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THYDE-B1/MOD1 : A COMPUTER CODE FOR ANALYSIS OF SMALL-BREAK LOSS-OF-COOLANT ACCIDENTS OF BOILING WATER REACTORS

August 1982

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THYDE-B1/MOD1 : A Computer Code for Analysis of Small-Break Loss-of-Coolant Accident of Boiling Water Reactors

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THYDE-B1/MOD1 is a computer code to analyze thermo-hydraulic transients of the reactor cooling system of a BWR, mainly during a small-break loss-of-coolant accident (SB-LOCA) with a special emphasis on the behavior of pressure and mixture level in the pressure vessel.

The coolant behavior is simulated with a volume-and-junction method based on assumptions of thermal equilibrium and homogeneous conditions for two-phase flow. A characteristic feature of this code is a three-region representation of the state of the coolant in a control volume, in which three regions, i.e., subcooled liquid, saturated mixture and saturated steam regions are allowed to exist. The regions are separated by moving boundaries, tracked by mass and energy balances for each region. The interior of the pressure vessel is represented by two volumes with three regions: one for inside of the shroud and the other for outside, while other portions of the system are treated with homogeneous model. This method, although it seems to be very simple, has been verified to be adequate for cases of BWR SB-LOCAs in which the hydraulic transient is relatively slow and the cooling of the core strongly depends on the mixture level behavior in the vessel. In order to simulate the system behavior, THYDE-B1 is provided with analytical models for reactor kinetics, heat generation and conduction in fuel rods and structures, heat transfer between coolant and solid surfaces, coolant injection systems, breaks and discharge systems, jet pumps, recirculation pumps, and so on.

The verification of the code has been conducted. A good predictability of the code has been indicated through the comparison of calculated results with experimental data provided by ROSA-III small-break tests.

This report presents the analytical models, solution method, and input data requirements of the THYDE-B1/MOD1 code.

Keywords: BWR, THYDE-B1 Code, Thermal-Hydraulic Analysis, Computer Code, ECCS, Small Break, LOCA, Accidents, Safety

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沸騰水型炉の小破断冷却材喪失事故解析用計算コード THYDE－B1／MOD1

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（1982年8月14日受理）

THYDE－B1／MOD1は沸騰水型炉（BWR）の非常用炉心冷却系の性能評価のために日本原子力研究所で開発された計算コードシステムの一部であり，小破断冷却材喪失事故における原子炉冷却系の過渡的挙動を，主として圧力容器内の圧力と水位の挙動に注目して解析する計算コードである。

冷却水の熱水力挙動は，流体の質量・熱・運動量の保存則を積分型で表現するいわゆる，ボリューム・ジャンクション法によって解く。二相流モデルは均質流・熱平衡の仮定を基礎としている。このコードの特徴は，1個のボリューム内の流体を未飽和相，飽和混合相，蒸気相の三領域に分けて個別に質量と熱の保存を考える三領域ノードモデルを導入した点である。圧力容器内部は炉心シュラウドの内側と外側に分けて2個の三領域ノードで表現する。この手法は単純であるが，小破断事故では系の圧力と水位の挙動が炉心の冷却状態を強く支配するので，そのような場合に対しては，適切である。

BWRの原子炉冷却系のシステム挙動を模擬するために，核動特性，燃料・構造物内の熱伝導，固体壁と冷却材の熱伝達，各種注水系，破断口における臨界流，ジェットポンプ及び再循環ポンプ等を模擬するモデルが備えられている。

コードの性能検証は原研のROSA－Ⅲ装置による小破断LOCA実験との比較により行っており，実験とのよい一致を得ている。

本報告書はこのTHYDE－B1／MOD1コードの解析モデル，解法，および入力データについて記述したものである。

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1. Introduction

This report is intended to be a user's manual on THYDE-B1/MOD1, the latest version of the THYDE-B1 code[1,2,3] as of August 1982. It provides a description of physical models, solution methods, and input requirements.

As an introduction to THYDE-B1 this chapter provides a very brief summary of the code at first, and then, gives an overview of the developmental works related to this code.

1.1 Summary of the Code THYDE-B1/MOD1

(1) Purpose of Development

THYDE-B1/MOD1 was developed as part of a computer code system developed in Japan Atomic Energy Research Institute (JAERI) for the evaluation of the performance of the emergency core cooling system(ECCS) of a boiling water reactor (BWR). In this system, THYDE-B1/MOD1 is intended to be used together with other three codes, namely, ALARM-B2[4,5], THYDE-B-REFLOOD[1] and SCORCH-B2[6] as a computational tool to evalute the ECCS performance with a reasonable coservatism.

(2) Function of the Code

THYDE-B1/MOD1 is to simulate the thermo-hydraulic transient of the reactor cooling system of a BWR during, mainly, a small-break loss-of-coolant accident (SB-LOCA) with a special emphasis on the behavior of pressure and mixture level in the pressure vessel under various modes of accident conditions and ECCS operation.

(3) Analytical Model

The coolant behavior is simulated with a volume-and-junction method based on assumptions of thermal equilibrium and homogeneous conditions for two-phase flow. A characteristic feature of this code is a three-region representation of the state of the coolant in a control volume, in which three regions, i.e., subcooled liquid, saturated mixture and saturated steam regions are allowed to exist. The regions are separated by moving boundaries, tracked by mass and energy balances for each region. The interior of the pressure vessel is represented by two volumes with three-regions: one for inside of the core shroud and the other for outside, while the other portions of the system are treated by a homogeneous model. This method, although it seems to be very

simple, has been verified to be adequate for cases of BWR SB-LOCAs in which the hydraulic transient is relatively slow and the cooling of the core strongly depends on the mixture level behavior in the vessel.

In order to simulate the system behavior, THYDE-B1 has various analytical models, including reactor kinetics, heat generation and conduction in fuel rods and structures, heat transfer between coolant and solid surfaces, coolant injection systems, breaks and discharge systems, jet pumps, recirculation pumps, and so on.

(4) Program Language

THYDE-B1 is programmed in FORTRAN-IV.

(5) Computer

THYDE-B1 is operational on both FACOM M-200 and IBM 3033 computer systems.

(6) Core Memory

Required core memory size is about 250 kwords.

(7) Running Time

The running time depends on the number of time steps and the complexity of the nodalization of the system to be analyzed. A rough estimate of CPU time requirement is about 6 ms/volume.step on FACOM M-200. As a BWR is usually modelled by 4 to 6 volumes with time step size of 3 to 10 miliseconds, the total CPU time for a transient of 500 seconds is about 0.5 to 2 hours.

(8) Auxiliary Program

The results of THYDE-B1 calculation can be plotted by SPLPLOT-1 program[7].

(9) Other Requirements

Since THYDE-B1 uses the steam table subroutines of RELAP4[8], a steam table data set which is the same as that used in RELAP4 must be supplied.

1.2 An Overview of THYDE-B1 Development and Related Works

JAERI's code development for ECCS performance evaluation was started in 1973. The approach taken in JAERI was to develop two independent code systems respectively for PWRs and BWRs considering the differences of the reactor cooling system, core structure, and method of ECCS between two types of LWR. The first version of the JAERI BWR code system was completed in 1979. This code system is designed to provide a computational tool to analyze the whole necessary processes of typical LOCAs and to evaluate the performance of the ECCS with an "Evaluation Model (EM)" in compliance with the requirements of "Safety Evaluation Guideline for the Performance of ECCS of LWRs"[9].

The code system consists of ALARM-B1[4], HYDY-B1[10] and THYDE-B1 for analysis of the system blowdown, THYDE-B-REFLOOD for the reflooding phase, and SCORCH-B2 for the calculation of the fuel assembly hot plane temperature (ALARM-B1 and HYDY-B1 have recently been replaced by ALARM-B2[5].). The performance studies for individual codes have been made through analyses of available experiments or sensitivity calculations. The performance of the codes as a system has also been studied from the view point of system consistency with use of a large commercial BWR to show the capability of an evaluation analysis in compliance with the Guideline. The first version has been delivered to the Institute of Nuclear Safety, Japan (JINS) and is under an assessment by JINS.

THYDE-B1/MOD1 described herein is a modified version of THYDE-B1 which was, as mentioned above, one of the codes comprized in the first version of the code system. THYDE-B1 was originally designed to analyze the coolant behavior for small breaks in which the mixture level behavior becomes important and, therefore, to be a similar but much simpler revision of the large break analysis code ALARM-B1. THYDE-B1 was also required to analyze a slow and long-term transient in as shorter running time as possible. According to the above design basis, the developmental work was commenced in 1975 and the programming was completed in 1978. Since that time the code had been tested against various related problems until the description of the initial version together with a performance study for a large commercial BWR were reported. The initial version was also examined for its validity from a physical point of view by comparisons with experimental data provided by the ROSA-III tests and with the calculated results of available computer code, namely, RELAP4/MOD6/U4/J3 which was an improved version of RELAP4/MOD6 made in JAERI. Especially, the results of an analysis for ROSA-III experiment RUN912[11], which was designated as the OECD/NEA CSNI (Committee on the Safety

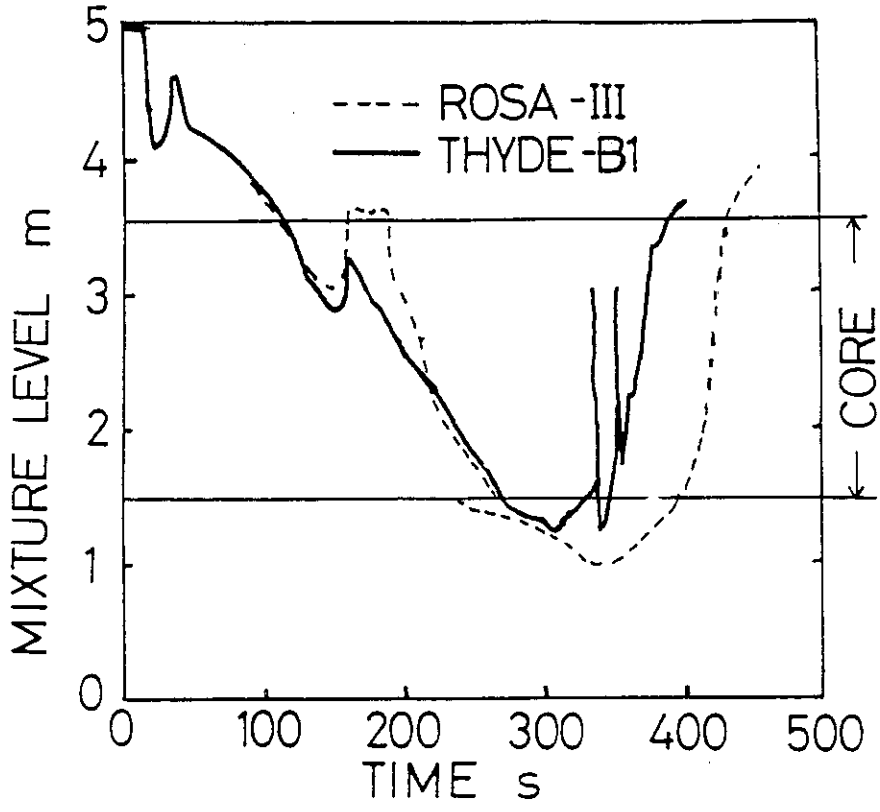


Fig.1.2.1 Results of a THYDE-B1 Calculation for ROSA-III RUN 912, Mixture Level inside the Core Shroud

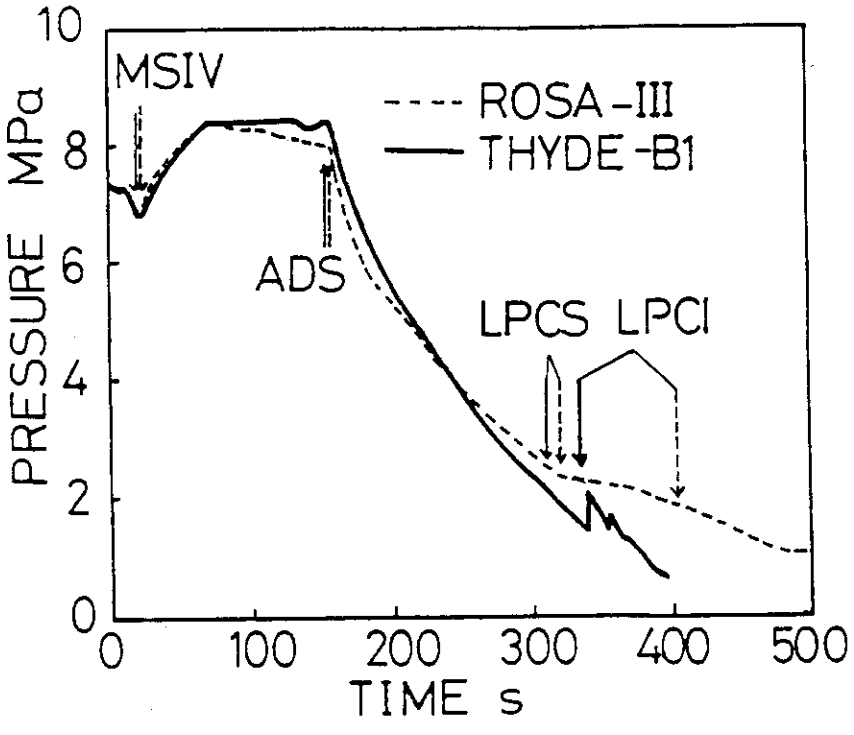


Fig.1.2.2 Results of a THYDE-B1 Calculation for ROSA-III RUN912, Pressure in the Lower Plenum

MSIV=main steam line isolation valve closure, ADS=actuation of automatic depressurization system, LPCS=actuation of low pressure core spray, LPCI=actuation of low pressure coolant injection.

of Nuclear Installations) LOCA standard problem No.12, indicated a very good predictability of the code. The results of this anlysis is shown in Figs.1.2.1 and 1.2.2. In addition JINS has made an independent assessment of the code system from a licensing point of view. Some recommendations were given from staffs of JINS to the authors on possible improvements of THYDE-B1.

The favorable results of the assessments encouraged the authors to continue developmental work to provide a more user-oriented version of the code. Considering the results of the assessments made in JAERI and the recommendations of JINS, following items were selected to be most desirable and worth doing.

(1) Extension of critical flow model options

The initial version had two critical flow model options: one was a incompressible liquid flow model and the other the Moody's model. By the implementation of the Henry-Fauske model and the Homogeneous Equilibrium Model, the code would be more straight forwardly compliant to the Guideline.

(2) Incorporation of RELAP4 pump model

In the pump model of the initial version, the pump is treated as a flow resistance during reverse flow conditions. Even if this treatment is adequate for an evaluation calculation, the implementation of the RELAP4 pump model would contribute to the user's convenience.

(3) Incorporation of a core spray heat transfer model

There was no special model for the spray cooling of the core in the initial version. It would be beneficial to incorporate a modelling option that allows the user to specify the heat transfer coefficient to be used for spray cooling. This makes it possible to use experimentally determined heat transfer coefficients such as those derived from BWR-FLECHT[34].

Above improvements have been implemented in THYDE-B1/MOD1 as described in this report.

Further improvements are now going on. Among possible improvements in the future, the most important is the reduction of running time. The authors believe that the present version of THYDE-B1/MOD1 is faster than , or as fast

as, most of the computer codes developed for LOCA/ECCS analysis. It is apparent, however, that the reduction of running time would greatly enhance the usability of the code. A forward explicit method is used in the present version of THYDE-B1/MOD1 for the solution of hydraulic equations. This method imposes a severe restriction on time step size. It can, therefore, be expected that the running time would be greatly reduced by incorporation of a more stable numerical method.

2. Analitycal Model

2.1 General Description of Analytical Model and Its Characteristic Features

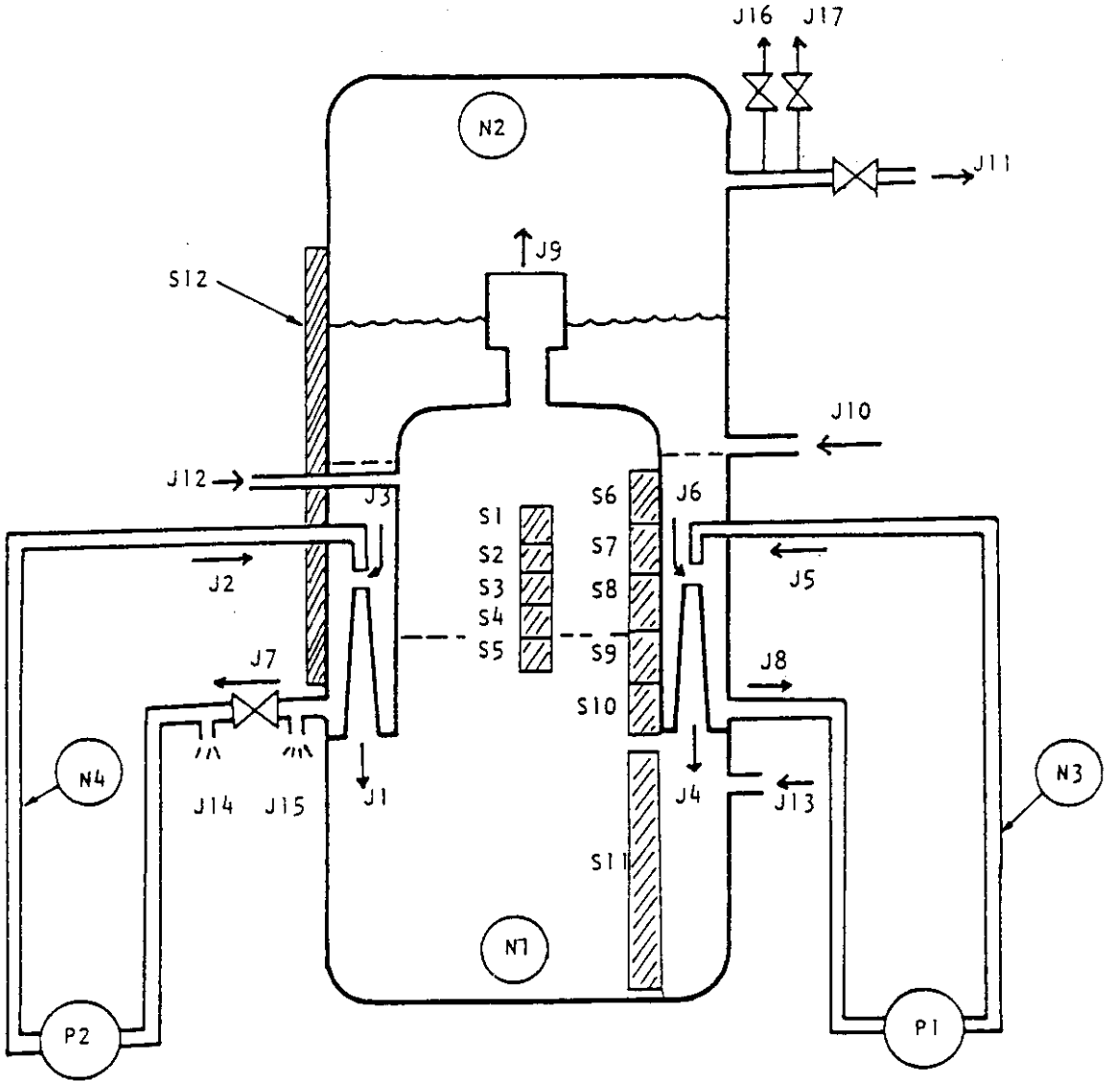
The hydraulic models of THYDE-B1 are based on a node-and-junction model. The interior of the primary system is divided into control volumes ,which are called nodes or volumes, to give integral forms of the conservation laws of mass and energy and of the thermodynamic state equations. Fluid flow rate is determined from momentum balance along a one-dimensional flow path called junction, which connects the two adjacent nodes. Heat transfer to fluid from fuel and other metals is calculated with use of a one-dimensional heat conductor model.

A typical nodalization example is shown in Fig. 2.1.1. The characteristic features of THYDE-B1 are summarised in the following.

(1) Homogeneous Node Model and Three-Region Node Model

A characteristic feature of THYDE-B1 is its node model. The subnode model with moving boundaries which was originaly used in the SAFE code[12] has been incorporated in the node-and-junction scheme of THYDE-B1. The inside of the pressure vessel is divided into two nodes corresponding to inside and outside of the core shroud. And each node is divided into three subnodes which are called the vapor region, the saturated mixture region, and the subcooled liquid region, according to the thermodynamic state of the fluid. The three regions are partitioned by two horizontal moving boundaries. The elevations of the boundaries are tracked by the mass and energy conservation for each region. This model has, in addition to the merit of simplicity, a remarkable advantage of making it possible to take into account the effect of incomplete mixing of the subcooled liquid injected by ECCS and the vapor in the pressure vessel. This effect strongly influences the pressure response in the vessel. In THYDE-B1 the subcooled liquid injected into the vapor region or the mixture region of a three-region node will be mixed with the fluid in the regions according to the mixing efficiency parameters given by the user. This effect is difficult to analyze by conventional homogeneous equilibrium codes.

The three-region node model of THYDE-B1 is similar to that of SAFE. The



S = heat slabs
S1...S5 = fuel rod
S6...S12 = vessel & shroud
N = nodes
N1 = inside shroud
N2 = outside shroud
N3 = intact loop
N4 = broken loop

J = junctions
J1...J6 = jetpump junctions
J7,J8 = recirculation pump suction line
J9 = steam separator
J10 = feed water line
J11 = main steam line
J12 = core spray
J13 = LPCI
J14 = break
J15 = break
J16 = safety relief valve
J17 = ADS

Fig. 2.1.1 An Example of THYDE-B1 Nodalization for a BWR

only difference between two codes in respect to the nodalization in the pressure vessel is that the pressure can be different between inside and outside of shroud in THYDE-B1, while only one pressure is allowed in SAFE.

Recirciulation pipes are represented by ordinary homogeneous nodes in which fluid is assumed to be homogeneous and in thermal equilibrium.

In Fig. 2.1.1, the interior of the pressure vessel is represented by two three-region nodes N1 and N2, while the recirculation pipes are represented by two normal (homogeneous) nodes N3 and N4.

(2) Junction Model Options

THYDE-B1 has several junction model options to represent the functions of various hydraulic components of a BWR. These options are listed below.

(i) normal junction (homogeneous junction)

The flow rate between two adjacent nodes is obtained by solving a momentum balance equation with the neglection of momentum flux terms and the effect of relative velocity of vapor and liquid phases.

(ii) steam separator junction (slip junction)

The normal junction model was modified so as to allow slip between vapor and liquid which may largely influence the flow quality through steam separators in a slow transient. Separation efficiency that determines the vapor carry under is specified by the user as a function of mixture level in the downcomer.

(iii) jet pump junction

A jet pump is modelled as a set of three special junctions for which momentum flux differences due to flow area change and momentum mixing are taken into account.

(iv) leak junction

The flow rate through breaks or relief valves can be calculated with use of flow rate table specified by the user or with use of a choked flow model.

(v) fill junction

Flow rate of a injection system is specified by the user as a function of time or pressure of the connected node.

(vi) main steam line junction

The steam flow rate through the main steam lines can be calculated either by the leak junction model or by a model similar to SAFE. The functions of turbine flow control valves, isolation valves, and flow restrictors are taken into account in the latter model.

The head of the recirculation pump can be included in the momentum balance equation for the normal junctions or the drive flow junctions of the jet pumps. The head is calculated with use of a centrifugal pump model based of the homologous law[15] . In Fig.2.1.1, this option is used in the junctions J7 and J8.

(3) Heat Transfer Model

Fuel rods and other structures are modelled as one dimensional heat conductors in cylindrical or rectangular geometry. Each unit of the conductor is called a heat slab. A heat slab may have one or two heat transfer surfaces, and each surface is allowed to face one hydraulics node. Examples of heat slab model applications are included in Fig.2.1.1. In this figure, the fuel rods are axially divided into five heat slabs, S1 to S5, while the pressure vessel and vessel internals are represented by heat slabs S6 to S12.

The heat generation rate in the fuel rods may be specified by the user as a function of time or calculated by the code by solving a one-point kinetics equation with radioactive decay heat by a method similar to that of RELAP4. The heat transfer coefficients between fluid and solid surfaces are determined by the correlations used in THETA1-B[13] .

(4) Numerical Method

The numerical method utilized in THYDE-B1 is very simple. Time integration for all differential equations are performed by a forward explicit difference technique with use of the time step size given by the user.

The initial condition of nodes and junctions are specified by the user, while the initial temperature of heat slabs are calculated by the code on the assumption of steady state condition.

(5) Nodalization

As THYDE-B1 is programmed with use of a variable dimension technique, no restriction is imposed on number of nodes , junctions, or heat slabs. However the nodalization of the interior of the pressure vessel is fixed as described before.

2.2 Homogeneous Node Model and Three-Region Node Model

Two types of models are provided in THYDE-B1 for describing the fluid state in a control volume. One is the "homogeneous node model", which is usually used for the representation of the recirculation lines and the other is the "three-region node model" for the inside of a reactor pressure vessel.

(1) Homogeneous Node Model

This model assumes homogeneity and thermal equilibrium in a node. Neglecting the kinetic energy terms, mass and enegy balance eqtions can be written as

$$\frac{dM_i}{dt} = (\Sigma W)_i \ , \tag{2.2.1}$$

$$\frac{d(M_i h_i)}{dt} = (\Sigma hW)_i + (\Sigma Q)_i + \frac{g_c}{J}\frac{dP_i}{dt} \ , \tag{2.2.2}$$

where

M_i = total mass in node i,

$(\Sigma W)_i$ = sum of mass flow rates of junctions connected to node i (treated as positive value when the flow enters node i),

$(\Sigma hW)_i$ = energy input due to convection,

h_i = specific enthalpy of fluid in node i,

V_i = volume of node i,

P_i = pressure in node i,

$(\Sigma Q)_i$ = heat input to node i from solid walls,

J = Joule constant (4186 J/kcal),

g_c = Gravitational conversion factor (9.80665 N/kg_f).

Since the volume of each node is unchanged with time,

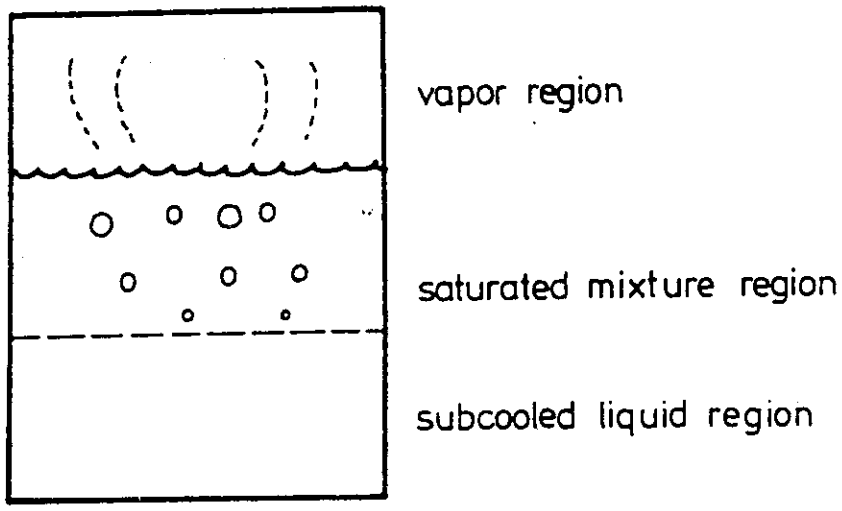
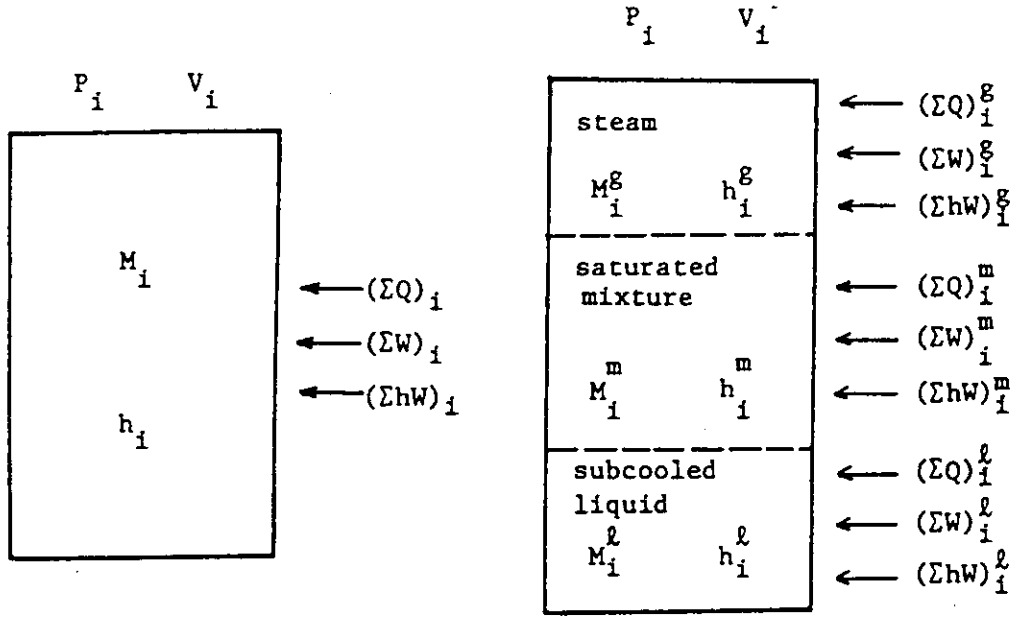


Fig. 2.2.1 Three-Region Node



(a) a homogeneous node (b) a 3-region node

Fig. 2.2.2 Major Quantities for Description of Mass and Energy Balance

$$\frac{dV_i}{dt} \equiv \frac{d}{dt}(M_i v_i) = 0 \ , \tag{2.2.3}$$

where v_i = specific volume of fluid.

From the equation of state, the specific volume is a function of pressure and specific enthalpy of the fluid and it can be written as

$$v_i = v(P_i, h_i) \ , \tag{2.2.4}$$

Equations (2.2.1) to (2.2.3) give necessary conditions for obtaining P, M, and h of the node assuming that the mass and energy input through junctions and heat input from solid walls are known. Models for junction flow calculation are described in sections 2.5 to 2.13, while the heat input to a node from solid walls is determined by the models in sections 2.14 to 2.17. The thermodynamic properties of water used in this code are all calculated with use of the steam table subroutines cited from RELAP4.

(2) Three-Region Node Model

The interior of the pressure vessel is divided into two special nodes. One node corresponds to the inside of the core shroud and the other to the outside. These two nodes are further divided into three subnodes (or they can be called regions), according to the thermodynamic state of the fluid as illustrated in Fig. 2.2.1. These three regions are the subcooled liquid, the mixture, and the vapor region. To derive the mass and energy equations for each subnode, following assumptions are made.

(i) The fluid properties of all regions can be calculated from one pressure P_i.
(ii) The vapor region are kept at saturated state, that is, thermodynamic equilibrium is assumed between the vapor region and the saturated mixture region.
(iii) The fluid state is uniform and in equilibrium within each region.

From above assumptions , the mass and energy equations for the three regions can be written as

$$\frac{dM_i^g}{dt} = (\Sigma W)_i^g + W_{sep,i} + \frac{(\Sigma Q)_i^g}{h_{gf}}, \tag{2.2.5}$$

$$\frac{dM_i^m}{dt} = (\Sigma W)_i^m - W_{sep,i} - \frac{(\Sigma Q)_i^g}{h_{gf}} + W_{l\to m}\ , \tag{2.2.6}$$

$$\frac{dM_i^l}{dt} = (\Sigma W)_i^l - W_{l\to m,i}\ , \tag{2.2.7}$$

$$h_i^g = h_g(P_i), \tag{2.2.8}$$

$$\frac{d}{dt}(M_i^m h_i^m + M_i^g h_i^g) = (\Sigma hW)_i^g + (\Sigma hW)_i^m + W_{l\to m,i} h_{l\to m,i} + (\Sigma Q)_i^g + (\Sigma Q)_i^m$$

$$+\frac{g_c}{J}(V_i^g + V_i^m)\frac{dP_i}{dt}, \tag{2.2.9}$$

$$\frac{d}{dt}(M_i^l h_i^l) = (\Sigma hW)_i^l - W_{l\to m,i} h_{l\to m,i} + (\Sigma Q)_i^l + \frac{g_c}{J} V_i^l \frac{dP_i}{dt}, \tag{2.2.10}$$

where

$(\Sigma W)_i^x$ $(x=l,m,g)$ = rate of mass input to a subnode

$(\Sigma hW)_i^x$ $(x=l,m,g)$ = rate of energy input to a subnode due to convection,

$(\Sigma Q)_i^x$ $(x=l,m,g)$ = heat addition from solid structures to a subnode,

h_g = specific enthalpy of saturated vapor,

h_f = specific enthalpy of saturated liquid,

$h_{gf} = h_g - h_f$ (latent heat of vaporization),

and superscripts l,m, and g represent the subcooled liquid, the mixture, and the vapor region, respectively. Figure 2.2.2 shows an illustration of the variables representing the mass and energy inputs to a node.

The term $(\Sigma Q)_i^g/h_{gf}$ in Eq. (2.2.5) and (2.2.6) is the rate of vapor

generation due to heat input to the vapor region. Since superheating of vapor in the vapor region is not allowed in this model (assumption (ii)), the heat transferred to the vapor region is assumed to be consumed in vapor generation at the mixture surface (boundary between the mixture and the vapor regions). The rate of vapor separation from the mixture region $W_{sep,i}$ is calculated by a bubble rise model described in section 2.3. The term $W_{l\to m,i}$ is a correction term to account for the effect of local temperature rise in the subcooled region, which will be explained in section 2.4. Equations (2.2.5) through (2.2.10), together with the state equation and the volume equation :

$$\frac{dV_i}{dt} \equiv \frac{d}{dt}(M_i^g v_i^g + M_i^m v_i^m + M_i^l v_i^l) = 0, \tag{2.2.11}$$

give necessary conditions to get solution for the unknown variables P_i, M_i^l, M_i^m, M_i^g, h_i^l, h_i^m and h_i^g.

Once mass and enthalpy of each subnode are determined, the elevation of the region boundaries are calculated by linear interpolation of a volume versus elevation table which is given as input.

$$Z_{ml,i} = f_i(V_i^l) \tag{2.2.12}$$

$$Z_{gm,i} = f_i(V_i^l + V_i^m) \tag{2.2.13}$$

where

$Z_{ml,i}$ = elevation of top of subcooled liquid region,

$Z_{gm,i}$ = elevation of top of mixture region,

$f_i(V)$ = elevation above bottom of a node as a function of fluid volume V.

Figure 2.2.3 shows the cross sectional flow areas of ROSA-III pressure vessel [11] as functions of elevation above the bottom of pressure vessel. This kind of information is required for the preparation of the function $f_i(V)$.

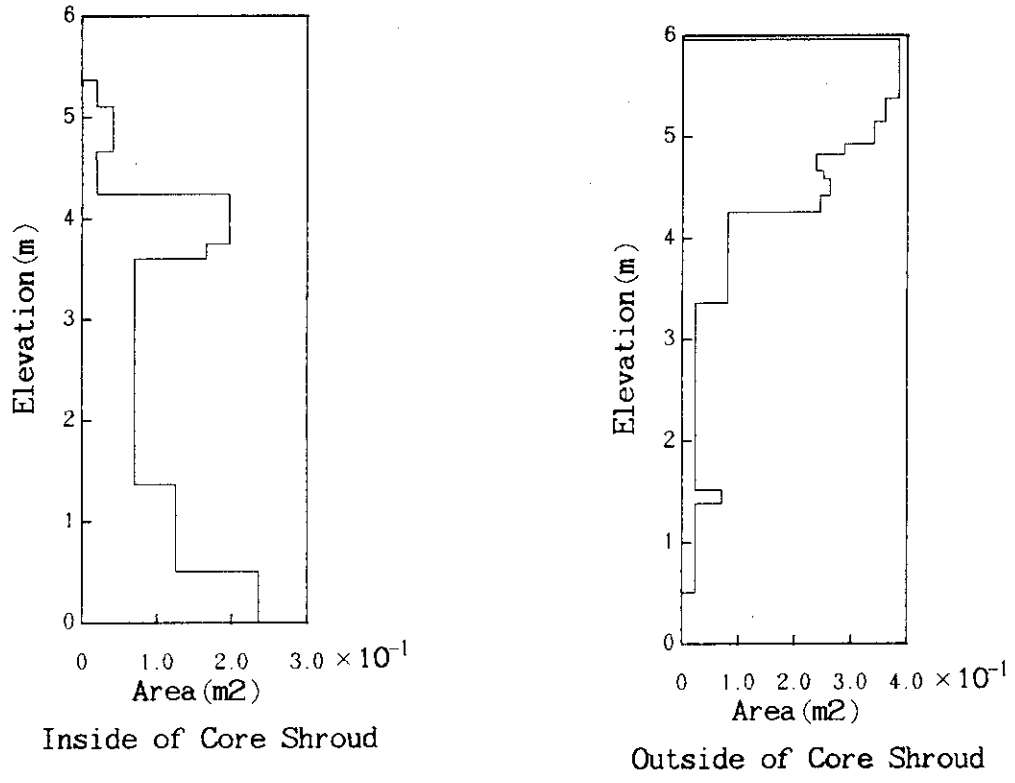


Fig.2.2.3 Cross Sectional Flow Area of ROSA-III Pressure Vessel

2.3 Phase Separation Model

Two optional models are provided for the calculation of vapor separation rate from the two phase mixture region in a three-region node.

Model 1. (Method of bubble separation calculation with void fraction correction factor)

The rate of vapor separation from a mixture surface can be written as

$$W_{sep} = A_s \alpha_s u_b \rho_g , \tag{2.3.1}$$

where

A_s = flow area at mixture surface,
α_s = void fraction just under the mixture level,
u_b = bubble rise velocity,
ρ_g = density of saturated vapor.

The void fraction at the top of the mixture region α_s is assumed to be proportional to the average void fraction in the mixture region $\bar{\alpha}$ and is calculated as

$$\alpha_s = \begin{cases} C_\alpha \bar{\alpha} & (\bar{\alpha} < 1/C_\alpha), \\ 1 & (\bar{\alpha} \geq 1/C_\alpha), \end{cases} \tag{2.3.2}$$

where the coefficient C_α is a constant given by the user.

The bubble rise velocity is calculated by the Wilson's correlation [14], which is a function of pressure, void fraction, and hydraulic diameter. The correlation is :

if $1/\{f_1(P) f_2(P)\} < 2.85$,

$$u_b = \left[\frac{\alpha}{0.136 f_1(P) f_2(P)}\right]^{1/1.78} \left[D_h f_2(P)^{1/0.19} g\right]^{0.5}, \tag{2.3.3}$$

and

if $1/\{f_1(P) f_2(P)\} \geq 2.85$,

$$u_b = \left[\frac{\alpha}{0.75 f_1(P) f_2(P)}\right]^{1/0.78} \left[D_h f_2(P)^{1/0.19} g\right]^{0.5},$$

where $f_1(P)$ and $f_2(P)$ are dimensionless functions of pessure defined as follows :

$$f_1(P) = \left(\frac{\rho_g}{\rho_f - \rho_g}\right)^{0.32}, \tag{2.3.4}$$

$$f_2(P) = \left[\frac{1}{D_h}\sqrt{\sigma / \{g(\rho_f - \rho_g)\}}\right]^{0.19} \tag{2.3.5}$$

where

σ = surface tension of water,
D_h = hydraulic diameter,
g = gravitational acceleration,
ρ_f = density of saturated liquid.

Model 2 (Bubble separation calculation with a sweep-out length)

In this model a parameter is introduced to represent the average length through which bubbles in the mixture region travel before they leave the mixture. Using this average length X_L and assuming that the void fraction in the mixture region is uniformly distributed, the bubble separation rate is calculated as

$$W_{sep} = M_{gb} \cdot \frac{u_b(\bar{\alpha})}{X_L}, \tag{2.3.6}$$

where M_{gb} = mass of bubbles in mixture region.

The term $u_b(\bar{\alpha})$ is the bubble rise velocity calculated by the Wilson's correlation with use of the average void fraction of the mixture region $\bar{\alpha}$.

The sweep-out length X_L is given by the user or, optionally, calculated by the code at the begining of the calculation from the steady state heat balance. This option can be used only for the node for the inside of the shroud. Further description can be found in section 2.7 for this option.

The given value of X_L is kept constant until the mixture level drops and the height of the mixture region becomes smaller than this X_L, then the given X_L is replaced by the height of the mixture region.

$$X_L = \min \{X_{L0}, (Z_{gm}-Z_{ml})\} , \tag{2.3.7}$$

where X_{L0} is the initial value of X_L.

2.4 Local Temperature Rise Model for Subcooled Liquid Region in a Three-Region Node

When the three-region node model is used to represent the inside of the core shroud as in Fig 2.1.1, the subcooled liquid region may expand beyond the bottom of the core. In such a case, the assumption of thermal equilibrium within a region causes unrealistic heat diffusion from the core to the lower plenum. To avoid this difficulty, a local temperature rise model was adopted.

In this model it is assumed that a certain fraction of the heat added to the subcooled liquid region from solid walls will not diffuse homogeneously but raise locally fluid temperature and bring this local part to saturation. The mass of liquid that is locally heated and becomes saturated per unit time is given as

$$W_{l\to m} = \frac{C_{l\to m}(\Sigma Q)^l}{h_f - h^l} , \tag{2.4.1}$$

where the term $C_{l\to m}$ is a constant coefficient that defines the fraction of heat consumed for this local heating, and is given as input by the user. The mass flow rate $W_{l\to m}$ is subtracted from the subcooled liquid region and added to the mixture region. At the same time, the energy rate convected by this flow

$$W_{l\to m}h_{l\to m} = W_{l\to m}h_f , \tag{2.4.2}$$

is also moved from the subcooled liquid region to the mixture region.

The coefficient $C_{l\to m}$ must be given by the user for each three-region

node. The values recommended by the authors are 1.0 for the node representing the inside of the core shroud and 0 for the node outside the shroud.

2.5 Momentum Balance Equation and Normal Junction Model

This section presents the basic model for the calculation of fluid flow between two adjacent nodes. This model is called the normal junction model as opposed to other derivative model options.

In this model, the fluid flow rate is calculated with use of a lumped-parameter momentum balance equation in which the momentum flux term is neglected and the homogeneous flow condition is assumed. Since THYDE-B1 is intended to be used with relatively coarse nodalization, the momentum flux term is usually much smaller than other terms in the lumped equation except for jet pumps for which a special model is provided (see section 2.8). This equation is written as

$$\frac{1}{g_c}\left(\frac{L}{A}\right)_{eff}\frac{dW}{dt} = P_{in}-P_{out}\ -\Delta P_{fric}+\Delta P_p-\Delta P_{grav}\ , \qquad (2.5.1)$$

where

$(L/A)_{eff}$ = effective inertia (given as input),

W = flow rate of junction ,

P_{in}, P_{out} = pressure of inlet node and outlet node,

ΔP_p = pump head,

ΔP_{fric} = frictional pressure drop,

ΔP_{grav} = gravitational pressure drop.

The loss term ΔP_{fric} and pump head ΔP_p are described in section 2.6 and 2.9, respectively.

The gravitational head ΔP_{grav} is calculated by

$$\Delta P_{grav} = \frac{g}{g_c}\left\{\int_{Z_{p,in}}^{Z_{j,in}}\rho_{in}dz - \int_{Z_{p,out}}^{Z_{j,out}}\rho_{out}dz\right\}\ , \qquad (2.5.2)$$

where

ρ_{in}, ρ_{out} = fluid density in inlet and outlet node,

$Z_{j,in}, Z_{j,out}$ = junction elevations above bottom of inlet node and outlet node (given as input),

$Z_{P,in}, Z_{P,out}$ = elevations of terminal points above bottom of inlet and outlet nodes.

The fluid density ρ_{in} and ρ_{out} are obtained with the assumption of homogeneous density distribution within a homogeneous node and within a subnode of a three-region node. The elevations of the two terminal points of the integration, $Z_{P,in}$ and $Z_{P,out}$, are specified by the user. These points are called "representative points" and the pressures at these points, P_{in} and P_{out}, are assumed to be the pressures of the nodes determined from the heat and mass balance described in section 2.2. The elevations of these points are usually specified to be the bottom of the nodes.

The properties of the flowing fluid are determined from the upstream condition as

$$\rho_j = \begin{cases} \rho_{in} & (W \geqq 0), \\ \rho_{out} & (W < 0), \end{cases} \tag{2.5.3}$$

$$h_j = \begin{cases} h_{in} & (W \geqq 0), \\ h_{out} & (W < 0), \end{cases} \tag{2.5.4}$$

where the terms ρ_j and h_j are the density and specific enthalpy of the fluid flowing at the junction.

When the upstream node is a three-region node, the upstream condition is that of the subnode at which the junction is connected. Since this method results in abrupt changes of the junction properties when a subnode boundary moves across the junction location in one time step, a numerical difficulty may arise. In order to avoid this difficulty, the property change can be smoothed by averaging the property within a certain range in vertical direction. This range must be given by the user as a junction diameter DIAMJ as described in section 5.3(6)*) .

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*) This option was provided only for leak junctions in the original version

At the user's option, the junction flow can be limited by critical flow models described in section 2.12. If this option is selected, the flow is calculated with both Eq.(2.5.1) and a critical flow model, and the smaller one is selected as the junction flow.

2.6 Frictional Pressure Drop

The frictional loss term ΔP_{fric} in Eq.(2.5.1) is calculated as

$$\Delta P_{fric} = R_0 \varphi^2 \frac{1}{\rho_l} |W| W, \tag{2.6.1}$$

where

R_0 = loss coefficient for single phase liquid,

ρ_l = density of flowing liquid,

φ^2 = two-phase multiplier.

The loss coefficient R_0 for single phase liquid can be given by the user or calculated by the code from initial steady state pressure distribution given by the user as

$$R_0 = \frac{(P_{in} - P_{out} + \Delta P_p - \Delta P_{grav})\rho_l}{|W| W \varphi^2}. \tag{2.6.2}$$

This is derived from Eq.(2.5.1).

The two-phase multiplier φ^2 is calculated from the correlations of Thom[16] and Martinelli[17]. These correlations are provided as a built-in table in the code.

In transient conditions, the direction of the flow may be different from the steady state and the pressure loss coefficient may not be equal to the value derived from the initial state. The user can give reverse loss coefficient for each junction. If not given, the loss coefficient for normal

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(JAERI-M 8119). The value L_{mix} in Fig.2.12.1 is equivalent to DIAMJ above.

flow is used also for the reverse flow.

2.7 Slip Junction Model for Steam Separators

The liquid and vapor flow rates through steam separators are important in the calculation of the liquid inventory and mixture level inside and outside the core shroud. The accuracy of the calculation of these flows are strongly influenced by the velocity difference between two phases flowing through upper plenum and stand pipes. The normal junction model, described in the section 2.5, is modified to take this slip effect into account. In addition to this, a model of the separation efficiency of steam separators is also provided.

This option is used when a junction is specified as the steam separator junction. The mass flow rate W of this junction is calculated by the same method as a normal junction but the vapor quality of the flow is modified with the consideration of the slip effect. The vapor and liquid components of the flow are calculated by solving next equations.

$$W_g + W_f = W, \tag{2.7.1}$$

$$W_g = \alpha_{top} u_g A_{top} \rho_g, \tag{2.7.2}$$

$$W_f = (1-\alpha_{top}) u_f A_{top} \rho_f, \tag{2.7.3}$$

$$u_g - u_f = u_b, \tag{2.7.4}$$

where the subscripts g and f indicate saturated vapor and liquid, and the subscript top stands for the fluid condition at the top of upstream node(node representing the inside of the shroud). The slip velocity u_b is calculated

by the Wilson's correlation. Above equations yield

$$W_g = (W-W_{slip})\frac{\rho_g\alpha_{top}}{\rho_g\alpha_{top}+\rho_f(1-\alpha_{top})} + W_{slip}, \tag{2.7.5}$$

$$W_l = W-W_g, \tag{2.7.6}$$

where

$$W_{slip} = \rho_g\alpha_{top}u_bA_{top}. \tag{2.7.7}$$

The void fraction at top of the upstream node is determined according to the bubble separation model specified for the inside node. When the Model 1 of the section 2.3 is chosen,

$$\alpha_{top} = \begin{cases} C_\alpha\bar{\alpha} & (\bar{\alpha}<1/C_\alpha), \\ 1 & (\bar{\alpha}\geqq 1/C_\alpha), \end{cases} \tag{2.7.8}$$

where C_α and $\bar{\alpha}$ are the same as those in Eq. (2.3.2). When the Model 2 is selected, α_{top} is determined from

$$W_{slip} \equiv \alpha_{top}u_g\rho_gA_{top} = \frac{M_{gb}u_b}{X_L}, \tag{2.7.9}$$

where the terms M_{gb} and X_L are the same as those in Eq. (2.3.6). This slip model is not used when the flow direction is negative or flow condition is one phase; the homogeneous flow model is used for these cases.

The steam separator actually has two flow path, that is, the upward separated steam flow and the downward liquid flow. Since the rate of vapor carry under may influence the mixture level calculation for the downcomer node, the separated steam flow is obtained using a separation efficiency specified by the user as

$$W_g^g = \eta W_g, \tag{2.7.10}$$

where

W_g = steam flow rate through junction,

W_g^g = separated steam flow that will be added to the vapor region of downcomer node,

η = steam separation efficiency.

The steam separator efficiency η is specified by the user as a function of the mixture level in the downcomer.

The liquid component of the junction flow and the rest of the steam flow will be added to the mixture region of the downcomer node.

2.8 Jet Pump Model

The momentum flux term plays an important role in the momentum balance for jet pumps. The jet pump model of ALARM-B1[4] was incorporated in THYDE-B1. ALARM-B1 had two methods of solution: one model ignored the temporal momentum change of the suction flow, while the other did not. The former was incorporated in THYDE-B1.

In THYDE-B1, two options can be selected for the treatment of the momentum flux terms in conjunction with the mixture level in the downcomer. In the first model the momentum flux terms are considered throughout the transient, while they are neglected after the mixture level drops below the top of a jet pump in the second model.

(1) Model 1

The characteristic magnitude of a jet pump is shown in Fig.2.8.1. A jet pump is treated as a combination of three junctions that correspond ,respectively, to the flow path from downcomer to point 1, from recirculation pipe to point 1, and from point 1 to lower plenum. Assuming that :

(i) P_1, P_2, P_3 are constant over the cross section,

(ii) fluid is incompressible,

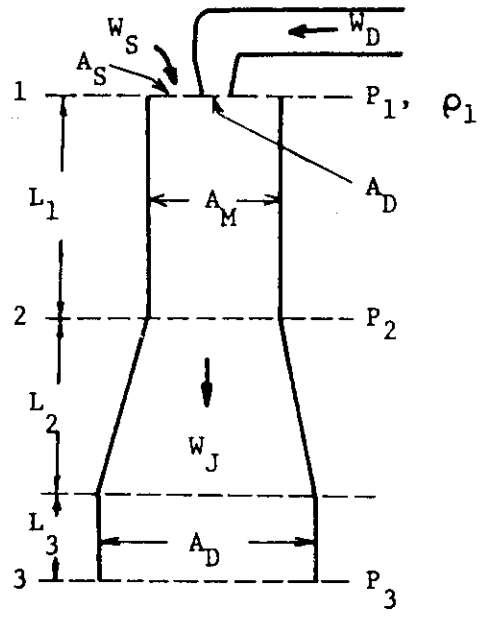


Fig. 2.8.1 Characteristic Magnitude of Jet Pump

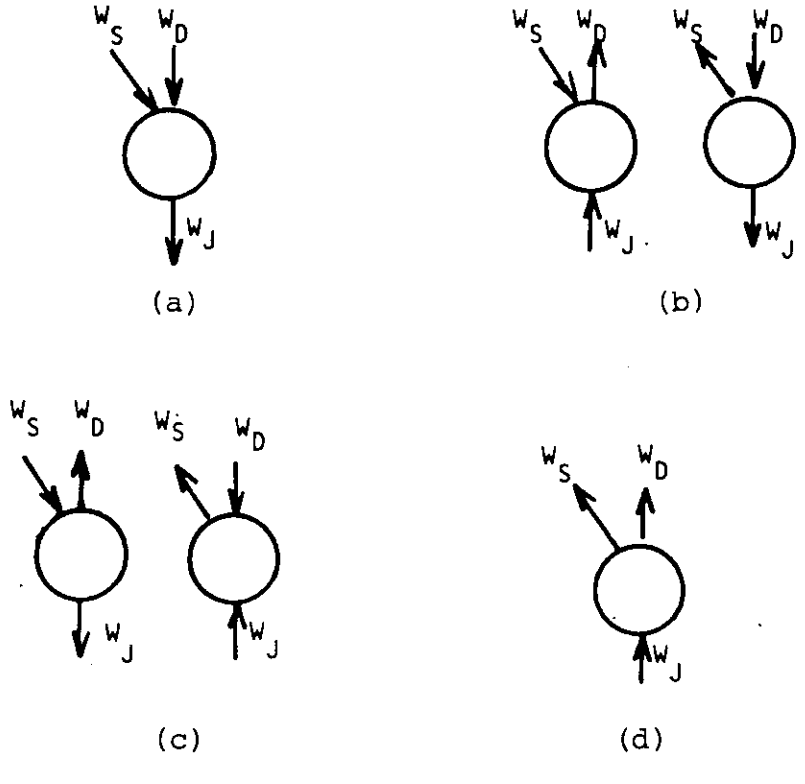


Fig. 2.8.2 Flow Patterns of Jet Pump

(iii) mixing of W_S and W_D is completed within L_1,

(iv) the inertia of the suction flow can be neglected,

the momentum equations for the three junctions are given by:

$$\frac{1}{g_c}\left(\frac{L}{A}\right)_J\frac{dW_J}{dt} = P_1-P_L+\Delta P_{m,J}+\frac{W_J^2}{\rho_J}\left\{\frac{1}{2}\left(\frac{1}{A_M^2}-\frac{1}{A_L^2}\right)-\frac{1}{A_M^2}\right\}-\Delta P_{grav,J}$$

$$-\Delta P_{fric,J}, \tag{2.8.1}$$

$$\frac{1}{g_c}\left(\frac{L}{A}\right)_D\frac{dW_D}{dt} = P_D-P_1+\Delta P_{m,D}-\Delta P_{grav,D}-\Delta P_{fric,D}+\Delta P_P, \tag{2.8.2}$$

$$0 = P_S-P_1+\Delta P_{m,S}-\Delta P_{grav,S}-\Delta P_{fric,S}, \tag{2.8.3}$$

where the subscripts J, D, and S refer to the throat, the drive, and the suction flow, respectively, and

P_1 = pressure at top of jet pump (point 1 in Fig.2.8.1),

P_S = pressure of the node representing outside of core shroud,

P_D = pressure of the node representing jet pump drive line,

P_L = pressure of the node representing inside of the core shroud,

A_L = flow area of lower plenum,

ΔP_m = pressure drop due to change in momentum flux,

$\Delta P_{m,J}$ = momentum flux at jet pump throat.

The momentum flux terms are determined with the consideration of the effect of flow directions of three junctions. Four flow patterns illustrated in Fig.2.8.2 are considered.

(a) $W_D>0$, $W_S>0$, $W_J>0$,

$$\Delta P_{m,J} = \frac{1}{g_c\rho_1 A_M}\left(\frac{W_S^2}{A_S}+\frac{W_D^2}{A_D^2}\right), \tag{2.8.4}$$

$$\Delta P_{m,D} = \frac{W_D^2}{2g_c\rho_D}\left(\frac{1}{A_{pipe}^2}-\frac{1}{A_D^2}\right), \tag{2.8.5}$$

$$\Delta P_{m,S} = \frac{W_S^2}{2g_c\rho_S}\left(\frac{1}{A_{down}^2}-\frac{1}{A_S^2}\right), \tag{2.8.6}$$

$$\rho_1 = \rho(P_1, h_1), \tag{2.8.7}$$

$$h_1 = (W_S h_S + W_D h_D)/W_J \ , \tag{2.8.8}$$

$$\rho_J = W_J/(\frac{W_S}{\rho_S} + \frac{W_D}{\rho_D}), \tag{2.8.9}$$

where A_{pipe} = drive pipe flow area,
A_{down} = downcomer flow area,
ρ_S = suction fluid density,
ρ_J = throat fluid density,
ρ_1 = fluid density at the cross section 1,
h_1 = specific enthalpy.

(b) $W_D<0$, $W_S>0$, $W_J<0$, and $W_D>0$, $W_S<0$, $W_J>0$, ,

$$\Delta P_{m,J} = \frac{W_J^2}{g_c \rho_1 A_M A_{Jet}} \ , \quad A_{Jet} = A_S |\frac{W_J}{W_S}| , \tag{2.8.10}$$

$$\Delta P_{m,D} = \frac{W_D^2}{2 g_c \rho_D} (\frac{1}{A_{pipe}^2} - \frac{1}{A_{drive}^2}), \quad A_{drive} = A_S |\frac{W_D}{W_S}| , \tag{2.8.11}$$

$$\Delta P_{m,S} = \frac{W_S^2}{2 g_c \rho_S} (\frac{1}{A_{down}^2} - \frac{1}{A_S^2}), \tag{2.8.12}$$

$$\rho_1 = \rho(P_1, h_1), \tag{2.8.13}$$

for $W_D<0$, $W_S>0$ and $W_J<0$,

$$h_1 = -(W_S h_S - W_J h_J)/W_D \ , \tag{2.8.14}$$

$$\rho_D = W_D/(\frac{W_J}{\rho_J} - \frac{W_S}{\rho_D}), \tag{2.8.15}$$

and for $W_D>0$, $W_S<0$ and $W_J>0$,

$$h_1 = h_D, \tag{2.8.16}$$

$$\rho_J = \rho_D, \tag{2.8.17}$$

$$\rho_S = \rho_D, \tag{2.8.18}$$

where h_S = suction flow enthalpy,
h_D = drive flow enthalpy,

(c) $W_D<0$, $W_S>0$, $W_J>0$, and $W_D>0$, $W_S<0$, $W_J<0$, ,

$$\Delta P_{m,J} = \frac{W_J^2 A_{Jet}}{g_c \rho_1 A_M A_S^2}, \quad A_{Jet} = A_S \left|\frac{W_J}{W_S}\right|, \tag{2.8.19}$$

$$\Delta P_{m,D} = \frac{W_D^2}{2 g_c \rho_D} \left(\frac{1}{A_{pipe}^2} - \frac{1}{A_{drive}^2}\right), \quad A_{drive} = A_S \left|\frac{W_D}{W_S}\right|, \tag{2.8.20}$$

where if $|W_D| \leq |W_S A_D / A_S|$, $A_{drive} = A_D$,

and if $|W_D| > |W_S A_D / A_S|$, $A_{drive} = A_S |W_D / W_S|$,

$$\Delta P_{m,S} = \frac{W_S^2}{2 g_c \rho_S} \left(\frac{1}{A_{down}^2} - \frac{1}{A_S^2}\right), \tag{2.8.21}$$

$$\rho_1 = \rho(P_1, h_1), \tag{2.8.22}$$

for $W_D<0$, $W_S>0$ and $W_J>0$,

$$h_1 = h_S, \tag{2.8.23}$$

$$\rho_J = \rho_S, \tag{2.8.24}$$

$$\rho_D = \rho_S, \tag{2.8.25}$$

and for $W_D>0$, $W_S<0$ and $W_J<0$,

$$h_1 = -(W_D h_D - W_J h_J)/W_S, \tag{2.8.26}$$

$$\rho_S = W_S / \left(\frac{W_J}{\rho_J} - \frac{W_D}{\rho_D}\right), \tag{2.8.27}$$

(d) $W_D<0$, $W_S<0$, $W_J<0$, ,

$$\Delta P_{m,J} = \frac{W_J^2}{g_c \rho_1 A_M}, \tag{2.8.28}$$

$$\Delta P_{m,D} = \text{same as (a)}, \tag{2.8.29}$$

$$\Delta P_{m,S} = \text{same as (b)}, \tag{2.8.30}$$

$$\rho_1 = \rho(P_1, h_1), \tag{2.8.31}$$

$$h_1 = h_J, \tag{2.8.32}$$

$$\rho_S = \rho_J, \tag{2.8.33}$$

$$\rho_D = \rho_J , \tag{2.8.34}$$

where $A_M = A_D + A_S$.

The frictional pressure drop ΔP_{fric} is calculated by the method given in section 2.6. The gravitational pressure drop ΔP_{grav} for the suction and the drive flows are obtained from Eq. (2.5.2). As for the throat flow, the head of the fluid in the jet pump diffusers must be considered. Equation (2.5.2) is replaced by

$$\Delta P_{grav} = \frac{g}{g_c} \{ -(L_1+L_2+L_3)\rho_j - \int_{Z_{p,out}}^{Z_{j,out}} \rho_{out} dz \} , \tag{2.8.35}$$

for the throat flow, where ρ_j is the density of fluid flowing through the throat junction.

(2) Model 2

The second model is the same as the Model 1 except that the momentum flux terms are ignored when the mixture level of downcomer becomes lower than the jet pump suction nozzle.

2.9 Recirculation Pump Model

The centrifugul pump model of THYDE-B1/MOD1 is almost equivalent to that of RELAP4/MOD5[8] except that the pump is treated in a junction model in THYDE-B1 while it is treated as a volume in RELAP4.

The performance of a centrifugal pump is represented by a set of homologous curves describing the relationships among normalized head h, normalized pump speed α, normalized flow υ, and normalized torque β. An example of such curves is illustrated in Fig.2.9.1 and Fig.2.9.2, where the definitions of normalized variables are as follows.

$$\alpha = \omega/\omega_R , \tag{2.9.1}$$

$$h = H/H_R , \tag{2.9.2}$$

$$\upsilon = Q/Q_R , \tag{2.9.3}$$

$$\beta = T_{hy}/T_{hy,R} \quad , \tag{2.9.4}$$

where the subscript R indicates a rated condition and

ω = pump speed,

H = pump head ($\Delta P_p/\rho$, ρ=fluid density),

Q = volumetric flow rate,

T_{hy} = hydraulic torque.

The user is required to provide tables of normalized head versus the ratio of normalized pump speed and volumetric flow and normalized torque versus the ratio of normalized pump speed and volumetric flow.

At the user's option, the degradation of pump performance for two-phase flow conditions can be taken into account by the use of a separate sets of homologous curves for head and torque for a degraded condition. These curves are in the form of difference curves, that is, the degraded head and torque are calculated as

$$H = H_{\varphi 1} - M_H(\alpha)(H_{\varphi 1} - H_{\varphi 2}) \tag{2.9.5}$$

$$T_{hy} = T_{\varphi 1} - M_T(\alpha)(T_{\varphi 1} - T_{\varphi 2}) \tag{2.9.6}$$

where

subscript $\varphi 1$ = single phase value,

subscript $\varphi 2$ = two-phase fully degraded value,

M_H = multiplier on head difference curve,

M_T = multiplier on torque difference curve,

α = void fraction of the flowing fluid (upstream condition).

Available data base for degraded pump performance is very limited. Figures 2.9.3, 2.9.4 and Table 2.9.1 shows an example of such curves.

The differential pressure change ΔP_p is calculated by

$$\Delta P_p = \rho_j H.$$

where ρ_j is the fluid density of the upstream node.

The coast down of a pump after the power supply has been shut off by the input trip signal, is calculated by a momentum conservation equation for the pump rotor.

$$I\frac{d\omega}{dt} = T,$$

where

T = net torque,

I = moment of inertia,

t = time.

The total pump torque is obtained by considering the hydraulic torque from the homologous curves, the pump frictional torque, and the motor torque as :

$$T = - T_{hy} - T_{fric} + T_{mot}$$

where

T_{fric} = frictional torque,

T_{mot} = motor torque.

The frictional torque is calculated as a cubic function of pump speed as

$$T_{fric} = C_0 + C_1(\frac{\omega}{\omega_R}) + C_2(\frac{\omega}{\omega_R})^2 + C_3(\frac{\omega}{\omega_R})^3,$$

where C_0, C_1, C_2 and C_3 are constants given by the user.

The motor torque before the pump motor has been shut off is calculated as a function of pump speed. An example of torque/speed relationship for an induction motor is given in Fig.2.9.5.

The heat addition to the fluid due to energy dissipation in the pump is ignored in THYDE-B1.

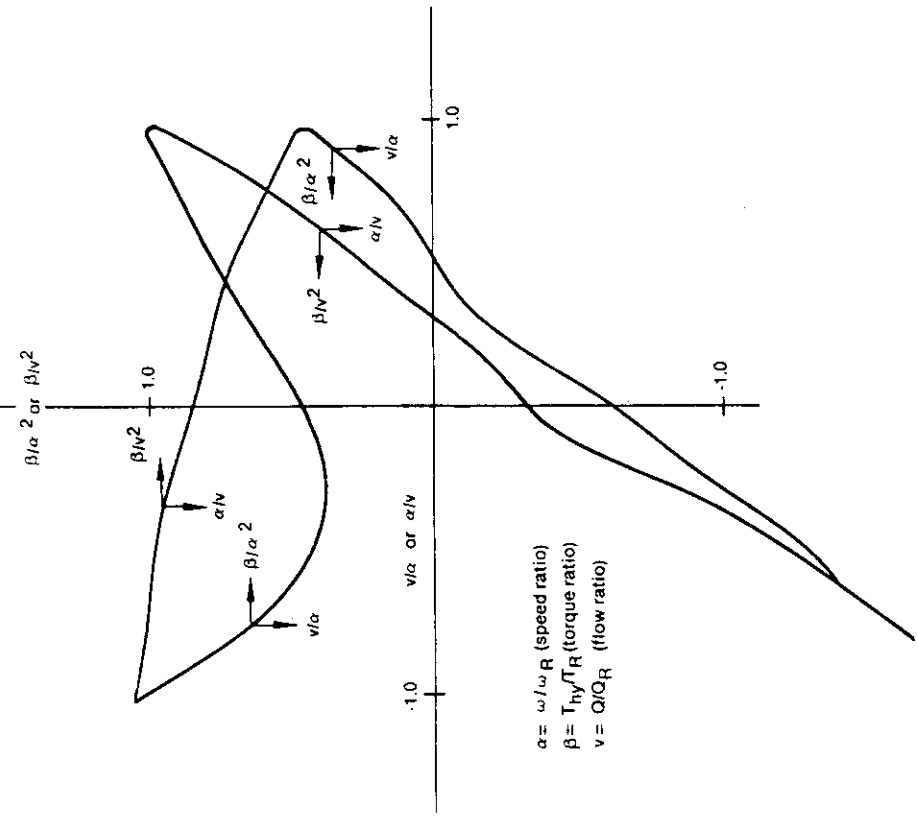


Fig.2.9.2 Pump Homologous Torque Curves (Reference 8)

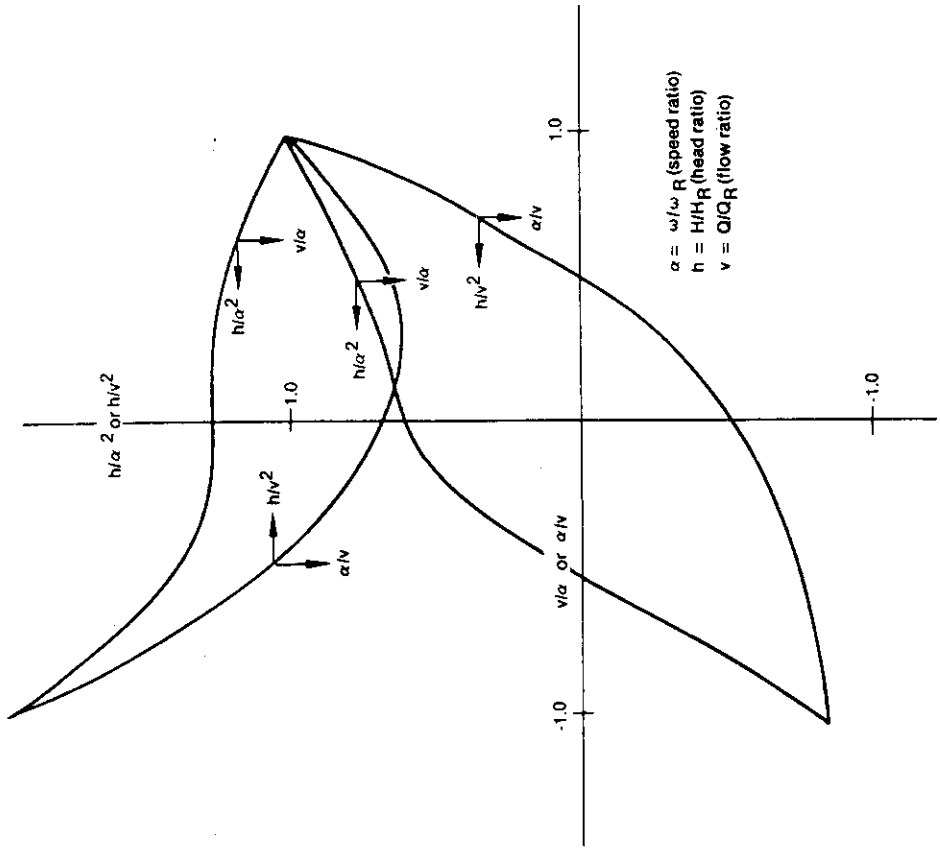


Fig.2.9.1 Pump Homologous Head Curves (Reference 8)

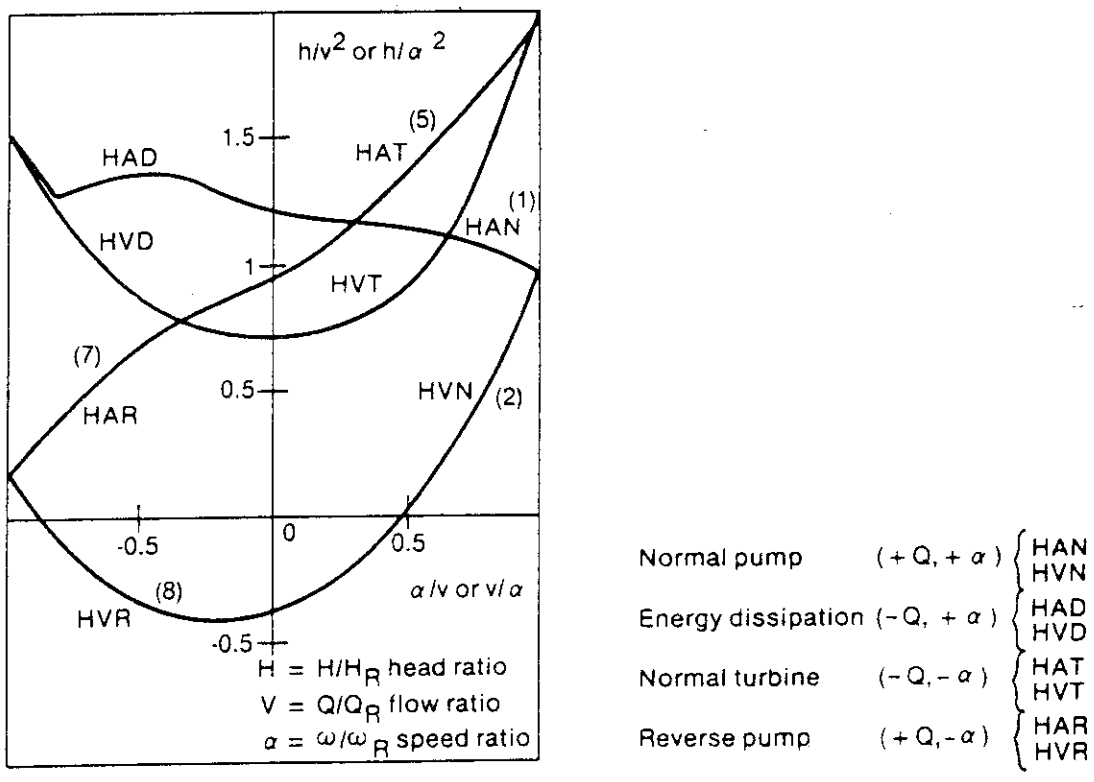


Fig.2.9.3 Single-Phase Homologous Head Curves for 1-1/2 Loop MOD-1 Semiscale Pumps (Reference 8)

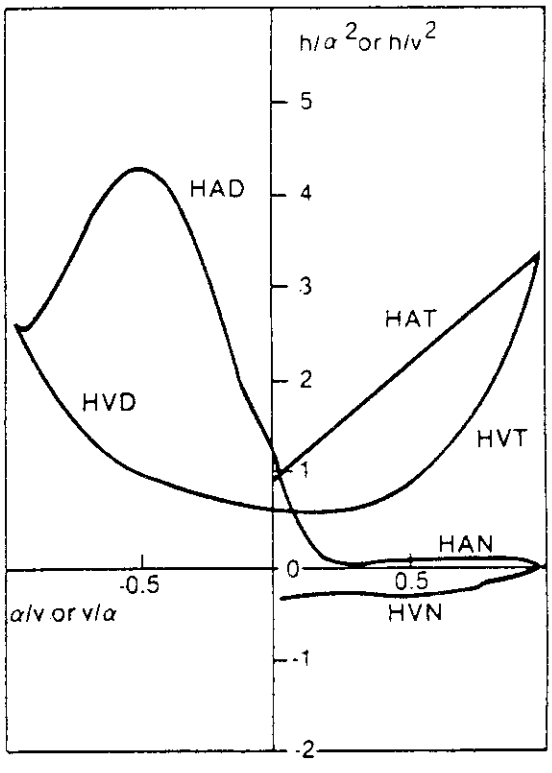


Fig.2.9.4 Fully Degraded Two-Phase Homologous Head Curves for 1-1/2 Loop MOD-1 Semiscale Pump (Reference 8)

Table 2.9.1 Head Multiplier and Void Fraction Data(Reference 8)

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

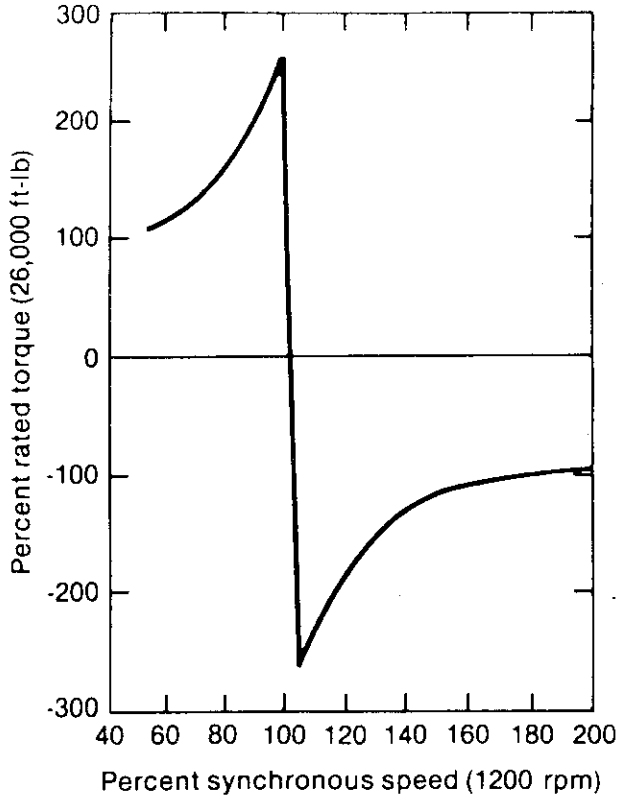


Fig.2.9.5 Torque versus Speed, Type 93A Pump Motor (Rated Voltage) (Reference 8)

2.10 Main Steam Line Model

The steam flow rate through the main steam lines can be calculated by the use of the leak junction model described in section 2.12 or by use of a model similar to SAFE[12]. This section describes the latter model.

The functions of the turbine flow control valves, the main steam line isolation valves, and the flow restrictors are taken into account in this model. The steam line flow is determined as the smaller of the flow allowed by the turbine control valves and the flow allowed by the isolation valves. The turbine control valves are controlled by the pressure just upstream the valves P_U to give a flow rate of

$$W_{ST} = W_{SR}\left(\frac{P_U - P_{US}}{G_S}\right), \tag{2.10.1}$$

where

W_{ST} = flow allowed by the turbine control valves,
W_{SR} = rated flow rate (junction flow rate at initial state),
P_{US} = pressure set point,
G_S = controller regulation band (input constant).

The upstream pressure is expressed as

$$P_U = P - \Delta P_R \left(\frac{W_{ST}}{W_{SR}}\right)^2, \tag{2.10.2}$$

where

ΔP_R = pressure drop for rated flow (input constant),
P= steam dome pressure (pressure of the node representing the outside of core shroud.

The controller set point is determined as

$$P_{US} = P_R - \Delta P_R - G_S, \tag{2.10.3}$$

where

P_R= rated steam dome pressure (initial value of P).

The flow rate through the turbine control valve is obtained from Eqs. (2.10.1), (2.10.2), and (2.10.3) as

$$W_{ST} = \frac{W_{SR}}{2\Delta P_R}\left[\sqrt{G_S^2 + \Delta P_R (P+\Delta P_R+G_S-P_R)} - G_S\right] , \tag{2.10.4}$$

Considering the function of the flow restrictors, W_{ST} is bounded by

$$0 \leqq W_{ST} \leqq W_{STM}. \tag{2.10.5}$$

where W_{STM} is the maximum flow rate specified by the user.

The flow rate allowed by the isolation valve W_{SI} is calculated with the consideration of the transitional flow area change as

$$W_{SI} = \begin{cases} W_{STM}, & (t>t_{sig}) \\ W_{STM}\left[1-\left\{(t-t_{sig})/\tau_c\right\}^4\right], & (t_{sig} \leqq t \leqq t_{sig}+\tau_c), \\ 0, & (t>t_{sig}+\tau_c) \end{cases} \tag{2.10.6}$$

where t_{sig} is the time at which the valve closure signal is actuated, and τ_c is the time constant of the closing action. The actuation of the valve closure signal can be specified with use of the trip control options described in section 2.13.

2.11 Fill Systems and Mixing Efficiency Model

The ECC water injection systems and the feed water system can be modelled in THYDE-B1 by a fill junction model. In this model the mass flow rate and the specific enthalpy of the injected liquid are specified by the user as functions of time or as functions of the pressure of the node at the outlet side of the junction. The trip control option for the actuation of fill systems is described in section 2.13.

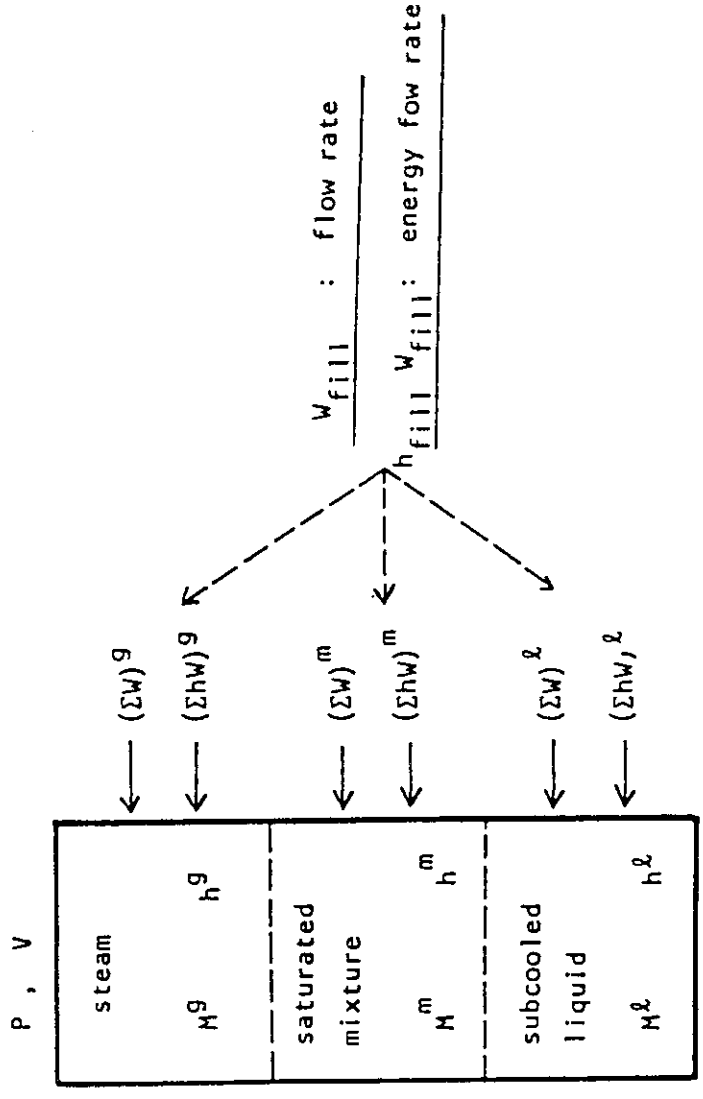


Fig. 2.11.1 Distribution of Injected Flow within a Three-Region Node

Since the coolant injected by the ECCS is usually highly subcooled and the system pressure response is strongly influenced by the degree of the mixing of injected liquid and steam inside the pressure vessel, a special model is provided to take the mixing efficiency into consideration. This model can be used only for junctions connected to a three-region node; complete mixing is assumed for injections to homogeneous nodes.

As illustrated in Fig. 2.11.1, the incompleteness of the mixing can be taken into account by adjusting the distribution of the injected mass and energy into three regions. This distribution is determined as a function of the elevations of the subnode boundaries with use of a set of mixing efficiency parameters given by the user.

Figure 2.11.2 shows an illustration of possible three cases. The first case is the injection of subcooled liquid into the steam region. In this case, the vapor condensation rate is calculated by the same model as SAFE. This is expressed as

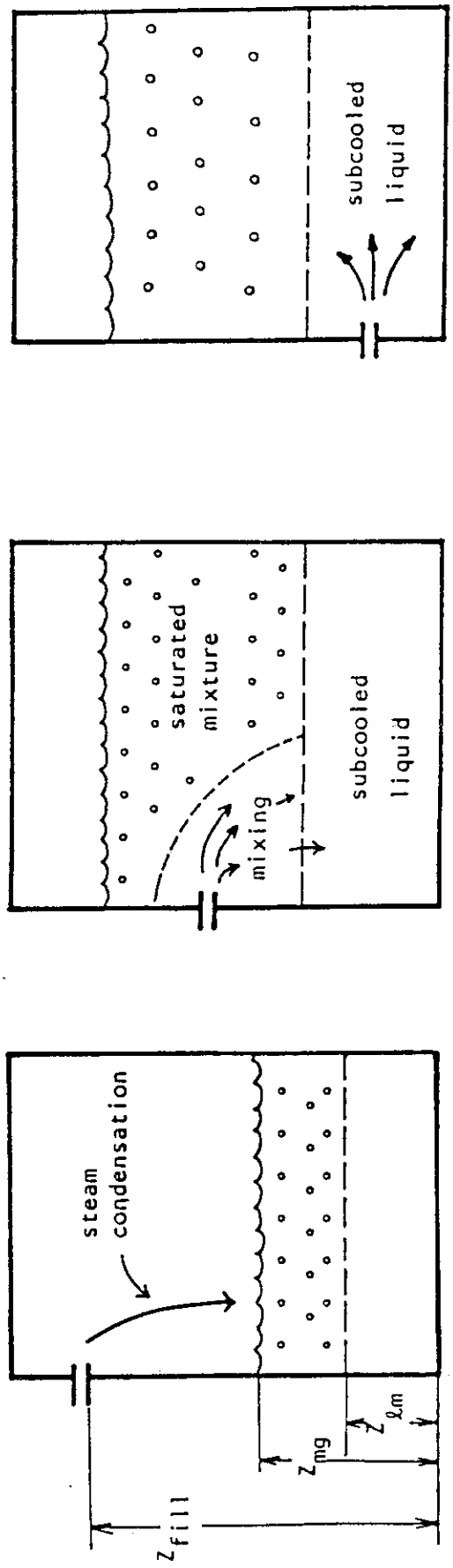
$$Q_g = F_g \cdot \min\left\{1, \frac{Z_{fill} - Z_{gm}}{L_g}\right\} \cdot (h_f - h_{fill}) \cdot W_{fill} \ , \qquad (2.11.1)$$

$$W_{cond} = \frac{Q_g}{h_g - h_f} \ , \qquad (2.11.2)$$

where

Q_g = heat transfer rate from vapor to injected liquid,
W_{cond} = rate of vapor condensation,
h_{fill} = specific enthalpy of injected liquid,
W_{fill} = mass flow rate of injected liquid,
h_f = specific enthalpy of saturated liquid,
h_g = specific enthalpy of saturated vapor.

The parameters F_g and L_g are the mixing efficiency and the length which is required for mixing, respectively, and they must be given by the user. The values of F_g=0.95 and L_g=1.0 feet are recommended in reference 21 for a high pressure injection system (HPCI), which supplies water into the downcomer



$z_{fill} > z_{mg}$

$z_{mg} > z_{fill} > z_{m\ell}$

$z_{m\ell} > z_{fill}$

Fig. 2.11.2 Mixing Conditions of a Fill Junction

through feed water spargers. As for core sprays, the authors recommend the values of F_g=1. and L_g=0.1m.

The condensed vapor W_{cond} and its enthalpy $h_g W_{cond}$ will be subtracted from the vapor region and added to the injected liquid.

The second case is the injection of subcooled liquid into the mixture region. As shown in Fig.2.11.2, this case is encountered when the elevation of a fill junction is located within the range of the mixture region. And this case also occurs when the subcooled liquid injected to the vapor region is not fully mixed with vapor in that region.

In the mixture region, the mixing of the injected liquid with the two-phase mixture is assumed to occur in a limited part in the region. The amount of the two-phase mixture that is mixed with the injected liquid is assumed to be proportional to the injection rate. It is calculated as

$$W_m = F_m \cdot \frac{Z_{fill}-Z_{ml}}{L_m} \cdot W_{fill} \qquad (2.11.3)$$

where W_m is the amount of mixture mixed with the injected liquid per unit time. F_m and L_m are a mixing efficiency and a length factor of the mixing, respectively, and they must be given by the user. If this amount of saturated mixture is mixed with the injected liquid, the amount and the specific enthalpy of the resultant fluid become

$$W_{mix} = W_m + W_{fill}, \qquad (2.11.4)$$

$$h_{mix} = \frac{W_m h^m + W_{fill} h_{fill}}{W_{mix}}, \qquad (2.11.5)$$

where

h^m = average enthalpy of the saturated mixture region,

W_{mix} = flow rate of mixed flow,

h_{mix} = specific enthalpy of mixed fluid.

If this fluid is saturated ($h_{mix} > h_f$), it will be added to the mixture

region, and if not, it will be added to the subcooled liquid region.

The authors recommend the values of F_m=1. and L_m=0., which correspond to 100% efficiency, for the core sprays because a good mixing can be expected in the upper plenum and in the core channel. And the values of F_m=0.0 and L_g=1.m which correspond to 0% mixing efficiency, could be recommended for other safety injections from the conservative point of view. The use of lower mixing efficiency yields higher calculated pressure and, consequently, lower flow rates of safety injections. However, it is best to use experimentally supported data as far as possible.

The last case is the injection of subcooled liquid into the subcooled liquid region. In this case, all the injected liquid will be added to the subcooled region.

2.12 Leak Flow Model

The breaks and the relief or safety valves can be represented by a leak junction model. Following two ways of modelling are allowed.

(1) Calculate mass flow rate as a function of time or node pressure given by the user,
(2) Calculate mass flow rate by critical flow models in the code.

As for method (1), the user must specify the flow rate by a table of following types.

(1.a) a table of time versus mass flow rate
(1.b) a table of upstream node pressure versus mass flow rate
(1.c) a table of upstream node pressure versus mass flux

As for method (2), following models can be used.

(2.a) Incompressible Liquid Flow Model

This is a model for the case in which critical flow does not occur. This model determines the flow rate as

$$W = C_D A\sqrt{2\rho_j g_c (P_0 - P_b)}\ , \qquad (2.12.1)$$

where

C_D = discharge coefficient,

A = junction flow area,

ρ_j = fluid density evaluated from upstream node condition,

P_0 = stagnation pressure (upstream node pressure is used),

P_b = sink pressure given as input.

(2.b) Moody Model [18]

(2.c) Henry-Fauske Model [19]

(2.d) Homogeneous Equilibrium Model [20]

The flow rate for models (2.b), (2.c) and (2.d) is calculated by built-in tables of mass flux as a function of stagnation enthalpy and stagnation pressure. The tables were cited from RELAP4/MOD5 [8] .

Since the applicable ranges of above models differ from each other, the user can specify three models for application to subcooled liquid, saturated mixture and super heated steam, respectively. The discharge coefficients to be used are also allowed to be different.

In addition the user can specify a quality range, in which the flow rate are determined by a linear interpolation between the flow rates determined by two models, that is, the flow rate is determind as :

$$W = AC_{Dsub}G_{sub}(h_0, P_0), \quad (\text{for } \chi<0) \tag{2.12.2}$$

$$W = \left(\frac{\chi_{tran1}-\chi}{\chi_{tran1}}\right)AC_{Dsub}G_{sub}(h_0, P_0)$$

$$+ \left(\frac{\chi}{\chi_{tran1}}\right)AC_{Dsat}G_{sat}(h_0, P_0), \quad (\text{for } 0 \leqq \chi < \chi_{tran1}) \tag{2.12.3}$$

$$W = AC_{Dsat}G_{sat}(h_0, P_0) \quad (\text{for } \chi_{tran1} \leqq \chi < \chi_{tran2}) \tag{2.12.4}$$

$$W = \left(\frac{1-\chi}{1-\chi_{tran2}}\right)AC_{Dsat}G_{sat}(h_0,P_0)$$

$$+ \left(\frac{\chi-\chi_{tran2}}{1-\chi_{tran2}}\right)AC_{Dvap}G_{vap}(h_0,P_0), \quad (\text{for } \chi_{tran2} \leqq \chi < 1) \tag{2.12.5}$$

$$W = AC_{Dvap}G_{vap}(h_0,P_0) \quad (\text{for } 1 \leqq \chi) \tag{2.12.6}$$

where

χ = quality evaluated at (P_0,h_0),

C_D = discharge coefficients specified by the user,

$G(h_0,P_0)$ = mass flux determined by the model selected by the user,

χ_{tran1} and χ_{tran2} = transition qualities specified by the user,

and the subscripts *sub*, *sat*, *vap* indicate the subcooled, saturated and single-phase steam conditions, respectively.

In the course of a LOCA transient, the pressure in the reactor cooling system eventually drops near the pressure outside the system and critical flow conditions will be terminated. Considering this possibility, the flow rate for the incompressible flow model is calculated at any time and this flow rate will be adopted as the junction flow rate if it becomes larger than the value for the critical flow model selected by the user.

When the pressure of the upstream node drops below the pressure outside the break P_b, the flow direction will be reversed. In this case, the junction flow rate is calculated by the incompressible flow model and the fluid enthalpy h_j, is assumed to be that of saturated steam.

$$h_j = h_g(P_b). \tag{2.12.7}$$

The stagnation properties are determined from the pressure and specific enthalpy of the inlet node of the junction (node from which break flow goes out). If this inlet node is a three-region node, they are determined from the fluid properties of the subnode to which the junction is facing. In this case, the upstream specific enthalpy can be discontinuously changed due to the

moving subnode boundaries. To avoid this discontinuous enthalpy change, the upstream enthalpy is determined by averaging the subnode enthalpies in a certain range L_{mix} (input constant), as illustrated in Fig.2.12.1. The value L_{mix} is given by the user as a junction diameter DIAMJ (See section 5.3(6)).

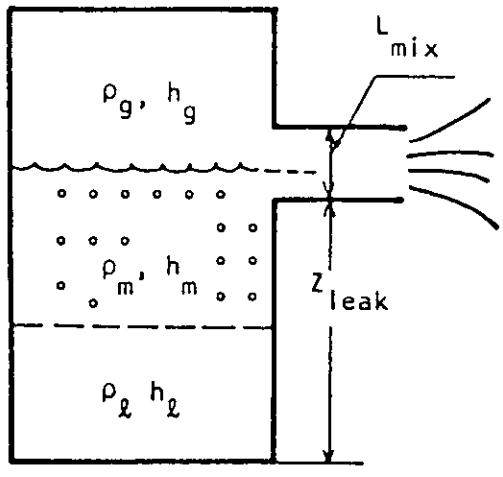


Fig. 2.12.1 Inlet Property Smoothing Method for Leak Junctions

2.13 Hypothetical Valves and Trip Control Options

Each junction may have a hypothetical valve attached to it. These valves control the junction flow by opening or closing actions. The transitional area change is not considered but the valves are allowed only to be fully open or fully closed.

A trip control logic is provided to initiate valve actions and other trips.

The trip actions provided in THYDE-B1 are :

(1) termination of the calculation,
(2) opening or closing of the valves,
(3) pump trip,
(4) initiation of a leak,
(5) actuation of a fill system,

The system variables that can be monitored are :

(1) time,
(2) node pressure,
(3) liquid level of a three-region node,
(4) flow rate at a junction,
(5) difference between pressures of two nodes,
(6) difference between flow rate of two junctions.

Since liquid levels in BWRs are usually obtained from the measurement of differential pressure between two points, the liquid level used for the trip control is the collapsed level determined by next equation.

$$Z_{sig} = (1-\alpha) \cdot \min \{Z_{gm}, Z_2\} + \alpha \cdot \max \{Z_{ml}, Z_1\} \quad , \qquad (2.13.1)$$

where

Z_{sig} liquid level in a three-region node,
Z_{gm} = upper boundary of mixture region,
Z_{ml} = upper boundary of subcooled liquid region,
α = void fraction of mixture region,

Z_1, Z_2 = elevations of level sensors, lower one and upper one, respectively (input constants).

2.14 Heat Slab Model for Fuel Rods and Internal Structures

A one-dimentional heat slab model is provided for the representation of the fuel rods and other structures in the primary system. The models for the calculation of heat generation rate in the heat slabs is explained in section 2.15 while the heat transfer model that gives the boundary conditions for the slabs is described in section 2.16.

The geometry of a heat slab is assumed to be rectangular or cylindrical as shown in Fig.2.14.1. The number of the heat slabs is arbitrary. An application example is shown in Fig.2.1.1. As can be seen in this figure, the fuel rods are ,usually, axially divided into several heat slabs. The axial conduction between heat slabs is not considered in this code. A heat slab is allowed to have one or two(only for rectangular type) heat transfer surfaces and each of the surface is allowed to face only one fluid node.

By nodalizing the heat slab, the heat conduction is represented by a heat transfer circuit illustrated in Fig. 2.14.2. In this model, the node temperature is obtained by

$$\frac{dT_n}{dt} = \frac{1}{C_n} \left(-q_{n,n-1}+q_{n+1,n}+Q_n\right), \tag{2.14.1}$$

$$q_{n,n-1} = \frac{1}{r_{n,n-1}} \left(T_n-T_{n-1}\right), \tag{2.14.2}$$

where

n = node number (1,2...,N),

N = number of nodes,

C_n = heat capacity of node n,

$q_{n,n-1}$ = heat transfer rate from node n to node (n-1),

Q_n = heat generation rate in node n,

$r_{n,n-1}$ = thermal resistance between node n and node (n-1).

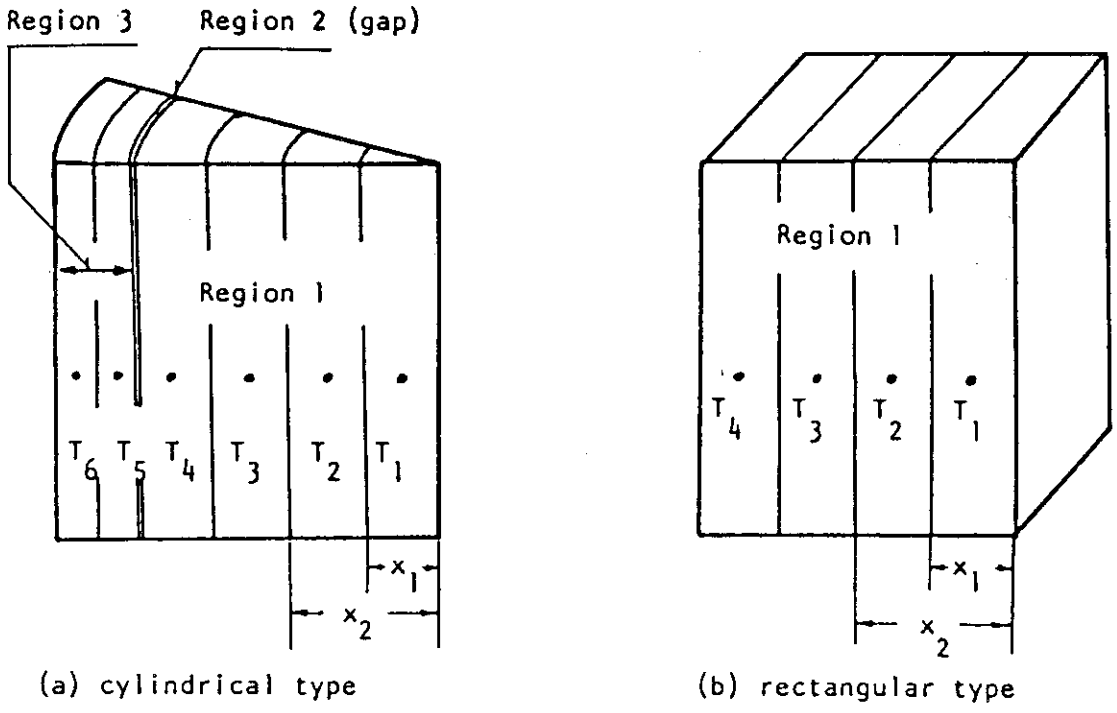


Fig. 2.14.1 Examples of Heat Slab Nodalization

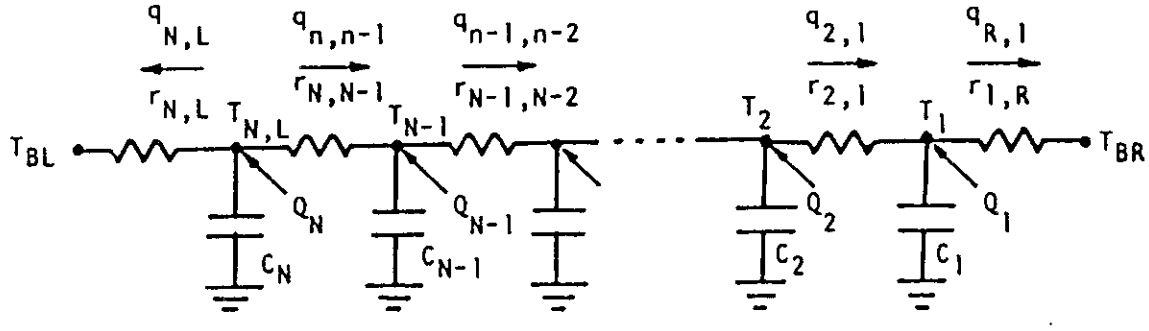


Fig. 2.14.2 Heat Transfer Circuit Model

The heat capacity and thermal resistance are obtained by

$$C_n = V_n \rho_n c_n , \tag{2.14.3}$$

$$r_{n,n-1} = \frac{1}{2\pi Z k_n} \{ ln(\frac{x_{n+1}+x_n}{2}) - ln(x_n) \} + \frac{1}{2\pi Z k_{n-1}} \{ ln(x_n)$$

$$- ln(\frac{x_n+x_{n-1}}{2}) \} , \text{ (for cylindrical type)} \tag{2.14.4}$$

and

$$r_{n,n-1} = \frac{1}{A} (\frac{x_{n+1}-x_n}{2k_n} + \frac{x_n-x_{n-1}}{2k_{n-1}}), \text{ (for rectangular type)} \tag{2.14.5}$$

where

ρ_n = density of heat slab node n,
V_n = volume of heat slab node n,
Z = axial length of heat slab ,
A = heat transfer area,
x = radii or thickness.

The thermal conductivity k and the specific heat capacity c must be specified by the user as a function of temperature. Density of a material is assumed to be constant and given as input. For the specification of material properties, the heat slabs can be divided into regions according to the difference in composing materials. Each of the material region can be divided into several nodes of equal thickness.

The gap between the fuel pellet and the cladding is treated as a gap region as illustrated in Fig.2.14.1(a). The gap region is allowed to have heat resistance but not to have heat capacity. For each gap region, the user must specify a temperature-dependent gap conductance table. The temperature of the gap is determined by simple averaging of the temperatures of two adjacent

nodes.

2.15 Heat Generation in Fuel Rods

The heat slab model for fuel rods and other metal structures has been described in section 2.14. This section describes the heat genaration model that determines the heat generation rate in the heat slabs representing the fuel rods.

The spacial power distribution in the core is assumed to be fixed and the heat generation rate in each heat slab node is calculated as the product of total power and the power distribution factor specified by the user. The transient of the power generation can be calculated in the code by solving a one-point kinetics equation or can be specified by the user as a function of time.

Using : the initial reactor power, Q_{T0} ; normalized power at time t, $(Q_T/Q_0)(t)$; and power distribution factor for node n, E_n, the heat generation rate for a slab node n is calculated as

$$Q_n = Q_{T0} \cdot \left(\frac{Q_T}{Q_{T0}}\right)(t) \cdot E_n, \tag{2.15.1}$$

The distribution factor E_n is determined from four input parameters as

$$E_n = \frac{1}{N_{Si}} \cdot E_{Si} \cdot E^i_{Rj} \cdot E^j_{Mn} , \tag{2.15.2}$$

where

E_n = power distribution factor for a node n of slab i,

N_{Si} = number of fuel rods that are represented by slab i,

E_{Si} = ratio of the total heat generation rate of fuel rods represented by slab i relative to the total reactor power, $(\Sigma E_{Si}=1)$,

E^i_{Rj} = ratio of the heat generation rate in region j to the heat generation in slab i, $(\Sigma E^i_{Rj}=1)$,

E^j_{Mn} = ratio of the heat generation rate in node n to the heat generation in region j, $(\Sigma E^j_{Mn}=1)$.

The power distribution factor in a material region E^{j}_{Mn} is calculated with the assumption of uniform heat generation rate in a material region as

$$E^{j}_{Mn} = \frac{V_n}{V_{Rj}} \ , \tag{2.15.3}$$

where

V_{Rj} = total volume of region j,

V_n = volume of node n.

Two options are provided for the calculation of the total reactor power at time t normalized to the initial power, $(Q_T/Q_{T0})(t)$. The options are :

(1) specification by the user as a table of time vs. normalized power,

(2) program solution of one-point kinetics equations with radioactive decay heat.

The reactor kinetics equations and the solution method for the equations are similar to those used in RELAP4[8] and IREKIN[23] . The kinetics equations used are

$$\frac{dn}{dt} = \frac{\beta}{\Lambda} \{R-1\} n + \sum_{i=1}^{6} \lambda_i C_i \ , \tag{2.15.4}$$

$$\frac{dC_i}{dt} = -\lambda_i C_i + \frac{\beta_i}{\Lambda} n, (i=1...6), \tag{2.15.5}$$

$$\beta = \sum_{i=1}^{6} \beta_i , \tag{2.15.6}$$

where

n = reactor fission power,

β = effective delayed neutron fraction,

Λ = neutron generation time,

R = total reactivity normalized to the delayed neutron fraction,

λ = decay constant of delayed neutron group i,

C_i = concentration of delayed neutron group i,

β_i = effective fraction for delayed neutron group i.

The delayed neutron constants used in the code are shown in Table 2.15.1. The value of the ratio Λ/β must be given by the user. The reactivity is obtained by next equation.

$$R(t) = R_s(t)+R_F(\overline{T}_F)+R_\alpha(\overline{\alpha})-R_s(0)-R_F(\overline{T}_{F0})-R_\alpha(\overline{\alpha}_0), \tag{2.15.7}$$

where

$R_s(t)$ = scram reactivity given by the user as a function of time t,

$R_F(\overline{T}_F)$ = fuel rod temperature feedback specified by the user as a function of average fuel rod temperature $\overline{T}_F$,

$R_\alpha(\overline{\alpha})$ = void feedback specified by the user as a function of average void fraction of the node that represent the inside of the core shroud, $\overline{\alpha}$,

The subscript 0 refers to the initial condition. The average fuel rod temperature $\overline{T}_F$ is the weighted arithmetic mean of the all heat slab nodes that represent the fuel rods. For this averaging, the user must specify the weighting factors in a manner similar to that for the power distribution factors.

The radioactive decay heat is calculated as the sum of decay heat of fission products and actinides. Since the half lives of actinides are long enough, the actinide decay heat is assumed to be constant during the transient. The fission product decay heat is approximated by eleven decay heat groups as is done in RELAP4. Through these assumptions the normalized power is calculated by

$$\frac{Q_T}{Q_{T0}}(t) = (1-E_d-E_{act})\frac{n(t)}{n(0)} + \sum_{j=1}^{11}E_{dj}X_{dj} + E_{act}, \tag{2.15.8}$$

where

E_{dj} = yield fraction of decay heat group j,

E_d = sum of E_{dj} (j=1...11),

E_{act} = contribution of actinide decay heat,

X_{dj} = concentration of decay heat group j normalized to the initial steady

state value.

The concentration X_{dj} is obtained by

$$\frac{dX_{dj}}{dt} = \lambda_{dj} \{-X_{dj} + \frac{n(t)}{n(0)} \} \quad , \tag{2.15.9}$$

where λ_{dj} = decay constant of decay heat group j.

Table 2.15.2 contains the constants used in above equations. The contribution of actinides is assumed to be 0.0032 at present.

Table 2.15.1 Delayed neutron constants

Group	β_i/β	λ_i (1/s)
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

(Reference (8))

Table 2.15.2 Radio active decay constants

Group	E_j	λ_j (1/s)
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}
6	0.00231	5.344×10^{-6}
6	0.00164	5.726×10^{-7}
6	0.00035	1.036×10^{-7}
6	0.00043	2.959×10^{-8}
6	0.00057	7.585×10^{-10}

(Reference (8))

2.16 Heat Transfer between Coolant and Heat Slabs

This subsection describes the heat transfer model that provide the boundary condition for the heat slab model described in section 2.14.

The heat transfer rates between the coolant and the metal surfaces are calculated with use of the heat transfer coefficient correlations similar to those used in THETA1-B[13] . Table 2.16.1 and Fig.2.16.1 shows the correlations and their selection logic. The critical heat flux is calculated by the correlations shown in Table 2.16.2.

Another option is provided to specify heat transfer coefficients to be used for wall surfaces above a mixture level. This option is described in section 2.17.

It has been stated in section 2.14 that one heat slab is allowed to have left and right heat transfer surfaces and each surface is allowed to face only one fluid node. The fluid condition parameters necessary for the use of the correlations, such as the fluid bulk temperature and pressure, are determined from the state variables of the fluid node to which the slab is facing.

For a homogeneous node, the mass flux G is calculated in terms of the node flow area and the node averaged flow rate defined by

$$W_n = \frac{1}{2} \Sigma W_i , \tag{2.16.1}$$

where ΣW_i is the sum of the flow rates of the junctions connected to the node.

In case of a three-region node, the heat transfer area of a slab may be divided into three parts by the subnode boundaries in the fluid node and the heat transfer calculation is performed separately for each subnode as illustrated in Fig.2.16.2.

The average flow rate in a subnode is defined with the consideration of the motion of the subnode boundaries as

$$W_{sn} = \Sigma \frac{F_{Zi}}{2} W_i + \frac{1}{2} A(Z_{top}) \rho \frac{\Delta Z_{top}}{\Delta t} + \frac{1}{2} A(Z_{bot}) \rho \frac{\Delta Z_{bot}}{\Delta t} , \tag{2.16.2}$$

where

W_{sn} = subnode average flow rate,

W_i = mass flow entering the subnode including the inter-subnode flows, $W_{l\to m}$ and W_{sep}, described in sections 2.3 and 2.4,

$A(Z_{top}), A(Z_{bot})$ = flow area at top and bottom of subnode,

$\Delta Z_{top}, \Delta Z_{bot}$ = increment of boundary elevation within a time step,

ρ = fluid density of a subnode.

The coefficient F_{Zi} is -1 if W_i is entering the node through the upper boundary and $+1$ if W_i is entering the node through the lower boundary. If W_i is entering through a junction located at a intermediate elevation between the two boundaries, F_i is calculated by the interpolation between $+1$ and -1 in terms of the elevations of the junction between the two subnode boundaries.

The mass flux G is obtained from W_{sn} by the use of the flow area given by the user as a function of elevation above the bottom of the node. Flow area at the top of the subnode is used for this calculation.

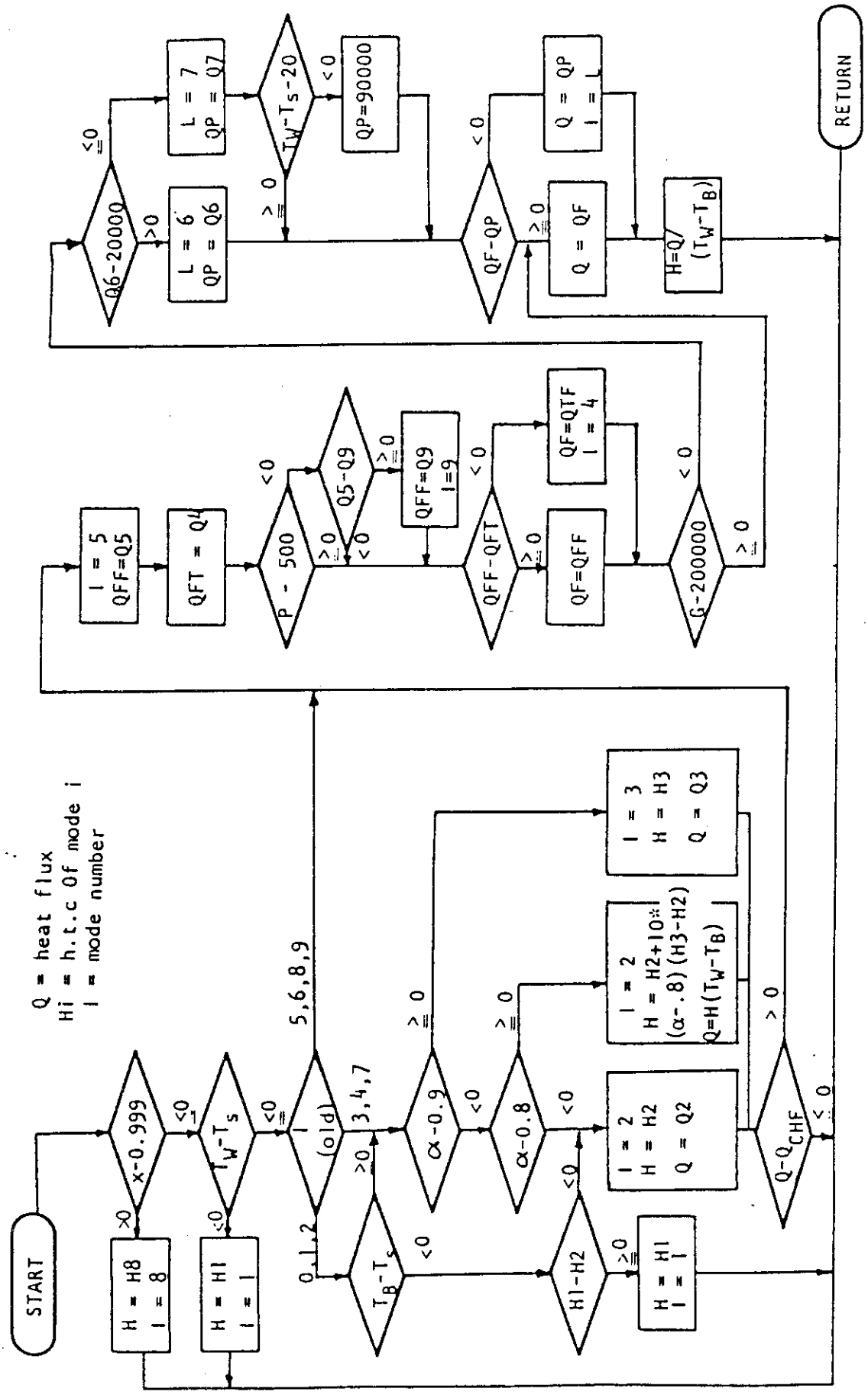
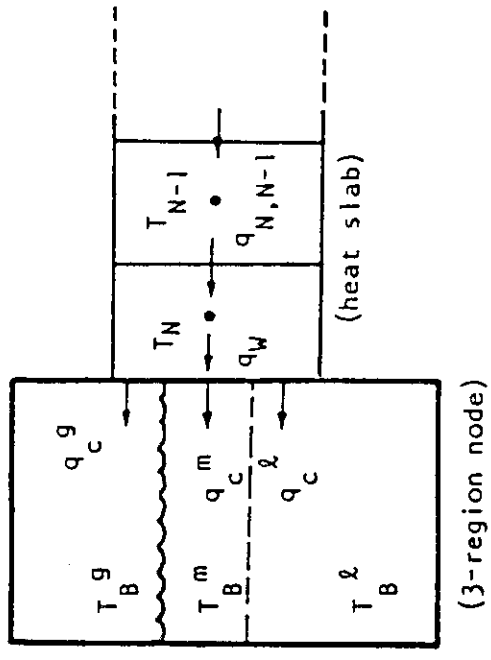


Fig. 2.16.1 Selection Logic of Heat Transfer Correlations in THYDE-B1



$$q_c^x = A^x \cdot H^x \cdot (T_N - T_B^x)$$

$$(x = g, m, \ell)$$

$$q_W = q_c^g + q_c^m + q_c^\ell$$

Fig. 2.16.2 Boundary Condition for a Heat Slab Facing a Three-Region Node

Table 2.16.1 Heat Transfer Correlations

Mode 1 (Forced Convection in Subcooled Liquid)
Dittus and Boelter[24]

$$h = 0.023 \left(\frac{k_f}{D_e}\right)(P_{rf})^{0.4}\left(\frac{GD_e}{\mu_f}\right)^{0.8}, \text{evaluated at } T_B$$

Mode 2 (Nucleate Boiling)
Thom [25]

$$q = \left(\frac{\Delta T_{sat} e^{(P/1260)}}{0.072}\right)^2$$

Mode 3 (Forced Convection Vaporization)
Schrock and Grossman [26]

$$h = (2.5)(0.023)\left(\frac{k_f}{D_e}\right)(P_{rf})^{0.4}\left[\frac{GD_e(1-x)}{\mu_f}\right]^{0.8}\left(\frac{1}{X_{tt}}\right)^{0.75}$$

evaluated at T_B, where

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

Mode 4 (Transition Boiling)
Mcdonough, Milich, and King [27]

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

Table 2.16.1 (Continued)

where $C(P)$ is dependent on pressure as follows

P	$C(P)$
2000	979.2
1200	1180.8
800	1501.2

Mode 5 (Stable Film Boiling) Groeneveld [28]

$$h = A\left(\frac{k_g}{D_e}\right)(P_{rv,w})^C\left[\frac{GD_e}{\mu_g}\left(x+\frac{\rho_g}{\rho_f}(1-x)\right)\right]^B Y^D$$

where

$$Y = 1.0 - 0.1(1-x)^{0.4}\left(\frac{\rho_f}{\rho_g} - 1\right)^{0.4} \quad \text{or} \quad 0.1 \text{ whichever is greater and}$$

A = 0.052, B = 0.688, C = 1.26, D = -1.06 (Groeneveld's equation 5.7)
Both k_g and μ_g are evaluated at T_B, and P_r is evaluated at T_w.

Mode 6 (Pool Film Boiling)
Berenson [29]

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

where

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

Table 2.16.1 (Continued)

Above equation is approximated in the coding by

$$q = F(P)(\Delta T_{sat})^{3/4}$$

where F(P) is dependent on pressure as follows:

P	F(P) (Btu/ft^2 hr°F$^{0.75}$)
15	128
100	236
500	412
1000	510
1500	615
2000	705

If $q < 20000$ Btu/ft^{2}hr in the Mode 6 equation, then the Mode 7 equation is evaluated and larger value of q will be adopted.

Mode 7 (Transition Pool Boiling)

$$q = 20000\left(\frac{\Delta T_{min}}{\Delta T_{sat}}\right)\frac{1.504}{ln(\Delta T_{min}/20)}$$

where

$$\Delta T_{min} = \left(\frac{20000}{F(P)}\right)^{4/3}$$

If $\Delta T_{sat} < 20$, then q for Mode 7 is set equal to 90000 Btu/ft^{2}hr in the program.

Table 2.16.1 (Continued)

Mode 8 (Forced Convection in Vapor)
Dittus and Boelter[24]

$$h = 0.023 \left(\frac{k_g}{D_e}\right)(P_{rg})^{0.4}\left(\frac{GD_e}{\mu_g}\right)^{0.8},$$

evaluated at T_B.

Mode 9 (Low pressure Flow Film Boiling)
Dougall and Rohsenow [30]

$$h = 0.023 \left(\frac{k_g}{D_e}\right)(P_{rg})^{0.4}\left[\left(\frac{GD_e}{g}\right)\left(\frac{Q_g+Q_f}{A_{flow}}\right)\right]^{0.8}$$

The equation is approximated in the coding by

$$h = 0.023 \left(\frac{k_g}{D_e}\right)(P_{rg})^{0.4}\left[\left(\frac{GD_e}{\mu_g}\right)\left(X + \frac{\rho_g}{\rho_f}(1-x)\right)\right]^{0.8}$$

evaluated at T_{sat} .

Quantities and their units used in this table and Table 2.16.2 are listed below.

h = heat transfer coefficient, Btu/ft^2 hr°F
k = thermal conductivity, Btu/ft hr °F
De = equivalent diameter, ft
P_r = Prandle number, $c_p u/k$
R_e = Reynolds number, GD_e/μ
G = mass flux, lb$_m$/ft^2 hr
G' = G/10^6
μ = viscosity, lb$_m$/ft hr
c_p = specific heat, Btu/lb$_m$°F
T_B = bulk coolant temperature, °F
T_{sat} = saturation temperature, °F

Table 2.16.1 (Continued)

T_w = wall temperature, °F

ΔT_{sat} = $T_w - T_{sat}$, °F

D = diameter, ft

q = heat flux, Btu/ft^2 hr

P = pressure, psia

x = quality

ρ = density, lb_m/ft^3

H = saturated liquid enthalpy, Btu/lb

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

H_{in} = inlet enthalpy, Btu/lb

L = channel length, in

D_{HE} = heated equivalent diameter
(= 4(flow area)/(heated perimeter)), in.

D_{HY} = $\sqrt{D_r (D_r + D_{HE})} - D_r$ where D_r = rod diameter, in.

g = gravitational acceleration, ft/s^2

g_c = gravitational conversion factor, ft lb_m/lb_f s^2

σ = surface tension, lb_f/ft

Q = volumetric flow rate, ft^3/s

A_{flow} = flow area, ft^2

and subscripts

f = saturated liquid conditions

g = saturated vapor conditions

v = superheated vapor conditions

w = wall.

Table 2.16.2 Critical Heat Flux Correlations

(See Table 2.16.1 for nomenclature.)

The critical heat flux is obtained by:

P > 1500	B&W-2
1500 > P > 1300	Interpolation between B&W-2 and Barnet
1300 > P > 1000	Barnett
1000 > P > 725	Interpolation between Barnett and Modified Barnett
725 > P	Modified Barnet

using following correlations.

Babcock and Wilcox Company, B&W-2 [31]

$$q_{CHF} = \frac{1.15509-0.40703(12De)}{12.71 \times (3.0545G')^{A}} \left[(0.3702\times10^{8})(0.59137G')^{B}-0.15208H_{fg}G \right]$$

where $A = 0.71186+(2.0729 \times 10^{-4})(P-2000)$

$B = 0.834+(6.8479 \times 10^{-4})(P-2000)$

Barnet [32]

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

where $A = 67.45\ D_{HE}^{0.68} G'^{0.192}\ (1.0 - 0.744\ exp(-6.512 D_{HY} G'))$

$B = 0.2587\ D_{HE}^{1.261}\ G'^{0.817}$

$C = 185.0\ D_{HY}^{1.415}\ G'^{0.212}$

Modified Barnet [33]

$$q_{CHF} = 10^{6} \left\{ \frac{A+B(H_f-Hin)}{C+L} \right\}$$

where

$A = 73.71 D_{HE}^{0.052} G'^{0.663}\ (1.0 - 0.315\ exp(-11.34 D_{HY} G'))888.6/H_{fg}$

$B = 0.104\ D_{HE}^{1.445}\ G'^{0.691}$

$C = 45.55\ D_{HY}^{0.0817}\ G'^{0.5866}$

2.17 Steam Cooling and Core Spray Cooling

The standard method for determining heat transfer coefficients have been described in section 2.16. Since THYDE-B1 ignores superheating of steam in the steam region of a three-region node, the use of a heat transfer coefficient determined from a correlation based on forced covection mode, i.e., the Dittus-Boelter correlation, may give greater heat transfer rate than actual situation. In addition, there are no special correlation for spray cooling in the standard method (Table 2.16.1).

Considering above limitations, an optional method was introduced. In this option, the user is allowed to specify, for each slab, a heat transfer coefficient to be used when the slab is exposed to steam or is cooled by a core spray. The heat transfer coefficient is given as a function of spray flow rate and pressure. The user must specify this function in the form of two dimensional table. The values for zero spray flow rate corresponds to the coefficients for the steam flow cooling.

It should be noted that this model is a phenomenological one, and is not based on firm understanding on phenomena that may actually occur under a spray cooling condition. Due to the lack of sufficiently mechanistic understanding, it is not clear whether this type of correlation is appropriate, or not. This option, however, is expected to be useful because it allows sensitivity studies and a direct application of the experimentally determined values.

On the other hand, it has been reported by Gururaj et.al. [35] that the General Electric Company uses, in the SAFE code[12], the value of 12 Btu/ft^2 hr °F as a core spray heat transfer coefficient in its Small-Break LOCA Analysis Method and the value of 4 Btu/ft^2 hr °F for licensing calculations. The former value may be appropriate for the purpose of evaluating the overall system behaviors such as the transient of system pressure. It should be noted, however, that above values are not to be used for the evaluation of the peak cladding temperature (PCT).

If an estimation of PCT is required, smaller heat transfer coefficients should be used. For instance, the values that are usually used in a core heatup calculation performed for obtaining PCT in a licensing procedure are 3.0, 3.5, 1.5, and 1.5 Btu/ft^2 hr °F for fuel rods in the outer corners, outer row, next to outer row, and to those remaining in the interior, respectively, of the assembly [36]. These values were determined from the BWR-FLECHT experiments with consideration of the effect of radiative heat transfer[34]. Since THYDE-B1 ignores the radiative heat transfer, the use of these values should yield cladding temperatures higher than actually observed.

3. Calculation Flow and Numerical Method

The calculation sequence of THYDE-B1 is illustrated in Fig.3.1.1. As shown in the figure, the whole calculation is divided into two parts , the establishment of steady state condition and the transient calculation. Outlines of each part are as follows.

The initialization stage includes following processes.

1) Input of steam table data
2) Input of problem specification data
3) Initialization of state variables of nodes and junctions
   Node variables such as fluid density, void fraction, quality, etc., are determined from pressure and enthalpy(or temperature) given by the user.
4) Initialization of temperatures of heat slabs
   The initial temperatures of the heat slab nodes are calculated by the code assuming the steady state temperature distribution in slabs.

The transient calculation is performed by applying a simple forward explicit integration method to the ordinary differential equations described in chapter 2. The time step size must be specified by the user.

4. Code Organization

4.1 Program Control

The program execution can be controlled by the following ways.

(1) Termination of Calculation

There are three ways of specification for the program termination.

i) Specification of available CPU time

The available CPU time in second can be given with use of the CPU limit card which is read from FORTRAN Unit 3 (see section 5.1). The program is terminated before this time is exceeded.

ii) Specification of end time with trip control card

The calculation is terminated when the calculated state variables of the

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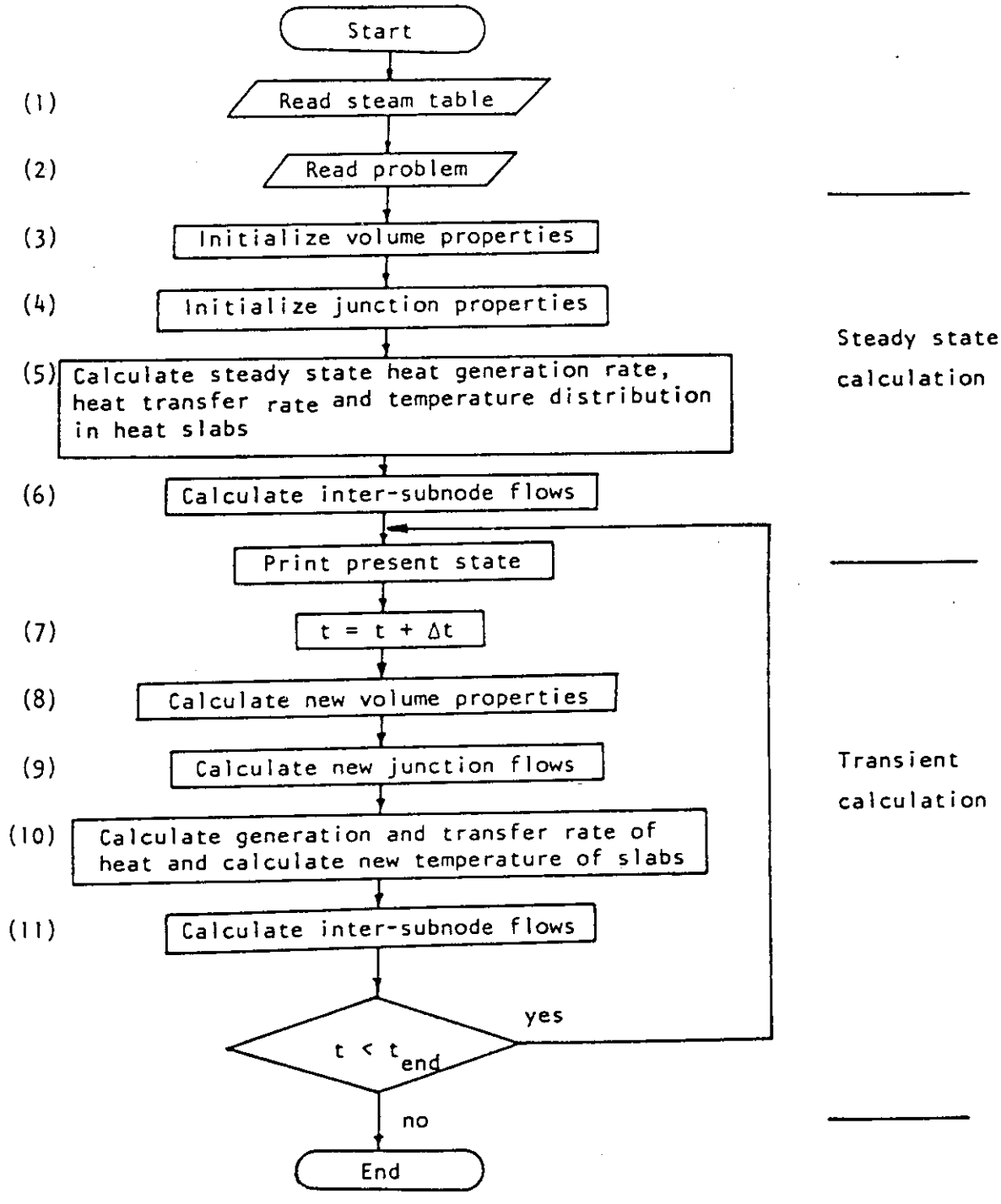

Fig. 3.1.1 Outline of THYDE-B1 Calculation Flow

system reach a given condition specified with the trip control cards (see sections 2.13 and 5.3).

iii) Specification of end time in time step control card

The calculation will be terminated when the physical time exceeds the end time of the last time step control card (see section 5.3).

(2) Trip Control Options

The trips related to the junctions such as valve actions, pump trips, leak initiations, and fill initiations, can be controlled with use of trip control cards(see sections 2.13 and 5.3).

The reator scram should be considered if the user specifies the reactor power to be calculated by the code. The time dependent reactivity cards (see sections 2.15 and 5.3) can be used to simulate the scram action.

4.2 Restart and Dump Options

The restart and dump options are provided for the user's convenience. The dump option is to store all the variables necessary for the continuation of the calculation on an external data storage. Data dump is executed with the time interval specified by the user with the time step control cards. This function is also executed when the program is terminated due to the CPU limit given by the user(see section 4.1(1)).

The restart option is to initiate the calculation using the dumped results. The required data storage is described in section 5.1 and the required input cards for restart calculation are described in paragraph (2) of section 5.3.

4.3 Editing and Plotting

The variables calculated by the code can be plotted by the use of SPLPLOT-1 program. The data editing for this purpose is done at the user's option. The user can request this data editing by the use of Restart Control Card and Time Step Control Card described in section 5.3. The edited variables are fixed but, if necessary, the user can easily add any variable by a small modification of the subroutine SPLEDT in the FORTRAN source of THYDE-B1.

The identification names of the variables and their short descriptions (used as graph captions) will be written at the top of the plot data tape and can be listed by the SPLPLOT-1 program.

5. Input Data Requirements

5.1 Required Resources and Auxiliary Program

The THYDE-B1 code is written in FORTRAN-IV to be used on the FACOM M-200 computer system. The required core memory is about 980 kilo-bytes. The CPU time requirement depends proportionally on the number of time steps. An approximate value of the CPU requirement is about 6 ms/volume.step .

The calculated results can be plotted by a X-Y plotter, COM or other graphics terminal with use of the SPLPLOT-1 program[7] .

THYDE-B1 uses several units of external memory devices such as magnetic tapes or disks. Requirements for these data storage is summarised in Table 5.1.1.

In this table the FORTRAN Unit 1 and 2 are temporary data storages. The Unit 2 is needed only when the plot data editing is required and this unit must be of direct-access type.

The CPU limit card (FORTRAN Unit 3) is used for restart data dump (see section 4.1). By this card , the code recognizes the CPU time available for the job and executes the restart data dump before the calculation is terminated by the operating system of the computer due to excess time. The data to be punched in this card is only the CPU time limit in second and the card format is E10.0.

The FORTRAN Unit 5 is the card reader, for which the data requirements are specified in section 5.3.

The FORTRAN Unit 8 must be assigned to the steam table data set. This table is the same as that for RELAP4[8] .

The FORTRAN Unit 31 and 41 are the data storage for restart data and plot data, respectively. The Units 30 and 40 are neccesary only for a restart calculation. These units must be assigned to the data sets that have been generated in the preceding run as Units 31 or 41. The contents of Unit 40 will be copied in the head of Unit 41 before the extended results are added. Therefore only one data set must be kept for plotting.

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Table 5.1.1 Required Data Files for a THYDE-B1 Calculation

FORTRAN Logical Unit	Description	Required space
1	temporary data storage	5 kwords(*)
2	temporary data storage	200 kwords
3	cpu limit card	1 card
5	input card deck	300 cards (*)
6	line printer	300 lines/edit (*)
8	steam table data set	17 kwords
30	input data set for restart (result of preceding run)	25 kwords/dump (*)
31	output data set for restart	25 kwords/dump (*)
40	input data set for plot (result of preceding run)	0.7 kwords/edit (*)
41	output data for plot	0.7 kwords/edit (*)

(*) indicates approximate values.

5.2 Free Format Data Input Subroutine REAG

All input data are read into THYDE-B1 via a generalized subroutine REAG which is briefly described in the following. Subroutine REAG for FACOM M-200 converts BCD information to integer or floating point binary information; three convergion types, i.e., types of reading $4*N_1$ characters, N_2 integers, and N_3 floating point numbers, respectively, are allowed by corresponding subroutines.

To explain how to arrange the data, a typical example of the function of this subroutine is shown below. Suppose the following three punched cards:

```
105, 318, -14, 1.5E-3, 3.12E-3/THIS IS A COMMENT,
2(1.0, 1.5), 3(0)/,
1.0, 5*0.1, 2*-0.2/.
```

The subroutine will convert BCD number 105 and 318 to their binary integer equivalents. In a similar fashion -14 will be converted to a negative binary integer and 1.5E-3 will be converted to floating point binary (0.0015). Data punched on a card may be delimited by blank column or comma. The slash (/) indicates the end of the BCD field to be converted. If no slash is present 72 columns of the first card are scanned and scanning the columns of following cards continues so far as to satisfy the number of required data.

The second card indicates that the data words 1.0 and 1.5 in the first parentheses and 0 in the second are repeated twice a three times, respectively and therefore it is equivalent with a card punched as

```
1.0, 1.5, 1.0, 1.5, 0, 0, 0/.
```

The last card indicates that the first word is 1.0, the second word 0.1 is successively accumulated to the previous word five times and the last word -0.2, twice. Therefore it is equivalent with a card punched as

```
1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.3, 1.1/.
```

JAERI-M 4458, "A Subroutine Reading Data in Free Format[37]" should be referred to for more detailed information.

A slash (/) and an aster sign (*) appearing in the first and second column respectively identify the card as a comment card. Any information on the remainder of the card, including blank columns are treated as comments. Comment cards may be placed anywhere in the input deck.

5.3 Data Card Summary

A data deck for a run consists of following card blocks and each block has a block number for identification in the program. Block numbers with an asterisque (*) indicate that those blocks were changed from or added to the original version of THYDE-B1.

Block Title	Block Number
(1) Title Card	(does not have a number)
(2) Restart Control Card	000
(3) Problem Dimension Card	001
(4) Time Step and Edit Control Card	003
(5) Volume Data Cards	004
(6) Junction Data Cards	005*
(7) Jet Pump Data Cards	006
(8) Jet Pump Geometry Data Cards	007
(9) Recirculation Pump Data Cards	008*
(10) Main Steam Line Data Cards	009
(11) Leak Data Cards	010*
(12) Fill System Data Cards	011
HPCI Data Cards	012
LPCI Data Cards	013
(13) Core Spray Data Cards	014
(14) Steam Separator Data Cards	015
(15) Trip Control Data Cards	016
(16) Heat Slab Dimension Cards	017
(17) Heat Slab Data Cards	018*
(18) Core Heat Generation Data Cards	019
(19) Slab Geometry Data Cards	020
(20) Material Property Data Cards	021
(21) Other Heat Slab Data Cards	022
(22) Critical Flow Model Selection Cards	051*
(23) Pump Motor Torque Table Data Cards	053*
(24) Pump Characteristic Data Cards	054*
(25) Core spray and Steam Coolig Heat Transfer Data Cards	055*
(26) End-of-Data Sign	999

In the following description of each block, the descriptive title is given at first. Then the description of composing cards will follow. In each card description, order of the data entry in the card (W1,W2,...), the format (I,R, or A), the variable name, and the input data requirement are given where applicable. The format of the variable, integer, real or floating, or alphanumeric, is indicated by I, R, or A respectively. The variable names are, in principle, the same as those used in the program.

Each card block must begin with a number card, in which the block identification number must be punched. The respective data cards must be punched from the second card.

The order of the cards and blocks must be in accord with following description. But any block may be omitted if not necessary.

(1) Title Card

The character string punched in the first column through 72nd of the first card is used as a calculation title. This title will be printed in each page of the output list. It can, also, be used as the calculation title in the data plotting by the SPLPLOT-1 program (Appendix A). Number card for this block is not required.

As for a restart calculation, the title must be the same as the preceding calculation.

(2) Restart Control Card (000)

Card 1

W1-I NREST = Restart control
= 0, not restart
> 0, restart with the NREST'th restart information on FORTRAN Unit 30.

W2-I IDUMP = Restart data dump control.
= 0, generate no data set for restart
= 1, store restart information on FORTRAN Unit 31.

W3-I X = Dummy variable. Set X=1.

W4-I ISPL = Plot data edit control
= 0, generate no plot information data set
= 1, store plot information on FORTRAN Unit 41
= 2, for a restart calculation, make a copy of the results of preceding run from FORTRAN Unit 40 to Unit 41, and extend

Unit 41 with new results.

As for a restart calculation, the required card blocks are only the title card, restart control card (000), problem dimension card (001), time step control card (003), and end-of-data sign (999). Other cards are not allowed to be entered.

(3) Problem Dimension Card (001)

Card 1

W1-I NVOL = Number of nodes
W2-I NJUN = Number of junctions of all types
W3-I NPUMP = Number of pump data sets
W4-I NJETGP = Number of jet pump geometry data sets
W5-I NJETP = Number of jet pump junctions
W6-I NSTRM = Number of main steam line junctions
W7-I NLEAK = Number of leak junctions
W8-I NFILL = Number of fill junctions
W9-I NHPCI = Number of HPCI junctions
Model for HPCI, LPCI and core spray are completely the same as that for the fill junctions at present. Therefore the fill junction model should be used. Set NHPCI=NLPCI=NCSP=0.
W10-I NLPCI = Number of LPCI junctions
W11-I NCSP = Number of core spray junctions
W12-I NTRIP = Number of trip control cards
W13-I NSEP = Number of steam separator junctions (slip junctions)
NSEP must be less than or equal to 1.
W14-I NTMAX = Number of time step control cards.

(4) Time Step Control Data Cards (003)

NTMAX data sets are required. Each set consists of one card containing following data.

Card 1

W1-I NTIM1 = Number of time steps per restart data dump.
W2-I NTIM2 = Number of time steps per printer output.
W3-I NTIM3 = Number of time steps per plot data edit.
W4-R DELT = Time step size.

W5-R TMAX = End of current time step data. The calculation will be terminated when time exceeds TMAX in the last time step card.

(5) Volume Data Cards (004)

NVOL data sets are required. The sequence number of data entry will be used as a node index (identification number).

Card 1

W1-I IHOMO = Type of the node.
1 = homogeneous node
2 = theree region node

Card 2

W1-R PRESS = Initial pressure (kg_f/m^2).
W2-R ZMAX = Height of the node measured from node bottom (m).
W3-R ZELEV = Elevation of the node bottom above a reference level (m).
W4-R ZPRES = Elevation of the representative point of node pressure above node bottom (m).
W5-R VMAX = Volume of node (m^3).

Card 3 (for homogeneous nodes only)

This card is required only for homegeneous nodes (IHOMO=1).

W1-R X = Void fraction or specific enthalpy.
If $0 \leq X \leq 1$, void fraction ALPHA will be set equal to X and enthalpy will be calculated from ALPHA and PRESS. If $X \geq 1$, enthalpy ENTH(kcal/kg) will be set equal to X and void fraction will be calculated.
W2-R AREA = Flow area for calculation of the average mass flux in a node (m^2).

Card 4 (for three-region nodes)

W1-R ENTN(1) = Specific enthalpy of the subcooled liquid region (kcal/kg). If ENTN(1) $\leq$ 0, -ENTN(1) will be regarded as temperature (°C) and specific enthalpy will be calculated from this input.
W2-R ALPHA(2)= Void fraction of the saturated mixture region.

Card 5 (for three-region nodes)

W1-R ZLEV(1) = Elevation of the top of subcooled liquid region (Z_{ml})

measured from the bottom of the node (m).

W2-R ZLEV(2) = Elevation of the top of mixture region (Z_{gm}) measured from the bottom of the node (m).

Card 6 (for three region nodes)

W1-R CAS = Coefficient for bubble separation model.
If CAS > 0, Model 1 described in subsection 5.2.3 will be used. CAS will be used as C_α in Eq.(2.3.2). C_α is dimensionless.
If CAS < 0, Model 2 will be applied and X_{L0} (m) in Eq.(2.3.7) will be set equal to |CAS|.
If the node is representing the inside of the shroud, X_{L0} can be calculated in the code assuming steady state energy balance for the node. This option can be used by setting CAS=0.

W2-R CLM = Coefficient $C_{l\to m}$ used in the local temperature rize model. The model and recommended values are given in section 2.4

W3-R HP1 = Elevation of lower sensor location for liquid level signal calculation (m).

W4-R HP2 = Elevation of upper sensor location. (m)
HP1 and HP2 are used as Z_1 and Z_2 in Eq.(2.13.1). They are elevations measured from the bottom of the node.

Volume geometry data cards for a three-region node

Card 7

W1-I NTBV = Number of data points in the elevation versus volume table.

Card 8 (Elevation versus volume table)

This table is used for mixture level calculation described in section 2.3.

W1-R TABVOL(1) = Elevation above bottom of the node for first point (m).

W2-R TABVOL(2) = Volume integrated from bottom of the node to TABVOL(1) (m^3).

W3-R TABVOL(3) = Elevation for second point.

.... , until NTBV points are entered.

Card 9

W1-I NTBA = Number of data points in the elevation versus flow area

table.

Card 10 (Elevation versus area table)

This table is used for two purposes. It is used for the determination of average mass flux for each subnode in heat transfer calculation described in section 2.16. It is also used for the determination of flow area at mixture surface in the calcualtion of bubble separation rate as described in section 2.3 (only for Model 1).

W1-R TABA(1) = Elevation above bottom of the node for first point (m).
W2-R TABA(2) = Flow area for first point (m^2).
W3-R TABA(3) = Elevation for second point.
... ... , until NTBA points are entered.

Card 11

W1-I NTBHD = Number of data points in the elevation versus hydraulic diameter table.

Card 12 (Elevation versus hydraulic diameter table)

This table is used for determination of hydraulic diameter to be used in the bubble velosity calculation described in section 2.3.

W1-R TABHD(1) = Elevation above bottom of the node (m) for first point.
W2-R TABHD(2) = Hydraulic diameter for first point (m).
W3-R TABHD(3) = Elevation for second point.
... ... , until NTBA points are entered.

(6) Junction Data Cards (006)

NJUN sets of data are required.Junctions will be numbered according to the sequence of data entry.

Card 1

W1-I NIN = Inlet node index (node identification number) or junction type index for junctins which have no inlet node.
NIN > 0, Node index.
= 0, Jet pump throat flow.
= -1, Fill junction.
= -2, HPCI junction.
= -3, LPCI junction.
= -4, Core spray junction.

W2-I NOUT = Outlet node index(node identification number) or junction type index for junctions which have no outlet node.
NIN > 0, Node index.
= 0, Drive or suction flow of a jet pump.
= −1, Leak junction.
= −2, Main steam line junction.

W3-I IPUMP = Pump index (IPUMP ≦ NPUMP)
If this junction is a steam separator junction, set IPUMP=−1.
When NIN< 0 or NOUT < 0, the junction concerned has no pump and this index is used as a data identification index of following types.
(NIN=−1) FILL index (IPUMP ≦ NFILL)
(NIN=−2) HPCI index (IPUMP ≦ NHPCI)
(NIN=−3) LPCI index (IPUMP ≦ NLPCI)
(NIN=−4) Core spray index (IPUMP ≦ NCSP)
(NOUT=−1) Leak index (IPUMP ≦ NLEAK)
(NOUT=−2) Main steam line index (IPUMP ≦ NSTRM)

W4-I ICOKTP* = Option number of critical flow data set.
Critical flow data set is described in paragrph (22).

W5-I IVALVE |IVALVE| = Valve index
If valve is initially closed, IVALVE < 0.
If valve is initially open, IVALVE > 0.
If the junction has no valve, IVALVE =0.
Closing or opening of valves can be controlled by Trip Control Cards. The valve index given here will be used for identification of valves.

W6-R WIJ = Initial flow rate (kg/s).

W7-R ZIN = Elevation of the junction above the bottom of node NIN (m).
(If NIN > 0, 0 ≦ ZIN ≦ ZMAX)

W8-R ZOUT = Elevation of the junction above the bottom of node NOUT (m).
(If NOUT > 0, 0 ≦ ZOUT ≦ ZMAX)

W9-R AJUNC = Minimum flow area for choked flow calculation (m^2).
If AJUNC = 0., choking will be ignored.

W10-R INERTA = Inertia of junction (1/m).

W11-R RJUNC = Loss coefficient for normal flow direction ($s^2 kg_f / m^5 kg$).
This value will be used as R_0 in Eq.(2.6.1). If RJUNC=0, R_0 will be calculated using Eq.(2.6.2).

W12-R RNJUNC = Loss coefficient for reverse flow ($s^2 kg_f / m^5 kg$).

If RNJUNC=0, RJUNC will be used for reverse flow conditions.

W13-R DIAMJ* = Junction diameter used for smoothing of enthalpy change (m).

(7) Jet Pump Data Cards

NJETP sets of data are required.

Card 1

W1-I JMOPT = Jet pump model option (see section 2.8).
1 = Model 1 (Momentum flux terms are considered through out the transient.)
2 = Model 2 (Momentum flux terms will be considered until water level in the downcomer drops to the level 0.1 m above the top of a jet pump.

W2-I IJPUMP = Jet pump geometry data set index.

W3-I JETGRP(1) = Suction flow junction index.

W4-I JETGRP(2) = Drive flow junction index.

W5-I JETGRP(3) = Discharge flow junction index.

W6-R PIN = Outlet pressure of the suction flow (kg/m^2).
This value will be used as the initial value of P_1 in section 2.8.

(8) Jet Pump Geometry Data Cards (007)

NJETP sets of data are required.

Card 1

W1-R AS = Suction inlt flow area (m^2).

W2-R AD = Drive nozzle flow area (m^2).

W3-R AJ = Throat flow area. (m^2)
AJ should be determined so that AJ=AS+AD

W4-R ADIF = Diffuser outlet flow area (m^2).
ADIF is not used in the present version. Set ADIF=1.

W5-R DL1 = Flow path length of mixing section (m).

W6-R DL2 = Flow path length of diffuser section (m).

W7-R DL3 = Flow path length of diffuser outlet to lower plenum (m).
DL1, DL2, and DL3 are used as L_1, L_2 and L_3 for the gravitational head calculation (Eq.(2.8.35)).

W8-R AJS = Downcomer flow area. (m^2)

W9-R AJD = Jet pump drive line flow area. (m^2)

W10-R AJJ = Lower plenum flow area. (m^2)

Since THYDE-B1 ignores the momentum flux terms for junctions other than jet pump junctions, the authors recommend that AJS, AJD, and AJJ be set sufficiently large numbers (for instance, $10^{10} m^2$) in order to keep the ΔP_m terms reversible. The use of the large values is equivalent to the neglection of the momentum flux terms for dowcomer, recirculation lines, and lower plenum.

(9) Pump Data Cards (008)*

NPUMP data sets are required.

Card 1

W1-I IPC = Index of pump characteristic data. $0 \leq IPC \leq NPCVHO$.

W2-I IRP = Reverse flow option.

0 = Pump head ΔP_p will be set equal to zero for reverse flow conditions.

1 = Pump head will be calculated for both normal and reverse flow conditions.

W3-I IPM = Two phase flow option.

0 = Use single-phase pump data only.

> 0, Use two-phase degradation data. IPM is used as two-phase pump data index. $0 \leq IPM \leq NPCVTW$.

W4-I IMT = Index of pump motor torque data.

If IMT=0, the pump speed will be kept constant until the pump has been tripped.

W5-R ROMEGA = Rated pump speed (rad/s).

W6-R PSRAT = Ratio of initial pump speed and rated pump speed.

W7-R RFLOW = Rated flow rate (m^3).

W8-R RHEAD = Rated head ((kg_f/m^2)/(kg/m^3)).

W9-R RTORQ = Rated torque (kg_f m).

W10-R INERTA = Moment of inertia (kg m^2).

W11-R RRHOP = Rated fluid density (kg/m^3).

W12-R RTORQM = Rated motor torque (kg_f m).

W13-R CAVCON = Not used at present. Set CAVCON=0.

W14-R TORQF(1)= Constant for frictional torque calculation (kg_f m).

W15-R TORQF(2)= Constant for frictional torque calculation (kg_f m).

W16-R TORQF(3)= Constant for frictional torque calculation (kg_f m).

W17-R TORQF(4)= Constant for frictional torque calculation (kg_f m).

(10) Main Steam Line Data Cards (009)

NSTRM data sets are required.

Card 1

W1-R TAU = Time constant of isolation valve closure (s).

W2-R TIMTR = Delay time for initiation of isolation valve closure (s).
Delay time can also be considered by the trip control model.
In such cases TIMTR can be 0.

W3-R WSTRM = Maximum steam flow rate (kg/s).

W4-R GS = Controller regulation band (kg_f/m^2).

W5-R WSR = Rated steam flow rate (kg/s).

W6-R DPR = Rated pressure drop between reactor vessel and turbine admission valves (kg_f/m^2).

W7-R PR = Rated pressure in reactor vessel (kg_f/m^2).

(11) Leak Data Cards (010)*

NLEAK data sets are required.

Card 1

W1-I ICHOKE = Leak type. ICHOKE $\leq$ 0.
-3 = use time versus flow rate table.
-2 = use pressure versus mass flux table.
-1 = use pressure versus flow rate table.
0 = use critical flow model selected by ICOKTP in Junction Data Cards.

W2-R SINKPR = Sink pressure (kg_f/m^2).

Card 2

W1-I NFAT = Number of data points in leak data table.

Card 3

Leak data table.

W1-R TABFA(1)= Independent variable or first point.
If ICHOKE=-3 or > 0, elapsed time after leak initiation (s).
If ICHOKE=-2 or -1, pressure (kg_f/m^2).

W2-R TABFA(2)= Dependent variable for first point.
If ICHOKE=-3, flow rate (kg/s).
If ICHOKE=-3, flow rate (kg/s).

If ICHOKE=-2, mass flux ($kg/m^2 s$).
If ICHOKE=-1, flow rate (kg/s).
If ICHOKE=0, leak area normalized to AJUNC given in Junction Data Cards.

W3-R TABFA(3)= Independent variable for second point.
... ... , until NFAT points are entered.

(12) Fill Systems Data Card (011) and HPCI/LPCI Data Cards (012/013)

NFILL (or NHPCI/NLPCI) data sets are required.

As for HPCI and LPCI systems the calculation models are the same as that for fill systems, and required input data are also the same. Data block numbers are 012 and 013, respectively. Each block must contain NHPCI or NLPCI data set.

Card 1

W1-R CGL = Mixing length for steam region. (m)
W2-R CML = Mixing length for mixture region. (m)
W3-R FEG = Mixing coefficient for steam region. (m)
W4-R FEM = Mixing coefficient for mixture region. (m)

Card 2

W1-I NT = Number of data points in the table of reservoir temperature or enthalpy.
If NT = 0, temperature or enthalpy is constant.
If NT < 0, temperature or enthalpy is dependent on elapsed time after fill system actuation.
If NT > 0, temperature or enthalpy is dependent on the pressure of outlet node.

Card 3

Table of enthalpy or temperature

W1-R TABLT(1)= Time(s) or pressure(kg_f/m^2) for first point.
In case of NT=0, temperature or enthalpy must be entered.
W2-R TABLT(2)= temperature (°C) (TABLT(j)=-(temperature)) or enthalpy (kcal/kg) (TABLT(j)=enthalpy) for first point.
W3-R TABLT(3)= Time or pressure for second point.
... ... , until NT points are entered, where the independent variable must be in ascending order.

Card 4

W1-I NW = Number of data points in flow rate table.
If NW=0, flow rate is constant.
If NW>0, flow rate depends on pressure of outlet node.
If NW<0, flow rate depends on elapsed time after fill system initiation.

Card 5

Table of flow rate

W1-R TABLW(1)= time (s) or pressure (kg_f/m^2) for first point.
In case of NW=0, flow rate (kg/s) must be entered.
W2-R TABLW(2)= flow rate (kg/s) for first point.
W3-R TABLW(3)= time or pressure for second point.
... . , until |NW| pairs are entered, where the independent variable must be in ascending order.

(13) Core Spray Data Cards (014)

The user is allowed to specify heat transfer coefficients to be used during core spray operation (see paragraph (25)). Models for the coolant behavior are the same as that for fill systems and required input data are also the same. Data block number is 014. This block must contain NCSP data sets.

(14) Steam Separator Data Cards

This card block is required when NSEP=1.

Card 1

W1-I NTABF = Number of data points for separation efficiency data table.

Card 2

Separation efficiency as a function of mixture level in the downcomer node must be given.

W1-R TABEF(1)= Mixture level for first point (m).
W2-R TABEF(2)= Separation efficiency for first point.
W3-R TABEF(3)= Mixture level for second point.
... . , until NTABF points are entered.

(15) Trip Control Data Cards (016)

NTRIP data sets are required.

Card 1

W1-I IDACT = Index of action to be taken. IDACT is an integer of three figures.

IDACT = XY_1Y_2 ($-1 \leqq X \leqq 1$, $0 < Y_1Y_2 \leqq 99$)

If X= −1, action is to close a valve. Y_1Y_2 is valve index. The valve index is given in Junction Data Card.

If X = 1, action is to open a valve. Y_1Y_2 is valve index.

If X= 0, following actions are taken.

Y_1 =1 : Termination of calculation.

Y_1 =2 : Open a leak

Y_1 =3 : Pump trip

Y_1 =4 : Start a fill

Y_1 =5 : (not defined)

Y_1 =6 : Actuate a HPCI

Y_1 =7 : Actuate a LPCI

Y_1 =8 : Actuate a core spray

Y_2 is used as index of leak, pump, or fill system.

For an example, IDACT=102 means X=1, Y_1Y_2=2 and, therefore, the valve of index number 2 will be opened by this trip. If IDACT=42, the fill system of index number 2 will be actuated. Index number for leaks, pumps, or fills are given as IPUMP in Junction Data Cards.

W2-I KSIG = Signal to be compared.

1 = Elapsed time after problem initiation.

2 = Pressure of node IDVOL

3 = Collapsed liquid level of node IDVOL as defined in subsection 2.13.

4,5 = Not defined

6 = Flow rate of junction IDVOL.

If the sign of KSIG is minus, the trip will occur when the compared value drops below the set point. If KSIG is greater than 0, the trip will occur when the set point is exceeded.

W3-I IDVOL = Node or junction index.

W4-I IPVOL = Index of optional node or junction.

If IPVOL > 0, the difference between the values of nodes

(junctions) IDVOL and IPVOL will be used.

W5-R SETP = Signal set point. Units are s for time, m for liquid level, kg/s for flow rate, and kg_f/m^2 for pressure.

W6-R DELAY = Delay time for initiation of action after reaching setpoint. (s)

(16) Dimension Card for Heat Slabs (017)

W1-I NSLAB = Number of heat slabs.

W2-I NOCOR = Number of heat slabs with heat generation in them.

W3-I NGEOM = Number of heat slab geometry data sets.

W4-I NMAT = Number of material property data sets.

W5-I NMATG = Number of gap conductance data sets.

W6-I MAXRG = Maximum number of regions in a heat slab.

W7-I NTVSNP = Number of data points in normalized heat generation table. If NTVSNP>0, the heat generation in the core will be calculated by table interpolation. If NTVSNP=0, the one-point reactor kinetics model will be used. Following three variables NTROD, NTALP, and NTFUT must be 0, if NTVSNP>0.

W8-I NTROD = Number of data points for scram reactivity table.

W9-I NTALP = Number of data points for void reactivity table.

W10-I NTFUT = Number of data points for fuel temperature reactivity table.

(17) Heat Slab Data Cards (018)*

NSLAB data sets are required.

Card 1

W1-I NVSL = Index number of volume at left (or peripheral) surface. 0<NVSL.

W2-I NVSR = Index number of volume at right (or center) surface. If NVSR=0, adiabatic condition is applied for the right hand side. As for cylindrical geometry, NVSR must be 0.

W3-I IGEOM = Geometry index.

W4-I ISPHTC* = Index of steam cooling and spray cooling option.

ISPHTC=0 : use built-in heat transfer correlations.

0<ISPHTC≦NSPHTC : use heat transfer coefficient given by the user. ISPHTC is used as a index of table data. Tables are given by Steam Cooling and Spray Cooling Data Cards.

W5-R ZSLB = Elevation above the reference level (m).

The reference level must be the same as that for the node elevations.

W6-R RHSLB = Slab length (m).

W7-R VOLS = Total volume of slab (m^3).

If this slab is a part of the core section, the geometry data must be of one fuel rod (or part of a rod) as opposed to a lumped value for the whole core. The number of fuel rods will be input as IXSN in Core Section Data Cards.

Card 2

W1-R AHTL = Heat transfer area at left hand side (m^2).

W2-R HMDL = Left side hydraulic diameter (m).

W3-R DHEL = Left side heated equivalent diameter (m).

Card 3

This card is not required if NVSR=0.

W1-R AHTR = Heat transfer area at right hand side (m^2).

W2-R HMDR = Right side hydraulic diameter (m).

W3-R DHER = Right side heated equivalent diameter (m).

(18) Core Section Data Card (019)

NMCOR sets of data are required.

Card 1

W1-I ISLB = Slab index.

W2-I IXSN = Number of rods represented by this slab.

W3-R PSLB = Power fraction defined as Es in Eq. (2.15.2).

W4-R X = A dummy variable. Set X to 1.

W5-R TFCT = Weighting factor for calculation of average fuel temperature.

(19) Slab Geometry Data Cards (020)

NGEOM sets of data are required.

Card 1

W1-I JGOM = Geometry type.

1 = Rectangular type.

2 = Cylindrical type.

W2-I JREG = Number of regions

Card 2

W1-I JGAP(1) = Gap index for first region.
= 0 , not gap.
> 0 , index of temperature versus gap conductance table.

W2-I JGAP(2) = Gap index for second region.

... . until JREG data are entered. The sequence of the regions is from right to left for the rectangular type and center to peripheral for the cylindrical type.

Card 3

W1-I JMAT(1) = Material index for first region.

W2-I JMAT(2) = Material index for second region.

... . until JREG data are entered.

Card 4

W1-I JPNT(1) = Number of space mesh in first region.

W2-I JPNT(2) = Number of space mesh in second region.

... . until JREG data are entered.

Card 5

W1-R WREG(1) = Width of first region (m).

W2-R WREG(2) = Width of second region (m).

... . until JREG data are entered.

Card 6

W1-R DREG(1) = Density of first region (kg/m^3).

W2-R DREG(2) = Density of second region (kg/m^3).

... . until JREG data are entered.

Card 7

W1-R PREG(1) = Power distribution factor E_R in Eq.(2.15.2) for first region.

W2-R PREG(2) = Power distribution factor for second region.

... . until JREG data are entered.

Card 8

W1-R TREG(1) = Weighting factor for average temperature calculation for first region.

W2-R TREG(2) = Weighting factor for second region.

... . until JREG data are entered.

The authors recommend that TREG(i) be set equal to PREG(i) unless there is any special reason for different values.

(20) Material Property Data Cards (021)

(i) Thermal conductivity tables

Card 1

W1-I NTPK = Number of points in thermal conductivity table (NTPK ≧ 1).

Card 2

W1-R TPK(1) = Temperature for first point (°C).

W2-R TPK(2) = Thermal conductivity for first point (kcal/m°Cs).

W3-R TPK(3) = Temperature for second point.

... ... , until NTPK points are entered.

(ii) Specific heat tables

NMAT sets of data must be entered. The order of data must be arranged in accord with the material indeces.

Card 1

W1-I NTPC = Number of data points in the heat capacity table.

Card 2

W1-R TPC(1) = Temperature for first point (°C).

W2-R TPC(2) = Heat capacity for first point. (kcal/kg°C).

W3-R TPC(3) = Temperature for second point.

... ... , until NTPC points are entered.

(iii) Gap conductance tables

NMATG sets of data must be entered. The order of data must be arranged in accordance with the gap indeces.

Card 1

W1-I NTPG = Number of data points in the gap conductance table.

Card 2

W1-R TPG(1) = Temperature for first point (°C).
W2-R TPG(2) = Gap conductance for first point (kcal/m^2°C s).
W3-R TPG(3) = Temperature for second point.
... ... , until NTPG points are entered.

(21) Other Heat Slab Data Cards

Card 1
W1-I IVOLC = Index number of the node in which the core is located.
W2-R QINIT = Total reactor power at initial state (kcal/s).
W3-R BETABL = β/Λ in Eq.(2.15.4). If kinetics calculation option is not used (NTVSNP=0), set BETABL = 0..

Card 2 Time dependent power table
Card 2 is necessary only when NTVSNP>0, and Cards 3, 4, and 5 are necessary only when NTVSNP=0.
W1-R PTABL(1) = Time for first point (s).
W2-R PTABL(2) = Power normalized to QINIT for first point.
W3-R PTABL(3) = Time for second point.
... ... , until NTVSNP points are entered.

Card 3 Scram reactivity table
W1-R RROD(1) = Time for first point (s).
W2-R RROD(2) = Scram reactivity for first point (dollar).
W3-R RROD(3) = Time for second point.
... ... , until NTROD points are entered.

Card 4 Void reactivity table
W1-R RALP(1) = Void fraction for the first point (s).
W2-R RALP(2) = Reactivity feedback for the first point (dollar).
W3-R RALP(3) = Void fraction for the second point.
... ... , until NTALP points are entered.

Card 5 Fuel temperature reactivity table
W1-R RFUT(1) = Fuel temperature for first point (°C).
W2-R RFUT(2) = Reactivity feedback for first point (dollar).
W3-R RFUT(3) = Time for second point.
... ... , until NTFUT points are entered.

(22) Critical Flow Data Cards (051)*

Card 1

W1-I NCHOKE = Number of critical flow data sets.

Card 2

This card must be repeated NCHOKE times.

W1-I ISUB = Critical flow model index for subcooled liquid.

W2-I ISAT = Critical flow model index for saturated mixture.

W3-I IVAP = Critical flow model index for superheated steam.

Definitions of critical flow model indeces are as follows.

1 = Sonic model

2 = Moody Model

3 = Henry-Fauske Model

4 = Homogeneous Equilibrium Model

5 = Incompressible Flow Model.

W4-R CSUB = Discharge coefficient for subcooled liquid flow.

W5-R CSAT = Discharge coefficient for saturated mixture.

W6-R CVAP = Discharge coefficient for superheated steam.

W7-R XLM = Transition quality for subcool-saturate boundary.

W8-R XLG = Transition quality for saturate-superheat boundary.

Since THYDE-B1 does not consider superheating of steam in a three-region node, superheated (not saturated) steam will not appear in a THYDE-B1 calculation. Therefore, if the user does not have any idea for steam flow regime, XLG=1.0 , CVAP=CSAT, and IVAP=ISAT may be appropriate.

(23) Pump Motor Torque Data Cards (053)*

Card 1

W1-I NPMPTX = Number of pump motor torque tables.

Card 2

W1-I NPMP(1) = Number of data points in first table.

Card 3 Pump speed versus torque table

W1-R PTMO(1,1) = Pump speed for first point (rad/s).

W2-R PTMO(2,1) = Pump motor torque for first point ($kg_f m$).
W3-R PTMO(3,1) = Pump speed for second point.
.... , until NPMP(1) points are entered.
Card 2 and 3 are repeated until NPMPTX tables are entered.

(24) Pump Characteristic Data Cards (054)*

Card 1
W1-I NPCVHO = Number of single-phase characteristic curve data sets.
W2-I NPCVTW = Number of two-phase characteristic curve data sets.

Card 1 declares number of data sets to be entered. A pair of Card 2 and 3 describes a curve. 2*8*NPCVHO+2*9*NPCVTW pairs of Card 2 and 3 must be entered.

Card 2 (Description of a curve to be entered)
W1-I ISET = Index of pump characteristic data set.
ISET=1, 2,...NPCVHO, 1, 2..., or NPCVTW.
W2-I IT = Data index.
1 = single-phase pump head.
2 = single-phase pump torque.
3 = two-phase pump head
4 = two-phase pump torque
W3-I IC = Curve type index.

IC	α	v	v/α	Independent Variable	Dependent Variable
1	>0	$\geqq 0$	$\leqq 1$	v/α	h or β/α^2
2	>0	$\geqq 0$	>1	α/v	h or β/v^2
3	>0	<0	$\geqq -1$	v/α	h or β/α^2
4	>0	<0	>-1	α/v	h or β/v^2
5	$\leqq 0$	$\leqq 0$	$\leqq 1$	v/α	h or β/α^2
6	$\leqq 0$	$\leqq 0$	>1	α/v	h or β/v^2
7	$\leqq 0$	>0	$\geqq -1$	v/α	h or β/α^2
8	$\leqq 0$	>0	<-1	α/v	h or β/v^2
9	(two-phase multiplier data)			void	multiplier

W4-I NPOINT = Number of data points.

Card 3 (Characteristic data table)

W1-R TAB(1) = Independent variable for first point.

W2-R TAB(2) = Dependent variable for second point.

W3-R TAB(3) = Independent variable for second point.

.... , until NPOINT points are entered.

(25) Steam Cooling and Core Spray Cooling Data Cards (055)*

Card 1

W1-I NSPHTC = Number of data sets. NSPHTC sets of Cards 2, 3, and 4 will be required.

A set of Cards 2, 3, and 4 describes a heat transfer coefficient correlation as a function of pressure and spray flow rate. The values for the flow rate of zero corresponds to a heat transfer coefficient for steam cooling.

For each set, Card 2 specifies number of pressure points and then Card 3 and 4 describes a table of heat transfer coefficient as a function of spray flow rate. Card 3 and 4 is required for each of the pressure point.

Card 2

W1-I MAXPR = Number of pressure points.

W2-R FLOWA = Flow area for calculation of mass flux from spray flow rate (m^2).

Card 3

W1-I NPOINT = Number of data points in a table for a pressure point.

W2-R PRES = Pressure (kg/m^2)

Card 4

W1-R HTCTB(1) = Mass flux of spray flow for first point ($kg/m^2 s$). Mass flux is defined as

mass flux = ΣW_{spray} /FLOWA,

where ΣW_{spray} = sum of flow rates of all core sprays.

W2-R HTCTB(2) = Heat transfer coefficient for first point (kcal/m^2s°C).
W3-R HTCTB(3) = Mass flux of spray flow for first point.
.... , until NPOINT points are entered.

(26) End-of-Data Sign (999)

The end of data deck must be indicated by a card with an integer 999.

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Nomenclature

A	Flow area or heat transfer area (m^2)
c	Specific heat (kcal/kg°C)
C	Heat capacity (kcal/°C)
C_i	Concentration of delayed neutron precurser of group i ($1/m^3$)
$C_{l\to m}$	Constant used in local temperature rise model for a three-region node
C_α	Constant used in bubble separation model for a three-region node
D_h	Hydraulic diameter (m)
E_{act}	Fraction of actinide decay heat in initial reactor power
E_{dj}	Fraction of decay heat group j in initial reactor power
E_M	Constant used for description of power distribution in core
E_n	Constant used for description of power distribution in core
E_R	Constant used for description of power distribution in core
E_S	Constant used for description of power distribution in core
f	Function
F	Fraction or factor
F_m	Mixing efficiency for mixture region (-)
F_g	Mixing efficiency for vapor region (-)
F_z	Flow direction factor used for determination of volume averaged flow rate in heat transfer rate calculation (-)
g	Gravitational acceleration (9.80665 m/s^2)
g_c	Gravitational conversion factor (9.80665 N/kg_f)
G	Mass flux ($kg/m^2 s$)
G_M	Critical mass flux calculated with Moody's model ($kg/m^2 s$)
G_S	Steam flow controller regulation band (kg_f/m^2)
h	Specific enthalpy (kcal/kg)
$h_{l\to m}$	Specific enthalpy of fluid moved from subcooled liquid region to saturated mixture region (kcal/kg)
h	Heat transfer coefficient (kcal/ $m^2 s°C$)
I	Moment of inertia ($m^2 kg$)
J	Joule constant (4186 J/kcal)
k	Thermal conductivity (kcal/s m °C)
L	Length (m)
L_g	Mixing length for vapor region used in fill junction model (m)
L_m	Mixing length for mixture region used in fill junction model (m)
L_{mix}	Mixing length for leakage flow smoothing (m)

(L/A)	Junction inertia (m^{-1})
M	Mass of fluid (kg)
n	Neutron concentration
N_S	Number of heat slabs
P	Pressure (kg_f/m^2)
P_U	Upstream pressure of steam flow controller (kg_f/m^2)
P_{US}	Pressure set point for steam flow controller (kg_f/m^2)
q	Heat transfer rate (kcal/s)
Q	Heat genaration rate or heat transfer rate (kcal/s)
Q_T	Total heat generation in the core (kcal/s)
Q_{T0}	Q_T at initial state (kcal/s)
Q_d	Heat generation due to fission product decay (kcal/s)
r	Resistance of heat transfer ($s^oC/kcal$)
R	Reactivity normalized to the delayed neutron fraction (−)
R_F	Fuel temperature feedback reactivity (−)
R_S	Reactivity inserted by scram action (−)
R_α	Void feedback reactivity (−)
R_0	Loss coefficiet for single-phase liquid flow ($s^2 kg_f/m^5 kg$)
t	Time (s)
Δt	Time step size (s)
$t_{c.p}$	time constant of pump coast down (−)
T_R	Rated torque of a pump ($kg_f m$)
u	Velocity (m/s)
u_b	Velocity of bubbles relative to liquid (m/s)
v	Specific volume (m^3/kg)
V	Volume (m^3)
W	Flow rate (kg/s)
W_{sep}	Rate of bubble separation from mixture region (kg/s)
W_{slip}	Slip flow rate of vapor (kg/s)
x	Quality (−)
X_L	Bubble sweep-out length (m)
X_{dj}	Concentration of decay heat group j normalized to steady state value (−)
z	Elevation (m)
Z_{ml}	Elevation of boundary between subcooled liquid and mixture regions (m)
Z_{gm}	Elevation of boundary between mixture and vapor regions (m)
Z_J	Junction elevation (elevation of the boundary between two nodes

connected by a junction) (m)

Greek symbols

α	Void fraction (−)
β	Effective delayed neutron fraction (−)
β_i	Effective fraction of delayed neutron group i (−)
ΔP	Pressure difference (kg_f/m^2)
η	Separation efficiency of steam separator (−)
λ_i	Decay constant of delayed neutron group i (1/s)
λ_{dj}	Decay constant of decay heat group j (1/s)
Λ	Prompt neutron life time (s)
ρ	Density (kg/m^3)
σ	Surface tension (kg_f/m)
$(\Sigma Q)_i$	Total heat transfer rate to fluid in node i from heat slabs (kcal/s)
$(\Sigma W)_i$	Total flow rate of fluid entering node i (kg/s)
$(\Sigma hW)_i$	Total convection rate of energy entering node i (kcal/s)
τ_c	Time constant of isolation valve closure (s)
φ^2	Two-phase multiplier for frictional pressure drop (−)
ω	Angle velocity (rad/s)

Subscripts

b	Bubble
bot	Bottom
B	Bulk fluid
$cond$	Condensation of vapor
D	Jetpump drive flow
$down$	Downcomer
eff	Effective quantity
f	Saturated liquid
$fill$	Injection system
$flux$	Momentum flux
$fric$	Frictional loss
F	Fuel
g	Saturated vapor

grav	Gravitation
in	Node at inlet side of a junction
J	Jet pump flow or junction
leak	Leak junction
L	Lower plenum
M	Mixing section of jet pump
n	Node
out	Node at outlet side of a junction
p	Recirculation pump
ps	Recirculation pump suction
pipe	Jet pump drive pipe
R	Rated condition
s	Mixture surface
S	Jet pump suction flow
top	Top of node or subnode
w	Wall

Superscripts

g	Quantity of vapor region
l	Quantity of subcooled liquid region
m	Quantity of mixture region
new	New time
old	Old time