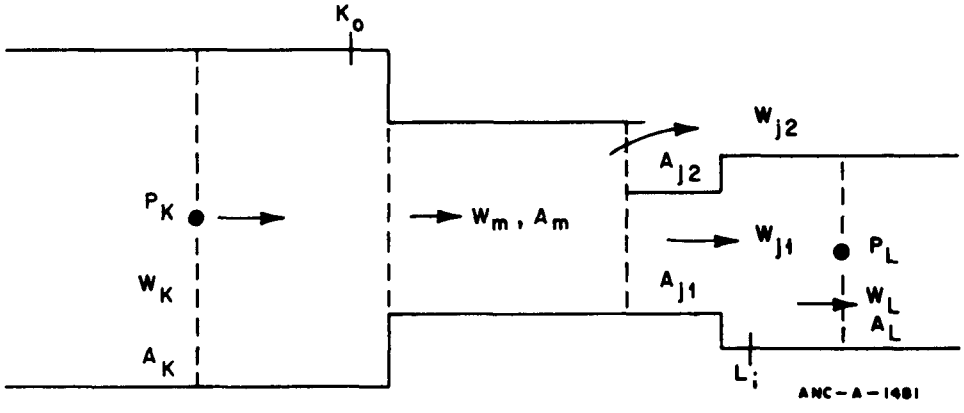


Fig. 3 Mixing geometry for positive flows out of Volume V_k.

The total stream flow in the outlet half of volume K is:

$$W_m = W_{j1} + W_{j2} \tag{18}$$

where W_m = flow in the mixing section. The pressure change term for Subform 2a is:

$$\Delta P_{j1} = 0. \tag{19}$$

For Subform 2b, both flows, W_{j1} and W_{j2}, are in the same direction into the common volume K as shown in Figure 4. The pressure across the junctions is also assumed to be uniform which results in an equation for mixing that implicitly includes a friction loss. The two streams exchange momenta resulting in a pumping action as occurs in a jet-pump. For Subform 2b, the pressure change term is:

$$\Delta P_{j1} = C_m^2 (\rho_m - \rho_{Ko}) + C_{j1} (\rho_{Li} - \rho_{j1}) + \frac{v_m W_m - v_{j1} W_{j1} - V_{j2} W_{j2}}{A_m} . \tag{20}$$

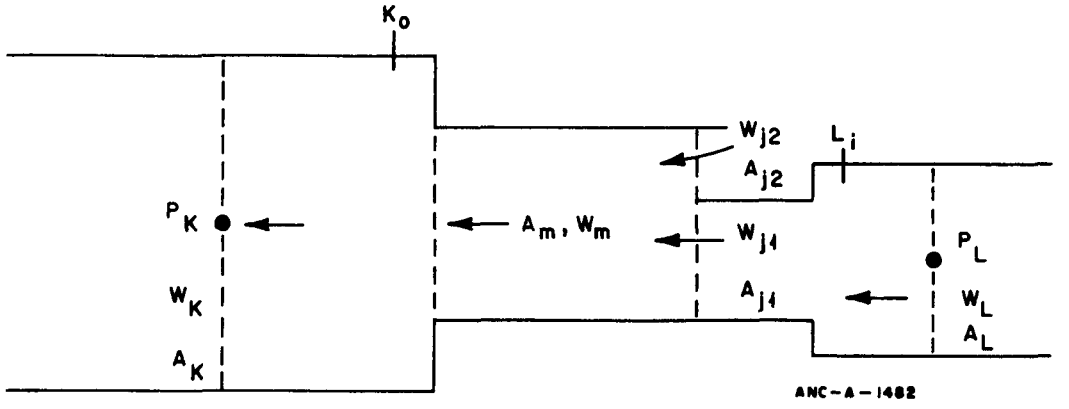


Fig. 4 Mixing geometry for reverse flows entering Volume V_k.

The mixed density, ρ_m, is defined from the mass continuity equation with equal velocities assumed, as:

$$\frac{1}{\rho_m} = \frac{\frac{W_{j1}}{\rho_{j1}} + \frac{W_{j2}}{\rho_{j2}}}{W_m} \tag{21}$$

and the mixed sonic velocity is assumed to be:

$$C_m^2 = \frac{W_{j1} C_{j1}^2 + W_{j2} C_{j2}^2}{W_m} \tag{22}$$

where

C_{j1}, C_{j2} = sonic velocity at A_{j1} and A_{j2}, respectively, as determined from the source volume conditions

ρ_{j1}, ρ_{j2} = fluid density at A_{j1} and A_{j2}, respectively

v_m = fluid velocity in mixing section

v_{j1}, v_{j2} = fluid velocities at A_{j1} and A_{j2}, respectively.

For Subform 2c, the junction flows are in opposite directions, with the flow W_{j1} in the same direction as W_m as shown in Figure 5.

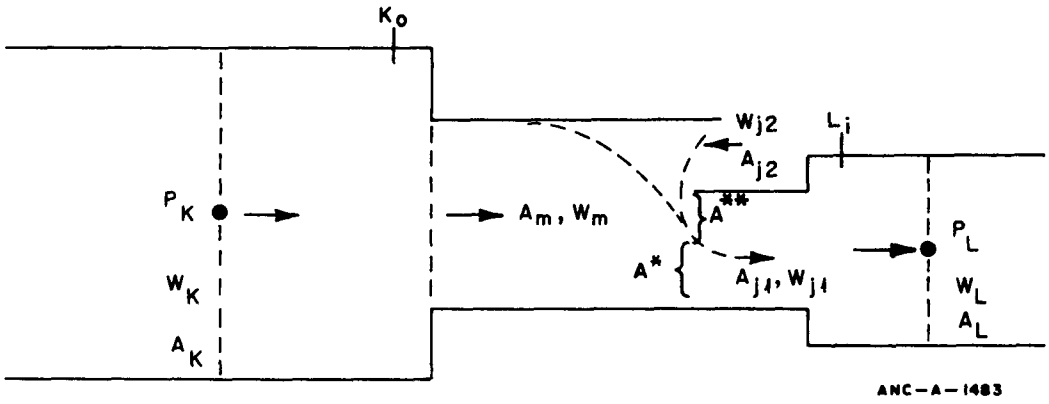


Fig. 5 Mixing geometry for opposing flow directions - Junction 1 flow in same direction as mixed flow.

If the velocities in the merged stream W_{j1} from W_m and W_{j2} are assumed equal, and if the flow areas for each stream in the vicinity of the entrance to W_{j1} are defined equivalent, the pressure change for Subform 2c is:

$$\Delta P_{j1} = \rho_{Li} (v_{Li}^2 + C_{j1}^2) - \rho_{Ko} (v_{Ko}^2 + C_{ko}^2) + \rho_m C_{Ko}^2 - \rho_{j1} C_{j1}^2. \qquad (23)$$

The frictional term is evaluated by assuming a sharp-edged area change from A_k to A_m and then to A* for the flow leaving volume K with another friction term for j2 where the area changes from A_{j2} to A**.

The equivalent flow areas, A* and A**, are the areas of the entrance to A_{j1} occupied by the flows W_m and W_{j2} where

$$A_{j1} = A^* + A^{**}. \tag{24}$$

For equal velocities at the entrance to A_{j1}, A* is defined by:

$$\frac{1}{A^*} = \frac{1}{A_{j1}} \frac{W_{j1}}{W_m} \frac{\rho_m}{\rho_{j1}} \tag{25}$$

The density of the mixed stream within A_{j1} is:

$$\frac{1}{\rho_{j1}} = \frac{\frac{W_m}{\rho_m} - \frac{W_{j2}}{\rho_{j2}}}{W_{j1}} \tag{26}$$

and the flow weighted junction sonic velocity is

$$C_{j1}^2 = \frac{C_{Ko}^2 \; W_m - C_{j2}^2 \; W_{j2}}{W_{j1}} \tag{27}$$

For Subform 2d, the flows W_{j1} and W_m are in opposite directions as shown in Figure 6.

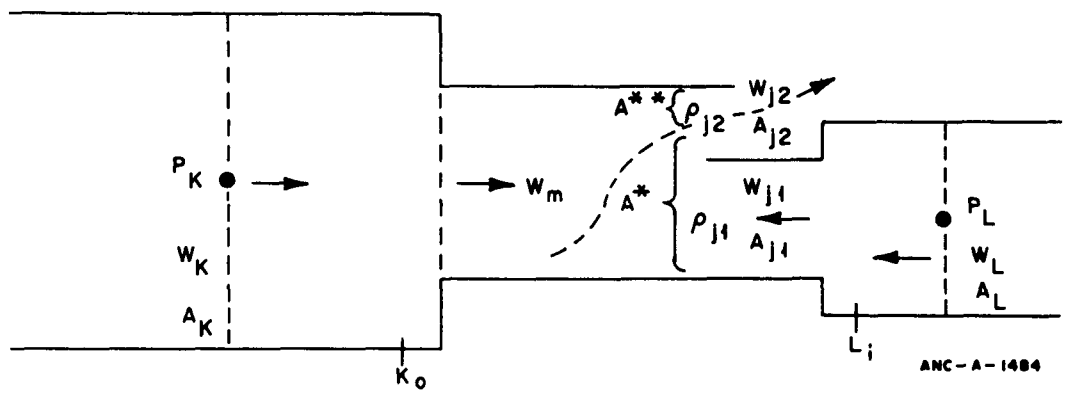


Fig. 6 Mixing geometry for opposing flow directions - Junction 1 flow opposite to mixed flow.

The form of the pressure change, ΔP_{j1}, for Subform 2d is identical to that for Subform 2c except for the definitions of the mixed stream density and sonic velocity at the entrance to A_{j2}. Thus, the pressure term is

$$\Delta P_{j1} + \rho_{Li} (v_{Li}^2 + C_{Lo}^2) - \rho_{Ko} (v_{Ko}^2 + C_{Ki}^2) + C_{Ki}^2 \rho_{j1} - C_{Lo}^2 \rho_{j2} \qquad (28)$$

where ρ_{j1} and ρ_{j2} are the densities of the streams with the equivalent flow areas A* and A**, respectively, that merge at A_{j2}.

(c) Incompressible Single-Stream Flow Without Momentum Flux (Form 3). The Incompressible Single-Stream Flow Equation (Form 3) neglects the momentum flux term d(vW)/A and is essentially identical to the basic flow equation used in RELAP3[15]. When the separate friction terms in the general flow Equation (10) are combined, the resulting flow equation is:

$$I_j \frac{dW_i}{dt} = (P_K + P_{Kgj}) - (P_L + P_{Lgj}) - K_f \frac{\rho_j v_j |v_j|}{2} \Phi_{2P} . \qquad (29)$$

(d) Compressible Integral Momentum Equation (Form 4). Figure 1 has been used for describing the general flow path between two user defined control volumes. By using a different control volume approach, Zuber[9] has derived a different form of the momentum equation. This Single-Stream Compressible Integral Momentum Equation (Form 4) is:

$$I_j \frac{dW_j}{dt} = (P_K + \frac{\bar{v}_K \bar{W}_K}{A_K} + P_{Kgj}) - (P_L + \frac{\bar{v}_L \bar{W}_L}{A_L} + P_{Lgj})$$

$$-F_{fK} - F_{fL} - F_{K,j,L} . \qquad (30)$$

(e) Incompressible Mechanical Energy Balance Equation (Form 5).

The Incompressible Mechanical Energy Balance Equation (Form 5) represents the incompressible form of the Compressible Single-Stream Flow With Momentum Flux Equation (Form 1). This is acceptable to the Nuclear Regulatory Commission for the Evaluation Model and is presently available in RELAP4. The equation is:

$$I_j \frac{dW_j}{dt} = (P_K + \frac{v_K W_K}{A_K} + P_{Kg}) - (P_L + \frac{v_L W_L}{A_L} + P_{Lg})$$

$$- \frac{W_j^2}{2} (\frac{1}{\rho_{jK} A_K^2} - \frac{1}{\rho_{jL} A_L^2})$$

$$- S_K (\frac{4f\ell}{2D_h})_K \frac{W_1^2}{2\rho_K A_K^2} - S_L (\frac{4f\ell}{2D_h})_L \frac{W_L^2}{2\rho_L A_L^2} - \frac{S_j K_j W_j^2}{2\rho_j A_j^2} \qquad (31)$$

where:

f = friction factor

S = 1 for forward flow, -1 for reverse flow.

K_j = residual friction term defined by steady state conditions.

*Note that for this case $\rho_{j1} = \rho_{j2}$ and the middle term can be written as:

$$- \frac{W_j^2}{2\rho_j} (\frac{1}{A_K^2} - \frac{1}{A_L^2})$$

3.3.2 Fluid Dynamics Options and Input Data. This subsection discusses the thermodynamic properties of water used by RELAP4 and the user-specified options and input data that are related to the fluid equations. User-specified options and input data requirements are presented for describing fluid volumes and junctions. A fluid volume is described by specifying the geometry of the volume, or the user can provide the fluid conditions within the volume. The program will either calculate the time-dependent fluid conditions within a volume, or the user can provide the fluid condition input as special boundary conditions. A junction is described by specifying the geometry, type, friction loss and inertia, flow-choking, and the form of the flow equations. Valves are handled as special cases of junctions.

(1) Fluid Volume. Each RELAP4 volume is defined by a set of Volume Data Cards consisting of up to nine cards per set. The data required to describe a volume include geometric information such as dimensions and elevation, initial conditions of the fluid in the volume, and option-control information. The format for these inputs on the Volume Data Cards is outlined in Volume II, Subsection 4.2.2 (11).

Initial conditions within the volume are completely specified by describing the state of the fluid and indicating the presence or absence of an air head. The input variables consist of temperature (TEMP), pressure (P), relative humidity or quality (HORX), and mixture level (ZM). The particular state in a volume is chosen from several possible, many of which are completely specified by a subset of the four input variables. The remaining input variables, if any (which if used to convey thermodynamic information would overspecify the state), pass control information to the program defining the particular subset of input variables to be used.

Subroutines are included in RELAP4 to compute the water properties in a given state from differing sets of input variables. The permissible sets of primary variables include:

(1) Temperature and quality (two-phase only)

(2) Pressure and quality (two-phase only)

(3) Temperature and pressure (single-phase)

(4) Temperature and specific volume (single- or two-phase).

Further detail is found in Section 3.13.

Figure 7 shows the volume positional variables required. A mixture level, (ZM), must be entered for each volume. This parameter defines the location of a vapor-mixture interface in the volume and has a value between zero and the volume height (ZVOL) input. Otherwise, the parameter specifies that the volume is filled with liquid water only (ZM = ZVOL) or is a space devoid of liquid (ZM = 0) which may be water (vapor or air or both). Elevation of the bottom of the volume entered as ELEV is measured from an arbitrary base chosen by the user.

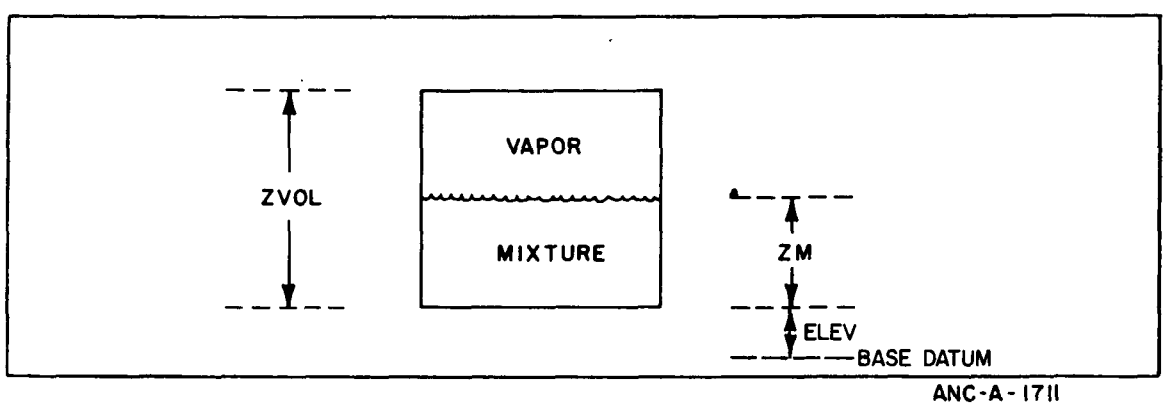


Fig. 7 Volume positional variables.

Volumes in which a vapor-mixture interface exists may optionally contain air as well as steam in the gas region. If air is present, the mixture region must be considered as liquid only. The options for volume content are summarized in Table I and discussed in the following subsections. The control variable is read by the program in conjunction with ZM to define the conditions present.

(a) Water Only in Volume (ZM = ZVOL). The thermodynamic properties required to define the state for water only are any two of the three quantities, viz. temperature (TEMP), pressure (P), and quality (X). The two-phase or saturated states are specified by quality and either temperature or pressure. Single-phase states require temperature and pressure. Note that relative humidity, alternately with quality, is entered in the volume data input format as HORX.

Two-phase or saturated conditions are indicated when the quality is between zero and one inclusive. The temperature is tested and, if greater than zero, the temperature-quality (TEMP, X) thermodynamic plane is selected. If the temperature variable is less than or equal to zero, the pressure-quality (P,X) thermodynamic plane is selected.

Superheated vapor and subcooled liquid conditions require temperature and pressure as input variables. The particular condition is specified by setting the quality variable input at greater than unity for superheated vapor and at less than zero for subcooled liquid. An error return will be made if the input data do not describe a state in the specified phase.

(b) Vapor-Mixture Interface in Volume (0 < ZM < ZVOL). A volume with a vapor-mixture interface may contain either: (1) a two-phase mixture or liquid which has a height ZM with the remainder of the volume filled with water vapor, or (2) liquid only which has a height ZM with the remainder of the volume filled with water vapor and air. The set of input variables which must be specified along with ZM depends

TABLE I

INITIAL CONDITIONS PRESENT FOR VARIOUS MIXTURE LEVELS

Conditions Present		Mixture Level	Control Variable Quality (X), Relative Humidity (H) or Pressure (P)	Thermodynamic Variables Used
Superheated Vapor	No Air Present	Volume filled	X > 1.0	P,T
Saturated Vapor	No Air Present	with water only	X = 1.0	P,X or T,X
Saturated Liquid	No Air Present	(ZM = ZVOL)	X = 0.0	P,X or T,X
Subcooled Liquid	No Air Present		X < 0.0	P,T
Two-Phase Mixture	No Air Present		0.0 < X < 1.0	P,X or T,X
Two-Phase Mixture or Liquid	No Air Present	Volume containing mixture	P = 0.0 if T > 0.0, P > 0.0 if T < 0.0 and 0.0 $\leq$ X < 1.0	P,X or T,X
Liquid	Air Present	(0 < ZM < ZVOL)	P > 0.0 and T > 0.0, X = 0.0[a]	T,X
Water Vapor	No Air Present	Volume filled	H < 0.0	P,T
Air	No Vapor Present	with gas	H = 0.0	P,T
Water Vapor	Air Present	(ZM = 0)	H > 0.0	P,T

[a] X = quality of liquid phase

upon whether or not air is present in the gas space. If air is not in the space, the input variables are either quality and temperature with pressure set to zero or, if the temperature is set to zero or a negative value, the input variables are quality and pressure. The quality in this case is that of the mixture only, not of the entire volume. The pressure of air in the volume is indicated by specifying both the temperature and total pressure in the volume. The mixture quality must be set at zero. The air pressure is the difference between the total pressure input (P) and the vapor pressure of water at the specified temperature. The air mass is computed from the perfect gas laws by the program.

(c) Gas Filled Volume (ZM = 0). A mixture level set at zero specifies that the volume contains no liquid. The volume may be filled with water vapor, air, or a combination of both. The input variables are pressure, temperature, and relative humidity with the latter variable also serving as a control variable (see Table I). If the vapor temperature is above the critical temperature of water, the relative humidity is undefined and the variable represents the ratio of vapor pressure to total pressure. A relative humidity set at zero specifies a volume filled with dry air. A negative value for the relative humidity specifies a volume filled with water vapor (no air present). A value between zero and one indicates that both air and vapor are present providing temperature is not above the critical temperature of water.

(d) Volumes with Time-Dependent Fluid Conditions. The option of using special boundary volumes with explicit time-dependent fluid boundary conditions is intended primarily for performing detailed calculations on part of a reactor system using results of previous RELAP4 calculations as boundary conditions. This option allows RELAP4 to perform a detailed core calculation. For this calculation, the special boundary volumes would be those of the upper and lower volumes which connect to the core regions. Any volume may be chosen independently to have fluid conditions described as an explicit function of time.

The fluid conditions in such boundary volumes are unaffected by the course of the detailed transient being calculated. The necessary fluid boundary data may be provided either as tabular data on input cards or by automatic retrieval from a data tape created during a previous RELAP4 calculation. Performing detailed calculations on part of a system by using special boundary volumes saves computer time as compared to modeling the complete system. A detailed calculation can be performed on any portion of the reactor system, such as a pump, by using special boundary volumes.

The time-dependent volume option is controlled by an index (IREAD) on a Volume Data Card. A positive index for any volume requires that pressure, temperature, quality, and mixture level, as functions of time, be supplied on the Time-Dependent Volume Data Cards. The format for these Time-Dependent Volume Data Cards is outlined in Volume II, Subsection 4.2.2 (19). A negative index causes the data to be retrieved from a RELAP4 data tape. The data retrieved from tape are those for the volume number corresponding to the negative index. The volume numbers used for the detailed calculation need not correspond to the volume numbers on the RELAP4 data tape. A zero index turns the option off for any volume.

The geometric detail for a time-dependent volume is required input, just as for a normal volume. Fluid conditions are required as a function of time and include pressure, temperature, quality, and mixture level. The geometric detail plus these four time-dependent functions provide sufficient information to completely define the fluid conditions in a volume. For each time step, the data supplied on either cards or tape is interpolated to obtain current fluid conditions. To perform calculations for a single core channel, a RELAP4 problem would be set up with the upper and lower volumes defined as time-dependent volumes. The data would be retrieved from the volumes representing the upper and lower plenums in a previous RELAP4 calculation of the entire primary loop. The power history would also be retrieved from the previous calculation as described in Subsection 3.5.3.

(e) Additional Volume Data Inputs. Volume II, Subsection 4.2.2 (11) outlines the input quantities required for the Volume Data Cards. Data input for the quantities IREAD, P, TEMP, HORX, V, ZVOL, ZM, and ELEV have deen described. The following presents the additional data required by the Data Card format for describing volumes or special conditions thereof.

A vertical bubble distribution model described in Subsection 3.6.6 must be specified. The bubble distribution is prescribed by a set of coefficients identified by a bubble data index, IBUB. If 0 is entered for IBUB, the program will assume a homogeneous liquid-vapor mixture.

The variable JTPMV is used to select a two-phase friction multiplier for the Fanning friction pressure loss. The actual multiplier applied is computed by the program for the hydraulic conditions at the time within the volume.

A flow area input FLOWA must be specified for each volume. The equivalent diameter DIAMV for this flow area must be entered for the Fanning friction computation. This is obtained by the formula:

$$\text{DIAMV} = \frac{4\ (\text{flow area})}{\text{perimeter}} \ . \tag{32}$$

If zero is entered for DIAMV, the program will compute the equivalent diameter from:

$$D = 2\sqrt{\frac{4\text{FLOWA}}{\pi}} \ . \tag{33}$$

The final variable required by the Volume Data Cards format is IAMBLO. This option is used to specify the computation of a single mixture level in a vertical stack of control volumes (see Subsection 3.6.6 (3)).

(2) Junction Physical Options. This subsection discusses the data required to describe a flow path (junction) between volumes. The format for junction data input is prescribed in Volume II, Subsection 4.2.2 (21). A junction connects a volume on the junction inlet side (indexed as IW1) to a volume on the junction outlet side (indexed as IW2). This indexing establishes the positive flow direction convention. Should the flow ever become IW2 to IW1 during the course of a problem run, the flow output, WP, will have a negative sign. The junction flow area is AJUN and the junction elevation, ZJUN, is referenced to the same datum as is the volume elevation, ELEV.

(a) Types of Junctions. The following three types of junctions are permitted:

(1) A normal junction connecting two control volumes

(2) A leak junction for which the null (or sink) volume index (IW2) is defined as zero

(3) A fill source junction for which the source volume index (IW1) is defined as zero. Fills can be either positive (mass injected) or negative (mass removed).

The zero IW1 or IW2 index indicates a null volume. This is an undefined volume except for pressures or temperatures specially defined within the Leak Table or Fill Table Data Cards.

Leak junction (IW2 = 0) input data must include an IPUMP index number which refers to a leak set within the Leak Table Data Cards. The format for this is prescribed in Volume II, Subsection 4.2.2 (44). The leak set number refers to the basic data for sink-pressure (SINK) and a leak junction area-vs-time curve.

The RELAP4 program, as presently coded, requires the user to specify the leak and fill junctions (Types 2 and 3) after normal junctions (Type I) are entered. Specifically, the card input sequence numbers for the leaks and fills must be larger than the sequence numbers for normal junctions. A further restriction is that no two directly connected volumes can have more that a total of 21 openings.

Fluid may be injected into any volume through one or more fill junctions and flow through any of these junctions may be initiated by use of the trip signal ITFILL. A fill curve is represented by the input table within the Fill Table Data Cards giving flow per unit area vs time or pressure. Several fill junctions can use one fill curve. Each fill table is indexed through the variable IPUMP. The format for the Fill Table Data Cards is outlined in Volume II, Subsection 4.2.2 (45).

Fluid may also be extracted from the system by using a negative fill rate. The junction flow equation option on the Junction Data Cards must be entered as MVMIX = -2.

(b) Friction Loss and Inertia Values. The flow in all junctions is initially assumed to be steady. Any imbalance is automatically absorbed in a residual friction coefficient that is applied equally throughout the transient calculation. By allowing the Junction Data Card input quantity JCALCI to be 1 or 3, the program will calculate forward (FJUNF) and reverse (FJUNR) flow form-loss coefficients (K_f) based on sharp-edge area changes. The total friction coefficient is then defined as the sum of the form-loss coefficient (as either provided by the input data or calculated by the program using the following expression) and the residual friction coefficient required to force initial steady flow conditions.

For a sudden expansion,

$$K_f = \left(1 - \frac{A_j}{A_{downstream}}\right)^2 \tag{34}$$

and for a sudden contraction,

$$K_f = 0.45 \left(1 - \frac{A_j}{A_{upstream}}\right) . \tag{35}$$

Both expressions are based on the junction flow area A_j entered as AJUN.

After the initial calculation of the residual friction coefficient, total forward and reverse friction coefficients are computed. If either of these is negative, the calculation is aborted, as negative friction coefficients are excluded.

Another option is omission of friction from the flow solution (JCALCI <0). It is only partially effective because the friction inherent in mixing streams cannot be eliminated. The Fanning [10,11] wall friction is automatically included in the calculation unless friction is eliminated by using JCALCI less than zero.

The quantity JCALCI is also used as a control to calculate junction inertia entered as INERTA. This option is useful if the user is describing simple pieces of piping with constant cross-sectional areas. If JCALCI is either 2 or 3, the inertia (INERTA) will be calculated as:

$$I = 0.5 \left(\frac{V_K}{A_K^2} + \frac{V_L}{A_L^2}\right) \tag{36}$$

where V is the volume and A is the volume flow area (FLOWA) specified on the Volume Data Cards.

The user can provide input values for the form loss and inertia terms, if it is not desired for the program to compute them. JCALCI must then be entered as 0.

(c) Choked Flow Options. The user has the option of selecting the combination of choking as calculated by the compressible flow equations and one of several explicit critical flow models (Section 3.6.8). The variables JCHOKE and ICHOKE are used to select a particular choked flow option from the wide range that is available. Entry of these on the Junction Data Cards is outlined in Volume II, Subsection 4.2.2 (21). Further detail for option selection is provided in Table V, Subsection 3.6.8. The following are recommended for general application:

JCHOKE	=	4	HEM including or not including subcooled blow-down depending upon selected ICHOKE
JCHOKE	=	5	Henry-Fauske-HEM with extended Henry tables in subcooled region and with transition to HEM in the saturated region.

The Evaluation Model requires JCHOKE = 0 or 1 and ICHOKE = 11. The user also has the option of using stagnation property values with each critical flow model as input to the critical flow data tables (see Section 3.6.9).

(d) Flow Equation Options. The user has the option of choosing the type of flow equation for each junction by entry on the Junction Data Cards. If MVMIX = 0, the flow equation is that for compressible single stream flow. If MVMIX is 1 or 2, the flow equation is that for compressible two-stream flow with one-dimensional momentum mixing. If MVMIX = 1, the momentum at the junction is combined on the outlet side of volume IW1. If MVMIX = 2, the momentum at the junctions is combined on the inlet side of volume IW2. The momentum mixing option requires two flow paths that must either originate or terminate in a common volume. The input data are checked and if these conditions are

not met, the calculation is aborted. If MVMIX = 3, the equation is for incompressible single stream flow and neglects the momentum flux terms. MVMIX = 4 provides the compressible single stream integral momentum equation.

In the case of more than one inlet junction for control volume i (that is if more than one IW2 is equal to i on the Junction Data Cards), the one with the largest absolute value of initial flow (WP on same cards) is chosen as the "major" inlet junction to volume i. If two or more inlet junctions for volume i have the same absolute value of inital flow, including 0.0, then the one with the lowest card number is chosen as the "major" inlet junction. The "major" outlet junction for volume i is determined in a similar manner if there is more than one outlet junction.

A fill junction may be a major inlet junction for a given volume, and a leak may be a major outlet junction. If a volume has only fill type junctions, no major outlet junctions should be designated for that volume even though one or more fills has negative flow. A special case is constituted for a volume with no normal outlet junction, but with a negative fill junction (where flow is negative) modeled as the actual volume outlet. In order for the correct volume flow to be calculated, the user must set MVMIX = -2 for the negative fill junction to represent the outlet junction. No equation form is associated with leaks or fills as these junctions are treated as boundary conditions.

The major inlet and outlet junction numbers are used in calculating the critical heat flux, in calculating the enthaply transport, and in checking volumes with the nonconduction heat exchangers described in Subsection 3.6.13 for the presence of an inlet junction and an outlet junction.

(e) Valves and Check Valves (IVALVE). A valve or a check valve may be placed in any RELAP4 junction by using a positive valve index (IVALVE) to refer to a Valve Data Card. The type of valve selected is determined by ITCV on the Valve Data Card. Several types are optional as described in Section 3.6.12.

(f) Vertical Junction Index (JVERTL). Enthalpy calculations at a junction require vertical height considerations. The user has the option of modeling a junction as having point vertical height, such as is usually true for junctions connecting vertically stacked control volumes, or having a circular (cross-section) area distributed vertically for horizontally connected control volumes. When JVERTL = 0, the junction is assumed to have a point value with respect to the bubble distribution in the control volume supplying the junction flow, and the junction enthalpy is "smooth". When JVERTL = 1, the junction is assumed to have a circular area with the cross section distributed in a vertical plane. When JVERTL = 2, the junction is assumed to have no vertical distribution and the enthalpy is not "smoothed".

The enthalpy smoothing (JVERTL = 0) is applicable only when steam separation is permitted and when the mixture level is near the junction elevation ZJUN. Under these conditions and when the junction lies within the steam dome, the total mass extracted from the volume during a single step ($W_j \Delta t$) is assumed to originate in the small steam region between the junction elevation (ZJUN) and the mixture interface height. If the required mass extraction exceeds the mass content of this small steam region, the difference is extracted from the mixture rather than from the steam dome. This model assumes that the mixture level swells to the junction elevation during the time-step advancement.

When junctions are used as vertically distributed areas (JVERTL = 1), the junction enthalpy is determined by integrating the bubble-distribution function over a circular area having a diameter of DIAMJ.

When JVERTL = 2, the enthalpy at the junction is defined by the phase that is currently present at the junction elevation. With this option, the enthalpy is not "smoothed" and can oscillate during each time advancement from the limits of the liquid-bubble mixture enthalpy to the pure steam enthalpy.

3.4 Heat Transfer

A heat conductor model is used to account for heat transfer to and from the fluid in given control volumes. The heat addition rate to the fluid of a volume is calculated as the product of the surface heat flux and the heat transfer area at the conductor (heat slab) surface in contact with the fluid. Conductors may be described as rods, pipes, cylindrical vessels, and plates. Internal heat generation may be specified for those conductors which represent core fuel pins. Most of the heat transfer correlations used at conductor surfaces and the method of determining which correlation to use are taken essentially from the Nuclear Reactor Core Thermal Analysis Code, THETA1-B[16]. A Metal-Water Reaction Model is available for core conductors.

Heat may also be transferred by means of a volume-associated heat exchanger model described in Subsection 3.6.13. Normally, this model is used to remove heat from the fluid of a volume when the user desires a faster and simpler way of accounting for heat removal than by modeling a heat exchanger as a heat conductor.

3.4.1 Heat Conductors. A heat conductor (sometimes referred to as a "heat slab") can be described as one or more materials which conduct heat into the fluid of a control volume, or between the fluids within two different volumes. In the former case, the conductor may represent core fuel pins, or a material insulated on one side and with no internal heat generation. The latter case may represent piping with one volume on the inside of the pipe and the other volume on the outside, or a flat plate separating two volumes. When a conductor connects two volumes, it may be thought of as analogous to a junction, where heat rather than fluid is flowing from one volume to the other. The Heat Slab Data Card input format is described in Volume II, Subsection 4.2.2 (51).

Any heat conductor described with a heat transfer surface on the "right" side but none on the "left" may have internal heat generation. If this conductor does have internal heat generation, it is considered to be a core conductor. A Core Slab Data Card must be supplied as

described in Volume II, Subsection 4.2.2 (53), which gives the additional input data needed. This includes QFRAC, the fraction of the total reactor power generated in the given core heat slab. It should be noted that the right and left side designation is a notation convention rather than an actual direction from a frame of reference.

3.4.2 Conductor Geometry. A conductor geometry may be cylindrical or rectangular. This is entered as IG on the Slab Geometry Data Cards, Volume II, Subsection 4.2.2 (55). Cylindrical geometry is used in describing the radial cross section of a rod, pipe, or cylindrical vessel, and rectangular in describing a flat plate. Several conductors may use the same geometry. The description of one specific geometry includes the width, node spacing, and material index for each region.

The user may specify the number of regions (NR on the Slab Geometry Data cards) up to a maximum of six. The thickness (or width) of the region in the direction of heat flow is entered as XR on the same card. The node thickness or width within each region will be determined by the program using the value entered for NDX as the total number of nodes for each region. Node spacing within a given region is constant but may vary from one region to the next as depicted in Figure 8.

A region is typically used to represent one material, such as the fuel, gap, or clad in a core fuel pin, or the steel in a pipe. However, two or more contiguous regions can represent the same material within a slab. For example, the user may wish to specify two regions in the fuel pin clad in order to get closer node spacing near the exterior surface. The heat conducting material is specified for each region by entering an index number for IM. This number will access the desired table of heat conducting properties.

If the conductor is a core conductor, the power fraction PF is specified for each region on the Slab Geometry Data Card. This fraction is that part of the total power produced by the core conductor which is generated in the given region. The sum of the fractions for the conductor regions of a given geometry should be 1.0.

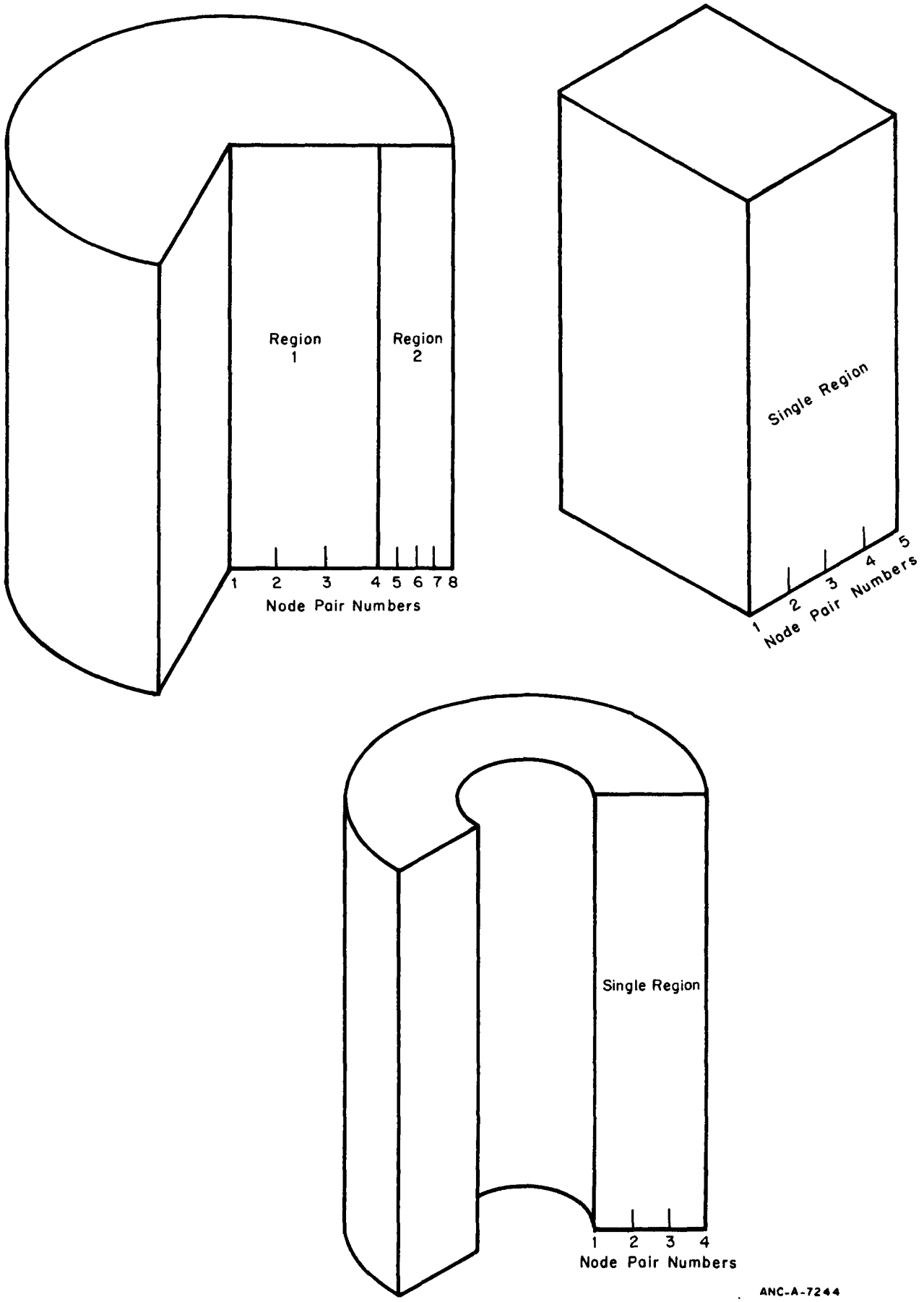


Fig. 8 Examples of heat conductor sections showing typical nodalization.

Nodes in a geometry are numbered from 1 to N, where N is the total number of incremental spaces specified, plus 1. In cylindrical geometry, Node 1 is at the center of a solid rod, or at the inner "left" surface of a pipe, and Node N is at the outer "right" surface. Regions are also numbered from "left" to "right" following the heat flow direction convention.

3.4.3 Conductor Configurations. Figure 9 illustrates possible configurations of heat conductors relative to boundary conditions at the left and right surfaces. These have orientations coinciding with the right and left conventions. Each of the six cases depicted represents a segment of conductor, either cylindrical or rectangular, with Node 1 on the left and Node N on the right. V_{il} and V_{ir} signify that there are control volumes on the left and right sides of the given slab, respectively. The hashed marks signify an area of no heat transfer. This could be either an insulated surface or the center of a solid rod.

Case 1 has volume fluid conditions on the right and no heat transfer on the left. It might represent a solid rod or a pipe insulated on the inside. It could also indicate a flat plate insulated on one side or surrounded by the fluid of a single volume. Case 2 shows a core heat slab - that is, there is internal heat generation. This normally is used to represent a solid rod. Internal heat generation is not provided for in Cases 3, 4, 5, or 6. Case 3 represents a pipe or cylindrical vessel insulated on the outside.

Cases 4, 5, and 6 show conductors with heat transfer at both surfaces. Each case might represent a pipe, a cylindrical vessel wall, or a flat plate. Case 4 has a control volume at each surface. Cases 5 and 6 each have a control volume at only one surface but have a "heat sink" at the other surface, which is, at least initially, the cooler surface. In Case 5, the sink side is on the outside of the piping, and in Case 6 it is on the inside. These latter two cases can be used to model a heat exchanger when the user does not wish to describe any control volumes on

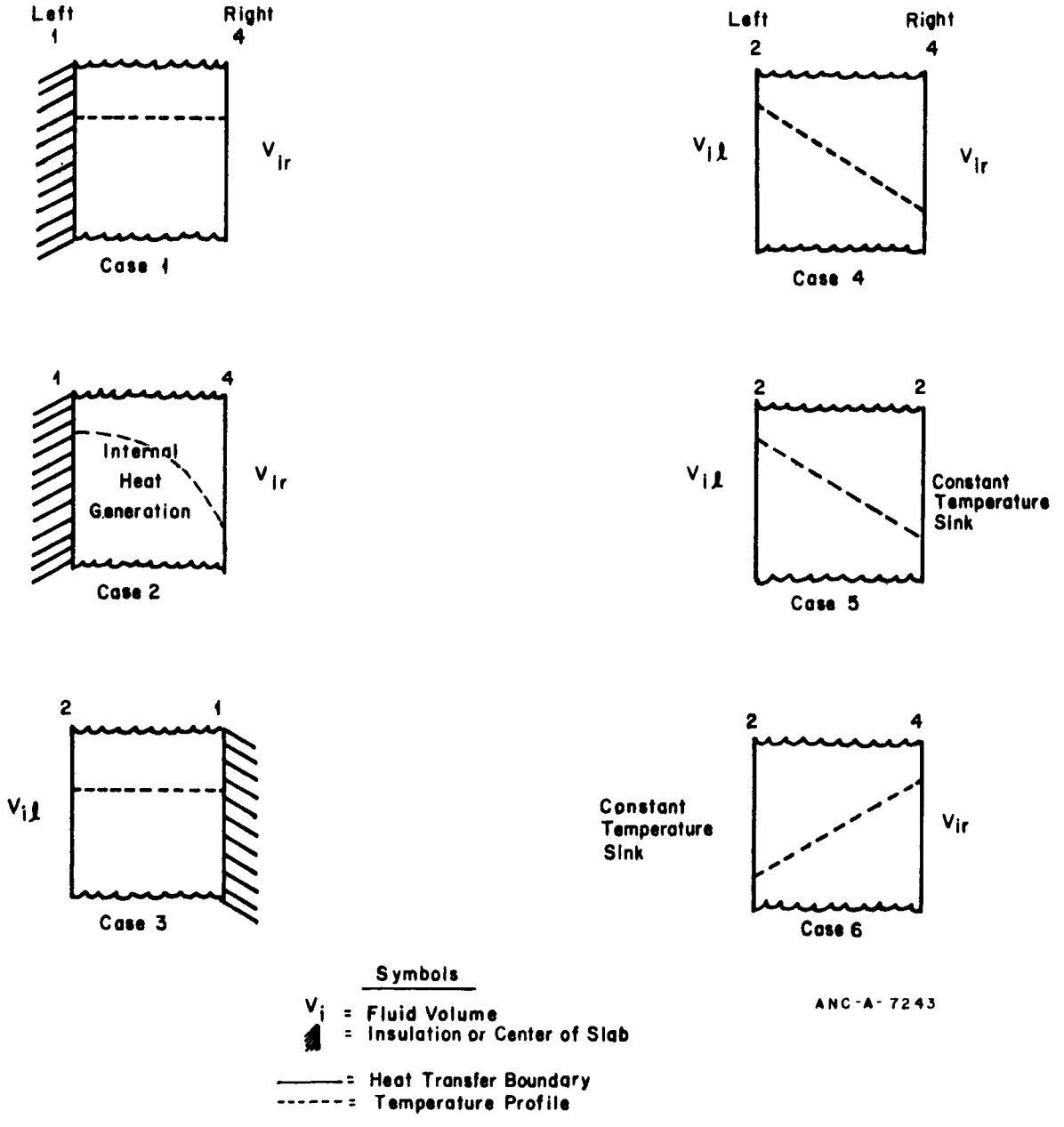


Fig. 9 Heat conductor configurations with typical initial temperature profiles, transient conduction boundary condition indicators, and left-right convention.

the secondary side. For the "sink" side, he must specify a constant heat transfer coefficient and a fraction of the total core power which the given conductor is to remove at time t = 0.

3.4.4 Conductor Thermal Properties. Temperature-dependent thermal properties are used in the conduction calculations. A set of input tables describing these properties for a given conducting material is specified for each material region in a conductor geometry. One set consists of a table of thermal conductivities entered as TPK (i) on the Thermal Conductivity Data Cards as outlined in Volume II, Subsection 4.2.2 (56). Temperatures (°F) are entered for the odd numbered i indices and conductivities (BTU/ft-hr-°F) are entered for the even number i indices. The second set of thermal properties is entered as TPC (i) on the volumetric Heat Capacity Data Cards outlined in Volume II, Subsection 4.2.2 (57). Temperature is entered for the odd numbered i indices and volumetric heat capacity (BTU/°F-ft^3) is entered for the even numbered i indices. The third set of thermal properties is entered as TPX (i) on the Linear Expansion Coefficient Data Cards as outlined in Volume II, Subsection 4.2.2 (58). Temperature is entered for the odd numbered i indices, and the linear expansion coefficient ($°F^{-1}$) is entered for the even numbered i indices.

The material index, IM, on the Slab Geometry Data Card specifies which set of property tables is to be used for each radial region in a given conductor. A given set of property tables may be used by several regions in different conductor geometries, or by more than one region in a single geometry.

3.4.5 Conduction Solution.

(1) Method. The heat conduction model is based on the method of the One-Dimensional Time Dependent or Steady State Heat Conduction Code HEAT-1[17], which uses a numerical solution of the one-dimensional heat conduction equations. Incremental volumes within a

conductor are determined by specified nodalization. For the incremental volume n in Figure 10, the heat balance equation is:

$$V_n C_n \frac{dT_n}{dt} = Q_n + \left(Ak \frac{dT}{dx}\right)_r - \left(Ak \frac{dT}{dx}\right)_\ell \tag{37}$$

where

V_n = incremental volume

C_n = volumetric heat capacity

T = temperature

T_n = temperature at node n

t = time

Q_n = internal heat generation rate

A = heat transfer area

k = thermal conductivity

x = radial distance

ℓ = left side of volume

r = right side of volume

In Figure 10, incremental volume V_n is on an interface between two regions with different node spacing. Except for the obvious exceptions at the conductor surfaces, the incremental volume surfaces are located midway between their respective node pairs. The height of each V_n is one unit (1-ft). T, k, and C are calculated at the nodes. However, k's are needed at the incremental volume surfaces; so at each surface an average of the k's at the nodes to the left and the right is used. At an interface between two regions, such as at n in Figure 10, C_n is a volume-weighted average of the C's for the two materials involved. The resulting finite difference approximation of Equation (37) can be written as:

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

$$\frac{A_{n-1}}{2\Delta X_{n-1}}\left[\bar{k}_{n-1,n}(T_n-T_{n-1}) + \bar{k}'_{n-1,n}(T'_n-T'_{n-1})\right] \qquad (38)$$

where

$$\bar{k}_{n,n+1} = \frac{k_n + k_{n+1}}{2}, \text{ etc.} \qquad (39)$$

and superscript prime $(')$ signifies the new time step.

Equation (38) is then put into the form:

$$a_n T'_{n-1} + b_n T'_n + g_n T'_{n+1} = d_n \qquad (39.1)$$

Boundary conditions are specified internally which allow the equations for T_1 and T_N (the conductor surface temperatures) to be completed and a total of N simultaneous equations is produced. These form a tridiagonal matrix and are then solved for the new temperatures.

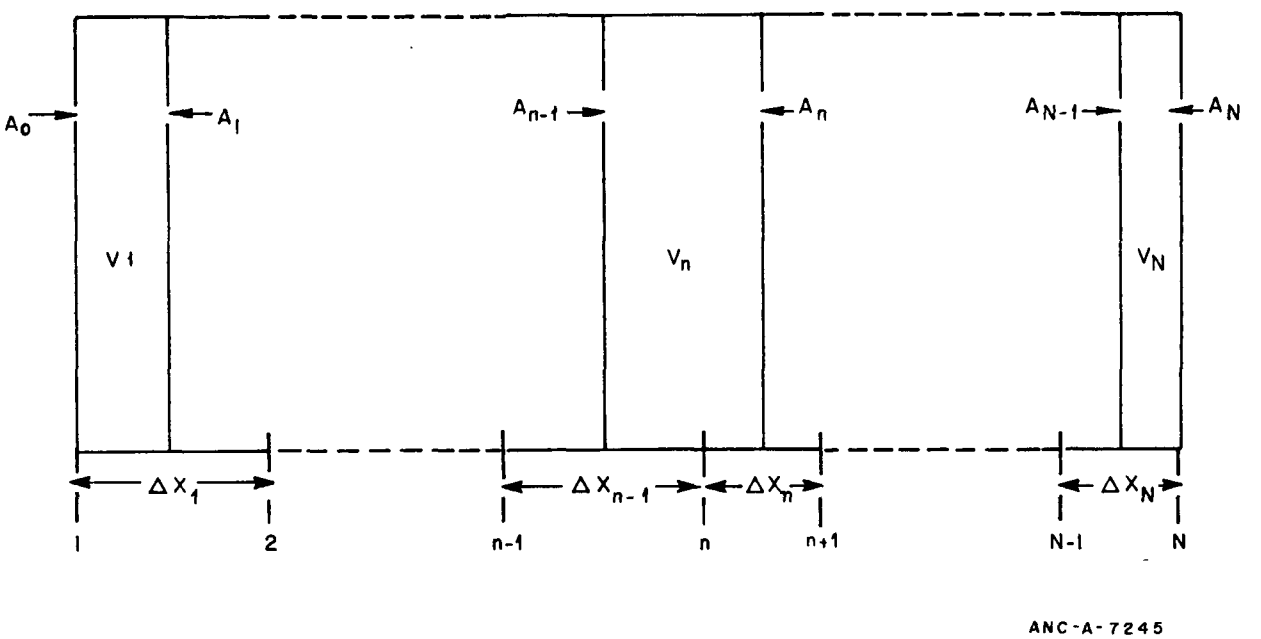


Fig. 10 Heat conductor nodalization.

(2) Conduction Boundary Conditions. The boundary conditions used at T_1 or T_N depend on conductor configuration, whether the calculation is initial or transient, and whether T_1 or T_N is under consideration. The transient boundary condition indicators are as shown in Figure 9 for the corresponding case numbers. The possible conduction boundary conditions are:

(1) No heat transfer $\frac{dT'}{dX} = 0$. This condition corresponds to the no heat transfer boundary configuration shown for Cases 1, 2, and 3. The temperature profile is always flat at this boundary due to no heat flow.

(2) Fluid temperature, T_f, and heat transfer coefficient, h, are given. (These are last-time-step values of T_f and h.) The heat flux can then be expressed as: $q = h(T'-T_f)$, and this value is substituted for $\pm K \frac{dT'}{dX}$. This boundary condition is used in the transient for all left convention conductor surfaces which are not described by Condition (1).

(3) T' is given. This condition is used only for initialization.

(4) T' is given by solving $q = h(T' - T_f) = AT' + B$, where the first equivalence of q (heat flux) comes from a particular heat transfer correlation and the second from the conduction equations themselves. This condition is used only for right convention surface and applies in conductor Cases 1, 2, 4, and 6.

(5) Flux is given. This condition is used only in the initialization of the "constant sink" side in Cases 5 and 6.

(3) Initialization of Conductor Temperature. Steady state heat transfer is assumed at time t = 0. Also, it is assumed that no heat flux at a conductor surface has exceeded the critical heat flux; i.e., only pre-CHF heat transfer modes are valid for t = 0. If a conductor

heat transfer surface cannot be initialized using one of these modes, the problem will be aborted. The pre-CHF modes are 1, 2, 3 and 8. (See the discussion of the heat transfer correlations, Subsection 3.4.6 following). Positive flux means that the conductor surface is hotter than the fluid and negative flux means the opposite.

The temperature at all nodes in configuration Cases 1 and 3 (Figure 9) are set at the temperature of the adjacent fluid, and the conduction solution is not needed.

For the core conductor (Case 2) the heat flux at the right surface is known at t = 0. A variation of conduction boundary condition 4 is used, with A = 0 and B = flux, to get the surface temperature. This is then used as conduction boundary condition 3 for the temperature profile conduction solution.

Surface fluxes at t = 0 are also known for Cases 5 and 6, since the fraction of the total core power is specified for each of these conductors. Conduction boundary condition 5 (flux known) is used on the cooler (sink) side of the conductor for initialization. On the hotter side, the same thing is done for initialization as outlined above for the core conductor surface.

Case 4, with fluid volumes on both sides of the conductor, is not as simple to initialize. First, the variation of boundary condition 4 with A = 0 and B = an estimated flux, is used at each surface to get the heat transfer coefficient h. In the heat transfer correlation of Modes 1, 3, and 8, h is a function of fluid properties only; so the correct h is obtained this way regardless of the flux estimate. On the hotter side of the conductor, the only modes allowed initially (and in the transient also as long as the flux is negative) are 1 and 8. Therefore, conduction boundary condition 2, with h and fluid temperature, is now established for the hotter side. On the cooler side of the conductor, heat transfer Modes 2 and 3 are also valid for initialization. If the

logic selects Modes 1, 3, and 8 on the cooler side, then the h and the fluid temperatures are used in conduction boundary condition 2. If Mode 2 is indicated, however, the h is not the correct value, since in the Thom Heat Transfer Correlation 2[18], h is a function of the surface temperature. In this case, a surface temperature is obtained iteratively by using the A = 0 and B = flux in the variation of boundary condition 4. The flux estimate is updated at each iteration. The surface temperature obtained is then used in the conduction solution (boundary condition 3).

After initialization of all conductor temperatures, the conduction boundary condition indicators are set for the transient calculation in accord with Figure 9.

3.4.6 Heat Transfer Correlations. In order to transfer heat from a conductor into a cooling fluid (or vice versa), heat transfer correlations are utilized for certain boundary conditions as noted in Subsections 3.4.3 and 3.4.5. Except for the reflood case (RELAP4 FLOOD), the heat transfer mode is based on the THETA1-B[16] model and selection procedure.

The heat transfer regimes which the core will undergo during a typical blowdown are illustrated in Figure 11. Heat transfer mode numbers 1-9 are assigned to the various regimes and subregimes to identify the proper correlations to be used. Table II identifies these modes and lists the correlations as they are used in RELAP4. In Modes 2 and 4 the correlation is given as q which is the product of Δt and h. This is done to provide correspondence to the referenced source. Figure 12 shows the logic used in correlation selection for RELAP4/MOD5 blowdown.

Figure 11 shows Regime A-B (subcooled forced convection, labeled Mode 1 in RELAP4) to be characterized by a coolant bulk temperature less than saturation temperature and having a surface temperature low enough so that boiling does not occur. If the surface temperature is less than saturation temperature, boiling is not possible and the Dittus-Boelter Subcooled Forced Convection Correlation[19] is used. Point B of Figure 11 shows the beginning of the nucleate boiling regime. In some

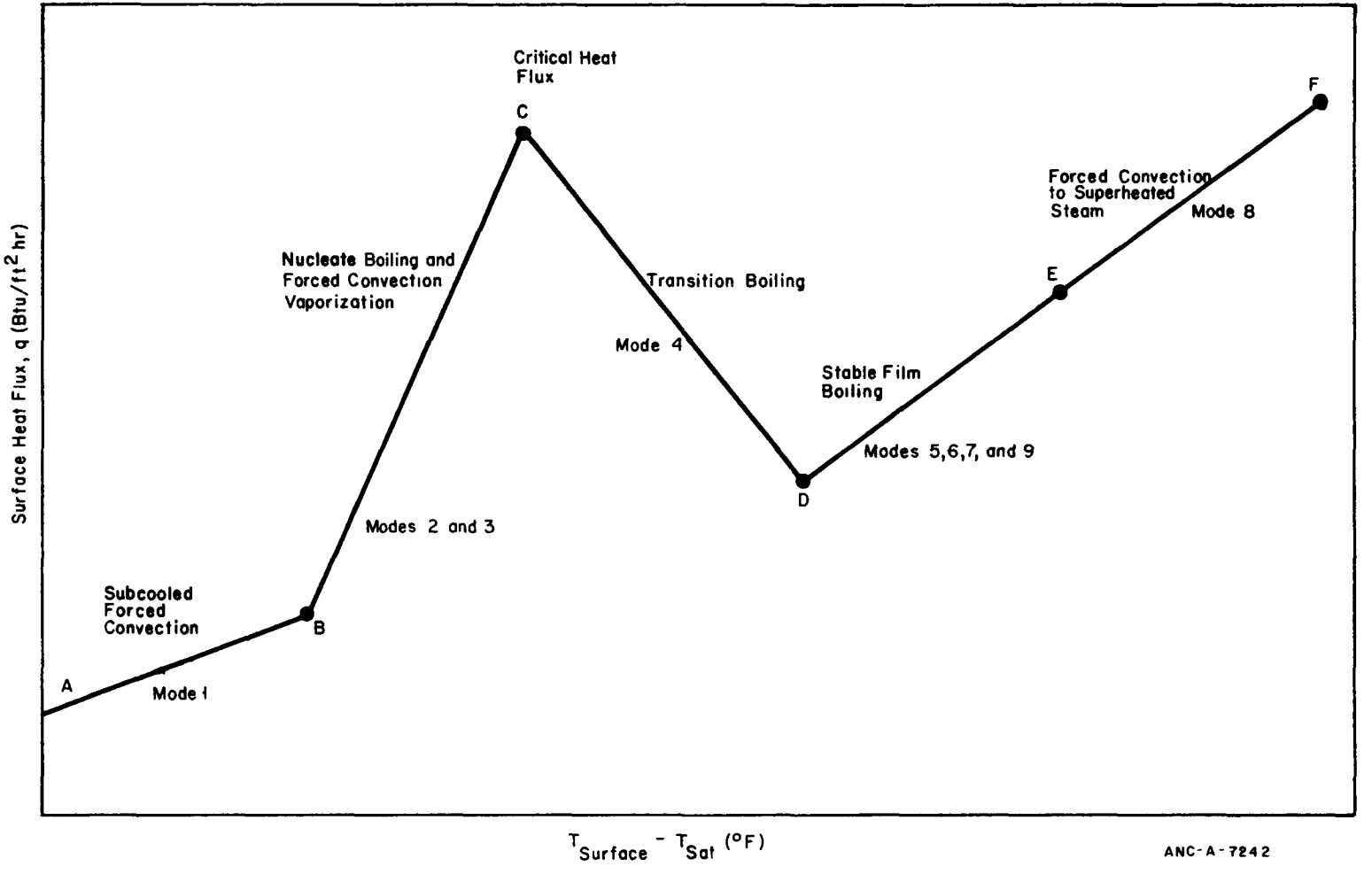


Fig. 11 Heat transfer regimes.

TABLE II

HEAT TRANSFER CORRELATIONS IN RELAP4[a]

Mode 1 Subcooled Liquid Forced Convection: Dittus and Boelter[19]

$$h = 0.023 \frac{k}{D_e} Pr^{0.4} Re^{0.8} \tag{40}$$

Mode 2 Nucleate Boiling: Thom[18]

$$q = \left[\frac{\Delta T_{sat} \exp (P/1,260)}{0.072}\right]^2 \tag{41}$$

Mode 3 Forced Convection Vaporization: Schrock and Grossman[20]

$$h = (2.5)\ (0.023) \frac{k_f}{D_e} Pr_f^{0.4} \left[Re_f\ (1-X)\right]^{0.8}$$

$$\left[\left(\frac{X}{1-X}\right)^{0.9} \left(\frac{\mu_g}{\mu_f}\right)^{0.1} \left(\frac{\rho_f}{\rho_g}\right)^{0.5}\right]^{0.75} \tag{42}$$

Mode 4 Transition Boiling: McDonough, Milich, and King[21]

$$q = q_{CHF} - C(P)\ (T_w - T_{w,CHF}) \tag{43}$$

Pressure, psi	C(P)
2,000	979.2
1,200	1,180.8
800	1,501.2

Mode 5 Stable Film Boiling: Groeneveld[22]

$$h = a \frac{k_g}{D_e} Pr_w^c \left\{Re_g \left[X + \frac{\rho_g}{\rho_f}(1-X)\right]\right\}^b$$

$$\left[1.0 - 0.1\ (1-X)^{0.4} \left(\frac{\rho_f}{\rho_g} - 1\right)^{0.4}\right]^d \tag{44}$$

	Groeneveld Equation (5.9) IMCL(or IMCR) = 0	Groeneveld Equation (5.7) IMCL(or IMCR) = 1
a.	0.00327	0.052
b.	0.901	0.688
c.	1.32	1.26
d.	-1.50	-1.06

TABLE II (contd.)

HEAT TRANSFER CORRELATIONS IN RELAP4

Mode 6 Low Flow Film Boiling: Modified Bromley

$$h = 0.62 \left[\frac{k_g^3 \, h_{fg} \, \rho_g \, g(\rho_f - \rho_g)}{\mu_g \, L \, \Delta T_{sat}} \right]^{0.25} \tag{45}$$

$$L = 2\pi \sqrt{\frac{g_c \sigma}{g \, (\rho_f - \rho_g)}} \tag{46}$$

Mode 7 Free Convection plus Radiation

$$h = h_c + h_r \tag{47}$$

$$h_c = 0.4 \, (Gr \, Pr_f)^{0.2} \tag{48}$$

$$Gr = \frac{L_g^3 \, \beta_g \, \rho_g^2 \, \Delta T_{sat}}{\mu_g^2} \tag{49}$$

$$L = \frac{D_e}{2} \tag{50}$$

$$h_r = 0.23 \, \frac{1.714(10^{-9}) \, (T_w^4 - T_{sat}^4)}{\Delta T_{sat}} \tag{51}$$

Mode 8 Superheated Vapor Forced Convection: Dittus and Boelter[19]

$$h = 0.023 \, \frac{k}{D_e} \, Pr^{0.4} \, Re^{0.8} \tag{52}$$

Mode 9 Low Pressure Flow Film Boiling: Dougall and Rohsenow[23]

$$h = 0.023 \, \frac{k_g}{D_e} \, Pr_g^{0.4} \left\{ Re_g \left[X + \frac{\rho_g}{\rho_f} \, (1-X) \right] \right\}^{0.8} \tag{53}$$

[a] Notation definitions follow in the text.

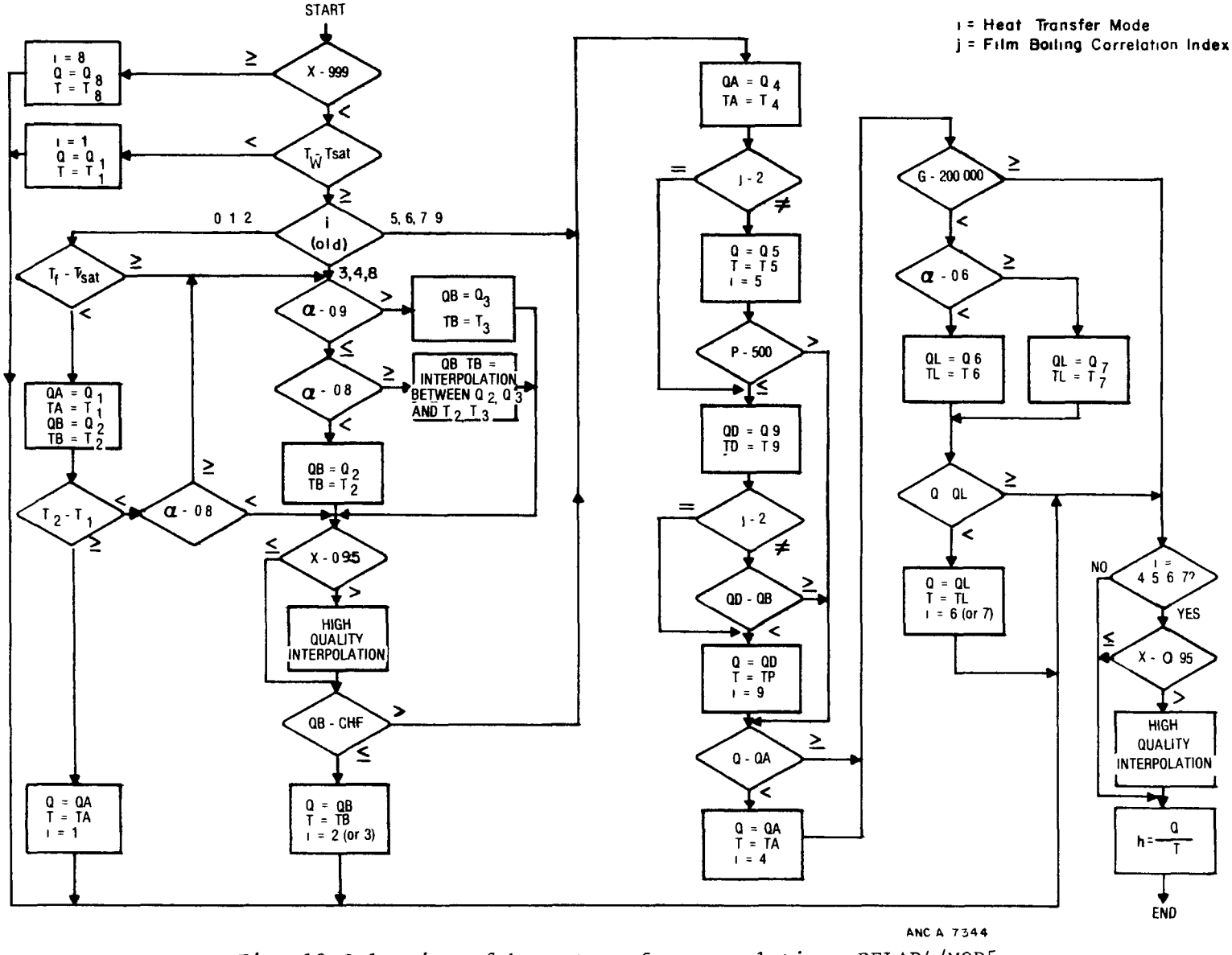


Fig. 12 Selection of heat transfer correlation, RELAP4/MOD5.

cases the coolant may still be subcooled, but the surface temperature be high enough for some boiling to occur. When the surface temperature is greater than the saturation temperature, the regime on either side of Point B is possible. For this condition, both the Dittus-Boelter Correlation and the Thom Correlation are evaluated and the surface temperatures calculated. The correlation resulting in the lower surface temperature is selected and the proper mode number assigned.

Region B-C of Figure 11 is defined by two modes, nucleate boiling (Mode 2) and forced convection vaporization (Mode 3). If the void fraction is less than 0.80, the Thom Nucleate Boiling Correlation is selected. For a void fraction above 0.90, the Schrock-Grossman Forced Convection Vaporization Correlation[20] is used. For void fractions between 0.80 and 0.90, the program interpolates the void fraction between the correlation limits in order to provide a smooth transition from the nucleate boiling to the forced convection vaporization regime. The Schrock-Grossman Correlation is applied until the quality reaches 95%. Above 99.9% the Dittus-Boelter Correlation for Single-Phase Forced Convection to Superheated Steam (Mode 8) is used. Between 95 and 99.9%, the program interpolates for quality to smooth the transition from forced convection vaporization (Mode 3) to forced convection to superheated steam (Mode 8).

The CHF (Point C of Figure 11) is evaluated at each core heat surface for each time step from the correlations defined in Subsection 3.4.6 (1). If the heat flux exceeds the calculated CHF, the correlations for the transition regime [region C-D of Figure 11 (Mode 4)] and the stable film boiling regime [region D-E (Modes 5, 6, 7 or 9)] are evaluated.

The selection of a post-CHF correlation is controlled by the IMCL (or IMCR) flag on the Heat Slab Data Cards described in Volume II, Subsection 4.2.2 (51). If the flag is 0 or 1, the selection procedures are as follows: The McDonough, Milich, and King Correlation[21] (Mode 4) and the desired Groeneveld Correlation[22](Mode 5) are evaluated. If pressure is less than 500 psi, the Dougall-Rohsenow Correlation[23](Mode 9)

is also evaluated. The minimum of Groeneveld and Dougall-Rohsenow is then chosen as the film boiling heat flux and compared to that of McDonough, Milich, and King. The maximum of these two heat fluxes is selected and thus determines the boiling regime. For the over 500-psi case, the comparison is between that of Groeneveld and that of McDonough. If the mass flux is greater than or equal to 200,000 lbm/ft^2-hr (high flow condition), this is the post-CHF heat flux and corresponding mode. However, if a low flow condition exists (G less than 200,000 lbm/ft^2-hr), either of the modified Bromley Correlations (Mode 6) or the Free Convection Plus Radiation Correlation (Mode 7) will be considered. If the void fraction is less than 0.6, then the modified Bromley Correlation is evaluated. Otherwise, the Free Convection Plus Radiation Correlation is evaluated. This heat flux is then compared to that chosen for the high mass flux case and the maximum chosen as the post-CHF heat flux and mode. For the case where IMCL = 2, Groeneveld is never evaluated, and Dougall-Rohsenow is the high mass flux film boiling correlation.

In the evaluation of both the Groeneveld and Dougall-Rohsenow Correlations, it should be noted that neither is valid below 10% quality. Both correlations underpredict experimental data at low qualities. The data in this range indicate a tendency to rewet the surface with resulting heat transfer coefficients which are much higher than true film boiling. A reasonable lower limit to the heat transfer coefficient is provided by computing heat transfer coefficients using a 10% quality value in the correlations for all calculated qualities of 10% or less.

Symbol definitions for Table II and for Subsections 3.4.6 (1) through (3) are as follows. Additional definitions for the latter are provided with the related equations.

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

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

D_e = equivalent diameter, ft

Pr = Prandtl number, $\frac{c_p \mu}{k}$

Re = Reynolds number, $\frac{GD_e}{\mu}$

μ = viscosity, $lb_m/ft\text{-}hr$

C_P = specific heat, $Btu/lb_m\text{-}°F$

T_{sat} = saturation temperature, °F

T_w = wall temperature, °F

ΔT_{sat} = $T_W - T_{sat}$, °F

q = heat flux, $Btu/ft^2\text{-}hr$

P = pressure, psia

X = quality

ρ = density, lb_m/ft^3

L = channel length, in.

g = local acceleration due to gravity, ft/sec^2

g_c = gravitational constant, $ft\text{-}lb_m/lb_f\text{-}sec^2$

σ = surface tension, lb_f/ft

Q = volumetric flow rate, ft^3/sec

A_{flow} = flow area, ft^2

β = coefficient of thermal expansion, $\frac{1}{°F}$

and subscripts

CHF = critical heat flux conditions

f = saturated liquid conditions

g = saturated vapor conditions

v = superheated vapor conditions

w = wall.

(1) Critical Heat Flux Correlations. CHF calculations are made for all heat slab surfaces. The Babcock and Wilcox Company B&W-2[24], Barnett[25], and Modified Barnett[26] correlations are used as follows:

$P > 1,500$	B&W-2
$1,500 > P > 1,300$	Interpolation between B&W-2 and Barnett
$1,300 > P > 1,000$	Barnett
$1,000 > P > 725$	Interpolation between Barnett and Modified Barnett
$725 > P$	Modified Barnett.

For a given pressure between 725 and 1,000 lb/in.^{2}, or between 1,300 and 1,500 lb/in.^{2}, the two relevant correlations are evaluated at that pressure and the corresponding enthalpy H_f. The two flux values are then weighted to give

$$q_{CHF} = \frac{(P_R - P)\, q_{CHF_L} + (P - P_L)\, q_{CHF_R}}{P_R - P_L} \qquad (54)$$

where P = pressure, and L and R represent the low and high ends of the interpolation range, respectively. A minimum critical heat flux value of 90,000 Btu/ft^2-hr is set if the predicted value falls below this number.

For a mass flux, G, less than 200,000 lb$_m$/ft^2-hr, the critical heat flux is interpolated between 90,000 Btu/ft^2-hr and the value given by the chosen correlation, where the former corresponds to G = 0 lb$_m$/ft^2-hr and the latter to G = 200,000 lb$_m$/ft^2-hr.

The inlet enthalpy used in the Barnett and Modified Barnett Correlations is dependent on the flow direction and is determined in the following manner:

Flow at Major Inlet	Flow at Major Outlet	H_{in}
>0	$\geq$0	H at normal inlet
$\leq$0	<0	H at normal outlet
All other cases		H of core volume.

If the term $H_f - H_{in}$ is negative, it is set to 0 in the correlations.

The heated equivalent diameter term, D_{HE}, is input in feet and converted to inches in the correlations. The other "diameter" used in the Barnett and Modified Barnett correlations is calculated as $D_{HY} = \sqrt{D_r (D_r + D_{HE})} - D_r$, where D_r is rod diameter. For a cylindrical heat slab with a left conduction surface, the D_r used for that surface is the actual inside diameter of the slab (pipe, tank, etc.). If the right side of the slab is a conducting surface, the D_r used for that surface is the outside diameter of the slab (pin, pipe, etc.). In some cases, D_{HY} will fall outside of the range of the correlations.

If the heat slab geometry is rectangular rather than cylindrical, then D_{HY} for each side of the slab is set to the hydraulic diameter of the volume on that side.

The B&W-2 Correlation can be evaluated down to a pressure of 1,300. The actual value of the term (P-2,000) is used even if it is negative.

(a) Babcock & Wilcox Company, B&W-2[24].

B&W-2 correlation[24] is:

$$q_{CHF} = \frac{1.15509 - 0.40703(12De)}{12.71 \times (3.0545G')^{A}} \left[(0.3702 \times 10^{8}) \quad (0.59137G')^{B} - 0.15208XH_{fg}G\right] \tag{55}$$

where

$$A = 0.71186 + (2.0729 \times 10^{-4})\,(P-2,000) \tag{56}$$

$$B = 0.834 + (6.8479 \times 10^{-4})\,(P-2,000) \tag{57}$$

and where

$$G' = \frac{G}{10^{6}}$$

H_{fg} = heat of vaporization.

The correlation was developed from rod bundles in water data over the parametric ranges given by:

Equivalent diameter	0.2 to 0.5 in.
Length	72 in.
Pressure	2,000 to 2,400 psia
Mass flux	0.75×10^{6} to 4.0×10^{6} lb_m/ft^2-hr
Burnout quality	-0.03 to 0.20.

(b) Barnett. The Barnett Correlation[25] is:

$$q_{CHF} = 10^6 \left[\frac{A + B(H_f - H_{in})}{C + L}\right] \quad (58)$$

where

$$A = 67.45\, D_{HE}^{0.68} G'^{0.192} \left(1.0 - 0.744 e^{(-6.512\, D_{HY} G')}\right) \quad (59)$$

$$B = 0.2587\, D_{HE}^{1.261}\, G'^{0.817} \quad (60)$$

$$C = 185.0\, D_{HY}^{1.415}\, G'^{0.212}. \quad (61)$$

For a rectangular conductor geometry, D_{HY} is set equal to the input value for the right side hydraulic diameter for the conductor. The correlation can be applied to rod bundles using equivalent diameters. The parametric range of the data is as follows:

Equivalent diameters	0.258 in. $< D_{HE} <$ 3.792 in.
	0.127 in. $< D_{HY} <$ 0.875 in.
Length	24 to 108 in.
Pressure	1,000 psi
Mass flux	0.14×10^6 to 6.20×10^6 lb_m/ft^2-hr
Inlet subcooling	0 to 412 Btu/lb_m.

(c) Modified Barnett[26]. The modified Barnett Correlation is:

$$q_{CHF} = 10^6 \left[\frac{A + B(H_f - H_{in})}{C + L}\right] \quad (62)$$

where

$$A = 73.71\, D_{HE}^{0.052}\, G'^{0.663} \left(1.0 - 0.315\, e^{(-11.34 D_{HY} G')}\right) \quad (63)$$

$$B = 0.104\, D_{HE}^{1.445}\, G'^{0.691} \quad (64)$$

$$C = 45.44\, D_{HY}^{0.0817}\, G'^{0.5866}. \quad (65)$$

Data were from rod bundles containing water and were over parametric ranges given by:

Rod diameter	0.395 to 0.543 in.
Length	32.9 to 174.8 in.
Pressure	150 to 725 psia
Mass Flux	0.03×10^6 to $1.7 \times 10^6 lb_m/ft^2\text{-hr}$
Inlet subcooling	6 to 373 Btu/lb_m.

(2) Additional Critical Heat Flux Correlations. There are two alternatives to using the B&W-2, Barnett, and Modified Barnett Correlations. These are a pair of General Electric CHF Correlations[27] and a Savannah River Correlation[28] for aluminum heaters. These may be selected by use of IMCL (or IMCR) on the Heat Slab Data Cards.

(a) General Electric Company. The General Electric Company Correlations are:

$$q_{CHF} = 10^6 \ (0.8 - X) \tag{66}$$

for $G \geq 0.5 \times 10^6 \ lb_m/ft^2\text{-hr}$

and

$$q_{CHF} = 10^6 \ (0.84 - X) \tag{67}$$

for $G < 0.5 \times 10^6 \ lb_m/ft^2\text{-hr}$.

(b) Savannah River. The Savannah River Correlation is:

$$Q_{CHF} = 188{,}000 \ (1.0 + 0.0515V) \ (1.0 + 0.069 \ T_{SUB}) \tag{68}$$

where

V = fluid velocity, ft/sec

T_{SUB} = fluid saturation temperature minus fluid temperature.

(3) Evaluation Model (EM) Blowdown. The RELAP4/5-EM heat transfer correlation selection logic is the same as that outlined in Section 3.6.6 (1) except that it is locked out of some regimes based on the NRC acceptance criteria[2]. The appropriate heat transfer correlations are specified in the criteria for post-CHF transfer correlations which provide:

(1) Correlations of heat transfer from the fuel cladding to the surrounding fluid in the post-CHF regimes of transition and film boiling shall be compared to applicable steady state and transient state data using statistical correlation and uncertainty analyses. Such comparisons shall demonstrate that the correlations predict values of heat transfer coefficients equal to or less than the mean value of the applicable experimental heat transfer data throughout the range of parameters for which the correlations are to be used. The comparisons shall quantify the relation of the correlations to the statistical uncertainty of the applicable data.

(2) The Groeneveld Flow Film Boiling Correlation (Equation 5.7 of Reference 22), the Dougal-Rohsenow Flow Film Boiling Correlation[23] and the Westinghouse Correlation of Steady State Transition Boiling[29] are acceptable for use in the post-CHF boiling regimes. In addition the transition boiling correlation of McDonough, Milich and King[21] is suitable for use between nucleate and film boiling.

Use of all the foregoing correlations shall be restricted as follows:

(1) The Groeneveld Correlation shall not be used in the region near its low-pressure singularity

(2) The first term (nucleate) of the Westinghouse Correlation and the entire McDonough, Milich, and King Correlation shall not be used during the blowdown after the temperature difference between the clad and the saturated fluid first exceeds 300°F

(3) Transition boiling heat transfer shall not be reapplied for the remainder of the LOCA blowdown, even if the clad superheat returns below 300°F, except for the reflood portion of the LOCA when justified by the calculated local fluid and surface conditions.

(4) Reflood. Detailed information relative to RELAP4/Flood is provided in Subsection 3.11.1 (1). Mention is made here for presentation continuity purposes only.

3.4.7 Conductor Gap Expansion Model. A simple gap-expansion model is available for cylindrical geometries. The expansion model is also appropriate for rectangular geometries for which the left boundary of the conductor is fixed and cannot move due to expansion. The model does not provide for any changes in incremental volume or surface areas, but only calculates a modified conductivity, k'(T), in a gap due to expansion in adjacent regions. Linear coefficients of expansion with respect to temperature for the materials on either side of the gap are used to form a ratio of cold gap width to hot gap width. This ratio is then used as multiplier in calculating gap conductivity. A gap is treated like any other region in the conductor; that is, its width, nodal spacing, and thermal properties are described in the problem input.

$$\text{In a gap, } k'(T) = k(T)\ \frac{\text{cold gap width}}{\text{hot gap width}}$$

and

$$k'(T) = k(T)\left[\frac{R_2 - R_1}{R_2\left(1 + \alpha_2(\bar{T}_2 - 68°F)\right) - R_1\left(1 + \alpha_1(\bar{T}_1 - 68°F)\right)}\right] \quad (69)$$

where

R = cold radius, ft

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

α = linear expansion coefficient, $°F^{-1}$

$\bar{T}$ = average temperature of region adjacent to gap, °F

and subscripts

1 = left side of gap

2 = right side of gap.

This model is accessed on the Slab Geometry Data Cards outlined in Volume II, Subsection 4.2.2 (55). If any conductors are programmed to use it, a table of linear expansion coefficients vs temperature must be entered for each conducting material on the Linear Expansion Coefficient Data Cards outlined in Volume II, Subsection 4.2.2 (58).

3.4.8 Conductor Stored Energy. The value of energy stored in a conductor is not used in any calculations, but it is edited. It is calculated for the program from

$$E = \int V \left(\int_{T_1}^{T} C dT \right) dV \approx \sum_{n=1}^{N} V_n \left(\sum CT \right)_n \qquad (70)$$

where

V = volume

C = volumetric heat capacity

T = temperature

T_1 = temperature of first data point in C vs T table, or 32°F, whichever is less

n = node number

N = node number at right surface

$\left(\sum CT\right)_n$ = interpolated value from "integral" table of CI vs. T. This table is formed on initialization (from the input C vs T table) as $CI_i = 1/2 \sum_i (C_i+C_{i+1}) (T_{i+1}-T_i)$, where i is the table data point number.

3.4.9 Conductor Quality Calculation. Generally, the heat transfer correlations use average volume conditions, including quality, which appears in several of the correlations. However, by considering only that part of the volume between the bottom and the top of a given heat conductor, this option provides more definition in the axial direction for conductor quality when two-phase conditions exist in that volume. The calculation of the average conductor quality, $\bar{X}$, is based on the volume bubble rise model[a] for that portion of the conductor below the two-phase mixture level, and on the assumption that X = 1.0 for any portion of the conductor above the mixture level. The former defines quality as a function of elevation for any given location within the fluid as follows:

$$X = \frac{a \frac{z}{z_m} + b}{e \frac{z}{z_m} + f} \qquad (71)$$

where

z = elevation

z_m = mixture level

[a] A description of the bubble rise model is given in Subsection 3.6.6 (1) and application of the conductor quality calculation follows in 3.6.6. (2).

a = slope of gas bubble density

b = intercept of gas bubble density

e = slope of mixture density

f = intercept of mixture density.

The model for conductor quality is shown in Figure 13 and the equation is:

$$\bar{X} = \frac{\text{Mass}_{gas}}{\text{Mass}_{total}} = \frac{\bar{\rho}_{gas}\,(z_t - z_b)\ \text{Area}}{\bar{\rho}_{total}\,(z_t - z_b)\ \text{Area}} \tag{72}$$

$$\bar{X} = \frac{\left(\frac{1}{\Delta z_b}\int_{z_b}^{z_2}\left(\frac{a}{z_m}\,z + b\right)dz\right)\Delta z_b + \left(\Delta\frac{1}{z_t}\int_{z_2}^{z_t}\rho_{gas}\,dz\right)\ z_t}{\left(\frac{1}{\Delta z_b}\int_{z_b}^{z_2}\left(\frac{e}{z_m}\,z + f\right)dz\right)\Delta z_b + \left(\Delta\frac{1}{z_t}\int_{z_2}^{z_t}\rho_{gas}\,dz\right)\ z_t} \tag{73}$$

$$\bar{X} = \frac{\left(z_2\left(\frac{a}{2z_m}\,z_2 + b\right) - z_b\left(\frac{a}{2z_m}\,z_b + b\right)\right) + \rho_{gas}\Delta z_t}{\left(z_2\left(\frac{e}{2z_m}\,z_2 + f\right) - z_b\left(\frac{e}{2z_m}\,z_2 + f\right)\right) + \rho_{gas}\Delta z_t} \tag{74}$$

where

z_b = height of bottom of conductor above bottom of volume

z_t = height of top of conductor above bottom of volume

z_2 = the minimum of Z_m and z_t.

3.4.10 Direct Moderator Heating. There is an option to provide for direct energy deposition in the water within control volumes containing core heat conductors. This option applies when the Reactor Kinetics calculations are used; i.e., a positive value for NODEL is entered on the Kinetics Constants Data Card listed in Volume II, Subsection 4.2.2 (46). Since this type of heating is not a conduction

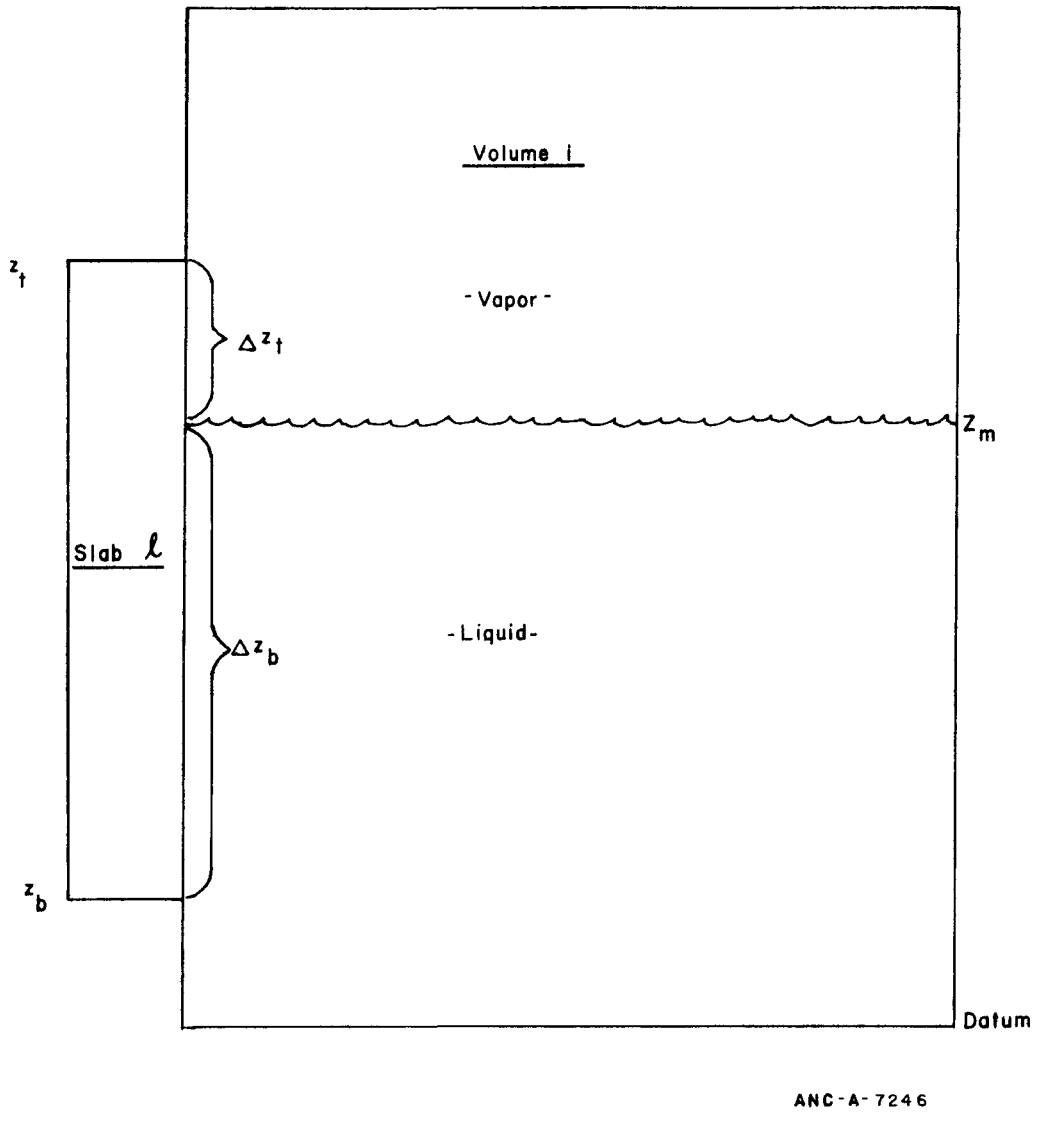


Fig. 13 Typical configuration for a conductor quality calculation.

phenomenon, this fraction of the energy produced by a given core conductor is subtracted from that total to get the internal heat source used in the conduction solution.

For each core conductor, the direct moderator heating may be split between a prompt power term and a delay power term. These are specified as QPMOD and QDMOD, respectively, on the Core Slab Data Card outlined in Volume II, Subsection 4.2.2 (53). QFRAC, the fraction of total reactor power generated by the given core conductor, also appears on the card. QPMOD and QDMOD thus are fractions of the value entered for QFRAC.

The direct moderator heating is calculated as

$$MQ(MW) = QFRAC(PPOW*QPMOD*P_o + DPOW*QDMOD*P_o) \frac{\rho}{\rho_o} \quad (75)$$

where

P_o = total initial reactor power

PPOW = normalized prompt power from reactor kinetics calculation

DPOW = Normalized delay power from reactor kinetics calculation

ρ/ρ_o = ratio of water density to initial water density.

The heat source for the conduction solution is

$$FQ(MW) = QFRAC*P - MQ \quad (76)$$

where

P = current reactor power = P_o (PPOW + DPOW).

3.4.11 Metal-Water Reaction. A subroutine provided in the program calculates the amount of heat generated when fuel pin cladding

temperature and steam conditions are appropriate for the occurrence of an exothermic metal-water reaction. The reaction calculated is the reaction between zirconium and steam, and is expressed by the following chemical equation

$$Zr + 2\ H_2O \rightarrow ZrO_2 + 2H_2. \tag{77}$$

When sufficient steam is available, the rate of this reaction is assumed to follow the parabolic rate law of Baker and Just[30]. When less steam is available than would be consumed by a reaction following the parabolic rate law, a steam-limited rate law is assumed in which all available steam reacts. Equation (78) is a mathematical statement of the parabolic rate law

$$-\frac{dr}{dt} = \left(\frac{0.0615}{RO - r}\right) \quad \exp\left(-\frac{41,200}{T}\right) \tag{78}$$

where

exp = $e^{(\text{indicated power})}$

r = radius of the reacting metal-oxide interface (in.)

RO = initial rod radius (in.)

T = absolute temperature at the reacting metal-oxide interface (°Rankine)

t = time (sec)

Setting up Equation (78) for integration over a time step gives

$$-\int_{r_1}^{r_2} (RO - r)\, dr = \int_{t_1}^{t_2} 0.0615 \exp\left(-\frac{41,200}{T}\right) dt. \tag{79}$$

If the expression $0.0615 \exp(-\frac{41,200}{T})$ is assumed to be constant during the time step, then integration gives

$$-\int_{r_1}^{r_2} (RO - r)\, dr = 0.0615 \exp(\frac{41,200}{T})\, \Delta T \tag{80}$$

where $\Delta T = t_2 - t_1$ is the time-step size in seconds. A new variable, $r' = RO - r$, and its differential, $dr' = dr$, are substituted into Equation (80) to obtain

$$\int_{DRP}^{DRP1} r'dr' = 0.0615 \exp(-\frac{41,200}{T})\, \Delta T \tag{81}$$

where

DRP1 = the depth the reaction has penetrated the cladding at the end of a time step, in.

DRP = the depth the reaction has penetrated the cladding at the start of a time step, in.

Integration of Equation (81) gives

$$\frac{DRP1^2 - DRP^2}{2} = 0.0615 \exp(-\frac{41,200}{T})\, \Delta T \tag{82}$$

which reduces to

$$DRP1^2 - DRP^2 = 0.123 \exp(-\frac{41,200}{T})\, \Delta T. \tag{83}$$

A new variable is defined as

$$AP = DRP1^2 - DRP^2 = 0.123 \exp(-\frac{41,200}{T})\, \Delta T. \tag{84}$$

Solving for the unknown DRP1 in terms of DRP and AP gives

$$DRP1 = (DRP^2 + AP)^{1/2}. \tag{85}$$

The mass of zirconium reacted per unit length during the time step is obtained from the product of the density and the difference between the old and new oxide areas as

$$MZR = \rho_{zr}\left[\pi(RO - DRP)^2 - \pi(RO - DRP1)^2\right] \tag{86}$$

where

ρ_{zr} = the density of zirconium (0.231 lbm/in.^{3}).

Equation (86) is expanded to the form

$$MZR = \pi\rho_{zr}\left[RO^2 - 2RO\,(DRP) + DRP^2 - RO^2 + 2\,RO\,(DRP1) - DRP1^2\right]. \tag{87}$$

Collecting like terms and substituting AP for certain other terms of Equation (87) yields

$$MZR = \pi\rho_{zr}\left[2\,RO\,(DRP1 - DRP) - AP\right]. \tag{88}$$

The heat of reaction is approximately 2,800 Btu per pound of zirconium reacted. Therefore

$$QMWR = \frac{2{,}800\ MZR}{\Delta T} \tag{89}$$

where QMWR = a heat rate of Btu per second per inch length of rod. The stoichiometric mass of steam required for the parabolic rate law to apply is

$$MSR = 0.395\ MZR. \tag{90}$$

If the amount of steam (MSR) is greater than the amount of steam available (MSTA) (steam-limited condition), all available steam is assumed to react. Consequently

$$MZR = \frac{MSTA}{0.395} \tag{91}$$

and the steam-limited reaction heat is computed through use of Equations (89) and (91). The depth the reaction has penetrated the cladding (DRP1), corresponding to the steam-limited condition, is computed by solving Equation (86) as follows

$$DRP1 = RO - \left[(RO - DRP)^2 - \frac{MZR}{\pi\rho_{zr}}\right]^{1/2}. \tag{92}$$

The output quantities of the Metal-Water Reaction Model are:

QMWR using Equations (89) and (88) or (91)
DRP1 using Equations (85) or (92).

The consumption of steam and the evolution of hydrogen during the metal-water reaction are not accounted for in the mass and momentum equations.

Selection of the Pin Swelling and Rupture Model described in Section 3.10.2 imposes certain changes in the Metal-Water Reaction calculation. These same changes are also imposed by use of the Evaluation Model Option. The changes are:

(1) The model assumes an unlimited supply of steam for the metal-water reaction

(2) The inside surface of the clad reacts after rupture occurs.

It should be noted that the reaction within the clad is limited to that portion of the pin(s) modeled within the heat slab where rupture occurs. Also, an oxide layer is not present on the interior of the clad at the

time of the rupture. In addition, the model delivers the heat of the interior reaction to the clad exterior surface.

The internal reaction changes the term (RO - r) in Equation (78) to (RO + r). If this change is followed through the subsequent steps, Equation (85) is unchanged. There are several changes in Equation (86), but Equation (88) has only the sign of AP changed to plus. That is:

$$MZR = \pi\rho_{zr}\left[2\ RO\ (DRP1 - DRP) + AP\right] \tag{93}$$

for a reaction proceeding on the internal surface of the cladding.

3.4.12 Suggestions to Users. For each conductor surface adjacent to a fluid volume or a constant sink, the user must enter a heat transfer area for either AHTL or AHTR on the Heat Slab Data Cards described in Volume II, Subsection 4.2.2 (51). The total volume, V, in each conductor must be entered for VOLS on the Heat Slab Data Cards. The user should observe the relationship of heat transfer area on the left and/or right sides of the conductor to its volume, and also of these area(s) to the surface area(s) implicit in the description of the particular geometry used for the given conductor. The code calculates the surface area(s) and the volume for a 1-ft section of the conductor from the geometry description entered on the Slab Geometry Data Cards. An effective conductor length is then obtained as $\ell = V/V_1$, where V_1 is the volume of the 1-ft section. The total surface area for the relevant side of the conductor (left or right) is calculated as $A_g = A_1\ell$, where A_1 is the area on the relevant side of the 1-ft section. The input value of the heat transfer surface area, A_T, is then compared with the total geometrical surface area, A_g. A disparity does not abort the computation, but a warning message is printed if A_T is greater than 1.001 A_g. Thus, the user can specify a heat transfer area less than (or even more than) the total geometrical surface area for that conductor. If he does not wish to do so, he should make sure that $A_T = A_g$. If he does, he should be aware that the ratio of A_T/A_g is used in the conduction solution. The assumption is that each linear foot of conductor has the

same ratio of actual heat transfer area to total surface area as the whole conductor. Surface heat flux will be affected inversely as the ratio of A_T/A_g.

Because of the above, changing the input heat transfer areas of a conductor without changing the total volume accordingly will give different heat fluxes and temperatures on initialization. In setting up a problem, a user may change heat transfer areas in order to change the rate of heat transfer into one or more fluid volumes. This is probably done most frequently with a conductor between two fluid volumes, where the initial fluxes are usually not predictable. When doing this, the conductor volume should be changed by the same ratio as used for the heat transfer area(s).

The user should also be aware that, on initialization, the code does not check for heat balances, either for the total system or for each fluid volume. In the latter, the heat transfer rate from one or more heat conductors to the fluid in a volume is not checked against the volume heat removal rate realized by the product of volume flow and the change in enthalpy between inlet and outlet junctions.

An extrapolation option is available for the thermal property tables entered on the Thermal Conductivity, Volumetric Heat Capacity, and Linear Expansion Coefficient Data Cards referred to in Subsection 3.4.4. This feature is obtained by entering a negative value for the data point total input, NKP, NCP, or NXP, respectively, within the data card format outlined in Volume II, Subsections 4.3.2 (56) through (58). The use of the option will allow the program to continue if unanticipated values for the parameters are encountered during computation. The extrapolation option on the thermal property tables can lead to an error, however, if the property value at the last data point in a table is less than that of the previous data point. The extrapolation for temperatures beyond the upper end of the table uses a straight line projected from the last two data points. A zero or negative property value can be obtained if the required temperature is high enough.

3.5 Reactor Kinetics, Radioactive Decay Heat, and Power Generation

3.5.1 Reactor Kinetics. The normalized power may be calculated from the reactor kinetics equations with reactivity feedback by entering "1" for the power calculation indicator NODEL on the Kinetics Constants Data Card outlined in Volume II, Subsection 4.2.2 (46). The reactor kinetics equations are solved by the code using a method similar to that employed in the IREKIN program[31]. The reactor kinetics equations thus used are

$$\frac{dn}{dt} = \frac{\beta}{\Lambda} \left[R - 1 \right] n + \sum_{i=1}^{6} \lambda_i C_i + S \tag{94}$$

$$\frac{dC_i}{dt} + \lambda_i C_i = \frac{\beta i}{\lambda} n \tag{95}$$

$$\beta = \sum_{i=1}^{6} \beta i \tag{96}$$

where

i = 1, 2, ..., 6
n = reactor fission power
β = effective delayed neutron fraction
Λ = neutron generation time
R = total reactivity normalized to the delayed neutron fraction
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.

The term $\frac{\beta}{\Lambda}$ is entered as BOVL on the Kinetic Constants Data Card.

Table III contains the delayed neutron constants[32] used by the program.

TABLE III

DELAYED NEUTRON CONSTANTS

Group	β_i/β	λ_i (sec^{-1})
1	0.038	0.0127
2	0.213	0.0317
3	0.188	0.115
4	0.407	0.311
5	0.128	1.40
6	0.026	3.87

The driving function for the reactor kinetics equations is reactivity. Contributions to the reactivity include a time-dependent (scram) reactivity and individual reactivitites due to feedback effects in each core region. Feedback effects include fuel temperature, water density, and water temperature. The feedback reactivity is calculated from:

$$R(t) = R_o + R_{exp}(t) - R_{exp}(0) + \sum_i R^i(t) - \sum_i R^i(0) \qquad (97)$$

where

$$R^i(t) = W^i_\rho R_\rho \left(\frac{\rho^i(t)}{\rho^i(0)} \right) + W^i_{FT} R_{FT} T^i_F(t) + \alpha^i_{FT} T^i_F(t) + \alpha^i_{WT} T_W(t) \qquad (98)$$

and where

R = total reactivity normalized to the delayed neutron fraction

R_o = initial reactivity (entered as RHOIN)

R_{exp} = explicit time-dependent reactivity

R^i = feedback reactivity from core region i

W_ρ^i = weighting factor for water density feedback of core region i (entered as VOIDWT on the Reactivity Coefficients Data Cards)

R_ρ = reactivity as a function of normalized water density for entire core

ρ^i = water density of core region i

W_{FT}^i = weighting factor for fuel temperature feedback of core region i (entered as DOPWT on the Reactivity Coefficients Data Cards)

R_{FT} = reactivity as a function of average fuel temperature in entire core

T_F^i = average fuel temperature of core region i

α_{FT}^i = fuel temperature coefficient for core region i (calculated as ALPHTM)

α_{WT}^i = water temperature coefficient for core region i (calculated as ALPHTW)

T_W = water temperature

t = time.

The first term of the right hand side of Equation (98) describes the reactivity effects due to water density changes, (VOIDRO), including those due to a change in water temperature. The water temperature coefficient (ALPHTW) used in the fourth term must be calculated with the water density constant. The usual procedure of measuring or calculating a water temperature coefficient at constant pressure cannot be used because the first and fourth terms would then include effects due to density changes. The second and third terms describe the reactivity effects of a change in fuel temperature. Description of the fuel temperature effects is recommended. This should include Doppler broadening of the capture resonances by using either the temperature reactivity curve (DOPRO) or the fuel temperature coefficients (ALPHTM). Overinsertion of reactivity due to fuel temperature will result if both are used however.

The Reactor Kinetics option is implemented by inserting a number greater than zero for NCOR on the Problem Dimensions Card [Volume II, Subsection 4.2.2 (2)]. This number corresponds to the number of core sections modeled which in turn requires the use of the following input data cards:

(1) Kinetics constants

(2) Scram table (for time dependent scram reactivity)

(3) Density reactivity table (relates reactivity to moderator density)

(4) Doppler table (relates reactivity to fuel temperature)

(5) Reactivity coefficients.

The formats for the foregoing are described in Volume II, Subsections 4.2.2 (46) through (50). The complete range of input variables is presented at that User's Manual location. Some are:

(1) Scram Table Data Cards - The input table is constructed using TSCR(I) where I is an index number. Data are entered for pairs of index numbers i.e., 1 and 2, 3 and 4, etc. The odd index is used for time and the even index is used for a corresponding reactivity or power.

(2) Density Reactivity Table Data Cards - The input table is constructed using VOIDRO(I) where I is an index number. Data are entered for pairs of index numbers; 1 and 2, etc. The odd index is used for water density (ρ^i) and the even index is used for a corresponding reactivity $R\rho$.

(3) Doppler Table Data Cards - The input table is constructed using DOPRO(I) where I is an index number. Data are entered for pairs of index numbers; 1 and 2, etc. with the odd index used for fuel temperature T_F^i and the even index used for reactivity (R_{FT}).

The foregoing tables are entered by the program with time, density, or temperature. The corresponding parameters of reactivity are read for use in the iterative solution of the applicable equations.

Reactivity feedback phenomena in the moderator can include the effects of any vapor volume produced during subcooled boiling. The vapor volume fraction is estimated within the program by the equation shown below. It should be noted however, that vapor transport is neglected. The equation for the vapor volume fraction is

$$\frac{dR}{dt} + \frac{R}{\tau} = \lambda K q' \qquad (99)$$

where

R = volume fraction of vapor in coolant channel

τ = bubble collapse life time

λ = fraction of surface heat flux utilized in producing vapor

q' = surface heat flux

K = conversion factor

t = time.

The parameters, τ and λ are entered as "TAU" and "LAMBDA" on the Kinetics Constants Data Card.

The solution of Equation (99) is:

$$R = R_o e^{-t/\tau} + \lambda K (1-e^{-t/\tau}). \qquad (100)$$

where

R_o = the value of R at beginning of a time step.

3.5.2 Reactor Kinetics with Radioactive Decay Heat. The power calculation indicator NODEL is entered as "2" or "3" on the Kinetics Constants Data Card in order to select the option of reactor kinetics with radioactive decay heat from the fission products. The other input requirements are the same as those described in Section 3.5.1. Radioactive decay terms are calculated by the following equations:

$$\frac{d\lambda_j}{dt} + \lambda_j \gamma_j = E_j n \qquad (101)$$

where

$j = 1, 2, \ldots, 11$

γ_j = concentration of decay heat group j

λ_j = decay constant of decay heat group j

E_j = yield fraction of decay heat group j.

Table IV contains the constants used in the radioactive decay equations. These constants were obtained by fitting Equation (101) to the data published by Shure[33]. The decay heat model used in RELAP4 is similar to the proposed ANS standard model[34]. The RELAP4 model has the additional capability of considering time variations in reactor fission power and of providing continuity in the decay heat as a function of time.

TABLE IV

RADIOACTIVE DECAY CONSTANTS

Group	E_j	λ_j (sec^{-1})
1	0.00299	1.772×10^{-0}
2	0.00825	5.774×10^{-1}
3	0.01550	6.743×10^{-2}
4	0.01935	6.214×10^{-3}
5	0.01165	4.739×10^{-4}
6	0.00645	4.810×10^{-5}
7	0.00231	5.344×10^{-6}
8	0.00164	5.726×10^{-7}
9	0.00085	1.036×10^{-7}
10	0.00043	2.959×10^{-8}
11	0.00057	7.585×10^{-10}

The total power in a region is the sum of the direct fission power and the radioactive decay power. The inclusion of the decay heat terms gives a more realistic shutdown power calculation. It is assumed all power is generated in the fuel elements. The effect of direct gamma heating of the cladding, coolant, and structure, is discussed in Section 3.4. The total power, P, is

$$P = nE_f + \sum_{j=1}^{11} \lambda_j \gamma_j \qquad (102)$$

where E_f = fraction of power produced at steady state conditions by fissioning. If the gamma heating option is not used, then $E_f = 1$; otherwise $E_f = 0.93$ and $\sum E_j = 0.07$.

An option is available which permits the user to specify the prompt power fraction i.e., modify the fraction of the total power that is released immediately thus generating a heat source. The option is implemented by entering a value on the Kinetics Constants Data Card for PROMPT. The default value in the program for this is 1.0 if no delayed gamma groups (emitters) are specified by the value entered for NODEL on the same card. The default value will be 0.93001 if delayed gamma groups are present and PROMPT was entered as 0.0. The user is cautioned that the use of values for PROMPT other than the default values can result in a power imbalance.

3.5.3 Power Generation. Four options are available to describe internally generated power. For all of these options, a total power must be supplied as described in Volume II, Subsection 4.2.2 (3). The four options are (a) data retrieved from a previous RELAP4 calculation, (b) a normalized power supplied by a table of power-versus-time, (c) program solution of the space-independent reactor kinetics equations, and (d) program solution of the space-independent core kinetics equations with radioactive decay heat. These four methods all require a time-independent distribution of the power among the various heat conducting regions as described in Subsection 3.4.1.

(1) Tabular Power Data. To select the option of power-versus-time, the power calculation indicator (NODEL) must be set to zero. A set of tabular data entered on the Scram Table Data Cards (Volume II, Subsection 4.2.2 (47)) is then used to describe the power history during the transient. The zero time entry in the table will be used until the conditions specified by the designated trip number (ITSCRM) are satisfied. From this point on, power is obtained by interpolation

from the table with the time axis translated so that zero time of the table corresponds to the time at which the trip conditions are satisfied.

The user must supply dummy values on the Kinetics Constants Data Card described in Volume II, Subsection 4.2.2 (46) for the effective delayed neutron fraction divided by the mean lifetime (BOVL) and the initial reactivity (RHOIN). If the power-versus-time option is used, the user does not input the Density Reactivity Table Data Cards, the Doppler Table Data Cards, and the Reactivity Coefficient Data Cards.

(2) Power Data Retrieval. To retrieve normalized power data from a previous RELAP4 run, the power calculation indicator (NODEL on the Kinetics Constants Data Card) must be set to minus one. The data stored in the plot records of a previous run (TPIN2) are interpolated to obtain the normalized power at each time step. The user must supply dummy values for the effective delayed neutron fraction divided by the mean lifetime (BOVL) and the initial reactivity (RHOIN). If normalized power data are retrieved from a previous RELAP4 calculation, the user does not input the Scram Table, the Density Reactivity Table, the Doppler Table, or the Reactivity Coefficient Data Cards.

3.6 RELAP4/MOD5 Special Models

RELAP4/MOD5 has several special models or options that may be employed in the execution of a program run. These will be discussed in the following order in the subsections that comprise the special model section:

(1) Trip Control
(2) Vertical Slip and Slip Velocity Correlation
(3) Horizontal Slip
(4) Flooding

(5) Lower Plenum Entrainment
(6) Bubble Rise and Related options
(7) Water Packing, Choking-Smoothing, Liquid Mass Depletion and Mixture Level Crossing from Above
(8) Critical Flow
(9) Stagnation Properties
(10) Centrifugal Pumps
(11) Jet Pumps
(12) Valves
(13) Heat Exchangers
(14) Enthalpy Transport

3.6.1 Trip Control. The control functions normally needed to simulate a reactor system may be described through the trip-control data. An arbitary number (up to a maximum of 20) of these control cards may be specified by entering the desired number for NTRP on the Problem Dimensions Data Card as outlined in Volume II, Subsection 4.2.2 (2). Trips can be controlled by elapsed time, reactor power or period, volume pressure or temperature, mixture or liquid levels within fluid volumes, junction flow, and temperatures within the core fuel or cladding. These controlling variables can be used to perform a number of actions such as reactor scram, leak area openings, valve actions, fill water injections, pump shut off, and simplified heat exchanger control. At least one problem termination condition must be specified as a trip.

Specific trip action is provided by coding within the various data card sets. This coding (e.g., $2 \leq$ ITPUMP ≤ 20 within the Pump Description Data Cards) corresponds with the same coding (or index) number entered as IDTRP on the Trip Data Cards. This correspondence will cause the selected mechanism within the various data card sets to be controlle by the parameters entered on the trip data card having the same IDTRP number. The program user must select a parameter for trip signal comparison from those listed for IDSIG in the Trip Control Data Cards in Volume II, Subsection 4.2.2 (10). Examples of the 10 available are elapsed time, pressure, liquid level, etc. The trip can be set for a

higher than or a lower than comparison for actuation. An index number must be entered for IX1 when the comparison is to be made for a parameter identified to a specific element in the model i.e., volume, junction, etc. Should the trip actuation be derived under control of a differential pressure or temperature obtaining between two other model elements, an index representing each must be entered using IX1 and IX2. When a specific value is utilized for a comparison datum, it is entered under SETPT. Should a delay be desired after the set point condition has been satisfied (e.g., pump start delay), the derived delay time can be entered under DELAY.

An example of the foregoing is provided for illustration purposes. The modeled reactor is to be scrammed at the same time that valves in Junctions 12 and 18 are to be closed. The valves then must be specified on the 12th and 18th sets of Junction Data Cards with an index number IVALVE relating to the Valve Data Cards as outlined in Subsection 3.6.12. Assuming that the selected index number happened to be 3 for both junctions, the valve type must be selected and entered as ITCV. The number 5 could be selected as identifying a valve under trip control. The number entered under IDTRP on the Trip Data Cards must be 5 to correspond to the 5 entered for ITCV to place the modeled component under control at the desired trip. Since the reactor scram is also to be initiated concurrently, 5 must also be entered for ITSCRM on the Scram Table Data Card, as outlined in Volume II, Subsection 4.2.2 (47). The point in the transient that the foregoing trips are to occur can be setup to be the earlier of the times defined by either the power level exceeding 120% with a 0.3 sec delay or the flow in Junction 6 falling below 100 lb/sec with a 1.1 sec delay. Two trip cards must then be supplied with IDTRP set equal to 5. One card must specify the trip signal IDSIG as 2 (positive integer) for high normalized reactor power, the setpoint SETPT as 1.20, and the delay DELAY as 0.3. The other card must similarily specify IDSIG as 9 for high flow, junction index IX1 as 6, SETPT as 100, and DELAY as 1.1.

The trip control parameters may be changed or reset when a RELAP4 problem is restarted. Some trip data may be erased when a program is

restarted unless new trip data are entered. Volume II, Subsection 4.2.4 provides further discussion relative to handling restart situations along with available options and program implications.

3.6.2 Vertical Slip Model and Slip Velocity Correlation.

(1) Vertical Slip Model. The vertical slip model is designed to compute the separated fluid component velocities at flow junctions in vertically modeled system components. The model is postulated on the assumption that gravity forces govern the slip between phases and therefore the model is especially applicable during relatively slow transients when inertia effects are negligible. The model computes the junction liquid and vapor phase velocities which are used to compute the convective energy transfer between control volumes. The homogeneous mass and momentum equations have not been modified with the addition of slip. Since the slip model affects only the energy equation, the possibility exists that the net energy transfer between control volumes may be in the opposite direction of the net junction mass flow.

The following flow combinations are possible at a slip junction with the assumption of gravity dominated flow.

(a) Cocurrent flow downward
(b) Cocurrent flow upward
(c) Countercurrent flow with vapor flow up and liquid flow down.

The slip model slip velocity is computed from a separate correlation which is a function only of void fraction. When countercurrent flow has been computed for a slip junction, a flooding correlation can be used to provide an upper limit for the junction slip velocity.

Application of the slip model at user-specified vertical flow junctions proceeds in the following manner. The net junction mass flow and the adjacent volume thermodynamic properties are assumed to be known. The net junction mass flow, W_{NET}, can then be written in terms of the liquid and vapor component flow as:

$$W_{NET} = W_{\ell} + W_g \tag{103}$$

where component flows are defined as positive for downward flow direction and where

$$W_{\ell} = (1-\alpha)\ \rho_{\ell}\ V_{\ell}\ A \tag{104}$$

$$W_g = \alpha\ \rho_g\ V_g\ A \tag{105}$$

and

ρ_{ℓ} = saturated liquid density

ρ_g = saturated vapor density

V_{ℓ} = liquid velocity

V_g = vapor velocity

α = junction void fraction

A = junction flow area.

The junction slip velocity can be written as:

$$V_{SLIP} = V_{\ell} - V_g \tag{106}$$

The sign of V_{SLIP} is positive or negative depending on the convention used for flow direction through the vertical flow junction. V_{SLIP} will be positive when flows are defined as positive downward and negative when flows are defined as positive upward.

By solving Equations (103), (104), (105), and (106) simultaneously, expressions for W_g and W_{ℓ} in terms of the known quantities W_{NET} and V_{SLIP} can be obtained:

$$Wg = \alpha \rho_g \frac{W_{NET} - (1-\alpha) \rho_\ell A V_{SLIP}}{(1-\alpha) \rho_\ell + \alpha \rho_g} \quad (107)$$

and

$$W_\ell = (1-\alpha) \rho_\ell \frac{W_{NET} + \alpha \rho_g A V_{SLIP}}{(1-\alpha) \rho_\ell + \alpha \rho_g} \quad (108)$$

If the signs of the component mass flow rates are different (i.e., countercurrent flow), a check for flooding will be made if the user has so specified by entering flooding model cards as discussed in Subsection 3.6.4. The use of these flooding correlations will place an upper limit on the junction slip velocities.

The fluid energy Equation (5), Subsection 3.3.1 (4), is rewritten in terms of the liquid and vapor component velocities as follows:

$$\frac{dU_i}{dt} = -\frac{\ell_i}{2A_i} \frac{d}{dt}\left(\frac{\bar{W}_i^2}{\bar{\rho}_i}\right) + Q_i + \sum_J W_{\ell_{ij}} \left(h_{\ell_{ij}}\right)$$

$$+ \sum_J W_{g_{ij}} \left(h_{g_{ij}}\right) + \sum_J W_{NET}\left(\frac{V_{ij}^2}{2} + Z_{ij} - \bar{Z}_i\right) \quad (109)$$

where

$W_{\ell_{ij}}$ = liquid flow into volume V_i from junction j

$W_{g_{ij}}$ = vapor flow into volume V_i from junction j

$h_{\ell_{ij}}$ = donor volume liquid thermodynamic enthalpy at junction j

$h_{g_{ij}}$ = donor volume vapor thermodynamic enthalpy at junction j

ℓ_i = flow length of volume V_i

$Z_{iJ} - \bar{Z}_i$ = elevation change from the center of mass of volume V_i at $\bar{Z}_i$ to junction j.

A normal flow junction can be converted to a vertical slip junction by specifying $0 < SRCOS \leq 1$ on the Junction Data Cards as outlined in Volume II, Subsection 4.2.2 (21). The value entered must represent the cosine of the angle subtended by the line joining the geometric centers of the connected volumes and by the vertical. The program uses the input value for SRCOS as a multiplier for slip velocity as follows:

$$\text{Slip velocity} = V_{SLIP} \quad SRCOS$$

where V_{SLIP} is computed as described in Subsection 3.6.2 (2). If SRCOS = 0.0, the junction flow is homogeneous with the liquid and vapor phase having equal velocities. Vertical slip should not be specified at leak or fill junctions, or at junctions connecting normal volumes with time-dependent volumes.

(2) Vertical Slip Velocity Correlation. A variable slip velocity correlation which is solely a function of void fraction can be used to compute junction slip velocities. The form of the correlation is given as follows:

$$V_{SLIP} = \left[u_\infty + u_{S1} (\Delta \alpha)\right] \bar{\alpha} (1-\bar{\alpha})^{(1-P\bar{\alpha})} + u_c \qquad (110)$$

where

u_∞ = slip velocity coefficient

u_{S1} = slip velocity coefficient

u_c = slip velocity constant

P = slip velocity exponent

$\bar{\alpha}$ = average junction void fraction

$\Delta\alpha = \left(\bar{\alpha}_{BOT} - \bar{\alpha}_{TOP}\right) \geq 0.0)$

$\bar{\alpha}_{BOT}$ = average void fraction of volume beneath the junction

$\bar{\alpha}_{TOP}$ = average void fraction of volume above the junction.

The foregoing equation applies for average void fractions less than α_ℓ which is entered as SLVAMX on the Slip Velocity Card described in Volume II, Subsection 4.2.2 (13). Should α rise above the void fraction limit, α_ℓ, V_{SLIP} then will have the value computed by the program for $\bar{\alpha} = \alpha_\ell$.

Input data for the vertical slip velocity correlation equation is entered on the Slip Velocity Card as follows

u_∞ = SLVELZ

P = SLVPWR

u_{S1} = SLVSL1

u_c = SLVDP1.

Should the optional Slip Velocity Card not be entered, a default computation will be made by the program utilizing the following correlation formula. Note that u_c default is zero.

$$V_{SLIP} = (10 + 4\,\Delta\alpha)\,\bar{\alpha}\,(1-\bar{\alpha})^{(1 - 1.25\,\bar{\alpha})}. \qquad (111)$$

At low void fractions ($0.0 < \bar{\alpha} < 0.3$), the default correlation reflects the experimental air-water cocurrent and countercurrent bubbly flow data of Fantini[35], Shulman[36], Towell[37], Ellis[38], and Lackme[39]. In the annular flow region ($\bar{\alpha} > 0.8$), it reflects the Transparent Vessel Air-Water Flooding data[40] reported by Whitbeck. The correlation yields slip velocities similar to those computed from the Zuber Churn-turbulent drift flux model[41].

3.6.3 Horizontal Slip Model. The fluid flow in large diameter horizontal components could become stratified as system pressure reduces during a small break blowdown of a large pressurized reactor system. Components where subcooled ECC water is injected also are likely to have separated flow. The possibility of countercurrent or cocurrent vapor-liquid flow in many horizontal components exists and needs to be modeled analytically to account for the effects of such flow behavior on LOCA predictions. A horizontal slip model therefore has been included to provide an approximation of stratified flow in horizontal components in the RELAP4 program. This model option is intended for use in small break analysis. Application to volumes where flow will not remain stratified may adversely affect central processing unit time however. It may also be useful for reflooding calculations. The horizontal slip model allows for the calculation of vapor and liquid flows as two separate components rather than as a homogeneous mixture in the standard RELAP4 junction flow. The horizontal slip model has variable flow areas, variable inertias, and includes both wall friction and interfacial (liquid surface) shear pressure loss calculations.

(1) Model Description. Flow through a long section of horizontal pipe may be modeled using RELAP4 as shown in Figure 14.

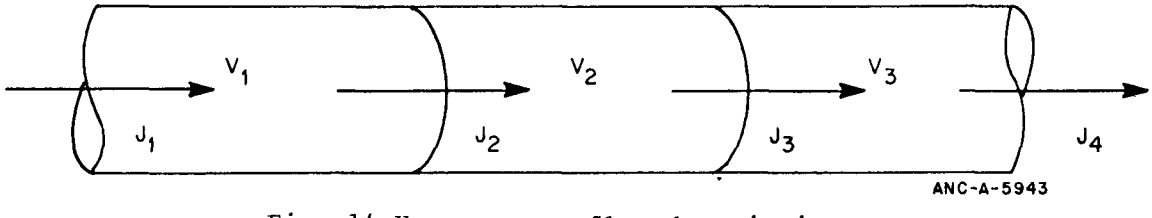


Fig. 14 Homogeneous flow description.

The code user must specify junction pairs connecting the volumes in order to incorporate the horizontal slip flow model into the above system. The specification requires a particular input geometry. It also requires input of the specific RELAP4 option by IADJUN on the Junction Data Card.

Figure 15 shows a horizontal component nodalized as in Figure 14, but with the horizontal slip junction specification.

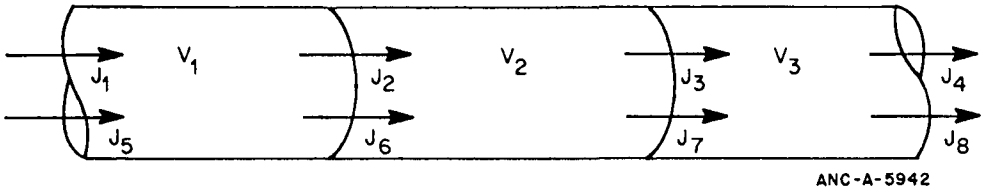


Fig. 15 Horizontal slip flow description.

The number of junctions connecting the three volumes has been doubled. The upper junctions represent cross sections for the vapor flow component and the lower junctions represent the cross sections for liquid flow. Each interface between two volumes is thus modeled with a pair of junctions. Each junction of the pair has its own distinct junction number and input data. The areas A_1 through A_8 for junctions J_1 through J_8 are time dependent and are determined as a function of the mixture level in the "from" volume. Defining the "from" mixture level as Z_m, and the "from" volume height as Z_v, specify the conditions:

1. $Z_m \leq 0$ $\quad A_g = A_T$, $A_\ell = 0$

2. $Z_m \geq Z_v$ $\quad A_g = 0$, $A_\ell = A_T$

3. $0 < Z_m < Z_v$ $\quad A_\ell + A_g = A_T$

where

A_g = vapor flow area

A_ℓ = liquid flow area

A_T = total flow area ($A_\ell + A_g$).

If the void fraction is less than 0.1, where void fraction is defined as:

$$\alpha = A_g/A_T \tag{112}$$

then the flow is considered to be homogeneous, the mixture level definition is ignored, and the flow areas (AJUN) are defined as:

$$A_g = 0$$
$$A_\ell = A_T$$

To implement the horizontal slip junctions, code users must identify the adjacent member of the junction pair by IADJUN and must correctly specify the geometric data shown in the right hand side of Figure 16. These inputs are entered on the junction data cards as prescribed in Volume II, Subsection 4.2.2 (21). Each junction within the pair of junctions has its own input data and is cross referenced by IADJUN.

The initial geometric data must be specified as follows. For a horizontal component with cross-sectional area A_T, and diameter D_T at elevation A_J, the user should input two junctions such that:

$$\text{DIAMJ} = \frac{D_T}{\sqrt{2}} \qquad \text{(both junction data cards)} \tag{113}$$

$$\text{AJUN} = \frac{A_T}{2} = A_\ell = A_g \qquad \text{(both junction data cards)} \tag{114}$$

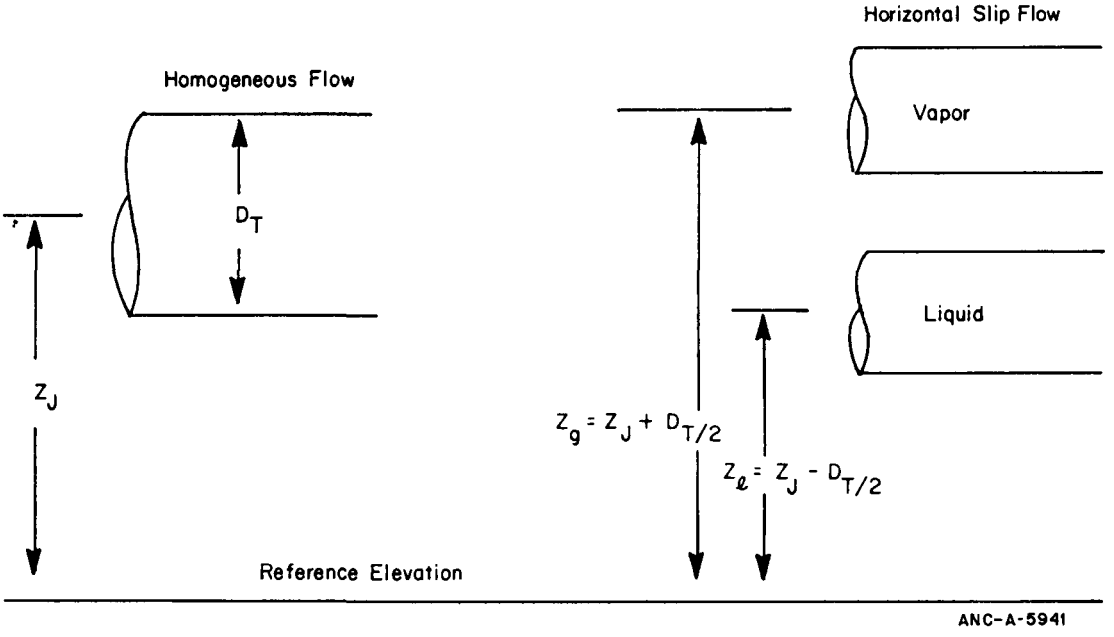


Fig. 16 Geometry input specification.

$$ZJUN = Z_g = Z_J + D_{T/2} \quad \text{(vapor junction data card)} \qquad (115)$$

$$ZJUN = Z_\ell = Z_J - D_{T/2} \quad \text{(liquid junction data card).} \qquad (116)$$

With the above approximate input, the code will recompute the areas and diameters for the two junctions based on the mixture level in the "from" volume. The computation of corrected elevations is necessary for the determination of the volume mixture level with respect to the calculated equivalent total junction diameter.

3.6.4 Flooding Models. The flooding phenomenon that occurs in countercurrent annular flows serves to limit the maximum downward liquid flow for a given vapor upflow. The Wallis, the Wallis-Crowley, and the Battelle-Columbus Laboratory (BCL) downcomer model options are available for use at vertical slip junctions for which the slip calculation has predicted countercurrent flow. The flooding criteria can be thought of as putting an upper limit on the magnitude of the slip velocity. That is, at any slip junction for which a flooding model is used, the junction slip velocity is the smaller of the value computed from the slip correlation or that computed from a user-specified flooding model.

(1) Wallis Flooding Model . The general form of the Wallis Correlation[42] is:

$$W_{C2} = \left[J_g \left(\frac{\rho_g}{g \Delta \rho} \right)^{1/2} \right]^{1/2} + W_{C1} \left[J_\ell \left(\frac{\rho_\ell}{g \Delta \rho} \right)^{1/2} \right]^{1/2} \qquad (117)$$

where

J_g = upward volumetric flux of vapor

J_ℓ = downward volumetric flux of liquid

ρ_g, ρ_ℓ = vapor and liquid component densities

$\Delta \rho = \rho_\ell - \rho_g$

g = gravitational constant

W_{C1} = first Wallis Flooding Correlation parameter

W_{C2} = second Wallis Flooding Correlation parameter.

The coefficients W_{C1} and W_{C2} are entered for WALSC1 and WALSC2 respectively on the Wallis Flooding Correlation Card as outlined in Volume II, Subsection 4.2.2 (14). The default values of WALSC1 = 0.7 and WALSC2 = 0.47 were developed from Semiscale countercurrent flow test data[43]. The Wallis correlation is solved simultaneously with the equation for conservation of mass at a given junction to obtain the slip velocity and component phase velocities. The Wallis model, when specified, will be applied at all vertical slip flow junctions for which countercurrent flow has been computed by operation of the program.

(2) Wallis-Crowley Flooding Model. The Wallis-Crowley flooding criterion is the result of recent work by Wallis and Crowley[44, 45, 46]. This correlation is applicable only at the junction between the upper annulus and downcomer in a pressurized water reactor. The specific junction must be entered for JCNDWN on the Wallis Crowley Flooding Correlation Card outlined in Volume II, Subsection 4.2.2 (15).

The Wallis-Crowley flooding correlation is defined by straight line segments bounded by the intersections of the following three equations.

$$W_{C3} = \left[J_g \left(\frac{\rho_g}{2gS\Delta\rho} \right)^{1/2} \right]^{1/2} + W_{C4} \left[J_\ell \left(\frac{\rho_\ell}{2gS\Delta\rho} \right)^{1/2} \right]^{1/2} \quad (118)$$

$$J_g \rho_g h_{fg} = J_\ell \rho_\ell \Delta h_{sub} \quad (119)$$

$$W_{C5} \left(\frac{\pi D}{S} \right)^{1/4} = \left[J_g \left(\frac{\rho_g}{2gS\Delta\rho} \right)^{1/2} \right]^{1/2} + W_{C6} \left[J_\ell \left(\frac{\rho_\ell}{2gS\Delta\rho} \right)^{1/2} \right]^{1/2} \quad (120)$$

where

Δh_{sub} = difference in liquid enthalpy between volumes on either side of specified junction

S = downcomer gap (ft)

D = downcomer diameter (ft)

h_{fg} = latent heat of vaporization.

The coefficients W_{C3}, W_{C4}, W_{C5}, and W_{C6} are entered for WALSC3, WALSC4, WALSC5, and WALSC6 respectively on the Wallis-Crowley Flooding Correlation Card.

A graphic representation of the foregoing is shown in Figure 17. Starting with $\left[J_\ell \left(\frac{\rho_\ell}{2gS\Delta\rho} \right)^{1/2} \right]^{1/2}$ (the X-axis argument) equal to zero, the correlation follows the plot of Equation (118) until its intersection with the plot of Equation (119). It then follows the plot of Equation (119) until its intersection with Equation (120). At that point the correlation has a constant value for increasing values of the x-axis argument. The option of disregarding Equation (120) in the correlation is provided. This is accomplished by enering "1" for IDWNEM on the Wallis-Crowley Flooding Correlation Card.

The Wallis-Crowley Correlation attempts to account for the effect of subcooled ECC water on liquid delivery to the lower plenum. The subcooling is computed across the junction at which the correlation is applied. Note also that for zero subcooling, the correlation reduces to the standard Wallis flooding model. The user must specify the downcomer gap S and downcomer diameter D in addition to the slip junction at which the correlation is to be applied. The gap is entered for DWNGAP and the diameter for DTRDWN on the Wallis-Crowley Flooding Correlation Card.

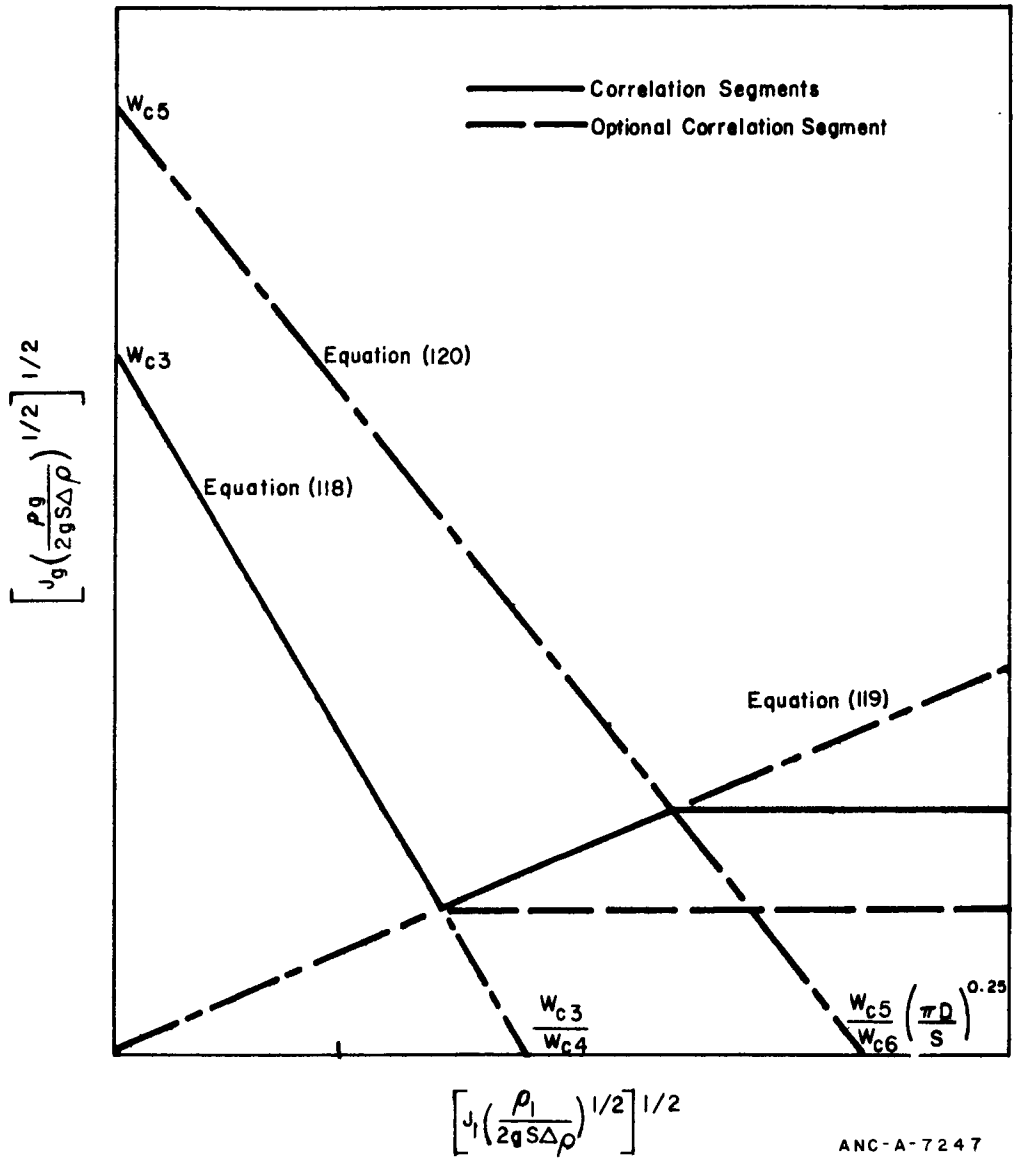


Fig. 17 Wallis-Crowley flooding correlation.

(3) Downcomer Penetration Model. The purpose of the downcomer penetration model is to predict ECC liquid penetration of a PWR downcomer during periods of reverse vapor flow in a reactor core. The model represents recent work by the Battelle Columbus Laboratories[47,48]. It computes the component mass flows at the downcomer-lower plenum junction based on liquid flow into the upper annulus, liquid subcooling, and vapor flow from the core into the lower plenum.

The model uses the correlation of the Battelle downcomer penetration given by

$$J^*_{\ell_{JDLP}} = G + B\, J^*_{\ell_{IN}} - C\, J^*_{G_{CORE}} \,(1-D\ \Delta T_{SUB}) \qquad (121)$$

where

G, B, C, D = Battelle coefficients

$$J^*_{\ell_{JDLP}} = \left(\frac{J^2_{\ell_{JDLP}}\ \rho_\ell}{g\ D_h\ \Delta\rho} \right)^{1/2} \qquad (122)$$

$$J^*_{\ell_{IN}} = \left(\frac{J^2_{\ell_{IN}}\ \rho_{\ell_{IN}}}{g\ D_h \Delta\rho} \right)^{1/2} \qquad (123)$$

$$J^*_{G_{CORE}} = \left(\frac{J^2_G\ \rho_g}{g\ D_h \Delta\rho} \right)^{1/2} \qquad (124)$$

and where

$J_{\ell_{JDLP}}$ = volumetric flux of liquid at junction of downcomer and lower plenum based on annulus area

J_G = volumetric flux of vapor at junction of core and lower plenum based on annulus area

$J_{\ell_{IN}}$ = volumetric flux of liquid from cold leg into the upper annulus based on annulus area

ρ_ℓ = liquid density

D_h = hydraulic diameter (ft)

$\Delta T_{SUB} = T_\ell$ (lower plenum) $- T_\ell$ (cold leg) ≥ 0

ρ_g = vapor density

$\Delta\rho = \rho_\ell - \rho_g$.

The program uses the following default values for the Equation (121) Battelle coefficients:

G = 0.36266
B = 1.13400
C = 1.62500
D = 0.00387.

The user has the option of using other coefficients by entering desired values for G, B, C, or D on the Downcomer Penetration Correlation Coefficient Card described in Volume II, Subsection 4.2.2 (17).

The Battelle correlation computes the volumetric flux of water from the downcomer into the lower plenum. To compute the component mass flow rates, the void fraction at the downcomer lower plenum portion must be known. No experimental information regarding the void fraction or vapor volumetric flux has been found for the Battelle data. The correlation thus is utilized in RELAP4 with the assumption that the net junction mass flow computed from the conservation equations remains unchanged

upon application of the downcomer penetration model. An average junction void fraction is computed by averaging volume void fractions on either side of the junction.

The downcomer penetration model is consistent with the vertical slip model outlined in Subsection 3.6.2 in that

$$V_{SLIP} = V_{\ell} - V_g = \frac{J_{\ell_{JDLP}}}{1 - \alpha_j} - \frac{J_{g_{JDLP}}}{\alpha_j} \qquad (125)$$

where

α_j = junction void fraction.

The term $J_{\ell_{JDLP}}$ is computed from the BCL correlation, Equation (121)

and the term $J_{g_{JDLP}}$ as follows:

$$J_{g_{JDLP}} = \frac{G_{NET_{JDLP}} - \rho_{\ell} J_{\ell_{JDLP}}}{\rho_g} \qquad (126)$$

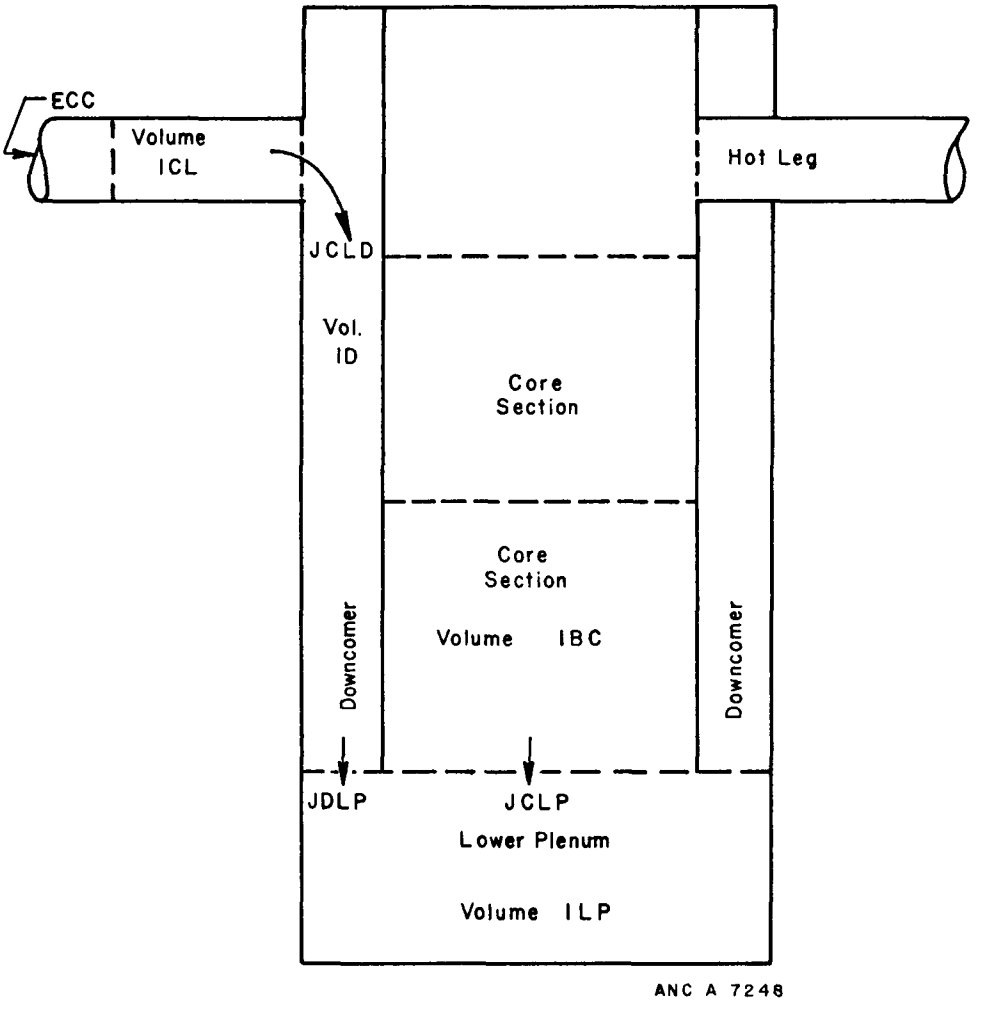
where

$G_{NET_{JDLP}}$ = net junction mass flow

ρ_{ℓ} = saturated liquid density

ρ_g = saturated vapor density.

The proper application of the downcomer penetration model restricts the user to the nodalization depicted in Figure 18. The input data must be entered on the Lower Plenum Entrainment Card in accord with the



Note: Volume and Junction Designations are Those Used on the Downcomer Penetration - Lower Plenum Entrainment Card

Fig. 18 Nodalization required for RELAP downcomer penetration model.

format described in Volume II, Subsection 4.2.2 (16). The volume designations for the model are entered as follows on the Lower Plenum Entrainment Card:

ICL = intact loop cold leg adjacent to downcomer

ILP = lower plenum volume in communication with downcomer and core

IBC = core barrel immediately above lower plenum

ID = downcomer volume immediately above the lower plenum.

The junction designations for the model are similiarly entered on the Lower Plenum Entrainment Card.

JCLP = junction between volumes entered for core and lower plenum (IBC and ILP)

JDLP = junction between downcomer and lower plenum (ID and ILP)

JCLD = junction between cold leg and downcomer (ICL and ID).

The hydraulic diameter of the downcomer is entered for DH as computed by the user from the relationship DH = 2(downcomer gap).

The model is activated by lower plenum pressure dropping lower than that entered by the user for TPRES on the Downcomer Penetration-Lower Plenum Entrainment Card. The specific mode of operation is selected by the user by entering one of the following for IX.

IX = 1-Lower Plenum Entrainment Model only (see Subsection 3.6.5)

IX = 2-Downcomer Penetration model only

IX = 3-Both Lower Plenum Entrainment and Downcomer Penetration Models where the former may override the latter

IX = 0-Neither model is used.

It should be noted that use of the Downcomer Penetration Model requires that slip flow be defined for the junctions between the core and lower plenum and between the downcomer and the lower plenum. This is done by entering a value greater than zero for SRCOS on the Junction Data Cards.

Comparisons have been made between the downcomer penetration model and the use of vertical slip only to calculate ECC bypass. Vertical slip only was found to give a better comparison to Semiscale experimental data (Volume III, Appendix H), and is therefore recommended. Improvements to the downcomer penetration model to account for hot wall and fluid depressurization effects will be made in a future version of RELAP.

3.6.5 Lower Plenum Entrainment Model. This model computes the entrainment of liquid from the lower plenum during periods of reverse vapor flow through a reactor core. The reverse core vapor flow is assumed to entrain liquid from the lower plenum and carry it up into the downcomer. The model is based on studies reported by Crowley and Block[49]. The model adjusts the component mass flows at the downcomer-lower plenum junction based on the lower plenum liquid level and the vapor flow at the core-lower plenum junction. The flow adjustments are consistent with the gravity-dominated slip model. If there is no vapor flow from the core to the lower plenum, the model is bypassed. The critical distance between the bottom of the downcomer and lower plenum liquid level is given as

$$h_{CRIT} = \frac{1}{2\, g\, \rho_g\, \Delta\rho} \left(\frac{\dot{M}_{VAP}}{C\, A_{ANN}} \right)^2 \qquad (127)$$

where

$\dot{M}_{VAP}$ = mass flow rate of vapor from core to lower plenum

C = user input contraction coefficient

A_{ANN} = cross sectional area of downcomer (flow area of downcomer lower plenum junction)

g = gravitational constant

ρ_g = vapor density

$\Delta\rho$ = difference between liquid and vapor densities.

The value computed by the program for h_{CRIT} determines the existence of liquid entrainment in the reverse vapor flow. Entrainment will be calculated for elevation differences less than h_{CRIT}.

Use of the model requires entry of the input data listed in Volume II, Subsection 4.2.2 (16) on the Downcomer Penetration-Lower Plenum Entrainment Card. The input is identical to that used for downcomer penetration as described in Subsection 3.6.4 (3) with the following exceptions. The input flag IX must be set to 1 for entrainment only and to 3 for entrainment and downcomer penetration. The latter value will allow the entrainment model to override the downcomer penetration model as appropriate. A value for the contraction coefficient CCF should be entered if the default value of 0.6 is not desired. In addition, vertical slip must be specified at the core-lower plenum and the downcomer lower-plenum junctions. This is accomplished by entering $0 < \text{SCROS} \leq 1$ on the Junction Data Cards listed in Volume II, Subsection 4.2.2 (21).

Proper use of the model restricts the user to a single-volume lower plenum in direct communication with the core and downcomer similar to the nodalization shown in Figure 18. The model is activated after the pressure in the lower plenum drops below a user specified, input pressure TPRES on the Downcomer Penetration-Lower Plenum Entrainment Card.

3.6.6 Bubble Rise and Related Options. Physical phenomena which occur within fluid filled volumes will influence the choice of code option used to simulate hydraulic and heat transfer models. Specific options have been introduced in RELAP4 to compute the following:

(1) Vapor bubbles within liquid

(2) Quality of liquid vapor mixture for heat transfer consideration

(3) Single mixture level in vertically stacked volumes

(4) Vertical and horizontal junction cross section modeling

(5) Equivalent liquid level for combined volumes.

The foregoing are discussed in turn in the following subsections.

(1) General Model Description. The purpose of the bubble rise model is to account for non-homogeneous conditions within a control volume by providing for improved estimates of enthalpy and density as a function of vertical elevation. The result of applying the bubble rise model to a homogeneous volume is shown in Figure 19.

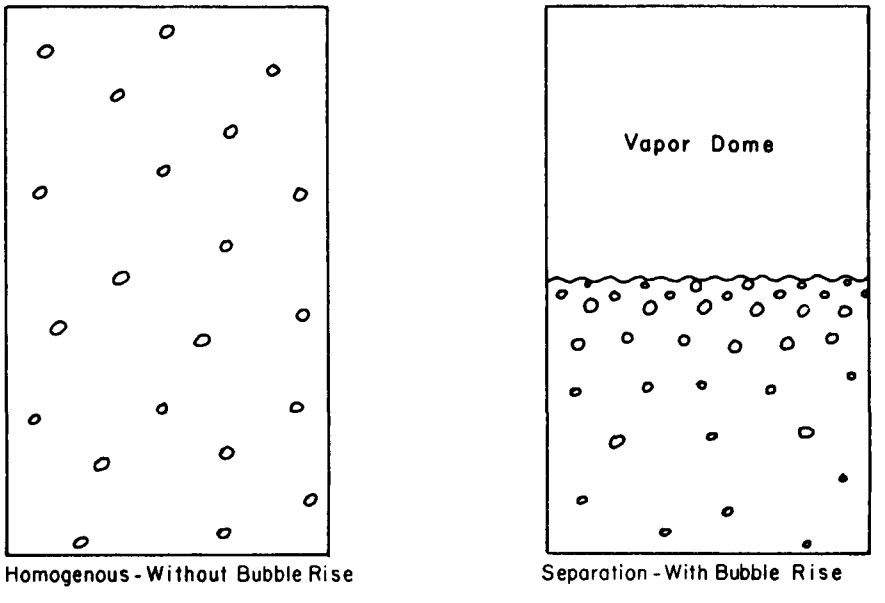


Fig. 19 Application of the bubble rise model.

The separation model shown in Figure 19 assumes that the density of bubbles is least near the bottom of the volume. This is because the static pressure is greatest at the bottom, and bubbles tend to accumulate as they rise through the mixture. This leads to the following model which assumes a linear increase in bubble density as a function of normalized height within a two-phase mixture[50].

$$\rho_{g_b} = a \frac{z}{z_m} + b \tag{128}$$

where

ρ_{g_b} = partial steam density within the mixture (bubbles)

a,b = time-dependent slope and intercept coefficients

z = height above the bottom of the volume

z_m = time dependent height of mixture interface.

In a similar fashion, an expression for mixture density can be written as:

$$\rho_{mix} = e \frac{z}{z_m} + f \tag{129}$$

where

e,f = time dependent slope and intercept coefficients.

Steam can be added to a volume either through a junction or by flashing of liquid within the mixture. The rate of change of entrained steam

within the liquid region of a volume equals the total rate of change of steam within the volume, less the new flux of steam out of the steam dome, less the mass flow of steam bubbles out of the mixture. In differential equation form, the mass balance of the entrained steam within a given control volume is:

$$\dot{M}_{g_b} = \dot{M}_s - \sum_i \Psi_i X_i W_i - A\, V_{bub}\, (\rho_{g_b})_{z_m} \qquad (130)$$

where

$\dot{M}_{g_b}$ = mass of gas bubbles entrained in the mixture

$\dot{M}_s$ = total mass of steam within the volume

Ψ_i = fraction of steam flowing at the junction and terminating or originating within the steam dome

X_i = junction quality

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

A = cross-sectional area of the volume

V_{bub} = bubble velocity relative to the mixture interface

$(\rho_{g_b})_{z_m}$ = gas bubble density at the mixture interface.

The bubble density gradient, Equation (128), and the bubble mass balance, Equation (130), are solved by the program to yield the mass of steam entrained within the mixture region of a modeled volume.

The RELAP4 user may designate the bubble density gradient by entering a value for C_o as ALPH on the Bubble Data Card as outlined in Volume II, Subsection 4.2.2 (18). Utilizing C_o, Equation (128) has the following relationships for the general slope a and intercept b:

$$a = 2C_o\left(\frac{M_{g_b}}{V_m}\right) \tag{131}$$

$$b = (1-C_o)\frac{M_{g_b}}{V_m} \tag{132}$$

for

$$0 < \frac{M_{g_b}}{\rho_g V_m} \leq 0.5$$

and

$$a = 2\,C_o\,(\rho_g - \frac{M_{g_b}}{V_m}) \tag{133}$$

$$b = (1 + C_o)\frac{M_{g_b}}{V_m} - C_o\rho_g \tag{134}$$

for

$$0.5 \leq \frac{M_{g_b}}{\rho_g V_m} \leq 1.0$$

where

ρ_g = vapor density

V_m = mixture volume (mixture contains all liquid in the volume plus the bubble mass M_{g_b}).

Similar expressions have been used to compute the general slope and intercept coefficients e and f in the mixture density Equation (129).

The constant C_o, which must be limited to values between zero and one, determines the mixture and bubble density gradients at any instant in time. Figures 20 and 21 show the effect of C_o and of average mixture void fraction on the mixture bubble density gradient. If the input variable ALPH or C_o is set equal to zero, the mixture is considered to be homogeneous. If it is set equal to one, the bubble density gradient is a maximum within the following constraints:

$$\int_o^{Z_M} \rho_{g_b} \, dz = \frac{M_{g_b}}{A} \tag{135}$$

where

$0 < \rho_{g_b} < \rho_g$ at any elevation.

Within RELAP, each volume may have its own C_o as specified by the user. Small volumes with high mass flow rates, such as core channels or pipe

sections during large break transients, are best described by the homogeneous model. In plenums, tanks, or components where separated flow may be expected, values of C_o between 0.8 and 1.0 are recommended.

The last term in Equation (130) contains the variable V_{bub} which is the velocity of the vapor relative to the mixture interface. This is entered as VBUB on the Bubble Data Cards and can be different for each volume modeled.

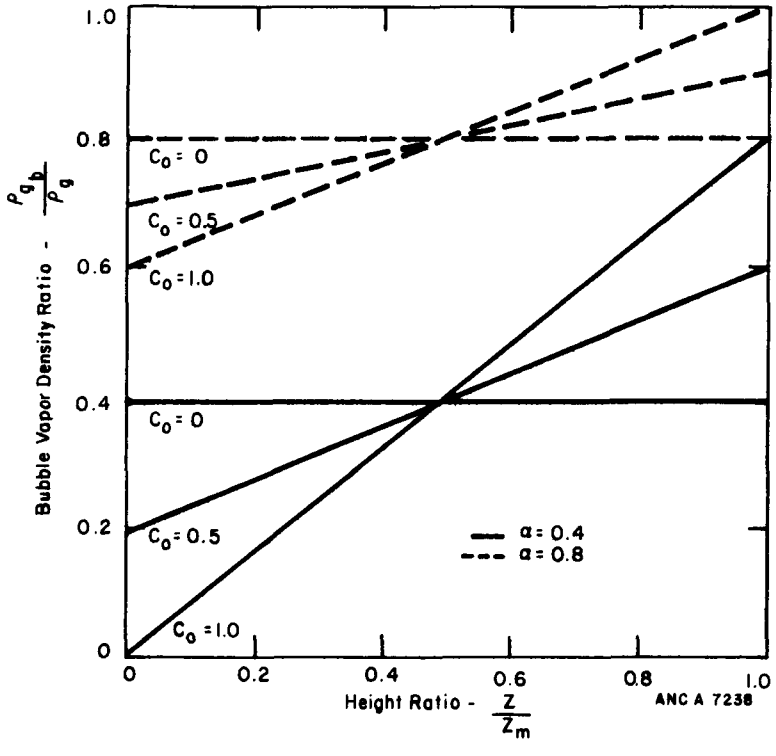


Fig. 20 Effect of C_o on bubble density gradient for $\alpha = 0.4$ and $\alpha = 0.8$.

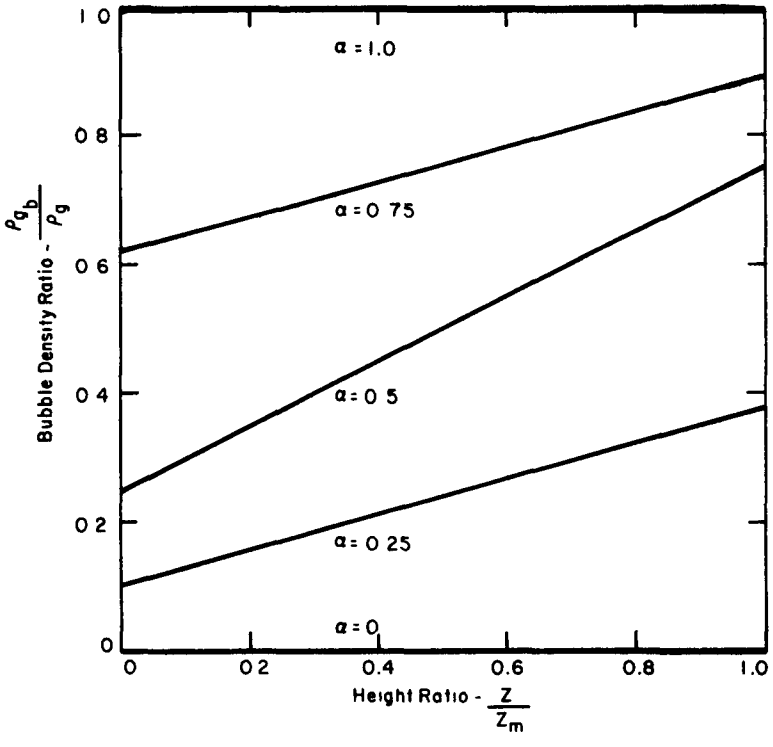


Fig. 21 Effect of void fraction on bubble density gradient for C_o = 0.5.

Depending on the magnitude of V_{bub}, a mixture level between the collapsed liquid level and the top of a volume can be computed. That is, for a V_{bub} = 0.0, no separation will occur and the mixture level equals the volume height. A gradient C_o can still be specified, however. To achieve nearly complete separation of the liquid and vapor phases within a volume, a value of $V_{bub} = 10^6$ should be used. Typical values of V_{bub} from 0.5 to 3.0 can be used to achieve separation that is physically realistic during decompression transients at high pressures. Higher bubble rise velocities should be used at low pressures. It should be noted that for volume mass fluxes exceeding 2×10^6 lb/hr-ft^2, the Bubble Rise Model will be overridden. The volume thus will be made homogeneous and mixture level full.

(2) Local Quality Calculation for Use in Heat Transfer.

The presence of a mixture level within a reactor core brings about a discontinuity in the heat transfer coefficient at the mixture-steam interface. This model attempts to improve the local heat transfer calculations in the vicinity of that mixture level. In the calculation of slab heat transfer coefficients, the average volume conditions including quality are used in the various correlations. In this option, a local fluid quality $\bar{X}$ based on the volume bubble rise model is computed for each heat slab. The quality is determined taking the ratio of the total vapor weight to the total mixture weight. For the slab that contains the vapor-mixture interface, the bubble rise model quality is integrated between the bottom of the slab to the mixture level as follows:

$$\bar{X}_{LOCAL} = \frac{A\int_{Z_{BOT}}^{Z_{TOP}} \rho_{g_b} dz}{A\int_{Z_{BOT}}^{Z_{TOP}} \rho_{MIX} dz} \qquad (136)$$

where

A = cross-sectional area

Z_{TOP} = top of heat slab in question

Z_{BOT} = bottom of heat slab in question.

The result of the Equation (136) ratio[a] is simplified by canceling the area terms A. A quality of 1.0 is assumed for the portion of the slab above the mixture level. An average slab quality is then computed. Since the selection of the heat transfer regime is quality dependent, adjacent heat slabs in the same fluid volume may be in different regimes.

The fluid volumes of interest must have a bubble rise model specified in order to use the local quality calculation. Multiple heat slabs can be specified within a single fluid volume. Non-zero values must, however, be entered on the Heat Slab Data Cards outlined in Volume II, Subsection 4.2.2 (51) for the following:

(1) IXLO - Indicator for side(s) of Heat Slab to receive quality calculations

(2) ZBOT - Elevation of Heat Slab bottom above the volume bottom

(3) ZTOP - Elevation of Heat Slab top above volume bottom.

(3) Computation of Single Mixture Level In Vertically Stacked Volumes. The bubble rise model can be used in a single control volume to account for the separation of a vapor phase from a mixture of vapor and saturated liquid. If this model is used indiscriminately in a series of connected control volumes representing vertical sections such as a core or steam generator, unrealistic vapor-mixture layering can occur.

To compute a single mixture level in a vertical stack of volumes thereby nearly eliminating vapor mixture layering, the user must:

(1) Identify the stack using the IAMBLO input quantity on the Volume Data Card, as outlined in Volume II, Subsection 4.2.2 (11).

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[a] A more detailed presentation of the Equation (136) integration is given in Section 3.4.9.

(2) Specify vertical slip at all junctions between volumes in the vertical stack by input SRCOS > 0.0 on the Junction Data Card as outlined in Volume II, Subsection 4.2.2 (21).

(3) Specify a bubble rise velocity VBUB > 0.0 on the Bubble Data Cards as outlined in Volume II, Subsection 4.2.2 (18) for each volume in the vertical stack. A value of 0.0 for ALPH (ie., homogeneous mixture) on the Bubble Data Cards is recommended for all volumes in the vertical stack.

If the above procedure is followed, the program will compute a mixture level in the uppermost two-phase volume in the stack. The remaining volumes below the mixture level will be assumed homogeneous and mixture full.

In general, IAMBLO should be used between vertically stacked volumes which have similar flow areas for relatively slow transients with small inertia effects. IAMBLO should not be used if a flow restriction or large area change occurs between vertically stacked volumes such as between a downcomer and lower plenum. In the latter situation, the vertical slip model and bubble rise models may still be considered, as vapor-mixture layering may be a reasonable assumption.

(4) Explanation of Junction Modeling Option. Thermodynamic properties at a junction may be calculated by modeling a junction as having a point vertical height such as is usually true for vertically stacked control volumes. Horizontal flow junctions may be modeled as a circular area distributed vertically. If 0 is entered for JVERTL on the Junction Data Cards outlined in Subsection 4.2.2 (21), the junction is assumed to have a point value with respect to the bubble distribution in the control volume supplying the junction flow and the junction properties are "smoothed". If 1 is entered for JVERTL, the junction is assumed to have a circular area with the diameter (DIAMJ) distributed vertically. If 2 is entered for JVERTL, the junction is assumed to have no vertical distribution and the junction properties are not "smoothed".

Smoothing of junction properties (density, quality, and enthalpy with JVERTL = 0) is applicable only when steam separation is permitted and when the mixture level is near the junction elevation entered for ZJUN on the Junction Data Cards. Under these conditions and when the junction lies within the steam dome, the total mass extracted from the volume during a single time step ($W_i \Delta t$) is assumed to originate in the steam region between the junction elevation ZJUN and the mixture-interface height. If the required mass extraction exceeds the mass content of this steam region, the difference is extracted from the mixture rather than overextracting steam from the steam dome. This model assumes that the mixture level swells to the junction elevation during the time step advancement. In effect, this model attempts to maintain constant volumetric flow through a junction thereby accounting for density discontinuities brought about by the presence of a mixture level.

When junctions are used as vertically distributed areas (JVERTL = 1), junction properties are determined by integrating the bubble-distribution function over the circular area with the diameter entered for DIAMJ.

When 2 is entered for JVERTL, junction properties are defined by the phase that is currently present at the junction elevation. With this option, the fluid present at the junction is not "smoothed" and may possibly oscillate each time advancement between pure liquid and pure vapor. If this happens, the oscillatory behavior could lead to increased running time.

(5) Liquid Level Calculation. A conglomerate volume combining up to 20 of the RELAP4 volumes may be specified for the purpose of obtaining an equivalent liquid level. This option is accessed by entering the desired volume index numbers for ILVC(i) on the Liquid Level Volume Calculation Card as outlined in Volume II, Subsection 4.2.2 (12). The order of the RELAP4 volumes used to describe the conglomerate volume is arbitrary except that the first RELAP4 volume becomes the reference volume. The total liquid mass in the conglomerate

volume is obtained by summing the liquid mass in each of the RELAP4 volumes. A total liquid volume is obtained by dividing the total liquid mass by the density of saturated liquid in the reference volume. The level the total liquid volume would reach in the conglomerate is then calculated. Finally, the liquid level in the conglomerate volume is compared to the elevation of the bottom of the reference volume and the result printed for each major edit. This option is useful in determining the beginning of core reflooding.

3.6.7 Water Packing, Choking Smoothing, Liquid Mass Depletion and Mixture Level Crossing from Above. Difficulty was encountered with use of earlier RELAP4 versions due to the appearance of anomalous pressure spikes and oscillations in the output data. Rapid changes in calculated state variables cause shorter time steps during program execution. This results in added total processing time. The following subsections outline changes in the program and various options to the user to reduce spurious data spikes or oscillation.

(1) The Water Packing Option. "Water Packing" is used to describe the difficulty which may occur in a RELAP4-modeled problem when the conditions in a volume change from a compressible state to an essentially incompressible state and there is simultaneously a net influx of mass into the volume. If a water packing correction is not applied, a fictitious pressure spike of considerable magnitude may occur. The program then responds by greatly descreasing the time step size and increasing the running time.

Consider the simple case in which subcooled water is entering a steam filled tank or pipe which is nodalized into two volumes. A water packing problem may occur in the lower volume when the water level reaches the arbitrary boundary between the two volumes. Steam may be forced out of the lower volume due to incoming water or may be flowing into the lower volume due to decompression caused by the condensation of the steam by the cooler water. If the junction flow is not instantaneously changed to allow an amount of water equal to the entry flow to

exit into the upper volume, the undesired pressure spike will occur. The framework of the RELAP4 conservation equation solution requires the junction inertia to represent an integral quantity from the center of one volume to the center of the other volume. This inertia thus prevents the needed instantaneous change of flow.

The method of determining the magnitude of the desired flow at the time step at which water packing occurs is to set dm/dt equal to zero. This would have to be the case if the fluid were truly imcompressible. However, adjusting the flow at the end of the time step would be an insufficient solution since a pressure spike would already have occurred during the time step. This pressure spike would be in proportion to the time step size. Due to incompressibility of subcooled water, however, it would be significant even at the very small time steps calculated by the saturation line crossing time step control.

The amount of mass which caused the increase in pressure above the saturation pressure is backed out of the following equation to prevent an incorrect pressure at the end of the time step at which water packing occurs.

$$\Delta P = \frac{\partial P}{\partial U}\Big|_M \Delta U + \frac{\partial P}{\partial M}\Big|_U \Delta M \qquad (137)$$

where

$$U = h_f \Delta M \qquad (138)$$

$$\Delta P = P_{new} - P_{sat} \qquad (139)$$

and where

ΔP = the increase in pressure above the saturation pressure

P_{new} = the pressure calculated at the end of the time step

P_{sat} = the saturation pressure

ΔM = the amount of mass causing the pressure rise above the saturation pressure

ΔU = the total volume internal energy associated with ΔM

h_f = the saturated liquid specific enthalpy for the volume.

These equations are inaccurate using the saturation properties at the originally calculated (bad) pressure. The program thus will iterate over the water packing subroutine and steam table calls until the pressure spike is reduced to slightly over the saturation pressure.

The excess flow is redistributed on an incremental basis for all incoming and outgoing flows associated with compressible volumes. That is, the change in flow needed to get dm/dt equal to zero is added to the original flow. The incremental method has the effect of minimizing the aberration in the conservation of momentum for the occasional time step at which the water packing correction is applied.

The method of distributing the adjustable flow is on an area times specific volume basis. The reason for the area factor is obvious. The specific volume factor is used because it is easier to reverse or accelerate the junction flow into a volume containing high specific volume fluid than into one containing a low specific volume fluid.

The mass and its associated energy are redistributed in the same manner as the flows to adjacent volumes. Water hammer effects are not excluded since the water packing adjustment is made only when the saturation line is being crossed and then only if there is at least one adjacent compressible volume. Water hammer effects can be expected in small diameter dead end volumes. RELAP4 will slow down greatly in order to follow the hydrodynamic effects of such legitimate pressure spikes.

The program input allows the user to delay the starting time at which the water packing correction is applied. The ability to turn off the water packing correction is obtained by an excessively late start. The use of the default value of zero (which applies the water packing fix throughout the problem) is recommended. The user can observe how often the water packing correction is being applied by requesting a significant number of water packing edits per volume. This edit will print each iteration of each occurence of water packing in each volume up to the maximum number of occurrences specified, showing old and new flows and enthalpies. The above options are specified on the Water Packing and Choking Smoothing Card outlined in Volume II, Subsection 4.3.3 (8).

(2) Choking Smoothing Option. A so-called "choking smoothing" option is available to reduce oscillations in and out of choking. When the flow is near the choked flow value and the volume conditions are near the saturation line, a discontinuity in the calculation of the rate of change of flow with respect to time (dw/dt) can cause pressure oscillations. The discontinuity is due to the calculation of dw/dt for unchoked flow by the momentum equation and the choked flow value as the ratio of the critical flow value minus the previous flow value over the time step size. The critical flow value for the new time step and the previous flow value do not necessarily approach each other as the time step size approaches the minimum. Thus, dw/dt can get too large, causing oscillations. The correction is applied by limiting the minimum size of the dt used for the dw/dt calculation when the oscillation and resultant running time problem exists. This problem can occur when the upstream volume conditions are near the saturation line.

The use of the Water Packing and Choking Smoothing Card allows the user to start the application of choking smoothing at any transient time. Default results in the choking smoothing option being operated throughout the problem.

(3) Liquid Mass Depletion and Mixture Level Crossing from Above. This model computes the correct net junction mass flow and liquid and the vapor component mass fluxes during the time step in which a mixture level drops through a junction. Similarly, the model will compute the liquid component flows out of a volume for which VBUB is entered as 0.0 on the Bubble Data Cards and for which depletion of liquid mass is calculated to occur. The junction flow calculation performed by this model overrides the net junction flows computed by the simultaneous solution of the conservation equations for the time step in which the model is activated. The junction flow calculation performed by the model will prevent the over-extraction of liquid mass and energy from a modeled volume thereby eliminating the physically unreal volume superheating, pressure spikes, and mixture level fluctuation that may otherwise occur.

The Liquid Mass Depletion and Mixture Level Crossing from above model can be activated at the beginning of a run or during restart by use of the Mixture Level Smoothing Card outlined in Volume II, Subsection 4.2.2 (9). The maximum number of edits indicating that the model has been applied as well as the starting time to activate the model are placed on the card.

The model should be used only if required due to the probability of superheating, mixture level crossing problems, or indication that the liquid mass depletion control is governing the time step. The liquid mass depletion time step control which is normally used will be bypassed when the model is activated. The model has proved to be of value in the analyses of small break transients when the vertical slip model and the bubble rise model are used to track a single mixture level in a reactor core.

3.6.8 Critical Flow Models. The depressurization rate for any system is dependent upon the rate of mass depletion. The speed with which a vessel or system can be emptied is, in turn, determined by the rate of fluid flow through breaks or openings in the structure. Critical flow governs the rate at which fluid will be discharged from a system during most of a depressurization and, consequently, it largely controls the time of blowdown.

Experience has shown that the simple momentum equation for inertial flow rate is quite accurate at relatively low flows but becomes greatly exaggerated as junction pressure ratio increases and critical conditions are approached. Critical flow criteria are therefore invoked to limit the flow rate through an opening or junction to a more realistic level under these circumstances. Thus, RELAP4 logic has been written so that no matter what critical flow model is selected, a comparison with inertial flow is always effected and the minimum flow rate selected as shown by Figure 22.

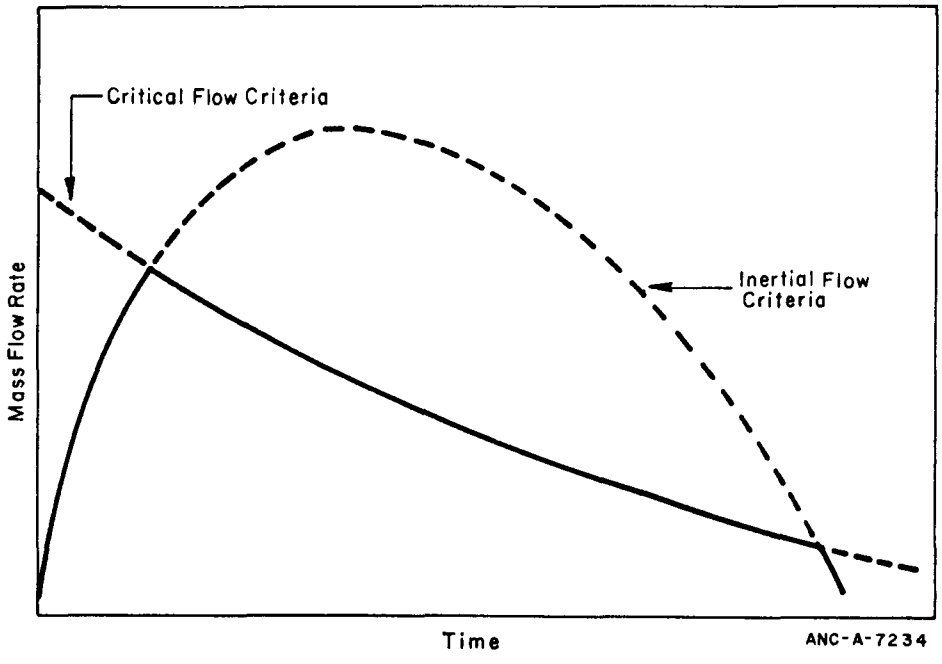

Fig. 22 RELAP4 junction mass flow rate selection.

This is done to ensure that, under both low and high junction pressure ratio conditions, the most realistic junction flow rate will be calculated.

Several junction flow models have been incorporated into RELAP4/MOD5. Numbered among these are:

(1) The Simple Momentum or Inertial Flow Model

(2) A Sonic Critical Flow Model

(3) The Moody Critical Flow Model[51]

(4) The Henry-Fauske Critical Flow Model[52]

(5) The Homogeneous Equilibrium Critical Flow Model[53]

as well as many variations and combinations of the foregoing. The complete matrix of available flow-critical flow models included in RELAP4/MOD5 has been cataloged in Table V. Also in this table is the information required to access each model or combination listed. This is accomplished by specifying the proper ICHOKE-JCHOKE combination (I-J in Table V) on the Junction Data Card outlined in Volume II, Subsection 4.2.2 (21).

The method of junction flow rate solution can best be described as implicit in that a flow rate estimate (inertial or critical depending upon local conditions) is computed for the current time step and appropriate terms of the momentum equation (i.e., friction, acceleration). It is then adjusted to force the actual flow rate into convergence with the estimated value. Securing accurate flow rate estimates is the object of the various flow and critical-flow models to be described.

(1) Inertial Flow. Junction flow can be restricted to that calculated from momentum considerations by specifying JCHOKE equal to a

TABLE V

CRITICAL FLOW MODELS, COMBINATIONS, AND CALLING SEQUENCES

I \ J	-1	0#	1	2	3	4	5
-4	IN	S in SUB Min(M,HF) in SAT	IN in SUB Min(M,HF) in SAT	S	MM-HEM	S in SUB HEM in SAT	HF-HEM
-3		S in SUB Max(M,HF) in SAT	IN in SUB Max(M,HF) in SAT				
-2		S in SUB HF in SAT	IN in SUB HF in SAT				
-1		S in SUB M in SAT	IN in SUB M in SAT				
0		S in SUB Max(M,HF) in SAT	IN in SUB Max(M,HF) in SAT				
1		M*					
2		HF*					
3		Max (M,HF)*					
4		Min (M,HF)*					
10		HF in SUB Max (M,HF) in SAT				HEM	
11#		HF in SUB M in SAT					
12		HF					
13		HF in SUB Max (M,HF) in SAT					
14		HF in SUB Min (M,HF) in SAT					

IN Inertial or Momentum Flow Model
S Sonic Critical Flow Model
M Moody Critical Flow Model
HF Henry-Fauske Critical Flow Model
HEM Homogeneous Equilibrium Critical Flow Model
MM Modified Momentum Critical Flow Model

I ICHOKE (Junction Data Card 08XXXY)
J JCHOKE (Junction Data Card 08XXXY)
Max Maximum
Min Minimum
SAT Saturated Regime
SUB Subcooled Regime

* The model at zero quality is used in the subcooled regime.

Evaluation Model critical flow criterion

negative number (-1 in Table V) with ICHOKE arbitrary, or JCHOKE equal to 2 with ICHOKE greater than or equal to 11 on the Junction Data Card. Under these conditions the current time step junction flow rate is not estimated but simply computed through the normal simultaneous solution of the continuity, momentum, and energy equations detailed in Section 3.3. No adjustments are made to any of the terms in the momentum equation and no limits are placed upon the flow rate that can be achieved through any junction.

For all other ICHOKE-JCHOKE combinations, the calculation of a momentum or inertial junction flow rate estimate is standard procedure. It is obtained from the following linearized expression, derived from the integrated form of the momentum equation:

$$\dot{W}_{t+\Delta t} = \dot{W}_t + (\Delta p - F \dot{W}_t^2) \frac{\Delta t \, g_c}{I} \qquad (140)$$

where

F = lumped parameter accounting for junction friction and momentum changes

I = junction inertia

Δp = junction pressure differential

Δt = time step size

$\dot{W}$ = junction flow rate

and with subscript denotation:

t = time at any particular time step

$t+\Delta t$ = time at following time step.

This estimate is then compared with that for the particular critical flow model specified and the minimum identified. The fluid acceleration and junction friction required to force the actual flow rate to the minimum estimate is determined and the appropriate terms in the momentum equation modified before simultaneous solution of the continuity, energy and momentum equations.

(2) Critical Flow. The flow rate through a duct or opening becomes a maximum or the critical value when reduction of downstream pressure no longer causes an increase in this flow rate for given upstream conditions and duct or exit geometry. In this way, a limit is imposed upon the amount of fluid that can pass through any junction. What the realistic limit is, is not agreed upon which is the primary reason a number of analytical critical flow models have been included in RELAP/MOD5.

(a) Sonic Model: Two-Component System. The volumes used to model a reactor system are allowed to contain air. Examples include the air space in the accumulator and the compartments in the containment. The containment option (ISPROG equal to 3 on Problem Dimensions Data Card) must be specified if this air is to be permitted to pass through a junction. If this is the case and air is the only component in the upstream volume, then the critical velocity through the junction is given by the familiar expression for isentropic critical speed

$$a^2 = \gamma g_c RT \tag{141}$$

where

a = critical or sonic velocity

R = gas constant

T = temperature

γ = ratio of specific heat capacities.

The values of these parameters are based upon upstream volume conditions. If the upstream volume contains an air-steam-water mixture, then the critical junction velocity is:

$$a^2 = \left[X_s v_s + (1-X_a-X_s)v_\ell\right]^2 g_c T (p'_s)^2 \Big/ \Big\{-X_a v_a T p'_s \beta_a - (1-X_a-X_s)\, T'_s v_\ell (\beta_\ell - p'_s K_\ell) + \Big[X_s p'_s (C_{p_s} J + T p'_s v_s (-2\beta_s + K_s p'_s)) + X_a p'_s (C_{p_a} J + T p'_s v_a b_a) + (1-X_a-X_s) p'_s (C_{p_\ell} J - T p'_s v_\ell \beta_\ell)\Big] (\partial T/\partial p)_S\Big\} \quad (142)$$

where

C_p = specific heat capacity at constant pressure

J = mechanical equivalent of heat energy

K = coefficient of isothermal compressibility

p = pressure

v = specific volume

X = mass fraction (quality in one-component systems)

β = coefficient of isobaric thermal expansion

and with the subscript denotation

a = air

ℓ = liquid

s = steam

S = isentropic.

The superscript, ′, signifies the derivative of vapor pressure with respect to temperature. Again, the independent variables in Equation (142) are based upon upstream volume conditions. If the upstream volume contains only superheated steam and air, then the critical junction velocity is denoted by the relation:

$$a^2 = \left. \frac{g_c v}{K - \frac{Tv\beta^2}{C_p J}} \right|_{mix} \tag{143}$$

with

$$v_{mix} = \frac{V}{M_a + M_s} \tag{144}$$

$$K_{mix} = \frac{M_s K_s + \frac{M_a}{p_a}}{M_s + M_a} \tag{145}$$

$$\beta_{mix} = \frac{\frac{M_a}{T} + M_s \beta_s}{M_a + M_s} \tag{146}$$

and

$$C_{p_{mix}} = \frac{M_a C_{p_a} + M_s C_{p_s}}{M_a + M_s} \tag{147}$$

where

M = mass

V = volume

and the subscript denotation

mix = mixture.

Once again, emphasis should be placed upon the fact that the input parameters to these equations are dependent upon the state of the upstream volume.

The critical mass flow estimate through the junction is calculated from the familiar one-dimensional continuity equation

$$\dot{W} = \rho A a \tag{148}$$

where

A = junction area

ρ = mass density.

The density is that for the upstream volume, adjusted for the frictional loss and kinetic energy change to the junction. The fluid is then expanded isentropically from the Mach number just upstream from the junction to that in the junction, which is Mach one, when sonically choked. This junction density is that used in Equation (148).

Note should be taken of what "upstream volume conditions" implies. The steam tables are entered with upstream volume specific internal energy and specific volume as the independent variables. All other volume parameters, including pressure and sonic velocity, are dependent upon these two quantities. The air in the system is presumed to be a perfect gas, however, and its properties are assumed to be constant. The result is that volume critical velocities are calculated and then impressed upon the local downstream junction.

The two-component (air-steam/water) critical velocity or sonic model equations are accessed by entering 3 for ISPROG on the Problem Dimensions Date Card as outlined in Volume II, Subsection 4.2.2 (2). JCHOKE must be set equal to 2 and ICHOKE less than 10 on the Junction Data Card.

(b) Sonic Model: One-Component System. The one-component sonic velocity equation applies if the system under consideration contains only water or if the air in the system is not allowed to pass through any junction. Starting with the air-steam-water sonic velocity equation (Equation 142), the limit is taken as the mass fraction of air, X_a, goes to zero. The sonic velocity in a steam-water mixture is obtained as follows:

$$a^2 = \left[X_s v_s + (1-X_s)\, v_\ell\right]^2 g_c T(p_s^`)^2 \Big/ \left\{X_s \left[C_{p_s} J + T p_s^` v_s (-2\beta_s + p_s^` K_s)\right]\right.$$

$$\left. + (1-X_s) \left[C_{p_\ell} J + T p_s^` v_\ell (-2\beta_\ell + p_s^` K_\ell)\right]\right\}. \qquad (149)$$

As in a two-component system, the critical mass flow estimate through the junction is calculated from the equation for one-dimensional continuity shown as Equation (148). The comments of the previous subsection regarding the significance of "upstream volume conditions" also apply. This critical flow model is accessed by entering 2 for JCHOKE and a number less than 10 for ICHOKE on the Junction Data Card as outlined in Volume II, Subsection 4.2.2 (21). The Problem Dimensions Data Card must have a 0, 1, or 2 entered for ISPROG.

(c) Moody Model. The Moody analysis[51] is based upon an annular, two-phase, one-dimensional, flow model with uniform axial velocity of each phase and thermodynamic equilibrium between the phases. Additional assumptions are:

(1) Both phases experience the same local static pressure

(2) The flow is isentropic from entrance to exit, hence stagnation enthalpy is constant throughout the system

(3) The liquid phase is incompressible.

An equation for mass flux can be derived by combining the following:

(1) The energy equation derived from the reversible First and Second Law

(2) The momentum equation neglecting frictional and gravitational effects

(3) The definition of quality

(4) The definition of mixture specific enthalpy

(5) The definition of void fraction formulated with mixture specific volume, quality and slip ratio.

The equation is as follows:

$$G(P,k) = \left[\frac{2\left[h_0 - h_L - \frac{h_{VL}}{s_{VL}}(s_0 - s_L)\right] g_c J}{\left[\frac{k(s_V - s_0)\, v_L}{s_{VL}} + \frac{(s_0 - s_L)\, v_V}{s_{VL}}^2\right]\left[\frac{s_0 - s_L}{s_{VL}} + \frac{s_V - s_0}{k^2 s_{VL}}\right]} \right]^{1/2} \quad (150)$$

where

G = mass flux

h = specific enthalpy

k = vapor/liquid velocity or slip ratio

s = specific entropy

and with subscripts denotation

L = liquid

0 = stagnation

V = vapor

VL = vapor minus liquid.

Equation (150) is a function of pressure and slip ratio if stagnation enthalpy and entropy are known. Assuming that slip ratio and pressure are independent, then

$$\left.\frac{\partial G}{\partial k}\right|_p = 0 \tag{151}$$

and

$$\left.\frac{\partial G}{\partial p}\right|_k = 0 \tag{152}$$

at the point that mass flux is a maximum or is critical. Applying the first criterion reveals that

$$k = \left(\frac{v_v}{v_L}\right)^{1/3} \tag{153}$$

at critical conditions. Substituting the value for k from Equation (153) into Equation (150) and applying the second criterion, the critical flow tables listed as Table VI can be generated.

The Moody Critical Flow Tables are constructed to reflect critical mass flux versus the upstream volume stagnation pressure and enthalpy in the saturated regime. In practice, however, they are entered with upstream volume pressure (static or stagnation, depending upon selected options) and junction enthalpy (again, static or stagnation depending upon options). This difference between table composition and usage should be borne in mind during problem definition and execution. The Table VI format is as follows. There are 21 groups of mass flux-stagnation enthalpy values. Each group is headed by a stagnation absolute pressure value which follows the symbol DATA GO(I)/. Following this pressure and reading from left to right are a total of 17 pairs of mass flux-stagnation enthalpy values for each of 21 stagnation pressure entrys. The format for Tables VII, VIII, and IX, describing the Henry-Fauske and HEM values, are similar to that of Table VI.

The Moody model is strictly applicable only in the saturated region, a regime generally encountered at lower system pressures. Accordingly, it should be used in conjunction with other critical flow models that are appropriate to the subcooled domain. A number of combinations are available. These are listed, along with their calling sequences, in Table V. In particular, the Moody model may be called with the inertial flow model in the subcooled region (JCHOKE = 1, ICHOKE = -1) or the Henry-Fauske model in the subcooled region (JCHOKE = 0 or 1, ICHOKE = 11) by entering the indicated ICHOKE-JCHOKE combination on the Junction Data Card.

(d) Henry-Fauske Model. The significant features of the Henry-Fauske[52] critical flow model are:

(1) It can handle stagnation conditions ranging from subcooled liquid to superheated vapor

(2) It treats the expansion in the low quality region as a non-equilibrium process.

TABLE VI

MOODY CRITICAL MODEL FLOW TABLES

```
      BLOCK DATA                                                                DATB0010
      IMPLICIT REAL*8 (A-H,O-Z)                                                 DATB0020
C                                                                               DATB0030
      COMMON / LEAKC / G01(35), G02(35), G03(35), G04(35), G05(35),             DATB0040
     1         G06(35), G07(35), G08(35), G09(35), G10(35), G11(35),            DATB0050
     2         G12(35), G13(35), G14(35), G15(35), G16(35), G17(35),            DATB0060
     3         G18(35), G19(35), G20(35), G21(35), NG, NPI                      DATB0070
C                                                                               DATB0130
C     CRITICAL FLOW TABLES                                                      DATB0140
C                                                                               DATB0150
C     GXX(1)      = STAGNATION PRESSURE  (PSIA)                                 DATB0160
C     GXX(EVEN)   = MAXIMUM FLOW RATE  (LBM/FT**2-SEC)                          DATB0170
C     GXX(ODD)    = STAGNATION ENTHALPY  (BTU/LB)                               DATB0180
C                                                                               DATB0190
C     NG     = NUMBER OF PAIRS OF FLOW AND ENTHALPY VALUES PER PRESSURE         DATB0200
C     NPI    = NUMBER OF PRESSURE VALUES                                        DATB0210
C                                                                               DATB0220
      DATA  NG, NPI / 17, 21 /                                                  DATB0230
C                                                                               DATB0240
      DATA G01 /      1.0D0,  214.71D0,  69.733D0,   20.11D0, 173.340D0,DATB0250
     1   10.95D0, 276.948D0,    7.54D0, 380.555D0,    5.76D0, 484.163D0,DATB0260
     2    4.65D0, 587.771D0,    3.91D0, 691.378D0,    3.37D0, 794.986D0,DATB0270
     3    2.96D0, 898.593D0,    2.64D0,1002.201D0,    2.38D0,1105.809D0,DATB0280
     4    2.50D0,1112.678D0,    2.00D0,1238.828D0,    1.80D0,1369.999D0,DATB0290
     5    1.60D0,1507.606D0,    1.40D0,1652.162D0,    1.30D0,1803.545D0/DATB0300
      DATA G02 /      5.0D0,  527.49D0,  130.196D0,   90.72D0,  230.286D0,DATB0310
     1   50.86D0, 330.376D0,   35.44D0, 430.465D0,   27.21D0, 530.555D0,DATB0320
     2   22.09D0, 630.645D0,   18.60D0, 730.734D0,   16.06D0, 830.824D0,DATB0330
     3   14.13D0, 930.913D0,   12.62D0,1031.003D0,   11.39D0,1131.093D0,DATB0340
     4   11.70D0,1142.565D0,    9.80D0,1264.479D0,    8.60D0,1390.263D0,DATB0350
     5    7.70D0,1521.800D0,    7.10D0,1659.584D0,    6.60D0,1803.492D0/DATB0360
      DATA G03 /     10.0D0,  767.75D0,  161.261D0,  171.18D0,  259.470D0,DATB0370
     1   97.76D0, 357.678D0,   68.64D0, 455.887D0,   52.93D0, 554.096D0,DATB0380
     2   43.09D0, 652.305D0,   36.34D0,750.513D0,   31.42D0,  848.722D0,DATB0390
     3   27.67D0, 946.931D0,   24.73D0,1045.140D0,   22.35D0,1143.348D0,DATB0400
     4   22.90D0,1157.466D0,   19.30D0,1277.542D0,   17.10D0,1400.619D0,DATB0410
     5   15.40D0,1529.045D0,   14.20D0,1663.351D0,   13.10D0,1803.425D0/DATB0420
      DATA G04 /     14.7D0,  943.01D0,  180.179D0,  242.34D0,  277.210D0,DATB0430
     1  140.17D0, 374.240D0,   98.93D0, 471.270D0,   76.51D0, 568.300D0,DATB0440
     2   62.40D0, 665.331D0,   52.69D0, 762.361D0,   45.60D0, 859.391D0,DATB0450
     3   40.19D0, 956.421D0,   35.93D0,1053.452D0,   32.49D0,1150.482D0,DATB0460
     4   33.10D0,1166.3770D0,  28.20D0,1258.449D0,   24.90D0,1406.903D0,DATB0470
     5   22.60D0,1533.437D0,   20.80D0,1665.624D0,   19.30D0,1803.363D0/DATB0480
      DATA G05 /     50.0D0, 1787.76D0,  250.212D0,  706.24D0,  342.600D0,DATB0490
     1  432.14D0, 434.988D0,  312.25D0, 527.376D0,  244.68D0,  619.764D0,DATB0500
     2  201.24D0, 712.153D0,  170.93D0, 804.541D0,  148.58D0,  896.929D0,DATB0510
     3  131.40D0, 989.317D0,  117.79D0,1081.705D0,  106.74D0,1174.093D0,DATB0520
     4  107.50D0,1196.581D0,   92.90D0,1312.998D0,   83.20D0,1428.913D0,DATB0530
     5   76.00D0,1548.789D0,   70.40D0,1673.458D0,   65.80D0,1802.893D0/DATB0540
      DATA G06 /    100.0D0, 2546.50D0,  298.538D0, 1252.95D0,  387.401D0,DATB0550
```

TABLE VI (contd.)

```
51          1  802.83D0, 476.264D0,  591.90D0, 565.127D0,  469.15D0, 653.989D0,DATB0560
52          2  388.73D0, 742.852D0,  331.92D0, 831.715D0,  289.63D0, 920.578D0,DATB0570
53          3  256.92D0,1009.440D0,  230.86D0,1098.303D0,  209.60D0,1187.166D0,DATB0580
54          4  209.20D0,1214.890D0,  182.30D0,1330.371D0,  164.50D0,1442.897D0,DATB0590
55          5  151.10D0,1558.489D0,  140.30D0,1678.248D0,  131.60D0,1802.229D0/DATB0600
56           DATA G07 /    200.0D0, 3608.16D0, 355.506D0, 2153.39D0, 439.789D0,DATB0610
57          1 1463.65D0, 524.071D0, 1108.91D0, 608.354D0,  893.05D0, 692.637D0,DATB0620
58          2  747.78D0, 776.920D0,  643.27D0, 861.202D0,  564.45D0, 945.485D0,DATB0630
59          3  502.88D0,1029.768D0,  453.44D0,1114.051D0,  412.87D0,1198.334D0,DATB0640
60          4  407.00D0,1234.101D0,  357.60D0,1349.174D0,  325.00D0,1458.103D0,DATB0650
61          5  300.00D0,1568.929D0,  279.90D0,1683.135D0,  263.30D0,1800.900D0/DATB0660
62           DATA G08 /    400.0D0, 5384.55D0, 424.167D0, 3560.62D0, 502.210D0,DATB0670
63          1 2601.91D0, 580.252D0, 2044.87D0, 658.294D0, 1683.97D0, 736.337D0,DATB0680
64          2 1413.45D0, 814.379D0, 1244.89D0, 892.421D0, 1101.42D0, 970.464D0,DATB0690
65          3  987.66D0,1048.506D0,  895.23D0,1126.548D0,  818.64D0,1204.591D0,DATB0700
66          4  792.40D0,1253.154D0,  701.20D0,1368.603D0,  641.80D0,1473.887D0,DATB0710
67          5  595.90D0,1579.509D0,  558.50D0,1687.509D0,  527.30D0,1798.245D0/DATB0720
68           DATA G09 /    600.0D0, 6192.24D0, 471.697D0, 4682.13D0, 544.893D0,DATB0730
69          1 3588.84D0, 618.089D0, 2897.01D0, 691.285D0, 2426.85D0, 764.481D0,DATB0740
70          2 2087.61D0, 837.677D0, 1831.53D0, 910.873D0, 1631.43D0, 984.069D0,DATB0750
71          3 1470.77D0,1057.265D0, 1338.95D0,1130.461D0, 1228.83D0,1203.657D0,DATB0760
72          4 1172.40D0,1262.896D0, 1040.80D0,1379.241D0,  956.20D0,1482.588D0,DATB0770
73          5  890.60D0,1585.098D0,  837.00D0,1689.262D0,  792.00D0,1795.591D0/DATB0780
74           DATA G10 /    800.0D0, 7103.30D0, 509.811D0, 5630.54D0, 578.769D0,DATB0790
75          1 4472.42D0, 647.726D0, 3689.49D0, 716.684D0, 3135.77D0, 785.641D0,DATB0800
76          2 2725.47D0, 854.599D0, 2409.78D0, 923.557D0, 2159.53D0, 992.514D0,DATB0810
77          3 1956.33D0,1061.472D0, 1788.08D0,1130.429D0, 1646.48D0,1199.387D0,DATB0820
78          4 1550.10D0,1268.822D0, 1378.50D0,1386.128D0, 1269.40D0,1488.245D0,DATB0830
79          5 1184.90D0,1588.533D0, 1115.70D0,1689.882D0, 1057.40D0,1792.940D0/DATB0840
80           DATA G11 /   1000.0D0, 7883.70D0, 542.551D0, 6458.25D0, 607.589D0,DATB0850
81          1 5277.33D0, 672.628D0, 4434.96D0, 737.666D0, 3818.11D0, 802.705D0,DATB0860
82          2 3349.91D0, 867.743D0, 2983.26D0, 932.782D0, 2688.66D0, 997.820D0,DATB0870
83          3 2446.89D0,1062.859D0, 2244.95D0,1127.898D0, 2073.79D0,1192.936D0,DATB0880
84          4 1928.00D0,1272.169D0, 1715.80D0,1390.601D0, 1582.30D0,1491.960D0,DATB0890
85          5 1479.30D0,1590.602D0, 1394.80D0,1689.784D0, 1323.60D0,1790.290D0/DATB0900
86           DATA G12 /   1200.0D0, 8566.61D0, 571.853D0, 7194.59D0, 633.149D0,DATB0910
87          1 6018.53D0, 694.445D0, 5141.21D0, 755.741D0, 4478.45D0, 817.037D0,DATB0920
88          2 3964.05D0, 878.333D0, 3554.43D0, 939.629D0, 3221.01D0,1000.925D0,DATB0930
89          3 2944.51D0,1062.221D0, 2711.61D0,1123.517D0, 2512.78D0,1184.813D0,DATB0940
90          4 2306.00D0,1274.362D0, 2052.90D0,1393.811D0, 1895.20D0,1494.624D0,DATB0950
91          5 1773.90D0,1591.920D0, 1674.40D0,1689.289D0, 1590.60D0,1787.642D0/DATB0960
92           DATA G13 /   1400.0D0, 9171.02D0, 598.830D0, 7857.52D0, 656.477D0,DATB0970
93          1 6705.77D0, 714.125D0, 5813.30D0, 771.773D0, 5119.72D0, 829.420D0,DATB0980
94          2 4569.95D0, 887.068D0, 4125.04D0, 944.716D0, 3758.28D0,1002.364D0,DATB0990
95          3 3450.98D0,1060.011D0, 3189.90D0,1117.659D0, 2965.42D0,1175.307D0,DATB1000
96          4 2684.80D0,1275.682D0, 2390.20D0,1396.083D0, 2208.30D0,1496.504D0,DATB1010
97          5 2068.80D0,1592.681D0, 1954.50D0,1688.499D0, 1858.30D0,1784.994D0/DATB1020
98           DATA G14 /   1600.0D0, 9708.52D0, 624.202D0, 8458.62D0, 678.235D0,DATB1030
99          1 7345.72D0, 732.268D0, 6454.71D0, 786.300D0, 5743.98D0, 840.333D0,DATB1040
100         2 5169.19D0, 894.366D0, 4696.66D0, 948.399D0, 4302.13D0,1002.431D0,DATB1050
```

TABLE VI (contd.)

```
     3 3968.12D0,1056.464D0, 3681.89D0,1110.497D0, 3433.97D0,1164.530D0,DATB1060
     4 3067.10D0,1275.712D0, 2729.00D0,1397.285D0, 2522.30D0,1497.542D0,DATB1070
     5 2364.50D0,1592.855D0, 2235.40D0,1687.403D0, 2126.80D0,1782.347D0/DATB1080
      DATA G15 /   1800.0D0,10186.24D0, 648.490D0, 9005.71D0, 698.875D0,DATB1090
     1 7943.45D0, 749.258D0, 7068.47D0, 799.642D0, 6353.40D0, 850.027D0,DATB1100
     2 5763.77D0, 900.411D0, 5271.40D0, 950.795D0, 4855.02D0,1001.179D0,DATB1110
     3 4498.77D0,1051.564D0, 4190.73D0,1101.948D0, 3921.87D0,1152.332D0,DATB1120
     4 3448.60D0,1275.998D0, 3067.70D0,1398.372D0, 2836.40D0,1498.413D0,DATB1130
     5 2660.50D0,1592.891D0, 2516.90D0,1686.228D0, 2396.00D0,1779.701D0/DATB1140
      DATA G16 /   2000.0D0,10608.22D0, 672.111D0, 9504.17D0, 718.734D0,DATB1150
     1 8503.14D0, 765.356D0, 7657.68D0, 811.979D0, 6950.77D0, 858.601D0,DATB1160
     2 6356.68D0, 905.224D0, 5852.74D0, 951.846D0, 5420.97D0, 998.468D0,DATB1170
     3 5047.45D0,1045.091D0, 4721.42D0,1091.713D0, 4434.55D0,1138.336D0,DATB1180
     4 3833.80D0,1257.411D0, 3408.30D0,1398.751D0, 3151.70D0,1498.725D0,DATB1190
     5 2957.50D0,1592.538D0, 2799.20D0,1684.851D0, 2666.10D0,1777.056D0/DATB1200
      DATA G17 /   2200.0D0,10975.67D0, 695.462D0, 9956.80D0, 738.132D0,DATB1210
     1 9027.41D0, 780.802D0, 8224.65D0, 823.471D0, 7538.67D0, 866.141D0,DATB1220
     2 6951.18D0, 908.811D0, 6444.80D0, 951.481D0, 6004.98D0, 994.150D0,DATB1230
     3 5620.04D0,1036.820D0, 5280.64D0,1079.490D0, 4979.37D0,1122.159D0,DATB1240
     4 4220.10D0,1274.756D0, 3749.80D0,1398.911D0, 3467.80D0,1498.821D0,DATB1250
     5 3255.10D0,1592.023D0, 3082.30D0,1683.386D0, 2937.10D0,1774.411D0/DATB1260
      DATA G18 /   2400.0D0,11209.60D0, 718.953D0,10316.18D0, 757.431D0,DATB1270
     1 9486.43D0, 795.909D0, 8750.33D0, 834.387D0, 8105.54D0, 872.866D0,DATB1280
     2 7541.38D0, 911.344D0, 7046.15D0, 949.822D0, 6609.24D0, 988.300D0,DATB1290
     3 6221.66D0,1026.779D0, 5875.90D0,1065.257D0, 5565.81D0,1103.735D0,DATB1300
     4 4619.20D0,1271.798D0, 4096.70D0,1397.651D0, 3787.00D0,1497.913D0,DATB1310
     5 3554.70D0,1590.843D0, 3366.60D0,1681.584D0, 3208.80D0,1771.765D0/DATB1320
      DATA G19 /   2600.0D0,11428.29D0, 744.475D0,10644.57D0, 778.232D0,DATB1330
     1 9914.50D0, 811.988D0, 9254.60D0, 845.745D0, 8664.25D0, 879.502D0,DATB1340
     2 8137.27D0, 913.259D0, 7666.18D0, 947.016D0, 7243.77D0, 980.772D0,DATB1350
     3 6863.58D0,1014.529D0, 6520.03D0,1048.286D0, 6208.34D0,1082.043D0,DATB1360
     4 5012.40D0,1270.621D0, 4441.80D0,1397.239D0, 4105.40D0,1497.515D0,DATB1370
     5 3854.20D0,1589.972D0, 3651.40D0,1679.930D0, 3481.50D0,1769.120D0/DATB1380
      DATA G20 /   2800.0D0,11589.07D0, 770.686D0,10931.29D0, 799.200D0,DATB1390
     110314.45D0, 827.715D0, 9746.45D0, 856.230D0, 9227.42D0, 884.745D0,DATB1400
     2 8754.35D0, 913.260D0, 8323.15D0, 941.774D0, 7929.53D0, 970.289D0,DATB1410
     3 7569.46D0, 998.804D0, 7239.24D0,1027.319D0, 6935.60D0,1055.834D0,DATB1420
     4 5411.00D0,1269.067D0, 4789.20D0,1396.501D0, 4425.40D0,1496.853D0,DATB1430
     5 4154.90D0,1588.914D0, 3937.10D0,1678.177D0, 3755.00D0,1766.475D0/DATB1440
      DATA G21 /   3000.0D0,11604.42D0, 801.845D0,11109.66D0, 823.687D0,DATB1450
     110640.97D0, 845.529D0,10200.60D0, 867.371D0, 9788.61D0, 889.213D0,DATB1460
     2 9403.93D0, 911.055D0, 9044.98D0, 932.898D0, 8709.95D0, 954.740D0,DATB1470
     3 8397.01D0, 976.582D0, 8104.38D0, 998.424D0, 7830.38D0,1020.266D0,DATB1480
     4 5816.40D0,1267.043D0, 5139.50D0,1395.404D0, 4747.10D0,1495.908D0,DATB1490
     5 4456.80D0,1587.660D0, 4223.80D0,1676.323D0, 4029.40D0,1763.830D0/DATB1500
C                                                                       DATB1510
      END                                                               DATB3540
```

Some of the more important assumptions utilized in the development of this model are:

(1) System flow is one-dimensional and isentropic

(2) Slip between phases is negligible

(3) Interphase heat and mass transfer during expansion is essentially nil

(4) Liquid phase is incompressible

(5) Vapor phase expands <u>at the throat</u> in a polytropic manner to account for some of the heat transfer at that location.

The foregoing (1) through (3) imply that each phase expands individually in an isentropic manner and, in particular, the vapor phase expands as an ideal gas. Derivation of the Henry-Fauske critical flow model begins with the complete, general expression for one-dimensional, steady state, and single and two-phase critical mass flux, which is as follows:

$$-G^{-2} = \frac{1}{g_c k}\left\{X\left[1 + X(k-1)\right]\frac{dv_V}{dp} + k\left[1 + X(k-2) - X^2(k-1)\right]\frac{dv_L}{dp} + \left[v_V\left[1 + 2X(k-1)\right] + v_L k\left[(k-2) - 2X(k-1)\right]\right]\frac{dX}{dp} + X(1-X)\left[v_L k - \frac{v_V}{k}\right]\frac{dk}{dp}\right\} \quad (154)$$

where X = quality.

Equation (154) can be simplified using the following assumptions and relationships:

(1) The homogeneous assumption

$$k = 1 \quad (155)$$

(2) The incompressible liquid phase assumption

$$\frac{dv_L}{dp} = 0 \tag{156}$$

(3) The polytropic exponent, n, of Tangren[54] in polytropic vapor expansion at the throat

$$\left.\frac{dv_V}{dp}\right|_t = -\left.\frac{v_V}{np}\right|_t \tag{157}$$

with

$$n = \frac{(1 - X)\frac{C_{v_L}}{C_V} + X}{(1 - X)\frac{C_{v_L}}{C_V} + \frac{X}{\gamma}} \tag{158}$$

(4) The negligible interphase mass transfer assumption

$$X_t = X_0 \tag{159}$$

(5) The empirical result

$$\left.\frac{dk}{dp}\right|_t \approx 0 \tag{160}$$

where

C_v = specific heat capacity at constant volume

γ = ratio of specific heat capacities (vapor)
(note that this is a different definition for γ)

with subscript denotation

0 = stagnation

t = throat or critical point.

The foregoing serve to reduce Equation (154) to

$$G = \left\{ \frac{X_0 v_V}{np} - (v_V - v_{L_0}) \frac{dX}{dp} \right\}_t^{-1/2} g_c^{1/2} \tag{161}$$

Formulating the actual throat fluid quality in terms of the equilibrium quality at that location and making use of some empirical data as well as some mathematical manipulation, Equation (154) becomes:

$$G = \left\{ \frac{X_0 v_V}{np} + (v_V - v_{L_0}) \left[\frac{(1 - X_0)N}{s_{VL_E}} \frac{ds_{L_E}}{d} - \frac{X_0 C_{P_V}}{p s_{VL_0}} \left(\frac{1}{n} - \frac{1}{\gamma} \right) \right] \right\}_t^{-1/2} g_c^{1/2} \tag{162}$$

where

N = nonequilibrium parameter

n = polytropic process exponent

and with the subscript denotation

E = equilibrium.

The nonequilibrium parameter N is of primary import in the low quality regime. Based upon experimental data, this parameter can be related to equilibrium throat quality X_{E_t} as follows:

$$N(X_{E_t}) = \begin{cases} X_{E_t}/0.14, & X_{E_t} < 0.14 \\ 1, & X_{E_t} \geq 0.14. \end{cases} \tag{163}$$

The relation for critical mass flux, Equation (162), is coupled with the two phase momentum equation as follows:

$$(1 - X_0)\, v_{L_0}\, P_0\, (1 - \eta) + \frac{\gamma X_0 P_0}{\gamma - 1} (v_{V_0} - \eta v_{V_t})$$

$$= 1/2\, G^2 \left[X_0 v_{V_t} + v_{L_0} (1 - X_0) \right]^2 \frac{1}{g_c} \qquad (164)$$

where

η = throat or critical pressure/stagnation pressure ratio.

This provides a solution based only on upstream stagnation conditions. Solving these two equations simultaneously generates the Henry-Fauske critical flow tables in Tables VII and VIII.

Table VII records the solution in the subcooled region, where quality is set to zero in Equations (162) and (164). Table VIII details the results in the saturated regime. The end of Table VII should mesh with the beginning of Table VIII but observation will show that this is not the case. The Evaluation Model/Critical Flow Model Criterion (see Section 3.10) specifies use of the Henry-Fauske model in the subcooled region and the Moody model in the saturated region. To effect a smooth transition, therefore, the first point in the Moody Critical Flow Model Table (Table VI) has been placed in the last position of the table for the Henry-Fauske critical flow model extended into the subcooled region (Table VII). This limitation of the subcooled Henry-Fauske table should be realized during critical flow model selection. Further, the comments regarding table entry discussed with the Moody critical flow model, Section 3.6.8 (2) (c), apply to Tables VII and VIII.

The Henry-Fauske critical flow model may be accessed by entering 0 or 1 for JCHOKE and 12 for ICHOKE on the Junction Data Card. Many combinations with other critical flow models are available and are listed in Table V.

TABLE VII

HENRY FAUSKE CRITICAL FLOW TABLES - SUBCOOLED REGION

```
      BLOCK DATA                                                        DATE0010
      IMPLICIT REAL*8 (A-H,O-Z)                                         DATE0020
C                                                                       DATE0030
      COMMON / LEAKHE / PE01(23), PE02(23), PE03(23), PE04(23),         DATE0040
     1          PE05(23), PE06(23), PE07(23), PE08(23), PE09(23),      DATE0050
     2          PE10(23), PE11(23), PE12(23), PE13(23), PE14(23),      DATE0060
     3          PE15(23), PE16(23),NHHE,NPHE                           DATE0070
C                                                                       DATE0080
C     HENRY MODEL CRITICAL FLOW TABLES EXTEND TO SUBCOOLED REGION       DATE0090
C                                                                       DATE0100
C     PE(   1,I) = STAGNATION PRESSURE (PSIA)                           DATE0110
C     PE(EVEN,I) = MAXIMUM FLOW RATE (LB/FT**2-SEC)                     DATE0120
C     PE( ODD,I) = STAGNATION ENTHALPY (BTU/LB)                         DATE0130
C                                                                       DATE0140
C     NPHE = NUMBER OF PRESSURE VALUES                                  DATE0150
C     NHHE = NUMBER OF PAIRS OF ENTHALPY AND FLOW VALUES PER PRESSURE   DATE0160
C                                                                       DATE0170
      DATA NHHE,NPHE / 11,16 /                                          DATE0180
C                                                                       DATE0190
      DATA PE01 /  10.0D0,    2293.0D0,  64.630D0,  2255.0D0,  74.271D0,DATE0200
     1  2204.0D0,  83.914D0,  2140.0D0,  93.560D0,  2059.0D0, 103.210D0,DATE0210
     2  1955.0D0, 112.866D0,  1820.0D0, 122.527D0,  1647.0D0, 132.195D0,DATE0220
     3  1415.0D0, 141.871D0,  1108.0D0, 151.556D0,   768.0D0, 161.261D0/DATE0230
C                                                                       DATE0240
      DATA PE02 /  14.7D0,    2788.0D0,  74.023D0,  2744.0D0,  84.605D0,DATE0250
     1  2684.0D0,  95.190D0,  2609.0D0, 105.780D0,  2512.0D0, 116.377D0,DATE0260
     2  2388.0D0, 126.981D0,  2227.0D0, 137.594D0,  2014.0D0, 148.217D0,DATE0270
     3  1735.0D0, 158.852D0,  1369.0D0, 169.501D0,   943.0D0, 180.179D0/DATE0280
C                                                                       DATE0290
      DATA PE03 /  50.0D0,    5174.0D0, 108.576D0,  5094.0D0, 122.624D0,DATE0300
     1 4989.0D0,  136.686D0,  4853.0D0, 150.766D0,  4679.0D0, 164.868D0,DATE0310
     2 4449.0D0,  178.996D0,  4156.0D0, 193.154D0,  3771.0D0, 207.349D0,DATE0320
     3 3273.0D0,  221.585D0,  2646.0D0, 235.869D0,  1787.8D0, 250.212D0/DATE0330
C                                                                       DATE0340
      DATA PE04 / 100.0D0,    7314.0D0, 131.690D0,  7203.0D0, 148.066D0,DATE0350
     1 7059.0D0,  164.470D0,  6870.0D0, 180.909D0,  6624.0D0, 197.390D0,DATE0360
     2 6304.0D0,  213.922D0,  5895.0D0, 230.515D0,  5361.0D0, 247.176D0,DATE0370
     3 4691.0D0,  263.917D0,  3853.0D0, 280.749D0,  2546.5D0, 298.538D0/DATE0380
C                                                                       DATE0390
      DATA PE05 / 200.0D0,   10316.0D0, 159.379D0, 10157.0D0, 178.555D0,DATE0400
     1 9940.0D0,  197.788D0,  9668.0D0, 217.089D0,  9303.0D0, 236.474D0,DATE0410
     2 8846.0D0,  255.958D0,  8256.0D0, 275.557D0,  7513.0D0, 295.289D0,DATE0420
     3 6567.0D0,  315.174D0,  5460.0D0, 335.236D0,  3608.2D0, 355.506D0/DATE0430
C                                                                       DATE0440
      DATA PE06 / 400.0D0,   14530.0D0, 191.387D0, 14278.0D0, 213.823D0,DATE0450
     113967.0D0,  236.367D0, 13556.0D0, 259.042D0, 13043.0D0, 281.874D0,DATE0460
     212377.0D0,  304.892D0, 11537.0D0, 328.128D0, 10496.0D0, 351.621D0,DATE0470
     3 9199.0D0,  375.416D0,  7708.0D0, 399.574D0,  5084.6D0, 424.167D0/DATE0480
C                                                                       DATE0490
      DATA PE07 / 600.0D0,   17719.0D0, 212.798D0, 17412.0D0, 237.429D0,DATE0500
```

TABLE VII (contd.)

```
      117020.0D0,  262.216D0, 16499.0D0, 287.192D0, 15845.0D0, 312.394D0,DATE0510
      215027.0D0,  337.865D0, 13996.0D0, 363.658D0, 12730.0D0, 389.838D0,DATE0520
      311153.0D0,  416.489D0,  9378.0D0, 443.724D0,  6192.2D0, 471.697D0/DATE0530
C                                                                        DATE0540
      DATA PE08 / 800.0D0,   20397.0D0, 229.413D0, 20026.0D0, 255.753D0,DATE0550
      119544.0D0,  282.295D0, 18943.0D0, 309.081D0, 18176.0D0, 336.159D0,DATE0560
      217231.0D0,  363.591D0, 16028.0D0, 391.452D0, 14557.0D0, 419.842D0,DATE0570
      312758.0D0,  448.894D0, 10734.0D0, 478.793D0,  7103.3D0, 509.811D0/DATE0580
C                                                                        DATE0590
      DATA PE09 /1000.0D0,   22751.0D0, 243.188D0, 22316.0D0, 270.943D0,DATE0600
      121779.0D0,  298.941D0, 21080.0D0, 327.236D0, 20219.0D0, 355.890D0,DATE0610
      219140.0D0,  384.982D0, 17782.0D0, 414.616D0, 16138.0D0, 444.930D0,DATE0620
      314147.0D0,  476.119D0, 11891.0D0, 508.470D0,  7883.7D0, 542.551D0/DATE0630
C                                                                        DATE0640
      DATA PE10 /1200.0D0,   24864.0D0, 255.011D0, 24372.0D0, 283.995D0,DATE0650
      123760.0D0,  313.263D0, 23001.0D0, 342.879D0, 22039.0D0, 372.919D0,DATE0660
      220839.0D0,  403.484D0, 19364.0D0, 434.707D0, 17546.0D0, 466.775D0,DATE0670
      315369.0D0,  499.957D0, 12891.0D0, 534.672D0,  8566.6D0, 571.853D0/DATE0680
C                                                                        DATE0690
      DATA PE11 /1400.0D0,   26793.0D0, 265.587D0, 26256.0D0, 295.666D0,DATE0700
      125596.0D0,  326.069D0, 24745.0D0, 356.869D0, 23706.0D0, 388.160D0,DATE0710
      222400.0D0,  420.065D0, 20806.0D0, 452.751D0, 18847.0D0, 486.459D0,DATE0720
      316460.0D0,  521.548D0, 13753.0D0, 558.615D0,  9171.0D0, 598.830D0/DATE0730
C                                                                        DATE0740
      DATA PE12 /1600.0D0,   28582.0D0, 275.051D0, 28009.0D0, 306.109D0,DATE0750
      127278.0D0,  337.529D0, 26357.0D0, 369.396D0, 25230.0D0, 401.819D0,DATE0760
      223832.0D0,  434.945D0, 22100.0D0, 468.978D0, 20014.0D0, 504.219D0,DATE0770
      317468.0D0,  541.136D0, 14547.0D0, 580.548D0,  9708.5D0, 624.202D0/DATE0780
C                                                                        DATE0790
      DATA PE13 /1800.0D0,   30263.0D0, 283.684D0, 29633.0D0, 315.637D0,DATE0800
      128856.0D0,  347.990D0, 27868.0D0, 380.836D0, 26676.0D0, 414.304D0,DATE0810
      225180.0D0,  448.564D0, 23329.0D0, 483.862D0, 21090.0D0, 520.563D0,DATE0820
      318388.0D0,  559.264D0, 15234.0D0, 601.066D0, 10186.3D0, 648.990D0/DATE0830
C                                                                        DATE0840
      DATA PE14 /2000.0D0,   31856.0D0, 291.617D0, 31201.0D0, 324.390D0,DATE0850
      130358.0D0,  357.598D0, 29294.0D0, 391.347D0, 28034.0D0, 425.781D0,DATE0860
      226436.0D0,  461.098D0, 24486.0D0, 497.583D0, 22124.0D0, 535.676D0,DATE0870
      319264.0D0,  576.119D0, 15855.0D0, 620.360D0, 10608.2D0, 672.111D0/DATE0880
C                                                                        DATE0890
      DATA PE15 /2200.0D0,   33369.0D0, 298.970D0, 32664.0D0, 332.498D0,DATE0900
      131782.0D0,  366.495D0, 30655.0D0, 401.079D0, 29295.0D0, 436.411D0,DATE0910
      227643.0D0,  472.715D0, 25603.0D0, 510.319D0, 23115.0D0, 549.741D0,DATE0920
      320073.0D0,  591.888D0, 16430.0D0, 638.625D0, 10975.7D0, 695.462D0/DATE0930
C                                                                        DATE0940
      DATA PE16/2400.0D0,    34803.0D0, 305.833D0, 34045.0D0, 340.062D0,DATE0950
      133104.0D0, 374.792D0, 31947.0D0, 410.154D0, 30531.0D0, 446.326D0,DATE0960
      228787.0D0, 483.557D0, 26642.0D0, 522.220D0, 24030.0D0, 562.918D0,DATE0970
      320862.0D0, 606.736D0, 16975.0D0, 656.028D0, 11209.6D0, 718.953D0/DATE0980
C                                                                        DATE0990
      END                                                                DATE1000
```

TABLE VIII

HENRY FAUSKE CRITICAL FLOW TABLES - SATURATED REGION

```
      BLOCK DATA                                                        DATH0010
      IMPLICIT REAL*8 (A-H,O-Z)                                         DATH0020
C                                                                       DATH0030
      COMMON /LEAKH/ PM(59,18),NHH,NPH                                  DATH0040
C                                                                       DATH0050
C     HENRY MODEL CRITICAL FLOW TABLES                                  DATH0060
C                                                                       DATH0070
C     PM(   1,I) = STAGNATION PRESSURE (PSIA)                           DATH0080
C     PM(EVEN,I) = MAXIMUM FLOW RATE (LB/FT**2-SEC)                     DATH0090
C     PM( ODD,I) = STAGNATION ENTHALPY (BTU/LB)                         DATH0100
C                                                                       DATH0110
C     NPH = NUMBER OF PRESSURE VALUES                                   DATH0120
C     NHH = NUMBER OF PAIRS OF ENTHALPY AND FLOW VALUES PER PRESSURE    DATH0130
C                                                                       DATH0140
      DATA NHH,NPH / 29,18 /                                            DATH0150
      DATA PM( 1, 1),PM( 2, 1),PM( 3, 1),PM( 4, 1),PM( 5, 1),PM( 6, 1), DATH0160
     1     PM( 7, 1),PM( 8, 1),PM( 9, 1),PM(10, 1),PM(11, 1),PM(12, 1), DATH0170
     2     PM(13, 1),PM(14, 1),PM(15, 1),PM(16, 1),PM(17, 1),PM(18, 1), DATH0180
     3     PM(19, 1),PM(20, 1),PM(21, 1),PM(22, 1),PM(23, 1),PM(24, 1)/ DATH0190
     4 0.100000000 01, 0.136248010 03, 0.697325160 02, 0.574748630 02,  DATH0200
     5 0.707685930 02, 0.452521670 02, 0.718046690 02, 0.387211910 02,  DATH0210
     6 0.728407450 02, 0.344704250 02, 0.738768210 02, 0.313846550 02,  DATH0220
     7 0.749128970 02, 0.290588870 02, 0.759489740 02, 0.271375740 02,  DATH0230
     8 0.769850500 02, 0.255530860 02, 0.780211260 02, 0.242628130 02,  DATH0240
     9 0.790572020 02, 0.230989010 02, 0.800932780 02, 0.167259150 02/  DATH0250
      DATA PM(25, 1),PM(26, 1),PM(27, 1),PM(28, 1),PM(29, 1),PM(30, 1), DATH0261
     1     PM(31, 1),PM(32, 1),PM(33, 1),PM(34, 1),PM(35, 1),PM(36, 1), DATH0270
     2     PM(37, 1),PM(38, 1),PM(39, 1),PM(40, 1),PM(41, 1),PM(42, 1), DATH0280
     3     PM(43, 1),PM(44, 1),PM(45, 1),PM(46, 1),PM(47, 1),PM(48, 1)/ DATH0290
     4 0.904540400 02, 0.137558920 02, 0.100814800 03, 0.119708730 02,  DATH0300
     5 0.111175560 03, 0.107372550 02, 0.121536330 03, 0.982545100 01,  DATH0310
     6 0.131897090 03, 0.910923950 01, 0.142257850 03, 0.852722630 01,  DATH0320
     7 0.152618610 03, 0.805283370 01, 0.162979370 03, 0.764985380 01,  DATH0330
     8 0.173340140 03, 0.548435420 01, 0.276947760 03, 0.450999800 01,  DATH0340
     9 0.380555380 03, 0.392236600 01, 0.484163000 03, 0.351415100 01/  DATH0350
      DATA PM(49, 1),PM(50, 1),PM(51, 1),PM(52, 1),PM(53, 1),PM(54, 1), DATH0361
     1     PM(55, 1),PM(56, 1),PM(57, 1),PM(58, 1),PM(59, 1)/           DATH0370
     2 0.587770620 03, 0.321897420 01, 0.691378240 03, 0.298277330 01,  DATH0380
     3 0.794985850 03, 0.279702910 01, 0.898593470 03, 0.263900340 01,  DATH0390
     4 0.100220110 04, 0.250553680 01, 0.110477260 04/                  DATH0400
      DATA PM( 1, 2),PM( 2, 2),PM( 3, 2),PM( 4, 2),PM( 5, 2),PM( 6, 2), DATH0410
     1     PM( 7, 2),PM( 8, 2),PM( 9, 2),PM(10, 2),PM(11, 2),PM(12, 2), DATH0420
     2     PM(13, 2),PM(14, 2),PM(15, 2),PM(16, 2),PM(17, 2),PM(18, 2), DATH0430
     3     PM(19, 2),PM(20, 2),PM(21, 2),PM(22, 2),PM(23, 2),PM(24, 2)/ DATH0440
     4 0.500000000 01, 0.479623310 03, 0.130196430 03, 0.238557240 03,  DATH0450
     5 0.131197330 03, 0.192555490 03, 0.132198230 03, 0.167639970 03,  DATH0460
     6 0.133199120 03, 0.151504360 03, 0.134200020 03, 0.139286600 03,  DATH0470
     7 0.135200910 03, 0.129912620 03, 0.136201810 03, 0.122210700 03,  DATH0480
     3 0.137202710 03, 0.115600950 03, 0.138203600 03, 0.110153220 03,  DATH0490
     9 0.139204500 03, 0.105342320 03, 0.140205400 03, 0.775403500 02/  DATH0500
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TABLE VIII (contd.)

```
      DATA PM(25, 2),PM(26, 2),PM(27, 2),PM(28, 2),PM(29, 2),PM(30, 2)  DATH0511
     1     PM(31, 2),PM(32, 2),PM(33, 2),PM(34, 2),PM(35, 2),PM(36, 2),  DATH0520
     2     PM(37, 2),PM(38, 2),PM(39, 2),PM(40, 2),PM(41, 2),PM(42, 2),  DATH0530
     3     PM(43, 2),PM(44, 2),PM(45, 2),PM(46, 2),PM(47, 2),PM(48, 2)/  DATH0540
     4 0.15021436D 03, 0.642597330 02, 0.16022332D 03, 0.56157645D 02,  DATH0550
     5 0.17023229D 03, 0.50489196D 02, 0.18024125D 03, 0.46206807D 02,  DATH0560
     6 0.19025021D 03, 0.42921448D 02, 0.20025918D 03, 0.40242906D 02,  DATH0570
     7 0.21026814D 03, 0.38004360D 02, 0.22027710D 03, 0.36096869D 02,  DATH0580
     8 0.23028606D 03, 0.26061890D 02, 0.33037570D 03, 0.21439832D 02,  DATH0590
     9 0.43046533D 03, 0.186379360 02, 0.53055496D 03, 0.16730373D 02/  DATH0600
      DATA PM(49, 2),PM(50, 2),PM(51, 2),PM(52, 2),PM(53, 2),PM(54, 2),  DATH0611
     1     PM(55, 2),PM(56, 2),PM(57, 2),PM(58, 2),PM(59, 2)/          DATH0620
     2 0.63064459D 03, 0.15310835D 02, 0.73073423D 03, 0.14193602D 02,  DATH0630
     3 0.83082386D 03, 0.13297319D 02, 0.93091349D 03, 0.12562481D 02,  DATH0640
     4 0.10310031D 04, 0.11931808D 02, 0.11300918D 04/                  DATH0650
      DATA PM( 1, 3),PM( 2, 3),PM( 3, 3),PM( 4, 3),PM( 5, 3),PM( 6, 3),  DATH0660
     1     PM( 7, 3),PM( 8, 3),PM( 9, 3),PM(10, 3),PM(11, 3),PM(12, 3),  DATH0670
     2     PM(13, 3),PM(14, 3),PM(15, 3),PM(16, 3),PM(17, 3),PM(18, 3),  DATH0680
     3     PM(19, 3),PM(20, 3),PM(21, 3),PM(22, 3),PM(23, 3),PM(24, 3)/  DATH0690
     4 0.10000000D 02, 0.75318591D 03, 0.16126089D 03, 0.43285386D 03,  DATH0700
     5 0.16224298D 03, 0.35535460D 03, 0.16322507D 03, 0.31383336D 03,  DATH0710
     6 0.16420716D 03, 0.28523252D 03, 0.16518924D 03, 0.26376728D 03,  DATH0720
     7 0.16617133D 03, 0.24680325D 03, 0.16715342D 03, 0.23277071D 03,  DATH0730
     8 0.16813550D 03, 0.22097308D 03, 0.16911759D 03, 0.21063055D 03,  DATH0740
     9 0.17009968D 03, 0.20202426D 03, 0.17108177D 03, 0.14956550D 03/  DATH0750
      DATA PM(25, 3),PM(26, 3),PM(27, 3),PM(28, 3),PM(29, 3),PM(30, 3),  DATH0761
     1     PM(31, 3),PM(32, 3),PM(33, 3),PM(34, 3),PM(35, 3),PM(36, 3),  DATH0770
     2     PM(37, 3),PM(38, 3),PM(39, 3),PM(40, 3),PM(41, 3),PM(42, 3),  DATH0780
     3     PM(43, 3),PM(44, 3),PM(45, 3),PM(46, 3),PM(47, 3),PM(48, 3)/  DATH0790
     4 0.18090264D 03, 0.12392453D 03, 0.19072351D 03, 0.10827265D 03,  DATH0800
     5 0.20054439D 03, 0.97367417D 02, 0.21036526D 03, 0.89289035D 02,  DATH0810
     6 0.22018613D 03, 0.82948515D 02, 0.23000701D 03, 0.77851424D 02,  DATH0820
     7 0.23982788D 03, 0.73584648D 02, 0.24964875D 03, 0.69944358D 02,  DATH0830
     8 0.25946963D 03, 0.50774594D 02, 0.35767836D 03, 0.41893032D 02,  DATH0840
     9 0.45588710D 03, 0.36437539D 02, 0.55409583D 03, 0.32732120D 02/  DATH0850
      DATA PM(49, 3),PM(50, 3),PM(51, 3),PM(52, 3),PM(53, 3),PM(54, 3),  DATH0861
     1     PM(55, 3),PM(56, 3),PM(57, 3),PM(58, 3),PM(59, 3)/          DATH0870
     2 0.65230457D 03, 0.29926221D 02, 0.75051330D 03, 0.27763339D 02,  DATH0880
     3 0.84872204D 03, 0.26036863D 02, 0.94693077D 03, 0.24540110D 02,  DATH0890
     4 0.10451395D 04, 0.23315677D 02, 0.11423661D 04/                  DATH0900
      DATA PM( 1, 4),PM( 2, 4),PM( 3, 4),PM( 4, 4),PM( 5, 4),PM( 6, 4),  DATH0910
     1     PM( 7, 4),PM( 8, 4),PM( 9, 4),PM(10, 4),PM(11, 4),PM(12, 4),  DATH0920
     2     PM(13, 4),PM(14, 4),PM(15, 4),PM(16, 4),PM(17, 4),PM(18, 4),  DATH0930
     3     PM(19, 4),PM(20, 4),PM(21, 4),PM(22, 4),PM(23, 4),PM(24, 4)/  DATH0940
     4 0.14700000D 02, 0.95464474D 03, 0.18015866D 03, 0.59008746D 03,  DATH0950
     5 0.18112898D 03, 0.49724978D 03, 0.18209929D 03, 0.44236427D 03,  DATH0960
     6 0.18306961D 03, 0.40419340D 03, 0.18403992D 03, 0.37397280D 03,  DATH0970
     7 0.18501024D 03, 0.34877987D 03, 0.18598055D 03, 0.32947835D 03,  DATH0980
     8 0.18695087D 03, 0.31179302D 03, 0.18792118D 03, 0.29828762D 03,  DATH0990
     9 0.18889149D 03, 0.28604877D 03, 0.18986181D 03, 0.21399258D 03/  DATH1000
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TABLE VIII (contd.)

```
      DATA PM(25, 4),PM(26, 4),PM(27, 4),PM(28, 4),PM(29, 4),PM(30, 4),  DATH1011
     1     PM(31, 4),PM(32, 4),PM(33, 4),PM(34, 4),PM(35, 4),PM(36, 4),  DATH1020
     2     PM(37, 4),PM(38, 4),PM(39, 4),PM(40, 4),PM(41, 4),PM(42, 4),  DATH1030
     3     PM(43, 4),PM(44, 4),PM(45, 4),PM(46, 4),PM(47, 4),PM(48, 4)/  DATH1040
     4 0.19956495D 03, 0.17866195D 03, 0.20926810D 03, 0.15644271D 03,   DATH1050
     5 0.21897124D 03, 0.14106049D 03, 0.22867439D 03, 0.12936958D 03,   DATH1060
     6 0.23837753D 03, 0.12023086D 03, 0.24808068D 03, 0.11265247D 03,   DATH1070
     7 0.25778382D 03, 0.10652524D 03, 0.26748697D 03, 0.10129854D 03,   DATH1080
     8 0.27719011D 03, 0.73494212D 02, 0.37422156D 03, 0.60732326D 02,   DATH1090
     9 0.47125301D 03, 0.52867074D 02, 0.56828446D 03, 0.47471313D 02/   DATH1100
      DATA PM(49, 4),PM(50, 4),PM(51, 4),PM(52, 4),PM(53, 4),PM(54, 4),  DATH1111
     1     PM(55, 4),PM(56, 4),PM(57, 4),PM(58, 4),PM(59, 4)/            DATH1120
     2 0.66531591D 03, 0.43403395D 02, 0.76234736D 03, 0.40260188D 02,   DATH1130
     3 0.85937881D 03, 0.37744367D 02, 0.95641026D 03, 0.35611021D 02,   DATH1140
     4 0.10534417D 04, 0.33806072D 02, 0.11495028D 04/                   DATH1150
      DATA PM( 1, 5),PM( 2, 5),PM( 3, 5),PM( 4, 5),PM( 5, 5),PM( 6, 5),  DATH1160
     1     PM( 7, 5),PM( 8, 5),PM( 9, 5),PM(10, 5),PM(11, 5),PM(12, 5),  DATH1170
     2     PM(13, 5),PM(14, 5),PM(15, 5),PM(16, 5),PM(17, 5),PM(18, 5),  DATH1180
     3     PM(19, 5),PM(20, 5),PM(21, 5),PM(22, 5),PM(23, 5),PM(24, 5)/  DATH1190
     4 0.50000000D 02, 0.19737055D 04, 0.25021169D 03, 0.15646048D 04,   DATH1200
     5 0.25113557D 03, 0.13565724D 04, 0.25205945D 03, 0.12308706D 04,   DATH1210
     6 0.25298333D 03, 0.11436917D 04, 0.25390721D 03, 0.10752452D 04,   DATH1220
     7 0.25483110D 03, 0.10185428D 04, 0.25575498D 03, 0.97083113D 03,   DATH1230
     8 0.25667886D 03, 0.93021163D 03, 0.25760274D 03, 0.89387452D 03,   DATH1240
     9 0.25852662D 03, 0.86110107D 03, 0.25945050D 03, 0.66295517D 03/   DATH1250
      DATA PM(25, 5),PM(26, 5),PM(27, 5),PM(28, 5),PM(29, 5),PM(30, 5),  DATH1261
     1     PM(31, 5),PM(32, 5),PM(33, 5),PM(34, 5),PM(35, 5),PM(36, 5),  DATH1270
     2     PM(37, 5),PM(38, 5),PM(39, 5),PM(40, 5),PM(41, 5),PM(42, 5),  DATH1280
     3     PM(43, 5),PM(44, 5),PM(45, 5),PM(46, 5),PM(47, 5),PM(48, 5)/  DATH1290
     4 0.26868932D 03, 0.56070828D 03, 0.27792814D 03, 0.49476602D 03,   DATH1300
     5 0.28716696D 03, 0.44791507D 03, 0.29640577D 03, 0.41234855D 03,   DATH1310
     6 0.30564459D 03, 0.38239687D 03, 0.31488341D 03, 0.36066602D 03,   DATH1320
     7 0.32412223D 03, 0.34007266D 03, 0.33336104D 03, 0.32244723D 03,   DATH1330
     8 0.34259986D 03, 0.23835027D 03, 0.43498804D 03, 0.19788794D 03,   DATH1340
     9 0.52737621D 03, 0.17271407D 03, 0.61976439D 03, 0.15491979D 03/   DATH1350
      DATA PM(49, 5),PM(50, 5),PM(51, 5),PM(52, 5),PM(53, 5),PM(54, 5),  DATH1361
     1     PM(55, 5),PM(56, 5),PM(57, 5),PM(58, 5),PM(59, 5)/            DATH1370
     2 0.71215256D 03, 0.14195042D 03, 0.80454074D 03, 0.13158943D 03,   DATH1380
     3 0.89692891D 03, 0.12333136D 03, 0.98931709D 03, 0.11636890D 03,   DATH1390
     4 0.10817053D 04, 0.11049875D 03, 0.11731695D 04/                   DATH1400
      DATA PM( 1, 6),PM( 2, 6),PM( 3, 6),PM( 4, 6),PM( 5, 6),PM( 6, 6),  DATH1410
     1     PM( 7, 6),PM( 8, 6),PM( 9, 6),PM(10, 6),PM(11, 6),PM(12, 6),  DATH1420
     2     PM(13, 6),PM(14, 6),PM(15, 6),PM(16, 6),PM(17, 6),PM(18, 6),  DATH1430
     3     PM(19, 6),PM(20, 6),PM(21, 6),PM(22, 6),PM(23, 6),PM(24, 6)/  DATH1440
     4 0.10000000D 03, 0.29556555D 04, 0.29853843D 03, 0.25755588D 04,   DATH1450
     5 0.29942706D 03, 0.22727658D 04, 0.30031569D 03, 0.21244463D 04,   DATH1460
     6 0.30120431D 03, 0.19997874D 04, 0.30209294D 03, 0.18969554D 04,   DATH1470
     7 0.30298157D 03, 0.18107587D 04, 0.30387020D 03, 0.17376395D 04,   DATH1480
     8 0.30475882D 03, 0.16720310D 04, 0.30564745D 03, 0.16155240D 04,   DATH1490
     9 0.30653608D 03, 0.15639696D 04, 0.30742471D 03, 0.12327273D 04/   DATH1500
```

TABLE VIII (contd.)

```
      DATA PM(25, 6),PM(26, 6),PM(27, 6),PM(28, 6),PM(29, 6),PM(30, 6), DATH1511
     1     PM(31, 6),PM(32, 6),PM(33, 6),PM(34, 6),PM(35, 6),PM(36, 6), DATH1520
     2     PM(37, 6),PM(38, 6),PM(39, 6),PM(40, 6),PM(41, 6),PM(42, 6), DATH1530
     3     PM(43, 6),PM(44, 6),PM(45, 6),PM(46, 6),PM(47, 6),PM(48, 6)/ DATH1540
     4 0.31631098D 03, 0.10535740D 04, 0.32519725D 03, 0.93682529D 03,  DATH1550
     5 0.33408353D 03, 0.85188840D 03, 0.34296980D 03, 0.78682947D 03,  DATH1560
     6 0.35185607D 03, 0.73521478D 03, 0.36074235D 03, 0.69247896D 03,  DATH1570
     7 0.36962862D 03, 0.65632884D 03, 0.37851489D 03, 0.62588827D 03,  DATH1580
     8 0.38740117D 03, 0.46351225D 03, 0.47626390D 03, 0.38637513D 03,  DATH1590
     9 0.56512664D 03, 0.33730874D 03, 0.65398937D 03, 0.30293104D 03/  DATH1600
      DATA PM(49, 6),PM(50, 6),PM(51, 6),PM(52, 6),PM(53, 6),PM(54, 6), DATH1611
     1     PM(55, 6),PM(56, 6),PM(57, 6),PM(58, 6),PM(59, 6)/           DATH1620
     2 0.74285211D 03, 0.27749769D 03, 0.83171484D 03, 0.25767401D 03,  DATH1630
     3 0.92057758D 03, 0.24134689D 03, 0.10094403D 04, 0.22772273D 03,  DATH1640
     4 0.10983030D 04, 0.21601458D 03, 0.11862771D 04/                  DATH1650
      DATA PM( 1, 7),PM( 2, 7),PM( 3, 7),PM( 4, 7),PM( 5, 7),PM( 6, 7), DATH1660
     1     PM( 7, 7),PM( 8, 7),PM( 9, 7),PM(10, 7),PM(11, 7),PM(12, 7), DATH1670
     2     PM(13, 7),PM(14, 7),PM(15, 7),PM(16, 7),PM(17, 7),PM(18, 7), DATH1680
     3     PM(19, 7),PM(20, 7),PM(21, 7),PM(22, 7),PM(23, 7),PM(24, 7)/ DATH1690
     4 0.20000000D 03, 0.43651886D 04, 0.35550571D 03, 0.40070512D 04,  DATH1700
     5 0.35634854D 03, 0.37208476D 04, 0.35719137D 03, 0.35288077D 04,  DATH1710
     6 0.35803419D 03, 0.33695798D 04, 0.35887702D 03, 0.32358215D 04,  DATH1720
     7 0.35971985D 03, 0.31224023D 04, 0.36056268D 03, 0.30132691D 04,  DATH1730
     8 0.36140551D 03, 0.29253698D 04, 0.36224833D 03, 0.28389835D 04,  DATH1740
     9 0.36309116D 03, 0.27643289D 04, 0.36393399D 03, 0.22457138D 04/  DATH1750
      DATA PM(25, 7),PM(26, 7),PM(27, 7),PM(28, 7),PM(29, 7),PM(30, 7), DATH1761
     1     PM(31, 7),PM(32, 7),PM(33, 7),PM(34, 7),PM(35, 7),PM(36, 7), DATH1770
     2     PM(37, 7),PM(38, 7),PM(39, 7),PM(40, 7),PM(41, 7),PM(42, 7), DATH1780
     3     PM(43, 7),PM(44, 7),PM(45, 7),PM(46, 7),PM(47, 7),PM(48, 7)/ DATH1790
     4 0.37236227D 03, 0.19506153D 04, 0.38079055D 03, 0.17492891D 04,  DATH1800
     5 0.38921883D 03, 0.16002193D 04, 0.39764711D 03, 0.14863112D 04,  DATH1810
     6 0.40607539D 03, 0.13936630D 04, 0.41450367D 03, 0.13163808D 04,  DATH1820
     7 0.42293195D 03, 0.12519428D 04, 0.43136023D 03, 0.11950330D 04,  DATH1830
     8 0.43978851D 03, 0.90097399D 03, 0.52407130D 03, 0.75535767D 03,  DATH1840
     9 0.60835410D 03, 0.66135012D 03, 0.69263689D 03, 0.59482801D 03/  DATH1850
      DATA PM(49, 7),PM(50, 7),PM(51, 7),PM(52, 7),PM(53, 7),PM(54, 7), DATH1861
     1     PM(55, 7),PM(56, 7),PM(57, 7),PM(58, 7),PM(59, 7)/           DATH1870
     2 0.77691969D 03, 0.54484912D 03, 0.86120248D 03, 0.50516775D 03,  DATH1880
     3 0.94548528D 03, 0.47332953D 03, 0.10297681D 04, 0.44700688D 03,  DATH1890
     4 0.11140509D 04, 0.42393744D 03, 0.11974908D 04/                  DATH1900
      DATA PM( 1, 8),PM( 2, 8),PM( 3, 8),PM( 4, 8),PM( 5, 8),PM( 6, 8), DATH1910
     1     PM( 7, 8),PM( 8, 8),PM( 9, 8),PM(10, 8),PM(11, 8),PM(12, 8), DATH1920
     2     PM(13, 8),PM(14, 8),PM(15, 8),PM(16, 8),PM(17, 8),PM(18, 8), DATH1930
     3     PM(19, 8),PM(20, 8),PM(21, 8),PM(22, 8),PM(23, 8),PM(24, 8)/ DATH1940
     4 0.40000000D 03, 0.62248854D 04, 0.42416748D 03, 0.60196738D 04,  DATH1950
     5 0.42494790D 03, 0.58119695D 04, 0.42572833D 03, 0.56233463D 04,  DATH1960
     6 0.42650875D 03, 0.54510115D 04, 0.42728917D 03, 0.53047132D 04,  DATH1970
     7 0.42806959D 03, 0.51690987D 04, 0.42885002D 03, 0.50429130D 04,  DATH1980
     8 0.42963044D 03, 0.49250981D 04, 0.43041086D 03, 0.48147552D 04,  DATH1990
     9 0.43119129D 03, 0.47202183D 04, 0.43197171D 03, 0.39940543D 04/  DATH2000
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TABLE VIII (contd.)

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201          DATA PM(25, 8),PM(26, 8),PM(27, 8),PM(28, 8),PM(29, 8),PM(30, 8), DATH2011
202         1     PM(31, 8),PM(32, 8),PM(33, 8),PM(34, 8),PM(35, 8),PM(36, 8), DATH2020
203         2     PM(37, 8),PM(38, 8),PM(39, 8),PM(40, 8),PM(41, 8),PM(42, 8), DATH2030
204         3     PM(43, 8),PM(44, 8),PM(45, 8),PM(46, 8),PM(47, 8),PM(48, 8)/ DATH2040
205         4 0.43977594D 03, 0.35416765D 04, 0.44758017D 03, 0.32002223D 04, DATH2050
206         5 0.45538440D 03, 0.29407182D 04, 0.46318863D 03, 0.27551255D 04, DATH2060
207         6 0.47099286D 03, 0.25961585D 04, 0.47879709D 03, 0.24648031D 04, DATH2070
208         7 0.48660132D 03, 0.23521214D 04, 0.49440555D 03, 0.22540944D 04, DATH2080
209         8 0.50220978D 03, 0.17602868D 04, 0.58025209D 03, 0.14844242D 04, DATH2090
210         9 0.65829439D 03, 0.13047630D 04, 0.73633670D 03, 0.11751240D 04/ DATH2100
211          DATA PM(49, 8),PM(50, 8),PM(51, 8),PM(52, 8),PM(53, 8),PM(54, 8), DATH2111
212         1     PM(55, 8),PM(56, 8),PM(57, 8),PM(58, 8),PM(59, 8)/          DATH2120
213         2 0.81437900D 03, 0.10768626D 04, 0.89242131D 03, 0.99878059D 03, DATH2130
214         3 0.97046361D 03, 0.93647207D 03, 0.10485059D 04, 0.88265694D 03, DATH2140
215         4 0.11265482D 04, 0.83859745D 03, 0.12038101D 04/                 DATH2150
216          DATA PM( 1, 9),PM( 2, 9),PM( 3, 9),PM( 4, 9),PM( 5, 9),PM( 6, 9), DATH2160
217         1     PM( 7, 9),PM( 8, 9),PM( 9, 9),PM(10, 9),PM(11, 9),PM(12, 9), DATH2170
218         2     PM(13, 9),PM(14, 9),PM(15, 9),PM(16, 9),PM(17, 9),PM(18, 9), DATH2180
219         3     PM(19, 9),PM(20, 9),PM(21, 9),PM(22, 9),PM(23, 9),PM(24, 9)/ DATH2190
220         4 0.50000000D 03, 0.69737926D 04, 0.44952416D 03, 0.68146575D 04, DATH2200
221         5 0.45027930D 03, 0.66247303D 04, 0.45103445D 03, 0.64492787D 04, DATH2210
222         6 0.45178959D 03, 0.62865341D 04, 0.45254474D 03, 0.61350164D 04, DATH2220
223         7 0.45329988D 03, 0.59934762D 04, 0.45405502D 03, 0.58733289D 04, DATH2230
224         8 0.45481017D 03, 0.57480762D 04, 0.45556531D 03, 0.56414308D 04, DATH2240
225         9 0.45632046D 03, 0.55403751D 04, 0.45707560D 03, 0.47230444D 04/ DATH2250
226          DATA PM(25, 9),PM(26, 9),PM(27, 9),PM(28, 9),PM(29, 9),PM(30, 9), DATH2261
227         1     PM(31, 9),PM(32, 9),PM(33, 9),PM(34, 9),PM(35, 9),PM(36, 9), DATH2270
228         2     PM(37, 9),PM(38, 9),PM(39, 9),PM(40, 9),PM(41, 9),PM(42, 9), DATH2280
229         3     PM(43, 9),PM(44, 9),PM(45, 9),PM(46, 9),PM(47, 9),PM(48, 9)/ DATH2290
230         4 0.46462704D 03, 0.42183741D 04, 0.47217848D 03, 0.38606560D 04, DATH2300
231         5 0.47972991D 03, 0.35816476D 04, 0.48728135D 03, 0.33561932D 04, DATH2310
232         6 0.49483279D 03, 0.31726605D 04, 0.50238423D 03, 0.30171415D 04, DATH2320
233         7 0.50993567D 03, 0.28832049D 04, 0.51748711D 03, 0.27663115D 04, DATH2330
234         8 0.52503854D 03, 0.21823377D 04, 0.60055293D 03, 0.18484963D 04, DATH2340
235         9 0.67606731D 03, 0.16261758D 04, 0.75158169D 03, 0.14654769D 04/ DATH2350
236          DATA PM(49, 9),PM(50, 9),PM(51, 9),PM(52, 9),PM(53, 9),PM(54, 9), DATH2361
237         1     PM(55, 9),PM(56, 9),PM(57, 9),PM(58, 9),PM(59, 9)/          DATH2370
238         2 0.82709608D 03, 0.13430019D 04, 0.90261046D 03, 0.12467413D 04, DATH2380
239         3 0.97812484D 03, 0.11689150D 04, 0.10536392D 04, 0.11019686D 04, DATH2390
240         4 0.11291536D 04, 0.10473119D 04, 0.12039128D 04/                 DATH2400
241          DATA PM( 1,10),PM( 2,10),PM( 3,10),PM( 4,10),PM( 5,10),PM( 6,10), DATH2410
242         1     PM( 7,10),PM( 8,10),PM( 9,10),PM(10,10),PM(11,10),PM(12,10), DATH2420
243         2     PM(13,10),PM(14,10),PM(15,10),PM(16,10),PM(17,10),PM(18,10), DATH2430
244         3     PM(19,10),PM(20,10),PM(21,10),PM(22,10),PM(23,10),PM(24,10)/ DATH2440
245         4 0.60000000D 03, 0.76366824D 04, 0.47169686D 03, 0.75284944D 04, DATH2450
246         5 0.47242882D 03, 0.73416621D 04, 0.47316078D 03, 0.71675681D 04, DATH2460
247         6 0.47389274D 03, 0.70211837D 04, 0.47462470D 03, 0.68676885D 04, DATH2470
248         7 0.47535666D 03, 0.67381718D 04, 0.47608862D 03, 0.66155795D 04, DATH2480
249         8 0.47682059D 03, 0.64993123D 04, 0.47755255D 03, 0.63888412D 04, DATH2490
250         9 0.47828451D 03, 0.62836970D 04, 0.47901647D 03, 0.54300528D 04/ DATH2500
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TABLE VIII (contd.)

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      DATA PM(25,10),PM(26,10),PM(27,10),PM(28,10),PM(29,10),PM(30,10),  DATH2511
     1     PM(31,10),PM(32,10),PM(33,10),PM(34,10),PM(35,10),PM(36,10),  DATH2520
     2     PM(37,10),PM(38,10),PM(39,10),PM(40,10),PM(41,10),PM(42,10),  DATH2530
     3     PM(43,10),PM(44,10),PM(45,10),PM(46,10),PM(47,10).PM(48,10)/  DATH2540
     4 0.48633607D 03, 0.48957119D 04, 0.49365568D 03, 0.45000172D 04,  DATH2550
     5 0.50097528D 03, 0.41881224D 04, 0.50829489D 03, 0.39387951D 04,  DATH2560
     6 0.51561450D 03, 0.37305406D 04, 0.52293410D 03, 0.35532560D 04,  DATH2570
     7 0.53025371D 03, 0.34000042D 04, 0.53757331D 03, 0.32658432D 04,  DATH2580
     8 0.54489292D 03, 0.26109690D 04, 0.61808898D 03, 0.22129391D 04,  DATH2590
     9 0.69128503D 03, 0.19526223D 04, 0.76448109D 03, 0.17601513D 04/  DATH2600
      DATA PM(49,10),PM(50,10),PM(51,10),PM(52,10),PM(53,10),PM(54,10),  DATH2611
     1     PM(55,10),PM(56,10),PM(57,10),PM(58,10),PM(59,10)/          DATH2620
     2 0.83767715D 03, 0.16130819D 04, 0.91087321D 03, 0.14964686D 04,  DATH2630
     3 0.98406926D 03, 0.14032957D 04, 0.10572653D 04, 0.13238290D 04,  DATH2640
     4 0.11304614D 04, 0.12581096D 04, 0.12029254D 04/                  DATH2650
      DATA PM( 1,11),PM( 2,11),PM( 3,11),PM( 4,11),PM( 5,11),PM( 6,11),  DATH2660
     1     PM( 7,11),PM( 8,11),PM( 9,11),PM(10,11),PM(11,11),PM(12,11),  DATH2670
     2     PM(13,11),PM(14,11),PM(15,11),PM(16,11),PM(17,11),PM(18,11),  DATH2680
     3     PM(19,11),PM(20,11),PM(21,11),PM(22,11),PM(23,11),PM(24,11)/  DATH2690
     4 0.70000000D 03, 0.82272668D 04, 0.49160266D 03, 0.81498527D 04,  DATH2700
     5 0.49231290D 03, 0.79877197D 04, 0.49302314D 03, 0.78160272D 04,  DATH2710
     6 0.49373338D 03, 0.76722650D 04, 0.49444362D 03, 0.75360272D 04,  DATH2720
     7 0.49515386D 03, 0.74066762D 04, 0.49586410D 03, 0.71879050D 04,  DATH2730
     8 0.49657434D 03, 0.70880561D 04, 0.49728458D 03, 0.69923649D 04,  DATH2740
     9 0.49799482D 03, 0.69005522D 04, 0.49870506D 03, 0.60963439D 04/  DATH2750
      DATA PM(25,11),PM(26,11),PM(27,11),PM(28,11),PM(29,11),PM(30,11),  DATH2761
     1     PM(31,11),PM(32,11),PM(33,11),PM(34,11),PM(35,11),PM(36,11),  DATH2770
     2     PM(37,11),PM(38,11),PM(39,11),PM(40,11),PM(41,11),PM(42,11),  DATH2780
     3     PM(43,11),PM(44,11),PM(45,11),PM(46,11),PM(47,11),PM(48,11)/  DATH2790
     4 0.50580745D 03, 0.55291256D 04, 0.51290985D 03, 0.51035043D 04,  DATH2800
     5 0.52001224D 03, 0.47706372D 04, 0.52711464D 03, 0.44972029D 04,  DATH2810
     6 0.53421703D 03, 0.42674835D 04, 0.54131942D 03, 0.40754548D 04,  DATH2820
     7 0.54842182D 03, 0.39046526D 04, 0.55552421D 03, 0.37546837D 04,  DATH2830
     8 0.56262661D 03, 0.30317924D 04, 0.63365055D 03, 0.25781012D 04,  DATH2840
     9 0.70467449D 03, 0.22760148D 04, 0.77569843D 03, 0.20557324D 04/  DATH2850
      DATA PM(49,11),PM(50,11),PM(51,11),PM(52,11),PM(53,11),PM(54,11),  DATH2861
     1     PM(55,11),PM(56,11),PM(57,11),PM(58,11),PM(59,11)/          DATH2870
     2 0.84672238D 03, 0.18823585D 04, 0.91774632D 03, 0.17491320D 04,  DATH2880
     3 0.98877026D 03, 0.16408859D 04, 0.10597942D 04, 0.15482744D 04,  DATH2890
     4 0.11308181D 04, 0.14715057D 04, 0.12011318D 04/                  DATH2900
      DATA PM( 1,12),PM( 2,12),PM( 3,12),PM( 4,12),PM( 5,12),PM( 6,12),  DATH2910
     1     PM( 7,12),PM( 8,12),PM( 9,12),PM(10,12),PM(11,12),PM(12,12),  DATH2920
     2     PM(13,12),PM(14,12),PM(15,12),PM(16,12),PM(17,12),PM(18,12),  DATH2930
     3     PM(19,12),PM(20,12),PM(21,12),PM(22,12),PM(23,12),PM(24,12)/  DATH2940
     4 0.80000000D 03, 0.87567068D 04, 0.50981140D 03, 0.87154785D 04,  DATH2950
     5 0.51050097D 03, 0.85078314D 04, 0.51119055D 03, 0.83812664D 04,  DATH2960
     6 0.51188013D 03, 0.81926782D 04, 0.51256970D 03, 0.80788236D 04,  DATH2970
     7 0.51325928D 03, 0.79697136D 04, 0.51394885D 03, 0.78476794D 04,  DATH2980
     8 0.51463843D 03, 0.77310006D 04, 0.51532800D 03, 0.76353792D 04,  DATH2990
     9 0.51601758D 03, 0.75277311D 04, 0.51670715D 03, 0.67200413D 04/  DATH3000
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TABLE VIII (contd.)

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      DATA PM(25,12),PM(26,12),PM(27,12),PM(28,12),PM(29,12),PM(30,12),  DATH3011
     1     PM(31,12),PM(32,12),PM(33,12),PM(34,12),PM(35,12),PM(36,12),  DATH3020
     2     PM(37,12),PM(38,12),PM(39,12),PM(40,12),PM(41,12),PM(42,12),  DATH3030
     3     PM(43,12),PM(44,12),PM(45,12),PM(46,12),PM(47,12),PM(48,12)/  DATH3040
     4 0.52360290D 03, 0.61284947D 04, 0.53049866D 03, 0.56870826D 04,   DATH3050
     5 0.53739441D 03, 0.53315664D 04, 0.54429016D 03, 0.50374146D 04,   DATH3060
     6 0.55118591D 03, 0.47888960D 04, 0.55808167D 03, 0.45804089D 04,   DATH3070
     7 0.56497742D 03, 0.43940918D 04, 0.57187317D 03, 0.42249035D 04,   DATH3080
     8 0.57876892D 03, 0.34531471D 04, 0.64772645D 03, 0.29519391D 04,   DATH3090
     9 0.71668397D 03, 0.26073216D 04, 0.78564150D 03, 0.23553107D 04/   DATH3100
      DATA PM(49,12),PM(50,12),PM(51,12),PM(52,12),PM(53,12),PM(54,12),  DATH3111
     1     PM(55,12),PM(56,12),PM(57,12),PM(58,12),PM(59,12)/            DATH3120
     2 0.85459903D 03, 0.21596086D 04, 0.92355655D 03, 0.20050590D 04,   DATH3130
     3 0.99251408D 03, 0.18787281D 04, 0.10614716D 04, 0.17729950D 04,   DATH3140
     4 0.11304291D 04, 0.16852387D 04, 0.11986970D 04/                   DATH3150
      DATA PM( 1,13),PM( 2,13),PM( 3,13),PM( 4,13),PM( 5,13),PM( 6,13),  DATH3160
     1     PM( 7,13),PM( 8,13),PM( 9,13),PM(10,13),PM(11,13),PM(12,13),  DATH3170
     2     PM(13,13),PM(14,13),PM(15,13),PM(16,13),PM(17,13),PM(18,13),  DATH3180
     3     PM(19,13),PM(20,13),PM(21,13),PM(22,13),PM(23,13),PM(24,13)/  DATH3190
     4 0.90000000D 03, 0.92362501D 04, 0.52670425D 03, 0.91865453D 04,   DATH3200
     5 0.52737394D 03, 0.90369446D 04, 0.52804363D 03, 0.88943492D 04,   DATH3210
     6 0.52871332D 03, 0.87582263D 04, 0.52938301D 03, 0.86479047D 04,   DATH3220
     7 0.53005270D 03, 0.85225989D 04, 0.53072240D 03, 0.84025206D 04,   DATH3230
     8 0.53139209D 03, 0.83051367D 04, 0.53206178D 03, 0.81938684D 04,   DATH3240
     9 0.53273147D 03, 0.81036202D 04, 0.53340116D 03, 0.72920543D 04/   DATH3250
      DATA PM(25,13),PM(26,13),PM(27,13),PM(28,13),PM(29,13),PM(30,13),  DATH3261
     1     PM(31,13),PM(32,13),PM(33,13),PM(34,13),PM(35,13),PM(36,13),  DATH3270
     2     PM(37,13),PM(38,13),PM(39,13),PM(40,13),PM(41,13),PM(42,13),  DATH3280
     3     PM(43,13),PM(44,13),PM(45,13),PM(46,13),PM(47,13),PM(48,13)/  DATH3290
     4 0.54009806D 03, 0.66965516D 04, 0.54679497D 03, 0.62379268D 04,   DATH3300
     5 0.55349187D 03, 0.58649979D 04, 0.56018877D 03, 0.55609597D 04,   DATH3310
     6 0.56688568D 03, 0.52961645D 04, 0.57358258D 03, 0.50732526D 04,   DATH3320
     7 0.58027949D 03, 0.48397859D 04, 0.58697639D 03, 0.47060436D 04,   DATH3330
     8 0.59367330D 03, 0.38866563D 04, 0.66064234D 03, 0.33160080D 04,   DATH3340
     9 0.72761138D 03, 0.29396782D 04, 0.79458042D 03, 0.26531311D 04/   DATH3350
      DATA PM(49,13),PM(50,13),PM(51,13),PM(52,13),PM(53,13),PM(54,13),  DATH3361
     1     PM(55,13),PM(56,13),PM(57,13),PM(58,13),PM(59,13)/            DATH3370
     2 0.86154946D 03, 0.24383619D 04, 0.92851851D 03, 0.22649972D 04,   DATH3380
     3 0.99548755D 03, 0.21213654D 04, 0.10624566D 04, 0.20031482D 04,   DATH3390
     4 0.11294256D 04, 0.19048698D 04, 0.11957250D 04/                   DATH3400
      DATA PM( 1,14),PM( 2,14),PM( 3,14),PM( 4,14),PM( 5,14),PM( 6,14),  DATH3410
     1     PM( 7,14),PM( 8,14),PM( 9,14),PM(10,14),PM(11,14),PM(12,14),  DATH3420
     2     PM(13,14),PM(14,14),PM(15,14),PM(16,14),PM(17,14),PM(18,14),  DATH3430
     3     PM(19,14),PM(20,14),PM(21,14),PM(22,14),PM(23,14),PM(24,14)/  DATH3440
     4 0.10000000D 04, 0.96698127D 04, 0.54255066D 03, 0.96379718D 04,   DATH3450
     5 0.54320104D 03, 0.95187110D 04, 0.54385143D 03, 0.93815534D 04,   DATH3460
     6 0.54450182D 03, 0.92716327D 04, 0.54515220D 03, 0.91447421D 04,   DATH3470
     7 0.54580259D 03, 0.90430138D 04, 0.54645297D 03, 0.89251616D 04,   DATH3480
     8 0.54710336D 03, 0.88306660D 04, 0.54775374D 03, 0.87208202D 04,   DATH3490
     9 0.54840413D 03, 0.86327477D 04, 0.54905451D 03, 0.78397755D 04/   DATH3500
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TABLE VIII (contd.)

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      DATA PM(25,14),PM(26,14),PM(27,14),PM(28,14),PM(29,14),PM(30,14),  DATH3511
     1     PM(31,14),PM(32,14),PM(33,14),PM(34,14),PM(35,14),PM(36,14),  DATH3520
     2     PM(37,14),PM(38,14),PM(39,14),PM(40,14),PM(41,14),PM(42,14),  DATH3530
     3     PM(43,14),PM(44,14),PM(45,14),PM(46,14),PM(47,14),PM(48,14)/  DATH3540
     4 0.55555837D 03, 0.72352608D 04, 0.56206222D 03, 0.67645686D 04,   DATH3550
     5 0.56856608D 03, 0.63866703D 04, 0.57506993D 03, 0.60384454D 04,   DATH3560
     6 0.58157379D 03, 0.57754700D 04, 0.58807764D 03, 0.55206634D 04,   DATH3570
     7 0.59458150D 03, 0.53212736D 04, 0.60108535D 03, 0.51900123D 04,   DATH3580
     8 0.60758921D 03, 0.43117547D 04, 0.67262775D 03, 0.37069297D 04,   DATH3590
     9 0.73766630D 03, 0.32785492D 04, 0.80270485D 03, 0.29640857D 04/   DATH3600
      DATA PM(49,14),PM(50,14),PM(51,14),PM(52,14),PM(53,14),PM(54,14),  DATH3611
     1     PM(55,14),PM(56,14),PM(57,14),PM(58,14),PM(59,14)/            DATH3620
     2 0.86774340D 03, 0.27184155D 04, 0.93278195D 03, 0.25268527D 04,   DATH3630
     3 0.99782049D 03, 0.23699277D 04, 0.10628590D 04, 0.22380367D 04,   DATH3640
     4 0.11278976D 04, 0.21249484D 04, 0.11922857D 04/                   DATH3650
      DATA PM( 1,15),PM( 2,15),PM( 3,15),PM( 4,15),PM( 5,15),PM( 6,15),  DATH3660
     1     PM( 7,15),PM( 8,15),PM( 9,15),PM(10,15),PM(11,15),PM(12,15),  DATH3670
     2     PM(13,15),PM(14,15),PM(15,15),PM(16,15),PM(17,15),PM(18,15),  DATH3680
     3     PM(19,15),PM(20,15),PM(21,15),PM(22,15),PM(23,15),PM(24,15)/  DATH3690
     4 0.14000000D 04, 0.11153878D 05, 0.59882953D 03, 0.11114695D 05,   DATH3700
     5 0.59940601D 03, 0.11023777D 05, 0.59998248D 03, 0.10935160D 05,   DATH3710
     6 0.60055896D 03, 0.10824250D 05, 0.60113544D 03, 0.10740498D 05,   DATH3720
     7 0.60171192D 03, 0.10658759D 05, 0.60228839D 03, 0.10578952D 05,   DATH3730
     8 0.60286487D 03, 0.10501005D 05, 0.60344135D 03, 0.10402988D 05,   DATH3740
     9 0.60401782D 03, 0.10328995D 05, 0.60459430D 03, 0.96529195D 04/   DATH3750
      DATA PM(25,15),PM(26,15),PM(27,15),PM(28,15),PM(29,15),PM(30,15),  DATH3761
     1     PM(31,15),PM(32,15),PM(33,15),PM(34,15),PM(35,15),PM(36,15),  DATH3770
     2     PM(37,15),PM(38,15),PM(39,15),PM(40,15),PM(41,15),PM(42,15),  DATH3780
     3     PM(43,15),PM(44,15),PM(45,15),PM(46,15),PM(47,15),PM(48,15)/  DATH3790
     4 0.61035907D 03, 0.90851395D 04, 0.61612385D 03, 0.86244273D 04,   DATH3800
     5 0.62188862D 03, 0.82315907D 04, 0.62765339D 03, 0.78916747D 04,   DATH3810
     6 0.63341817D 03, 0.75939611D 04, 0.63918294D 03, 0.73054111D 04,   DATH3820
     7 0.64494771D 03, 0.72131545D 04, 0.65071249D 03, 0.70524429D 04,   DATH3830
     8 0.65647726D 03, 0.60582937D 04, 0.71412499D 03, 0.52735113D 04,   DATH3840
     9 0.77177272D 03, 0.46694008D 04, 0.82942045D 03, 0.42278200D 04/   DATH3850
      DATA PM(49,15),PM(50,15),PM(51,15),PM(52,15),PM(53,15),PM(54,15),  DATH3861
     1     PM(55,15),PM(56,15),PM(57,15),PM(58,15),PM(59,15)/            DATH3870
     2 0.88706818D 03, 0.38845710D 04, 0.94471591D 03, 0.36116173D 04,   DATH3880
     3 0.10023636D 04, 0.33915424D 04, 0.10600114D 04, 0.32023508D 04,   DATH3890
     4 0.11176591D 04, 0.30463219D 04, 0.11747303D 04/                   DATH3900
      DATA PM( 1,16),PM( 2,16),PM( 3,16),PM( 4,16),PM( 5,16),PM( 6,16),  DATH3910
     1     PM( 7,16),PM( 8,16),PM( 9,16),PM(10,16),PM(11,16),PM(12,16),  DATH3920
     2     PM(13,16),PM(14,16),PM(15,16),PM(16,16),PM(17,16),PM(18,16),  DATH3930
     3     PM(19,16),PM(20,16),PM(21,16),PM(22,16),PM(23,16),PM(24,16)/  DATH3940
     4 0.18000000D 04, 0.12092534D 05, 0.64848967D 03, 0.12060637D 05,   DATH3950
     5 0.64899351D 03, 0.11997142D 05, 0.64949736D 03, 0.11934703D 05,   DATH3960
     6 0.65000120D 03, 0.11873291D 05, 0.65050504D 03, 0.11812880D 05,   DATH3970
     7 0.65100889D 03, 0.11753444D 05, 0.65151273D 03, 0.11694956D 05,   DATH3980
     8 0.65201657D 03, 0.11637392D 05, 0.65252041D 03, 0.11580728D 05,   DATH3990
     9 0.65302426D 03, 0.11524943D 05, 0.65352810D 03, 0.10990746D 05/   DATH4000
```

TABLE VIII (contd.)

```
      DATA PM(25,16),PM(26,16),PM(27,16),PM(28,16),PM(29,16),PM(30,16),  DATH4011
     1     PM(31,16),PM(32,16),PM(33,16),PM(34,16),PM(35,16),PM(36,16),  DATH4020
     2     PM(37,16),PM(38,16),PM(39,16),PM(40,16),PM(41,16),PM(42,16),  DATH4030
     3     PM(43,16),PM(44,16),PM(45,16),PM(46,16),PM(47,16),PM(48,16)/  DATH4040
     4 0.658566520 03, 0.105293410 05, 0.663604950 03, 0.101258210 05,  DATH4050
     5 0.668643370 03, 0.976922760 04, 0.673681800 03, 0.945130080 04,  DATH4060
     6 0.678720220 03, 0.924568310 04, 0.683758650 03, 0.919223600 04,  DATH4070
     7 0.688797080 03, 0.906030080 04, 0.693835500 03, 0.899927050 04,  DATH4080
     8 0.698873930 03, 0.792429010 04, 0.749258180 03, 0.692859610 04,  DATH4090
     9 0.799642430 03, 0.614461650 04, 0.850026690 03, 0.556270910 04/  DATH4100
      DATA PM(49,16),PM(50,16),PM(51,16),PM(52,16),PM(53,16),PM(54,16),  DATH4111
     1     PM(55,16),PM(56,16),PM(57,16),PM(58,16),PM(59,16)/            DATH4120
     2 0.900410940 03, 0.511685940 04, 0.950795190 03, 0.476684120 04,  DATH4130
     3 0.100117940 04, 0.448670600 04, 0.105156370 04, 0.424275610 04,  DATH4140
     4 0.110194800 04, 0.403939170 04, 0.115182830 04/                  DATH4150
      DATA PM( 1,17),PM( 2,17),PM( 3,17),PM( 4,17),PM( 5,17),PM( 6,17),  DATH4160
     1     PM( 7,17),PM( 8,17),PM( 9,17),PM(10,17),PM(11,17),PM(12,17),  DATH4170
     2     PM(13,17),PM(14,17),PM(15,17),PM(16,17),PM(17,17),PM(18,17),  DATH4180
     3     PM(19,17),PM(20,17),PM(21,17),PM(22,17),PM(23,17),PM(24,17)/  DATH4190
     4 0.200000000 04, 0.125486250 05, 0.672111350 03, 0.125274330 05,  DATH4200
     5 0.672577580 03, 0.124775840 05, 0.673043800 03, 0.124283590 05,  DATH4210
     6 0.673510020 03, 0.123540950 05, 0.673976250 03, 0.123064290 05,  DATH4220
     7 0.674442470 03, 0.122593430 05, 0.674908700 03, 0.122128260 05,  DATH4230
     8 0.675374920 03, 0.121668660 05, 0.675841150 03, 0.120976230 05,  DATH4240
     9 0.676307370 03, 0.120530560 05, 0.676773600 03, 0.115933330 05/  DATH4250
      DATA PM(25,17),PM(26,17),PM(27,17),PM(28,17),PM(29,17),PM(30,17),  DATH4261
     1     PM(31,17),PM(32,17),PM(33,17),PM(34,17),PM(35,17),PM(36,17),  DATH4270
     2     PM(37,17),PM(38,17),PM(39,17),PM(40,17),PM(41,17),PM(42,17),  DATH4280
     3     PM(43,17),PM(44,17),PM(45,17),PM(46,17),PM(47,17),PM(48,17)/  DATH4290
     4 0.681435840 03, 0.111578090 05, 0.686098090 03, 0.107656520 05,  DATH4300
     5 0.690760330 03, 0.104673440 05, 0.695422580 03, 0.102845630 05,  DATH4310
     6 0.700084820 03, 0.102759590 05, 0.704747070 03, 0.101801330 05,  DATH4320
     7 0.709409310 03, 0.101127060 05, 0.714071560 03, 0.100472700 05,  DATH4330
     8 0.718733800 03, 0.898781040 04, 0.765356250 03, 0.781727520 04,  DATH4340
     9 0.811978700 03, 0.690306970 04, 0.858601150 03, 0.625022540 04/  DATH4350
      DATA PM(49,17),PM(50,17),PM(51,17),PM(52,17),PM(53,17),PM(54,17),  DATH4361
     1     PM(55,17),PM(56,17),PM(57,17),PM(58,17),PM(59,17)/            DATH4370
     2 0.905223600 03, 0.576119570 04, 0.951846050 03, 0.538977220 04,  DATH4380
     3 0.998468500 03, 0.508105730 04, 0.104509090 04, 0.481543700 04,  DATH4390
     4 0.109171340 04, 0.458928020 04, 0.113786960 04/                  DATH4400
      DATA PM( 1,18),PM( 2,18),PM( 3,18),PM( 4,18),PM( 5,18),PM( 6,18),  DATH4410
     1     PM( 7,18),PM( 8,18),PM( 9,18),PM(10,18),PM(11,18),PM(12,18),  DATH4420
     2     PM(13,18),PM(14,18),PM(15,18),PM(16,18),PM(17,18),PM(18,18),  DATH4430
     3     PM(19,18),PM(20,18),PM(21,18),PM(22,18),PM(23,18),PM(24,18)/  DATH4440
     4 0.220000000 04, 0.128134580 05, 0.695462320 03, 0.127977060 05,  DATH4450
     5 0.695889020 03, 0.127375130 05, 0.696315720 03, 0.127038560 05,  DATH4460
     6 0.696742410 03, 0.126704560 05, 0.697169110 03, 0.126123540 05,  DATH4470
     7 0.697595810 03, 0.125797340 05, 0.698022500 03, 0.125473580 05,  DATH4480
     8 0.698449200 03, 0.125152230 05, 0.698875900 03, 0.124595990 05,  DATH4490
     9 0.699302600 03, 0.124281950 05, 0.699729290 03, 0.120637980 05/  DATH4500
```

TABLE VIII (contd.)

```
451            DATA PM(25,18),PM(26,18),PM(27,18),PM(28,18),PM(29,18),PM(30,18),  DATH4511
452           1     PM(31,18),PM(32,18),PM(33,18),PM(34,18),PM(35,18),PM(36,18),  DATH4520
453           2     PM(37,18),PM(38,18),PM(39,18),PM(40,18),PM(41,18),PM(42,18),  DATH4530
454           3     PM(43,18),PM(44,18),PM(45,18),PM(46,18),PM(47,18),PM(48,18)/  DATH4540
455           4 0.70399626D 03, 0.11751453D 05, 0.70826323D 03, 0.11464110D 05,   DATH4550
456           5 0.71253020D 03, 0.11375772D 05, 0.71679717D 03, 0.11364155D 05,   DATH4560
457           6 0.72106414D 03, 0.11429088D 05, 0.72533111D 03, 0.11397517D 05,   DATH4570
458           7 0.72959808D 03, 0.11351836D 05, 0.73386505D 03, 0.11291398D 05,   DATH4580
459           8 0.73813202D 03, 0.10144490D 05, 0.78080172D 03, 0.84951C54D 04,   DATH4590
460           9 0.82347142D 03, 0.74811964D 04, 0.86614112D 03, 0.68680311D 04/   DATH4600
461            DATA PM(49,18),PM(50,18),PM(51,18),PM(52,18),PM(53,18),PM(54,18),  DATH4611
462           1     PM(55,18),PM(56,18),PM(57,18),PM(58,18),PM(59,18)/            DATH4620
463           2 0.90881083D 03, 0.64129876D 04, 0.95148053D 03, 0.60360975D 04,   DATH4630
464           3 0.99415023D 03, 0.57181600D 04, 0.10368199D 04, 0.54250196D 04,   DATH4640
465           4 0.10794896D 04, 0.51763832D 04, 0.11217326D 04/                   DATH4650
466            END                                                                DATH4660
```

(e) Homogeneous Equilibrium Model (HEM). The homogeneous equilibrium critical flow model is also, in reality, a sonic model. It differs from the sonic model described in Section 3.6.8 (2) (b) only in how it is utilized by the RELAP4 code. HEM critical velocity and sonic model critical velocity are calculated from the same formula, Equation (149). The HEM critical mass flux is then calculated from

$$G = \rho a\Big|_{throat} \tag{165}$$

where the throat density, ρ, is that for an isentropic expansion from the same stagnation conditions as are used to fix the acoustic or critical velocity. These values of HEM critical mass flux are listed in Table IX against upstream volume stagnation pressure and enthalpy.

An understanding is needed as to exactly how this model differs from the sonic model described in Section 3.6.8 (2) (b). As mentioned there, the local upstream volume specific internal energy and specific volume are the independent variables entered in the steam tables. Parameters returned include the corresponding pressure, enthalpy, and sonic velocity for this upstream volume.

The local downstream junction critical mass flow rate is computed from the one-dimensional continuity equation for the sonic model using the following:

(1) The junction critical velocity is equal to the upstream volume critical velocity

(2) The junction density is first equated to the upstream volume density. This is modified by the frictional loss and kinetic energy change to the junction. The fluid is then expanded isentropically from the Mach number just upstream from the junction to a Mach number of one in the junction. The junction density used in the continuity equation, Equation (148), is the upstream volume density after the foregoing transformation.

TABLE IX

HOMOGENOUS EQUILIBRIUM MODEL CRITICAL FLOW TABLES

```
      BLOCK DATA                                                        DATT0010
      IMPLICIT REAL*8 (A-H,O-Z)                                         DATT0030
C                                                                       DATT0040
      COMMON / LEAKT / T01(55), T02(55), T03(55), T04(55), T05(55),     DATT0050
     1         T06(55), T07(55), T08(55), T09(55), T10(55), T11(55),    DATT0060
     2         T12(55), T13(55), T14(55), T15(55), T16(55), T17(55),    DATT0070
     3         T18(55), T19(55), T20(55), T21(55), NGHT, NPT            DATT0080
C                                                                       DATT0100
C     CRITICAL FLOW TABLES (HOMOGENEOUS EQUILIBRIUM MODEL)              DATT0110
C                                                                       DATT0120
C     TXX(1)      = STAGNATION PRESSURE  (PSIA)                         DATT0130
C     TXX(EVEN)   = CRITICAL FLOW RATE   (LBM/SEC-FT2)                  DATT0140
C     TXX(ODD)    = STAGNATION ENTHALPY  (BTU/LBM)                      DATT0150
C                                                                       DATT0160
C     NGHT = NUMBER OF PAIRS OF FLOW RATE AND ENTHALPY VALUES PER       DATT0170
C            PRESSURE                                                   DATT0180
C     NPT  = NUMBER OF PRESSURE VALUES                                  DATT0190
C                                                                       DATT0200
      DATA NGHT, NPT / 27,21 /                                          DATT0210
C                                                                       DATT0220
      DATA T01 /                                                                1.0D0,DATT0230
     1  716.13D0,   8.030D0,  711.91D0,  18.057D0,  658.45D0,  28.062D0,DATT0240
     2  681.49D0,  38.054D0,  535.31D0,  48.038D0,  447.12D0,  58.019D0,DATT0250
     3  442.29D0,  67.999D0,   20.41D0,  69.733D0,    6.75D0, 173.340D0,DATT0260
     4    5.02D0, 276.948D0,    4.17D0, 380.555D0,    3.65D0, 484.163D0,DATT0270
     5    3.29D0, 587.771D0,    3.01D0, 691.378D0,    2.80D0, 794.986D0,DATT0280
     6    2.62D0, 898.594D0,    2.48D0,1002.201D0,    2.35D0,1105.809D0,DATT0290
     7    2.35D0,1114.029D0,    2.18D0,1186.541D0,    1.97D0,1260.427D0,DATT0300
     8    1.81D0,1336.135D0,    1.67D0,1423.810D0,    1.55D0,1514.346D0,DATT0310
     9    1.46D0,1607.840D0,    1.38D0,1704.280D0,    1.31D0,1803.545D0/DATT0320
      DATA T02 /                                                                5.0D0,DATT0430
     1 1681.25D0,   8.042D0, 1665.45D0,  38.065D0, 1579.07D0,  68.010D0,DATT0440
     2 1378.69D0,  87.975D0, 1162.01D0, 107.955D0,  852.83D0, 117.953D0,DATT0450
     3  385.75D0, 127.958D0,   83.89D0, 130.196D0,   31.49D0, 230.286D0,DATT0460
     4   23.69D0, 330.376D0,   19.80D0, 430.465D0,   17.36D0, 530.555D0,DATT0470
     5   15.65D0, 630.645D0,   14.36D0, 730.734D0,   13.35D0, 830.824D0,DATT0480
     6   12.52D0, 930.914D0,   11.83D0,1031.003D0,   11.25D0,1131.093D0,DATT0490
     7   11.22D0,1139.325D0,   10.47D0,1213.338D0,    9.53D0,1288.228D0,DATT0500
     8    8.80D0,1364.831D0,    8.20D0,1443.519D0,    7.71D0,1524.467D0,DATT0510
     9    7.30D0,1607.747D0,    6.90D0,1704.209D0,    6.56D0,1803.492D0/DATT0520
      DATA T03 /                                                               10.0D0,DATT0630
     1 2391.40D0,   8.057D0, 2236.70D0,  78.004D0, 2047.90D0, 107.967D0,DATT0640
     2 1724.77D0, 127.970D0, 1505.41D0, 137.983D0, 1192.82D0, 148.006D0,DATT0650
     3  659.12D0, 158.038D0,  151.52D0, 161.261D0,   60.84D0, 259.470D0,DATT0660
     4   46.07D0, 357.678D0,   38.62D0, 455.887D0,   33.92D0, 554.096D0,DATT0670
     5   30.60D0, 652.305D0,   28.10D0, 750.513D0,   26.13D0, 848.722D0,DATT0680
     6   24.53D0, 946.931D0,   23.18D0,1045.140D0,   22.04D0,1143.348D0,DATT0690
     7   22.01D0,1146.574D0,   20.69D0,1221.805D0,   18.86D0,1297.280D0,DATT0700
     8   17.44D0,1374.284D0,   16.28D0,1453.321D0,   15.32D0,1534.604D0,DATT0710
     9   14.50D0,1618.208D0,   13.80D0,1704.121D0,   13.12D0,1803.425D0/DATT0720
```

TABLE IX (contd.)

```
      DATA T04 /                                                                14.7D0,DATT0830
     1 2904.72D0,   8.071D0, 2774.33D0,  78.016D0, 2495.47D0, 117.977D0,DATT0840
     2 2216.69D0, 137.995D0, 1750.08D0, 158.049D0, 1384.01D0, 168.094D0,DATT0850
     3  789.99D0, 178.152D0,  209.49D0, 180.179D0,   87.60D0, 277.210D0,DATT0860
     4   66.61D0, 374.240D0,   55.94D0, 471.270D0,   49.19D0, 568.300D0,DATT0870
     5   44.41D0, 665.331D0,   40.80D0, 762.361D0,   37.95D0, 859.391D0,DATT0880
     6   35.63D0, 956.421D0,   33.68D0,1053.452D0,   32.03D0,1150.482D0,DATT0890
     7   31.98D0,1154.345D0,   30.06D0,1230.480D0,   27.45D0,1306.438D0,DATT0900
     8   25.40D0,1383.809D0,   23.74D0,1463.184D0,   22.36D0,1544.795D0,DATT0910
     9   21.18D0,1628.719D0,   20.17D0,1714.939D0,   19.28D0,1803.363D0/DATT0920
      DATA T05 /                                                                50.0D0,DATT1030
     1 5371.63D0,   8.175D0, 5190.51D0, 108.067D0, 4775.18D0, 158.130D0,DATT1040
     2 4009.67D0, 198.393D0, 3318.03D0, 218.632D0, 2105.91D0, 238.966D0,DATT1050
     3  703.71D0, 249.174D0,  571.57D0, 250.212D0,  389.44D0, 277.928D0,DATT1060
     4  267.62D0, 351.839D0,  192.22D0, 490.421D0,  159.83D0, 619.764D0,DATT1070
     5  144.72D0, 712.153D0,  133.23D0, 804.541D0,  124.11D0, 896.929D0,DATT1080
     6  116.64D0, 989.317D0,  110.38D0,1081.705D0,  105.03D0,1174.093D0,DATT1090
     7  104.66D0,1184.119D0,   99.07D0,1254.716D0,   91.70D0,1323.151D0,DATT1100
     8   85.78D0,1391.904D0,   80.85D0,1461.887D0,   76.11D0,1543.804D0,DATT1110
     9   72.09D0,1627.948D0,   68.62D0,1714.337D0,   65.60D0,1802.894D0/DATT1120
      DATA T06 /                                                               100.0D0,DATT1230
     1 7600.63D0,   8.324D0, 7337.38D0, 128.187D0, 6764.11D0, 188.413D0,DATT1240
     2 5606.26D0, 239.065D0, 4208.59D0, 269.774D0, 3474.36D0, 280.078D0,DATT1250
     3 2333.70D0, 290.420D0,  989.42D0, 298.538D0,  721.04D0, 325.197D0,DATT1260
     4  564.01D0, 369.629D0,  412.34D0, 476.264D0,  329.23D0, 609.558D0,DATT1270
     5  282.31D0, 742.852D0,  260.32D0, 831.715D0,  242.80D0, 920.578D0,DATT1280
     6  228.41D0,1009.440D0,  216.31D0,1098.303D0,  205.95D0,1187.166D0,DATT1290
     7  205.33D0,1194.192D0,  194.62D0,1269.141D0,  180.35D0,1339.551D0,DATT1300
     8  168.93D0,1409.519D0,  159.42D0,1480.449D0,  151.30D0,1552.838D0,DATT1310
     9  144.28D0,1626.855D0,  137.31D0,1713.484D0,  131.25D0,1802.229D0/DATT1320
      DATA T07 /                                                               200.0D0,DATT1430
    110751.06D0,   8.620D0,10327.76D0, 158.476D0, 9241.84D0, 239.264D0,DATT1440
     2 8058.31D0, 280.257D0, 5812.39D0, 321.858D0, 3688.74D0, 342.949D0,DATT1450
     3 1759.85D0, 353.581D0, 1685.31D0, 355.506D0, 1515.39D0, 363.934D0,DATT1460
     4 1139.95D0, 406.075D0,  940.63D0, 456.645D0,  778.11D0, 532.500D0,DATT1470
     5  631.88D0, 658.924D0,  528.84D0, 819.061D0,  475.74D0, 945.485D0,DATT1480
     6  448.14D0,1029.768D0,  424.86D0,1114.051D0,  404.87D0,1198.334D0,DATT1490
     7  402.87D0,1210.131D0,  384.10D0,1280.034D0,  355.73D0,1353.710D0,DATT1500
     8  333.37D0,1425.503D0,  314.79D0,1497.762D0,  298.97D0,1571.261D0,DATT1510
     9  285.28D0,1646.255D0,  273.29D0,1722.810D0,  262.69D0,1800.900D0/DATT1520
      DATA T08 /                                                               400.0D0,DATT1630
    115203.90D0,   9.212D0,14540.28D0, 189.071D0,13309.29D0, 270.329D0,DATT1640
    211259.93D0, 332.672D0, 8740.94D0, 375.266D0, 5255.00D0, 407.962D0,DATT1650
     3 3105.55D0, 419.039D0, 2818.39D0, 424.168D0, 2475.99D0, 439.776D0,DATT1660
     4 2091.97D0, 470.993D0, 1858.15D0, 502.210D0, 1539.99D0, 572.448D0,DATT1670
     5 1347.66D0, 642.686D0, 1155.65D0, 751.945D0, 1013.44D0, 876.813D0,DATT1680
     6  935.86D0, 970.464D0,  860.17D0,1087.527D0,  800.37D0,1204.591D0,DATT1690
     7  795.86D0,1216.493D0,  775.13D0,1271.230D0,  720.21D0,1341.438D0,DATT1700
     8  672.03D0,1417.029D0,  633.05D0,1491.300D0,  600.27D0,1566.139D0,DATT1710
     9  572.15D0,1642.145D0,  547.66D0,1719.505D0,  526.11D0,1798.245D0/DATT1720
```

TABLE IX (contd.)

```
101          DATA T09 /                                                                  600.0D0,DATT1830
102         118618.66D0,   9.803D0,18103.35D0, 169.421D0,16833.40D0, 270.700D0,DATT1840
103         214751.27D0, 343.512D0,11204.24D0, 408.123D0, 7987.71D0, 441.582D0,DATT1850
104         3 4173.67D0, 464.480D0, 3768.85D0, 471.697D0, 3048.55D0, 508.295D0,DATT1860
105         4 2660.54D0, 544.893D0, 2206.12D0, 618.089D0, 1847.98D0, 720.564D0,DATT1870
106         5 1598.54D0, 837.677D0, 1486.45D0, 910.873D0, 1395.25D0, 984.069D0,DATT1880
107         6 1319.13D0,1057.265D0, 1254.32D0,1130.461D0, 1198.26D0,1203.657D0,DATT1890
108         7 1190.77D0,1215.928D0, 1173.16D0,1262.896D0, 1082.18D0,1340.030D0,DATT1900
109         8 1016.37D0,1408.262D0,  954.91D0,1484.762D0,  903.95D0,1560.997D0,DATT1910
110         9  860.60D0,1638.031D0,  823.13D0,1716.199D0,  790.29D0,1795.591D0/DATT1920
111          DATA T10 /                                                                 800.0D0,DATT2030
112         121495.90D0,  10.393D0,20695.34D0, 200.012D0,19081.41D0, 301.983D0,DATT2040
113         216623.91D0, 375.727D0,13495.09D0, 430.431D0, 9141.10D0, 476.098D0,DATT2050
114         3 5199.07D0, 499.841D0, 4606.04D0, 509.811D0, 4101.00D0, 530.499D0,DATT2060
115         4 3572.38D0, 564.977D0, 3163.63D0, 606.352D0, 2724.61D0, 675.310D0,DATT2070
116         5 2320.01D0, 778.746D0, 1974.80D0, 923.557D0, 1857.32D0, 992.514D0,DATT2080
117         6 1758.77D0,1061.472D0, 1674.52D0,1130.429D0, 1601.39D0,1199.387D0,DATT2090
118         7 1599.58D0,1201.250D0, 1575.19D0,1255.513D0, 1444.57D0,1339.288D0,DATT2100
119         8 1353.25D0,1410.638D0, 1280.53D0,1478.126D0, 1210.09D0,1555.829D0,DATT2110
120         9 1150.71D0,1633.910D0, 1099.71D0,1712.893D0, 1055.23D0,1792.940D0/DATT2120
121          DATA T11 /                                                                1000.0D0,DATT2230
122         124029.48D0,  10.981D0,23096.00D0, 210.517D0,20845.04D0, 333.571D0,DATT2240
123         217336.14D0, 419.454D0,13305.23D0, 476.061D0, 9253.32D0, 511.794D0,DATT2250
124         3 5593.07D0, 536.693D0, 5360.70D0, 542.551D0, 4399.43D0, 588.078D0,DATT2260
125         4 3734.83D0, 646.612D0, 3169.41D0, 731.162D0, 2854.64D0, 802.705D0,DATT2270
126         5 2638.81D0, 867.743D0, 2466.26D0, 932.782D0, 2324.07D0, 997.821D0,DATT2280
127         6 2204.17D0,1062.859D0, 2101.26D0,1127.898D0, 2011.64D0,1192.936D0,DATT2290
128         7 1992.55D0,1210.394D0, 1947.82D0,1266.456D0, 1784.28D0,1352.309D0,DATT2300
129         8 1671.66D0,1425.265D0, 1582.13D0,1494.115D0, 1507.04D0,1561.913D0,DATT2310
130         9 1442.48D0,1629.779D0, 1377.37D0,1709.586D0, 1320.92D0,1790.290D0/DATT2320
131          DATA T12 /                                                                1200.0D0,DATT2430
132         126318.85D0,  11.569D0,25241.12D0, 221.027D0,23173.53D0, 333.875D0,DATT2440
133         220471.70D0, 408.632D0,16445.88D0, 476.035D0,11934.79D0, 523.846D0,DATT2450
134         3 6472.79D0, 562.204D0, 6049.68D0, 571.853D0, 5568.88D0, 590.242D0,DATT2460
135         4 5097.52D0, 614.760D0, 4519.85D0, 657.667D0, 4112.88D0, 700.575D0,DATT2470
136         5 3622.62D0, 774.130D0, 3230.02D0, 859.944D0, 2926.91D0, 951.888D0,DATT2480
137         6 2724.25D0,1031.573D0, 2536.18D0,1123.517D0, 2430.66D0,1184.813D0,DATT2490
138         7 2407.37D0,1201.318D0, 2347.06D0,1263.089D0, 2139.70D0,1353.651D0,DATT2500
139         8 2001.03D0,1428.978D0, 1892.11D0,1499.365D0, 1801.41D0,1568.314D0,DATT2510
140         9 1723.77D0,1637.122D0, 1656.18D0,1706.277D0, 1587.34D0,1787.642D0/DATT2520
141          DATA T13 /                                                                1400.0D0,DATT2630
142         128423.09D0,  12.156D0,27421.06D0, 211.368D0,25287.74D0, 334.181D0,DATT2640
143         222242.52D0, 419.757D0,17361.80D0, 499.447D0,12557.47D0, 548.676D0,DATT2650
144         3 7095.83D0, 588.776D0, 6683.12D0, 598.830D0, 5658.27D0, 644.548D0,DATT2660
145         4 4962.20D0, 696.831D0, 4439.64D0, 754.478D0, 3963.13D0, 829.421D0,DATT2670
146         5 3688.03D0, 887.068D0, 3464.35D0, 944.716D0, 3277.60D0,1002.364D0,DATT2680
147         6 3118.52D0,1060.011D0, 2980.82D0,1117.659D0, 2860.05D0,1175.307D0,DATT2690
148         7 2827.79D0,1194.086D0, 2787.21D0,1241.299D0, 2526.46D0,1341.691D0,DATT2700
149         8 2352.10D0,1420.820D0, 2218.97D0,1493.200D0, 2109.54D0,1563.395D0,DATT2710
150         9 2016.60D0,1633.103D0, 1936.14D0,1702.966D0, 1854.56D0,1784.994D0/DATT2720
```

TABLE IX (contd.)

```
      DATA T14 /                                                          1600.0D0,DATT2830
     130380.68D0,  12.741D0,29111.17D0, 231.954D0,26342.19D0, 366.053D0,DATT2840
     222067.79D0, 464.563D0,15699.63D0, 548.276D0, 8599.02D0, 602.066D0,DATT2850
     3 7531.45D0, 616.772D0, 7267.39D0, 624.202D0, 6283.48D0, 667.428D0,DATT2860
     4 5642.15D0, 710.654D0, 4937.82D0, 780.897D0, 4517.75D0, 840.333D0,DATT2870
     5 4218.70D0, 894.366D0, 3973.36D0, 948.399D0, 3767.13D0,1002.431D0,DATT2880
     6 3590.46D0,1056.464D0, 3436.84D0,1110.497D0, 3301.60D0,1164.530D0,DATT2890
     7 3252.42D0,1189.014D0, 3203.28D0,1239.587D0, 2882.68D0,1344.071D0,DATT2900
     8 2679.74D0,1425.221D0, 2526.18D0,1498.984D0, 2400.68D0,1570.241D0,DATT2910
     9 2294.50D0,1640.826D0, 2202.85D0,1711.435D0, 2122.55D0,1782.348D0/DATT2920
      DATA T15 /                                                          1800.0D0,DATT3030
     132218.38D0,  13.326D0,30781.42D0, 242.471D0,27490.19D0, 387.615D0,DATT3040
     222773.30D0, 487.560D0,15821.59D0, 573.754D0, 8589.41D0, 630.734D0,DATT3050
     3 7857.19D0, 646.795D0, 7806.53D0, 648.490D0, 6876.29D0, 688.797D0,DATT3060
     4 6044.93D0, 744.220D0, 5470.07D0, 799.642D0, 5073.59D0, 850.027D0,DATT3070
     5 4754.88D0, 900.411D0, 4490.93D0, 950.795D0, 4267.42D0,1001.179D0,DATT3080
     6 4074.81D0,1051.564D0, 3906.50D0,1101.948D0, 3757.71D0,1152.332D0,DATT3090
     7 3680.50D0,1186.215D0, 3618.59D0,1239.460D0, 3394.22D0,1298.836D0,DATT3100
     8 3109.78D0,1390.193D0, 2912.11D0,1468.170D0, 2756.26D0,1541.440D0,DATT3110
     9 2626.84D0,1613.133D0, 2499.56D0,1696.332D0, 2391.32D0,1779.701D0/DATT3120
      DATA T16 /                                                          2000.0D0,DATT3230
     133955.66D0,  13.909D0,32613.64D0, 232.777D0,29236.62D0, 387.847D0,DATT3240
     224722.20D0, 487.530D0,18371.14D0, 573.194D0, 9715.11D0, 645.003D0,DATT3250
     3 8655.25D0, 661.733D0, 8302.92D0, 672.111D0, 7264.52D0, 718.734D0,DATT3260
     4 6562.68D0, 765.356D0, 6041.26D0, 811.979D0, 5631.87D0, 858.601D0,DATT3270
     5 5298.39D0, 905.224D0, 5019.40D0, 951.846D0, 4781.25D0, 998.469D0,DATT3280
     6 4574.70D0,1045.091D0, 4393.22D0,1091.713D0, 4232.05D0,1138.336D0,DATT3290
     7 4201.10D0,1148.283D0, 4112.19D0,1185.706D0, 4021.18D0,1240.893D0,DATT3300
     8 3584.17D0,1351.059D0, 3324.89D0,1435.455D0, 3102.61D0,1523.952D0,DATT3310
     9 2927.42D0,1608.933D0, 2783.04D0,1693.009D0, 2660.89D0,1777.056D0/DATT3320
      DATA T17 /                                                          2200.0D0,DATT3430
     135607.23D0,  14.492D0,34096.21D0, 243.279D0,30883.91D0, 388.082D0,DATT3440
     226527.79D0, 487.510D0,19443.82D0, 585.859D0,10853.33D0, 659.615D0,DATT3450
     3 9433.73D0, 677.129D0, 8756.94D0, 695.462D0, 7803.37D0, 738.132D0,DATT3460
     4 7126.33D0, 780.802D0, 6608.61D0, 823.471D0, 6194.12D0, 866.141D0,DATT3470
     5 5851.60D0, 908.811D0, 5561.87D0, 951.481D0, 5312.35D0, 994.150D0,DATT3480
     6 5094.36D0,1036.820D0, 4901.66D0,1079.490D0, 4729.64D0,1122.159D0,DATT3490
     7 4637.43D0,1149.415D0, 4548.59D0,1187.522D0, 4510.73D0,1218.025D0,DATT3500
     8 3988.37D0,1339.694D0, 3683.13D0,1427.787D0, 3428.14D0,1518.459D0,DATT3510
     9 3229.88D0,1604.716D0, 3067.72D0,1689.682D0, 2931.24D0,1774.411D0/DATT3520
      DATA T18 /                                                          2400.0D0,DATT3630
     137184.51D0,  15.073D0,35898.96D0, 223.542D0,32783.10D0, 377.694D0,DATT3640
     226889.76D0, 510.759D0,19090.97D0, 612.528D0,10166.01D0, 693.052D0,DATT3650
     3 9303.38D0, 714.054D0, 9076.25D0, 718.953D0, 8262.73D0, 757.431D0,DATT3660
     4 7645.11D0, 795.909D0, 7153.80D0, 834.387D0, 6749.86D0, 872.866D0,DATT3670
     5 6409.55D0, 911.344D0, 6117.39D0, 949.822D0, 5862.79D0, 988.300D0,DATT3680
     6 5638.20D0,1026.779D0, 5438.06D0,1065.257D0, 5258.18D0,1103.735D0,DATT3690
     7 5075.29D0,1153.449D0, 4935.95D0,1222.206D0, 4672.68D0,1270.727D0,DATT3700
     8 4333.15D0,1344.672D0, 3999.72D0,1433.843D0, 3756.82D0,1512.909D0,DATT3710
     9 3534.24D0,1600.480D0, 3353.62D0,1686.350D0, 3202.40D0,1771.765D0/DATT3720
```

TABLE IX (contd.)

```
201          DATA T19 /                                                                2600.0D0,DATT3830
202         138696.59D0,  15.653D0,36813.83D0, 264.310D0,33210.24D0, 409.968D0,DATT3840
203         227825.36D0, 522.481D0,19896.25D0, 625.813D0,10829.86D0, 709.590D0,DATT3850
204         3 9699.24D0, 733.410D0, 9407.96D0, 744.475D0, 8710.29D0, 778.232D0,DATT3860
205         4 8155.16D0, 811.988D0, 7698.71D0, 845.745D0, 7314.08D0, 879.502D0,DATT3870
206         5 6983.79D0, 913.259D0, 6695.85D0, 947.016D0, 6441.74D0, 980.772D0,DATT3880
207         6 6215.19D0,1014.529D0, 6011.47D0,1048.286D0, 5826.93D0,1082.043D0,DATT3890
208         7 5703.57D0,1107.711D0, 5518.77D0,1160.241D0, 5446.62D0,1197.675D0,DATT3900
209         8 5320.20D0,1227.844D0, 4834.08D0,1315.521D0, 4474.94D0,1397.239D0,DATT3910
210         9 4129.57D0,1494.237D0, 3750.08D0,1633.563D0, 3474.36D0,1769.120D0/DATT3920
211          DATA T20 /                                                               2800.0D0,DATT4030
212         140150.85D0,  16.232D0,38230.31D0, 264.699D0,34648.04D0, 410.174D0,DATT4040
213         228674.42D0, 534.279D0,20589.80D0, 639.301D0,11213.02D0, 727.621D0,DATT4050
214         310138.64D0, 753.572D0, 9699.30D0, 770.686D0, 9126.99D0, 799.200D0,DATT4060
215         4 8649.96D0, 827.715D0, 8243.83D0, 856.230D0, 7892.20D0, 884.745D0,DATT4070
216         5 7583.59D0, 913.260D0, 7309.70D0, 941.774D0, 7064.33D0, 970.289D0,DATT4080
217         6 6842.75D0, 998.804D0, 6641.28D0,1027.319D0, 6457.00D0,1055.834D0,DATT4090
218         7 6124.36D0,1121.221D0, 5885.61D0,1205.299D0, 5392.81D0,1282.213D0,DATT4100
219         8 4929.99D0,1372.797D0, 4567.09D0,1461.125D0, 4297.59D0,1540.859D0,DATT4110
220         9 4081.41D0,1617.173D0, 3901.13D0,1692.106D0, 3747.13D0,1766.475D0/DATT4120
221          DATA T21 /                                                               3000.0D0,DATT4230
222         141553.34D0,  16.811D0,39752.96D0, 254.984D0,36393.30D0, 399.685D0,DATT4240
223         230895.16D0, 522.232D0,22518.30D0, 638.147D0,11703.88D0, 745.797D0,DATT4250
224         310519.37D0, 775.147D0, 9873.87D0, 801.845D0, 9458.94D0, 823.687D0,DATT4260
225         4 9094.64D0, 845.529D0, 8771.22D0, 867.371D0, 8481.36D0, 889.213D0,DATT4270
226         5 8219.52D0, 911.055D0, 7981.34D0, 932.898D0, 7763.38D0, 954.740D0,DATT4280
227         6 7562.87D0, 976.582D0, 7377.56D0, 998.424D0, 7205.58D0,1020.266D0,DATT4290
228         7 6928.15D0,1060.464D0, 6563.23D0,1135.614D0, 6448.04D0,1179.815D0,DATT4300
229         8 5515.02D0,1328.310D0, 5042.64D0,1425.647D0, 4714.22D0,1509.351D0,DATT4310
230         9 4459.17D0,1587.660D0, 4218.81D0,1676.323D0, 4020.72D0,1763.830D0/DATT4320
231          END                                                                      DATT4440
```

The upstream volume pressure, specific volume, and the pressure and enthalpy returned from the steam tables, for HEM are assumed to be stagnation quantities. The junction critical velocity and density are those derived by an isentropic expansion from the upstream volume assumed stagnation conditions for the critical or sonic state.

HEM is called by entering 4 for JCHOKE and a number greater than zero for ICHOKE on the Junction Data Card (see Table V).

(f) Henry-Fauske/Homogeneous Equilibrium Model. The Henry-Fauske/HEM is a simple combination of these two critical flow models with a specified transition from one to the other. Except as discussed in Section 3.10 in connection with the Evaluation Model/Critical Flow Model, the various flow model combinations may exhibit finite mass flow discontinuities at the point where they join, usually the subcooled saturated boundary. This is avoided in the Henry-Fauske/HEM by prescribing a partially quadratic transition path from the subcooled to the saturated state as illustrated in Figure 23.

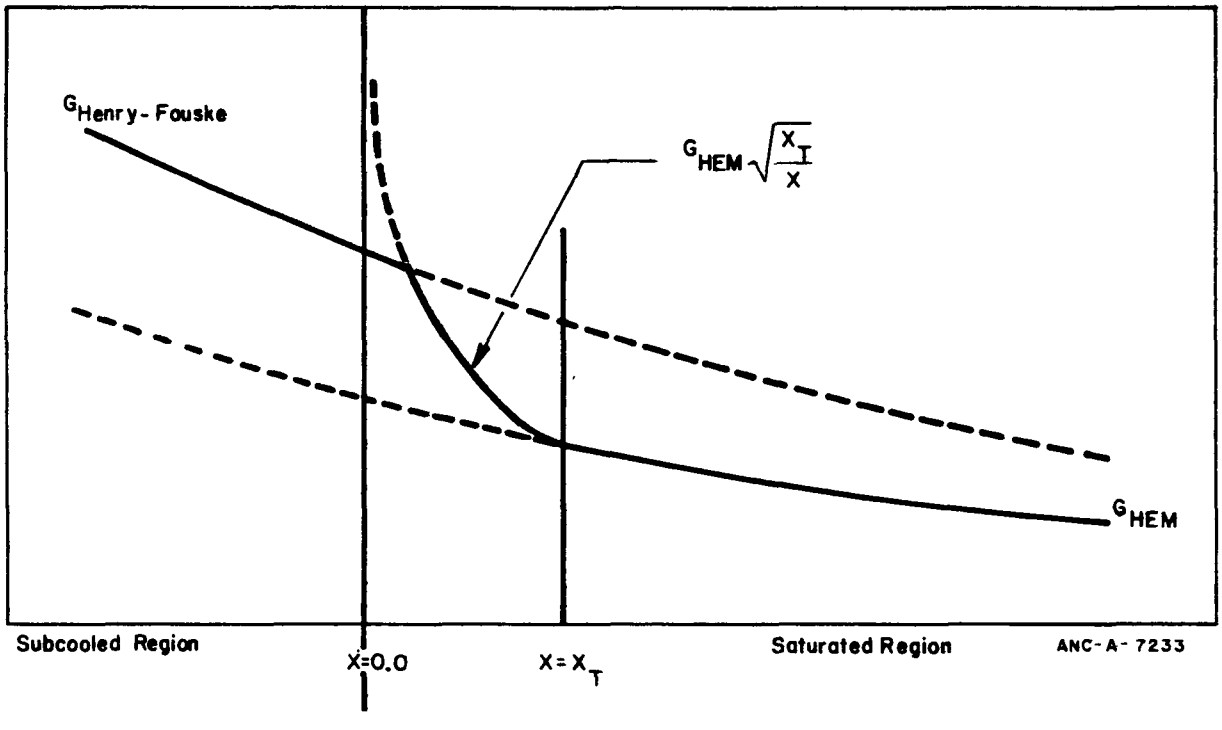


Fig. 23 Henry-Fauske/homogenous equilibrium critical flow model.

The Henry-Fauske critical flow model is utilized in the subcooled region and into the saturated region until it intersects the transition curve described by

$$G_T = G_{HEM} \sqrt{\frac{X_T}{X}} \tag{166}$$

where

X_T = transition quality.

This transition curve is followed until the nominal transition quality, X_T = default value of 0.02 or such other user specified value is reached, at which point conversion is complete. HEM is then utilized on through the saturated into the superheated region.

The Henry-Fauske/HEM is accessed by entering 5 for JCHOKE on the Junction Data Card. Any allowed value may be entered for ICHOKE (see Table V).

(g) Modified Momentum/Homogeneous Equilibrium Model. Reference was made in Section 3.6.8 that the simple momentum or inertial flow solution is quite accurate at low junction pressure ratios but tends to exaggerate the flow rate as critical conditions are approached. To compensate for this exaggeration, the modified momentum model utilizes a correction to the downstream pressure based upon the retardation of vapor formation by the surface tension of the flashing fluid.

This more realistic downstream or back pressure is given by:

$$P_b = C\left(1.0 - \frac{X_{UP}}{X_T}\right)^2 P_{SAT_{UP}} \tag{167}$$

with

$$C = 1.0 - 0.284 \frac{\sigma@P_{SAT_{UP}}}{\sigma@P_{SAT_{200\ PSIA}}} \tag{168}$$

where

σ = surface tension

and with the subscript denotation

b = downstream or back

SAT = saturated conditions

T = transition completion point.

In the subcooled region, X_{UP} is set to zero and a flow rate estimate calculated from Bernoulli's equation with Δp based upon the modified back pressure, p_b:

$$W = A \sqrt{2g_c \rho \Delta p} \tag{169}$$

where

$$\Delta p = p_{STAG} - p_b \tag{170}$$

and

$$P_{STAG} = \frac{- \rho U^2}{2g_c} + P_{STAT} + P_{ELEV} \tag{171}$$

with

$$U^2 = \left(\frac{\dot{W}_t - \Delta t^{\nu}}{A} \right)^2 \tag{172}$$

where

U = velocity

and the subscripts

ELEV = elevation

STAG = stagnation

$t - \Delta t$ = time at previous time step.

This estimate is compared with the normal flow estimate from Equation (140), the minimum identified, and the momentum equation parameters (friction, acceleration) set accordingly. If, however, the modified back pressure is less than or equal to the downstream volume thermodynamic pressure then the inertial flow estimate is used in any case.

In the transition region ($0.00 \leq X < 0.02$) these two flow estimates are compared with a third calculated from HEM data by the relation:

$$W_{MHEM} = A \sqrt{\frac{X_T}{X_{UP}}} \; G_{HEM} \tag{173}$$

with subscript denotation

HEM = homogeneous equilibrium model

MHEM = modified homogeneous equilibrium model.

As before, the minimum of the three flow rate estimates is identified and the appropriate momentum equation parameters set.

HEM is used for upstream volume qualities equal to or greater than the transition quality, 0.02. A HEM critical flow rate estimate is compared with inertial and Bernoulli flow rate estimates, the minumum identified, as before, and the relevant momentum equation parameters (friction, acceleration) again set.

The modified momentum/HEM is accessed by entering 3 for JCHOKE on the Junction Data Card. The value of ICHOKE, as in some other cases, may be any allowed integer (see Table V).

(3) Conclusion. The number and combinations of critical flow models available to the user in the RELAP4/MOD5 code may cause some apprehension when the task of selecting one or more is approached. The results obtained during the process of validating the ICHOKE/JCHOKE critical flow model selection matrix in Table V may prove helpful.

A seven volume model was set up incorporating a single volume feeding both a normal junction emptying into a large containment and a leak junction with ambient pressure equal to the essentially constant containment pressure. Normal and leak junction areas and opening times were arranged such that the leak opened first and the normal junction opened 0.01 sec later (while the contents of the upstream volume were still in a subcooled state). The leak fully opened to twice normal junction area 0.09 sec later. The system was allowed to blow down for an additional 0.20 sec and the problem then terminated. The results from this study, for selected critical flow models, are presented in Table X.

This checkout problem in no way represents a particular reactor system or configuration. It simply poses a set of standard conditions for exercising RELAP4. The results should be viewed as relative and representative only of how the flow models performed for that particular problem. Nonetheless, they illustrate some general conclusions that have been reached over a period of time:

(1) The inertial flow or momentum model depressurizes a system most rapidly as expected and, in addition, exhibits the highest subcooled blowdown rate

(2) The sonic model requires the most computer processing time for a given problem blowdown time

TABLE X

CRITICAL FLOW MODEL SELECTION MATRIX VALIDATION STUDY RESULTS

Initial System Mass: 11588.8 lbm

Flow--Critical Flow Model		Time to Plenum Saturation	Problem Termination (0.30 Seconds)				
Subcooled Regime	Saturated Regime	(seconds)	w_{EX}	$\dot{w}_{EX}$	P_P	X_P	CPU
IN		0.014	7354.23	9623.07	720.42	0.15454	17.25
IN	M	0.014	5924.41	9651.47	918.17	0.07956	16.67
IN	HF	0.014	5877.05	7942.43	926.99	0.07754	15.92
S		0.014	4726.46	6269.92	1049.56	0.03550	26.85
S	M	0.014	5920.13	9651.03	918.15	0.07960	19.71
S	HF	0.014	5874.51	7949.50	927.16	0.07738	16.99
M*		0.023	5890.30	9697.92	921.84	0.07824	17.49
HF*		0.020	5857.19	7971.76	929.50	0.07699	17.13
HF		0.017	5867.65	7956.21	928.47	0.07734	16.32
HF#	M#	0.017	5909.94	9677.98	920.09	0.07880	17.39
HEM		0.026	5061.59	7224.35	1018.17	0.04516	18.12
MM - HEM		0.019	5320.11	6923.54	992.71	0.05369	17.93
HF - HEM		0.016	5313.79	6930.82	993.26	0.05345	17.48

IN Inertial or Momentum Flow Model
S Sonic Critical Flow Model
M Moody Critical Flow Model
HF Henry-Fauske Critical Flow Model
HEM Homogeneous Equilibrium Critical Flow Model
MM Modified Momentum Critical Flow Model

* The model at zero quality is used in the subcooled regime.

\# Evaluation Model critical flow criterion

CPU computer processing units — sec
P pressure — lbf/in^2
w mass — lbm
$\dot{w}$ mass flow rate — lbm/sec
X quality

Subscripts

EX exhaust or exhausted
P plenum

(3) Nearly all the flow models and combinations, with the exception of the inertial model, the sonic model and the homogeneous equilibrium model, exhaust about the same amount of water from a system in the same blowdown time

(4) The differences among the models lie in the path taken. Some exhibit a higher flow rate during subcooled conditions while for others the reverse is true.

The foregoing conclusions are very general and do not constitute criteria for critical flow model selection. These criteria should be selected from other sources.

Information is available to allow verification of flow model selection after the code has been executed. Table XI portrays a portion of a RELAP4/MOD5 typical major edit applicable to junction properties. Two columns of numbers, with letters following the second column in some instances, will be noted on an edit under the heading CHOKE. The first column indicates the critical flow model being utilized in the junction at edit time, as follows:

0 = the inertial or momentum flow model

1 = one of the critical flow models incorporated into RELAP4 in tabular form

2 = The sonic critical flow model.

The second column of numbers lists the ICHOKE input parameter applicable to that particular junction. The letters following this column indicate the particular tabular critical flow model being utilized according to the following key:

M = Moody Critical Flow Model

E = Henry-Fauske Critical Flow Model (subcooled)

H = Henry-Fauske Critical Flow Model (saturated)

D = Homogeneous Equilibrium Critical Flow Model

Y = Henry-Fauske/Homogeneous Equilibrium Critical Flow Model

B = Modified Momentum/Homogeneous Equilibrium Critical Flow Model

S = Sonic Critical Flow Model (non-tabular)

TABLE XI

JUNCTION NUMBER	CONNECTING VOLUMES	CHOKE	JCT. FLOW (LB/SFC)	JCT. ENTH (BTU/LB)
1	1 TO 2	0 11	-2.69247E+02	5.36556E+02
2	2 TO 3	0 11	4.01669E+02	5.36573E+02
3	3 TO 4	0 11	2.05054E+03	5.36874E+02
4	4 TO 5	0 11	2.07739E+03	5.40177E+02
5	5 TO 6	0 11	2.03778E+03	5.59033E+02
6	6 TO 1	0 11	-2.76287E+03	5.73627E+02
7	1 TO 7	1 -2H	4.94751E+03	5.73628E+02
8	1 TO 0	2 -2S	2.43456E+03	5.73628E+02

RELAP4 MAJOR EDIT (JUNCTION PROPERTIES)

3.6.9 Stagnation Properties. Stagnation properties are necessary for the correct use of the critical flow models in RELAP4. All critical flow models (with the exception of sonic choking) require upstream stagnation properties to determine the maximum allowable mass flow rate through the junction. The use of static (flow condition) properties rather than stagnation properties can result in significantly different predictions.

RELAP4 calculates the stagnation pressure and enthalpy from the static pressure and enthalpy using a calculated fluid velocity. An isentropic path from the static enthalpy-pressure point to the stagnation enthalpy-pressure point is followed.

The stagnation enthalpy is calculated from the kinetic energy relationship:

$$H_o = H_1 + \frac{V^2}{2C} \tag{174}$$

where V is calculated from the following relationship:

$$V = \frac{W*SPT}{A} . \tag{175}$$

The symbol definitions are:

H_1 = junction static enthalpy
H_o = stagnation enthalpy
V = calculated fluid velocity
W = junction weight flow
A = upstream volume flow area
SPT = junction specific volume
C = conversion factor from ft-lbm to BTU

In Equation (174), V is not allowed to be greater than the isentropic sonic velocity of the upstream volume associated with the junction.

Applying the basic energy equation in differential form for a fluid undergoing flow change provides:

$$T\,dS = dH - \nu dP. \tag{176}$$

For an isentropic process, $dS = 0$.
Then

$$dP = \frac{dH}{\nu} \tag{177}$$

Integrating this for the change in enthalpy and applying static and stagnation limits provides:

$$P_o = P_1 + \int_{H_1}^{H_o} \frac{dH}{\nu} \tag{178}$$

where $\nu = \nu(H,P)$ is the specific volume.

The remaining terms are:

P_1 = upstream volume static pressure
P_o = stagnation pressure.

Equation (178) is advanced from (H_1,P_1) to (H_o,P_o) by a fourth order Runge-Kutta subroutine. The specific volume ν is evaluated by use of STH2O5, one of the RELAP4 steam table routines.

There are certain restrictions placed on stagnation property calculations in RELAP4. Stagnation properties will not be calculated for a junction if the upstream volume phase is not liquid and at the same time the Mach number of the average volume flow is less than 0.3. Also, if

$$\frac{H_o - H_1}{H_1} \leq 0.001,$$

stagnation properties are not calculated for that junction. These two restrictions save computer processing time by not calculating stagnation properties when they would not differ significantly from static properties.

Stagnation properties can be utilized by entering 1 for ISTAGP on the Stagnation Properties Card as outlined in Volume II, Subsection 4.2.2 (22). Should 2 have been entered for JCHOKE on the Junction Data Cards, the stagnation properties will not be computed. This input corresponds to a source choking situation for which critical flow is fully accounted in the applicable fluid flow equations.

3.6.10 Centrifugal Pump Model. RELAP4 contains a pump model which describes the interaction between a centrifugal pump and the system fluid. A standard RELAP4 control volume is identified as a pump, with the pump behavior calculated through the use of pump characteristic curves, frequently referred to as "four-quadrant" curves. Modeling the pump as a volume, rather than a junction as was done in most versions of RELAP3, eliminates potential instabilities due to rapidly oscillating flows and radically different thermodynamic states of adjacent control volumes.

The pump characteristic curves are empirically developed by pump manufacturers and uniquely define head and torque response of a pump as functions of volumetric flow and pump speed. A typical set of four-quadrant curves is given in Figure 24. The four-quadrant curves can be converted to a simpler form by the development of homologous curves where the head and torque ratios (actual value to rated value) are input as functions of the pump speed and volumetric flow ratios[55]. The developed homologous curves are for single-phase conditions. Typical homologous curves are shown in Figure 25 for the head and Figure 26 for torque.

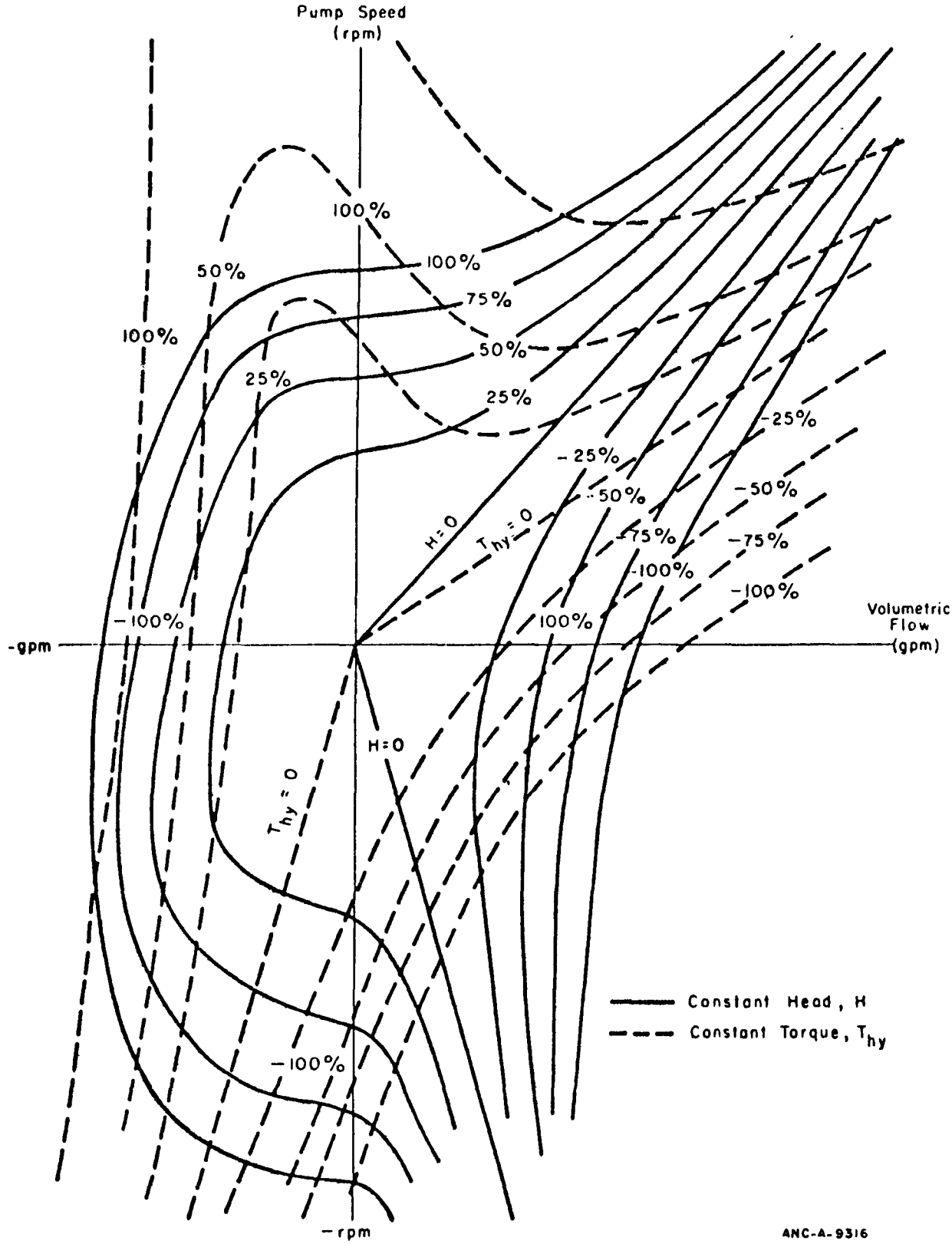


Fig. 24 Pump characteristic four-quadrant curves.

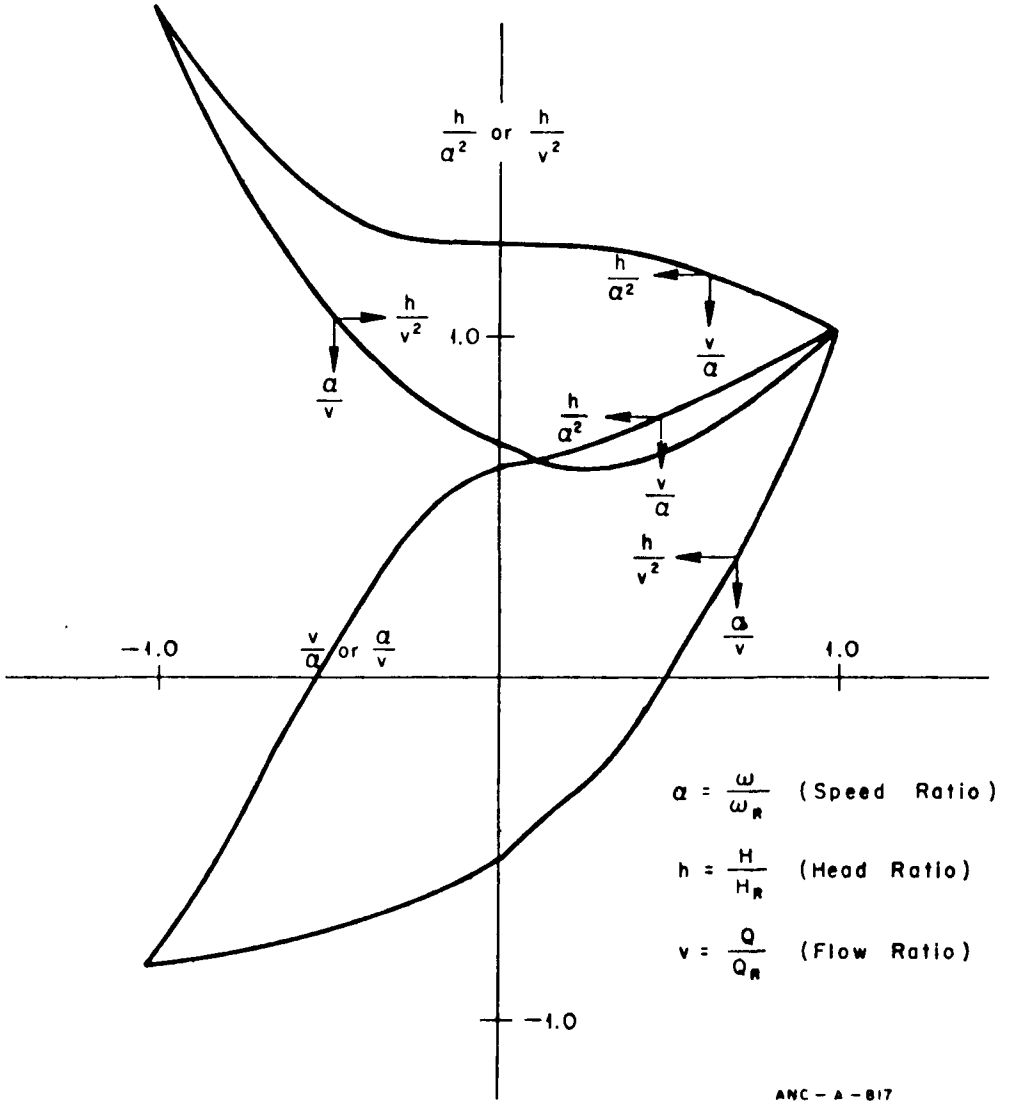


Fig. 25 Pump homologous head curves.

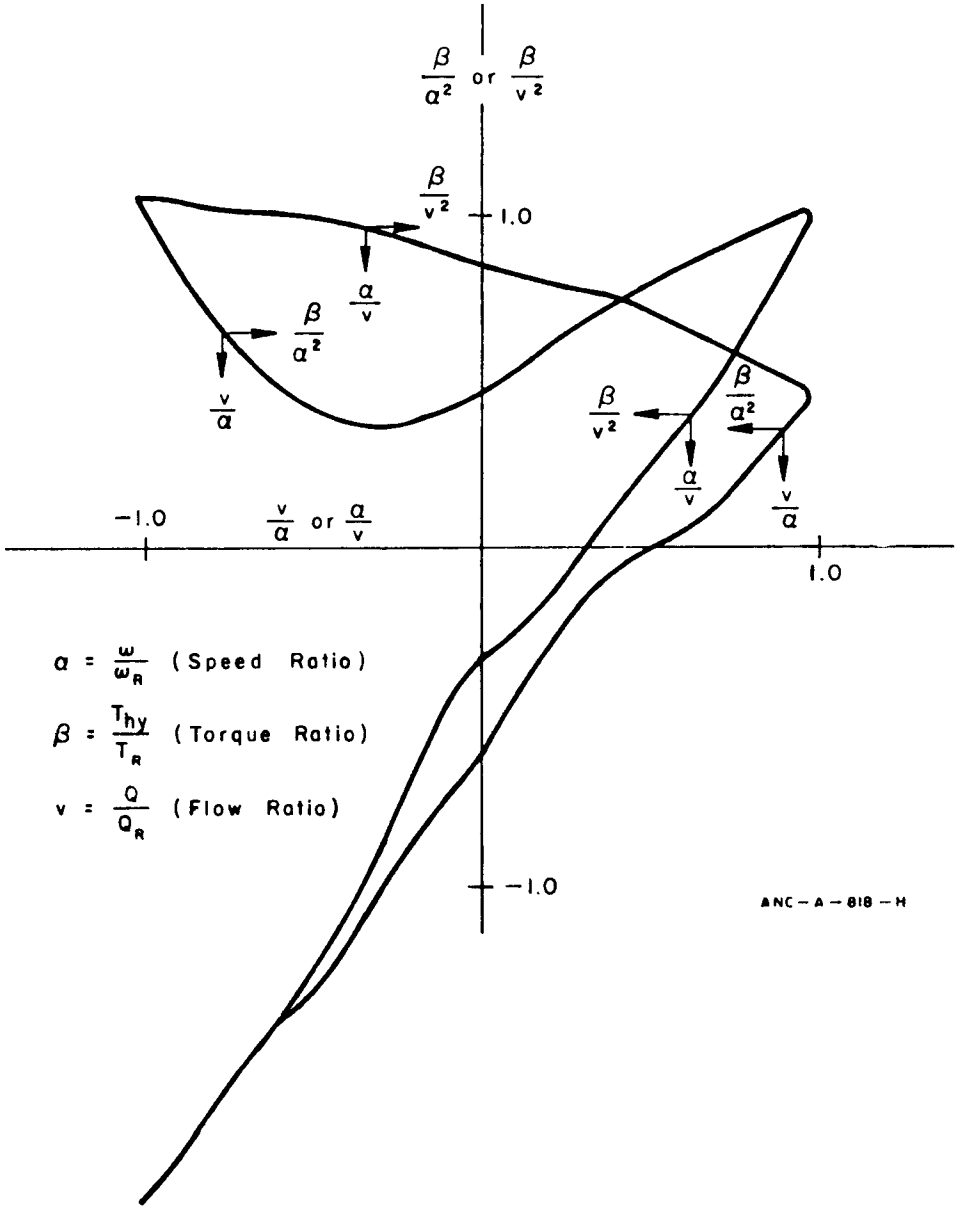


Fig. 26 Pump homologous torque curves.

The volume pump model allows the user the option of accounting for cavitation or two-phase degradation effects on pump response. The user must supply a separate set of homologous two-phase curves for head and torque which are in the form of difference curves. Difference curves are used. This is because, in the analysis of available two-phase pump data, it was noted that when the fluid being pumped had a void fraction between 0.2 and 0.9, little head was developed by the pump being tested. Outside this range of void fraction, the pump-developed head varied from zero to undegraded single-phase performance. The limited available data indicate pump performance in the void fraction range 0.2 to 0.9 is significantly degraded from single-phase behavior. To consider the degraded performance, a set of dimensionless homologous curves was fitted to the head data and the fully-degraded two-phase head was expressed as a function of the standard pump model arguments (v/α or α/v).

To consider the ranges of void fraction where the pump was able to develop head (0 to 0.2 and 0.9 to 1.0), a multiplier as a function of void fraction was used. The multiplier varied from 0 to about 1.0 as the void fraction varied from 0 to 0.2, and the multiplier varied from about 1.0 to 0 as the void fraction varied from 0.9 to 1.0.

Available pump data from the 1-1/2 Loop Model Semiscale and Westinghouse Canada Limited (WCL) experiments were used in developing the two-phase pump data for RELAP4. Assumptions inherent in the pump model for two-phase flow include:

(1) The head multiplier $M(\alpha)$, that was determined empirically for the normal operating region of the pump, is also valid as an interpolating factor in all other operating regions.

(2) The relationship of the two-phase to the single-phase behavior of the semiscale pump is applicable to large reactor pumps. This assumes an independent pump specific speed for the pump model for two-phase flow.

Normal Pump	$(+Q,+\alpha)$	HAN, HVN
Energy Dissipation	$(-Q,+\alpha)$	HAD, HVD
Normal Turbine	$(-Q,-\alpha)$	HAT, HVT
Reverse Pump	$(+Q,-\alpha)$	HAR, HVR

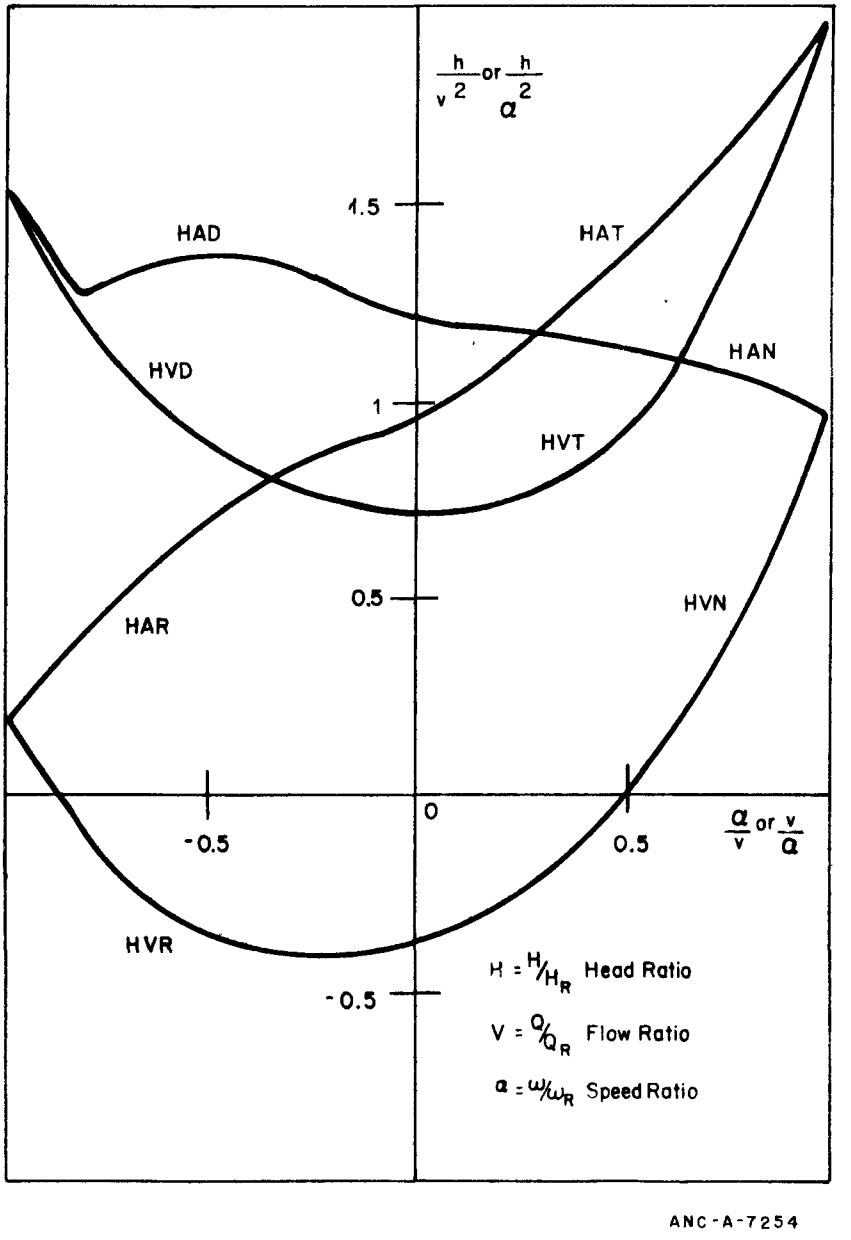


Fig. 27 Single-phase homologous head curves for 1-1/2 loop MOD-1 Semiscale pumps.

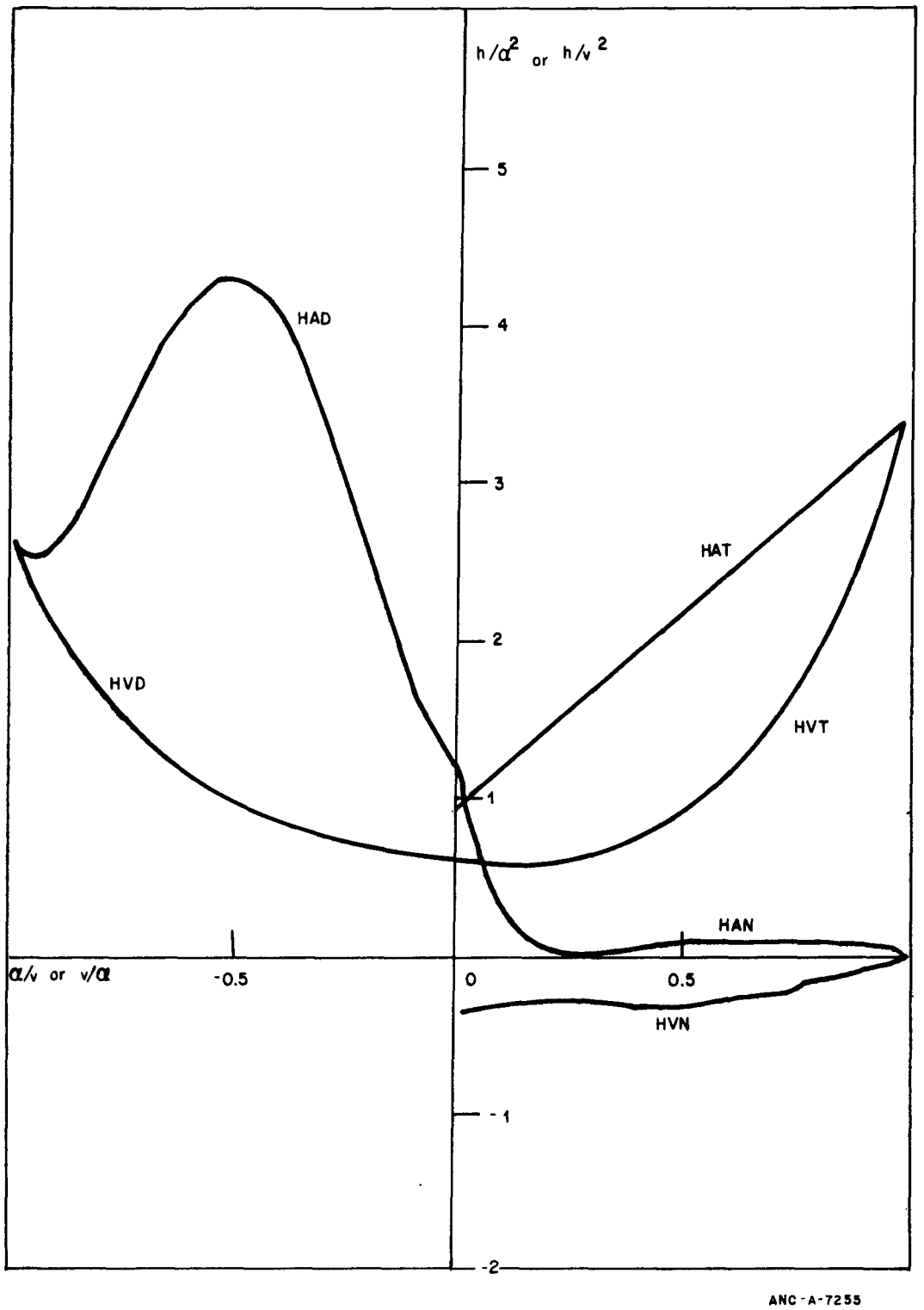


Fig. 28 Fully degraded two-phase homologous heat curves for 1-1/2 loop MOD-1 Semiscale pump.

The single-phase pump head (dimensionless) curve for the semiscale pump is shown in Figure 27.

The following definitions refer to Figure 27:

H = head
Q = volumetric flow
ω = angular speed
R = subscript denoting rated operating value.

The two-phase pump head curves shown in Figure 29 represent complete pump characteristics for the semiscale pump while operating under two-phase conditions when the average of the void fractions of the pump inlet and outlet mixtures is between 0.2 and 0.9. The lines drawn through the data were determined by least square polynomial fits to the data using known constraints.

A comparison of the two-phase data of Figure 28 with the single-phase data in Figure 27 shows that the two-phase dimensionless head ratio (h/v^2 or h/α^2) is significantly less than the single-phase dimensionless head ratio for the normal pump operation region (HAN and HVN). For negative ratios of v/α such as those which occur in the HAD region, the pump flow becomes negative. When the pump flow is negative, the two-phase dimensionless head ratio is greater than the single-phase dimensionless head ratio. Two-phase flow friction losses are generally greater than single-phase losses, and friction is controlling in this energy dissipation region (HAD). The other regions of the two-phase dimensionless head ratio data show similar deviations from single-phase data.

Table XII shows the difference between the single-phase and the two-phase dimensionless head ratio data as a function of v/α and α/v for the various pumping regions shown in Figures 27 and 28. The differences shown in Table XII are for the eight curve types used in RELAP4 for determining pump head.

TABLE XII

SEMISCALE DIMENSIONLESS HEAD RATIO DIFFERENCE
(SINGLE-PHASE MINUS TWO-PHASE) DATA

$$X = \frac{v}{a} \text{ or } \frac{a}{v}$$

$$y = \left(\frac{h}{a^2}\right)_1 - \left(\frac{h}{a^2}\right)_2 \text{ or } \left(\frac{h}{v^2}\right)_1 - \left(\frac{h}{v^2}\right)_2$$

Curve Type	x	y	Curve Type	x	y
1 (HAN)	0.00	0.00	4 (HVD)	-1.00	-1.16
	0.10	0.83		-0.90	-0.78
	0.20	1.09		-0.80	-0.50
	0.50	1.02		-0.70	-0.31
	0.70	1.01		-0.60	-0.17
	0.90	0.94		-0.50	-0.08
	1.00	1.00		-0.35	0.00
				-0.20	0.05
2 (HVN)	0.00	0.00		-0.10	0.08
	0.10	-0.04		0.00	0.11
	0.20	0.00			
	0.30	0.10	5 (HAT)	0.00	0.00
	0.40	0.21		0.20	-0.34
	0.80	0.67		0.40	-0.65
	0.90	0.80		0.60	-0.93
	1.00	1.00		0.80	-1.19
				1.00	-1.47
3 (HAD)	-1.00	-1.16			
	-0.90	-1.24	6 (HVT)	0.00	0.11
	-0.80	-1.77		0.10	0.13
	-0.70	-2.36		0.25	0.15
	-0.60	-2.79		0.40	0.13
	-0.50	-2.91		0.50	0.07
	-0.40	-2.67		0.60	-0.04
	-0.25	-1.69		0.70	-0.23
	-0.10	-0.50		0.80	-0.51
	0.00	0.00		0.90	-0.91
				1.00	-1.47
			7 (HAR)	-1.00	0.00
				0.00	0.00
			8 (HVR)	-1.00	0.00
				0.00	0.00

TABLE XIII

HEAD MULTIPLIER AND VOID FRACTION DATA

α	$M(\alpha)$
0.00	0.00
0.10	0.00
0.15	0.05
0.24	0.80
0.30	0.96
0.40	0.98
0.60	0.97
0.80	0.90
0.90	0.80
0.96	0.50
1.00	0.00

The head multiplier $M(\alpha)$ and void fraction data shown in Table XIII were obtained in the following manner. The semiscale and WCL pump data[56] were converted to dimensionless head ratios of h/α^2 or h/v^2. Values of the dimensionless head ratios were obtained for those pump speeds and volumetric flow rates which were within 50% of the rated speed and flow rate for the pumps. The difference between the single-phase and two-phase dimensionless ratios was developed as a function of the average of the void fractions of the pump inlet and outlet mixtures. The difference between the single-phase and two-phase dimensionless ratios was then normalized to a value between 0 and 1.0 and the normalized result was tabulated as a function of the void fraction.

If the two-phase option is selected, the pump head and torque are calculated by:

$$H = H_{1\phi} - M_h(\bar{\alpha})(H_{1\phi} - H_{2\phi}) \tag{179}$$

$$T = T_{1\phi} - M_t(\bar{\alpha})(T_{1\phi} - T_{2\phi}) \tag{180}$$

where

1ϕ = single-phase value
2ϕ = two-phase fully degraded value $0.2 < \alpha < 0.9$
M = multiplier on difference curve
$\bar{\alpha}$ = average volume void fraction.

The differential pressure change across the pump is dependent upon the head value and the average pump volume density (ρ). Thus the pressure change is given by

$$\Delta P = \rho H. \tag{181}$$

The pump torque is used to calculate pump speed after the pump has been shut off by the input trip signal (ITPUMP). The speed is calculated by the deceleration equation:

$$I\frac{d\omega}{dt} = T \tag{182}$$

the solution of which is:

$$\omega_{t+\Delta t} = \omega_t - \frac{T\Delta t}{I} \tag{183}$$

where

T = total torque
I = moment of inertia
t = time
Δt = time step
ω = speed.

The rate of energy addition to the pump fluid is given by ωT.

The total pump torque is calculated by considering the hydraulic torque from the homologous curves and the pump frictional torque. The total torque is given by:

$$T = T_{hy}\frac{\rho}{\rho_r} + \sum_{i=1}^{4} T_{fri}\left(\frac{|\omega|}{\omega_r}\right)^{i-1} \tag{184}$$

or

$$T = T_{hy} + T_{fr} \tag{185}$$

where

T_{hy} = hydraulic torque

ρ = density

T_{fri} = i^{th} coefficient of frictional torque

The frictional torque is in the form of a cubic equation. The value of the frictional torque is also dependent on the sign of the pump speed. An option is available to specify whether or not reverse rotation of the pump is allowed.

The RELAP4 pump model has been modified to include the influence of the electric drive motor on the speed behavior of the pump while the motor remains connected to its power source. The effect of the motor is incorporated into the pump model by adding the value of motor torque, T_m, to the torque summation:

$$T = T_{hy} - T_{fr} + T_m \tag{186}$$

where the sign of the motor torque is opposite to that of the hydraulic and frictional torque at normal operating conditions.

The machines used to drive primary coolant pumps are induction motors. At constant voltage the motor torque is an explicit function of speed. This torque-speed relationship is normally available from the motor manufacturer.

Motor torque is supplied to the RELAP4 model as a tabular function of torque vs speed as defined by the manufacturer's data. A typical torque-speed curve for an induction motor is shown in Figure 29.

The capability to simulate a locked rotor condition of the pump was included in the RELAP4 computer program. This option provides for simulation of the pump rotor lockup as a function of input elapsed time, maximum forward speed, or maximum reverse speed. At the time the rotor locks and at all times thereafter, the pump speed is set equal to zero.

Four sets of single-phase head and torque data may be used as input to RELAP4. The pump model has built-in single-phase pump data for both a Bingham Pump Company pump with a specific speed of 4200 (Curve Set 1)

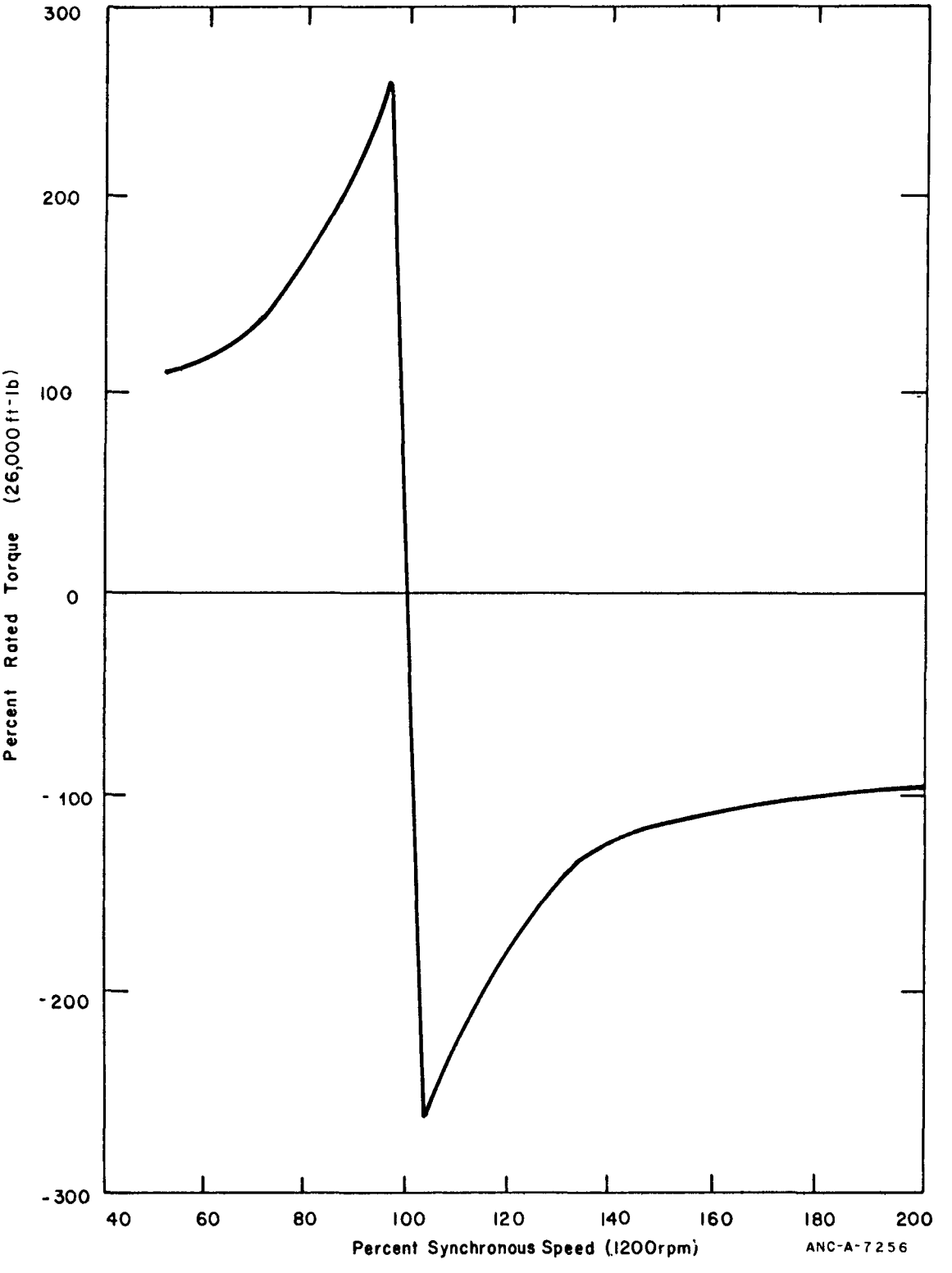


Fig. 29 Torque versus speed, type 93A pump motor (rated voltage).

and a Westinghouse Electric Corporation pump with a specific speed of 5200 (Curve Set 2). If the two-phase option is selected, the difference curves are input into Curve Set 4. Entry of data for curve Set 1 or 2 on the Pump Head and Torque Data Cards listed in Volume II, Subsection 4.2.2 (42) will over-ride the built-in curve data.

Each pump curve set is divided into eight types of input data depending upon the values of the speed ratio (α) and the flow ratio (v). The independent variable is either

$$\frac{h}{\alpha^2}, \frac{\beta}{\alpha^2}, \frac{h}{v^2}, \text{ or } \frac{\beta}{v^2}.$$

The definition of each is shown in Table XIV.

TABLE XIV

PUMP CURVE INPUT DATA

Type	α	V	v/α	Independent Variable	Dependent Variable	
					Head	Torque
1	>0	$\geq$0	$\leq$1	v/α	h/α^2	β/α^2
2	>0	$\geq$0	>1	α/v	h/v^2	β/v^2
3	>0	<0	$\geq$-1	v/α	h/α^2	β/α^2
4	>0	<0	<-1	α/v	h/v^2	β/v^2
5	$\leq$0	$\leq$0	$\leq$1	v/α	h/α^2	β/α^2
6	$\leq$0	$\leq$0	>1	α/v	h/v^2	β/v^2
7	$\leq$0	>0	$\geq$-1	v/α	h/α^2	β/α^2
8	$\leq$0	>0	<-1	α/v	h/v^2	β/v^2

All pump model options are available for use with standard RELAP4 or RELAP4-EM calculations.

The pump model input data is entered as follows from the format outlined in Volume II:

(1) Pump information and options derived - Pump Description Data Cards described in Subsection 4.2.2 (36)

(2) Homologous head and torque curves - Pump Curve Input Indicator Data Card and Pump Head and Torque Data Cards described in Subsections 4.2.2 (41) and 4.2.2 (42) respectively

(3) Two-phase multiplier data - Pump Head Multiplier Data Cards and Pump Torque Multiplier Data Cards described in Subsections 4.2.2 (37) and 4.2.2 (38) respectively

(4) Pump stop option data - Pump Stop Data Card described in Subsection 4.2.2 (39)

(5) Pump motor torque data - Pump Motor Torque Data Card described in Subsection 4.2.2 (40).

3.6.11 Jet Pump Model. The RELAP4 field equations were developed so that momentum interactions between mixing fluid streams may be described. The momentum mixing model is particularly applicable to modeling of jet pump components in BWR analysis, even though the model was not developed specifically for jet pump analysis. The jet pump driving loop is modeled separately as a centrifugal pump with piping volumes.

The compressible two-stream flow with one-dimensional momentum mixing form (Form (2) of the fluid flow equations as described in Subsection 3.3.1 (5)(b)) is used for jet pump modeling. Equation (15) of that subsection contains the terms dw_{j2}/dt and ΔP_{j1} which describe the interactions. The first is an acceleration term that accounts for the mixing fluid contribution to the downstream thermodynamic properties. The second is a reversible pressure term which describes the momentum flux exchange between the fluid streams. This latter term gives rise to four subforms of Form (2) dependent on the stream flow pattern obtaining within the junction. The momentum equations are then solved as normal RELAP4 flowpaths.

The reversible pressure change is calculated two significantly different ways depending on the JCHOKE index entered on the Junction Data Card described in Volume II, Subsection 4.2.2 (21). The particular solution of the four subforms of the Form (2) equation depends on whether sonic choking is allowed by the particular index entered.

The mixing model is flagged by the MVMIX option on the Junction Data Cards. If the mixing occurs in the upstream volume (entered as IW1 on the Junction Data Cards), then MVMIX is set to 1. If the mixing occurs in the downstream volume (entered as IW2) MVMIX is set to 2. The normal convention is to have the stream mix in the downstream (jet pump) volume.

3.6.12 Valves. A valve or check valve may be modeled in any RELAP4 junction by entering the total number of valve types for NCKV on the Problem Dimensions Data Card and the applicable type index number for IVALVE on the Junction Data Cards. The formats for the foregoing are presented in Volume II, Subsection 4.2.2 (2) and 4.2.2 (21) respectively. The type of valve modeled can be selected from the following and the proper value entered for ITCV on the Valve Data Cards as outlined in Volume II, Subsection 4.2.2 (43):

(1) Normally closed - trip opened
(2) Normally open - trip closed
(3) Flow dependent pressure operated with hysteresis
(4) Flow dependent pressure operated without hysteresis
(5) Static pressure controlled (with or without trip closing)
(6) Inertial.

(1) Valve Action Under Trip Control. A choice of ITCV in the range of $20 < ITCV < -2$ results in a valve which is closed until the trip conditions are satisfied and is then opened for the remainder of the transient. A choice of ITCV in the range of $2 < ITCV < 20$ results in a valve which is open until the trip conditions are satisfied and is

then closed for the remainder of the transient. Either of these two types of valves is controlled by a signal related to information entered on the Trip Control Data Cards described in Volume II, Subsection 4.2.2 (10). The control action for a specific valve is keyed to trip control through the correspondence between IDTRP on the Trip Data Control Card and ITCV on the Valve Data Card. The absolute value of ITCV must equal IDTRP for the trip signal characteristics desired.

(2) Check Valves Controlled by Flow Dependent Pressure Losses. Either of the two types of check valves may be chosen; Type 0 without a hysteresis loop in the characteristic flow-vs.-pressure curve, or Type 1 with the hysteresis loop. The characteristic curves for these two types are shown in Figure 30.

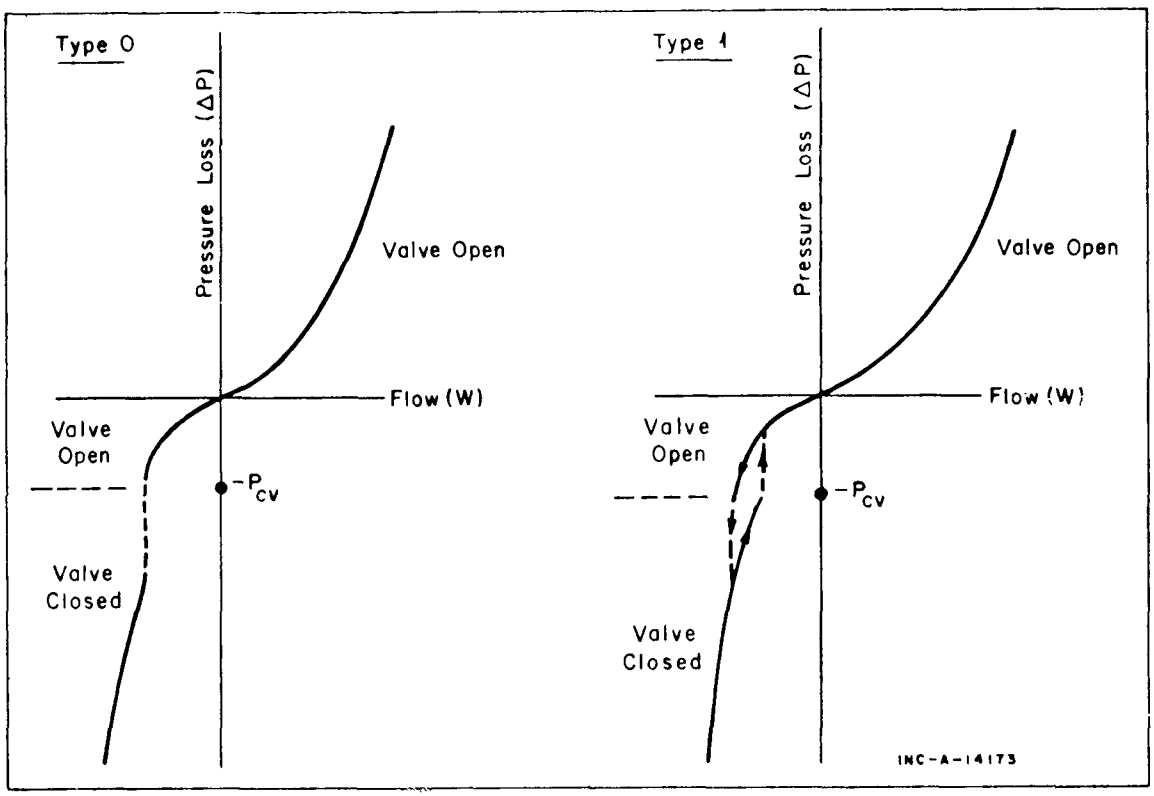


Fig. 30 Check valve characteristic curves.

Both types of check valves are controlled by flow dependent pressure losses of the form

$$\Delta P \propto (CV_i) \frac{W|W|}{\rho} \tag{187}$$

where W is the mass flow rate and ρ is the density. Three regions of operation are defined for each check valve by entering the appropriate friction flow coefficient (CV_i) for CV1, CV2, or CV3 on the Valve Data Cards. These regions are:

(1) Positive flow with the valve open
(2) Negative flow with the valve open
(3) Negative flow with the valve closed (leakage).

For positive flow, the valve remains open and exhibits a pressure loss proportional to the forward flow friction coefficient CV1. For negative flow, the valve remains open if the pressure loss related to the reverse flow friction coefficient CV2 is less than PCV, the back pressure required to close the valve. After valve closure, the leakage flow pressure loss is proportional to the closed valve reverse flow friction coefficient CV3.

The hysteresis difference between Type 0 and Type 1 check valves is apparent in Figure 30. Type 0 check valves open in exactly the reverse sequence of the closing sequence. A Type 0 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 1 valve reopens only when the pressure loss developed across the valve in the closed position is less than the required back pressure.

A time-dependent flow area may be associated with a valve defined by $|ITCV| \geq 2$. The normalized junction area for any time step is interpolated from an input table of area-versus-time. The junction area used during the time step is then given by

$$A = AJUN*CONCO*A(t) \tag{188}$$

where

A	=	junction area computed by the program
AJUN	=	total junction area with valve wide open
CONCO	=	contraction coefficient
A(t)	=	normalized area-i.e. actual flow area divided by AJUN-entered as TAREA on Leak Table Data Cards
t	=	time.

This option is accessed by setting IACV on the Valve Data Cards equal to the desired Leak Table Card set number.

(3) Check Valves Controlled by Static Pressure Differential. By specifying ITCV = 21, a valve will open or close based on the static pressure differential across the junction.

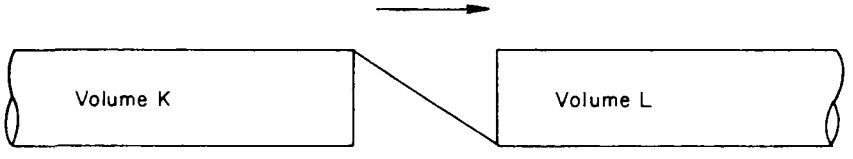


Fig. 31 Static pressure check valve operation.

By defining a pressure differential across the valve shown in Figure 31.

$$DPV = (P_k + P_{g_k}) - (P_L + P_{g_L}) \tag{189}$$

where

DPV = pressure differential computed by the program

P_k, P_L = thermodynamic pressure in each volume

P_{g_k}, P_{g_L} = static pressure head due to gravity from each volume to junction.

A comparison between the back pressure for closure (PCV on valve card) and this differential can be made. Then, for the pressure difference, the valve operation is:

DPV - PCV $\geq$ 0, valve open

DPV - PCV < 0, valve closed.

This type of valve has particular application for modeling vent valves that occur in B&W plants and for modeling check valves in pressurizer and accumulator lines.

If a code user desires this valve to trip off after a period of time, he may specify 22 $\leq$ ITCV $\leq$ 40. The valve will then be operated by a static pressure differential but will also close under trip control.

(4) Inertial Valves. Valves having inertial properties differ from check valves in that the valve gates have a significant inertia which controls the rate of opening for a given differential pressure across the valve. The valve gates are assumed to be hinged on each side and open from the center. The differential pressure across the valve acts as a torque on the gates. The gate angle at any time is found by integrating the equation of motion. A viscous damping coefficient may be optionally used for the equation of motion. Once the gates reach a rotation of 90 degrees, they may be latched fully open or allowed to open and close repeatedly by selecting the appropriate value for LATCH on the Valve Data Card.

Inertial valves are defined by setting ITCV = -1 in the Valve Data Card. Each valve must also be associated with a table of normalized areas versus angles by setting IACV on the Valve Data Card to the appropriate Leak Table Data Card number. The table cards for the valve normalized area versus angle are combined with the Leak Table Cards. They may be intermixed with them but not used as source data for both functions.

The differential equation of motion for the valve gate may be written in time function as

$$I\ddot{\theta}(t) = \bar{A}\,P(t) - K\dot{\theta}(t) \tag{190}$$

where

θ = opening angle in degrees

$\dot{\theta}$ = $\frac{d\theta}{dt}$

$\ddot{\theta}$ = $\frac{d^2\theta}{dt^2}$

I = moment of inertia = $\int x^2 dm$

$\bar{A}$ = area x moment arm = $\int x dA$

P = differential pressure ($P = P_{in} - P_{out} - P_{cv}$)

K = damping constant.

The term P_{cv} in the expression P is the Valve Data Card input PCV for the back pressure tending to hold the gates closed.

Converting Equation (190) from time function to angular velocity by substituting $\omega = \dot{\theta}$ and $\dot{\omega} = \ddot{\theta}$ along with grouping in terms of ω, results in:

$$I\dot{\omega} + K\omega = AP. \tag{191}$$

This has the solution

$$\omega e^{\frac{Kt}{I}} = \frac{\bar{A}}{I}\int e^{\frac{Kt}{I}} P(t)dt + \omega_o \tag{192}$$

where ω_o is a constant representing angular velocity at the beginning of the time step. The pressure term can be taken out of the integral if integration will be piecewise over time steps small enough for P to be considered constant. Performing the indicated integration gives

$$\omega e^{\frac{Kt}{I}} = \frac{\bar{A}P}{K} e^{\frac{Kt}{I}} + C + \omega_o. \tag{193}$$

Evaluating C at the beginning of the time step where $t = 0$ and $\omega = \omega_o$ provides

$$C = -\frac{\bar{A}P}{K}. \tag{194}$$

Substitution for C and division by $e^{\frac{Kt}{I}}$ gives

$$\omega = \omega_o e^{-\frac{Kt}{I}} + \frac{\bar{A}P}{K}\left(1 - e^{-\frac{Kt}{I}}\right). \tag{195}$$

Adding $(\omega_o - \omega_1)$ and rearranging terms gives

$$\omega = \omega_o + \left(\frac{\bar{A}P}{K} - \omega_o\right)\left(1 - e^{\frac{-Kt}{I}}\right) \tag{196}$$

Substituting $\theta = \omega$ and integrating each side of the equation gives

$$\theta\Big|_{\theta_o}^{\theta} = \omega_o t + \left(\frac{\bar{A}P}{K} - \omega_o\right)\left(t + \frac{I}{K} e^{-\frac{Kt}{I}}\right)\Bigg|_0^t \tag{197}$$

for an angular advance from θ_o to θ over a discrete time step starting at t = 0. Evaluating the integrals for the limits shown and rearranging terms gives

$$\theta = \theta_o + \omega_o t + \left(\frac{AP}{K} - \omega_o\right)\left[t - \frac{I}{K}\left(1 - e^{\frac{-Kt}{I}}\right)\right]. \tag{198}$$

The limiting value for K is 0, when there is viscious damping. Taking the limit of the above, considering K as the only variable in the limit process, then

$$\lim_{K \to 0} \theta = \theta_o + \omega_o t + \frac{APt^2}{2I}. \tag{199}$$

3.6.13 Heat Exchanger Models. Four distinct methods are available to represent a heat exchanger using the RELAP4 code. Two are based on the utilization of the standard heat slab as described in Section 3.4. The remaining two schemes are more simplified in that they do not describe the intervening structure (e.g., pipe wall) separating the primary and secondary. The models are described in the following subsections.

(1) Conduction Models. The two models employing the heat slab input are the standard conductor and a model for a conductor with a special sink.

(a) Standard Conductor. The user specifies fluid control volumes on both sides of the slab. For a standard tube-type steam generator, the volume specified on the left would be a primary side volume (i.e., adjacent to the tube I.D.) and the volume on the right would be the secondary side volume (i.e., adjacent to the tube O.D.). The slab surface area, volume, hydraulic diameter, and heated equivalent diameter would represent aggregate values for the series of tubes considered. The slab geometry input data need only describe the geometry of a single tube. This is entered on the slab Geometry Data Cards as described in Volume II, Subsection 4.2.2 (55).

(b) Conductor with Special Sink. This model consists of a heat conductor with one surface adjacent to a volume which represents the primary side of the exchanger, and the other surface adjacent to a special sink volume representing the secondary side, where the fluid properties and flow are assumed to be constant. Two additional parameters, the fraction of total power generated that is removed by the slab and the secondary slab surface heat transfer coefficient (h), are entered as PFR and HTC at the end of the Heat Slab Data Cards as outlined in Volume II, Subsection 4.2.2 (51). The initial heat transfer rate W_o is calculated from the fraction of heat removed. The secondary side surface temperature T_w is calculated from the conduction solution. The constant secondary sink temperature is computed from

$$T_{sec} = T_w - \frac{W_o}{Ah} \tag{200}$$

where A is the surface area on the secondary side. In the transient analysis, the updated value of T_w is used to solve for the heat removal rate as follows:

$$W = Ah(T_w - T_{sec}) \ . \tag{201}$$

(2) Nonconduction Models. The nonconduction models are the volume-associated models which were used in RELAP3[15]. Neither model explicitly describes the intervening structure separating the primary and secondary.

(a) Flow and Temperature Dependent Heat Exchanger. The Heat Exchanger Data Cards supply a constant secondary sink temperature T_{sec}, a constant effective heat transfer coefficient C, and the fraction of total power generated which the exchanger removes. From the latter, the initial heat removal rate W_o in Btu/hr is calculated. If the input value of C is zero, C is then calculated as

$$C = W_o \left(\frac{1}{F_o}\right) \left(\frac{1}{T_{pri_o} - T_{sec}}\right) \tag{202}$$

where

F_o = initial flow, lbm/sec

T_{pri_o} = initial temperature of primary coolant.

In the transient calculation, the updated values of F and T_{pri} are used to calculate the heat removal rate as

$$W = CF(T_{pri} - T_{sec}) \ . \tag{203}$$

(b) Time-Dependent Heat Exchanger. This model uses an input table of normalized power versus time supplied by the Heat Exchanger Data Cards. The normalized power represents that fraction of total power generated which the heat exchanger is removing.

3.6.14 Enthalpy Transport. The junction enthalpy is normally calculated as the average enthalpy of the volume upstream of the junction as modified by the bubble rise model. However, for volumes with slabs or a heat exchanger, heat is being added (or subtracted) to the volume throughout its length. Thus, the enthalpy at the outlet of the volume is greater than the average enthalpy (the enthalpy at the volume center). Accordingly, the "enthalpy transport" option is provided to increase the junction enthalpy in proportion to the heat added to the fluid over the length of the volume. If this option is used, the amount of heat added to the junction exceeds that at the center of the volume by a function of time and the total heat added during the time step. For heat exchangers, the heat added is a negative quantity.

The junction enthalpy h_{ij} and the junction velocity v_{ij} are evaluated immediately upstream of the actual junction flow area A_j that connects a volume from another volume or flow source. By definition, the junction enthalpy and kinetic energy are determined by the fluid properties of the source of flow. Specifically, h_{ij} and v_{ij} are determined by the properties of the source volume V_i. Hence, the junction enthalpy with respect to the source volume is:

$$h_{ij} = \bar{h}_i + \frac{\bar{v}_i^{\,2}}{2g_c J} - \frac{v_{ij}^{\,2}}{2g_c J} + (\Delta h_i)_q + (\Delta h_{ij})_s \qquad (204)$$

where

h_{ij} = local enthalpy at junction j of the fluid entering or leaving volume V_i

v_{ij} = local fluid velocity at junction j of the fluid entering or leaving volume V_i,

$\bar{h}_i$ = average enthalpy of source volume V_i

$\frac{\bar{v}_i^{\,2}}{2g_c J}$ = average kinetic energy of volume V_i

$\frac{\bar{v}_{ij}^{\,2}}{2g_c J}$ = kinetic energy of flow W_{ij} immediately upstream of the junction area A_j

g_c = gravitational constant

J = mechanical equivalent of heat

$(\Delta h_i)q$ = junction enthalpy change from center of volume to junction due to heating within the source volume V_i

$(\Delta h_{ij})s$ = enthalpy change due to phase separation at junction j within the source volume V_i.

The rate of enthalpy increase due to heating within volume V_i at junction j is modeled by the equation

$$Q_i = M_i \frac{dh_{ij}}{dt} + (\Delta h_i)_q \left|\bar{W}_i + W_i\right| \qquad (205)$$

where

M_i = mass in volume V_i

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

W_j = mass flow at junction j

Q_i = rate of heat energy transferred into volume V_i.

The enthalpy transport heating model, Equation (205), is applicable only for a single-path volume with one inlet and one outlet junction and for a homogeneous fluid with no phase separation. This model is obtained from the integral mass and energy conservation equations applied to the half-volume that represents the outlet side of a heated RELAP4 control volume. Kinetic and potential energy changes are neglected and pressure is assumed to be independent of time.

Equation (205) can be solved assuming the volume average and junction flows are cocurrent and dropping the volume indices as follows:

$$h_{t+1} = \ell^{-t/\tau} (h_t - Q') + Q' \qquad (206)$$

where

h_{t+1} = the new time step junction enthalpy (formerly h_{ij})

h_t = the previous time step junction enthalpy

$\tau = \frac{M}{W'}$

$W' = |\bar{W} + W_j|$

Q' = a function of Q, τ and a volume associated enthalpy, as defined in Cases I through V below.

Note that the limiting value of Equation (201) as $\tau \to 0$ is $\bar{h}$ and the limit as $\tau \to \infty$ is h_t. This is as it should be since τ represents the time required for the fluid at the center of the volume to reach the junction.

Equation (205) reduces to the following for steady flow:

$$(\Delta h_i)_q = Q_i / 2\bar{W}_i \tag{207}$$

which is the proper limit for heating with negligible pressure changes. The heating model also has the numerical property that the junction enthalpy changes smoothly when the flow direction reverses. Without the heating model, the junction enthalpy is defined strictly by the source volume conditons. The junction enthalpy is permitted to change discontinuously during a flow reversal when the source volume changes. Thus, the heating model is physically reasonable during a flow reversal for a volume representing a single flow path channel when the volumes on either side of the junction do not differ greatly in enthalpy. The standard junction enthalpy defined by the source volume can be discontinuous during flow reversals and is physically reasonable in unheated volumes in which the fluid is well mixed.

While Equation (205) does not allow more than one phase to exist within the volume, the model has been extended to allow this case by using the following fluid temperature equation. The additional variable definitions here apply to Cases I through V following

$$T = T_s - (T_s - T_{in})\, e^{-\alpha X} \tag{208}$$

where

$$\alpha = \frac{hA}{|\bar{W}\, C_p L|} \tag{209}$$

and where

A = surface area for heat transfer

C_p = specific heat at constant pressure

h = average heat transfer coefficient

L = volume flow length

T = junction temperature

T_s = volume average surface temperature

$\bar{T}$ = volume average fluid temperature

T_{sat} = saturation temperature

h_{sat} = saturation enthalpy (liquid or vapor depending on which saturation line is being crossed)

h_{in} = inlet junction enthalpy

$\frac{dU}{dt}$ = rate of total energy addition to the volume

X_{sat} = distance from volume inlet to saturation line interface

$\bar{X}$ = distance from volume inlet to volume average conditions.

Equation (208) allows the prediction of the location of the saturation line relative to the volume inlet and outlet, so that the heat addition from the saturation line interface to the volume outlet may be calculated. It also allows a more accurate calculation of where the average volume conditions exist in the volume, since under transient conditions the volume conditions do not necessarily exist at the center of the volume for enthalpy transport calculation purposes. The following five cases are considered:

Case I: Volume is two-phase and junction outlet is two-phase;

$$Q' = \bar{h} + \frac{Q}{W'} . \tag{210}$$

Case II: Volume is two-phase and junction outlet is single phase:

$$Q' = h_{sat} + \frac{Q''}{W'} \tag{211}$$

where

$$Q'' = |T-T_{sat}| \; e^{-\alpha X_{sat}} \left[1-e^{-\alpha(L-X_{sat})} \right] |\bar{W}| Cp \tag{212}$$

and where

$$X_{sat} = \frac{L}{2} \left(\frac{h_{sat}-\bar{h}}{h_t-\bar{h}} \right) + \frac{L}{2} . \tag{213}$$

Case III: Volume is single phase, junction outlet is single phase and junction inlet is single phase:

$$Q' = \bar{h} + \frac{Q''}{W'} \tag{214}$$

where

$$Q'' = Qe^{-\alpha \bar{X}} \left(\frac{1-e^{-\alpha(L-\bar{X})}}{1-e^{-\alpha L}} \right) \tag{215}$$

and where

$$X = -\ln \left[\frac{T_s-\bar{T}}{T_s-\bar{T} + \left(\frac{\bar{h}-h_{in}}{C_p} \right)} \right] . \tag{216}$$

Case IV: Volume is single phase, junction outlet is single phase and junction inlet is two phase:

$$Q''_a = |T_s - T_{sat}| e^{-\alpha X_{sat}} \left(1 - e^{-\frac{\alpha L}{2}}\right) |\bar{W}| C_p \tag{217}$$

$$Q''_b = |T_s - T_{sat}| e^{-\alpha X_{sat}} \left[1 - e^{-\alpha (L - X_{sat})}\right] |\bar{W}| C_p \tag{218}$$

$$Q'_a = \bar{h} + \frac{Q''_a}{W'} \tag{219}$$

$$Q'_b = h_{sat} + \frac{Q''_b}{W'} \tag{220}$$

where

$$Q' = \max (Q'_a, Q'_b), \text{ if } Q \geq 0$$

$$Q' = \min (Q'_a, Q'_b), \text{ if } Q < 0.$$

Case V: Volume is single phase and junction is two phase:

$$Q' = hAL \, |T_s - T_{sat}| \left(1 - \frac{X_{sat}}{L}\right) \tag{221}$$

$$X_{sat} = -\ln \left(\frac{T_s - T_{sat}}{T_s - \bar{T} + \frac{\bar{h} - h_{in}}{C_p}} \right) . \tag{222}$$

The enthalpy transport model is optional and is controlled by the value entered for IHQCOR on the Junction Data Cards outlined in Volume II, Subsection 4.2.2 (21). The flow may be in either direction through the junction, and the volume on one side may be a core volume for which the enthalpy addition is needed. The volume on the other side may be a plenum in which the heat added could be evenly distributed throughout the volume. In the latter case, the volume average specific enthalpy

approximates the junction enthalpy as modified by the bubble rise model, and the addition of an enthalpy contribution would not be desired for flow from this volume.

A figure for zero is entered for IHQCOR on the Junction Data Cards if enthalpy change is not to be calculated. A 1 is entered for IHQCOR if the enthalpy change is to be added when the flow is toward the junction from the normal inlet side of the junction, but is not to be added for flow into the normal outlet side of the junction. A 2 is entered for IHQCOR if the enthalpy change is to be added when the flow is toward the junction from the normal outlet side of the junction, but is not to be added for flow into the normal inlet side of the junction. A 3 is entered for IHQCOR if the enthalpy change is to be added to the junction enthalpy transport whenever the flow is toward the junction from either the normal inlet or outlet sides. An enthalpy change is never calculated for flow away from the junction.

A significant problem exists with the enthalpy transport model under certain circumstances. These usually occur only late in the transient during refill or reflood. If enthalpy transport is used between volumes with greatly differing enthalpies and a flow reversal occurs, the built-in time lag may be large enough to cause an unrealistic junction enthalpy to be calculated. For example, the flow from a high quality core volume is flowing into a low quality core volume and the flow direction then reverses. The junction enthalpy would, for a period of time determined by the transport time τ, be approximately the enthalpy of the high quality fluid. This would cause an over extraction of energy from the low quality volume. This could cause the program to subcool the fluid unrealistically. If the user observes an unreasonable temperature distribution late in the transient for volumes using enthalpy transport, he should restart the run at a point prior to the problem occurrence omitting the use of enthalpy transport. This may be accomplished through use of the Water Packing and Choking Smoothing Card described in Volume II, Subsection 4.2.2 (8).

3.7 Advancement Procedures for Hydrodynamic Equations

The advancement procedures used in RELAP4/MOD5 closely follow those used in the FLASH-4[57] program. The principal differences are the addition of air flow capability, the use of a weighting factor so that the user can vary the advancement algorithm from explicit to implicit, and the provision for slip flow.

3.7.1 Advancement Equations. The hydrodynamic equations advanced in time by RELAP4 can be written as:

differential form

$$\dot{W}_k = f_k(P_i, P_j, W_k, t) \tag{223}$$

algebraic form

$$0 = f_k(P_i, P_j, W_k, t) \tag{224}$$

and

$$W_k = W_{\ell k} + W_{gk} \tag{225}$$

$$W = \rho v A \tag{226}$$

$$v_{\ell k} - v_{gk} = v_{sk} \tag{227}$$

$$\dot{U}_n = \sum_{\nu \epsilon T_n} \left(H_{\ell\nu} W_{\ell\nu} + H_{g\nu} W_{g\nu} \right) - \sum_{\nu \epsilon I_n} \left(H^*_{\ell\nu} W_{\ell\nu} + H^*_{g\nu} W_{g\nu} \right) + Q_n \tag{228}$$

$$\dot{M}_{\omega n} = \sum_{\nu \epsilon T_n} R_{\omega\nu} W_\nu - \sum_{\nu \epsilon I_n} R_{\omega\nu} W_\nu \tag{229}$$

$$\dot{M}_{an} = \sum_{\nu \epsilon T_n} R_{a\nu} W_\nu - \sum_{\nu \epsilon I_n} R_{a\nu} W_\nu \tag{230}$$

$$P_n = \Gamma(U_n, M_{\omega n}, M_{an}) \tag{231}$$

with

$k = 1,2,3, \ldots, K$

$n = 1,2,3, \ldots, N$

where (units of quantity given in SI units)

W_k = net flow (kg/sec) in junction k

$W_{\ell k}$ = flow (kg/sec) of liquid in junction k

W_{gk} = flow (kg/sec) of vapor in junction k

W = flow (kg/sec)

ρ = density (kg/m^3)

v = velocity (m/sec)

A = area (m^2)

$v_{\ell k}$ = velocity (m/sec) of liquid in junction k.

v_{gk} = velocity (m/sec) of vapor in junction k

v_{sk} = slip velocity (m/sec) in junction k

$M_{\omega n}$ = mass (kg) of water in volume n

M_{an} = mass (kg) of air in volume n

T_n = set of junctions which terminate in volume n

I_n = set of junctions which initiate with volume n

$H^*_{\ell\nu}$ = enthalpy (J/kg) of vapor flowing in junction ν and associated with flow out of a volume

$H^*_{g\nu}$ = enthalpy (J/kg) of liquid flowing in junction ν and associated with flow out of a volume

$H_{\ell\nu}$ = enthalpy (J/kg) of liquid flowing in junction ν and associated with flow into a volume

$H_{g\nu}$ = enthalpy (J/kg) of vapor flowing in junction ν and associated with flow into a volume

P_n = pressure (Pa) in volume n

Q_n = heat addition (J/sec) to volume n due to heat transfer and heat exchangers

K = the number of junctions

N = the number of volumes

$R_{\omega\nu}$ = mass fraction of water flowing in junction ν

$R_{a\nu}$ = mass fraction of air flowing in junction ν

and where

$$R_{\omega v} + R_{av} = 1. \tag{232}$$

Subscript ℓ indicates liquid water, subscript g indicates a mixture of water vapor and air, subscript ω indicates water in liquid and vapor form, and subscript a indicates air.

The differential form (Equation (223)) is usually derived from the time dependent momentum equation. The algebraic form (Equation (224)) can be derived from a pseudo-steady-state momentum equation, boundary conditions such as fills and leaks, choked flow correlations both for leaks and internal junctions between volumes, and component models such as reflood. In the last case, flow is usually directly dependent on other flows and these are omitted in the functional notation of f_k in Equation (224).

Combining Equations (225), (226), and (227), liquid and vapor flows are related to net flow by

$$W_{\ell k} = \rho_{\ell k} \frac{W_k - \rho_{gk} A_k v_{sk}}{\rho_{\ell k} + \rho_{gk}} \tag{233}$$

$$W_{gk} = \rho_{gk} \frac{W_k - \rho_{\ell k} A_k v_{sk}}{\rho_{\ell k} + \rho_{gk}} \tag{234}$$

Flows in the above expressions are considered to be positive quantities, and enthalpies $H_{\ell v}$, H_{gv}, $H^*_{\ell v}$, and H^*_{gv} are defined accordingly. In practice, flows can reverse. When that occurs, the T_n and I_n sets could be changed, but it is more convenient to treat flows as algebraic quantities and define enthalpies according to current flow direction. The program computes two junction enthalpies for liquid and vapor flows, one for enthalpy leaving the initiating volume (H^*) and the other for enthalpy entering the terminating volume (H without *). Actual enthalpy

in a junction leaving the initiating volume is the same as that entering the terminating volume. For programming convenience, volume related quantities that are also multiplied by flow, such as gravity terms, are added to the junction enthalpy.

Quantities $H_{\ell\nu}$, $H_{g\nu}$, $H^*_{\ell\nu}$, $H^*_{g\nu}$, $\rho_{\ell\nu}$, $\rho_{g\nu}$, $R_{\omega\nu}$, $R_{a\nu}$, and $V_{s\nu}$ are functions of adjacent volumes with the strongest dependence being on the initiating or upstream volume. Procedures for computing these quantities are given in the description of slip flow. The procedures are sufficiently complex that no attempt is made to include these terms in the quasi-linearization process that follows. Instead, a donor cell philosophy is used in that quantities transported across control volume surfaces for mass and energy equations are primarily derived from upstream conditions, are evaluated at the beginning of a time step, and are assumed constant over the time step.

Pressures appearing in Equations (223) and (224) are the sum of thermodynamic pressure and other terms such as spatial acceleration (momentum transfer) terms. In the quasi-linearization process, only thermodynamic pressure is linearized. Other terms are evaluated at the beginning of the time step and remain constant over the time step.

Defining

$$F_k = f_k(P_i, P_j, W_k, t) \tag{235}$$

$$F_{K+n} = \sum_{\nu \epsilon T_n} \left[H_{\ell\nu} W_{\ell\nu} + H_{g\nu} W_{g\nu} \right] - \sum_{\nu \epsilon I_n} \left[H^*_{\ell\nu} W_{\ell\nu} + H^*_{g\nu} W_{g\nu} \right] + Q_n \tag{236}$$

$$F_{K+N+n} = \sum_{\nu \epsilon T_n} R_{\omega\nu} W_\nu - \sum_{\nu \epsilon I_n} R_{\omega\nu} W_\nu \tag{237}$$

$$F_{K+2N+n} = \sum_{\nu \epsilon T_n} R_{a\nu} W_\nu - \sum_{\nu \epsilon I_n} R_{a\nu} W_\nu \tag{238}$$

$$\bar{y} = \text{col}\ (W_1, \ldots, W_K; U_1, \ldots, U_N; M_{\omega 1}, \ldots, M_{\omega N}; M_{a1}, \ldots, M_{aN}; t) \tag{239}$$

$$\bar{F} = \text{col}\ (F_1, \ldots, F_K; F_{K+1}, \ldots, F_{K+N}; F_{K+N+1}, \ldots, F_{K+2N}; F_{K+2N+1}, \ldots, F_{K+3N}; 1)\ . \tag{240}$$

Equations (223), (224), (228), (229), and (230) can be written as

$$\dot{\bar{y}} = \bar{F}(\bar{y}). \tag{241}$$

Note that an element of $\dot{\bar{y}}$ can be zero when the algebraic form of the flow equation is used and that $t = t$ or $\dot{t} = 1$ has been added for completeness.

A single step, implicit, numerical advancement algorithm for differential equations is given by

$$\frac{\Delta \bar{y}}{\Delta t} = [1 - \delta]\ \bar{F}(\bar{y}^m) + \delta\ \bar{F}(\bar{y}^{m+1}) \tag{242}$$

where

Δt = the time step

$\bar{y}^m$ = the value of y at the beginning of the time step t^m

$\bar{y}^{m+1}$ = the value of y at the end of the time step where $t^{m+1} = t^m + \Delta t$

$\Delta\bar{y} = \bar{y}^{m+1} - \bar{y}^m$.

If $\delta = 0$, the method is explicit; if $\delta = 0.5$, the method is Crank-Nicolson; and if $\delta = 1$, the method is fully implicit. Algebraic equations are advanced by

$$\bar{F}(\bar{y}^{m+1}) = 0 . \tag{243}$$

To quasi-linearize Equations (242) and (243), $\bar{F}(\bar{y}^{m+1})$ is expanded in the first two terms of its Taylor series:

$$\bar{F}(\bar{y}^{m+1}) \approx \bar{F}(\bar{y}^m) + \left.\frac{\partial \bar{F}(\bar{y})}{\partial \bar{y}}\right|_m \Delta\bar{y} \tag{244}$$

where $\frac{\partial \bar{F}(\bar{y})}{\partial \bar{y}}$ is the Jacobian matrix of $\bar{F}$. The term quasi-linearization is used to indicate that the Taylor series expansion is performed each time step. Using Equation (244), Equations (242) and (243) become:

differential form

$$\left[1 - \Delta t\ \delta \left.\frac{\delta \bar{F}(\bar{y})}{\delta \bar{y}}\right|_m\right]\Delta y = \Delta t\ \bar{F}(\bar{y}^m) \tag{245}$$

algebraic form

$$\left[-\left.\frac{\partial \bar{F}(\bar{y})}{\partial \bar{y}}\right|_m\right]\Delta\bar{y} = F(\bar{y}^m) . \tag{246}$$

In many cases, dependence of elements of $\bar{F}(\bar{y})$ on t in Equation (241) is easily separated, i.e., $\dot{\bar{y}} = \bar{F}(\bar{y},t) = \bar{F}(\bar{y}) + \bar{F}(t)$ where $\bar{y}$ no longer includes t as an element. In these cases, advancement procedures can use either $\frac{\partial F(t)}{\partial t}$ or $\bar{F}(t^{m+1})$.

Applying Equation (245) to Equations (228), (229), and (230), expressions for ΔU_n, $\Delta M_{\omega n}$, and ΔM_{an} in terms of ΔW_ν are directly obtained:

$$\Delta U_n = \Delta t \left\{ F_{K+n} + Q_n^* + \delta \left[\sum_{\nu \epsilon T_n} H_\nu^+ \Delta W_\nu - \sum_{\nu \epsilon I_n} H_\nu^{*+} \Delta W_\nu \right] \right\} \tag{247}$$

$$\Delta M_{\omega n} = \Delta t \left\{ F_{K+N+n} + \delta \left[\sum_{\nu \epsilon T_n} R_{\omega\nu} \Delta W_\nu - \sum_{\nu \epsilon I_n} R_{\omega\nu} \Delta W_\nu \right] \right\} \tag{248}$$

$$\Delta M_{an} = \Delta t \left\{ F_{K+2N+n} + \delta \left[\sum_{\nu \epsilon T_n} R_{a\nu} \Delta W_\nu - \sum_{\nu \epsilon I_n} R_{a\nu} \Delta W_\nu \right] \right\} \tag{249}$$

$$Q_n^* = (1 - \delta)\, Q_n^m + \delta\, Q^{m+1} \tag{250}$$

$$H_\nu^+ = \frac{\rho_{\ell\nu} H_{\ell\nu} + \rho_{g\nu} H_{g\nu}}{\rho_{\ell\nu} + \rho_{g\nu}} \tag{251}$$

$$H_\nu^{*+} = \frac{\rho_{\ell\nu} H_{\ell\nu}^* + \rho_{g\nu} H_{g\nu}^*}{\rho_{\ell\nu} + \rho_{g\nu}} \tag{252}$$

Applying Equations (245) and (246) to Equations (223) and (224) gives:

differential form

$$(1 - \Delta t\ \delta_k \frac{\partial f_k}{\partial W_k})\ \Delta W_k - \Delta t\ \delta_k \left\{ \frac{\partial f_k}{\partial P_i} \left[\frac{\partial P_i}{\partial U_i} \Delta U_i + \frac{\partial P_i}{\partial M_{\omega i}} \Delta M_{\omega i} + \frac{\partial P_i}{\partial M_{ai}} \Delta M_{ai} \right] \right.$$

$$\left. + \frac{\partial f_k}{\partial P_j} \left[\frac{\partial P_j}{\partial U_j} \Delta U_j + \frac{\partial P_j}{\partial M_{\omega j}} \Delta M_{\omega j} + \frac{\partial P_j}{\partial M_{aj}} \Delta M_{aj} \right] \right\} = \Delta t\ F_k \qquad (253)$$

algebraic form

$$- \frac{\partial f_k}{\partial W_k} \Delta W_k - \left\{ \frac{\partial f_k}{\partial P_i} \left[\frac{\partial P_i}{\partial U_i} \Delta U_i + \frac{\partial P_i}{\partial M_{\omega i}} \Delta M_{\omega i} + \frac{\partial P_i}{\partial M_{ai}} \Delta M_{ai} \right] \right.$$

$$\left. + \frac{\partial f_k}{\partial P_j} \left[\frac{\partial P_j}{\partial U_j} \Delta U_j + \frac{\partial P_j}{\partial M_{\omega j}} \Delta M_{\omega j} + \frac{\partial P_j}{\partial M_{aj}} \Delta M_{aj} \right] \right\} = \frac{\partial f_k}{\partial t} \Delta t + F_k \ . \qquad (254)$$

In the MOD5 version of RELAP4, internal junctions are described by the differential equation form [Equation (223)] and leaks and fills are described by the algebraic form [Equation (224)]. An internal junction is a junction joining two volumes, while leaks and fills connect to only one volume. For programming convenience in MOD5, the user must enter the junction description data (for K junctions) in the order of internal junctions ($k \leq K_d$) followed by leaks and fills ($K_d < k \leq K$). The algebraic forms of leaks and fills are further restricted to:

$$W_k = g_k(P_i) \text{ or } W_k = g_k(t) \qquad (255)$$

$$W_{\ell k} = W_k \qquad (256)$$

$$W_{gk} = 0 \tag{257}$$

$$H_{g\nu} = 0 \tag{258}$$

$$H^*_{g\nu} = 0 \tag{259}$$

$$\rho_{\ell\nu} = 1 \tag{260}$$

$$\rho_{g\nu} = 0 \ . \tag{261}$$

The only exception to the differential equation form for internal junctions is a closed valve, and the equation is then $W_k = 0$.

Because of the restricted form of the algebraic equations, the algebraic form of Equation (254) involves only one volume:

$$\Delta W_k = \frac{\partial g_k}{\partial P_i}\left[\frac{\partial P_i}{\partial U_i}\ \Delta U\ + \frac{\partial P_i}{\partial M_{\omega i}}\ \Delta M_{\omega i} + \frac{\partial P_i}{\partial M_{ai}}\ \Delta M_{ai}\right] + \frac{\partial g_k}{\partial t} \tag{262}$$

where $k>K_d$.

Furthermore; Equation (262) is used only for leaks, leaks are limited to outflow, fill junctions are advanced explicitly, and $\Delta W_k = 0$ for fills. Equation (262) is substituted into Equations (247) through (249). Sets of three simultaneous equations result where each set involves only the quantities ΔU_n, $\Delta M_{\omega n}$, and ΔM_{an} for one volume. Using determinants, the solutions are:

$$G_{hn} = (\Delta t)\ \delta \sum_{\substack{\nu \epsilon I_n \\ \nu > K_d}} \frac{\partial g_\nu}{\partial P_n} H^*_\nu \tag{263}$$

$$G_{\omega n} = (\Delta t)\ \delta \sum_{\substack{\nu \epsilon I_n \\ \nu > K_d}} \frac{\partial g_\nu}{\partial P_n} R_{\omega\nu} \tag{264}$$

$$G_{an} = (\Delta t)\ \delta \sum_{\substack{\nu \epsilon I_n \\ \nu > K_d}} \frac{\partial g_\nu}{\partial P_n} R_{a\nu} \tag{265}$$

$$\Gamma_n = 1 + \frac{\partial P_n}{\partial U_n} G_{hn} + \frac{\partial P_n}{\partial M_{\omega n}} G_{\omega n} + \frac{\partial P}{\partial M_{an}} G_{an} \tag{266}$$

$$\alpha_{1n} = 1 - \frac{\partial P_n}{\partial U_n} \frac{G_{hn}}{\Gamma_n} \tag{267}$$

$$\beta_{1n} = - \frac{\partial P_n}{\partial M_{\omega n}} \frac{G_{hn}}{\Gamma_n} \tag{268}$$

$$\lambda_{1n} = - \frac{\partial P_n}{\partial M_{an}} \frac{G_{an}}{\Gamma_n} \tag{269}$$

$$\eta_{1n} = \beta_{1n} - \lambda_{1n} \tag{270}$$

$$\gamma_{1n} = \alpha_{1n} F_{K+n} + \beta_{1n} F_{K+N+n} + \lambda_{1n} F_{K+2N+n} \tag{271}$$

$$\alpha_{2n} = - \frac{\partial P_n}{\partial U_n} \frac{G_{\omega n}}{\Gamma_n} \tag{272}$$

$$\beta_{2n} = 1 - \frac{\partial P_n}{\partial M_{\omega n}} \frac{G_{\omega n}}{\Gamma_n} \tag{273}$$

$$\lambda_{2n} = - \frac{\partial P_n}{\partial M_a} \frac{G_{\omega n}}{\Gamma_n} \tag{274}$$

$$\eta_{2n} = \beta_{2n} - \lambda_{2n} \tag{275}$$

$$\gamma_{2n} = \alpha_{2n} F_{K+n} + \beta_{an} F_{K+N+n} + \lambda_{2n} F_{K+2N+n} \tag{276}$$

$$\alpha_{3n} = - \frac{\partial P_n}{\partial U_n} \frac{G_{an}}{\Gamma_n} \tag{277}$$

$$\beta_{3n} = - \frac{\partial P_n}{\partial M_{\omega n}} \frac{G_{an}}{\Gamma_n} \tag{278}$$

$$\lambda_{3n} = 1 - \frac{\partial P_n}{\partial M_{an}} \frac{G_{an}}{\Gamma_n} \tag{279}$$

$$\eta_{3n} = \beta_{3n} - \lambda_{3n} \tag{280}$$

$$\gamma_{3n} = \alpha_{3n} F_{K+n} + \beta_{3n} F_{K+N+n} + \lambda_{3n} F_{K+2N+n} \tag{281}$$

$$\Delta U_n = (\Delta t)\, \gamma_{1n} + (\Delta t)\, \delta \left\{ \sum_{\substack{\nu \epsilon T_n \\ \nu \leq K_d}} \left[\alpha_{1n} H_\nu^{+} + \eta_{1\nu} R_{\omega\nu} + \lambda_{1\nu} \right] \Delta W_\nu \right.$$
$$\left. - \sum_{\substack{\nu \epsilon I_n \\ \nu \leq K_d}} \left[\alpha_{1n} H^{*+} + \eta_{1\nu} R_{\omega\nu} + \lambda_{1\nu} \right] \Delta W_\nu \right\} \tag{282}$$

$$\Delta M_{\omega n} = (\Delta t)\, \gamma_{2n} + (\Delta t)\, \delta \left\{ \sum_{\substack{\nu \epsilon T_n \\ \nu \leq K_d}} \left[\alpha_{2\nu} H_\nu^{+} + \eta_{2\nu} R_{\omega\nu} + \lambda_{2\nu} \right] \Delta W_\nu \right.$$
$$\left. - \sum_{\substack{\nu \epsilon I_n \\ \nu \leq K_d}} \left[\alpha_{2\nu} H_\nu^{*+} + \eta_{2\nu} R_{\omega\nu} + \lambda_{2\nu} \right] \Delta W_\nu \right\} \tag{283}$$

$$\Delta M_{an} = (\Delta t)\ \gamma_{3n} + (\Delta t)\ \delta \left\{ \sum_{\substack{\nu \epsilon I_n \\ \nu \leq K_d}} \left[\alpha_{3\nu}\ H_\nu^+ + \eta_{3\nu}\ R_{\omega\nu} + \lambda_{3\nu} \right]\ \Delta W_\nu \right.$$

$$\left. - \sum_{\substack{\nu \epsilon I_n \\ \nu \leq K_d}} \left[\alpha_{3\nu}\ H_\nu^{*+} + \eta_{3\nu}\ R_{\omega\nu} + \lambda_{3\nu} \right]\ \Delta W_\nu \right\} . \tag{284}$$

Equations (282), (283), and (284) are substituted into Equation (254) and a set of K_d simultaneous equations results.

$$\bar{\bar{A}}\ \bar{W} = \bar{Z} . \tag{285}$$

Elements for $\bar{\bar{A}}$ and $\bar{Z}$ are given below:

$$Z_k = (\Delta t)\ F_k + (\Delta t)^2\ \delta \left\{ \frac{\partial f_k}{\partial P_i} \left[\gamma_{1i} \frac{\partial P_i}{\partial U_i} + \gamma_{2i} \frac{\partial P_i}{\partial M_{\omega i}} + \gamma_{3i} \frac{\partial P_i}{\partial M_{ai}} \right] \right.$$

$$\left. + \frac{\partial f_k}{\partial P_j} \left[\gamma_{1j} \frac{\partial P_j}{\partial U_j} + \gamma_{2j} \frac{\partial P_j}{\partial M_{\omega j}} + \gamma_{3j} \frac{\partial P_j}{\partial M_{aj}} \right] \right\} \tag{286}$$

and

$$a_{kk} = 1 - (\Delta t)\ \delta \frac{\partial f_k}{\partial W_k}$$

$$+ (\Delta t)^2\ \delta^2 \left\{ \frac{\partial f_k}{\partial P_i} \left[\frac{\partial P_i}{\partial U_i} \left(\alpha_{1i}\ H_k^{*+} + \eta_{1i}\ R_{\omega k} + \lambda_{1i} \right) + \frac{\partial P_i}{\partial M_{\omega i}} \left(\alpha_{2i}\ H_k^{*+} + \right. \right. \right.$$

$$\left. \eta_{2i}\ R_{\omega k} + \lambda_{2i} \right) + \frac{\partial P_i}{\partial M_{ai}} \left(\alpha_{3i}\ H_k^{*+} + \eta_{3i}\ R_{\omega k} + \lambda_{3i} \right) \Big] - \frac{\partial f_k}{\partial P_j} \left[\frac{\partial P_j}{\partial U_j} \left(\alpha_{1j}\ H_k^{+} + \right. \right.$$

$$\left. \eta_{1j}\ R_{\omega k} + \lambda_{1j} \right) + \frac{\partial P_j}{\partial M_{\omega j}} \left(\alpha_{2j}\ H_k^{*} + \eta_{2j}\ R_{\omega k} + \lambda_{2j} \right) + \frac{\partial P_j}{\partial M_{aj}} \left(\alpha_{3j}\ H_k^{+} + \right.$$

$$\left. \left. \left. \eta_{3j}\ R_{\omega k} + \lambda_{3j} \right) \right] \right\} . \tag{287}$$

Elements $a_{k\nu}$, $\nu \neq k$, depend on whether $\nu \varepsilon T_i$, T_j, I_i, or I_j. Expressions for possible combinations are:

Case 0, $\nu \notin T_i$, $\nu \notin I_i$, $\nu \notin T_j$, $\nu \notin I_j$

where

ε = included in set

$\notin$ = not included in set,

(288)

$$a_{k\nu} = 0.$$

Case 1, $\nu \notin T_i$, $\nu \notin I_i$, $\nu \notin T_j$, $\nu \varepsilon I_j$

$$a_{k\nu} = (\Delta t)^2 \delta^2 \frac{\partial f_k}{\partial P_j} \left[\frac{\partial P_j}{\partial U_j} \left(\alpha_{1j} H_\nu^{*+} + \eta_{1j} R_{\omega\nu} + \lambda_{1j} \right) + \frac{\partial P_i}{\partial M_{\omega j}} \right.$$

$$\left. \left(\alpha_{2j} H_\nu^{*+} + \eta_{2j} R_{\omega\nu} + \lambda_{2j} \right) + \frac{\partial P_j}{\partial M_{aj}} \left(\alpha_{3j} H_\nu^{*+} + \eta_{3j} R_{\omega\nu} + \lambda_{3j} \right) \right] . \tag{289}$$

Case 2, $\nu \notin T_i$, $\nu \notin I_i$, $\nu \varepsilon T_j$, $\nu \notin I_j$

$$a_{k\nu} = -(\Delta t)^2 \delta^2 \frac{\partial f_k}{\partial P_j} \left[\frac{\partial P_j}{\partial U_j} \left(\alpha_{1j} H_\nu^{+} + \eta_{1j} R_{\omega\nu} + \lambda_{1j} \right) + \frac{\partial P_j}{\partial M_{\omega j}} \right.$$

$$\left. \left(\alpha_{2j} H_\nu^{+} + \eta_{2j} R_{\omega\nu} + \lambda_{2j} \right) + \frac{\partial P_j}{\partial M_{ai}} \left(\alpha_{3j} H_\nu^{+} + \eta_{3j} R_{\omega\nu} + \lambda_{3j} \right) \right] . \tag{290}$$

Case 4, $\nu \notin T_i$, $\nu \in I_i$, $\nu \notin T_j$, $\nu \notin I_j$

$$a_{k\nu} = - (\Delta t)^2 \delta^2 \frac{\partial f_k}{\partial P_i} \left[\frac{\partial P_i}{\partial U_i} \left(\alpha_{1i} H_\nu^{*+} + \eta_{1i} R_{\omega\nu} + \lambda_{1i} \right) + \frac{\partial P_i}{\partial M_{\omega i}} \right.$$

$$\left. \left(\alpha_{2i} H_\nu^{*+} + \eta_{2i} R_{\omega\nu} + \lambda_{2i} \right) + \frac{\partial P_i}{\partial M_{ai}} \left(\alpha_{3i} H_\nu^{+} + \eta_{3i} R_{\omega\nu} + \lambda_{3i} \right) \right] . \tag{291}$$

Case 6, $\nu \notin T_i$, $\nu \in I_i$, $\nu \in T_j$, $\nu \notin I_j$

Expressions for Case 6 are the sum of those for Cases 2 and 4.

Case 8, $\nu \in T_i$, $\nu \notin I_i$, $\nu \notin T_j$, $\nu \notin I_j$

$$a_{k\nu} = - (\Delta t)^2 \delta^2 \frac{\partial f_k}{\partial P_i} \left[\frac{\partial P_i}{\partial U_i} \left(\alpha_{1i} H_\nu^{+} + \eta_{1i} R_{\omega\nu} + \lambda_{1i} \right) + \frac{\partial P_i}{\partial M_{\omega i}} \right.$$

$$\left. \left(\alpha_{2i} H_\nu^{+} + \eta_{2i} R_{\omega\nu} + \lambda_{2i} \right) + \frac{\partial P_i}{\partial M_{ai}} \left(\alpha_{3i} H_\nu^{+} + \eta_{3i} R_{\omega\nu} + \lambda_{3i} \right) \right] . \tag{292}$$

Case 9, $\nu \in T_i$, $\nu \notin I_i$, $\nu \notin T_j$, $\nu \in I_j$

Expressions for Case 9 are the sum of those for Cases 1 and 8.

The differential form of the momentum equation currently used in RELAP4 is

$$\dot{W}_k = f_k = \frac{1}{I_k} \left[P_i - P_j - f_{rk} W_k |W_k| \right] \tag{293}$$

where I_k is the inertia, and the pressures include several terms besides thermodynamic pressure. Derivatives of f_k are:

$$\frac{\partial f_k}{\partial W_k} = - \frac{2 f_{rk}}{I_k} |W_k| \tag{294}$$

$$\frac{\partial f_k}{\partial P_i} = \frac{1}{I_k} \tag{295}$$

$$\frac{\partial f_k}{\partial P_j} = - \frac{1}{I_k} . \tag{296}$$

3.7.2 Solution of Simultaneous Equations. As shown in Reference 57, many RELAP4 problems are such that a suitable ordering of Equation (285) leads to a matrix with many of the elements in block tridiagonal form. The nonzero elements are computed in this order, normalized so that the diagonal elements are 1, and stored in a sequential array. If the matrix is diagonally dominant and if the number of equations is greater than 14, the equations are solved interatively. Otherwise, the matrix is expanded to a two-dimensional array, and the equations are directly solved using the method for a block tridiagonal matrix described in the reference.

The iterative solution uses a point overrelaxation procedure which converges if the matrix is diagonally dominant. The procedure is (using superscripts for iteration number)

$$e_k^{m+1} = \left[Z_k - \sum_{\nu<k} a_{k\nu} \, \Delta W_\nu^{m+1} - \sum_{\nu \geq k} a_{k\nu} \, \Delta W_\nu^{m} \right] \omega \tag{297}$$

$$\Delta W_k^{m+1} = \Delta W_k^{m} + e_k^{m+1} \tag{298}$$

where ν includes only nonzero values of $a_{k\nu}$ and $a_{kk} = 1$ from equation normalization. The initial guess for ΔW_k^{m+1} is the result of the last advancement. Each interation starts at k = 1 and proceeds in order to k = K_d. Iterations continue until all e_k^{m+1} are less then 10^{-8}.

The overrelaxation factor, ω, starts at 1 for each advancement and is updated during the iterations by the following:

$$\ell^{m+1} = \left[\sum_k \left(e_k^{m+1} \right)^2 \right]^{\frac{1}{2}} \tag{299}$$

and

$$\rho^{m+1} = \frac{\ell^{m+1}}{\ell^{m}} \quad . \tag{300}$$

$$\text{If } \left| \rho^{m+1} - \rho^{m} \right| \leq 0.01$$

then

$$\rho^{*} = \frac{(1 - \rho^{m+1})}{\rho^{m+1} \; (\omega^{old})^2} \left[\rho^{m+1} - (\omega^{old} - 1)^2 \right] \tag{301}$$

$$\omega^{new} = \frac{2}{1 + (\rho^{*})^{\frac{1}{2}}} \, . \tag{302}$$

The overrelaxation factor is reset to 1 after 25 iterations. Iterations are abandoned and the direct solution used if a $\rho^{m+1} > 1$ is computed or if 200 iterations without convergence are done. Testing has shown that the iterative solution is faster than the direct solution, primarily because the iterative solution takes advantage of the sparseness of the matrix. Also, current application practices are leading to a smaller number of equations in block tridiagonal form and this significantly lengthens the computer time for direct solution.

3.7.3 Programming Considerations. The CHAIN subroutine is called during input processing to order the equations in block tridiagonal form, to set the indices for the nonzero elements of A in Equation (285), and to store the T_n and I_n sets. The subroutines NIFTE and GAUSS implement the hydrodynamic advancement procedures. CHAIN and NIFTE are modified versions of the original subroutines taken from the FLASH-4[58] program.

3.7.4 User Control of Hydrodynamic Advancement. The only user control over the hydrodynamic advancement other than time step control, is the specification of δ. The variables are called OMEGA in the input description and the user may specify $0 \leq \delta \leq 1$. Using $\delta = 0$ results in an explicit advancement procedure similar to early versions of RELAP3. Because of stability considerations and time step limitations, the program should not be run with $\delta = 0.5$. Using $\delta = 0.5$ results in a Crank-Nicolson advancement, and $\delta = 1.0$ gives a fully implicit advancement procedure. Specifying $\delta \geq 0.5$ gives a stable advancement procedure with Crank-Nicolson having the lowest truncation error.

3.8 Edit and Time Step Control

The edit and time step control within RELAP4 are detailed in the following subparagraphs.

3.8.1 Edit Control. RELAP4 provides major edits and minor edits of printed output during problem execution. The frequency of the edits is specified on the Time Step Data Cards as outlined in [Volume II, Subsection 4.2.2 (6)]. The major edit follows a fixed format. The minor edit allows the user to choose, for frequent printout, up to nine variables from a large number of calculated variables. All of the variables available for minor edit are stored on the plot-restart tape for plotting purposes and for generating additional sets of printed output. An edit detail option is provided whereby the major and minor edits can be provided for specifically indexed time steps rather than for edit output based on a cumulative number (frequency) of time steps. Use of this option requires the Detailed Edit Card described in Volume II, Subsection 4.2.2 (7).

A restarting capability is included in RELAP4. Virtually all of the computations prior to a computer termination can be salvaged and the problem can be continued with a new sequence of time steps, if desired. The choice of edited variables and the edit frequency may also be modified in the continuation. Thus, a selected portion of a RELAP4 run can be evaluated with different program control conditions without resolving the entire problem.

Integers entered for NMIN and NMAJ on the Time Step Data Card control the amount of edited information to be printed, and the integer entered for NDMP controls the amount of information saved on tape for plotting and restart. If these integer constants are entered as zero, the defaults specified for the Time Step Data Cards are used.

3.8.2 Time Step Control. RELAP4 allows time step control as a user option. The user should determine the number of increments within the estimated RELAP4 problem time. This number (from 1 to 20) is entered for NTC on the Problem Dimensions Card outlined in Volume II, Subsection 4.2.2 (2). The time duration for each increment must also be specified along with other required time step data on the Time Step Data Card. All periods of the problem time must be accounted for in setting up the increment durations.

Some judgment on the part of the user is required in setting up the time step limits. The program advances equations through time by means of an iterative process; hence, time steps that are too small unnecessarily increase CPU time while those too large can lead to unacceptable inaccuracy. RELAP4 is set up to determine suitable time steps within prescribed limits or to accept user specified time step selections (for linear, nonlinear, or both equation types).

The best maximum and minimum time step size to use is highly problem dependent, however, an understanding of how the time step control works may be helpful. The program chooses the maximum time step size unless calculations from the previous time step indicate that the transient has undergone or is about to undergo some sort of rapid or critical change. Thus, in some cases it is only after the fact that the time step control responds. This means that the user should not use a large maximum time step and depend totally on the program to calculate the time step duration. For example, if the program is using 100 actual time steps for each standard (maximum) time step, the user should not be surprised if his job aborts. A fairly small minimum time step is needed so that the problem can avoid difficulty when crossing zero flow or the saturation line during the simulation. The smallest minimum time step ever needed appears to be about 50 microseconds. The subcooled blowdown and the refill portions of the transient require much smaller maximum time step sizes than does the saturated portion of the blowdown. Since the time-step control option checks on several nonlinearities that may exist during a transient, use of full time step control is generally recommended.

The integer constant (NCHK) on the Time Step Data Card controls the use of three time step control options as follows:

(1) NCHK = 1: Time step control is not requested. The program uses the time step maximum size specified by the user (DELTM).

(2) NCHK = -1: Time step control is applied to nonlinear conditions only. The control routine compares the user requested time step size against internally computed time step size based on the estimated zero flow crossing and the estimated saturation line crossing within the next time step for both increasing and decreasing pressure.

(3) NCHK = 0: Time step control is applied to linear and nonlinear conditions. The control routine compares the user requested time step size (DELTM) against the three nonlinear calculations and five additional linear calculations based upon current physical conditions of the volumes and junctions within the problem.

With time step control, the program selects the minimum of the calculated control time steps and the user specified time step. This minimum time step is then compared to the user specified minimum allowable time step size (DTMIN) and the larger of the two is chosen. The time step control option will, therefore, limit the time step size between DTMIN and DELTM.

Although the fluid flow equations are solved implicitly, the mathematical connections between the heat conduction, power generation, and hydraulics are explicit. The explicit connection technique can require smaller time steps than required by the fully implicit hydrodynamic solution.

3.8.3 Time-Step Length Determination. RELAP4 will determine time step length based on the user control input. Differential equations are selected by the program under guidance of the time step control input. Symbols used in these equations are:

DT_i = time step size, i = 1, 2, 3, 4, . . ,9 (time step check number)

M = mass of water in volume

M_a = mass of air in volume

$\dot{M}$ = dM/dt

$\dot{M}_a$ = dM_a/dt

W_j = junction flow

j = junction identification

$\overline{W}$ = volume average flow

U = total volume internal energy

$\dot{U}$ = dU/dt

P = pressure

$\dot{P}$ = dP/dt

C_1 = constant = 0.01

C_2 = constant = 1,000.0

C_3 = constant = 50.0

C_4 = constant = ∞ (for Δh_j < 50 BTU/lbm)

= -1.0 (for 50 BTU/lbm $\leq \Delta h_j \leq$ 200 BTU/lbm)

= -0.8 (for Δh_j > 200 BTU/lbm)

C_5 = constant = 0.9

Δh_j = enthalpy change that occurs during a flow reversal with j being the junction number.

Based upon volume conditions, the following five checks on solution accuracy used in the time-step control routine, limit the maximum fractional change per time step of mass or energy of the volume.

The calculation

$$DT_1 = C_1 \left| \frac{P}{\dot{P}} \right| \tag{303}$$

is based on the smallest ratio of pressure to pressure rate change in any volume. It applies when NCHK = 0.

The calculation

$$DT_2 = C_2 \left| \frac{M + M_a}{\overline{W}} \right| \tag{304}$$

is based on the smallest ratio of volume mass to volume average flow in any fluid control volume. This is to limit the maximum permitted mass change and applies when NCHK = 0.

The calculations

$$DT_3 = \frac{C_3}{\left| \dot{M} \frac{\partial P}{\partial M} \right|} \tag{305}$$

where U, M_a are constant

$$DT_4 = \frac{C_4}{\left| M_a \frac{\partial P}{\partial M_a} \right|} \tag{306}$$

where U, M are constant

and

$$DT_5 = \frac{C_5}{\left| \dot{U} \frac{\partial P}{\partial U} \right|} \tag{307}$$

where M, M_a are constant,

limit the change in pressure allowed. This is to reduce time step size prediction problems due to the linearization of the water properties and resultant truncation errors. These apply when NCHK = 0.

Additional time step checks are performed to estimate the time at which flows reverse direction and when the volume conditions change from single-phase to two-phase liquid or from two-phase to single-phase liquid. A flow reversal can cause a nonlinear change in both the junction friction factor and the junction enthalpy, and a phase change can cause a nonlinear change in the physical properties of the fluid. These time estimates are used to approximate the point at which the nonlinear changes can occur. This allows the time step to be readjusted to permit a more nearly accurate calculation of the junction friction factor and enthalpy along with the physical properties of the fluid. Equations (308) through (310) for the foregoing utilize the following additional symbols:

P_s = saturation pressure

P = volume pressure

X = quality

ρ = density

V_g = saturated gas specific volume

V_f = saturated liquid specific volume.

The calculation

$$DT_6 = C_4 \frac{W_j}{\dot{W}_j} \tag{308}$$

is a time increment estimate for the occurrence of a flow reversal. It applies when NCHK = 0 or -1.

The calculation

$$DT_7 = C_5 \frac{P_s - P}{\dot{P}} \tag{309}$$

is a time increment estimate for a change from liquid to two-phase fluid for decreasing pressure such that $\dot{P} < 0$ and $P > P_s$. It applies when NCHK = 0 or -1.

The calculation

$$DT_8 = C_5 \, X \, \rho \, (V_g - V_f) \frac{M}{\dot{M}} \tag{310}$$

is a time increment estimate for changing from two-phase fluid to liquid such that $\dot{M} > 0$ and $X < 0.1$. It applies when NCHK = 0 or -1.

The preceeding Equations, (306) through (310), have the constants C_4 and C_5. The constant C_4 was selected such that the time of occurrence of the nonlinearity due to flow reversal would be slightly underestimated. The constant C_5 was selected to control the estimate of the time of occurrence of the two-phase nonlinearity.

An additional time step control is used to prevent overextraction of energy from volumes being depleted of liquid mass. This control is used only for slip junctions and only if the mixture level smoothing option is not used. It applies when NCHK = 0.

$$DT_9 = C_6 \left| \frac{M_1}{\dot{M}_1} \right| \qquad (311)$$

where

M_1 = liquid mass in the volume above the slip junction

$\dot{M}_1$ = liquid mass flow rate through the slip junction from above

C_6 = constant = 0.8.

3.8.4 Program Termination. The user may frequently wish to terminate the problem based on computer CPU time rather than transient problem time. If the user were to end on a CPU time limit sensed externally by the system, he would not get a final major edit and restart dump for the last part of his calculation. The time from the last restart to the end of the original problem would be wasted upon restarting. Thus, the ENDCPU option is provided on the first Time Step Control Card. This option provides an internal check on CPU time which allows the user to get the final major edit and restart dump.

3.9 Dials

A set of so-called "dials" has been included in RELAP4/MOD5. These dials allow the code user to vary the output from selected RELAP4 correlations and/or models, such as the critical flow models. In most cases, the number entered on the Dial Card is a multiplier or coefficient that will be applied by the program to the value otherwise computed or used. If not a multiplier, the Dial Card value will be substituted for the default value listed. The purpose of this feature is to allow sensitivity or uncertainty analyses to be made. A default value is specified for each dial. The default value is the best-estimate value of that dial, and should be used for normal RELAP4 "best-estimate" type runs.

The dials available in RELAP4/MOD5 are accessed by entering specific data on the following optional cards:

(1) Modified Burnell Critical Flow Model Dial Card outlined in Volume II, Subsection 4.2.2 (23):

DLHEM = Dial applied to HEM in the saturated and superheated regions. Default = 1.0.

DLMHEM = Dial applied to modified HEM value in the transition region (0 < QUALITY < DLXTR). Default = 1.0.

DLXTR = Transition quality used to define transition region (not a multiplier). Default = 0.05.

DLPB = Dial to adjust modified back pressure in subcooled and transition regions. Default = 1.0.

(2) HEM Critical Flow Model Dial Card outlined in Volume II, Subsection 4.2.2 (24):

DLHEM = Dial applied to HEM flow in all regions. Default = 1.0.

(3) Henry-Fauske HEM Critical Flow Model Dial Card outlined in Volume II, Subsection 4.2.2 (25):

DLHEM = Flow rate multiplier for HEM. Default = 1.0.

DLHRY = Flow rate multiplier for Saturated Henry critical flow. Default = 1.0.

DLEHRY = Flow rate multiplier for Subcooled (Extended) Henry critical flow. Default = 1.0.

DLXTFE = Transition quality boundary for model (not a multiplier). Default = 0.02.
NOTE: This enters the value for X_T shown in Figure 23, Subsection 3.6.8 (2) (f).

(4) Moody Critical Flow Model Dial Card outlined in Volume II, Subsection 4.2.2 (26):

DLMDY = Flow rate multiplier for Moody critical flow model. Default = 1.0.

(5) Henry Critical Flow Model Dial Card outlined in Volume II, Subsection 4.2.2 (27):

DLHRY = Flow rate multiplier for Saturated Henry critical flow model. Default = 1.0.

(6) Subcooled Henry Critical Flow Model Dial Card outlined in Volume II, Subsection 4.2.2 (28):

DLEHRY = Flow rate multiplier for Subcooled (Extended) Henry critical flow model. Default = 1.0.

(7) Downcomer Penetration Model Dial Card outlined in Volume II, Subsection 4.2.2 (29):

DDWNPN = Liquid flow rate multiplier to the lower plenum (XJL) for the Battelle downcomer penetration model. Default = 1.0.

(8) Lower Plenum Entrainment Model Dial Card outlined in Volume II, Subsection 4.2.2 (30):

DPLNEN = Multiplier of the calculated value of the critical distance (HCRIT) between the bottom of the downcomer and the lower plenum liquid level for the Wallis Lower plenum entrainment model. Default = 1.0.

(9) Two Phase Friction Factor Multiplier Dial Card outlined in Volume II, Subsection 4.2.2 (31):

DLTFFM = Multiplier for 2-phase friction factor multiplier. Default = 1.0.

(10) Metal-Water Reaction Dial Card outlined in Volume II, Subsection 4.2.2 (32):

DLMWR = Multiplier for metal water reaction heat production. Default = 1.0.

(11) Critical Heat Flux Dial Card outlined in Volume II, Subsection 4.2.2 (33):

DCHF = Multiplier for all critical heat fluxes. Default = 1.0.

(12) Heat Transfer Coefficient Dial Card outlined in Volume II, Subsection 4.2.2 (34):

CAUTION: It is particularly risky to use Heat Transfer Dials without understanding the heat transfer logic and the ramifications of these dials. For example, a large DHTC1 could produce a meaningless solution in heat transfer mode 1 with a heat flux

greater than the CHF value. A large DHTC5 could produce a solution in heat transfer mode 5 with a flux greater than the CHF value but with a delta T less than that of CHF.

Note: No multiplier is provided for heat transfer mode 4, since this curve is attached to the CHF value on the left (see Figure 11, Subsection 3.4.6).

DHTC1 = Multiplier for heat transfer coefficient in Heat Transfer Mode 1

DHTC2 = Multiplier for heat transfer coefficient in Heat Transfer Mode 2

DHTC3 = Multiplier for heat transfer coefficient in Heat Transfer Mode 3

DHTC5 = Multiplier for heat transfer coefficient in Heat Transfer Mode 5

DHTC6 = Multiplier for heat transfer coefficient in Heat Transfer Mode 6

DHTC7 = Multiplier for heat transfer coefficient in Heat Transfer Mode 7

DHTC8 = Multiplier for heat transfer coefficient in Heat Transfer Mode 8

DHTC9 = Multiplier for heat transfer coefficient in Heat Transfer Mode 9.

Default for all of the above = 1.0.

(13) Pool Boiling Correlation Choice Dial Card outlined in Volume II, Subsection 4.2.2 (35):

DPBAL = Void fraction used to select pool boiling heat transfer correlation (not a multiplier). Default = 0.6.

All of the above dial cards are optional. If values are not entered, the default values are used. If a dial card is used, all allowed values for that card must be entered.

3.10 Evaluation Model (EM) Options

RELAP4/MOD5 forms the basis for the RELAP4/MOD5-EM program which is a part of the Nuclear Regulatory Commission's (NRC) Water Reactor Evaluation Model (WREM). The WREM package[1] consists of several computer programs developed to evaluate the transient behavior of a light-water-cooled power reactor when subjected to a postulated LOCA. RELAP4-EM calculations are performed using specified EM options within the basic RELAP4 program. This section describes these EM options. A discussion of RELAP4-EM is also given in Reference 1.

RELAP4-EM was generated as a joint effort between Aerojet Nuclear Company (ANC) and the NRC staff. It was generated as one of several computer programs to be used by the NRC staff to perform independent audits of vendor and applicant analyses of the transient following a postulated LOCA. RELAP4-EM does not, however, fully comply with the requirements set forth in Appendix K to 10 CFR Part 50[2], and thus, is not a stand-alone code for licensing purposes. The WREM package is used by NRC in auditing various portions of a LOCA, but requires external input before performing a complete calculation.

RELAP4-EM is used to perform system thermal-hydraulic decompression analyses and detailed fuel rod thermal behavior calculations for both PWR and BWR. For PWR systems, the RELAP4-EM blowdown analyses provide a

calculational model of the reactor primary and secondary systems, including the hot fuel assembly or assemblies in the core, the remainder of the core, the reactor vessel downcomer, upper head, upper plenum regions, secondary coolant systems, and emergency core coolant injection. The RELAP4-EM analysis begins from steady state or assumed initial operating conditions and continues through pipe rupture and system decompression to the onset of the reactor core recovery with emergency coolant. RELAP4-EM computes the space and time variations of thermal-hydraulic conditions of the primary and secondary coolant system. Included in the calculation are:

(1) Coolant flows between regions
(2) Heat transfer between the primary and secondary coolant system
(3) Heat transfer from system metal surfaces and the core to the coolant
(4) Hydraulic effects of system components such as pumps, valves, and the core
(5) The temperature of the hot fuel assembly and the remainder of the core
(6) Fuel rod swelling and rupture
(7) ECC bypass.

RELAP4-EM is then used to model the reactor core, including a hot fuel rod (hot channel analysis). Time-dependent boundary conditions are supplied by the previous RELAP4-EM calculation to represent the fluid conditions in the adjacent upper and lower plenum regions. The RELAP4-EM program then performs a detailed calculation of the core and hot fuel rod temperature transient for the same time period as the system calculation previously performed by RELAP4-EM.

The RELAP4-FLOOD program (see Section 3.11) performs essentially a continuation of the system blowdown calculation through the period of ECC reflood of the reactor core. The program itself is a special version

of the RELAP4-EM program with modifications, primarily in the core region, to calculate reflooding rates and fluid conditions as required by the NRC acceptance criteria.

For BWR systems, the RELAP4-EM computer program is used to model the hot fuel assembly and the remainder of the core, the fluid system within the reactor vessel, and the recirculating loops. The analysis begins with steady state operating conditions and is usually terminated at the end of lower plenum flashing unless further calculations are desired. The RELAP4-EM system analysis computes the space and time variation of thermal-hydraulic conditions of the fluid within the reactor vessel and recirculating loops, flows between system regions, heat transfer from system components and the core to the coolant, hydraulic effects of the pumps, fuel rod swelling and rupture, and power and temperature of both the core and the hot fuel rod assembly.

The features which have been added to or differ significantly from standard RELAP4 to obtain RELAP4-EM are:

(1) Fuel Rod Swelling, Rupture, and Blockage
(2) ECC Bypass Model
(3) Pump Model
(4) Liquid Level Calculations
(5) Core Flow Smoothing
(6) Heat Transfer Correlation
(7) Critical Flow Models
(8) Gap Conductance Model
(9) Fission Product Decay Heat Conservatism
(10) Critical Heat Flux Correlation
(11) Metal-Water Reaction.

These items are described in more detail in the following subsections.

3.10.1 Input Control. A flag has been added to the RELAP4-EM input data to specify an EM calculation. The flag (ISPROG) is on the

Problem Dimension Data Card outlined in Volume II, Subsection 4.2.2 (2) and should be specified as 1 to use all EM options.

Several options are available to perform sensitivity analyses or check calculations. However, if the EM is to be run (ISPROG = 1), then the following options and input must be specified:

	EVALUATION MODEL INPUT	
CARD		COMMENT
Problem Dimension Data Card - Volume II, Subsection 4.2.2 (2)	ISPROG = 1	This flag specifies that all EM are to be used.
Junction Data Cards - Volume II, Subsection 4.2.2 (21)	JCHOKE = 0 ICHOKE = 11	JCHOKE and ICHOKE are used to specify the EM critical flow model.
	MVMIX = 0,1,2,3,4	This input variable specifies the type of momentum equation to be used. For EM, the type should be selected for the geometry to be modeled and conform to the LOCA hydrodynamic selection as outlined in WREM[1].
Kinetics Constant Data Card - Volume II, Subsection 4.2.2 (46)	NODEL = 3	Specifies the thermal power calculation to be used.

	KMUL $\neq$ 0	Specifies the ANS standard to be multiplied by 1.2.
Heat Slab Data Cards - Volume II, Subsection 4.2.2 (51)	IMCR = 1 or 2 for PWR IMCR = 0 for BWR	Specifies the flow film boiling correlation.
Core Slab Data Cards - Volume II, Subsection 4.2.2 (54)	ISLBAJ= 2 for blowdown run ISLBAJ= 1 for single pin analysis	Flag to indicate calculation to be made after pin swelling.
	ISWTAB= 0 for blowdown run ISWTAB=1 for single pin analysis	Indicates table to be used for blockage data.
Blockage, swelling and Gap Reduction Data Card - Volume II, Subsection 4.2.2 (60)		Specific general properties for all fuel pins.
ECC Bypass Input Data Card - Volume II, Subsection 4.2.2 (61)		This card is required for PWR only.
Pin Clad Rupture and Flow Blockage Data Cards - Volume II, Subsection 4.2.2 (62) through (65)		Multiple and single pin clad rupture and blockage data.

3.10.2 Fuel Rod Swelling, Rupture, and Blockage. The fuel rod model in RELAP4-EM was obtained from portions of the FRAP code[59]. This group of models includes several effects not included by the standard RELAP4. These are always a part of an EM calculation but can be accessed separately as options for other RELAP4 calculations. Frequently, several heat slabs are used to model one rod (or group of rods) and the slabs must be described as a stack (ISB on the Heat Slab Data Cards) in order to indicate their connection.

(1) Fuel Rod Thermal and Pressure Response Model. The transient response of the fuel rod includes the following features:

(1) The expansion of the fuel material is based on the data of Conway[60] without allowance for melting. The curve used for T in °C is:

$$\varepsilon = -1.723 \times 10^{-4} + 6.797 \times 10^{-6} T + 2.896 \times 10^{-9} T^2. \quad (312)$$

(2) The radial expansion of the fuel pellet including allowance for cracking follows the model used in GAPCON-THERMAL-1[62], in which free expansion is assumed outside the calculational node of maximum circumferential thermal expansion of the material. In order to provide a smooth radial thermal expansion, 50 pseudo nodes are temporarily established to be comparable to the 50 used in GAPCON. The temperatures for these nodes are obtained by linear interpolation from the values produced by the heat conduction calculation (at the nodes defined by the input geometry).

(3) Axial thermal expansion of the fuel pellet stack is calculated at a contact radius which is provided by the user. Normally this radius is that of the shoulder at the edge of the dished out portion of the ends of pellets.

(4) The cladding expansion in both the radial and axial directions is calculated as the sum of a pressure-induced strain predicted by the thin wall formula plus thermal strain assuming an average temperature for the cladding. In addition, a plastic hoop strain is calculated as described in the next paragraph. The elastic modulus is obtained from an interpolation and extrapolation of available data:

$$E = (1.148 \times 10^{11} - 5.99 \times 10^{7}T)\ N/m^2$$

where (313)

$$T \leq 750°K$$

and

$$E = (1.07981 \times 10^{11} - 5.02236 \times 10^{7}T)\ N/m^2$$

where (314)

$$T > 750°K.$$

N/m^2 is the pressure measured in pascals.

The Poission ratio for the cladding is calculated by:

$$\nu = 0.32 + 5.0 \times 10^{-5}T, \quad (315)$$

where T is the temperature in °F.

The cladding thermal strain for zircaloy when heated from temperature T_1 to T_2 is calculated as follows:

$$\varepsilon = 3.2 \times 10^{-6}(T_2 - T_1)$$

where (316)

$$T_2 \leq 1550°F$$

$$\varepsilon = 3.2 \times 10^{-6}(1550 - T_1)$$

where (317)

$$1550 < T_2 \leq 1775°F$$

and

$$\varepsilon = 3.2 \times 10^{-6}(1550 - T_1) + 5.3 \times 10^{-6}(T_2 - 1775)$$

where (318)

$$T_2 > 1775°F.$$

The cladding thickness is decreased by the hoop strain assuming a constant cross sectional area, but is increased by the thermal strain in a first order calculation. The computer coding includes a check to insure that the gap thickness cannot be negative.

(5) The plastic hoop strain of the cladding before failure is calculated from a formulation using Hardy's[61] data. The following steps define the procedures of the model:

(a) From the table of rupture temperature versus pressure difference provided by the user for the fuel rod, determine $T_{rupture}$. Then $\Delta T = T_{rupture} - T_{clad}$. If ΔT is negative, rupture is predicted and the steps described in the cladding rupture model are taken.

(b) If ΔT is between 0° and 200°F, the user-provided table of flow blockage upon rupture is used to calculate the fractional change in the outer cladding radius assuming rupture at the present pressure difference. Denote this fractional change by F; then the plastic strain is calculated as:

$$\varepsilon = 0.2F \exp(-0.0153\ \Delta T). \quad (319)$$

The plastic strain behaves as a ratchet. Once a given plastic strain is reached, no decrease of this component is allowed. Upon rupture of the cladding, this ratchet is set to maintain the expanded condition. After rupture, the pressure strain is not calculated, but the thermal strain continues as a function of the transient temperature.

(6) At each time step, the thickness of an oxide layer on the cladding due to metal-water reaction (if any) is reduced according to any additional swelling of the slab.

(7) The gas pressure inside the fuel rod is calculated using the ideal gas law from the number of moles of gas entered for GSMOL in the Core Section Data Cards for EM outlined in Volume II, Subsection 4.2.2 (54) and transient values of the temperature and volume in each slab. The volume available to the gas is determined in each slab from the gap dimensions, the volume of cracks calculated by the code, and an input volume. The gas is assumed to flow freely along the rod, and one pressure is calculated for all slabs of a stack. The gap temperature is an average of the calculated fuel outer surface and cladding inner surface temperatures. The gas in the calculated crack volumes of a slab is assumed to be at the fuel surface temperature. Several options are available for treating the user input gas volume of a slab. The most important is the specification of a plenum, usually at the top of a rod. In other slabs the (hot) volume may represent a center void, extra surface cracks, or distributed volume. A corresponding choice is made from the centerline, surface, or radial average temperature in the fuel.

Large voids should probably also be accompanied by reduced power generation and modified material properties in the slab.

An upper plenum volume (at 68°F) must be supplied and is adjusted for differential axial expansion of the fuel stack and cladding at operating temperature. Part of this volume is normally occupied by a hold down spring. Additional plenums in a fuel rod may be obtained by providing volume and spring data on the input card for the adjacent core section. Each plenum gas temperature is obtained from a heat transfer calculation with convection between the pellet stack (which may be an insulator), the spring, and the cladding. Heat is conducted through the cladding to the coolant, and the heat capacity of the spring provides a time delay against coolant flow transients. An estimate is also calculated for the gamma ray heat deposited in the spring and cladding at the plenum.

The transmission of heat into the plenum gas from the exposed end of the fuel pellet stack is included. To handle the cases with an insulator pellet on the end of the stack, an input quantity FPEL is provided as an insulation factor. The effective end pellet temperature is:

$$T_{pel} = T_{gas} + (T_{fuel} - T_{gas})/FPEL. \qquad (320)$$

A typical value of FPEL for an insulator pellet is thought to be around 200. The spring geometry is defined by the quantities:

L = length of the coiled spring and the plenum

N = number of coils in the spring

D_C = outside diameter of the coiled spring

D_W = diameter of spring wire.

The length of the uncoiled wire is calculated by:

$$L_W = \left[\left(\pi N \left(D_C - D_W\right)\right)^2 + L^2\right]^{1/2} \tag{321}$$

after which the surface area and volume of the spring are obtained from

$$A = \pi D_W L_W \tag{322}$$

$$V = \frac{\pi}{4} D_W^2 L_W \tag{323}$$

It should be noted that when a RELAP slab is used to model a number of fuel rods, the spring length and number of coils, as well as the plenum volume and amount of gas in the core section, must represent all pins in the slab when input to the code. However the coil and wire diameters are intrinsic quantities for the spring, and are not multiplied by the number of pins.

A multiplier for the gamma heat deposited in the plenum spring and cladding allows the user to adjust for the presence of neighboring fuel rods or unusual geometry.

(2) Fuel Rod Swelling and Rupture Model. Rupture is predicted to occur as a function of ΔP (pin internal pressure minus coolant pressure) versus cladding temperature. This model requires the user to provide, from the available data, tabular values of rupture temperature as a function of pressure difference and of percentage blockage of flow area as a function of pin pressure differences. These are entered on the

various Clad Rupture and Flow Blockage Data after Rupture Data Cards outlined in Volume II, Subsection 4.2.2 (62,63,64, and 65). The cladding surface temperature and the difference between the internal fuel pin pressure and surrounding fluid pressure are both calculated during the transient. These are monitored and compared with tabular rupture data to determine when and if rupture occurs.

If rupture is predicted, selections are made from the following models to calculate the ruptured pin condition. The model selected depends on the fuel pin type that is being represented.

(1) The pin internal pressure is reduced in one time step to that in the coolant channel adjacent to the failed slab and for the remainder of the calculation equals the coolant channel pressure. The gas composition is set to steam at the local pressure in the ruptured axial node or heat slab at the point of rupture.

(2) The amount of blockage is determined from the selected tabular data of percent blockage as a function of pressure difference.

(3) The metal-water reaction is continued on the outside surface with the oxide layer being thinned in accordance with the calculated swelling. The metal water reaction is assumed not to be steam limited.

(4) The new rod radius is calculated assuming unrestricted swelling. Based on the new radius, the new surface area on the inside and the outside of the cladding is calculated. The length of the swollen zone is determined by the length of the axial node.

(5) Metal-Water reaction is started on the inside of the cladding, assuming no previous oxidation has occurred.

(6) The new cladding radius is calculated but limited to $0.2^{[61]}$ of the increase predicted by the blockage. This is the limiting value of the plastic hoop strain before failure (uniform hoop strain), which was described by item (5) in Subsection 3.10.2 (1) preceeding.

RELAP4-EM permits the consideration of two types of fuel pins. One is a single pin used to represent a hot pin in the hot assembly. The second is a "multiple" fuel pin which represents the average fuel pin in the remainder of the hot assembly or core. Therefore, RELAP4-EM requires the user to supply two sets of tables. One table is for multiple pin rupture criteria used if 0 is entered for ISWTAB on the Core Slab Data Cards for the Evaluation Model outlined in Volume II, Subsection 4.2.2 (54). The other is for single pin criteria and is used if ISWTAB = 1.

In addition to the six models listed above, RELAP4-EM performs calculations for multiple pin rupture as follows:

(7) The friction is increased at the junctions above and below the swollen zone. The amount of friction increase is calculated based on a sudden contraction and expansion. For example, if the flow is in the normal direction, a friction K factor based on a sudden contraction from the normal area to the blocked area is added to the friction terms in the junction immediately below the swollen zone. Likewise, a K factor based on a sudden expansion from the blocked area to the normal area is added at the junction above the swollen zone.

Three options are available for applying the swelling and rupture data in the RELAP4-EM model, and the user's choice is specified by the selection of a value for ISLBAJ on the Core Slab Data Cards for EM. These options are used to represent either a single rod, average rod in

an assembly or assemblies, average rod in the average core, or fuel rod with an associated fluid channel. These options are:

(1) Fuel Rod with an Associated Fluid Channel (ISLBAJ = 0). The selection of this option yields effects or calculations described in 1, 2, 3, 4, 5, and 7 above and should be used when a small core region, on the order of 3 inches of fuel rod and its associated channel, is being modeled. This option corresponds to a test section with a single rod in a close fitting tube and is not the regular EM option. The user should select single rod blockage data for this option (ISWTAB = 1).

(2) Single Rod Analysis (ISLBAJ = 1). The selection of this option yields effects described in 1, 2, 3, 4, and 5 above and should be used when a small core region such as a 3-inch fuel rod segment is modeled with bounding fluid conditions from a much larger volume. With this option, the user should select the single rod blockage data (ISWTAB = 1).

(3) Average Rod in Hot Assembly or Average Core (ISLBAJ = 2). The selection of this option yields effects or calculations described in 1, 2, 3, 6, and 7 above and should be used to model one assembly or more which will apply to large core volumes. It should use the multirod blockage tables (ISWTAB = 0).

In each case, swelling or rupture is tested on a stack of axial heat slabs and is allowed to occur at only one heat slab of an axial stack. In modeling the hot assembly, it is sometimes desirable to have more than one stack of heat slabs (i.e., the hot rod and an average hot assembly rod) connected to a given coolant volume. However, the code cannot handle rupture in more than one stack that might affect one

junction, regardless of the value of ISLBAJ. If such multiple blockage of a junction is predicted, the problem is halted. Rupture in more than one stack is permitted if they are separated.

3.10.3 Gap Conductance. The gap conductance model in the EM logic in RELAP4 is a calculation using a modification of the Ross-Stoute model found in the GAPCON THERMAL-1[62] program. The gap conduction model accounts for:

(1) fuel-clad contact conduction heat transfer

(2) gas conduction

(3) radiation heat transfer.

The composition of the gas is an input, and the conductivity is calculated as a function of temperature.

The following simplified GAPCON model is used. The effective gap conductance can be expressed generally as the sum of three terms:

$$h_g = h_c + h_{gas} + h_{rad} \tag{324}$$

where

h_g = effective gap conductance

h_c = effective conductance through points of contact of the cladding and fuel

h_{gas} = effective conductance through gas in the gap

h_{rad} = effective conductance due to radiation across the gap.

Gap conductance is predicted by the following equation for an annular gap (no contact):

$$h_g = \frac{1}{\Delta x} \frac{k_g}{1 + g/\Delta x} + h_{rad} \qquad (325)$$

where

Δx = the thickness of the annular gap (ft).

The gas conductivity, k_g, of the gap mixture is computed as a function of temperature based on the Bird, Stewart, and Lightfoot[10] Model as used in GAPCON THERMAL-1. Before cladding rupture is calculated, the gas composition is simplified by the user as an arbitrary mixture of helium, argon, krypton, xenon, hydrogen, nitrogen and steam. After cladding rupture is calculated, the gas composition in the ruptured heat slab is replaced by steam, and the gap conductance is calculated at the gap temperature and at a pressure equal to that in the associated fluid volume.

The hot gap dimensions are calculated on the basis of thermal expansion for both the fuel and cladding.

The correction for gap conditions in the Knudsen narrow gap flow domain is calculated by a procedure equivalent to that used in GAPCON-THERMAL-1.

$$g = 0.12049 \left(\frac{k_{gas}}{P_{gas}}\right) \left(T_{gas}\, MW_{gas}\right)^{1/2} \qquad (326)$$

where

k_{gas} = gas conductivity $\left(\frac{watts}{M\text{-}K}\right)$

P_{gas} = gas pressure (newtons/m^2)

T_{gas} = gas temperature (°K)

MW_{gas} = gas molecular weight $(\frac{g}{g\text{-mole}})$

g = "temperature jump distance" (meters)

Equation (326) follows from the GAPCON formula through use of the relation given by Bird, et al[10]. The relation is $k = 3.75\ R\mu/MW$,

where

μ = gas viscosity

and

R = gas constant.

The radiation heat transfer term (h_{rad}) uses the conventional temperature to the fourth power relationship. The radiation gray body view factor (F_{12}) used in the calculation is given by:

$$F_{12} = \frac{1}{1/\varepsilon_1 + A_1/A_2(1/\varepsilon_2 - 1)} \tag{327}$$

where

ε_1 = fuel emissivity
ε_2 = cladding emissivity
A_1 = area of the fuel
A_2 = area of the cladding.

When the cladding is determined to be in contact with the fuel, an input value for h_g must be entered as HCOND on the Core Slab Data Cards for the Evaluation Model as outlined in Volume II, Subsection 4.2.2 (54). It may be estimated by using the procedure outlined in GAPCON THERMAL-1[62] as follows. The gap conductance equation for this method is:

$$h_g = h_c + \frac{k_{gas}}{g + R} + h_{rad} \tag{328}$$

where

k_{gas} = conductivity of gas (Btu/hr-ft-°F)

g = combined jump distance (ft)

R = roughness factor (ft).

The roughness factor, R, should be calculated outside the code by an equation such as:

$$R = 0.165\ (R_f + R_c)\ e^{-0.00125\ P_i} \qquad (329)$$

where

P_i = fuel-to-cladding interfacial pressure (psi)

R_f = fuel arithmetic mean surface roughness (ft)

R_c = cladding arithmetic mean surface roughness (ft).

Since the roughness factor is a function of the interfacial pressure P_i which is not available, it must be estimated. Interfacial contact is not likely to be predicted by the calculation for blowdown problems. Therefore, the contact gap conduction input value will probably not be used by the calculation.

3.10.4 ECC Bypass. NRC acceptance criteria require that the Evaluation Model perform calculations to determine the end-of-bypass (EOB). After EOB, the expulsion or entrainment mechanisms responsible for the bypassing are then treated as not being effective.

RELAP4-EM contains the following model for computing ECC bypass. The check for EOB is performed by monitoring user specified junctions in the problem through use of the ECC Bypass Input Data Card described in

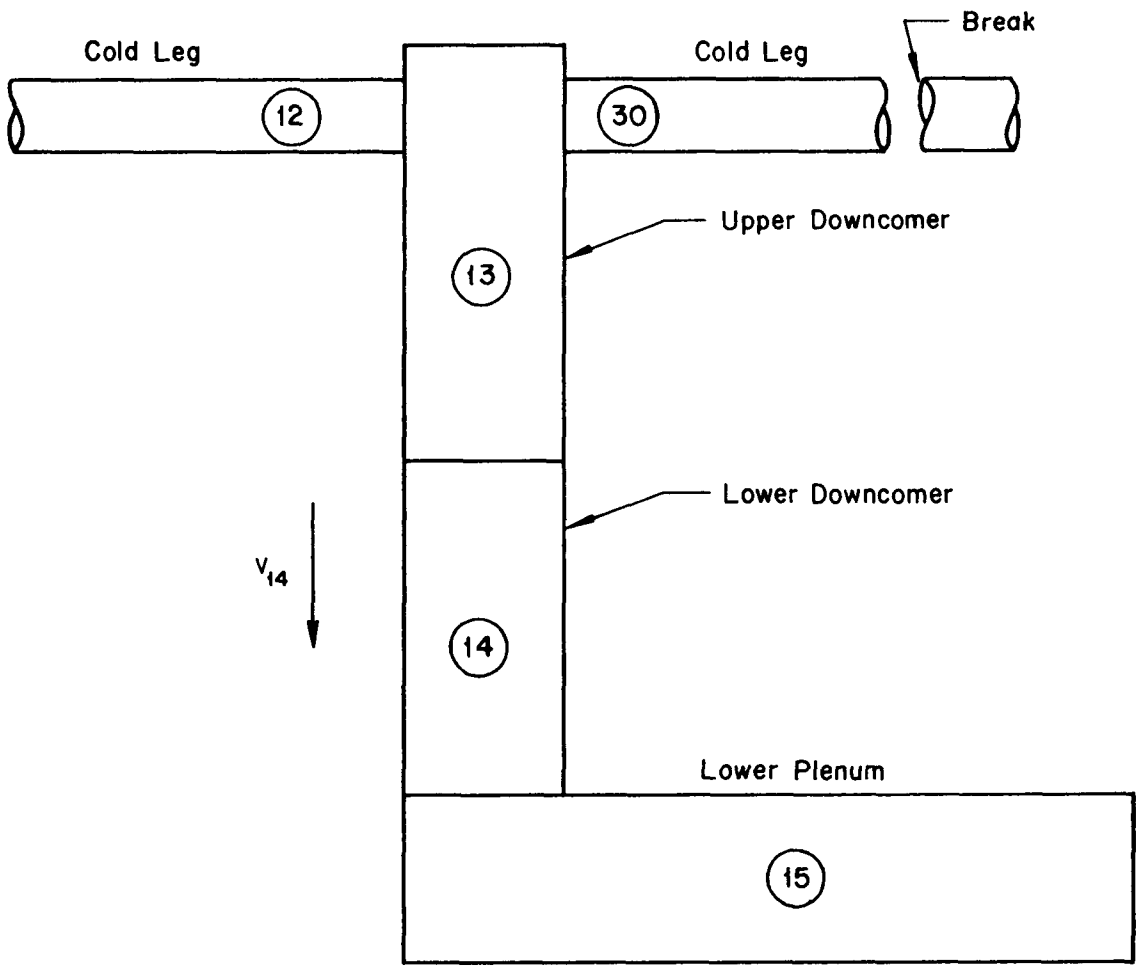
Volume II, Subsection 4.2.2 (61). These junctions are normally those connecting the unbroken loop accumulators to the system. This junction check serves two purposes:

(1) EOB check will not be computed at the input data initial steady state conditions

(2) EOB check will not be tested until the bypass period has begun.

At the time flow occurs in any one of these junctions, the initial mass in the user specified volumes (accumulator volumes) is calculated and stored. After this, the entrainment mechanisms that produce EOB are tested each time step.

The EOB entrainment mechanism tested is a computed velocity in a user specified volume (a downcomer volume). This velocity is computed based on the volume average mass flow rate, divided by the product of the volume density times the volume flow area. This calculated velocity is then compared with the velocity entered for VINPUT on the ECC Bypass Input Data Card. When the calculated velocity is greater than the input velocity, the time of EOB is established. To compute a proper volume velocity, a downcomer volume having a single inlet and outlet should be modeled and selected for this test. This model assumes the normal downward flow direction in the downcomer region as the positive flow direction. Input to RELAP4-EM must be consistent with this assumption. The input EOB velocity will normally be either zero, which is presently assumed by NRC, or an upward (negative) velocity, which must be justified by the user. A calculated velocity greater than this value (in the algebraic sense) will be either a smaller upward velocity or a downward velocity. A typical PWR downcomer model for EOB is shown in Figure 32.



End of Bypass Defined as Time When Velocity in Volume 14 Reverses ($V_{14} > 0$)

$$\text{Where } V_{14} = \frac{\text{VOLUME AVERAGE MASS FLOW}_{14}}{\rho_{14} \; A_{14}}$$

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Fig. 32 Downcomer bypass model.

At the time of EOB, the mass of water remaining in the user specified volumes (IACCV on the ECC Bypass Data Card for the unbroken loop accumulators) is determined. This mass is then subtracted from the initial mass in the accumulator volumes, and the difference is the ECC mass lost. This difference, or mass loss, is then subtracted from the calculated mass in certain user specified volumes such as reactor vessel lower plenum, downcomer regions, and inlet line regions. The subtraction is made progressively by subtracting the mass loss difference from the specified regions in the order given by the user input. If the liquid mass in a region is greater than the difference to be subtracted, the liquid mass in that region is reduced by the difference, and conditions for a saturated two-phase mixture with the remaining liquid mass at the existing calculated pressure are determined for that volume. If the liquid mass in a region is less than the difference to be subtracted, the liquid mass for the region is set to zero and the region is assumed to contain only saturated steam at the existing pressure. The mass loss difference is then reduced by the liquid mass removed, and the next region in the order of user input is tested. The mass removal is complete when the entire mass loss difference has been subtracted from the system or all the specified volumes contain only saturated steam. For large PWR inlet line breaks, the saturated steam conditions will usually be calculated for all the volumes specified in the vessel and cold legs.

These assumptions impose a severe condition on the system when they are implemented instantaneously, as the calculated mass flows are based on volume fluid densities which may be either liquid or two-phase. When these flows are instantaneously imposed on volumes with significantly reduced densities, the inconsistencies of flow, pressure distribution, and densities can create mathematical discontinuities. To make the conditions physically more representative, calculated flows from a volume at the EOB are modified by the ratio of volume densities after EOB to before EOB. Thus, volumetric flows are conserved while mass flows and densities are discontinuous.

After the EOB has been calculated, the RELAP4-EM calculations are continued with revised volume conditions. The arbitrary reduction of mass in a RELAP4-EM calculation can produce some effects which cause up flow in the downcomer region. This condition is the result of the injection of cold ECC liquid into cold leg volumes which at EOB contain only saturated steam leading to significant local depressurization. The rapid decompression causes calculated flow toward this point in the system. Thus, when EOB has been calculated by a downward flow in a downcomer region, the artificial assumptions for EOB mass loss can cause a flow reversal and subsequent upward flow in the downcomer. This condition is recognized as a result of the ECC bypass assumptions, and subsequent further mass loss because of these effects is not considered by RELAP4-EM.

3.10.5 Pump Model. A two-phase pump degradation model is available in RELAP4-EM; however, the degradation data must be specified. Presently, there is little data to account for two-phase degradation of the torque, thus two phase torque degradation is not used.

The pump torque model may include the torque of the electric motor. The motor torque as a function of speed is included using tabular data obtained from the manufacturer and entered on the Pump Motor Torque Data Card described in Volume II, Subsection 4.2.2 (40). The assumption is made that this relation is valid throughout the transient.

An option is also available to lock the pump rotor as a function of elapsed time, maximum forward speed, or maximum reverse speed. Data for this is entered on the Pump Stop Data Card outlined in Volume II, Subsection 4.2.2 (39). The pump speed is set to zero when the pump locks. For a more detailed discussion of the pump model refer to Subsection 3.6.10.

3.10.6 Liquid Level Calculation. A liquid level calculation option is available to help define the beginning of core reflooding. An equivalent liquid level is defined such that an effective water level in the lower plenum can be calculated as a function of time. A composite volume combining up to 20 individual volumes may be described using the Liquid Level Volume Calculation Card described in Volume II, Subsection 4.2.2 (12). The order of the volumes used to describe the composite volume is arbitrary except that the first volume becomes the reference volume. The total liquid mass in the composite volume is obtained by summing the liquid mass in each of the volumes. A total liquid volume is then obtained by dividing the total liquid mass by the density of saturated liquid in the reference volume. The liquid level in the composite volume is then calculated from the total liquid volume in all the volumes. Finally, the liquid level in the composite volume is compared to the elevation of the bottom of the reference volume and the result printed for each major edit. For the option to be used in determining the beginning of core reflooding, the reference volume would be chosen as the lowest core volume and other volumes would include downcomer volumes, lower plenum volumes, and the remaining core volumes.

3.10.7 Core Flow Smoothing. The separate core calculation options have been expanded to allow the smoothing of oscillatory flows. A tape previously created by RELAP4 for performing the full primary system calculation is used as a data base. Volume conditions to be smoothed and reactor normalized power may be retrieved in the same way as before the flow smoothing option was added. To retrieve a junction flow, rescale the flow, and smooth the oscillations, the following changes are made.

To perform the flow smoothing calculation, a convolution integral may be summed for a junction for each time step using an input smoothing function and a junction flow retrieved from the tape of the reference

calculation. The following equations define the convolution integrals performed during a separate core calculation using the flow smoothing option:

$$FLOFAC_i = \frac{WP_i(o)}{WP_j(o)} \tag{330}$$

$$WFINT = \int_o^{\tau_{max}} WFUN(\tau)\, d\tau \tag{331}$$

$$WP_i(t) = \frac{FLOFAC_i}{WFINT} \int_o^{\tau_{max}} WP_j(t-\tau)\, WFUN\ (\tau)\, d\tau \tag{332}$$

where

WP_j	= flow in junction j of the reference calculation
WP_i	= smoothed flow in junction i of the separate core calculation
WFUN	= smoothing function
FLOFAC	= flow rescaling factor
WFINT	= smoothing function normalization factor.

Figure 33 is an illustration of the smoothing process. An original and oscillatory flow is operated upon by a filter moving with time. A smoothed flow results.

The flow in junction i will be the smoothed flow of junction j of the reference calculation by setting the valve index (IVALVE) of junction i equal to -j on the Junction Data Cards outlined in Volume II, Subsection 4.2.2 (21). The smoothing function is input on up to nine cards in pairs of entries of τ and $f(\tau)$. Up to 20 pairs of entries are allowed in the smoothing function table. The table must be entered if any valve index (IVALVE) of the separate core calculation is negative and must not be entered if no valve index is negative. Up to 10 junction flows may be defined using flow smoothing.

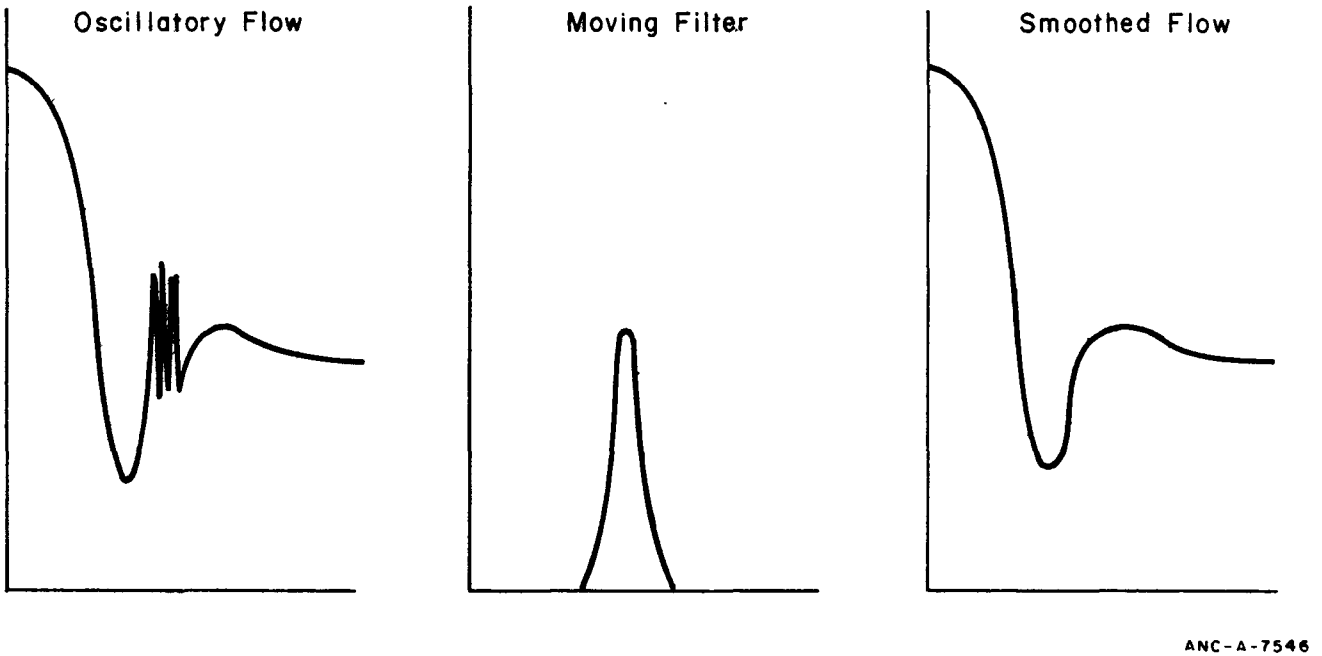

Fig. 33 Core flow smoothing.

3.10.8 Heat Transfer Correlation. If the EM heat transfer logic is used, the smaller of nucleate boiling (Mode 2) and transition boiling (Mode 4) is used once the critical heat flux (CHF) has been exceeded. After the temperature difference between the clad and saturated fluid first exceeds 300°F, return to transition boiling is not allowed. To signal that CHF has been calculated, a value of 10 is added to the heat transfer mode designation on the output listings and plots.

In situations after CHF where the Thom Correlation predicts heat fluxes less than the CHF, (indicating a return to nucleate boiling), both the Thom Correlation and the McDonough, Milich, and King Correlations are evaluated. The smaller predicted heat flux is used.

When the coolant reaches 100% quality, forced convection to superheated steam is initiated and the heat transfer coefficients are evaluated using the Dittus-Boelter[19] Correlation.

EM logic also prevents the return to transition boiling (Mode 4) if the cladding superheat exceeds 300°F. If the wall superheat subsequently drops below 300°F, the stable film boiling regime (Mode 5) is assumed to continue. When the return to transition boiling is precluded, a value of 20 is added to the heat transfer mode printout and plot values to signal this occurrence.

An option is also available to specify the use of either Dougall-Rohsenow (Mode 9) or Groeneveld 5.7 (Mode 5) Correlation. These are accessed through use of IMCL on the Heat Slab Data Cards outlined in Volume II, Subsection 4.2.2 (51).

3.10.9 Critical Flow Models. When the EM calculation is used, the Henry-Fauske model and the Moody model will be used for the subcooled and two-phase regions respectively.

The Moody critical flow model is an available option in RELAP4. Changes in the subcooled critical flow model were made so that there is a smooth transition between the subcooled and saturated regimes. In the subcooled region, the model uses the minimum of the flow calculated by the momentum equation (unchoked condition) or the Henry-Fauske model (choked condition). At saturation, the Moody model is used for the choked condition. The Henry-Fauske subcooled model gives slightly higher flow rates at the saturation point than the Moody model. A smooth transition using linear coupling between the two models in the subcooled region as shown in Figure 34 is used in the code.

Critical flow at internal junctions is calculated in the same manner as at the simulated break location. The flow is calculated using both the momentum equation and the tabulated critical flow values, and the minimum of the two values is used. If the tabulated critical flow rates are the minimum, the flow is considered to be choked.

Several RELAP4 options for critical flow are available for sensitivity studies and comparison purposes. If the EM is to be run, the user must enter 0 for JCHOKE and 11 for ICHOKE on the Junction Data Cards outlined in Volume II, Subsection 4.2.2 (21). This is as given in the RELAP-EM input data description of Section 3.10.1.

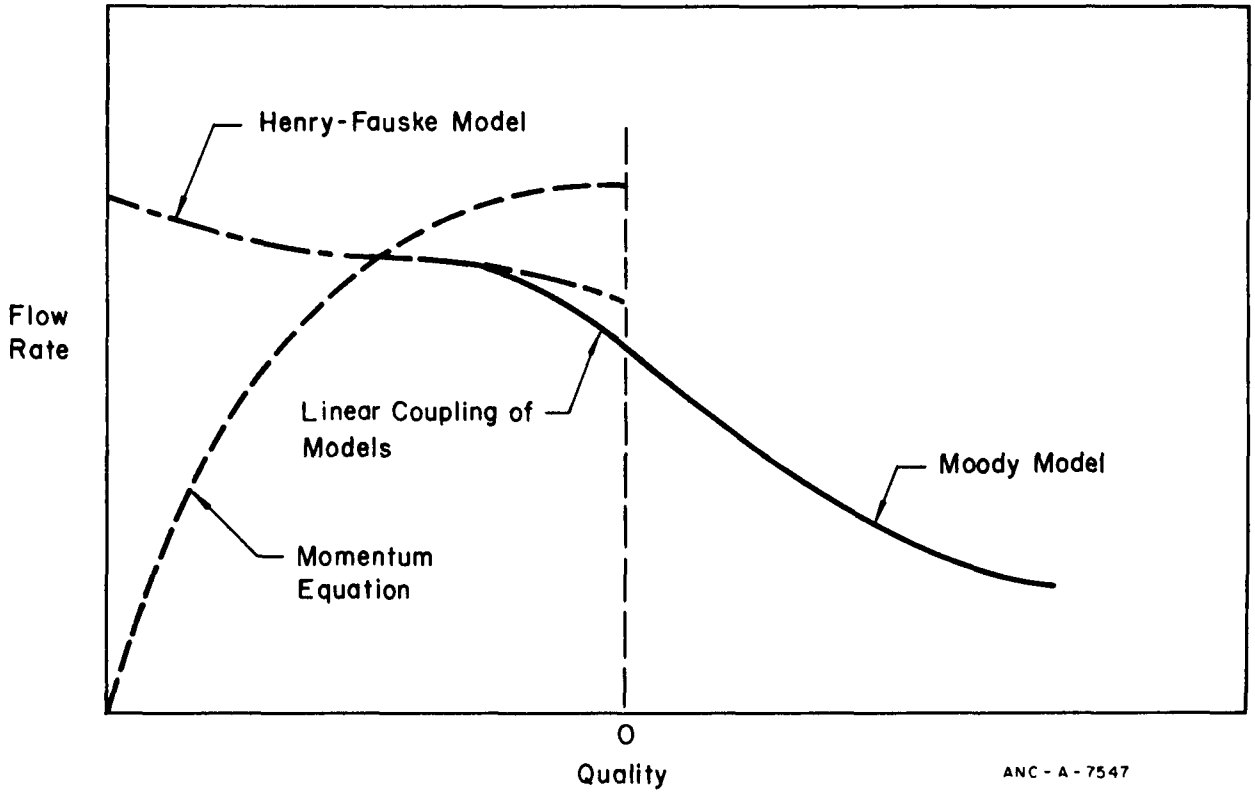

Fig. 34 Critical flow model.

3.10.10 Fission Product Decay Heat and Decay of Actinides. The NRC acceptance criteria require that several sources of neutron fission energy be considered in the EM. These are fission heat, decay of actinides, and fission product decay. RELAP4-EM considers all three of these in calculating the neutron fission energy sources.

Decay of U_{235} fission products is computed by a relationship of the form of the summation of eleven decay equations. The equation is as follows:

$$P/P_{total} = \sum_{j=1}^{11} E_j \exp(-\lambda_j t) \quad (333)$$

where

P/P_{total} = fraction of operating power
E_j = yield fraction of decay heat group j
λ_j = decay constant of decay heat group j
t = shutdown time, sec.

Values used in this relationship are given in Table XV.

TABLE XV

RADIOACTIVE DECAY CONSTANTS

Group	E_j	$\lambda_j (sec^{-1})$
1	0.00299	1.772
2	0.00825	0.5774
3	0.01550	6.743×10^{-2}
4	0.01935	6.214×10^{-3}
5	0.01165	4.739×10^{-4}
6	0.00645	4.810×10^{-5}
7	0.00231	5.344×10^{-6}
8	0.00164	5.726×10^{-7}
9	0.00085	1.036×10^{-7}
10	0.00043	2.959×10^{-8}
11	0.00057	7.585×10^{-10}

The fission product decay heat computed by the eleven group equations was evaluated and compared to the tabular values of the ANS standard[34] for infinite operating time. The comparison is shown in Table XVI along with the percentage error in the eleven group relationship relative to the ANS standard. As shown, agreement between the two relationships is within 4% over the entire range. Over the range of principal concern, 0.1 to 100 sec, the eleven group calculation is between -0.4 and +2.1% of the ANS standard with the eleven group value generally slightly higher. Based on this analysis, the ANS standard fission product decay heat data are well represented by this decay heat model.

The ANS standard equations[34] were added to RELAP4-EM to compute decay of U_{239} and Np_{239}. Assuming infinite operating time, the equations become:

$$\frac{P_{U_{239}}}{P_o} = 2.28 \times 10^{-3} \, C \, \frac{\sigma_{25}}{\sigma_{f25}} \, (e^{-4.91 \times 10^{-4} \, t_s}) \qquad (334)$$

$$\frac{P_{Np_{239}}}{P_o} = 2.17 \times 10^{-3} \, C \, \frac{\sigma_{25}}{\sigma_{f25}} \, [7.0 \times 10^{-3} \, (e^{-3.41 \times 10^{-6} t_s} - e^{-4.91 \times 10^{-4} t_s}) + e^{-3.41 \times 10^{-6} t_s}] \qquad (335)$$

where

P = decay power

P_o = operating power

$C \frac{\sigma_{25}}{\sigma_{f25}}$ = U_{238} atoms consumed per U_{235} atoms fissioned

t_s = shutdown time, sec.

TABLE XVI

COMPARISON OF RELAP4 AND ANS STANDARD DECAY HEAT CALCULATED RESULTS

Time (sec)	RELAP4	ANS STD	% Error
0.0000 E+00	0.069900	- -	0.0000
1.0000 E-01	0.068900	0.062500	2.0741
1.0000 E+00	0.062800	0.062500	0.4800
2.0000 E+00	0.059200	0.059000	0.3390
4.0000 E+00	0.055400	0.055200	0.3623
6.0000 E+00	0.053100	0.053300	- 0.3752
8.0000 E+00	0.051400	0.051200	0.3906
1.0000 E+01	0.049900	0.050000	- 0.2000
2.0000 E+01	0.044900	0.045000	- 0.2222
4.0000 E+01	0.039800	0.039600	0.5051
6.0000 E+01	0.037200	0.036500	1.9178
8.0000 E+01	0.035300	0.034600	2.0231
1.0000 E+02	0.033700	0.033100	1.8127
2.0000 E+02	0.028400	0.027500	3.2727
4.0000 E+02	0.023400	0.023500	- 0.4255
6.0000 E+02	0.021300	0.021100	0.9479
8.0000 E+02	0.020100	0.019600	2.5510
1.0000 E+03	0.019200	0.018500	3.7838
2.0000 E+03	0.016100	0.015700	2.5478
4.0000 E+03	0.012800	0.012800	0.0000
6.0000 E+03	0.011200	0.011200	0.0000
8.0000 E+03	0.010300	0.010500	- 1.9048
1.0000 E+04	0.009760	0.009650	1.1399
2.0000 E+04	0.008010	0.007950	0.7547
4.0000 E+04	0.006260	0.006250	0.1600
6.0000 E+04	0.005460	0.005660	- 3.5336
8.0000 E+04	0.005050	0.005050	0.0000
1.0000 E+05	0.004790	0.004750	0.8421
2.0000 E+05	0.004090	0.004000	2.2500
4.0000 E+05	0.003390	0.003390	0.0000
6.0000 E+05	0.003050	0.003100	- 1.6129
8.0000 E+05	0.002840	0.002820	0.7092
1.0000 E+06	0.002690	0.002670	0.7491
2.0000 E+06	0.002190	0.002150	1.8605
4.0000 E+06	0.001680	0.001660	1.2048
6.0000 E+06	0.001440	0.001430	0.6993
8.0000 E+06	0.001290	0.001300	- 0.7692
1.0000 E+07	0.001190	0.001170	1.7094
2.0000 E+07	0.000906	0.000890	1.7978
4.0000 E+07	0.000698	0.000680	2.6471
6.0000 E+07	0.000619	0.000620	- 0.1613
8.0000 E+07	0.000577	0.000570	1.2281
1.0000 E+08	0.000551	0.000550	0.1818
2.0000 E+08	0.000491	0.000485	1.2371
4.0000 E+08	0.000421	0.000415	1.4458
6.0000 E+08	0.000362	0.000360	0.5556
8.0000 E+08	0.000311	0.000303	2.6403
1.0000 E+09	0.000267	0.000267	0.0000

Summing these expressions and combining like terms gives the actinide decay equations in the form:

$$\frac{P_{actinide}}{P_o} = \sum_{j=1}^{2} E_j \exp(-\lambda_j t_s). \tag{336}$$

Thus, the actinide decay is included in RELAP4-EM by adding two additional decay equation terms to the eleven equations for fission product decay. This option is obtained by setting NODEL = 3 on the Kinetic Constants Data Card outlined in Volume II, 4.2.2 (46). The constants for Equation (336) are:

$$E_{j=1} = C\frac{\sigma_{25}}{\sigma_f 25} \left[2.28 \times 10^{-3} - 7 \times 10^{-3}(2.17 \times 10^{-3})\right] \tag{337}$$

$$E_{j=2} = C\frac{\sigma_{25}}{\sigma_f 25} (2.17 \times 10^{-3}) (1 + 7 \times 10^{-3}) \tag{338}$$

$$\lambda_1 = 4.91 \times 10^{-4} \text{ sec}^{-1} \tag{339}$$

$$\lambda_2 = 3.41 \times 10^{-6} \text{ sec}^{-1}. \tag{340}$$

The quantity $C\frac{\sigma_{25}}{\sigma_f 25}$ is a user supplied input for the variable *UDUF* on the Kinetics Constants Data Card.

A multiplier option is available for the fission product decay energy (plus the energy from the actinides when NODEL is entered as 3). This option, applied under NRC criteria, provides a 1.2 multiplier instead of 1.0. It is accessed by entering a nonzero value for KMUL on the Kinetics Constants Data Card described in Volume II, Subsection 4.2.2 (46).

In the RELAP4-EM computer program, reactor power as a function of time can be optionally computed as described in Section 3.5 and as above, supplied in tabular form by the user, or obtained from the output tape of a previous RELAP4-EM calculation.

3.10.11 Critical Heat Flux Correlation. The CHF correlations utilized in the EM are as described in Subsection 3.4.6 (3).

The General Electric Company transient CHF correlation[27] has been incorporated into the code as an optional replacement for the Barnett Correlation for BWR analysis. This option is exercised by adding 10 to the variables IMCL or IMCR on Heat Slab Data Cards outlined in Volume II, Subsection 4.2.2 (51). The correlation that was added to RELAP4-EM is:

$$q_{CHF} = 10^6 \ (0.8-x) \tag{341}$$

for

$$G \geq 0.5 \times 10^6 \text{ lbm/ft}^2\text{-hr}$$

and

$$q_{CHF} = 10^6 \ (0.84-x) \tag{342}$$

for

$$G < 0.5 \times 10^6 \text{lbm/ft}^2\text{-hr}$$

where

x = quality

G = mass flux.

In any case $q_{CHF} \geq 90{,}000$.

3.10.12 Metal-Water Reaction. The energy released by metal-water reaction is calculated for the outer surface of the cladding during the LOCA analysis. Once cladding rupture has been predicted, an inside reaction is also assumed. If the internal reaction is to extend over a 3 in. segment, the axial rods or core heat slab must be modeled in 3 in. segments. This calculation is also discussed in detail in Subsection 3.4.11.

The reaction rate between zircaloy cladding and steam is assumed to follow the parabolic rate law of Baker and Just[30] as specified by the criteria. Integration over a time step Δt and simplification of the parabolic rate law results in the following expressions for mass of zirconium reacted on the inside and outside surfaces of the cladding, MZR1 and MZR, respectively:

$$MZR = \pi \rho_{zr} \; 2R_s \; (DRP1 - DRP) - AP \tag{343}$$

$$MZR1 = \pi \rho_{zr} \; 2R_i \; (DRP2 - DRPI) + AP1 \tag{344}$$

where

DRP1 = depth the reaction has penetrated the cladding exterior at the end of a time step (in.)

DRP = depth the reaction has penetrated the cladding exterior at the beginning of a time step (in.)

DRP2 = depth the reaction has penetrated the cladding interior at the end of a time step (in.)

DRPI = depth the reaction has penetrated the cladding interior at the beginning of a time step (in.)

ρ_{zr} = density of zirconium $(\frac{lbm}{in.^3})$

R_s = initial rod radius (in.)

R_i = inside cladding radius (in.).

The quantities AP and AP1 are:

$$AP = DRP1^2 - DRP^2 = 0.123 \exp(\frac{41200}{T}) \; (XMWR) \; (\Delta t) \tag{345}$$

$$AP1 = DRP2^2 - DRPI^2 = 0.123 \exp(\frac{41200}{T_i}) (XMWR) (\Delta t) \tag{356}$$

where

T = outside cladding surface temperature at the reacting metal-oxide interface (°R)

T_i = inside cladding temperature (°R)

Δt = time step size (sec)

XMWR = fraction of the parabolic rate (dimensionless).

The metal water reaction heat flux is given by:

$$q_{mwr} = \frac{(\Delta H_r)\ (MZR + MZR1)}{(A_n)\ (\Delta t)} \tag{347}$$

where

A_n = surface area of a node (in.^{2})

ΔH_r = heat of reaction (Btu/lbm).

3.10.13 Momentum Equation. The conservation of momentum equation to be used by the EM computer programs should account for certain effects, as specified by the NRC acceptance criteria. According to the criteria, the following effects shall be taken into account in the conservation of momentum equation:

(1) Temporal change of momentum
(2) Momentum convection
(3) Area change momentum flux
(4) Momentum change due to compressibility
(5) Pressure loss resulting from wall friction
(6) Pressure loss resulting from area change
(7) Gravitational acceleration.

Several options are available to select the form of the momentum equation that is desired. These equations are selected by assigning a value to the input variable MVMIX on the Junction Data Cards listed in Volume II, Subsection 4.2.2 (21). This selection may be modified by the entered value of the input variables JCHOKE and ICHOKE also on the Junction Data Cards. The input variables JCHOKE and ICHOKE select the critical flow model to be used during the transient. In addition to the six options available through the selections of MVMIX, the user must choose a momentum equation based on the complexity of the junctions that connect the volumes in question.

As stated earlier, the form of the momentum equation to be used in RELAP4-EM is selected by the value used for MVMIX. Momentum equations that can be used are presented in the form used for sudden expansions or sudden contractions. The geometry, term definition, and derivation of these equations is presented in detail in Section 3.3

(1) Form 1: Compressible Single-Stream Flow with Momentum Flux (MVMIX = 0)

$$I_j \frac{dW_j}{dt} = \left(P_K + \frac{\bar{v}_K \bar{W}_K}{A_K} + P_{Kgj}\right) - \left(P_L + \frac{\bar{v}_L \bar{W}_L}{A_L} + P_{Lgj}\right)$$

$$+ \rho_{Li}(v_{Li}^2 + C_j^2) - \rho_{Ko}(v_{Ko}^2 + C_j^2) \qquad (348)$$

$$- F_{fK} - F_{fL} - F_{KjL}$$

This is Equation (14) in Subsection 3.3.1 (5) (a).

(2) Form 2: Compressible Two-Stream Flow with One-Dimensional Momentum Mixing (MVMIX = 1)

$$I_{j1} \frac{dW_{j1}}{dt} = -I'_{j2} \frac{dW_{j2}}{dt} + \left(P_K + \frac{\bar{v}_K \bar{W}_K}{A_K} + P_{Kgj1}\right)$$

$$- \left(P_L + \frac{\bar{v}_L \bar{W}_L}{A_L} + P_{Lgj1}\right) - F_{fK} - F_{fL} - F_{Kj1,j1,Lj1} + \Delta P_{j1} \qquad (349)$$

This is Equation (17) in Subsection 3.3.5 (1) (b). With MVMIX = 1, mixing takes place in volume "from side".

(3) Form 2: Compressible Two-Stream Flow with One-Dimensional Momentum Mixing (MVMIX = 2). The flow solution for mixing in the volume "to" side is obtained by appropriate changes in the subscripts of the preceeding equation.

(4) Form 3: Incompressible Single-Stream Flow without Momentum Flux (MVMIX = 3)

$$I_j \frac{dW_i}{dt} = (P_K + P_{Kgj}) - (P_L + P_{Lgj}) - K_f \frac{\rho_j v_j |v_j|}{2} \Phi_{2p} \qquad (350)$$

This is Equation (29) in Subsection 3.3.5 (1) (c).

(5) Form 4: Compressible Integral Momentum Equation (MVMIX = 4)

$$I_j \frac{dW_j}{dt} = (P_k + \frac{\bar{v}_k \bar{W}_k}{A_k} + P_{kgj}) - (P_L + \frac{\bar{v}_L \bar{W}_L}{A_L} + P_{Lgj}) - F_{fk} - F_{fL} - F_{k,j,L} \qquad (351)$$

This is Equation (30) in Subsection 3.3.1 (5) (d).

(6) A special case not involving flow equations is a fill with negative flow used to represent the outlet. A volume with no normal outlet junction, but with a negative fill used (flow is negative) as the actual volume outlet, constitutes a special case. In order for the correct volume flow to be calculated, the user must use MVMIX = -2 for the negative fill junction.

(7) Form 5: Incompressible Mechanical Energy Balance. Through the selection of JCHOKE and ICHOKE, a seventh form of the momentum equation can be selected. If JCHOKE = 0, ICHOKE = 11 and MVMIX = 1, a special form of the Compressible Single-Stream Flow with Momentum Flux equation is used which assumes incompressibility across the area change. This equation is given by:

$$I_j \frac{dW_j}{dt} = (P_1 + \frac{v_1 W_1}{A_1} + P_{1g}) - (P_2 + \frac{v_2 W_2}{A_2} + P_{2g})$$

$$- \frac{W_j^2}{2} (\frac{1}{\rho_{j1} A_1^2} - \frac{1}{\rho_{j2} A_2^2})$$

$$- S_1 (\frac{4f\ell}{2D_h})_1 \frac{W_1^2}{2\rho_1 A_1^2} - S_2 (\frac{4f\ell}{2D_h})_2 \frac{W_2^2}{2\rho_2 A_2^2} - \frac{S_j K_j W_j^2}{2\rho_j A_j^2} \qquad (352)$$

This is Equation 31 in Subsection 3.3.1 (5) (e).

Notice that for this case $\rho_{j1} = \rho_{j2}$ and the middle term can be written as

$$- \frac{W_j^2}{2\rho_j} (\frac{1}{A_1^2} - \frac{1}{A_2^2}).$$

This equation represents the incompressible form of the equation shown under item (1) preceeding. Selection of JCHOKE = 11 accesses the EM choking option using the Moody model for the two-phase region. Therefore, this special equation form represents the momentum equation used for all EM calculations where MVMIX = 1.

3.11 RELAP4-FLOOD Computer Program

The NRC acceptance criteria[2] for required and acceptable features of an EM, specify several special capabilities related only to the reflooding portion of a PWR LOCA analysis. To perform a reflooding analysis as required by the NRC criteria, the RELAP4-FLOOD computer program was developed. This program is accessed by setting ISPROG = 2 on the Problem Dimensions Data Card and subsequent use of the FLOOD cards described in Volume II, Subsections 4.2.2 (66) through (72). The RELAP4-FLOOD computer program is a special adaptation of the RELAP4-EM computer program designed to predict the thermal and hydraulic response

of a PWR during the reflood phase of a LOCA. Again much of the basic EM input (Section 3.10) structure is maintained and only the modifications are presented here. Modifications to the EM program were required to account for the nonequilibrium effects upon the core heat transfer and carryover rate fraction. Special models were also developed for the steam generator secondary system heat transfer as required by the acceptance criteria and to better represent the separated two-phase flow in the broken loop cold leg nozzle.

3.11.1 Nodalization. The RELAP4 FLOOD program assumes a general nodalization for the reactor vessel area of a plant simulation. This consists of single hydraulic volumes for the core region, upper plenum, lower plenum, and downcomer. Also, single junctions connecting these volumes are assumed. The broken cold leg nozzle is represented by two junctions as shown in the figure accompanying Subsection 3.11.4. The foregoing special volumes and junctions must be entered on the program by the use of the Junction and Volume Numbers Data Card outlined in Volume II, Subsection 4.2.2 (72).

3.11.2 Core Model. Experimental studies of reflood core heat transfer have shown that the fluid phases are not in equilibrium. Conventional heat transfer models in the EM cannot predict core heat transfer during reflood due to this non-equilibrium between phases. In addition, the advancing front and flow regime boundaries which are known to occur during reflood, result in transient liquid entrainment and mass storage effects which cannot be accurately predicted using the RELAP4 homogeneity assumptions. Consequently, empirical correlations are used and a core model developed to account for the experimentally observed phenomena. The core model includes the core heat transfer, core outlet enthalpy, core pressure, and core outlet flow rate.

The reactor core is represented by a single fluid volume with up to 12 axially stacked heat slabs, the exact number of slabs used is at the user's option. These are entered using the Initial Clad Surface Temperature Data Cards outlined in Volume II, Subsection 4.2.2 (68).

(1) Core Heat Transfer. The core heat transfer coefficients are calculated from two empirical heat transfer correlations which were developed from data obtained in the PWR FLECHT[64, 65] program. The correlation reported by the Westinghouse Electric Corporation in the PWR FLECHT documents is used for core heat slabs at elevations of 3 ft or greater. A correlation developed by the Aerojet Nuclear Company (ANC) is used for heat slabs at elevations of less than 3 ft. Both correlations are of the functional form:

$$h = h\ (V_{in},\ Q_{max},\ P,\ T_{init},\ \Delta T_{sub},\ B,\ t) \qquad (353)$$

where

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

V_{in} = core inlet flow velocity, (in./sec)(referred to herein as flooding rate)

Q_{max} = peak power density, (kW/ft)

P = pressure, (psia)

T_{init} = initial peak cladding temperature, °F

ΔT_{sub} = subcooling of the ECC fluid (°F)

B = fraction of channel blockage

t = time after start of reflood, (sec.)

The following restrictions have been applied when calling the subroutine that computes the heat transfer coefficient for the PWR FLECHT heat transfer correlation referenced above.

if $V_{in} > 10$ in./sec, $V_{in} = 10$ in./sec

if $V_{in} < 0.4$ in./sec, $V_{in} = 0.4$ in./sec

if $Z > 8$ ft, $Z = 8$ ft

if $Z < 4$ ft, $Z = 4$ ft.

} Apply only for PWR FLECHT correlations

The ANC heat transfer correlation is used for core elevations less than 3.0 ft. The correlation is:

$$h = HA + HB + HC \tag{354}$$

where

$$HA = 2.0 + \left(11 t_p / (Z+1)^{2.5}\right)\left[V_{in}\right]^{(0.467 + 0.0583^{Z})} \tag{355}$$

$$HB = (0.05Z+3) t_p V_{in}^{0.8} \exp\left[- \frac{t_p V_{in}^{0.3}}{3Z + 13} \right] \tag{356}$$

$$HC = A\left[\frac{t_p - t_z}{C_t/2}\right]^2 \tag{357}$$

with definitions

$$A = 2Z^{0.9} \tag{358}$$

$$t_Z = 9Z^{1.7} \left(\frac{0.526}{Q_{max}}\right)^{0.35} / V_{in}^{\left[1-0.1(V_{in}-1)\right]} \tag{359}$$

$$C_t = 27Z^{0.6}/V_{in}^{0.5} \tag{360}$$

and additional definitions

t_p = adjust time (sec)

Z = core elevation (<3.0)(ft)

v_{in} = flooding velocity (in./sec)

Q_{max} = power density (kW/ft)

with the additional restrictions of

if $t_p < t_Z$, HC = 0

if $t_p \geq \left(t_Z + C_t\right)$ HC = 0.

RELAP4-FLOOD input requires a FLECHT Heat Transfer Correlation Data Card as outlined in Volume II, Subsection 4.3.3 (67). This includes the core inlet subcooling (DTSUB), maximum initial cladding temperature (TINIT) at the time of bottom core recovery, peak power density (QMAXFD), channel blockage fraction (BFFF), core channel length (CORCHL), and heat transfer due to radiation immediately preceding reflood (HRAD). Both the ANC and the Westinghouse FLECHT correlations are valid only until the heat transfer coefficient reaches 50 Btu/hr-ft^2-°F, after which the coefficient remains constant at this value until the slab begins to quench. The RELAP4-FLOOD core model assumes that the cladding temperature must be less than or equal to a defined quench temperature before quenching can begin. The heat transfer coefficient, therefore, is not allowed to exceed 50 Btu/hr-ft^2-°F before the quench temperature is reached. After the quench temperature is reached, the heat transfer coefficient is increased to 1,000 Btu/hr-ft^2-°F over a time period which approximates the time required for the quench front to move the length of the heat slab. The reflood heat transfer coefficient and the quenching assumption are not used to generate a peak clad temperature. This model is used to calculate the steam generation rate in the core during reflood only. The peak clad temperature analysis is performed using the TOODEE2 program and the reflood rates are generated from RELAP4-FLOOD. TOODEE2 uses the flooding rates and a modified Westinghouse FLECHT correlation to calculate the heat transfer coefficients used for the hot pin analysis.

The quench temperature model used is one developed by Henry[63] and is a function of pressure. RELAP4-FLOOD approximates Henry's equation in tabular form for water. The quench time for the heat slabs is calculated from the carryover rate fraction (CRF) correlation used. The CRF correlations in RELAP4-FLOOD account only for mass storage below the quench front and thus can be expressed as:

$$CRF = 1 - \frac{V_q}{V_{in}} \tag{361}$$

where

V_{in} = core inlet velocity

V_q = velocity of the quench front

Solving for V_q gives:

$$V_q = V_{in}(1 - CRF). \tag{362}$$

The time required to quench a heat slab of length ΔL is given by

$$t_q = \Delta L/V_{in}(1 - CRF). \tag{363}$$

The heat transfer coefficient correlations were developed from data obtained with constant flooding rates. The flooding rates during an actual reflood transient are expected to vary with time; therefore, the heat transfer correlations were modified to allow for variable flooding rates. The mass integral method and equations given in the PWR FLECHT documents were extended to utlize the time-dependent integral of a continuously changing flooding rate as opposed to the step change in flooding rate analyzed in the PWR FLECHT report.

(2) Core Outlet Enthalpy. Two core outlet enthalpy model options are provided in RELAP4-FLOOD. The first option allows the user to specify a core outlet enthalpy held constant through the run. The

second option uses a model developed to account for liquid storage in the core below the moving quench front. The second option of the core outlet enthalpy model does not require any action on the part of the user. If the constant outlet enthalpy option is selected, the desired enthalpy must be specified on the Core Outlet Enthalpy Data Card described in Volume II, Subsection 4.3.3 (71).

(3) Core Pressure. The thermodynamic equilibrium pressure which is calculated in RELAP4-EM may be significantly different from the nonequilibrium core pressures expected during reflood. Thermodynamic equilibrium will, however, be reached in the upper plenum during reflood. RELAP4-FLOOD, therefore, sets the core pressure equal to the upper plenum pressure plus the appropriate friction gain and gravity head.

(4) Core Outlet Flow Rate. The core outlet flow rate during reflood has been correlated, based on FLECHT experimental data, as a function of the inlet core flow in the form of a CRF. The CRF is defined as:

$$CRF(t) = \frac{W_{out}(t)}{W_{in}(t)} \tag{364}$$

where W_{in} is the mass flow rate into the core and W_{out} is the mass flow rate out of the core. Subroutines have been written to provide the user with three optional CRF correlations. The options are specified by IENT on the Entrainment Correlation Option Card described in Volume II, Subsection 4.2.2 (66). Each of the correlations assumes a small CRF until a critical water level in the core is reached, after which the CRF increases rapidly until a maximum is reached.

Two of the correlations were developed by ANC. These correlations result in the CRF as shown in generalized form in Figure 35. ANC correlation A requires that the final CRF (EN2) and the controlling core liquid levels (HC1 and HC2) be entered by the user on the Aerojet

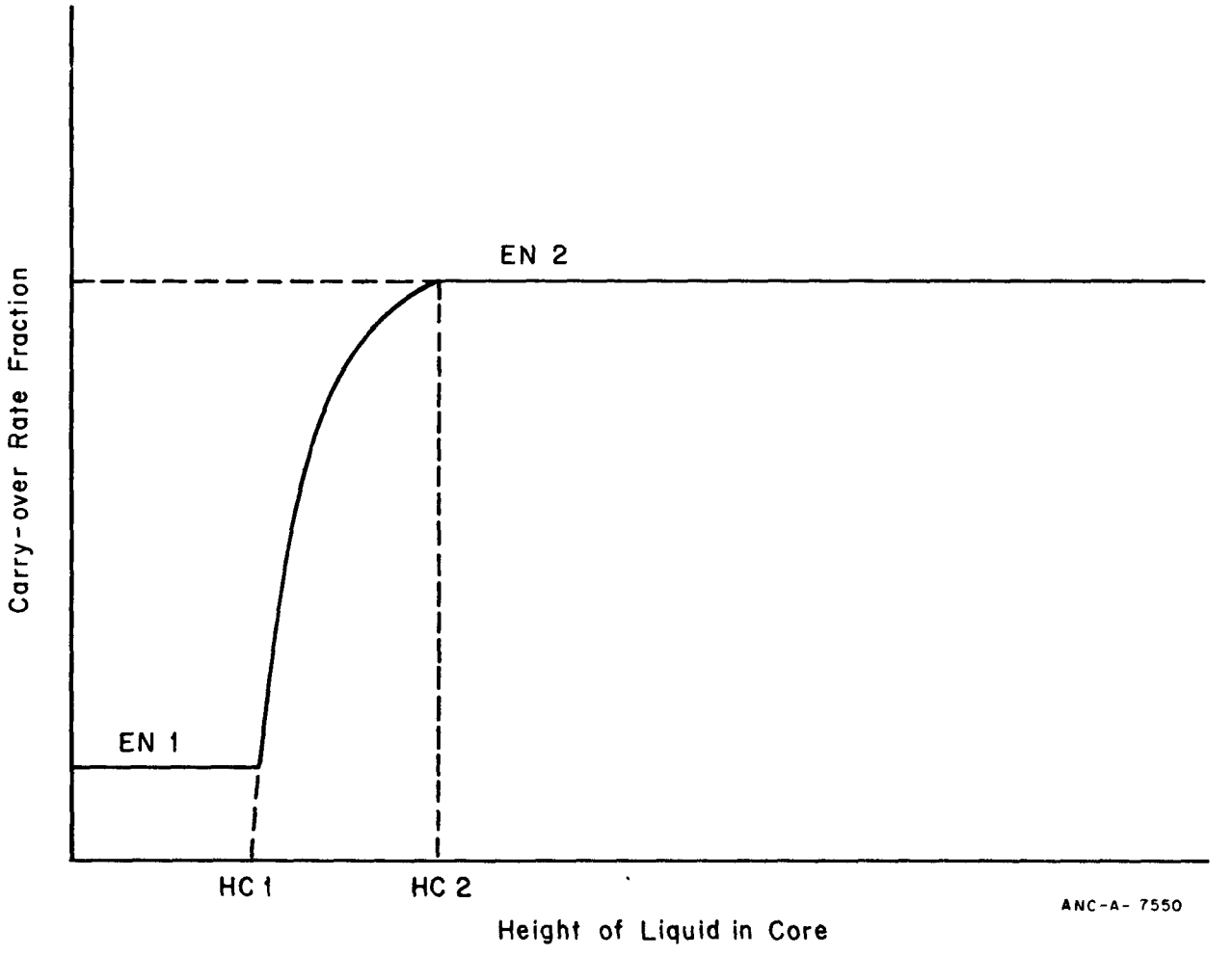

Fig. 35 ANC carryover-rate-fraction model.

A Entrainment Correlation Data Card described in Volume II, Subsection 4.2.2 (70). EN1 is calculated within the program to approximate the steam displacement. The ANC correlation B requires no input than that used by the Westinghouse FLECHT correlation.

The following correlation equations are used for ANC model A where HC1, HC2, and EN2 are input values. Defining the mixture level in the core as HC; then if HC $\leq$ HC1, CRF is defined by

$$CRF = \frac{EN2-0.0024}{HC1} (HC) + 0.0024 \quad (365)$$

If HC1 < HC < HC2,

$$CRF = 0.0024 + \frac{EN2-0.0024}{\exp(HC1-HC2) -1} [\exp(HC1-HC)-1] \quad (366)$$

If HC $\geq$ HC2

$$CRF = EN2 \quad (367)$$

where

HC = mixture level in core (ft)

HC1 = level for entrainment initiation (ft)

HC2 = level for maximum entrainment (ft)

EN2 = maximum entrainment value.

The entrainment calculated by ANC correlation B is determined by using the following equations. The maximum entrainment value is computed by:

$$EN2 = 1 - \frac{57.49}{T_{q6} V_{in}} \tag{368}$$

and the critical height for entrainment initiation is

$$HC1 = 1.04 V_{in}^{0.67} \tag{369}$$

and

$$HC2 = HC1 + 0.5 \tag{370}$$

where

V_{in} = core inlet velocity (in./sec)

T_{q6} = estimated quench time (sec) for the 6 ft elevation.

These data define the CRF value as:

$$CRF = \frac{EN2 - 0.0024}{\exp (HC1-HC2) - 1} [\exp (HC1-HC)-1] + 0.0024. \tag{371}$$

The 6 ft quench time T_{q6} is obtained from the expression given by the Westinghouse heat transfer correlation.

The third correlation was developed by Babcock and Wilcox Company[66] and requires no additional input other than that required for the Westinghouse FLECHT input. The carry-over rate fraction is defined by

$$CRF = 0.0024 + H \cdot T_1 \cdot T_2 \cdot T_3 \cdot T_4 \cdot T_5 \tag{372}$$

where

$$H = 0.8 \text{ sine } [\pi(Z-1)/6] \tag{373}$$

if

$$1.0 \leq Z \leq 1.5$$

or

$$H = 1.0 \tag{374}$$

if

$$Z > 1.5$$

and

$$H = 0.0 \tag{375}$$

if

$$Z < 1.0$$

and where

$$T_1 = A_o \exp\left[-A_1 \left(\frac{P}{60}\right)^2\right] \tag{376}$$

$$T_2 = 1 - \exp\left[\frac{-A_2 Q}{1.24}\right] \tag{377}$$

$$T_3 = 1 - \exp\left[\frac{-A_3 v}{6}\right] \tag{378}$$

$$T_4 = \exp\left[-A_4 \left(\frac{\Delta t}{140}\right)^2\right] \tag{379}$$

$$T_5 = 1 - \exp\left[-A_5 \frac{Z-1.5}{6}\right] \tag{380}$$

with

$A_o = 0.9739$ $\quad A_3 = 12.6124$

$A_1 = 0.0209$ $\quad A_4 = 0.0558$

$A_2 = 4.3648$ $\quad A_5 = 23.5254$

P = core pressure (psi)

Q = core power density (peak) (kW/ft)

V = flooding velocity (in./sec)

Δt = temperature subcooling of the ECC fluid (°F)

Z = mixture level in core (ft)

3.11.3 Steam Generator Primary-to-Secondary Heat Transfer. A requirement of the NRC acceptance criteria is that heat transfer between the primary and secondary system be considered.

In the reflood portion of the LOCA, heat is transferred in the steam generator from the secondary to primary side. A two-phase mixture from the core enters the inlet side of the steam generator and is converted to superheated steam. This conversion process leads to the "steam binding" effect which effectively limits the flood rate.

During the reflood phase of a LOCA, water flow in the secondary side of the steam generators is negligible. The secondary side heat transfer mode is therefore natural convection. Since the RELAP4-EM program does not have the natural convection mode, modifications were required to include this heat transfer mode in RELAP4-FLOOD. The RELAP4--FLOOD program requires two volumes for the secondary side of each steam generator. One volume initially contains only water and the other only steam. The water volume height is assumed to be equal to the total height of the primary side volumes (not including the inlet or outlet plenums). Heat is transferred from the secondary side water to primary side vapor. A typical steam generator nodalization is shown in Figure 36.

The secondary side heat transfer coefficient is calculated using an equation given by Brown and Marco[67] for long vertical cylinders as:

$$h = 0.13k(a\Delta t)^{1/3} \tag{381}$$

where

$$a = \frac{g\beta\rho^2 C_p}{\mu k} \tag{382}$$

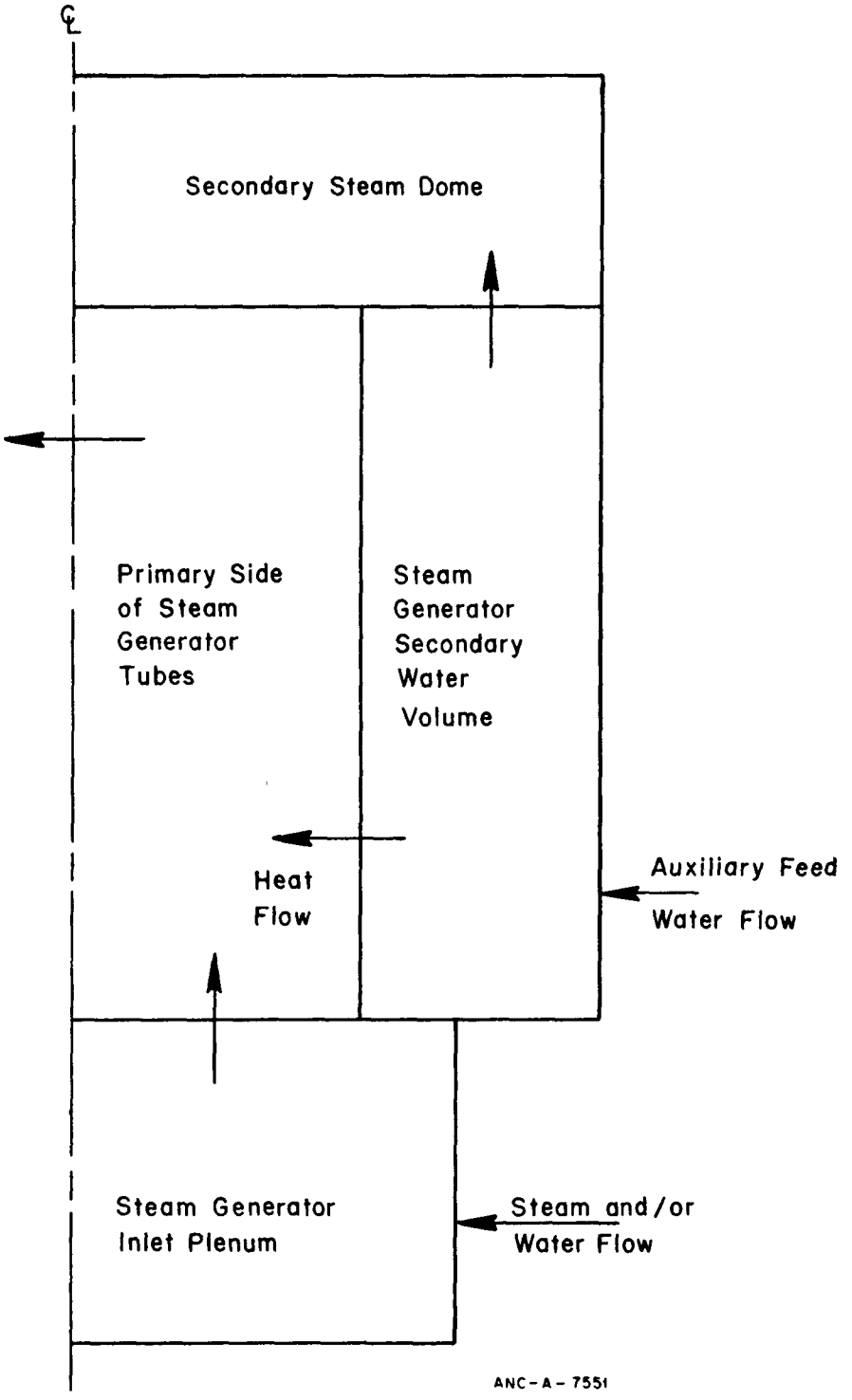

Fig. 36 Typical Steam generator nodalization for RELAP4-Flood.

and where

k = thermal conductivity of water (Btu/hr-ft-°F)

Δt = temperature difference (°F)

g = acceleration of gravity (ft/sec^2)

β = coefficient of expansion ($°F^{-1}$)

ρ = density, (lbm/ft^3)

C_p = specific heat at constant pressure (Btu/lbm°F)

μ = viscosity (lbm/ft-hr)

If the user desires to use the natural convection option, the program will total the number of steam generator primary volumes (not including inlet and outlet plenums) from the optional Steam Generator Volume Data Cards. These must be supplied in accord with Volume II, Subsection 4.3.3 (69). If the total is zero (no cards entered), the standard RELAP4-EM correlations are used for the secondary side heat transfer.

3.11.4 Broken Loop Cold Leg Nozzle Model. Part of the steam which is generated in the core during reflood passes through the intact loops to the downcomer and then flows around the top of the downcomer and out the broken loop cold leg nozzle to the containment vessel. In some cases, the downcomer water level will exceed the elevation of the cold leg nozzles. If this happens, the normal RELAP-4EM calculation assumes a homogeneous mixing of the intact loop steam flow with the water above the bottom of the cold leg nozzle. The resulting two-phase mixture then flows to the containment vessel with no slip between the phases. This phenomenon was observed in early calculations to result in unreasonably large pressure drops between the downcomer and the containment vessel.

The two-phase flow regime expected when the downcomer fills and begins to overflow is that of a separated flow with slip between the phases as shown in Figure 37. Since RELAP4-EM had no provision for slip flow of this type, a special model was developed for RELAP4-FLOOD to simulate slip flow. The model is shown in Figure 38. The broken loop cold leg nozzle is divided into two pipes or RELAP4-EM junctions, each of which has a variable area. The area of the liquid slip junction is calculated as a function of the height of the mixture level above the bottom of the cold leg nozzle, i.e., H_f in Figure 37. The steam slip junction area is, thus, the true junction flow area minus the liquid slip junction area. The elevation of the intact loop nozzle is artificially raised by one-half the nozzle diameter to prevent mixing of the steam with the water in the downcomer. Since each junction now has a common pressure drop to the containment, each will flow at the velocity required to reach that pressure drop, thus simulating slip between phases for separated flow in a single pipe. The friction at the liquid-vapor interface is neglected in the model.

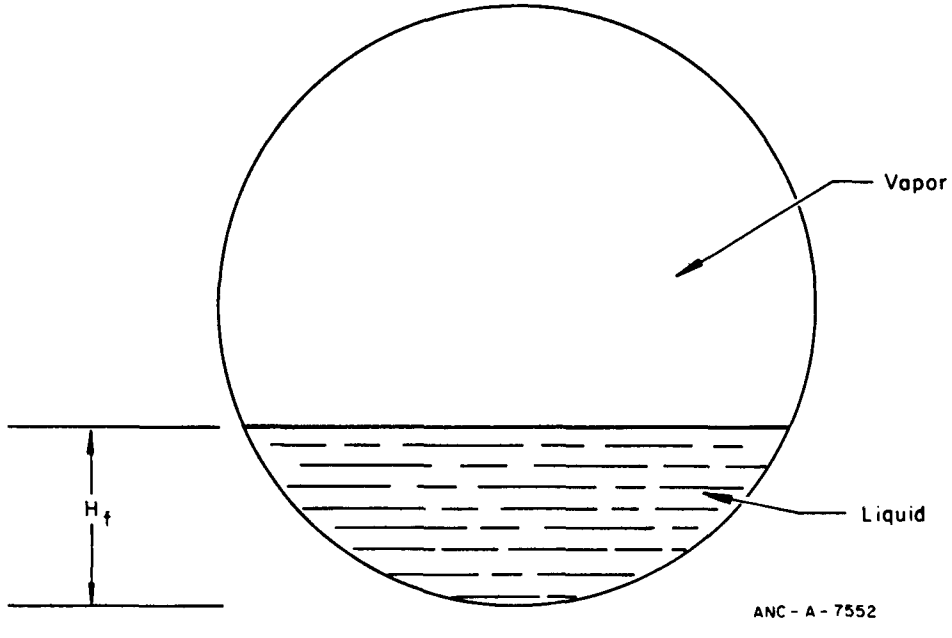

Fig. 37 Flow separation in cold leg nozzle.

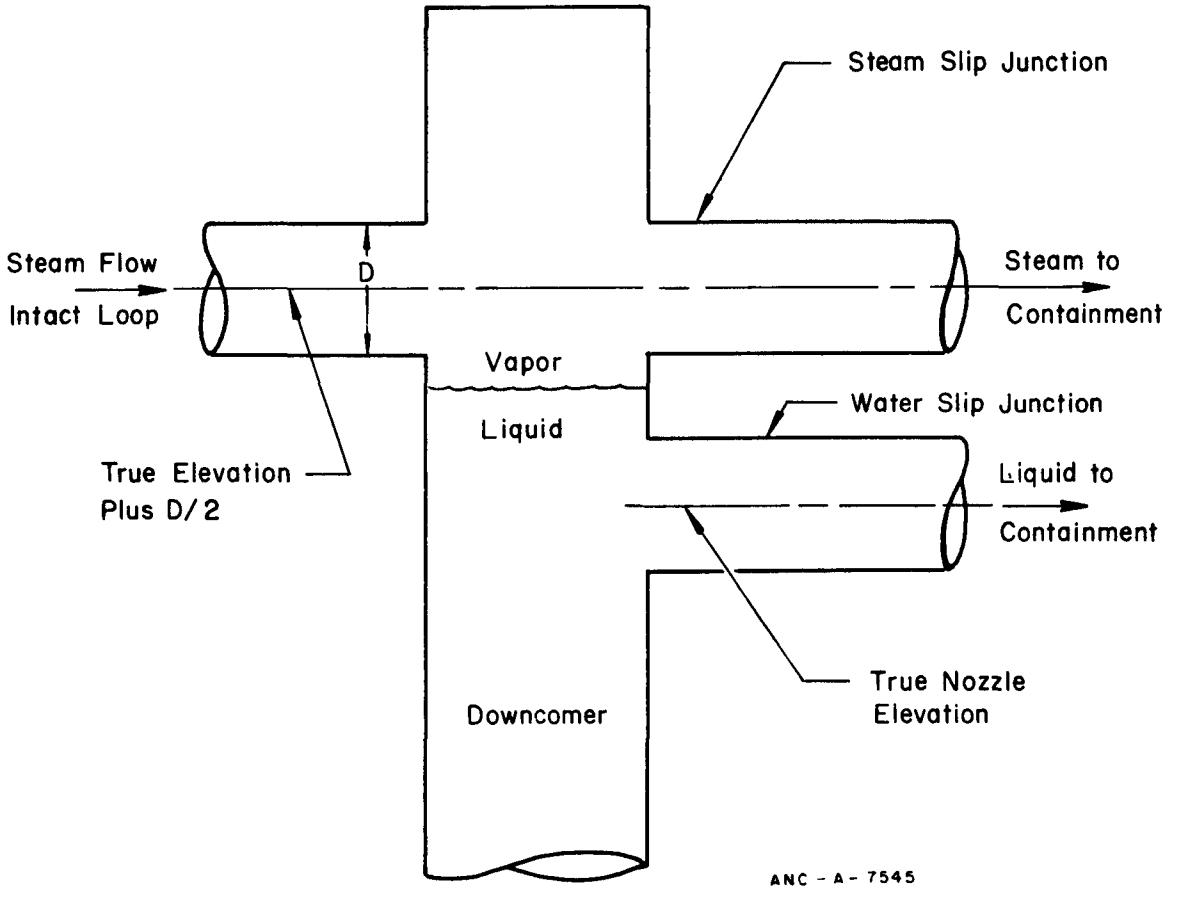

Fig. 38 Upper downcomer nodalization for cold leg nozzle slip flow.

The Junction and Volume Numbers Data card described in Volume II, Subsection 4.2.2 (72) requires the downcomer volume number and the junction numbers for the steam and water slip junction. The user should also be certain to specify on the RELAP4-EM Junction Data Cards the junction elevations as shown in Figure 38. The junction areas on the RELAP-EM Junction Data Cards for the slip junctions must sum to the true junction area.

It should be noted that the foregoing slip model for EM differs somewhat from the standard RELAP4 horizontal slip model described in Subsection 3.6.3. The significant differences are as follows:

(1) The interface drag forces are not computed between faces for EM

(2) The wall friction based on the relative area of each face is not used in EM

(3) The elevation definitions for the intact loop differ for EM.

3.12 Containment Options

RELAP4 was developed primarily to describe the transient behavior of water-cooled nuclear reactors due to postulated accidents or for nonnuclear applications such as experimental water-reactor simulators. Options have been added to RELAP4/MOD5 to describe air flow alone or in combination with single or two-phase water flow. Empirical treatment of energy absorption in volumes containing ice was added as a program option. Inertial valves were added to represent the response of ice chest doors in an ice condenser containment. The options of air flow, inertial valves, and ice melting, allow RELAP4/MOD5 to be used as a

containment analysis tool for subcompartment analyses or for evaluation of ice condenser containments. The air flow option is completely general and therefore not limited to containment analyses. A homogeneous equilibrium model is used in the sonic velocity calculation of air-steam-water mixtures (see Section 3.6.8) and is used in conjunction with standard RELAP4 flow equations to obtain critical flow.

3.12.1 Air-Steam-Water Flow Model. Section 3.3 should be consulted for the form of the fluid equations used in RELAP4/MOD5. These equations are altered in RELAP4/MOD5 to account for the presence of air (at the user's option).

The specific volume νj at the junction (described in Figure 39) is obtained from Equation (383).

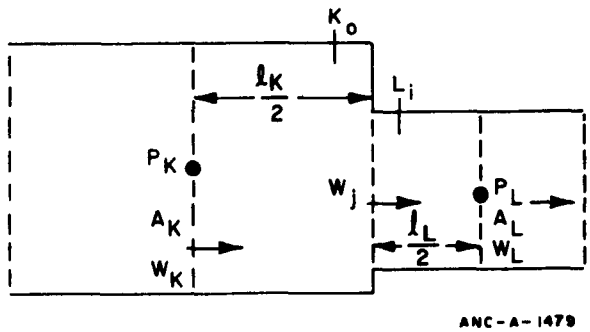

Fig. 39 Flow path control volume.

$$\nu_j = \nu_K + \left(\frac{\partial \nu}{\partial h}\right)(h_K - h_j) + \left(\frac{\partial \nu}{\partial P}\right)(P_K - P_j) \qquad (383)$$

where

ν_K = specific volume of volume K
h_K = enthalpy of volume K
h_j = enthalpy at junction j is set equal to the upstream enthalpy
P_K = thermodynamic pressure of volume K

P_j = thermodynamic pressure at junction j.

For a fluid mixture of air and steam, $(\frac{\partial \nu}{\partial h})_p$ is evaluated from

$$(\frac{\partial \nu}{\partial h})_p = \frac{\nu_{mix} \beta_{mix}}{C_{P_{mix}}} \tag{384}$$

where

$$\nu_{mix} = \frac{V}{M_a + M_s} \tag{385}$$

$$\beta_{mix} = \frac{M_a/T + M_s \beta_s}{M_a + M_s} \tag{386}$$

$$C_{P_{mix}} = \frac{M_a C_{pa} + M_s C_{ps}}{M_a + M_s} \tag{387}$$

and where

V = fluid volume

M_a = air mass in volume

M_s = steam mass in volume

T = absolute temperature of the fluid

β_s = coefficient of volumetric expansion of steam

C_{pa} = specific heat at constant pressure for air

C_{ps} = specific heat at constant pressure for steam.

For an air and steam mixture, $(\frac{\partial \nu}{\partial p})_h$ is obtained from

$$(\frac{\partial \nu}{\partial P})_h = -\nu_{mix}\left[\frac{M_s\ (k_s - \frac{T\nu_s\beta_s^2}{C_{ps}}) + \frac{M_a}{P_a\gamma}}{M_a + M_s} + (\frac{\partial \nu}{\partial h})_P\right] \tag{388}$$

where

k_s = isentropic compressibility of steam

ν_s = specific volume of steam

P_a = thermodynamic pressure of air

γ = ratio of air specific heats.

For a fluid mixture of air, steam and liquid water, $(\frac{\partial \nu}{\partial h})_P$ and $(\frac{\partial \nu}{\partial P})_h$ are calculated by

$$(\frac{\partial \nu}{\partial h})_P = \frac{M_{H20}\ (\frac{\nu_s - \nu_f}{h_s - h_f}) + M_a\left(\frac{\nu_a}{C_{pa}\ T}\right)}{M_{H20} + M_a} \tag{389}$$

where

ν_f = specific volume of liquid water

ν_a = specific volume of air

M_{H20} = total mass of steam and liquid water

h_s, h_f = specific enthalpy of steam and liquid water, respectively

and by

$$\left(\frac{\partial \nu}{\partial P}\right)_h = \frac{-M_{H2O}\left(\frac{C_v + [(1-x)\ \nu_f + x\ \nu_s]\ P'}{(TP')^2}\right) M_a \frac{\nu_a}{P_a}}{M_{H2O} + M_a} \tag{390}$$

where

$$C_v = x[C_p - T\ P'\nu\ (2\beta - k\ P')]_s + (1-x)\ [C_p - TP'\ \nu(2\beta - kP')]_f \tag{391}$$

$$P' = \frac{1}{T}\left(\frac{h_s - h_f}{\nu_s - \nu_f}\right) \tag{392}$$

and

x = quality

s,f = subscripts for vapor and liquid water, respectively.

The sonic speed for a mixture of air and steam is calculated as outlined in Subsection 3.6.8.

3.12.2 Inertial Valves. Inertial valves were added to RELAP4/MOD5 as an option to represent the response of ice chest doors in an ice condenser containment. Valves having inertial properties differ from check valves in that the valve gates have significant inertia which controls the rate of opening for a given differential pressure across the valve. These valves are described in Section 3.6.12.

3.12.3 Ice Melt and Heat Transfer. In the ice condenser model it is assumed that flow from the lower reactor compartment of an ice condenser containment structure is constrained to pass through volumes containing ice before reaching the upper compartment. Heat transfer to the ice is qualitatively similar to heat transfer in ordinary RELAP4 volumes with the exception that the heat transfer area is time dependent as the ice melts.

A mass of ice, having a volume and surface area, can be associated with any RELAP4 volume. The volume occupied by the ice is not considered part of the RELAP4 control volume and no corrections are made to the volume size or flow area as the ice melts. The ice is assumed to be in cylindrical columns which are described by input data together with the total ice mass.

The heat removed from a volume by convective transfer to the ice is evaluated explicitly for each time step using conditions at the beginning of the step. The surface of the ice is assumed to be 32.018 °F, its melting temperature, but the initial ice temperature may be below this value.

Because of the low thermal diffusivity of ice, the ice is assumed to remain at its initial temperature except at the melting surface. The user may input two constants which allow a fraction of the melted ice within a volume to be heated to a specified temperature. In the present model, the heated water is not entrained and is immediately lost from the total system, as is all ice melt water. The specific energy associated with heating ice up to the melting point, melting the ice, and heating a portion of the melt water to an input temperature is

$$\Delta u_{melt} = L_f + c_{ice}[32.018 - T_{ice}] + f_{ml}\, h_f\, (T_{in}) \qquad (393)$$

where

Δu_{melt} = effective specific energy change (Btu/lbm)

L_f = heat of fusion of ice (Btu/lbm)

c_{ice} = specific heat of ice (Btu/lbm °F)

T_{ice} = input temperature of ice (°F) ($\leq$ 32.018°F)

f_{ml} = input fraction of melt water that is heated to T_{in}

$h_f(T_{in})$ = specific enthalpy of liquid water at temperature T_{in} (Btu/lbm)

T_{in} = input temperature to which a portion of the melt water is increased (°F) ($\geq$ 32.018°F).

The mass of ice that is melted within any volume j during a time step is determined from

$$M_{ice,j} = Q_j/\Delta u_{melt} \tag{394}$$

where

$M_{ice,j}$ = mass of ice melted in volume j during time step (lbm)

Q_j = total heat energy removed during time step from volume j due to presence of ice (Btu).

Likewise the mass rate of melt water dropout from volume j is

$$R_{D,j} = \Delta M_{ice,j}/\Delta t \tag{395}$$

where

Δt = time step length (sec)

$R_{D,j}$ = dropout rate of melt water from volume j (lbm/sec).

It is assumed that the melt water will drop into a sump system. The present RELAP4 ice condenser model does not consider the various sumps, but they are included in the CONTEMPT4 ice condenser model, and the dropout rate from Equation (395) will be entered in the long term calculation.

The RELAP4 model assumes that the heat removed from an ice chest volume, by the ice, can be calculated by the following convective transfer equation:

$$Q_j = h_{ice,j} A_j At \ (T_j - 32.018)/3,600 \tag{396}$$

where

Q_j = heat removed from volume j (Btu)

$h_{ice,j}$ = convective heat transfer coefficient (Btu/hr-ft^2-°F)

A_j = surface area of ice in volume (ft^2)

T_j = temperature of volume (°F)

Δt = timestep length (sec).

The surface area of this ice is computed from the mass of ice in the volume at the beginning of the time step. The ice is assumed to remain in a cylindrical shape with the radius decreasing until all of the ice has melted. The ice surface heat transfer coefficient is evaluated and then Q_j is determined. The mass of ice to be melted is then determined from Equations (393) and (394).

The heat transfer coefficient is evaluated by modifying a pure steam condensing coefficient developed by Jakob[68] as modified by McAdams[69] and McCurdy[70] to account for the presence of non-condensable gases. The pure steam coefficient is given by

$$h_s = \frac{1100 + 9.9|v|}{L_c^{1/3}} \tag{397}$$

for saturated steam and

$$h_s = \frac{1130 + 5.05|v|}{L_c^{1/3}} \tag{398}$$

for superheated steam where

h_s = heat transfer coefficient (Btu/hr-ft^2-°F))

v = flow velocity in volume (ft/sec)

L_c = condensate layer length (ft).

The coefficient h_s is multiplied by a factor proportional to the steam to air mass ratio. In addition, two other input factors allow a RELAP4 user to modify or eliminate the use of h_s for each ice chest volume. Also, the user must input a maximum limiting value for $h_{ice,j}$ of Equation (396). If a calculated value of $h_{ice,j}$ exceeds the input limiting value, then the limit is used. It should be noted that the physical basis for developing Equations (397) and (398) does not resemble an ice condenser, and therefore the function of L_c is primary for adjusting calculations to agree with experimental data.

The heat transfer coefficient used in Equation (396) is determined from

$$h_{ice,j} = C_{1,j}\, h_s F_{sa} + C_{2,j} \qquad (399)$$

where

$C_{1,j}, C_{2,j}$ = user input constants [$C_{1,j}$ unitless, $C_{2,j}$ in Btu/(hr-ft^2-°F)°]

h_s = value from Equation (397) or (398) [Btu/(hr-ft^2°F)]

F_{sa} = modifier based on mass ratio of steam and air in volume j.

Values for $C_{1,j}$ and $C_{2,j}$ are input for each ice chest volume. Equation (399) results are not used if the calculated value exceeds the input maximum value. The correction modifier (F_{sa}) which accounts for the presence of non-condensible gases (air), is linearly interpolated between the values in Table XVII. Table XVII values are subject to refinement but are presently used in the RELAP4 model.

TABLE XVII

CORRECTION MODIFIER FOR PRESENCE OF AIR

Ratio (Mass of steam : Mass of air)	Modifier (F_{sa})
≥ 0.999	1.0
= 0.9	0.4
= 0.0	0.05

3.13 Equation of State

Equation (231) of Subsection 3.7.1, the equation of state, is written in a form to show functional dependence. The detailed form of the equations of state are:

with

$$M_w \neq 0$$

$$V = M_w V_w \tag{400}$$

$$U = M_w U_w\ (T,V_w) + M_a C_{va} T \tag{401}$$

$$P_a = \frac{M_a RT}{XM_w V_g}\ (T,V_w) \tag{402}$$

$$P = P_w\ (T,V_w) + P_a \tag{403}$$

with

$$M_w = 0$$

and

$$U = M_a C_{va} T \tag{404}$$

$$P = \frac{M_a RT}{V} \tag{405}$$

where

C_{va} = constant volume heat capacity of air
P_a = partial pressure of air
P_w = partial pressure of water
R = gas constant of air
T = temperature
V = volume
U_w = specific internal energy of water
V_w = specific volume of water
V_g = specific folume of saturated water vapor or superheated water vapor.

X is the quality of water (= 1 if superheated water vapor), and U, M_w, M_a, and P are defined for Equation (231) with slightly different notation in Section 3.7.1. The following assumptions are used in this equation of state:

(1) The components of water in possibly subcooled liquid, saturated, or superheated vapor states and air form a homogeneous mixture with a uniform temperature. Models such as bubble rise and slip flow are superimposed on the homogeneous equation of state.

(2) Water, if present, occupies the entire volume. Air if present, occupies the same volume as the water vapor according to the Gibbs-Dalton Law. Air is assumed insoluable in water and there can be no air present if the volume is filled with liquid water.

(3) Air is treated as a perfect gas.

(4) If air and liquid water are present, the water vapor is saturated (relative humidity is 1).

(5) If air is present, the liquid water conditions are the saturated conditions for P_w. A more accurate model would have liquid water at the subcooled conditions corresponding to P and T. This assumption is used to limit calls to water property routines to one per iteration.

If water is not present, Equation (404) and (405) are solved directly. If water is present, V_w is determined from Equation (400) and (401) is written as

$$F(T) = U - M_w U_w (T,V_w) - M_a C_{va} T = 0 \tag{406}$$

and is solved iteratively by Newton's method for the temperature. The pressure is computed directly once the temperature is available. The water property subroutine (see STH204 in Subsection 5.4.2) returns U_w, V_g, P_w, and the derivative quantities, β, κ and C_p, as a function of T and V_w. The derivative

$$F'(T) = - M_w C_{wv} (T,V_w) - M_a C_{va} \tag{407}$$

requires the constant volume heat capacity of water:

for single phase

$$C_{wv} = C_p - \frac{\beta^2 T V_w}{\kappa} \tag{408}$$

for two phase

$$C_{wv} = (1-x) \left[C_{pf} - V_f T P'_w \left(2\beta_f - P'_w \kappa_f\right) \right] +$$

$$X \left[C_{pg} - V_g T P'_w \left(2\beta_g - P'_w \kappa_g\right) \right] \tag{409}$$

where

$$P'_w = \left[\frac{1}{T} \quad \frac{h_g - h_f}{V_g - V_f} \right]. \tag{410}$$

The quantities, $\frac{\partial P}{\partial U}$, $\frac{\partial P}{\partial M}$, and $\frac{\partial P}{\partial M}$, needed for the hydrodynamic advancement algorithm are derived using the procedures for obtaining derivatives of implicit functions. For two-phase water and air these are:

$$\frac{\partial P}{\partial U} = \frac{1}{J} \left\{ \left[V_g - V_f \right] \left[P'_w + P_a \left(\frac{1}{T} - \left(\beta_g - \kappa_g P'_w\right) \right) \right] + \frac{P_a V'_w}{X} \right\} \tag{411}$$

$$\frac{\partial P}{\partial M_w} = \frac{1}{J} \left\{ \left[V_f U_g - V_g U_f \right] \left[P'_w + P_a \left(\frac{1}{T} - \left(\beta_g - \kappa_g P'_w\right) \right) \right] + \right.$$

$$\left. \frac{P_a}{M_w X} \left[V_f \left(M_a C_{va} + M_w C_{wx} \right) - M_w U_f V'_w \right] \right\} \tag{412}$$

$$\frac{\partial P}{\partial M_a} = \frac{P_a}{M_a} - C_{va} T \frac{\partial P}{\partial U} \tag{413}$$

$$J = \left[V_g - V_f \right] \left[M_a C_{va} + M_w C_{wx} \right] - \left[U_g - U_f \right] M_w V'_w \tag{414}$$

$$C_{wx} = \left.\frac{\partial U_u}{\partial T}\right|_X = (1-X)\left[C_{pf} - V_f\left(P_w\beta_f - P'(P_w\kappa_f - T\beta_f)\right)\right] + X\left[C_{pg} - V_g\left(P_w\beta_g - P'\,(P_w\kappa_g - T\beta_g)\right)\right] \tag{415}$$

$$V'_w = \left.\frac{\partial V_w}{\partial T}\right|_X = (1-X)\left[V_f\left(\beta_f - \kappa_f P'_w\right)\right] + X\left[V_g\left(\beta_g - \kappa_g P'_w\right)\right]. \tag{416}$$

For two-phase water without air

$$\frac{\partial P}{\partial U} = \frac{P'_g}{M_w\left[C_{wx} - V'_w\,(TP'_g - P_g)\right]} \tag{417}$$

$$\frac{\partial P}{\partial M_w} = \frac{\partial P}{\partial U}\left[V_w\left(TP'_g - P_g\right) - U_w\right] \tag{418}$$

$$\frac{\partial P}{\partial M_a} = \frac{RT}{M_w X V_g} - C_{va}T\,\frac{\partial P}{\partial U}\,. \tag{419}$$

For superheated vapor and air

$$\frac{\partial P}{\partial U} = \frac{\left[\frac{M_a R}{V} + \frac{\beta}{\kappa}\right]}{M_a C_{va} + MC_{vw}} \tag{420}$$

$$\frac{\partial P}{\partial M_w} = \frac{1}{M_w K} - \frac{\left[\frac{M_a R}{V} + \frac{\beta}{\kappa}\right]}{M_a C_{va} + MC_{vw}}\left[U_w - \frac{V_w\,(T\beta - P\kappa)}{\kappa}\right] \tag{421}$$

$$\frac{\partial P}{\partial M_a} = \frac{\frac{RTMG_{vw}}{V} - \frac{\beta TC_{va}}{\kappa}}{M_a C_{va} + MC_{vw}}\,. \tag{422}$$

For single phase water without air

$$\frac{\partial P}{\partial U} = \frac{\beta}{M\kappa C_{vw}} \tag{423}$$

$$\frac{\partial P}{\partial M_w} = \frac{C_p - PV_w\beta - \beta U_w}{M\kappa C_{vw}} \tag{424}$$

$$\frac{\partial P}{\partial M_a} = \frac{\frac{RTM_w C_{vw}}{V} - \frac{\beta T C_{va}}{\kappa}}{MC_{vw}} \tag{425}$$

3.14 PLOTR4M Program

A computer program is available to produce plots of variables from a RELAP4 data tape. The version in use at INEL generates Integrated Graphics System (IGS) microfilm and/or Calcomp plots. Other versions have been prepared for use at other installations, but the differing plot hardware and local system interface routines preclude the possibility of a universal version.

Options are available to the user to select the data to be plotted, with a choice of linear or logarithmic scales, axis lengths, scaling divisor, range of variables, and axis labels. Default values are provided for most option choices and the usual plot is a single variable versus time. Other options provide for parameter versus parameter plots, plots of the difference of two similar variables, and for multiple ordinates from a single run or from a few different RELAP4 runs. For multiple ordinate graphs, multiple ordinate axis labels may also be requested.

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