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ALARM-P1: A Computer Program for Pressurized Water Reactor Blowdown Analysis

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The computer program ALARM-P1 written in FORTRAN-IV for FACOM 230-75 is a part of the code series for evaluation of performance of the emergency core cooling system (ECCS) in pressurized water reactors according to the safety evaluation guidelines provided by the Atomic Energy Commission of Japan. ALARM-P1 is for analyzing the thermo-hydraulic phenomena during blowdown following a large break in the primary coolant system. ALARM-P1 models the PWR system fluid conditions including flow, pressure, mass inventory, fluid quality and heat transfer. It solves integral forms of fluid conservation and state equations for user-defined volumes treated as one-dimensional homogeneous, thermal-equilibrium elements with interconnecting flow paths and also finite difference forms of the one-dimensional heat conduction equations describing temperature profiles within solid material and the fluid-solid interface conditions. In addition, the ALARM-P1 provides the initial conditions for analysis of the last portion of the LOCA transient, a reflood phase, and the information for core heat-up analysis during the whole LOCA.

This report describes the state-of-art methods and models of ALARM-P1 in June 1978 and gives information for users.

Keywords: ECCS Performance, Blowdown, Large Break, Critical Flow, Blowdown Heat Transfer, PWR LOCA, Computer Code

加圧水型原子炉ブローダウン解析コードALARM－P 1

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計算プログラムALARM－P 1は加圧水型動力炉の非常用炉心冷却系の性能評価を行う一連のコードシリーズの一部を成すもので，我が国原子力委員会が制定した安全評価指針に準ずるものである。ALARM－P 1は一次冷却系の大破断に続くブローダウン期間中の熱水力学的現象を解析するものである。PWR系のブローダウン中の流れ，圧力，残存水量，クオリティー，熱伝達等をモデル化して計算する。いくつかの体積要素について積分された流体の保存式と状態方程式が一次元流れ，熱的平衡のもとに解かれる，また，一次元熱伝導方程式を差分化して，構造材等の固体内部の温度分布や表面の熱伝達も計算される。ALARM－P 1の重要な役割の一つは，ブローダウン後期の再冠水過程の解析のための初期条件を与えること及びLOCA全期間中を通して炉心のヒートアップ計算のための情報を与えることである。

この報告書にはALARM－P 1に含まれる解析モデルやその方法について1978年6月現在のもの及びプログラムの使用法を述べてある。

Contents

目　　次

Figures

Tables

1. Introduction

A series of computer codes are now being developed in Japan Atomic Energy Research Institute (JAERI) to evaluate the performance of emergency core cooling system (ECCS) during a postulated loss of coolant accident (LOCA) in light-water reactors. Postulating various modes of pipe break such as gillotine or split at a certain point in the primary coolant system, the performance of the ECCS is to be evaluated with adequate conservatism Two series of computer codes are being prepared for PWR and BWR plant in accordance with current domestic acceptance criteria.

ALARM-P1/MOD1 described herein is a part of the code series for evaluating the ECCS of a PWR plant, whose structure is shown in Fig. 1.1. ALARM-P1/MOD1 is for analyzing the thermohydraulic phenomena during blow-down following a large area break of the primary coolant system pipe. The portion of the LOCA transient treated by ALARM-P1/MOD1 will include system phenomena from initial operating condition at the time of pipe rupture through system depressurization up to the end of a refill phase, where the lower plenum is filled with ECCS fluid with the limitation of the model adopted. For example, ALARM-P1/MOD1 has no special features to calculate downcomer penetration. A coming modified version, ALARM-P1/MOD2 will be designed to incorporate various models for ECC water bypass, downcomer penetration, mixing of cold ECC water and two-phase fluid and so on. As shown in Fig. 1.1 the ALARM-P1 code supplies initial conditions to analyze the remaining portion of the LOCA transient, a reflood phase, and also provides information for the core heat-up analysis during whole LOCA period.

The ALARM-P1/MOD1 code written in FORTRAN-IV for FACOM 230-75 solves integral forms of fluid conservation and state equations for user-defined volume with interconnecting flow paths under inherent assumptions of a homogeneous two-phase fluid and thermal equilibrium between the phases. The program requires numerical input data that completely describe the initial conditions and geometry of each divided volume element and interconnecting flow paths for the system being analyzed. The numerical input data of physical characteristics such as pump characteristics, power generation, heat exchanger properties, and material composition are also required. Starting with a given initial condition, transients can be initiated by the control action inputs to the program. The program computes fluid conditions such as flow, and pressure, and also are computed thermal conditions within solid material such as temperature profiles and power

generation rate, and the fluid-solid interface conditions such as heat flux and surface temperature.

The development work of ALARM-P1 was commenced in Nov., 1974. The initial version was programmed in July, 1975. Since that time the code has been tested with various problems. About a year of extensive use of the initial version led to the correction of a number of errors in the code as well as some logic changes. These changes in testing the initial version identified as ALARM-P1/MOD1. MOD1 was used for analyzing CSNI's (Committee on Safety of Nuclear Installation) LOCA Standard Problem NO.3, NO.4 and NO.5 to test and obtain a better understanding of the characteristics of the code. From experience of verification calculations[7], many additions and improvements of the model are being planned for future versions of the code. Some of the more important of these are (1) a model for eliminating pressure spike due to the mixing of subcooled and two-phase fluid within one control volume under thermal equilibrium assumption when the accumulator injection starts, (2) improved two-phase model to calculate the counter current flow in the downcomer when the refill phase is initiated, and (3) accumulator water bypass model within the limitation of the control volume and junction model. These additions or improvement will be incorporated in a coming modified version, ALARM-P1/MOD2. Another important constraint that was observed in the past verification calculations is the computer running time requirements. No special care has been taken to provide efficient computational techniques. ALARM-P1 uses a simple explicit numerical technique to solve a set of difference equations for fluid conservations. A number of improvements in this respect are under progress, including a newly developed numerical technique. These improvements will be incorporated in the coming version, ALARM-P2.

This report describes the methods and models included ALARM-P1/MOD1, and provides user information. Chapter 3 describes the basic hydrodynamics, heat transfer methods and other component models such as the reactor coolant pump and steam generator. Some models used in ALARM-P1 are similar to these in RELAP3[1] or RELAP4[2]. Chapter 4 briefly describes the overall code organization. Chapter 4 is supplemented by Appendices A and B which supply, respectively, input specifications along with restarting input and a reeditting program for plot data file. An application to a sample problem is described in Chapter 5. The analysis of a sample problem was based on ALARM-P1 state-of-art analytical method in August, 1976.

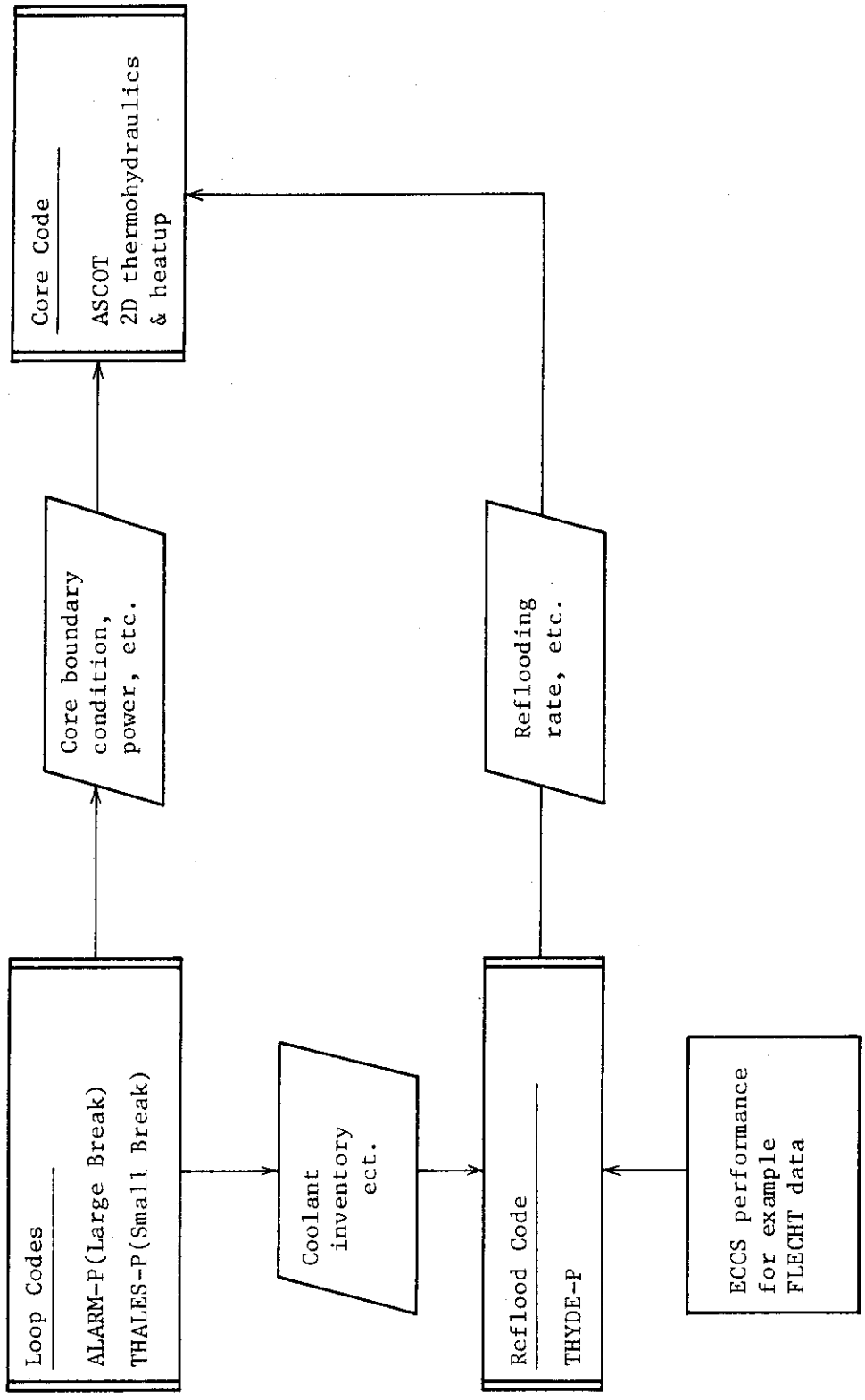


Fig. 1.1 Structure of PWR ECCS Evaluation Code System

2. Outline of the ALARM-P1 Code

The outline of the PWR blowdown analysis code, ALARM-P1 is summarized as follows;

(1) Description of problem or function: ALARM-P1 is intended primarily to analyze the blowdown phase following a large break LOCA for ECCS evaluation. ALARM-P1, however, provides some options for a "best estimate" analysis such as choked flow model. ALARM-P1 almost complies with the required features in a blowdown period[3] for the safety evaluation of ECCS recommended by the Atomic Energy Commission of Japan.

(2) Method of solution: The system of partial differential equations describing fluid conservations for stream-tube are integrated over a number of control volumes. The resulting set of simultaneous equations that is based on the assumptions of one-dimensional, homogeneous, thermal-equilibrium flow is linearized and advanced for a small time increment by a simple explicit numerical technique. The one-dimensional heat conduction equations describing temperature profiles within solid material are written in finite difference forms which are linearized and solved by Crank-Nicolson implicit method[4].

(3) Restrictions on the complexity of the problem: The program is of a variable dimension so the only limit on the size of a problem is the amount of core memory available. The number of control volumes, and the manner in which they are connected, is arbitrary. However, since the fluid flow equation in ALARM-P1 is based on the assumption of one-dimensional flow, the actual arrangement must be viewed in terms of the inherent assumption. A multiple-connected flow path should be used only when it can be approximated with one-dimensional flow.

(4) Typical running time: Running time is highly dependent on a problem and is a function of the number of control volumes, flow paths (junction) and heat conductors, and the time step size used. For example, the calculation with 31 control volumes, 35 junctions and one heat conductor for the analysis of LOFT L1-4[5] experiment required the CPU time of about 3.67 hours (0.165 sec/time step) in FACOM 230-75 computer.

(5) Related and auxiliary programs: One of the output files written by ALARM-P1 and output of PREEDIT (see Appendix B) contains graphic information which can be used to produce plots on paper and graphic display. All

input data are read in free format via a generalized subroutine REAG[6]. The subroutine REAG for FACOM 230-75 converts BCD information to integer or binary information.

(6) Others upon which the code is operable: This code will be easily converted to such as for IBM machine. Minor modification will be required in the free format input routine.

(7) Machine requirements: FACOM 230-75 computer with minimum 256K workds.

(8) Programming language: FORTRAN-IV

(9) Operating system or monitor under which program is executed: Standard FACOM 230-75 operating system with H level compiler.

3. Analytical Equations and their Numerical Solutions

3.1 Fluid equations and fluid dynamics options

3.1.1 Fluid eqations for stream-tube

The conservation equations for fluid mass, energy, and momentum in differential form are integrated to produce steam-tube equations[8]. These equations are as follows:

(1) Fluid Mass Equation

$$A\frac{\partial \rho}{\partial t} = -\frac{\partial W}{\partial x} \tag{3.1-1}$$

(2) Fluid Energy Equation

$$A\frac{\partial(\rho e)}{\partial t} = -\frac{\partial}{\partial x}\left[W\left(h + \frac{v^2}{2J} + \frac{gz}{J}\right)\right] + \frac{\partial Q_e}{\partial} \tag{3.1-2}$$

(3) Fluid Flow Equation

$$A\frac{1}{g_c}\frac{\partial(\rho v)}{\partial t} = -\frac{\partial(vW)}{g_c \cdot \partial x} - A\frac{\partial p}{\partial x} - A\rho\frac{g}{g_c}\cos\theta - P\tau_w \tag{3.1-3}$$

where $\partial Q_e/\partial x$ represents the heat transfer per unit length of duct (kcal/sec-m). The symbol definitions for above equations are as follows:

A = flow area (m^2)
ρ = fluid density (kgm/m^3)
W = mass flow rate (kgm/sec)
v = fluid velocity (m/sec)
p = thermodynamic pressure (kgf/m^2)
τ_w = average wall shear stress (kgf/m^2)
e = total fluid specific energy (kcal/kgm)
u = fluid specific internal energy (kcal/kgm)
h = fluid specific enthalpy ($h = u + \frac{p}{\rho}\frac{g_c}{J}$)
z = elevation coordinate value (m)
θ = inclination of the duct to the vertical
g = gravitational acceleration constant (9.8 m/sec^2)
g_c = gravitational conversion constant (9.8 Newton/Kgf)
Q_e = wall heat input ($A_w q_w$: product of wall heat flux and wall area for heat transfer)
t = time coordinate value (sec)
x = path length coordinate value (m)

J = Joule's constant (4.1868×10^3 joule/kcal)

P = wetted perimeter (m)

To obtain distribution of mass, energy and flow in a PWR reactor system, the system is divided into a number of spatial volume elements called control volume and the conservation equations are integrated over these control volumes. The thermodynamic pressure for each volume is defined by the stateproperty relations in terms of specific internal energy and density. The resulting set of simultaneous equations that is based on the assumptions of one-dimensional, homogeneous, thermal-equilibrium flow is linearized and advanced for a small time increment by a simple explicit numerical technique.

ALARM-P1 allows the volumes to be arbitrarily connected by multiple flow paths (junctions) despite the assumption of one-dimensional flow. A multidimensional flow path should be used only when the multidimensional flow can be sufficiently approximated with one-dimensional equations.

3.1.2 Conservation equations for a control volume

The actual fluid equations used in ALARM-P1 can be obtained by integrating the stream-tube equations over a fixed volume. The fluid mass and energy equations are integrated over i-th fluid volume that connects to j flow paths (junctions).

(1) Fluid Mass Equations The integrated mass equation is:

$$\frac{dM_i}{dt} = \sum_j W_{ij} \qquad (3.1\text{-}4)$$

where

M_i = mass in volume V_i,

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

(2) Fluid Energy Equations The energy equation for homogeneous flow is:

$$\frac{dU_i}{dt} = -\frac{d}{dt}\left(\frac{1}{2J}\frac{L_i}{A_i}\frac{\bar{W}_i^2}{\bar{\rho}_i}\right)\sum_j W_{ij}\left[h_{ij} + \frac{V_{ij}}{2J} + \frac{g}{J}(z_{ij} - \bar{z}_i)\right] + Q_i \qquad (3.1\text{-}5)$$

where

U_i = total fluid internal energy within volume V_i,

$\bar{W}_i$ = arrange flow of volume V_i,

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

Q_i = rate of heat energy transferred into volume V_i.

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

$$u = \frac{U}{M} \tag{3.1-6}$$

and the average fluid density is:

$$\bar{\rho} = \frac{M}{V} \quad . \tag{3.1-7}$$

The quantity, Q_i represents the sum of all the heat sources, heat transferred from the core and structural metal, and heat transferred through the steam generator tubes. The calculation of Q_i is described in §3.4.

The quantity, $W_{ij}h_{ij}$ represents the convective energy transfer rate through a flow path, and the junction enthalpy h_{ij} is evaluated in three ways depending on the model used in the source volume V_i, including enthalpy change due to phase separation at junction j and/or junction enthalpy change from center of volume to junction due to heating within source volume V_i. The rate of enthalpy change depending on the model used in the source volume is described in §3.1.5.

3.1.3 Bubble rise model

The bubble rise model used in ALARM-P1 is similar to that in RELAP-3[1]. The purpose of this model is to account for phase separation (bubble rise) in a volume with low velocity flow such as a pressurizer. This model provides an improved estimates of enthalpy and density as a function of vertical elevation. In each control volume which includes the phase separation model, two subvolumes are considered: the volume of separated steam and the volume of two phase mixture. Thermal equilibrium is assumed throughout the control volume. This means that all steam production occurs uniformly in the bulk fluid of the lower phase. In this model, the upward relative movement of steam voids below the mixture level is assumed to be expressed in terms of a gradient factor of the vapor distribution and the relative velocity at mixture surface. The assumed bubble distribution is

$$\alpha(z) = m \frac{z}{z_m} + b \ , \tag{3.1-8}$$

where

$\alpha(z)$ = void fraction at height, z,

m, b = time dependent slope and intercept,

z = height above the bottom of the volume,

z_m = time dependent height of mixture interface.

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

$$\rho_{mix} = e \frac{z}{z_m} + f \ , \tag{3.1-9}$$

where

ρ_{mix} = mixture density, $\alpha\rho_g + (1-\alpha)\rho_\ell$,

e, f = time dependent slope and intercept.

The slope and intercept of Eq. (3.1-8) are evaluated by assumed gradient factor and the average void fraction within the two-phase mixture. For an average void fraction less than 0.5, slope m and intercept b for Eq. (3.1-8) are as follows:

$$\left.\begin{aligned} m &= 2C_0\alpha_0 \ , \\ b &= (1-C_0)\alpha_0 \ , \end{aligned}\right\} \ 0.0 \le \alpha_0 \le 0.5 \tag{3.1-10}$$

and for the average void fraction between 0.5 and 1:

$$\left.\begin{aligned} m &= 2C_0(1-\alpha_0) \ , \\ b &= (1+C_0)\alpha_0 - C_0 \ , \end{aligned}\right\} 0.5 \le \alpha_0 \le 1.0 \tag{3.1-11}$$

where

α_0 = average void fraction within the mixture,

C_0 = assumed gradient factor specific by input.

The constan C_0, which must be limited between 0.0and 1.0 determines the maximum bubble gradient. If the C_0 of zero is chosen, the mixture is homogeneous: if 1.0, the bubble gradient is maximum within the permissible physical constraints. In the present version of ALARM-P1, C_0 is an input and kept constant during the transient.

The average void fraction within the mixture and the mixture level during the transient are estimated by applying the mass balance of the entrained steam within a fluid volume. Steam can be added to the fluid volume either through a junction or by flashing of liquid within the mixture. When condensation due to pressure rise occurs during the transient, it is assumed that the steam within the mixture and steam region are uniformly changed into liquid. The rate of change of entrained steam within the mixture is given by

$$\frac{dM_{gb}}{dt} = \frac{dM_s}{dt} - \sum_i C_i X_i W_i - A v_{bub} \rho_g \alpha(z_m) \qquad (3.1\text{-}12)$$

where

M_{gb} = mass of steam entrained in the mixture,
M_s = total mass of steam within the fluid volume,
C_i = 0.0 if the junction i in the mixture region,
1.0 if the junction i above the mixture region,
X_i = quality of the junction flow,
A = cross-sectional area of the volume,
v_{bub} = bubble velocity relative to the mixture surface,
ρ_g = saturated steam density at the pressure of the volume,
$\alpha(z_m)$= void fraction at the mixture interface.

The bubble velocity relative to the mixture surface is an input and kept constant during the transient. The bubble density gradient, Eq. (3.1-8) and the bubble mass balance, Eq. (3.1-12) are solved to obtain the mass of steam entrained, M_{gb}. The average void fraction within the mixture is calculated by the equation:

$$\alpha_0 = \frac{M_{gb}}{\rho_g V_m} \quad , \qquad (3.1\text{-}13)$$

where

V_m = volume of the mixture.

3.1.4 Fluid condition of a volume

The data required to describe a volume include geometric information such as dimensions and elevation, initial conditions of fluid in the volume and optional-control information. The geometric input and initial thermodynamic condition are given below.

(1) Geometric information

Geometric information includes the volume positional variables and the data used to calculate the frictional pressure drop. Figure 3.1.1 shows the volume positional variables required. A mixture level, ZM, defines the location of a vapor-mixture interface in the volume and has a value between zero and the volume height (ZVOL). ZM is also used for a control parameter to specify the thermodynamic condition of the volume as shown in Table 3.1.1, so must be entered for each volume. Elevation of the bottom of the volume (ELEV) is measured from an arbitrary base chosen by the user.

The data for frictional pressure drop are flow area (FLOWA), equivalent diameter (DIAM) and flow length (FLOWL). If both DIAM and FLOWL are zero, calculation is done by using FLOWA and the volume V based on the assumption of the pipe geometry (see Appendix A, §2.6).

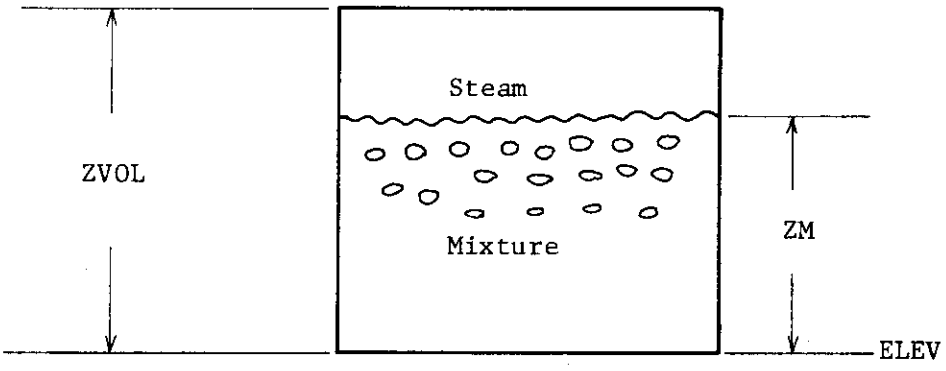


Fig. 3.1.1 Variable Definitions in a Control Volumes

(2) Initial thermodynamic condition

Initial thermodynamic conditions allowed in ALARM-P1 are summarized in Table 3.1.1. Volumes with air present such as accumulator and containment can be allowed. If the volume has a liquid level and air is above the liquid level, air is assumed to be 100% humidity during both initial and transient. The partial pressure of air in the volume is obtained from specifying both the temperature and total pressure in the volume:

$$p_{air} = p - p_{sat} \tag{3.1-14}$$

where

p_{air} = partial pressure of air (kgf/m^2),

p = total pressure in the volume (kgf/m^2),

Table 3.1.1 Allowable Initial Conditions

Model used in a Volume	Condition Present	Control Variable Quality(X), Relative Humidity(hm) or Pressure(p)	Thermodynamic Variables Used
Homogeneous Volume	Superheated Steam	X > 1.0	(p,T) or (p,h)
No Air Present	Saturated Steam	X = 1.0	(p,X), (T,X) or (h,X)
(ZM = ZVOL)	Saturated Liquid	X = 0.0	(p,X), (T,X) or (h,X)
	Subcooled Liquid	X < 0.0	(p,T) or (p,h)
	Two-phase Mixture	0.0 < X < 1.0	(p,X), (T,X) or (h,X)
Volume with Mixture Level	Two-phase Mixture	p=0.0 if T>0.0, p>0.0 if T<0.0 and 0.0<X<1.0 (Mixture Quality)	(p,X), (T,X) or (h, X)
No Air Present			
(0.0 < ZM < ZVOL)			
Volume with Liquid Level	Water and Air with	p>0.0, T>0.0 and X=0.0	(p,T) or (p,h)
Air Present	100% Humidity		
(0.0 < ZM < ZVOL)			
Homogeneous Volume	Water Vapor only	hm < 0.0	(p,T) or (p,h)
Air Present	Air only	hm = 0.0	(p,T)
(ZM = 0.0)	Water Vapor and Air	0.0 < hm < 1.0	(p,T)

P_{sat} = saturation pressure at given temperature T (kgf/m^2).

Other thermodynamic variables of air are obtained by the perfect gass equation:

$$v_{air} = G_{con} \cdot (T + 273.15)/p_{air} \cdot g_c \qquad (3.1\text{-}15)$$

where

v_{air} = specific volume of air (m^3/kgm)
G_{con} = gas constan of air (2.87 Joule/°C·kgm)
g_c = gravitational conversion factor (9.8 kgf/Newton)
T = given temperature in the volume (°C)

and specific enthalpy of air is

$$h_{air} = (T + 273.15) \cdot (C_{v_{air}} + G_{con}) \cdot F_{en} \qquad (3.1\text{-}16)$$

where

$C_{v_{air}}$ = specific isochoric heat capacity (7.18 Joule/°C·kgm),
F_{en} = 0.2389×10^{-3} kcal/Joule.

A mixture level of zero implies that the volume contains water vapor, air or a combination of both gases. The input variables are pressure, temperature and relative humidity. If air is in the volume, and the vapor is in subcritical state, the humidity, h_m represent the ratio of partial vapor pressure to saturation pressure at given temperature, so partial air pressure is given by

$$p_{air} = p - h_m \cdot p_{sat} \cdot \qquad (3.1\text{-}17)$$

ALARM-P1 does not allow air flows out of the volume, so initial air mass in the volume is kept constant during transient.

3.1.5 Junction enthalpy

In order to solve the energy balance on a fluid volume, the correct enthalpy, h_{ij} (cf. Eq. (3.1-5)) must be assigned to all incoming and exiting flows. Basically the junction enthalpy is calculated as the average enthalpy of the volume upstream of the junction. However, for volumes with heat slabs or heat exchanger and the bubble rise model, heat being added (or subtracted) to the volume and enthalpy distribution in the volume must

be considered. Accordingly, ALARM-P1 provides several options for the junction enthalpy.

The calculation for the junction enthalpy is controlled by the symobl JENTH in the Junction Data Cards (see Appendix A, §2.9). Each option is described bellow.

(i) JENTH = 0

If the bubble rise model is applied to the volume upstream, the exit enthalpy is assumed to be representative of the enthalpy of the fluid in contact with the exit junction. If the volume upstream is homogeneous and the enthalpy at the outlet is modified on the basis of the energy equation within volume V_i. The rate of enthalpy increase due to the heating within volume V_i at junction j is modeled by the equation:

$$M_i \frac{dh_{ij}}{dt} + (\Delta h_i)_q |\bar{W}_i + W_j| = Q_i \qquad (3.1\text{-}18)$$

where

M_i = mass in volume V_i,

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

$(\Delta h_i)_q$ = junction enthalpy change from center of volume to junction due to heating,

$\bar{W}_i$ = average mass flow in volume V_i (to be defined in §3.1.6)

W_j = mass flow at junction j,

Q_i = rate of total heat energy transferred into volume V_i.

Equation (3.1-18) can be solved assuming the volume average and junction flows are cocurrent:

$$h_{ij}^{new} = (h_{ij}^{old} - Q_{Hi})\exp\{-\frac{\Delta t}{\tau}\} + Q_{Hi} \qquad (3.1\text{-}19)$$

where

h_{ij}^{new} = the new time step junction enthalpy,

h_{ij}^{old} = the previous time step junction enthalpy,

$\tau = M_i/|\bar{W}_i + W_j|$,

$Q_{Hi} = \bar{h}_i + Q_i/|\bar{W}_i + W_j|$,

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

Δt = time increment.

If both the bubble rise model and heat slabs are applied to the volume upstream, only the change of enthalpy due to phase separation is considered.

If the volume upstream is a homogeneous fluid with no phase separation and no heat slabs, the junction enthalpy is calculated as the average enthalpy of the volume.

(ii) JENTH=1

In this option, logic for the junction enthalpy calculation is almost similar to JENTH=0 except for the enthalpy change due to the bubble rise model. The model described here is provided to assure a smoothly varying transition between flow from vapor phase and flow from mixture phase. Figure 3.1.2 shows the geometry to be analyzed. ZJ is a height of flow path center from the bottom of the volume. DIAJN is a junction diameter which

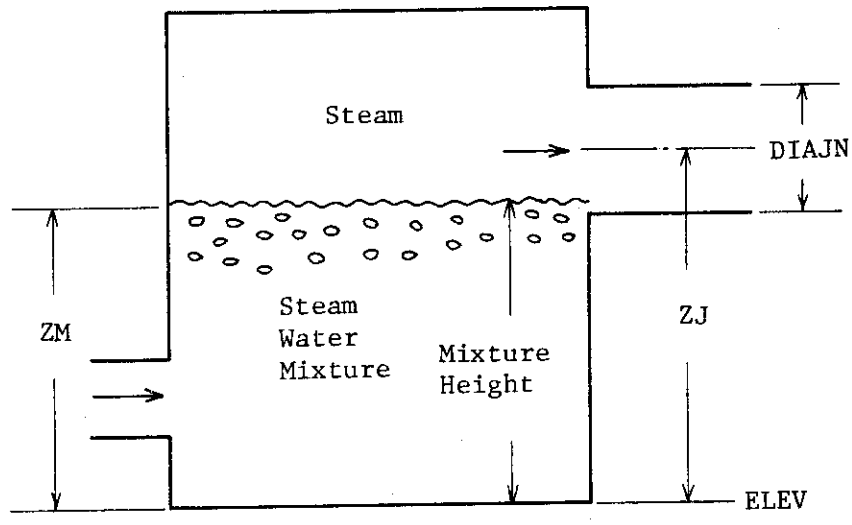


Fig. 3.1.2 Geometry of a Volume for JENTH=1

is calculated from input junction flow area AJUN. The junction enthalpy is calculated by the following manner:

If $ZJ < (ZM - \frac{1}{2} * DIAJN)$, $h_{ij} = h_{mix}(ZJ)$, mixture enthalpy at ZJ.

If $(ZM - \frac{1}{2} * DIAJN) < ZJ < (ZM + \frac{1}{2} * DIAJN)$, $h_{ij} = Fh_g + (1-F)h_{mix}$

where $$F = \frac{ZJ + \frac{1}{2} * DIAJN - ZM}{DIAJN} ,$$

h_g = vapor enthalpy,

h_{mix} = mixture enthalpy at $\{\frac{1}{2}(ZM-(ZJ-\frac{1}{2} * DIAJN))+(ZJ-\frac{1}{2} * DIAJN)\}$.

If $(ZM + \frac{1}{2} * DIAJN) < ZJ$, $h_{ij} = h_g$, vapor enthalpy.

It should be noted that this model is reasonable for horizontaly connected junctions. ALARM-P1 however allows to apply this model to vertically connected junctions.

(iii) JENTH=2

The option JENTH=2 includes the extended model to account for more than one phase to exist due to the heating within the volume. This model is based on RELAP4[2)] and uses the steady state energy equation with the fluid temperature instead of the fluid enthalpy as a dependent variable to predict the location of the saturation line relative to the volume inlet and outlet. The temperature profile within the volume provides to calculate the heat addition from the saturation line interface to the volume outlet. The temperature equation is

$$\bar{W}F_{\ell}c_p \frac{dT}{dZ} = hA(T_s - T) \tag{3.1-20}$$

where

$\bar{W}$ = volume average flow,
F_{ℓ} = volume flow length,
c_p = specific heat at constant pressure,
T = fluid temperature within volume,
h = average heat transfer coefficient,
A = surface area for heat transfer,
T_s = volume average surface temperature.

Equation (3.1-20) is solved for the fluid temperature:

$$T = T_s - (T_s - T_{in})e^{-\alpha z} \tag{3.1-21}$$

where

T_{in} = inlet fluid temperature,
$\alpha = hA/|\bar{W}F_{\ell}c_p|$.

By using Eq. (3.1-21), the distance from the volume inlet to the saturation line, Z_{sat} (see Fig. 3.1.3) is obtained. If the location of the saturation line, Z_{sat} is within the volume, the term Q_{Hi} in Eq. (3.1-19) is modified as given below:

$$Q_{Hi} = h_{i,sat} + Q_i'/|\bar{W}_i + W_j| \tag{3.1-22}$$

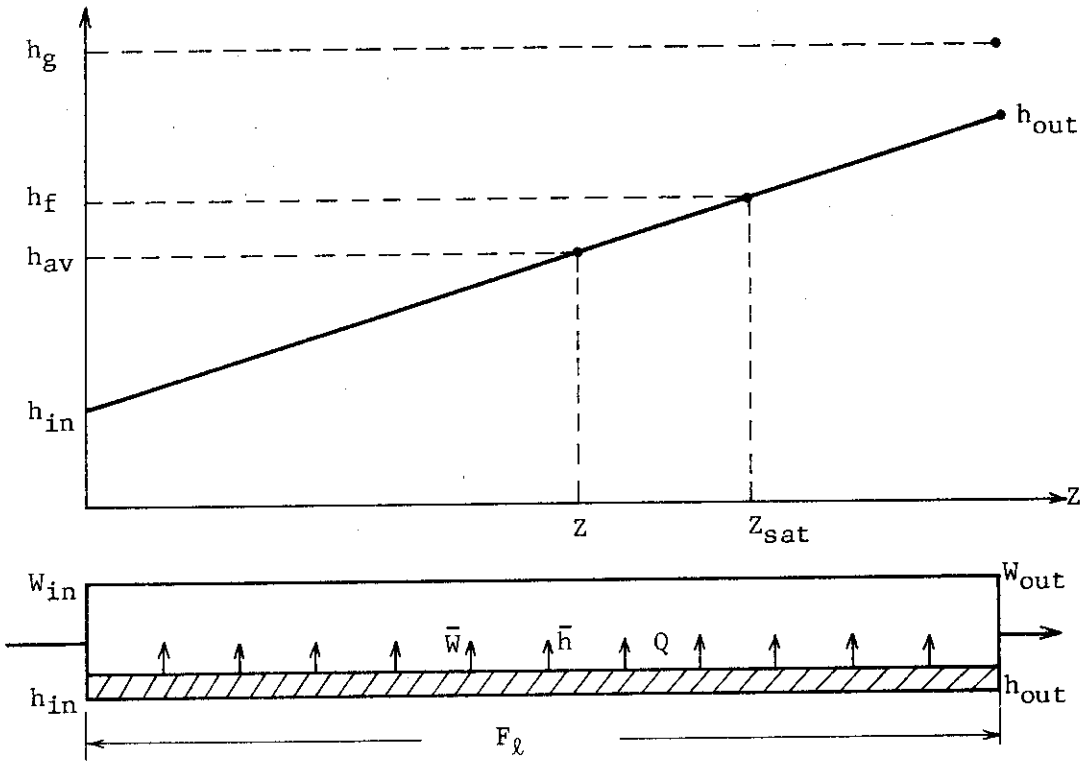


Fig. 3.1.3 Enthalpy Change due to Heat Slab

where

$h_{i,sat}$ = saturation enthalpy at the volume pressure,

Q_i' = heat additon from the saturation line interface to the volume outlet.

The heat additon Q_i' is determined in several ways depending on the various fluid conditions of inlet and outlet junctions. Basically, the Q_i' is estimated on the basis of the right hand side of Eq. (3.1-20). For example, when the average fluid condition of the volume is single phase and the outlet junction is two phase as shown in Fig. 3.1.3, the Q_i' is

$$Q_i' = hA|T_s - T_{sat}|(1 - \frac{Z_{sat}}{F_\ell}) \quad . \tag{3.1-23}$$

Other logic for determining the junction enthalpy is the same as in JENTH=1.

(iv) JENTH=3

If JENTH=3, the junction enthalpy is calculated as the average enthalpy of the volume upstream of the junction regardless to the model used in the volume.

3.1.6 Fluid flow equation between two control volumes

The fluid flow equation is obtained by integrating Eq. (3.1-3) over the flow volume between the midpoints of two adjacent control volume. The typical flow volume used in ALARM-P1 is shown in Fig. 3.1.4. The integration from the station 1 to the station 2 as shown in Fig. 3.1.4 takes the following general form:

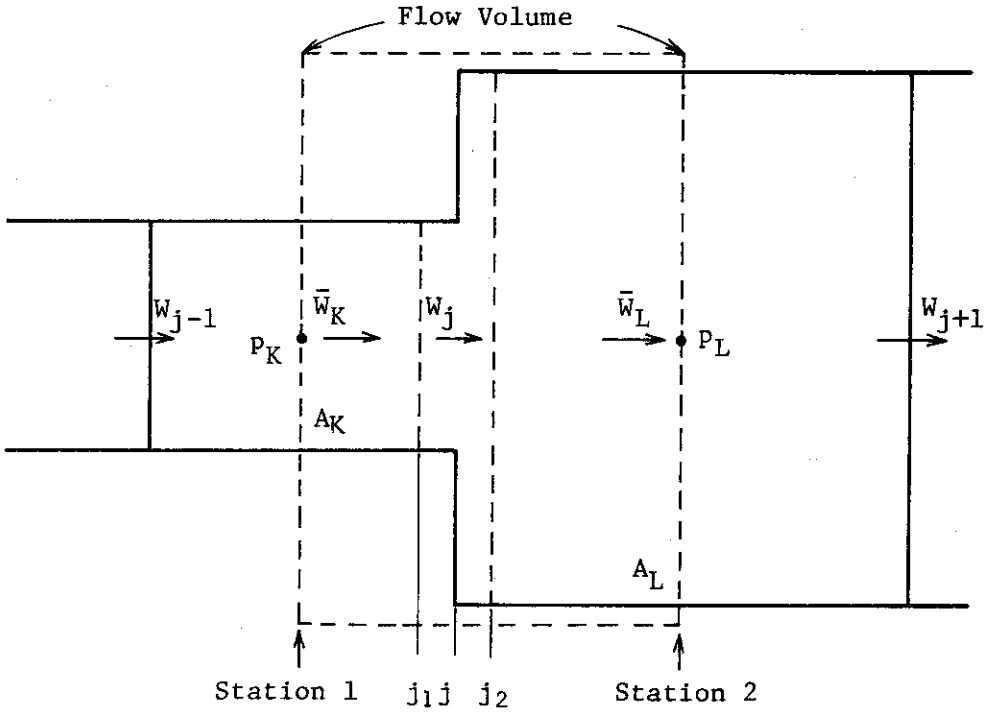


Fig. 3.1.4 Flow Volume

$$\frac{1}{g_c}\left(\frac{\ell}{A}\right)_j \frac{dW_j}{dt} = (p_K - p_L) + \Delta p_g + \Delta p_{flux} + \Delta p_{fric} + \Delta p_{pump} \qquad (3.1\text{-}24)$$

where

$(p_K - p_L)$ = thermodynamic pressure difference between two adjacent volumes,

Δp_g = pressure difference due to elevation change between two adjacent volumes,

Δp_{flux} = pressure difference due to momentum flux between two adjacent volumes,

Δp_{fric} = pressure difference due to friction in flowpath between two adjacent volumes,

Δp_{pump} = pressure rise due to rotating pump,

W_j = mass flow rate at junction j,

$(\frac{\ell}{A})_j$ = geometric inertia for junction j,

g_c = gravitational conversion factor (9.8 Newton/kgf).

Each term included in Eq. (3.1-24) is explained below in detail.

(1) Temporal momentum change

The geometric inertia included in the temporal momentun term is calculated in the code

$$(\frac{\ell}{A})_j = \frac{\ell_K}{2A_K} + \frac{\ell_L}{2A_L} \tag{3.1-25}$$

where

ℓ_K, ℓ_L = volume lengths for two adjacent volumes,

A_K, A_L = volume flow areas for two adjacent volumes.

Input geometric inertia is also allowed (see Appendix A §2.9).

(2) Momentum flux

The momentum flux term includes the effects due to the momentum convection, momentum change due to area change and compression. The integration of the first term of the right hand side in Eq. (3.1-3) over the flow volume gives:

$$-\frac{1}{g_c}\int_1^2 \frac{1}{A}\frac{d(vW)}{dx}dx = -\frac{\bar{V}_L\bar{W}_L}{g_cA_L} - \frac{\rho_{j1}v_{j1}^2}{g_c} + \frac{\bar{V}_K\bar{W}_K}{g_cA_K} + \frac{\rho_{j2}v_{j2}^2}{g_c} - \frac{1}{g_c}\int_{j1}^{j2}\frac{1}{A}d(vW)\ , \tag{3.1-26}$$

and the last term of the right hand side in Eq. (3.1-26) is simplified under the assumptions[9]: (1) mass flow rate W_j is spatially constant between j1 and j2, (2) flow is isentropic between j1 and j2, and this assumption allows Bernoulli equation with constant sonic velocity,

$$\frac{1}{g_c}\int_{j1}^{j2}\frac{1}{A}d(vW) = \frac{1}{g_c}\int_{j1}^{j2}\rho v dv = -c_j^2(\rho_{j2}-\rho_{j1}) \tag{3.1-27}$$

where

j1 = refers to the outlet side of Volume K adjacent to the junction Area A_j,

j2 = refers to the inlet side of Volume L adjacent to the junction Area A_j,

$\bar{W}$ = volume average mass flow to be defined later,

$\bar{v}$ = volume average velocity,

ρ_{j1}, ρ_{j2} = fluid density at the inlet side of volume K and the outlet side of volume L, respectively,

v_{j1}, v_{j2} = fluid velocity at the inlet side of volume K and the outlet side of volume L, respectively,

c_j = fluid sonic velocity or $\sqrt{g_c(\frac{\partial p}{\partial \rho})_s}$,

s = subscript refering to constant entropy.

Integration of Bernoulli equation with constant sonic velocity between j1 and j2 gives:

$$\int_{j1}^{j2} \frac{1}{\rho} d\rho = -\int_{j1}^{j2} \frac{v}{c} d(\frac{v}{c}) = \int_{j1}^{j2} - MdM$$

which is reduced to

$$\rho_{j2} = \rho_{j1} e^{-\frac{(M_{j2}^2 - M_{j1}^2)}{2}} \qquad (3.1\text{-}28)$$

where

M_{j1}, M_{j2} = Mach number at the inlet side of volume K and the outlet side of volume L, respectively.

According to the assumption (i) mentioned above, using the relation: $\rho_{j1} v_{j1} A_K = \rho_{j2} v_{j2} A_L$ simplifies Eq. (3.1-28):

$$(\frac{A_K}{A_L}) = (\frac{M_{j2}}{M_{j1}}) e^{-\frac{(M_{j2}^2 - M_{j1}^2)}{2}}$$

The downstream junction density and Mach number are calculated by both Eq. (3.1-28) and Eq. (3.1-29), respectively. The upstream junction density and Mach number used in ALARM-P1 are defined as given below:

(i) if $W_j > 0$, $\rho_{j1} = \rho_K$: density in volume K at junction elevation,

$$M_{j1} = \frac{|W_j|}{\rho_{j1} A_K c_K} ,$$

(ii) if $W_j < 0$, $\rho_{j2} = \rho_L$: density in volume L at junction elevation,

$$M_{j2} = \frac{|W_j|}{\rho_{j2} A_L c_L} ,$$

where

c_K, c_L = sonic velocity at the inlet side of volume K and the outlet side of volume L, respectively.

Newton-Raphson procedure is used to solve both Eq. (3.1-28) and Eq. (3.1-29). If the calculated Mach number in either the upstream or the downstream volume exceeds unity, the flow is assumed to be choked and the flow equation is redefined such that the temporal momentum term is ignored. An optional critical flow calculation is available from tables of critical mass flux versus source pressure and enthalpy or experimental correlations depending on the source fluid conditions (see §3.1). When mass flows are calculated from both the flow equation and critical flow model, the accepted value is the minimum of the two flows.

(3) Pressure difference due to elevation change

The pressure change due to elevation change between two fluid volumes is calculated in the following manner:

$$\Delta p_g = -\cos\theta \frac{g}{g_c} \int_1^2 \rho dz = -\frac{g}{g_c} \left[\int_{z_K}^{z_j} \rho_K dz + \int_{z_j}^{z_L} \rho_L dz \right] \qquad (3.1\text{-}30)$$

where

z_j = junction elevation,

z_K, z_L = elevation of the center of volume K and volume L, respectively,

ρ_K, ρ_L = density of volume K and volume L, respectively.

If the bubble rise model is not applied, densities used in Eq. (3.1-30) are volume average densities.

(4) Frictional pressure drop

The frictional pressure drop in flow path is expressed by the following four terms:

$$\Delta p_{fric} = F_{fK} + F_{fL} + F_{fR} + F_{EC} \qquad (3.1\text{-}31)$$

where

F_{fK}, F_{fL} = Fanning friction pressure loss within each half-volume or $4f \frac{\ell}{2D_h} \left(\frac{|\bar{W}|\bar{W}}{2g_c \rho A^2}\right) \Phi_{2p}$,

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

F_{EC} = expansion or contraction friction between volume K and L,

f = fanning friction factor,

ℓ = volume length,

D_h = hydraulic flow diameter,

ρ = fluid density,

$\bar{W}$ = volume average mass flow to be difined later,

Φ_{2p} = two-phase multiplier for increased friction,

A = volume flow area.

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

$$\frac{1}{\sqrt{f}} = -0.4 + 4 \log_{10}(Re\sqrt{f}) \quad \text{with } Re > 2100 \qquad (3.1\text{-}32)$$

and for laminar flow is

$$f = \frac{16}{Re} \quad \text{with } Re \leq 2100 \qquad (3.1\text{-}33)$$

where

Re = Reynolds number.

Though the cross-over Reynolds number between Eq. (3.1-32) and Eq. (3.1-33) is the value of 1000, the transition Reynolds number from laminar to turbulent flow used in ALARM-P1 is 2100[10]. The viscosity for calculating the Reynolds number is assumed to be dependent only on the fluid temperature, namely, saturated liquid viscosity for liquid phase and saturated gas viscosity for vapor phase are used. For two-phase fluid, the saturated liquid viscosity is used in conjunction with the two-phase friction multiplier.

For two-phase pressure loss, the single-phase friction loss for total mass flow rate as saturated liquid is first calculated by using the calculated Fanning value and fluid density for saturated fluid. The correct two-phase pressure drop is obtained by multiplying the single-phase value by the two-phase friction multiplier, which is calculated as a function of pressure and quality through the interpolation of tabular data based on Thom[11] and Martinell's[12] correlations.

The expansion or contraction friction loss, F_{EC} is defined in terms of a form-loss coefficient:

$$F_{EC} = K_f \frac{\rho_j v_j |v_j|}{2g_c} \qquad (3.1\text{-}34)$$

where

K_f = dimensionless form loss coefficient,

ρ_j = fluid density at junction j defined as the same as ρ_{j1} and ρ_{j2} in Eq. (3.1-28),

v_j = fluid velocity at junction j or $= \frac{W_j}{A_j \rho_j}$

A_j = junction flow area.

The form loss coefficient, K_f can be calculated on the basis of the junction flow area A_j and the upstream and downstream areas, A_K and A_L, and is dependent on the flow direction. If both the forward (FRIFF) and reverse form loss coefficient (FRIFR) are entered zeros, respectively, ALARM-P1 calculates special form loss coefficients based on sharp-edged area change depending on the flow direction.[10)]

For a sudden expansion,

$$K_f = \left(\frac{A_j}{A_{downstream}} - 1\right)^2 , \tag{3.1-35}$$

and for a sudden contraction,

$$K_f = 0.45\left(1 - \frac{A_j}{A_{upstream}}\right) . \tag{3.1-36}$$

If other form loss coefficients such as for orifices or elbows and combination of them are required, the user must provide those coefficients. ALARM-P1 does not multiply the form loss coefficients by the two-phase friction multiplier because of lack of experimental data.

The residual friction term is calculated from the given steady state flow and pressures of both the inlet and the outlet volume and is expressed as given below:

$$F_{fR} = R_{j0} \Phi_{2p} \frac{W_j |W_j|}{\rho_j} \tag{3.1-37}$$

where

R_{j0} = initial single phase residual coefficient corresponding to initial mass flow rate, which has dimension: $K_{gf} \cdot sec^2/Kgm \cdot m^5$,

Φ_{2p} = two-phase multiplier estimated by using junction pressure and quality.

The residual friction term includes other various effects to cause pressure drop than described above. ALARM-P1 tentatively applies the two-phase

friction multiplier for the residual term. ALARM-P1 allows the loss coefficients of a check valve and a stalled rotor of a pump which have the same dimensions as the residual coefficient (see Appendix A §2.8 and §2.10).

The volume average flow $\bar{W}$ appeared in the previous section and ealier part of this section is explained below. Since the fluid volume V_i is assumed to have basically a constant flow area A_i at both inlet and outlet side and this assumption is required to derive the fluid flow equation, the volume average mass flow is assumed to be the average of the inlet and outlet flows. The formulation for the volume average flow, which is finally the same as in RELAP4[2], is derived from the manner such that the momentum change between inlet and outlet is conserved[13]:

$$\Delta W_i \cdot (Av)_i = \bar{W}_i \cdot \Delta(Av)_i + \frac{\bar{W}_i}{\bar{\rho}_i} \Delta W_i = W_{out} \cdot (Av)_{out} - W_{in} \cdot (Av)_{in} \tag{3.1-38}$$

and solving this equation for $\bar{W}_i$ gives

$$\bar{W}_i = \frac{W_{out} \cdot (Av)_{out} - W_{in} \cdot (Av)_{in}}{\Delta(Av)_i + \frac{\Delta W_i}{\bar{\rho}_i}} \tag{3.1-39}$$

where

$\bar{W}_i$ = average folow of volume i,

$\Delta(Av)_i$ = volumetric flow change between inlet and outlet side,

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

ΔW_i = mass flow change between inlet and outlet side,

$W_{out} \cdot (Av)_{out}$ = momentum flux at outlet side,

$W_{in} \cdot (Av)_{in}$ = momentum flux at inlet side.

Furthermore, Eq. (3.1-39) is modified from using the junction quantities:

$$\bar{W}_i = \frac{\left(\sum_{j,inlet} W_{ij}\right)\left(\sum_{j,inlet} A_j v_j\right) - \left(\sum_{j,outlet} W_{ij}\right)\left(\sum_{j,outlet} A_j v_j\right)}{\sum_{j,inlet} A_j v_j - \sum_{j,outlet} A_j v_j + \frac{\sum_{j,inlet} W_{ij} - \sum_{j,outlet} W_{ij}}{\bar{\rho}_i}} \tag{3.1-40}$$

where

W_{ij} = mass flow entering or leaving volume V_i,

A_j = junction area,

v_j = junction velocity.

The volume flow resulting from Eq. (3.1-40) might be divergent when the flowing fluid is subcool and near steady ($W_{in} \doteqdot W_{out}$ and $(Av)_{in} \doteqdot (Av)_{out}$).

Therefore another formulation is provided to avoid the above drawback:

$$\bar{W}_i = \frac{1}{2}\left(\sum_{j,\text{inlet}} W_{ij} + \sum_{j,\text{outlet}} W_{ij}\right) \qquad (3.1\text{-}41)$$

The accepted volume average flow is the minimum of two values calculated by both Eq. (3.1-40) and Eq. (3.1-41).

Finally, the optional forms of the fluid flow equations which are provided in ALARM-P1 are described. ALARM-P1 provides the following three options:

(1) The mass flow is calculated by Eq. (3.1-24); IANGL=0 (see Appendix A §2.9)

(2) The mass flow for the flow path which injection fluid flows into is calculated by accounting for the momentum mixing due to inclined injection pipe flow. In ALARM-P1 the injection pipe must be connected to the peripheral side of volume K as shown in Fig. 3.1.5. To account for this condition a term is simply added to Eq. (3.1-26) for calculation of p_{flux}. The fluid flow equation for junction j+1 in Fig. 3.1.5 is then modified to the following:

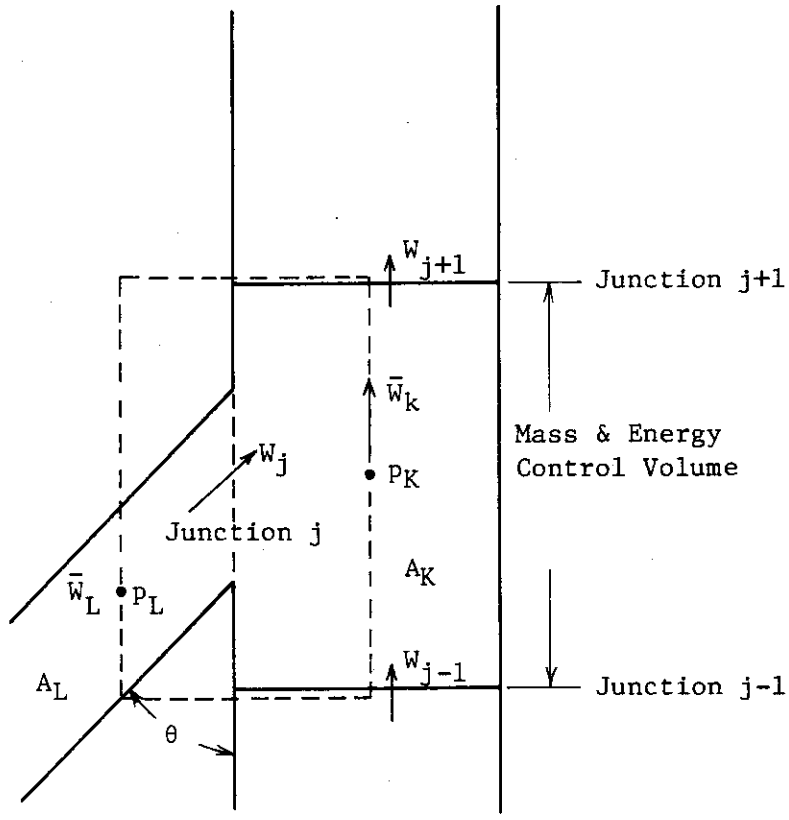


Fig. 3.1.5 Inclined Injection Pipe

$$\Delta p_{flux} \text{ of junction j+1 with injection pipe} = \Delta p_{flux} \text{ of Eq. (3.1-26)} + \frac{W_j v_{j,axial}}{g_c A_K} \quad (3.1\text{-}42)$$

where

W_j = injection mass flow,

$v_{j,axial}$ = axial component of injection velocity or $\frac{W_j \cos\theta}{\rho_j A_j}$,

θ = injection pipe angle to the vertical flow path.

In the above, the injection mass flow rate W_j is given by either (1) above or (3) below; IANGL=1 (see Appendix A §2.9)

(3) The mass flow is calculated by the equation ignoring Δp_{flux} of Eq. (3.1-24). This option is reasonable for T shaped connections such as the junction between the cold leg and the downcomer; IANGL=2 (see Appendix A §2.9)

3.1.7 Critical flow models

The critical flow calculation is the most important for the analysis of blowdown in terms of determining the depressurization rate for the system. For major period during blowdown the fluid flow rate through breaks is limitted due to the critical flow conditions and definitely controls the time of blowdown. ALARM-P1 provides the critical flow check not only at break junctions but in any junctions specified by the code input (MDCOEF > 0, see Appendix A §2.9). The following three models are used depending on the fluid conditions.

(1) Subcooled critical flow

For both subcooled liquid and two-phase fluid in low quality region, Moody's critical flow model[14] underpredicts the mass flow in comparison with experimental data. In ALARM-P1 Zaloudek's correlation[15] is modified and used for both subcooled region and saturated region when the stagnation quality is less than 2%:

$$G = C_0\sqrt{2g_c\rho(p - C_B P_{sat})} \quad (3.1\text{-}43)$$

where p is the reservoir pressure, the factor C_0 is a value of 4.64 and the back pressure factor C_B is unity according to Zaloudek's correlation.

However, in ALARM-P1, the C_B is an input and the C_0 is determined so as to smoothly connect critical flows between Zaloudek's and Moody's critical flow model at the transition quality

$$G_{moody}(p_{sat},X_t) = C_0\sqrt{2g_c\rho p_{sat}(1-C_B)} \qquad (3.1\text{-}44)$$

where

p_{sat} = saturation pressure at stagnation fluid temperature,
X_t = transition quality from Zaloudek's to Moody model,
$G_{moody}(p_{sat},X_t)$ = Moody critical mass flux at p_{sat} and X_t,
C_B = input constant $0.5 \leq C_B < 1$.

In the present version of ALARM-P1, the transition quality of 0.02 is used.

(2) Saturated critical flow

The saturated critical flow rate is calculated using Moody's correlation[14]. This correlation gives a mass velocity as a function of stagnation pressure and enthalpy. ALARM-P1 uses the Moody critical flow tables in the form of critical mass flux versus the upstream volume stagnation pressure and enthalpy in the saturated regime. The stagnation pressure and enthalpy are assumed to be those in the volume to which the junction is connected. The critical flow of the junction is calculated by

$$W_{choke} = A\cdot C_D\cdot G(p_0,h_0) \qquad (3.1\text{-}45)$$

where

W_{choke} = critical mass flow rate,
A = flow area,
G = mass velocity as a function of stagnation pressure p_0 and enthalpy h_0 built in tabular data,
C_D = multiplier to Moody's critical flow rate.

(3) Superheated critical flow

The critical flow calculation for superheat flow is performed from Murdock and Bauman[16] correlation which is based on the critical flow function, $\Phi = GT^{1/2}/p_1$ determined by the theoretical critical flow rate of superheated steam through nozzles or other passages:

$$G = 220.91\ \sqrt{p\cdot\rho} \qquad (kgm/m^2\text{-}sec)\ . \qquad (3.1\text{-}46)$$

3.1.8 Leak and fill system

The leak and fill systems specify the time dependent boundary conditions for the system to be calculated. Water such as the feed water of steam generator secondary may be injected into any volumes by means of fill junctions. Leak junctions also can be set up at any volume. Initiation of flow through these junctions may be controlled by various trip signals.

(1) The following two options can be selected as input leak data set:
  (i) Leak flow area vs. time,
  (ii) Leak mass flow rate vs. time.

In the option (i) above, the mass flow rate is sometimes limitted by choked flow as described in the previous section. The flow rate through the leak junction is chosen as the smaller of the choked flow and the flow calculated by the standard orifice equation:

$$G = \sqrt{2g_c\rho(p - p_{exit})} \qquad (3.1\text{-}47)$$

where p_{exit} is the sink pressure given by an input, and this equation is always used if choking flow is no longer occurring.

(2) The following three options can be selected as input fill data set:
  (i) fill flow rate vs. time,
  (ii) fill flow rate vs. pressure of the volume to be injected,
  (iii) fill flow rate vs. pressure difference between the volume and reservoir.

Temperature, enthalpy or quality is also specified as an input to determine injected fluid energy.

3.1.9 Valves and check valves

Valves and Check Valves may be placed, at the user's option, in any junction. Two hypothetical valves are available. One is an initially open valve which instantaneously closes by a trip control signal. Another is reverse to that. These valves are used to simulate such transient as the onset of the double-ended pipe breake.

The model of check valves used in ALARM-P1 is similar to in RELAP3[1] which provides two types of check valves. Three loss coefficients and the back pressure to close the valve are user supplied input constants. Two types are described in the following.

(1) Type 1 without a hysteresis loop in the characteristic flow versus pressure curve as shown in Fig. 3.1.6. For positive flow ($W \geqq 0$), the valve remains open and sustain a pressure loss given by

$$\Delta p_{CHK} = C_1 \frac{W^2}{\rho} \quad , \tag{3.1-48}$$

and for negative flow, the valve remains open if the pressure loss, whose loss coefficient is C_2, is less than the back pressure, p_{CV} required to close the valve:

$$\Delta p_{CHK} = C_2 \frac{W^2}{\rho} < p_{CV} \quad , \tag{3.1-49}$$

where p_{CV} is back pressure for closure (kgf/m^2).
After the valve closes, the pressure loss is calculated by

$$\Delta p_{CHK} = C_3 \frac{W^2}{\rho} \quad . \tag{3.1-50}$$

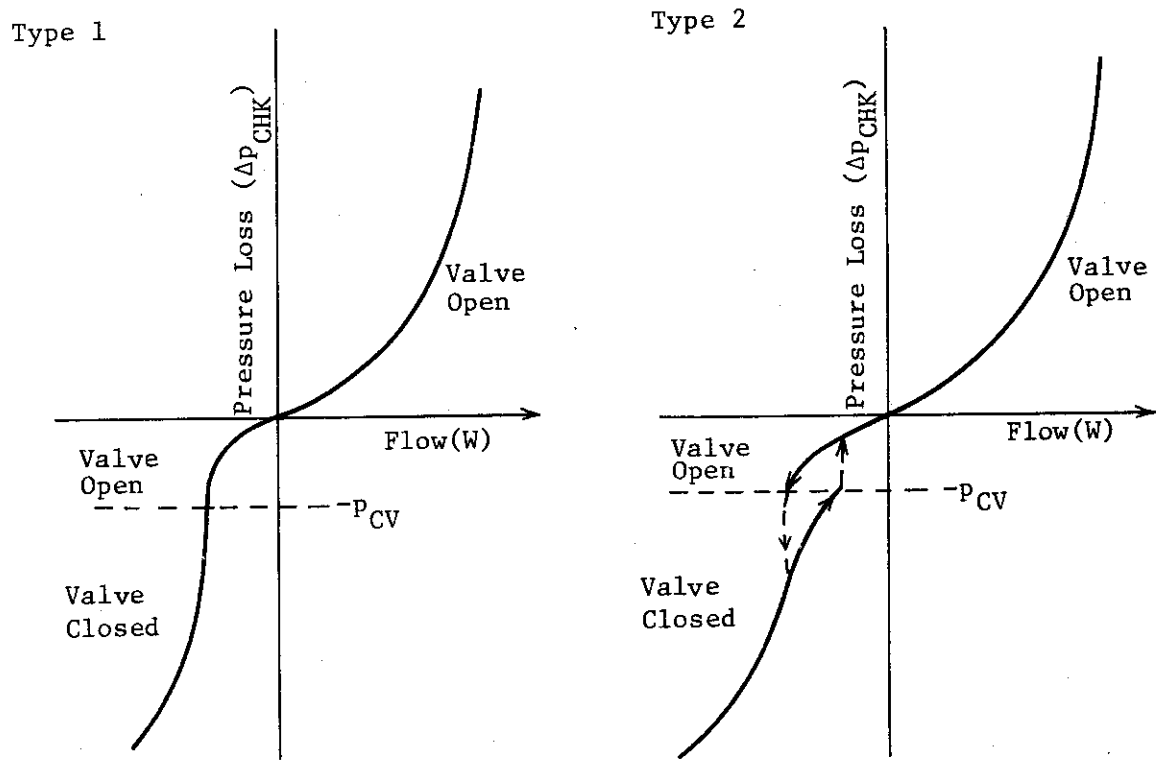


Fig. 3.1.6 Check Valve Characteristic Curves

where C_1, C_2, and C_3 is friction coefficient for forward flow, for reverse flow at valve open, and for reverse flow at valve closed respectively. Type 1 check valves reopen when negative flow has decreased to a value such that the pressure loss for the open phase (C_2W^2/ρ) is less than the back pressure, p_{CV} required to keep the valve closed.

(2) Type 2 with the hysteresis as shown in Fig. 3.1.6. The valve action for from positive flow to negative through a closure of the valve is completely the same as Type 1. The different action from Type 1 is that a Type 2 valve reopens only when the pressure loss developed in the closed position, which is given below, is less than the required back pressure:

$$\Delta p_{CHK} = C_3 \frac{W^2}{\rho} < p_{CV}. \qquad (3.1\text{-}60)$$

The hysteresis difference between Type 1 and Type 2 is apparent in Fig. 3.1.6.

3.1.10 Steam table

The thermodynamic properties of water required by ALARM-P1 are provided in the form of a external data set. The data set in the proper format for ALARM-P1 is generated by the STH2O program[17]. Properties stored in the tables of water properties as functions of pressure and temperature include specific volume, specific internal energy, coefficient of thermal expansion, isothermal compressibility, and isobaric heat capacity.

Subroutines to calculate the water properties at a given state from different sets of input variables, which are similar to those used in RELAP4,[2] are also included. The permissible set of primary variables includes (a) temperature and quality for a two-phase condition (b) pressure and quality for a two-phase (c) temperature and pressure for a single-phase (d) temperature and specific volume for a single or two-phase and (e) pressure and enthalpy for a single or two-phase.[18] Water properties in the STH2o data tables and above subroutines are in SI unit.

If the known thermodynamic quantities are not included in the above permissible set of variables, the quantities unknown are obtained from interating over known variables. For example, the quantities known within any volume after the mass and energy equations have been integrated over a time step are the total water mass, the total air mass and the combined internal energy of both water and air. From these variables, specific internal energy and volume of water within volume are directly obtained under

an assumption of air being a perfect gass with a constant specific heat. The fluid property routine iterates over the temperature by using the Newton-Raphson Method[2] until the computed internal energy converges to the valve obtained from integrating the energy equation.

3.2 Power generation in reactor core

During LOCA period, there are three sources of energy due to nuclear reaction. They are the fission power and the decay heat of fission products and actinides. ALARM-P1 takes all these three into account. ALARM-P1 has also an option with an input table specifying normalized power vs. time after scram where the initial core power continues until the trip has occurred. The description of calculation of these heat generations is given below.

3.2.1 Reactor kinetics

The fission heat calculated by ALARM-P1 utilizes a point reactor kinetics model with 6 groups of delayed neutrons, namely:

$$\frac{d}{dt} n(t) = \frac{\delta k - \beta}{\ell} n(t) + \sum_{i=1}^{6} \lambda_i C_i(t) , \qquad (3.2\text{-}1)$$

$$\frac{d}{dt} C_i(t) = -\lambda_i C_i(t) + \frac{\beta_i}{\ell} n(t) , \qquad (3.2\text{-}2)$$

where

n = neutron density,

β = effective delayed neutron fraction,

ℓ = neutron life time,

δk = total reactivity,

λ_i = decay constant of delayed neutron precursor of group i,

C_i = concentration of delayed neutron precursor of group i,

β_i = effective fraction for delayed neutron precursor of group i.

Normalizing above two equations to initial neutron density, it gives

$$\frac{d}{dt} n'(t) = \frac{\beta(R(t)-1)}{\ell} n'(t) + \frac{1}{\ell} \sum_{i=1}^{6} \beta_i C_i'(t) , \qquad (3.2\text{-}3)$$

$$\frac{d}{dt} C_i'(t) = \lambda_i \{n'(t) - C_i'(t)\}, \qquad (3.2\text{-}4)$$

where

$n'(t)$ = $n(t)/n(0)$ neutron density normalized to initial neutron density,

$R(t)$ = $\delta k/\beta$ total reactivity normalized to the delayed neutron fraction ($),

$C_i'(t) = \ell\lambda_i C_i(t)/\beta_i n(0)$ concentration of delayed neutron group i normalized to initial neutron density.

Default values of β_i and λ_i[2], if the delayed neutron constans are not supplied as input data (IPCT=0, ITBL=0), are shown in Table 3.2.1.

The reactivity insertion R(t) in Eq. (3.2-3) is calculated by:

$$R(t) = R_0 + R_{rod}(t) + \sum_{i}^{NOCOR} \{R_{\rho i}(t) + R_{FTi}(t)\} . \qquad (3.2\text{-}5)$$

Table 3.2.1 Delayed Nuetron Constants

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

The first term, R_0 represents initial reactivity. The second term, $R_{rod}(t)$ represents the reactivity contribution due to control rod insertion. This reactivity may be supplied by an input table specifying reactivity vs. the time after scram where the trip time is determined by the trip control as described in §4.1.

The third term $R_{\rho i}(t)$ describes the reactivity feedback associated with changes in moderator density and is estimated from the following two options.

The equation of option 1 (INWDOP=1) is given by

$$\sum_{i=1}^{NOCOR} R_{\rho i}(t) = A_\rho \bar{\rho}(t) + \frac{1}{2} B_\rho \bar{\rho}^2(t) + \frac{1}{3} C_\rho \bar{\rho}^3(t) - A_\rho \bar{\rho}(0) - \frac{1}{2} B_\rho \bar{\rho}^2(0) - \frac{1}{3} C_\rho \bar{\rho}^3(0), \qquad (3.2\text{-}6)$$

where A_ρ, B_ρ, and C_ρ are input constants, and $\bar{\rho}(t)$ is the average density weighted by the flow area in the core region,

$$\bar{\rho}(t) = \sum_{i=1}^{NOCOR} A_i \rho_i(t) / \sum_{i=1}^{NOCOR} A_i . \qquad (3.2\text{-}7)$$

The equation of option 2 (INWDOP=2) is given by

$$R_{\rho i}(t) = R_\rho\left\{\frac{\bar{\rho}(t)}{\bar{\rho}(0)}\right\} W_\rho^i - R_\rho\{1\}W_\rho^i \ , \qquad (3.2\text{-}8)$$

where

$R_\rho\{\frac{\bar{\rho}(t)}{\bar{\rho}(0)}\}$= reactivity as a function of normalized moderator density for entire core,

$\bar{\rho}(t)$ = average moderator density calculated with weighting factors based on the volumes in the core region,

W_ρ^i = weighting factor for moderator density feedback of core region i.

The reactivity R_ρ is be supplied by an input table specifying reactivity vs. moderator density. The weighting factors W_ρ^i is also supplied by input.

The final contribution to reactivity in Eq. (3.2-5) is Doppler broadening of capture resonance due to changes in fuel temperature. This contribution is also estimated from the following two options.

The equation of option 1 (IDOPOP=1) is given by

$$\sum_{i=1}^{NOCOR} R_{FTi}(t) = R_{FT}\{a_1\sqrt{a_2\bar{T}_F+a_3} - a_4\bar{T}_F - a_5\} - R_{FT}\{a_1\sqrt{a_2\bar{T}_{F0}+a_3} - a_4\bar{T}_{F0} - a_5\}, \qquad (3.2\text{-}9)$$

where a_1, a_2, a_3, a_4, and a_5 are built-in constants in the code, and the effective fuel temperature, $\bar{T}_F$ is calculated from the equation.

$$\bar{T}_F = \sum_{i=1}^{NOCOR} (0.85\bar{T}_{Fi} + 0.15T_{Si})A_i / \sum_{i=1}^{NOCOR} A_i \ , \qquad (3.2\text{-}10)$$

where

$\bar{T}_{Fi}$ = fuel average temperature of core region i,

T_{Si} = fuel surface temperature of core region i,

A_i = heat transfer area in core region i.

A value of -1.0 is normally used as Doppler multiplier, R_{FT}.

The equation of option 2 (IDOPOP=2) is given by

$$R_{FTi}(t) = R_{FT}\{\bar{T}_{Fi}(t)\}W_{FT}^i - R_{FT}\{\bar{T}_{Fi}(0)\}W_{FT}^i \ , \qquad (3.2\text{-}11)$$

where

$\bar{T}_{Fi}$ = average fuel temperature in core region i,

$R_{FT}\{\bar{T}_{Fi}(t)\}$= reactivity as a function of average fuel temperature in entire core,

W_{FT}^{i} = weighting factor for fuel temperature feedback of core region i.

The reactivity R_{FT} may be given by an input table of reactivity vs. fuel temperature. The weighting factor for each core region may also be given as input data.

In the ALARM-P1 code, the fuel and the moderator temperature reactivity coefficients are ignored since these effects are included in the density and the Doppler reactivity functions.

The numerical method to solve Eq. (3.2-3) and (3.2-4) is similar to that used in IREKIN[19] program.

3.2.2 Fission product decay and decay of actinides

Decay of ^{235}U fission products is calculated by a relationship of the form of the summation of eleven decay equations which are made so as to fit the value of ANS standard after the reactor power is stepwise decreased after infinite operation. Decay heat of actinides is assumed to be constant fraction, α_{act} of initial core power. This is conservative because the initial power fraction of the actinides is equal to α_{act} and decreases continuously during the transient.

The equation for decay of ^{235}U fission products is assumed to be the following equation:

$$\frac{d}{dt} \chi_{Dj} = \lambda_{Dj} \left(\frac{n(t)}{n(0)} - \chi_{Dj} \right) , \qquad (3.2\text{-}12)$$

where

χ_{Dj} = normalized concentration of fission product of group j,

λ_{Dj} = appearent decay constants of fision product of group j.

The normalized power with yield fraction of decay heat group j and actinides is given by

$$\frac{P(t)}{P(0)} = (1 - \alpha_D - \alpha_{act}) \frac{n(t)}{n(0)} + \sum_{j=1}^{11} \alpha_{Dj} \chi_{Dj} + \alpha_{act}, \qquad (3.2\text{-}13)$$

where

α_{Dj} = appearent yield fraction of decay heat group j,

$\alpha_D = \sum_{j=1}^{11} \alpha_{Dj}$.

Default values of α_{Dj}, λ_{Dj} and α_{act}[2], if the fission product constants

are not supplied as input data (IPCT=0, ITBL=0), are presented in Table 3.2.2. These built-in data are based on the ANS standard for infinite operating time. Equation (3.2-12) is solved by the same manner as the fission power equations are solved.

Table 3.2.2 Constants for Fission Product Decay Heat

Group	Steady state power fraction of F.P. α_{Dj}	Decay constant $\lambda_{Dj}(sec^{-1})$	α_{act}
1	0.00299	1.772	0.0032
2	0.00825	5.774×10^{-1}	
3	0.01550	6.743×10^{-2}	
4	0.01935	6.214×10^{-3}	
5	0.01165	4.739×10^{-4}	
6	0.00645	4.810×10^{-5}	
7	0.00231	5.344×10^{-6}	
8	0.00164	5.726×10^{-7}	
9	0.00085	1.036×10^{-7}	
10	0.00043	2.959×10^{-8}	
11	0.00057	7.585×10^{-10}	
Total	0.06999		

3.3 Reactor coolant pump

At the initiation of large break LOCA, the pump will begin to coast down because of a trip signal (postulated loss of electric power). The pump will operate with non-cavitating subcooled, cavitating subcooled, net two phase and super heated flow condition during different portions of the transient. The pump model in ALARM-P1 is based on all combination of flow and speed using the homologous relationships and cavitation model similar to Thoma's model.[21)]

The dimensionless homologous relations[22)] for head and torque can be expressed by

$$h/\alpha^2 = \text{const.} \ , \ v/\alpha = \text{const.} \ , \tag{3.3-1}$$

$$h/v^2 = \text{const.} \ , \ \alpha/v = \text{const.} \ , \tag{3.3-2}$$

$$\beta/\alpha^2 = \text{const.} \ , \ v/\alpha = \text{const.} \ , \tag{3.3-3}$$

$$\beta/v^2 = \text{const.} \ , \ \alpha/v = \text{const.} \ , \tag{3.3-4}$$

where

$h = H/H_0$: normalized head,

$v = Q/Q_0$: normalized volumetric flow,

$\alpha = N/N_0$: normalized speed,

$\beta = T/T_0$: normalized torque,

H = head,

Q = volumetric flow,

T = torque,

N = angular speed.

The head and torque are derived from the following set of pump characteristic curves specified as tabular input data, "0" indicates the rated operating value:

(A) head vs. flow at rated speed.

(B) head vs. flow at negative rated speed.

(C) head vs. speed at rated flow.

(D) head vs. speed at reversal rated flow.

(E) torque vs. flow at rated speed.

(F) torque vs. flow at negative rated speed

(G) torque vs. speed at rated flow.

(H) torque vs. speed at reversal rated flow.

The above eight characteristic curves are utilized in the following manner.

(i) $|v|<|\alpha|$,

if $v \geqq 0$ (A) and (E) are used,

if $\alpha < 0$ (B) and (F) are used.

(ii) $|v|>|\alpha|$,

if $v \geqq 0$ (C) and (G) are used,

if $v < 0$ (D) and (H) are used.

For example, in the case of $|v|<|\alpha|$ and $\alpha \geqq 0$, the normalized volumetric flow divided by the normalized speed gives the modified flow corresponding to the rated speed and the reduced head and hydraulic torque corresponding to the above modified flow is found from the curves (A) and (E) respectively. To find the true value, the reduced head and torque are multiplied by the square of the normalized speed according to the Eq. (3.3-1) and Eq. (3.3-2). In the case of using the curves at rated flow, the similar procedures are performed.

As the hydraulic torque found in the calculation above is for the fluid conditions at normal operation, it must be modified to account for the changes in the fluid density. This modification is made by

$$T_h = T_0 \beta \rho / \rho_0 \quad , \tag{3.3-5}$$

where

T_h = hydraulic torque,

T_0 = rated hydraulic torque,

β = normalized torque by homologous law,

ρ_0 = rated fluid density,

ρ = fluid density.

The pressure rise across the pump is determined from the normalized head:

$$\Delta P_{pump} = H_0 h \rho \quad , \tag{3.3-6}$$

where

H_0 = rated head,

h = normalized head by homologous law.

When cavitation is expected, the pump pressure and hydraulic torque are modified by the following cavitation model[23]:

$$\Delta p'_{pump} = \Delta p_{pump} - \sigma X_e \ , \tag{3.3-7}$$

$$T_h' = T_h - \sigma X_e W/\omega\rho \ , \tag{3.3-8}$$

where

Δp_{pump} = cavitated pump pressure rise,
T_h' = cavitated hydraulic torque,
σ = cavitation constant (input data),
X_e = quality at impeller eye,
W = mass flow rate,
ω = angular velocity ($2\pi N/60$).

The eye quality, X_e is evaluated from the pump suction enthalpy and the eye pressure. The eye pressure is calculated by

$$p_{eye} = p_{up} - \Delta p_{NPSH} \ , \tag{3.3-9}$$

where

p_{eye} = eye pressure,
p_{up} = pump suction pressure,
Δp_{NPSH} = required net positive suction pressure (tabular input as a function of mass flow rate).

The eye quality, X_e is evaluated from the saturation enthalpy at the eye pressure, p_{eye}. The occurrence of cavitation reduces the backpressure of the pump rotor. In a completely cavitated condition, the pump impeller will be insulated from the liquid phase. The value of quality to produce complete cavitation is estimated from the maximum head loss required to drop the pump head to zero at rated flow and zero speed:

$$X_{e,max}\sigma = H_{max}\alpha^2\rho \tag{3.3-10}$$

where

$X_{e,max}$ = maximum quality at impeller eye,
H_{max} = maximum head loss, this value is at rated flow and zero speed in the characteristic curves, or may be specified as input,
α = normalized speed.

In ALARM-P1, if the eye quality X_e becomes larger than $X_{e,max}$ defined above the pump rotor is assumed to be completely stalled thereafter. The pump

behaves as a flow resistance, and the loss coefficient for the stalled rotor is added to the form loss coefficient.

During coastdown after loss of power, the rate of change of angular momentum of the impeller-flywheel assembly is equated to the hydraulic torque with ignoring the frictional torque:

$$\frac{I}{g_c}\frac{d\omega}{dt} = - T_h(t) \ , \qquad (3.3\text{-}11)$$

where

I = inertia moment of the rotating member,

ω = angular velocity of the pump,

t = time after pump trip,

T_h = hydraulic torque exerted by the pump impeller,

g_c = conversion factor.

During the transient the pressure rise across the pump is calculated by $\Delta p_{pump} = H_0 h \rho$ from the pump characteristic curve as a function of volumetric flow rate which is obtained from the momentum balance including pump head and pump speed determined from the pump coastdown equation. It should be noted that the characteristic curves used in ALARM-P1 is not for transient but for a static condition. The pump coastdown equation is solved by conventional forward explicit method for the finite differences:

$$\omega(t+\Delta t) = \omega(t) - T_h(t)\frac{g_c}{I}\Delta t \ , \qquad (3.3\text{-}12)$$

where

Δt = time step width.

3.4 Heat transfer

The description in this section mainly concerns the models for the heat transfer calculation between the fluid and the heat conductor in a volume. Some heat conductors corresponding to such as fuel rods, pipes or plates may be assigned to a volume. Temperature distribution within each heat conductor is determined by solving the one-dimensional heat conduction equation by the method of the finite differences. Both the heat transfer correlations and the way of selection of heat transfer modes that are used in ALARM-P1 are similar to those used in THETA-1B[24] or RELAP4[2]. The CHF (Critical Heat Flux) prediction is applied only for heat conductors in the core region.

The heat transfer models are described in more detail in the following.

3.4.1 Heat conduction model and numerical method

Numerical approximations for the one-dimensional multi-region heat conduction equation are derived for slab and cylindrical geometry including annulus. Fig. 3.4.1 illustrates the placement of mesh points at which the temperature is to be calculated.

Mesh points are placed such that they lie on the external boundaries of the problem, at the interface between materials, and at equal intervals between the interfaces and/or boundaries except for the gap space. Mesh points in the gap space is not allowed. The heat capacity of gap space is not considered but the gap conductance is considered. A region contains the same material and has a constant spacing between mesh points except for the gap.

Fig. 3.4.2 shows three typical mesh points. Subscripts designate space indexes, namely subscripts 1, r and n designate quantities to the left, right of the mesh point and n-th mesh point respectively. The y's indicate the mesh point spacing, which are not necessarily equal for different regions. Between mesh points, k, (ρc_p), and A indicate the thermal conductivity (kcal/m-sec-°C), the volumetric heat capacity (kcal/m^3°C), and the heat conduction area (m^2), respectively and are assumed to be constant. The k_{1n} is not necessarily equal to the k_{rn}, and similarly for (ρc_p) and A. To obtain the spatial difference approximation for the n-th mesh point, one-dimensional heat conduction equation is integrated over a subvolume as indicated by the dashed line in Fig. 3.4.2. Due to the one dimensional assumption the dimensions of the volume other than the principal axis are

set to unity. For slab geometry, the volume is rectangular solid. For cylindrical geometry, the volume is a cylindrical annulus. The heat conduction terms in the heat conduction equation are modified by transforming the volume integral over the Laplacian to a surface integral using Green's theorem. So the area between mesh points are required. For convenience, the following quantities are defined. For slab geometry,

$$y^v_{1n} = \frac{y_{1n}}{2} \quad , \quad y^v_{rn} = \frac{y_{rn}}{2} \quad ,$$

$$y^s_{1n} = \frac{1}{y_{1n}} \quad , \quad y^s_{rn} = \frac{1}{y_{rn}} \quad , \quad y^b_0 = y^b_N = 1 \ . \tag{3.4-1}$$

For cylindrical geometry,

$$y^v_{1n} = 2\pi \frac{y_{1n}}{2} (x_n - \frac{y_{1n}}{4}), \ y^v_{rn} = 2\pi \frac{y_{rn}}{2} (x_n + \frac{y_{rn}}{4}) \ ,$$

$$y^s_{1n} = \frac{2\pi}{y_{1n}} (x_n - \frac{y_{1n}}{2}), \ y^s_{rn} = \frac{2\pi}{y_{rn}} (x_n + \frac{y_{rn}}{2}) \ ,$$

$$y^b_0 = 2\pi x_0 \ , \quad y^b_N = 2\pi x_n \ . \tag{3.4-2}$$

And for both geometries,

$$D_n = (\rho c_p)_{1n} y^v_{1n} + (\rho c_p)_{rn} y^v_{rn} \ . \tag{3.4-3}$$

The superscripts, v and s refer to volume and surface-gradient weights. The y^b_0 and y^b_N are surface weights used only at surface boundaries adjacent to the fluid.

Using a finite difference approximation to the integral form of the heat conduction equation, the basic difference equation for the n-th mesh point is

$$\frac{(T^{m+1}_n - T^m_n)D_n}{\Delta t} = (T_{n-1} - T_n)k_{1n}y^s_{1n} - (T_n - T_{n+1})k_{rn}y^s_{rn} + (Q_{1n}y^v_{1n} + Q_{rn}y^v_{rn}) \frac{P(t)}{P(0)} \ , \tag{3.4-4}$$

where

T^m_n = temperature at x_n at time t_m (°C),

Q = power density at steady state (kcal/m^3-sec),

$P(t)/P(0)$ = time dependent normalized power,

Δt = mesh width of time.

In Eq. (3.4-4), the source term is assumed to be space and time separable. The power density at steady state may be specified for each region of a heat conductor. While the time dependent normalized power, P(t)/P(0) is calculated from the nuclear kinetic equations including the fission product and actinide decay heat (see §3.2).

Setting the right-hand side of Eq. (3.4-4) equal to zero, the equation for steady state is obtained. For the time-dependent case, the Crank-Nicolson method[4] is applied.

$$\frac{(T_n^{m+1} - T_n^m)D_n}{\Delta t} = \{\frac{T_{n-1}^m + T_{n-1}^{m+1}}{2} - \frac{T_n^{m+1} + T_n^m}{2}\} k_{rn} y_{ln}^s$$
$$-\{\frac{T_n^{m+1} + T_n^m}{2} - \frac{T_{n+1}^{m+1} + T_{n+1}^m}{2}\} k_{rn} y_{rn}^s$$
$$+(Q_{ln} y_{ln}^v + Q_{rn} y_{rn}^v)\frac{1}{2P(0)} \{P(t_{m+1}) + P(t_m)\}. \quad (3.4\text{-}5)$$

In the above equation, the volumetric heat capacities $(\rho c_p)_{ln}$ and $(\rho c_p)_{rn}$ are estimated at the temperature, T_n^m while the thermal conductivity k_{ln} and k_{rn} are estimated at the temperature, $(T_{n-1}^m + T_n^m)/2$ and $(T_n^m + T_{n+1}^m)/2$ by interpolation of the tabular data of the thermal properties vs. temperature.

From Eq. (3.4-5), the difference approximation for the n-th interior mesh point for transient and steady state cases is given by

$$a_n T_{n-1}^{m+1} + b_n T_n^{m+1} + c_n T_{n+1}^{m+1} = d_n^m \quad , \quad (3.4\text{-}6)$$

where

$$a_n = -\frac{k_{ln} y_{ln}^s \Delta t}{2} \quad , \quad c_n = -\frac{k_{rn} y_{rn}^s \Delta t}{2} \quad ,$$

$$b_n = \sigma D_n - a_n - c_n \quad ,$$

$$d_n = -\sigma a_n T_{n-1}^m + \sigma(D_n + a_n + c_n) T_n^m - \sigma c_n T_{n+1}^m$$
$$+ \Delta t \{\frac{P(t_{m+1}) + \sigma P(t_m)}{2P(0)}\} (Q_{ln} y_{ln}^v + Q_{rn} y_{rn}^v),$$

and σ is 1.0 for transient and 0 for steady state with Δt = 1.0.

Figure 3.4.3 represents two mesh points adjacent gap region. For these mesh points, the difference equations corresponding to Eq. (3.4-4) are

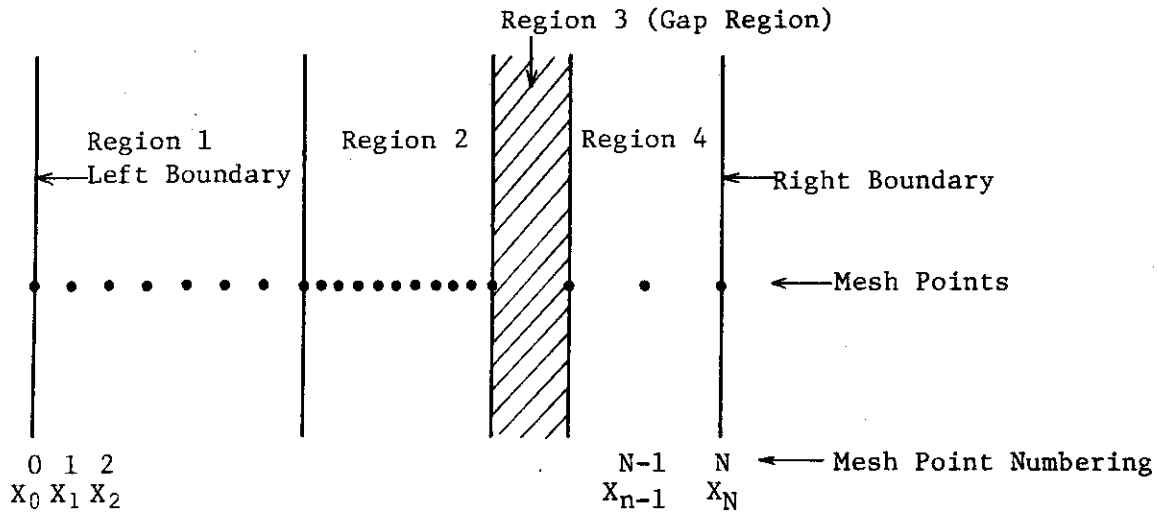


Fig. 3.4.1 Mesh Point Layout

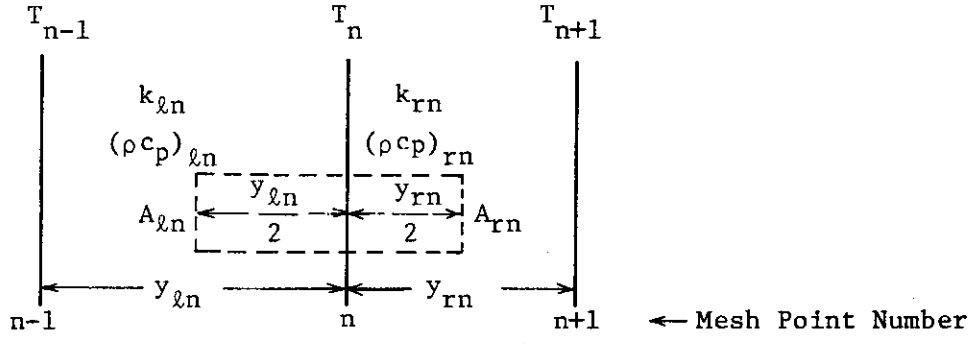


Fig. 3.4.2 Typical Mesh Points

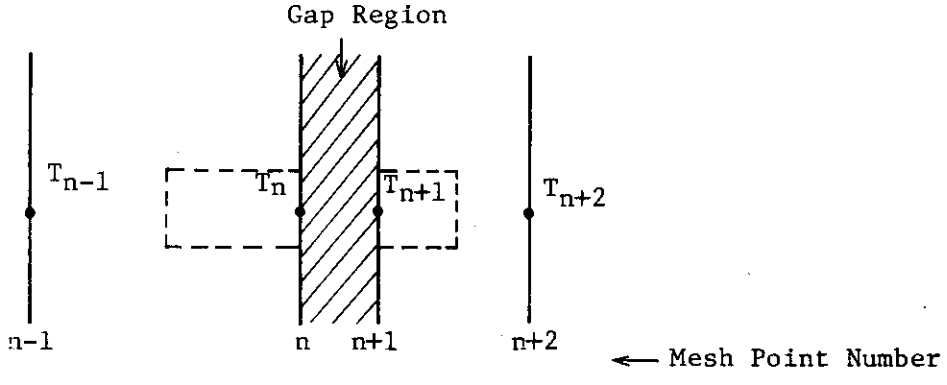


Fig. 3.4.3 Mesh Points adjacent Gap Region

$$\frac{(T_n^{m+1} - T_n^m)D_n'}{\Delta t} = (T_{n-1} - T_n)k_{ln}y_{ln}^s - (T_n - T_{n+1})G_{gap} + Q_{ln}y_{ln}^v \frac{P(t)}{P(0)} , \quad (3.4\text{-}7)$$

where

$D_n' = (\rho c_p)_{ln}y_{ln}^v$,

G_{gap} = temperature dependent gap conductance,

and

$$\frac{(T_{n+1}^{m+1} - T_{n+1}^m)D_{n+1}''}{\Delta t} = (T_n - T_{n+1})G_{gap} - (T_{n+1} - T_{n+2})y_{rn}^s k_{rn} + Q_{rn}y_{rn}^v \frac{P(t)}{P(0)} , \quad (3.4\text{-}8)$$

where

$D_n'' = (\rho c_p)_{ln+1}y_{ln+1}^v$.

These two equations can also be rearranged in a similar form to Eq. (3.4-6) using Crank-Nicolson method.

Figure 3.4.4 shows boundary mesh points. In ALARM-P1, the following two boundary conditions are allowed for either the left or right boundary:

$$k \frac{\partial T}{\partial x}\Big|_{boundary} = 0 , \quad (3.4\text{-}9)$$

$$k \frac{\partial T}{\partial x}\Big|_{boundary} = - h(T_N - T_{bulk}) , \quad (3.4\text{-}10)$$

where

k = thermal conductivity at boundary,

h = heat transfer coefficient,

T_N = surface temperature at x_N,

T_{bulk} = fluid bulk temperature.

If the Eq. (3.4-9) is applied to the left boundary, the method to drive Eq. (3.4-4) is again used to obtain the difference approximation at the left boundary, but with the volume of integration as indicated in Fig. 3.4.4. The equation for the mesh point at $x = x_0$ becomes

$$\frac{(T_0^{m+1} - T_0^m)}{\Delta t} (\rho c_p)_{r0}y_{r0}^v = - k_{r0}y_{r0}^s (T_0 - T_1) + Q_{r0}y_{r0}^v \frac{P(t)}{P(0)} . \quad (3.4\text{-}11)$$

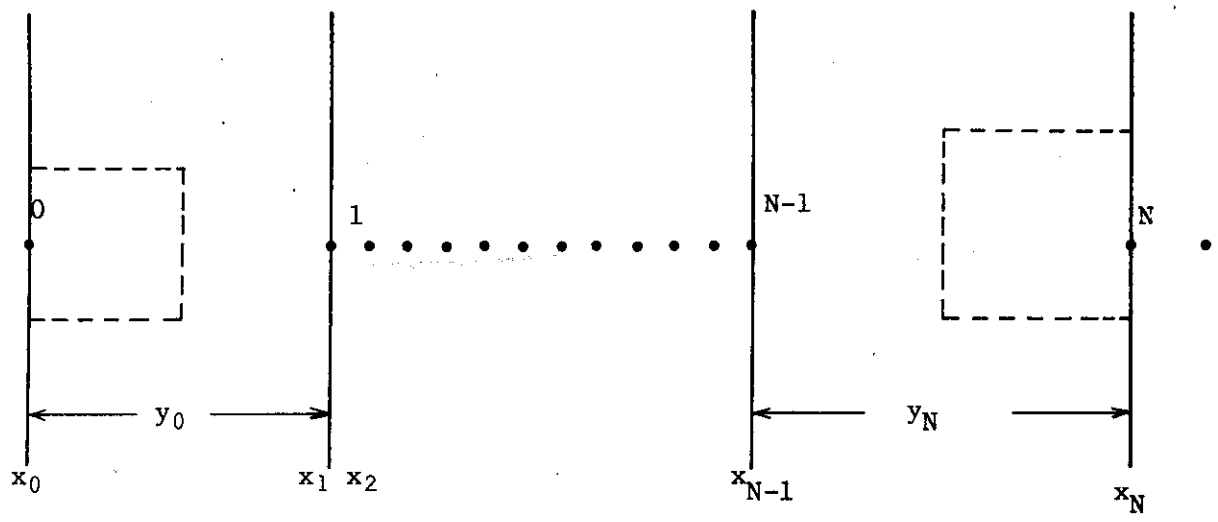


Fig. 3.4.4 Boundary Mesh Points

Approximations for boundary at $x = x_N$ are derived in a similar fashion. These equations for boundary mesh points are then converted to Crank-Nicolson formula in the same manner as for the interior points. Thus, for $x = x_0$

$$b_0 T_0^{m+1} + c_0 T_1^{m+1} = d_0 \tag{3.4-12}$$

where

$$c_0 = -\frac{k_{r_0} y^s_{r_0} \Delta t}{2} \quad , \quad b = \sigma(\rho c_p)_{r_0} y^v_{r_0} - c_0 \ ,$$

$$d_0 = -\sigma c_0 T_1^m + \sigma\{(\rho c_p)_{r_0} y^v_{r_0} + c_0\} T_0^m$$

$$+ \Delta t Q_{r_0} y^v_{r_0} \left\{\frac{\sigma P(t_m) + P(t_{m+1})}{2P(0)}\right\} \ .$$

For $x = x_N$

$$a_N T_{N-1}^{m+1} + b_N T_N^{m+1} = d_N \tag{3.4-13}$$

where

$$a_N = -\frac{k_{1N} y^s_{1N} \Delta t}{2} \quad , \quad b_N = \sigma(\rho c_p)_{1N} y^v_{1N} - a_N \ ,$$

$$d_N = -\sigma a_N T_{N-1}^m + \sigma\{(\rho c_p)_{1N} y^v_{1N} + a_N\} T_N^m$$

$$+ \Delta t Q_{1N} y^v_{1N} \left\{\frac{\sigma P(t_m) + P(t_{m+1})}{2P(0)}\right\} \ .$$

If Eq. (3.4-10) is applied to the left boundary, the difference approximations result in

$$\frac{T_0^{m+1} - T_0^m}{\Delta t} (\rho c_p)_{r0} y_{r0}^v = h_0 y_0^b (T_{bulk} - T_0) - k_{r0} y_{r0}^s (T_0 - T_1) + Q_{r0} y_{r0}^v \frac{P(t)}{P(0)} \quad . \tag{3.4-14}$$

The implicit formula for the above equation is

$$\frac{T_0^{m+1} - T_0^m}{\Delta t} (\rho c_p)_{r0} y_{r0} = q_0^m - k_{r0} y_{r0}^s \left\{ \frac{T_0^{m+1} + T_0^m}{2} - \frac{T_1^{m+1} + T_1^m}{2} \right\} + \frac{Q_{r0} y_{r0}^v}{2P(0)} \{P(t_m) + P(t_{m+1})\}, \tag{3.4-15}$$

where

$$q_0^m = h_0^m y_0^b (T_{bulk}^m - T_0^m) \quad .$$

Equation (3.4 - 15) can likewise be written

$$b_0 T_0^{m+1} + c_0 T_1^{m+1} = d_0' \quad . \tag{3.4-16}$$

Since the term d_0' includes the term q_0^m, the d_0' is given by

$$d_0' = d_0 + \Delta t q_0^m \quad . \tag{3.4-17}$$

For boundary at $x = x_N$, the implicit formula including surface heat flux, q_N is derived:

$$\frac{T_N^{m+1} - T_N^m}{\Delta t} (\rho c_p)_{1N} y_{1N}^v = \frac{1}{2} (q_N^{m+1} + q_N^m) - k_{1N} y_{1N}^s \left\{ \frac{T_{N-1}^{m+1} + T_{N-1}^m}{2} - \frac{T_N^{m+1} + T_N^m}{2} \right\} + \frac{Q_{1N} y_{1N}^v}{2P(0)} \{P(t_m) + P(t_{m+1})\} \quad , \tag{3.4-18}$$

where

$$q_N^{m+1} = h_N^{m+1} y_N^b (T_N^{m+1} - T_{bulk}^{m+1}),$$

$$q_N^m = h_N^m y_N^b (T_N^m - T_{bulk}^m) \quad .$$

Note that q_N^{m+1} includes the unknown term T_N^{m+1}. Equation (3.4-18) can be also written in the similar formula to Eq. (3.4-13) and the known term d_N'

is replaced by

$$d_N' = d_N + \frac{\Delta t}{2}\,(q_N^{m+1} + q_N^m). \tag{3.4-19}$$

Thus the difference approximations for the mesh points lead to a tridiagonal set of N+1 equations:

$$\begin{pmatrix} b_0 & C_0 & 0 & & & 0 \\ a_1 & b_1 & C_1 & & & \\ & a_2 & b_2 & C_2 & & \\ & & \ddots & \ddots & \ddots & \\ & & & a_{N-1} & b_{N-1} & C_{N-1} \\ 0 & & & 0 & a_N & b_N \end{pmatrix} \begin{pmatrix} T_0^{m+1} \\ T_1^{m+1} \\ T_2^{m+1} \\ \vdots \\ T_{N-1}^{m+1} \\ T_N^{m+1} \end{pmatrix} = \begin{pmatrix} d_0 \\ d_1 \\ d_2 \\ \vdots \\ d_{N-1} \\ d_N' \end{pmatrix} \tag{3.4-20}$$

Equation (3.4-20) in which d_N' includes unknown temperature T_N^{m+1} is solved by the following manner. Defining the following equations:

$$\left.\begin{aligned} w_0 &= \frac{c_0}{b_0}\ ;\ w_i = \frac{c_i}{b_i - a_i w_{i-1}}\ ,\ 1 \le i \le N\ , \\ g_0 &= \frac{d_0}{b_0}\ ;\ g_i = \frac{d_i - a_i g_{i-1}}{b_i - a_i w_{i-1}}\ ,\ 1 \le i \le N\ , \end{aligned}\right\} \tag{3.4-21}$$

Equation (3.4-20) is transformed to the equation:

$$\begin{pmatrix} 1 & w_0 & & & & 0 \\ & 1 & w_1 & & & \\ & & 1 & w_2 & & \\ & & & \ddots & \ddots & \\ & & & & 1 & w_{N-1} \\ 0 & & & & 0 & 1 \end{pmatrix} \begin{pmatrix} T_0^{m+1} \\ T_1^{m+1} \\ T_2^{m+1} \\ \vdots \\ T_N^{m+1} \\ T_N^{m+1} \end{pmatrix} = \begin{pmatrix} g_0 \\ g_1 \\ g_2 \\ \vdots \\ g_{N-1} \\ g_N \end{pmatrix} \tag{3.4-22}$$

Therefore T_N^{m+1} is given by

$$T_N^{m+1} = \frac{d_N' - a_N g_{N-1}}{b_N - a_N w_{N-1}}\ . \tag{3.4-23}$$

Rearranging Eq. (3.4-22) for unknown T_N^{m+1} gives

$$(-AA + h_N^{m+1})\, T_N^{m+1} = BB + h_N^{m+1}\, T_{bulk}^{m+1} \quad , \tag{3.4-24}$$

where

$$AA = \frac{b_N - a_N w_{N-1}}{\frac{\Delta t}{2}\, y_N^b} \quad , \tag{3.4-25}$$

$$BB = -\frac{d_N + \frac{\Delta t}{2}\, q^m - a_N g_{N-1}}{\frac{\Delta t}{2}\, y_N^b} \quad . \tag{3.4-26}$$

Equation (3.4-24) is solved in the following manner[2] depending on the correlations used. If the heat transfer correlation is Diffus-Beoelter type, the h_N^{m+1} is calculated by use of the fluid conditions at m+1-th time step. If Thom type correlation is assumed, T_N^{m+1} is obtained by solving the following quadratic equation:

$$\frac{q_N^{m+1}}{y_N^b} = \left\{\frac{(T_N^{m+1} - T_{sat}^{m+1}) \cdot 1.8 e^{p/88.608}}{4.23}\right\}^2 \times 2.713 = BB + AA \cdot T_N^{m+1} = h_N^{m+1}\,(T_N^{m+1} - T_{bulk}^{m+1}) \quad . \tag{3.4-27}$$

3.4.2 Heat transfer correlations

The heat transfer model in the ALARM-P1 is based on the THETA1-B and the RELAP4 models. The heat transfer regimes which could occur during a typical LOCA in the core region are shown in Fig. 3.4.5. Reference to Fig. 3.4.5, Regime A-B is subcooled forced convection which is characterized by the coolant bulk temperature less than saturation temperature and the surface temperature low enough that boiling does not occur. Whenever the surface temperature is less than saturation temperature, this heat trasnsfer mode is used since no boiling is possible. Regime BC is nucleate boiling and forced convection vaporization. This mode is characterized by the formation of bubbles from fixed sites randomly distributed over the surface. In this regime from subcooled boiling to forced convection vaporization is include with increasing superheat.

With further increase in superheat, bubbles begin to coalesce and local pathes formed with intermittent explosions of bubbles. The heat flux decreases with increasing superheat. This transition boiling is represented by Regime CD. Regime DE is film boiling characterized by the formation of a continuous blanket of vapor film on the heating surface with bubbles leaving the surface at regular intervals. Regime EF represents

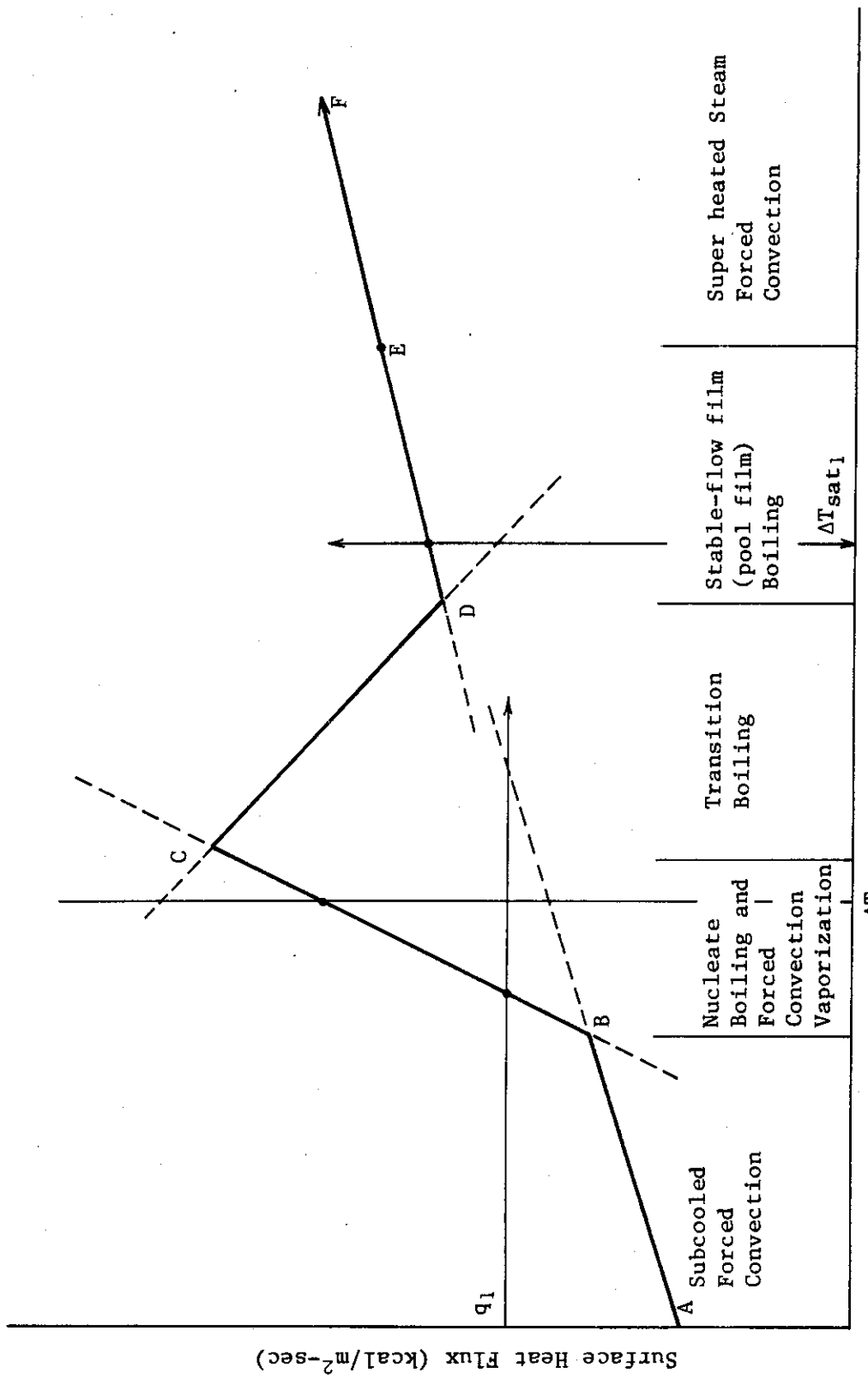


Fig. 3.4.5 Heat Transfer Regimes

forced convection of super heated steam.

The CHF is calculated at each core heat slab location for each time step. If the calculated heat flux exceeds the calculated critical heat flux (Point C of the Fig. 3.4.5), the heat transfer regime moves to either the transition regime or the stable film boiling regime.

Heat transfer correlations and CHF correlations as well as logic of their selection in ALARM-P1 are the same as those in RELAP4[2] orTHETA1-B[24]. In this section, the following correlations are represented by english unit.

(1) Pre-CHF Heat Transfer Correlations

Heat transfer mode number 1-3 and 8 are assigned to the pre-CHF heat transfer regimes. The pre-CHF heat transfer correlations are as follows:

(i) Mode 1 Forced Convection in Subcooled liquid

Dittus and Boelter[25]

$$h = 0.023 \left(\frac{k_f}{De}\right)(Pr_f)^{0.4}\left(\frac{GDe}{\mu_f}\right)^{0.8}, \text{ evaluated at } T_B \qquad (3.4\text{-}28)$$

Turbulent flow of water in circular tube

$L/D > 60$

$0.7 < Pr < 100$

$Re > 10^4$

(ii) Mode 8 Forced Convection in Superheated Vapor

$$h = 0.023\left(\frac{k_g}{De}\right)(Pr_g)^{0.4}\left(\frac{GDe}{\mu_g}\right)^{0.8}, \text{ evaluated at } T_B \qquad (3.4\text{-}29)$$

Turbulent flow of steam in circular tubes

Length : 36 in.(0.914 m)

Diameter: 0.5 in.(0.0127 m)

$L/D > 26$

Pressure: 25 to 75 psia (1.758×10^4 to 5.274×10^4 kgf/m^2)

Inlet temperature: 300 to 1100°F (148.9 to 593.3°C)

Wall temperature : to 1800°F (to 982.2°C)

Heat flux: 2400 to 31000 Btu/ft^2-hr(1.8081 to 23.362 kcal/m^2-sec)

(iii) Mode 2 Nucleate Boiling

Thom[26]

$$q = \left(\frac{\Delta T_{sat} e^{P/1260}}{4.32}\right)^2 \qquad (3.4\text{-}30)$$

vertical up flow

Round tube: 0.5 in. (0.0127 m) diameter, 60 in. (1.524 m) length

Annulus : 0.7 in.(0.01778m) I.D, 0.91 in.(0.02286m) O.D, 12 in.(0.3048m) length

Pressure: 750 to 2000 psia (52.74×10^4 to 140.65×10^4 kgf/m^2)

Mass flux: 0.77×10^6 to 2.80×10^6 lbm/hr-ft^2 (1.044×10^3 to 3.798×10^3 kgm/sec-m^2)

Heat flux: to 0.5×10^6 Btu/ft^2-hr (to 3.768 kcal/m^2-sec)

(iv) Mode 3 Forced Convection Vaporization

Schrock and Grossman[27]

$$h = (2.50)(0.023)\left(\frac{k_f}{De}\right)(Pr_f)^{0.4}\left[\frac{GDe(1-X)}{\mu}\right]^{0.8}\left(\frac{1}{X_{tt}}\right)^{0.75} \qquad (3.4\text{-}31)$$

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

Water in round tubes

Diameter : 0.1162 to 0.4317 in.(0.002951 to 0.010965 m)

Length : 15 to 40 in.(0.381 to 1.016 m)

Pressure : 42 to 505 psia (2.95×10^4 to 35.51×10^4 kgf/m^2)

Maxx flux: 0.175×10^6 to 3.28×10^6 lbm/ft^2-hr (2.374×10^2 to 4.449×10^3 kgm/m^2-sec)

Heat flux: 0.06×10^6 to 1.45×10^6 Btu/ft -hr(45.21 to 1093 kcal/m^2-sec)

Exit quality: 0.05 to 0.57

(2) Post-CHF Heat Transfer Correlation

Heat transfer mode number 4-8 are assigned to the post-CHF heat transfer regimes. The post-CHF heat transfer correlations are as follows:

(i) Mode 4 Transition Boiling

McDonough, Milich, and King[28]

$$q = q_{CHF} - C(p)(T_W - T_{W,CHF}) \qquad (3.4\text{-}32)$$

p	C(p)
2000 psia(140.62×10^4 kgf/m^2)	979.2 Btu/ft^2-hr-°F(1.3283 kcal/m^2-sec-°C)
1200 " (84.37×10^4 ")	1180.8 " (1.6018 ")
800 " (56.25×10^4 ")	1501.2 " (2.0364 ")

Vertical upflow of water in round tubes

Diameter: 0.152 in.(0.003861 m)

Length : 12.5 in.(0.3175 m)

Mass flux: 0.2×10^6 to 1.4×10^6 lbm/ft^2-hr(271.25 to 1898.8 kgm/m^2-sec)

Wall temperature: T_W < 1030°F (<554.4°C)

Pressure : 800, 1200, and 200 psia (56.3×10^4, 84.4×10^4, and 140.6×10^4 kgf/m^2)

(ii) Mode 5 Stable Film Boiling

Groeneveld[29]

$$h = 3.27\times10^{-3}\left(\frac{k_g}{De}\right)(Pr_{V,W})^{1.32}\left[\left(\frac{GDe}{\mu_g}\right)\left(X+\frac{\rho_g}{\rho_f}(1-X)\right)\right]^{0.901}Y^{-1.50} \quad (3.4\text{-}33)$$

$$Y = 1.0-0.1(1-X)^{0.4}\left(\frac{\rho_f}{\rho_g}-1\right)^{0.4},\ Pr_{V,W} \text{ is estimated at } T_W$$

Vertical and horizontal flow of water in round tubes and annuli

Diameter : 0.06 to 1.00 in.(0.001524 to 0.0254 m)

Pressure : 500 to 3100 psia (35.2×10^4 to 218.0×10^4 kgf/m^2)

Mass flux: 0.2×10^6 to 3.0×10^6 lbm/hr-ft^2(271.2 to 4068.9 kgm/m^2-sec)

Quality : 10 to 90 %

Heat flux: 35000 to 700000 Btu/ft^2-hr (26.38 to 527.5 kcal/m^2-sec)

(iii) Mode 6 Pool Film Boiling

Berenson's[30] equation is approximated as[2]

$$q = F(p)(\Delta T_{sat})^{3/4}\ , \quad (3.4\text{-}34)$$

where F(p) is depending on pressure as follows:

p	F(p)
15 psia(1.055×10^4 kgf/m^2)	128 Btu/ft^2-hr-°F$^{0.75}$ (0.1499 kcal/m^2-sec-°C$^{0.75}$)
100 " (7.032×10^4 ")	236 " (0.2764 ")
500 " (35.155×10^4 ")	412 " (0.4825 ")
1000 " (70.31×10^4 ")	510 " (0.5973 ")
1500 " (105.65×10^4 ")	615 " (0.7202 ")
2000 " (140.62×10^4 ")	705 " (0.8256 ")

Carbon tetrachloride, n-pentane

Horizontal flat plate facing upwards

Pressure : atmospheric

If $q < 20{,}000$ Btu/ft^2-hr (=15.072 kcal/m^2-sec) in the Mode 6 equation, then following equation is evaluated for transition pool boiling.

(iv) Mode 7 Transition Pool Boiling[2)]

$$q = 20{,}000\left(\frac{\Delta T_{min}}{\Delta T_{sat}}\right)^{\frac{1.504}{\ln(\Delta T_{min}/20)}}$$

$$\Delta T_{min} = \left(\frac{20{,}000}{F(p)}\right)^{4/3} \qquad (3.4\text{-}35)$$

However, if $\Delta T_{sat}<20°F(11.1°C)$, then q for the Mode 7 is set to 90,000 Btu/ft^2-hr (=67.825 kcal/m^2-sec). The q for Eq. (3.4-35) is interpolated between maximum and minimum heat flux value in log-log coordinates. The maximum or critical heat flux value used is 90,000 Btu/ft^2-hr (=67.825 kcal/m^2-sec) at the difference value of 20°F (=11°C) between the cladding surface temperature and the fluid saturation temperature. The minimum heat flux assumed to exist is 20,000 Btu/ft^2-hr (=15.072 kcal/m^2-sec) at the superheat ΔT_{min} in the Eq. (3.4-35).

(v) Mode 9 Low Pressure Flow Film Boiling

Dougall and Rohsenow[31)]'s correlation is approximated as

$$h = 0.023\left(\frac{k_g}{De}\right)(Pr_g)^{0.4}\left[\left(\frac{GDe}{\mu_g}\right)\left(X+\frac{\rho_g}{\rho_f}(1-X)\right)\right]^{0.8}, \qquad (3.4\text{-}36)$$

evaluated at T_{sat}.

Vertical upflow of Freon-113 in round tubes

Diameter : 0.408 and 0.108 in.(0.01036 and 0.00274 m)

Length : 15 in.(0.381 m)

Pressure : 2 to 9 psig (0.141×10^4 to 0.633×10^4 kgf,g/m^2)

Mass flux: 3.32×10^5 to 8.18×10^5 lbm/ft^2-hr (450.29 to 1109.5 kgm/m^2-sec)

Heat flux: 14,400 to 41,800 Btu/ft^2-hr(10.852 to 31.501 kcal/m^2-sec)

Quality : up to 50%

(3) Critical Heat Flux Correlations

Ligic for selecting the CHF correlation in ALARM-P1 uses pressure and mass flow rate as a basis for choosing the appropriate correlation. The critical heat flux is calculated for both core conductors and steam generator conductor with the static model (see §3.5.1). The Babcock &

Wilcox Company B&W-2[32], Barnett[33], and Modified Barnet[34] correlations are used in the following manner.

$p > 1500$ psia (105.5×10^4 kgf/m^2) B&W2

1500 psia (105.5×10^4 kgf/m^2) $> p >$ 1300 " (91.4×10^4 ") Interpolation between B&W2 and Barnett

1300 " (91.4×10^4 ") $> p >$ 1000 " (70.3×10^4 ") Barnett

1000 " (70.3×10^4 ") $> p >$ 725 " (51.0×10^4 ") Interpolation between Barnett and Modified Barnett

725 " (51.0×10^4 ") $> p$ Modified Barnett

A minimum critical heat flux of 90,000 Btu/ft^2-hr (67.825 kcal/m^2-sec) is assumed if the predicted value falls bellow this value.

For mass flux G less than 200,000 lbm/ft^2-hr (271.3 kgm/m^2-sec), the critical heat flux is interpolated between 90,000 Btu/ft^2-hr (67.825 kcal/m^2-sec) and the value given by the chosen correlation, where the former corresponds to G = 0 kgm/m^2-sec and 200,000 lbm/ft^2-hr (271.3 kgm/m^2-sec). The interpolation equation is given by

$$q_{CHF} = 90,000 + \frac{G}{200,000}(q(200,000) - 90,000) \quad . \qquad (3.4\text{-}37)$$

The inlet enthalpy used in the critical heat flux correlations is dependent on the flow direction and is determined in the following manner:

Flow at Normal Inlet	Flow at Normal Outlet	h_{in}
>0	≥0	h at normal inlet
≤0	<0	h at normal outlet
All other cases		h of core volume

The correlations are as follows:

(i) Babcok & Wilcox Company, B&W-2[32]

$$q_{CHF} = \frac{1.15509-0.40703De}{12.71\times(3.0545G')^A}\left[(0.3702\times10^8)(0.59137G')^B - 0.15208h_{fg}G\right] \qquad (3.4\text{-}38)$$

where

$$\left.\begin{aligned} A &= 0.71186 + (2.0729\times10^{-4})(p-2000), \\ B &= 0.834 + (6.8479\times10^{-4})(p-2000), \end{aligned}\right\} \qquad (3.4\text{-}39)$$

and $G' = G/10^6$.

Water in rod bundles

Equivalent diameter: 0.2 to 0.5 in.(0.00508 to 0.0127 m)

Length : 72 in.(1.8288 m)

Pressure : 2000 to 2400 psia (140.6×10^4 to 168.7×10^4 kgf/m^2)

Mass flux: 0.75×10^6 to 4.0×10^6 lbm/ft^2-hr(1017 to 5425 kgm/m^2-sec)

Burnout quality: 0.03 to 0.20

(ii) Barnett[33]

$$q_{CHF} = 10^6\left[\frac{A+B(h_f-h_{in})}{C+L}\right] , \qquad (3.4\text{-}40)$$

where

$$\left.\begin{aligned} A &= 67.45D_{HE}^{0.68}G'^{0.192}\,(1.0-0.744e^{(-6.512D_{HY}G')}), \\ B &= 0.2587D_{HE}^{1.261}G'^{0.817} , \\ C &= 1.850D_{DY}^{1.415}G'^{0.212} , \\ G' &= G/10^6. \end{aligned}\right\} \qquad (3.4\text{-}41)$$

For a rectangular conductor geometry, D_{HY} is set equal to the input value for the right side hydraulic diameter for the conductor.

Water in annulus: applied to rod bundles using "equivalent" diameter

Equivalent diameters: 0.258 in. (0.00655m)$<D_{HE}<$3.792 in. (0.09632m)

0.127 in. (0.00323m)$<D_{HY}<$0.875 in. (0.02223m)

Length : 24 to 108 in.(0.6096 to 2.7432 m)

Pressure : 1000 psia (70.31×10^4 kgf/m^2)

Mass flux: 0.14×10^6 to 6.20×10^6 lbm/ft^2-hr(189.88 to 8409.0 kgm/m^2-sec)

(iii) Modified Barnett[34]

$$q_{CHF} = 10^6\left[\frac{A+B(h_f-h_{in})}{C+L}\right] , \qquad (3.4\text{-}42)$$

where

$$\left.\begin{aligned} A &= 73.71D_{HE}^{0.052}G'^{0.663}(1.0-0.315e^{(-11.34D_{HY}G')})\frac{888.6}{h_{fg}} , \\ B &= 0.104D_{HE}^{1.445}G'^{0.691} , \\ C &= 45.55D_{HY}^{0.0817}G'^{0.5866} , \\ G' &= G/10^6. \end{aligned}\right\} \qquad (3.4\text{-}43)$$

Water in rod bundles

Rod diameter: 0.395 to 0.543 in.(0.0100 to 0.0138 m)

Length : 32.9 to 174.8 in.(0.8357 to 4.440 m)

Pressure : 150 to 725 psia (10.55×10^4 to 50.97×10^4 kgf/m^2)

Mass flux: 0.03×10^6 to 1.7×10^6 lbm/ft^2-hr(40.69 to 2305.7 kgm/m^2-sec)

Inlet subcooling: 6 to 373 Btu/lbm (3.3 to 207.2 kcal/kgm).

3.4.3 Procedure for selection of heat transfer correlations

The manner in which the heat transfer correlations are selected is described in this section. Both at steady state initialization and at each time step, ALARM-P1 determines the heat transfer mode to be used for a given heat conductor surface. The logic for selecting the heat transfer correlations in ALARM-P1 is essentially the same way as used in THETA1-B[24] and RELAP4[2]. For the steady state initialization, AA in Eq. (3.4-25) is zero and BB in Eq. (3.4-26) is taken as the surface heat flux level which is estimated on the basis of the localized power generation rate for the heat conductor such as fuel rods, while for the heat conductor between two normal fluid volumes such as steam generator tubes, the surface heat levels for both sides are initialy assumed on the basis of the two fluid temperatures. The steady state heat transfer mode for the above mentioned heat conductors is determined in an interative manner. For the transient state, heat transfer mode, heat flux and surface temperature are obtained simultaneously by use of Eq. (3.4-24) and the heat transfer selection logic.

Referring to Fig. 3.4.5, regime A-B (mode 1) represents subcooled forced convection which is characterized by the coolant bulk temperature less than saturation temperature and the surface temperature low enough that boiling does not occur. Whenever the surface temperature is less than saturation temperature, the mode 1 is selected since no boiling is possible. Point B in Fig. 3.4.5 shows the beginning of the nucleate boiling regime. The coolant may still be subcooled but the surface temperature is high enough that some boiling occurs. If the surface temperature is greater than saturation temperature, both mode 1 and mode 2 are evaluated and the surface temperatures are calculated by Eq. (3.4-24). Referring to Fig. 3.4.5 the correct heat transfer mode is that one which predicts the lower surface temperature.

Regime B-C of the Fig. 3.4.5 is defined by two modes: nucleate boiling, mode 2 and forced convection vaporization, mode 3. When the void fraction

is below about 0.8 to 0.9, a bubbly type or slug flow regime will be the most likely to exist[24] whereas for the void fraction below 0.8 the mode 2 is selected. For the void fraction above 0.9 the mode 3 is selected since the flow regime is expected to change to an annular or mist flow. For void fractions between 0.8 and 0.9, an interpolation between two correlations is used in order to avoid a discontinuity in the heat flux. The mode 3 is applied until the quality reaches 0.95. Above 1.0 quality, the mode 8, forced convection in superheated vapor is used. Between 0.95 and 1.0 quality, an interpolation based on quality is made to ensure a smooth transition from forced convection vaporization (mode 3) to forced convection in superheated vapor (mode 8). In two interpolations mentioned above, the relation between void fraction, α and quality, x is given by

$$\alpha = \frac{1}{1 + \frac{(1-X)\rho_g}{X\rho_g}} \quad . \tag{3.4-44}$$

If the heat flux predicted by the pre-CHF correlations is larger than the estimated CHF, both the transition (mode 4) and stable film boiling regime correlations (mode 5) are called. If the pressure is less than 500 psi (35.2×10^4 kgf/m^2), low pressure flow film boiling (mode 9) is always called instead of the mode 5. For the transition and film boiling regime, one which gives a larger heat flux is taken to be true.

ALARM-P1 allows the return to the nucleate boiling regime from the transition boiling regime. In case where the mode 2 predicts heat fluxes less than the CHF value, indicating a return to nucleate boiling, both the mode 2 and mode 4 are evaluated, and the smaller predicted heat flux is used.

When the fluid quality reaches unity in the film boiling regime (mode 5), the forced convection in superheated vapor (mode 8) is applied. A discontinuity exists at the quality of 1.0 between the mode 5 and the mode 8. To avoid this discontinuity, an interpolation based on quality is made over the range of 0.95 to 1.0 between the mode 5 and the mode 8.

If the mass flux drops below 200,000 lbm/ft^2-hr (271.2 kgm/m^2-sec), the pool film boiling correlations (mode 6) is applied. If the heat flux predicted by the mode 6 is less than 20,000 Btu/ft^2-hr (15.072 kcal/m^2-sec), transition pool boiling correlation (mode 7) is used. For this regime, if the predicted wall superheat is less than 20°F (11°C), a heat flux of 90,000 Btu/ft^2-hr (67.825 kcal/m^2-sec) is assigned.

3.5 Steam generator

The model of steam generator described herein primarily concerns the heat transfer between the primary (U-bend tubes) and secondary (shell) sides. The static model and the transient heat conduction model provided in the code are described in the following sections.

3.5.1 Static model

The rate of heat transfer between the primary and secondary sides is calculated from the equation:

$$Q_{sg}(t) = h_{sg}(t)A_{sg}\{T_{pri}(t) - T_{sec}(t)\}, \qquad (3.5\text{-}1)$$

where

$Q_{sg}(t)$ = rate of heat transfer from the primary to the scondary,
$h_{sg}(t)$ = overall heat transfer coefficient,
A_{sg} = overall heat transfer area,
$T_{pri}(t)$ = primary fluid temperature,
$T_{sec}(t)$ = secondary fluid temperature.

This model ignores the heat capacity of the tubes. The tubes are treated only as a resistance. The overall heat transfer coefficient $h_{sg}(t)$ is computed using the following relationship:

$$\frac{1}{h_{sg}(t)} = \frac{1}{h_{pri}(t)} + \frac{1}{h_{tube}(t)} + \frac{1}{h_{sec}(t)}, \qquad (3.5\text{-}2)$$

where

$h_{pri}(t)$ = primary side heat transfer coefficient,
$h_{tube}(t)$= tube overall heat transfer coefficient,
$h_{sec}(t)$ = secondary side heat transfer coefficient.

The heat transfer coefficients $h_{pri}(t)$ and $h_{sec}(t)$ are determined from heat transfer correlations depending on whether the heat flow is from primary to secondary or vice versa.

When the heat flow is from primary to secondary ($T_{pri}(t) > T_{sec}(t)$), the overall heat transfer coefficient $h_{sg}(t)$ is determined by assumptions that the secondary thermal resistance $1/h_{sec}(t)$ is neglected and the tube overall heat transfer is unchanged from the initial value. Hence, the Eq. (3.5-2) is reduced to

$$\frac{1}{h_{sg}(t)} = \frac{1}{h_{pri}(t)} + \left\{\frac{1}{h_{sg}(0)} - \frac{1}{h_{pri}(0)}\right\} \quad , \tag{3.5-3}$$

where $h_{sg}(0)$ is the initial overall heat transfer coefficient which is calculated by

$$h_{sg}(0) = Q_{sg}(0)/A_{sg}\{T_{pri}(0) - T_{sec}(0)\} \quad , \tag{3.5-4}$$

where $Q_{sg}(0)$ is the initial heat flow from primary to secondary, which is calculated from the heat balance of the primary control volume using the inlet and outlet enthalpy and the volume mass flow rate. The primary heat transfer coefficient, $h_{pri}(t)$ is determined by the same manner as shown in §3.4.

When the heat flow is reversal ($T_{sec}(t) > T_{pri}(t)$), the secondary side heat transfer coefficient, $h_{sec}(t)$ and the tube overall heat transfer coefficient are assumed to be constant. The heat flow from the primary fluid to the tube inside (primary) surface is equal to the heat flow from the tube inside surface to the secondary side fluid:

$$Q_{sg}(t) = h_{pri}(t)\{T_{pri}(t)-T_{wall}\} = H_{sec}\{T_{wall}-T_{sec}(t)\}, \tag{3.5-5}$$

where

$$\frac{1}{H_{sec}} = \frac{1}{h_{tube}(t)} + \frac{1}{h_{sec}(t)} \quad . \tag{3.5-6}$$

The Eq. (3.5-5) determines the tube inside surface temperature:

$$T_{wall} = \frac{\{H_{sec}T_{sec}(t)+h_{pri}(t)T_{pri}(t)\}}{H_{sec} + h_{pri}(t)} \quad . \tag{3.5-7}$$

The heat transfer coefficient, H_{sec} is an input constant. The primary heat transfer coefficient, $h_{pri}(t)$ is also determined by the same manner as shown in the Sec. 3.4.

3.5.2 Transient heat conduction model

Two fluid control volumes must be specified to describe both the primary and secondary sides of the steam generator. The transient heat conduction equation is applied to the U-bend tubes where the heat transfer coefficients of both the primary and secondary surface are determined by the following two options:

(1) Both the primary and secondary heat transfer coefficients during transient are supplied by an input table of the heat transfer coefficients vs. time.

(2) The heat transfer coefficients for both sides of the steam generator are calculated in the code by the same method as described in §3.4.

The user may also specify several control volumes to describe the primary side of the steam generator. In this case, the input for Heat Exchanger Data Cards (see Appendix A) are not required. The standard heat conduction model as described in §3.4.1 is applied.

4. ALARM-P1 Code Description

4.1 Program organization

ALARM-P1 is written in FORTRAN-IV for FACOM 230-75 computer. This code uses double precision (72 bits) floating point arithmetic and does not have any overlay structure, executable in a computer having more than 256 kW core storage.

The ALARM-P1 code has the functions such as restarting, and editting for restart and plot. Appendix A describes the sets of input cards for normal and restart problem.

Up to seven standard FORTRAN input or output units may be required. Unit 5 and 6 are used for card input and print out respectively. Unit 1 is used as a scratch unit for input data processing. Unit 2 is used for the input for restarting which is obtained from a restart tape previously written on Unit 3. Unit 4 is for plotting. Unit 10 is used to read the steam table generated by the ASTEM[17] package.

4.1.1 Problem dimension

Since ALARM-P1 employs variable dimensioning, the program allows the optimum use of available storage and there are no particular restrictions on the number of nodes and junctions, etc. as far as the computer memory allows. Basic integer data required for the dimensioning are read in immediately following the title card. After all data are read in, the required core memories are compared with available storage.

4.1.2 Restart and dump options

ALARM-P1 generates a dump/restart data file on FORTRAN unit 3, which contains every necessary information at the specified intervals during problem execution. Any one of these dumped informations may be used to initialize the whole system for subsequent calculations. The dump interval is specified on the Time Step Cards.

To use a dump file in restarting for a subsequent calculation, the file must be mounted on FORTRAN unit 2. The dump number from which the restart is desired must be specified on the Problem Dimension Card. The other data required for the restart are only those included on the Time Step Data Card, the Edit Data Variable Card and the Trip Control Cards.

4.1.3 Editting and plotting

ALARM-P1 provides two kinds of edits, which are similar to those in RELAP4[2]. One is edited with a fixed format and another allows a user to chose calculated variables to be edited without restriction on the number of variables. The frequency of both edits is specified by two integer data on the Time Step Data Card (refer to Appendix A).

A large number of calculated variables for plotting is stored on the FORTRAN unit 4 at the frequency speicifed by one integer on the Time Step Data Card. The plotting program such as PLOTR4[2] has been adapted to the JAERI computing system. The plotting program can be used for paper plotting as well as graphic display.

4.1.4 Trip control options

The control functions are usually required to simulate a reactor system. For instance, the pump is tripped at the time when the electric power is lost. These actions may be simulated by the trip control specified on the Trip Control Data Cards.

Trips can be controlled by the elapsed time, node pressure, mixture level, water temperature, or junction flow. Each controlling variable can control multiple actions such as leak area opening, valve action, fill water injection and so on. Trip control parameters are compared with specified set points and if the set point is reached, the trip action is generated after a specified delay time.

Trip control parameters not yet actuated may be changed or reset at a restart. (refer to section 3.5 of Appendix A)

4.2 Required resources

The ALARM-P1 code uses some generally available routines and environmental routines provided by the JAERI computer center.

Two routines which are contained in RELAP4 are used in conjunction with ALARM-P1. PLOTR4 produces microfilm plots and graphic-display plots of appropriate variables-versus-time from a PREEDIT output tape (refer to Appendix B). Input data format is the same as PLOTR4. Another computer program, STH2O water property routines[17] are also used in conjunction with ALARM-P1.

Both PACK and UNPACK written by FACOM 230-75 assembler language, which manupilate characters, are used in the input subroutine REAG[6] for free

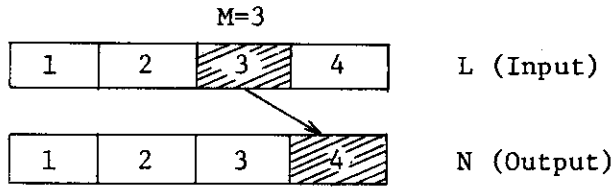
format. Two routines are used as following manner:

CALL UNPACK (L,M,N)

L a word to be unpacked

M location of a character in L ($1 \leq M \leq 4$)

N a word in which a character is put at the last byte.

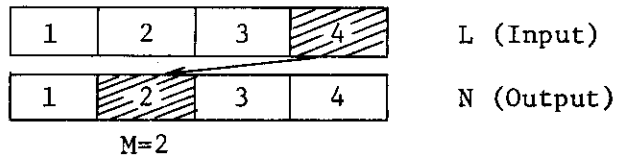


CALL PACK (L,M,N)

L the last character of L is moved

M location of a character in N ($1 \leq M \leq 4$)

N a word in which a character is put at M-th byte.



5. Performance of ALARM-P1

Since its completion of programming, ALARM-P1 has been tested for its performance by analysing and comparing with various experimental results. Many corrections, modifications and refinements have been made through such verification works, and will further be continued. Among various experiments so far analysed, the results of CSNI Standard Problem No.5 (hereafter called ISP 5) are described in this chapter.

SCNI Standard Problem has been sponsored by the OECD NEA CSNI (Committee on Safety of Nuclear Installations). This project is for its principal objective to promote a better understanding on the state-of-art of the analysis capability concerning LOCA and ECCS performance among the participating countries by selecting the most appropirate experiments and comparing the analytical results of the participants with the measurements.

Run No. 4 of the LOFT L1 series (L1-4) was selected as ISP-5 which was analysed on a blind basis. JAERI submitted two analyses by ALARM-P1 and RELAP-4J, a modified version of RELAP-4 by JAERI. These analyses have been reported more in detail in Ref. (35).

Fig. 5·1 shows the major components of LOFT L1-4, which was to simulate a double ended cold leg break in a PWR. No heat source was provided in the core region but an equivalent flow resistance called the core simulator was installed as seen in the figure. Table 5·1 lists the major experimental and analytical initial conditions. Fig. 5·2 shows the control volume and junctions arrangement for the present ALARM-P1 analysis.

Fig. 5·3 indicates the system coolant mass inventory. This quantity is extremely important for a blowdown analysis since it is directly related to the start time of the reflooding phase, and indicates an overall accuracy of the analysis. As seen in the figure, ALARM-P1, overpredicted the mass inventory from about 15 to 30 seconds after the break. As shown later the system pressure was predicted fairly accurately during this period. Therefore, this discrepancy might suggest either there existed a significant amount of heat released from the structure forming a large amount of superheated steam somewhere in the system though no measured data seemed apparently to support this speculation, or the measurements failed to be accurate enough due to very fast transients during this period. After about 30 seconds, the mass inventory was very correctly predicted. This may imply that the so-called accumulator bypass problem is no longer a serious difficulty for a LOCA analysis.

Fig. 5.4 shows the system pressure at the core simulator. ALARM-P1 prediction showed an excellent agreement with the measurement. The pressures of other locations were also excellently predicted by the analysis.

The mass flow rate in the intact cold leg is shown in Fig. 5.5. ALARM-P1 prediction was significantly lower than the measured for first several seconds, however, a good agreement was obtained thereafter. After about 35 seconds, a severe oscillation was observed in the measurement which would be due to the accumulator injection. ALARM-P1 predicted a smooth and averaged flow rate as seen in the figure. Considering the limitation of the homogeneous equilibrium flow model employed, this prediction seemed satisfactory, as discussed below with the density and temperature at this location.

Fig. 5.6 shows the fluid average density in the broken cold leg. As seen in the figure, agreement was excellent. Generally speaking, densities at various locations were fairly accurately predicted, however, difficulties were encountered at the intact cold leg density as shown in Fig. 5.7. Before the accumulator injection started, ALARM-P1 prediction was a little too high, but this discrepancy may not be too serious. Immediately after the injection started, ALARM-P1 predicted a rapid and continuous increase of the density, and within about 15 seconds of injection, it was indicated that the control volume was almost filled up with liquid water. On the contrary, the increase in density was delayed and showed a severe oscillation in the measurement. This oscillation may indicate that slugs of liquid water were intermittently passing by the detector location. This disagreement indicated the limitation of the homogeneous equilibrium flow model. This is more clearly indicated by the fluid temperature at the same location as shown in Fig. 5.8. The measurement was oscillating between the saturated or slightly superheated temperature and the subcooled liquid temperature. This implies that only a poor mixing of the injected water and the steam took place around the injection point, and a significant part of water was entrained immediately into the neighboring control volumes.

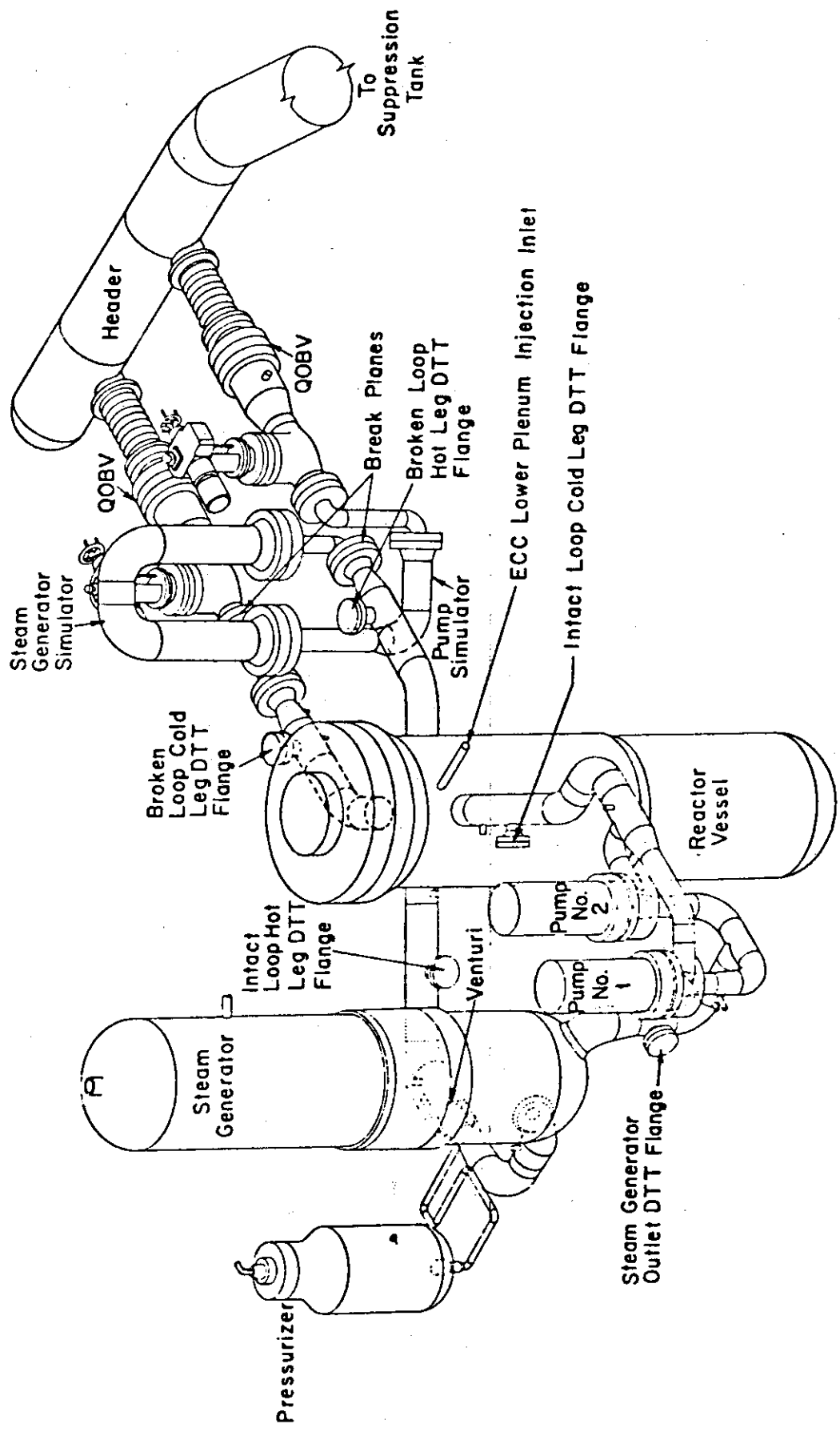


Fig. 5.1 LOFT major components

Table 5.1 Initial Operating Conditions for LOFT Test L1-4

Primary Coolant System		
Mass flow rate	(kg/s)	268.4
Pressure (absolute)	(MPa)	15.76
Temperature	(°K)	552.2
ECC Accumulator		
Gas volume	(m^3)	1.16
Water volume	(m^3)	2.52
Pressure (absolute)	(MPa)	4.22
Temperature	(°K)	306.5
Standpipe height	(m)	0.77
Pressurizer		
Steam volume	(m^3)	0.315
Water volume	(m^3)	0.648
Water temperature	(°K)	615.9
Pressure (absolute)	(MPa)	15.73
Suppression Tank		
Liquid level	(m)	2.87
Gas volume	(m^3)	43.5
Liquid volume	(m^3)	61.35
Water temperature	(°K)	356.2
Pressure (absolute)	(MPa)	0.10
Broken Loop		
Hot leg temperature	(°K)	552.6
Cold leg temperature	(°K)	553.7
Primary Coolant Pumps		
Pump, 1 speed	(rpm)	1694.4
Pump, 2 speed	(rpm)	1694.4

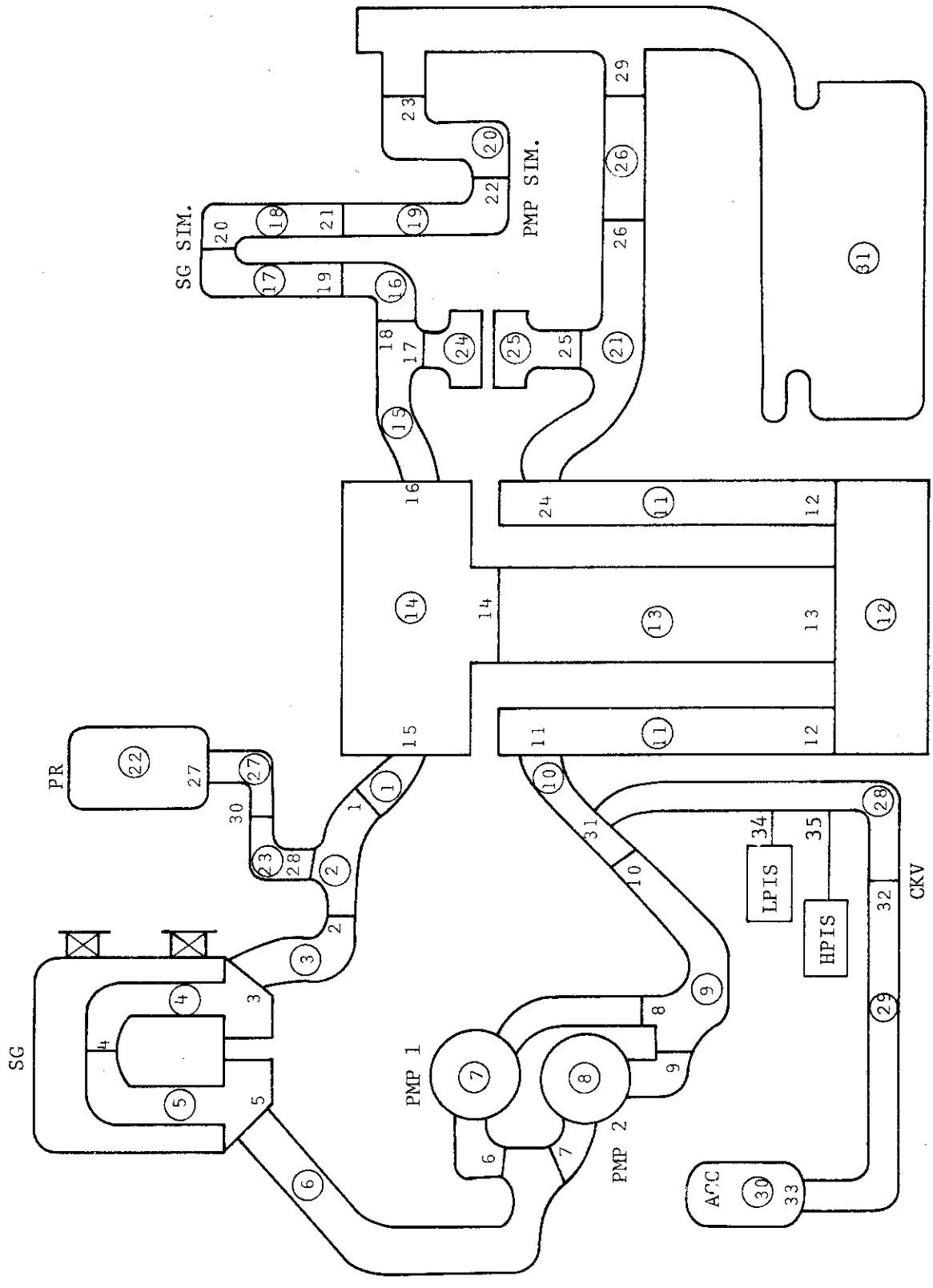


Fig. 5.2 LOFT Noding for L1-4 Analysis

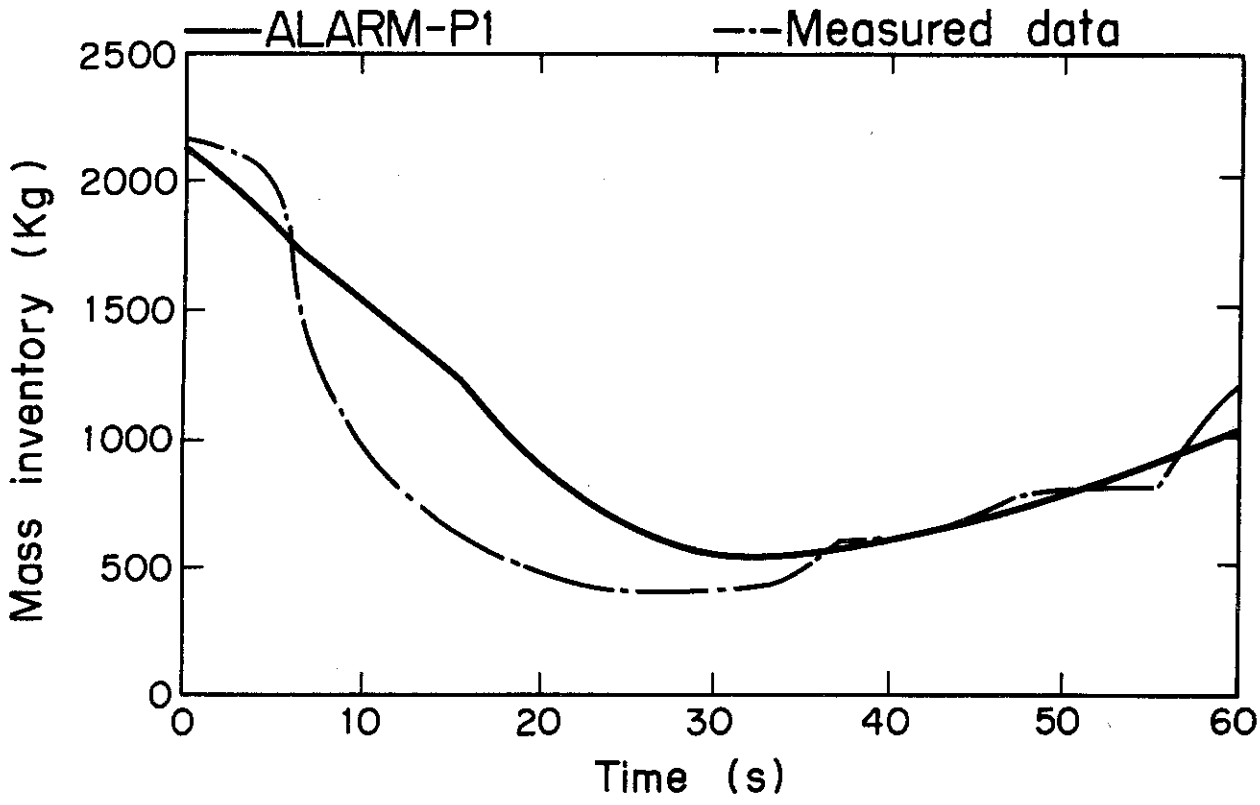


Fig. 5.3 ISP5 system mass inventory

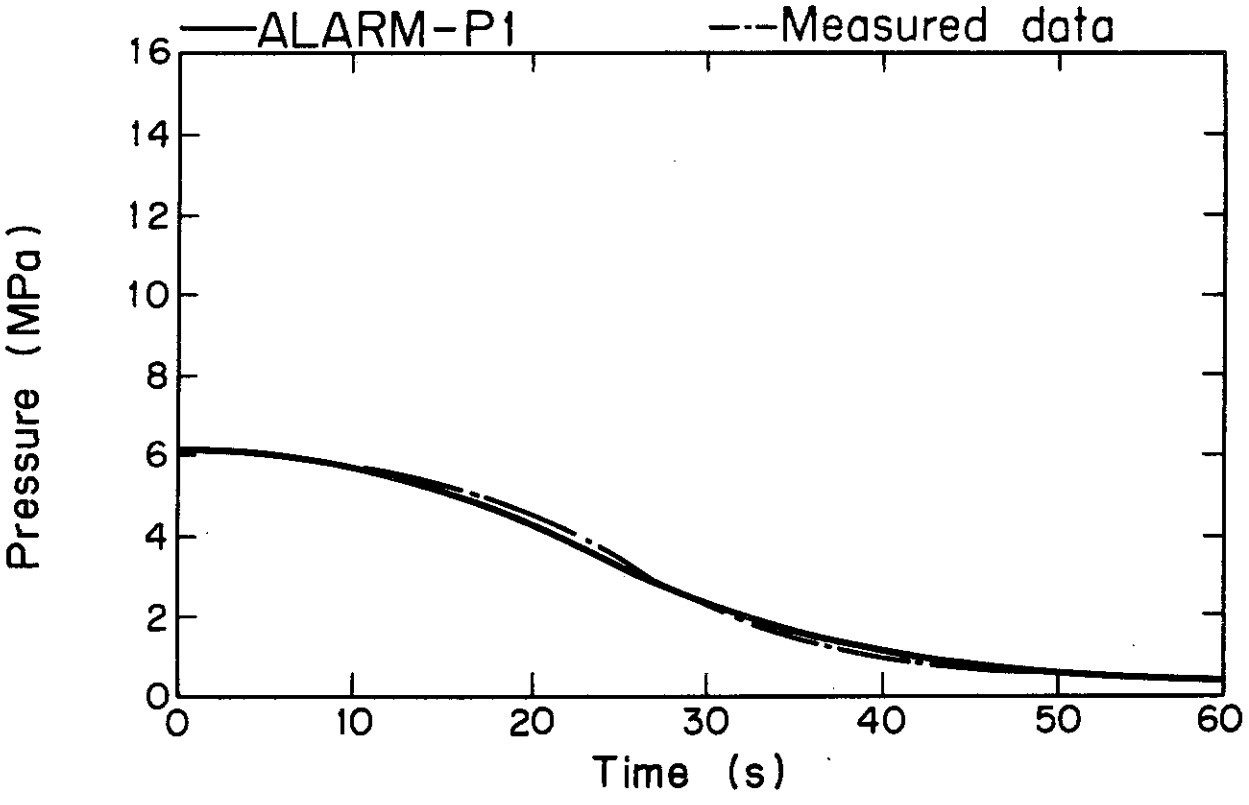


Fig. 5.4 ISP5 core simulator pressure

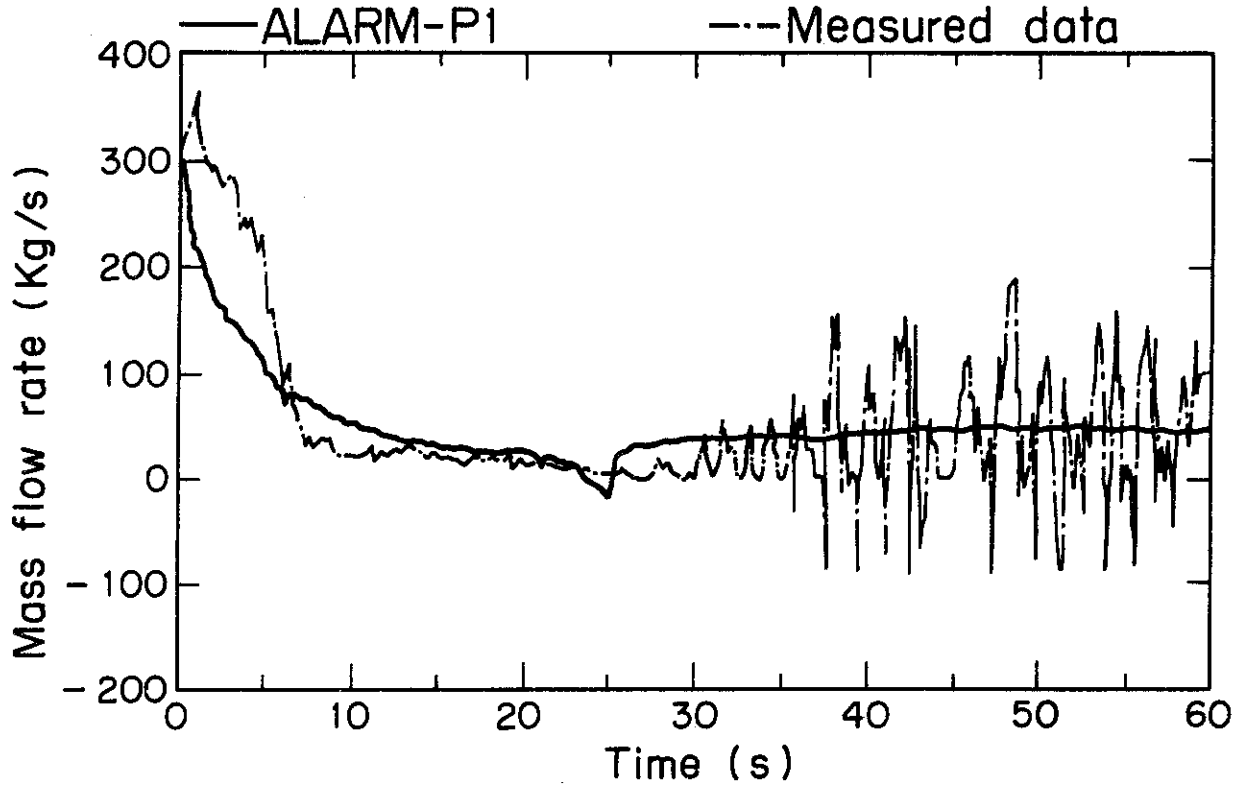


Fig.5.5 ISP5 mass flow rate in intact loop cold leg

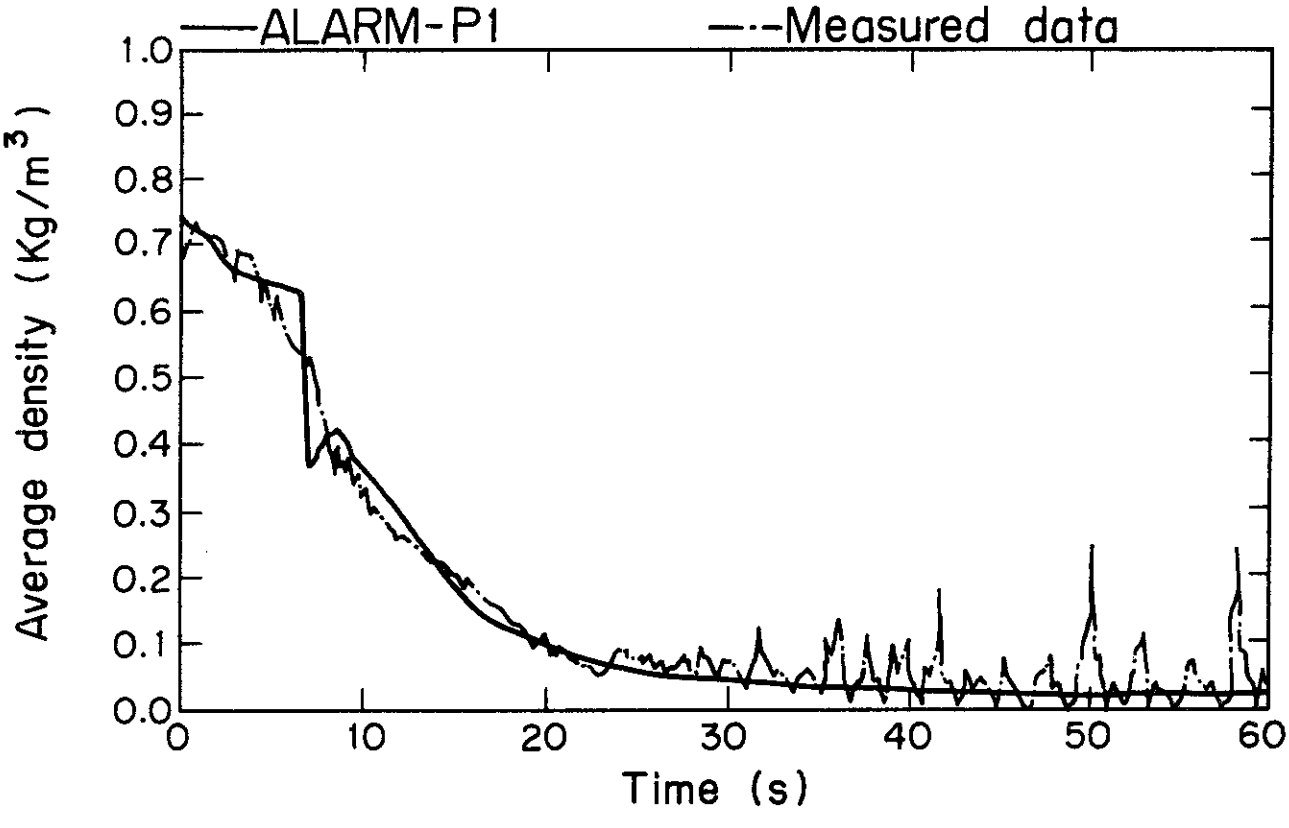


Fig.5.6 ISP5 average density broken loop cold leg

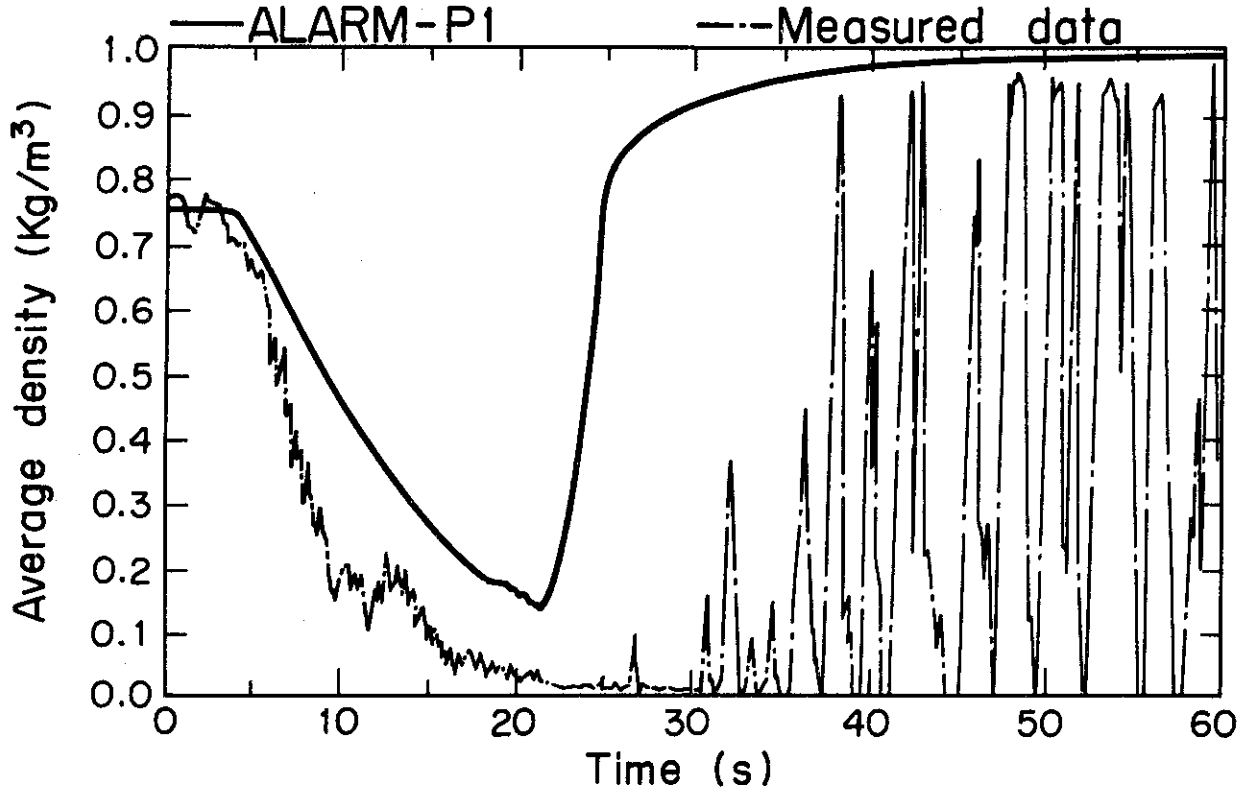


Fig.5.7 ISP5 density in intact loop cold leg

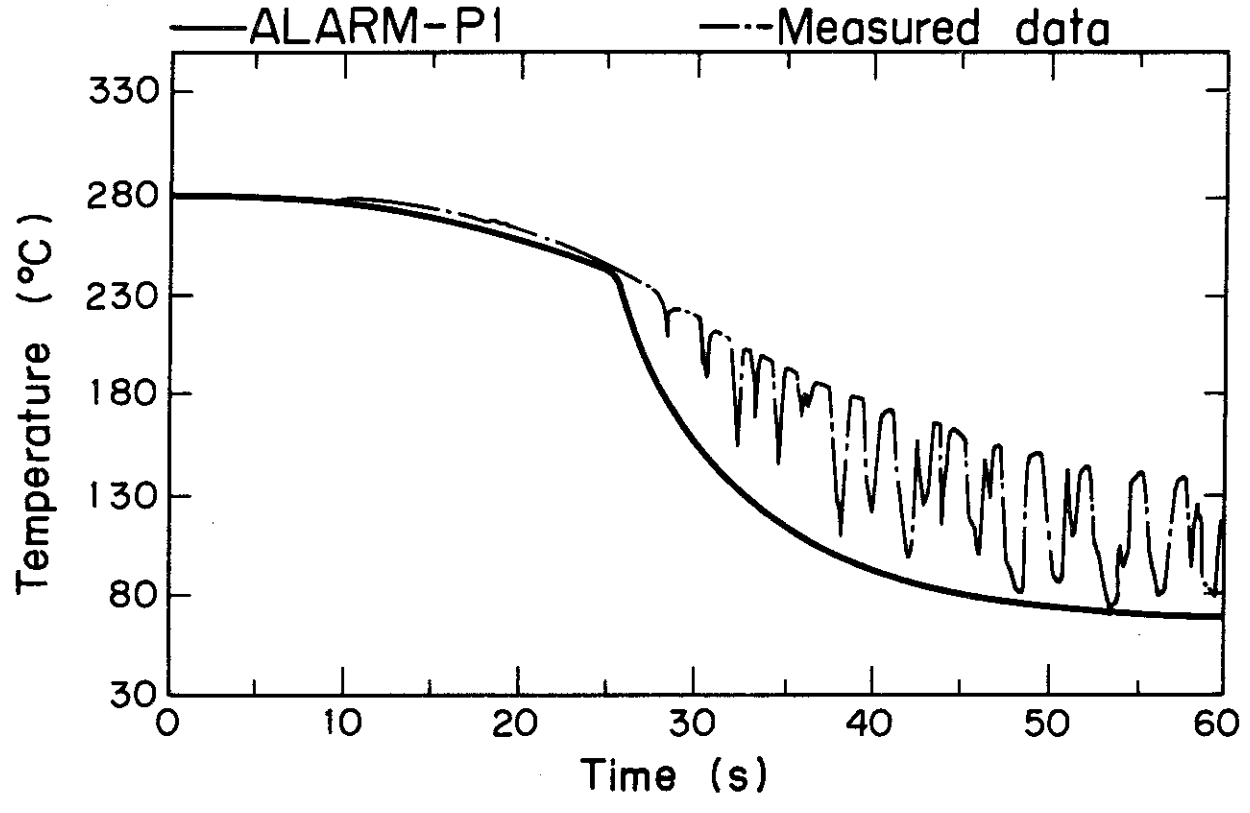


Fig.5.8 ISP5 fluid temperature in intact loop cold leg

Acknowledgments

The authors express their thanks to K. Katsumata and K. Tomiai of the Century Research Center Co. Ltd. for their programming and extensive test runs. They are also grateful to the members of the Reactor Safety Code Development Laboratory at JAERI for their valuable discussions and examination of a huge amount of test results.

Nomenclature

A = flow area (m^2)

C_B = coefficient for subcooled critical flow calculation by Zaloudek's equation

C_D = contraction coefficient for critical flow calculation by Moody's equation

c = fluid sonic velocity (m/sec)

c_p = specific heat at constant pressure (kcal/kgm-°C)

c_v = specific isochoric heat capacity (kcal/kgm-°C)

D = diameter (m)

e = fluid specific enthalpy (kcal/kgm)

F = frictional pressure loss (kgf/m^2)

$F\ell$ = flow length (m)

f = fanning friction factor

G = mass flux (kgm/m -sec)

G_{con} = gas constant of air (2.87 J/kgm-°C)

G_{gap} = gap conductance ($kcal/m^2$-°C-sec)

g = gravitational accerelation constant (9.8 m/sec^2)

g_c = gravitational conversion constant (9.8 N/kgf)

H = pump head (m)

h = fluid specific enthalpy (kcal/kgm), heat transfer coefficient ($kcal/m^2$-sec-°C), normalized pump head (H/H_o)

h_m = humidity

I = inertia moment of the rotating member ($kgm-m^2/rod^2$)

J = Joule's constant (4.1868×10^3 J/kcal)

K_f = dimensionless form less coefficient

k = thermal conductivity (kcal/m-sec-°C)

L = flow length (m)

l = flow length (m), neutron life time (sec)

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J = Joule's constant (4.1868×10^3 J/kcal)

K_f = dimensionless form less coefficient

k = thermal conductivity (kcal/m-sec-°C)

L = flow length (m)

l = flow length (m), neutron life time (sec)

M = total mass in control volume (kgm), Mach number

N = angular speed (r.p.m)

n = neutron density ($1/m^3$)

P = wetted perimeter (m), total power (MW)

P_r = Prandtl Number

p = thermodynamic pressure (kgf/m^2)

Δp = pressure loss or pressure difference (kgf/m^2)

Q = transferred heat energy (kcal/sec), volumetric flow (m^3/sec)

q = heat flux ($kcal/m^2$-sec)

R = total reactivity normalized to the delayed neutron fraction ($)

Re = Reynolds Number

T = temperature (°C), hydraulic torque (kgf-m/rad)

t = time (sec)

Δt = time step width (sec)

U = total fluid internal energy (kcal)

u = fluid specific internal energy (kcal/kgm)

V = volume of the node (m)

v = fluid velocity (m/sec), normalized volumetric flor (Q/Q_o)

v_{bub} = bubble velocity relative to the mixture surface (m/sec)

V = specific volume (m^3/kgm)

W = mass flow rate (kgm/sec)

X = quality

x = path length coordinate value (m)

z = elevation coordinate value (m)

Greek letters

α = void fraction, normalized speed (N/N_0), yield fraction of decay heat

β = effective delayed neutron fraction, normalized torque (T/T_0)

θ = inclination of the duct to the vertical

Φ_{2p} = two-phase multiplier

τ_w = average wall shear stress (kgf/m^2)

λ = decay constant (1/sec)

χ = normalized concentration of fission product

μ = absolute viscosity ($kgf\text{-}sec/m^2$)

ρ = fluid density (kgm/m^3)

σ = cavitation constant (kgf/m^2)

ω = angular velocity ($2\pi N/60$ rad/sec)

Subscripts

g : saturated vapor

in : inlet
m,mix: steam-water mixture
out : outlet
sat : saturated condition
0 : initial condition

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in : inlet
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APPENDIX A Input Data Requirements

1. REAG Input Routine

All input data are read into the ALARM-P1 program in free format via a generalized subroutine REAG. The subroutine REAG for FACOM 230-75 converts BCD information to integer or floating point binary information: three types, i.e. the type of reading N floating point numbers, the type of reading N integer numbers and the mixed type of reading $4*N_1$ characters, N_2 integers and N_3 floating point numbers, respectively are allowed by corresponding entries of subroutine.

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 and 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" 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.

2. Data Card Summary

2.1 Title Card (one card)

The information punched in the first column to the 72nd of a card will be printed at the top of the page of output.

2.2 Problem Dimension Card

Number of entries are 17 integers and one floating point number.

LDMP Restart control
- =0 No store restart and plot information
- =-1 Store only restart information on FORTRAN Unit 3
- =-2 Store only plot information on FORTRAN Unit 4
- =-3 Store both restart and plot information on FORTRAN Unit 3 and 4 respectively
- =N Restart at restart number N using the restart information on FORTRAN Unit 2
  After initialization of restart the value of LDMP for previous case is assigned to the symbol LDMP.
  In the restart calculation Edit Variable Card, Time Step Control Card and Trip Control Card must be prepared but the values of NEDI, NTC and NTRP must be same as those of the previous case.

NEDI Number of minor edit variable

NTC Number of time step cards

NTRP Number of trip control cards

NVOL Number of control volumes

NBUB Number of bubble-parameter sets
A set may be used in several volumes.

NJUN Number of junctions

NPMP Number of pumps

NPMPC Number of pump characteristic curve sets
A set may be used for a few pumps.

NCKV Number of check valve types
A parameter set may be used for several junctions.

NLK Number of leak data sets

NFLL	Number of fill system data sets
NSLB	Number of heat slabs
NOCOR	Number of core region
NGOM	Number of heat slab geometry
NMAT	Number of heat slab material
NHTX	Number of heat exchangers
POWRO	Initial power (MW)

2.3 Edit Variable Data Cards

NEDI is the number of the variable to be edited. The specification is made by using the following symbols.

Variables with reference to volume

Key word		
AP	Average pressure	(kg/m^2)
TM	Total mass	(kg)
TE	Total energy	(kcal)
AT	Average temperature	(°C)
AR	Average density	(kg/m^3)
AH	Average enthalpy	(kcal/kg)
AX	Average quality	
BM	Bubble mass	(kg)
ML	Mixture level	(m)
VF	Specific volume of saturated water	(m^3/kg)
VG	" " steam	(m^3/kg)
HF	Specific enthalpy of saturated water	(kcal/kg)
HG	" " steam	(kcal/kg)
TS	Saturation temperature	(°C)
PS	Saturation pressure	(kg/m^2)
WM	Liquid phase mass	(kg)

Variables with reference to core region

WQ	Heat transfer to coolant	(kcal/sec)
DF	DNB Heat flux	($kcal/m^2$-sec)
SF	Heat Flux	($kcal/m^2$-sec)
HC	Heat transfer coefficient	($kcal/m^2$-sec°C)
FT	Fuel average temperature	(°C)

CT	Fuel center temperature	(°C)
ST	Fuel surface temperature	(°C)
FQ	Heat generation	(MW)

Variables with reference to junction

JW	Mass flow rate	(kg/sec)
JH	Junction enthalpy	(kcal/kg)
JX	Junction quality	
LF	Dummy	
TD	Total pressure drop	(kg/m^2)
FD	Frictional pressure drop	(kg/m^2)
ED	Gravitational pressure drop	(kg/m^2)
PD	Pump head	(kg/m^2)
AD	Accelerative pressure drop	(kg/m^2)

Variables with reference to system balance

NQ	Normalized power	
AE	Total energy added during transient	(kcal)
FE	Energy stored in fuel	(kcal)
LE	Total energy leaked	(kcal)
HE	Energy removed by heat exchanger	(kcal)
EB	Energy balance term	(kcal)
TR	Total reactivity	($)
RV	Reactivity due to coolant voids	($)
RC	Reactivity due to control rod changes	($)
RD	Reactivity due to Doppler effect	($)
PO	Power	(MW)
HL	Total heat removed	(kcal/sec)
RP	Reactor period	(sec)

Symbols of available region number identification are as follows;

Volume data	N1, N2, etc.
Junction data	J1, J2, etc.
System balance data	T

example

```
      1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16    Column number
      A P     N 1     J W     J 2 0
```

2.4 Time Step Control Cards

NTC data blocks are required. Each data block consists of 4 integer entries and 2 floating point number entries.

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

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

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

NPLT Number of time steps per plot tape edit
(0 is interpreted as 1)

DELTM Time step size (sec)

TLAST End of current time step data (sec)

2.5 Trip Control Cards

NTRP data blocks are required. Each data block consists of 4 integer entries and 2 floating point number entries.

IDTRP Action to be taken $|IDACT| \leq 20$
= 1 End of problem
= 2I Open leak from junction with I-th leak data set
= 3 Start reactor scram
= 4J Trip J-th pump
= 5K Start fill from junction with K-th fill data set
= 6∿N Open (or close) valve

IDSIG Signal being compared
= 1 Elasped time (sec)
= 2 Normalized reactor power
= 3 Reactor period (sec)
= 4 Pressure (kg/m^2)
= 5 Mixture level (m)
= 6 Liquid level of accumulator (m)
= 7 Water temperature (°C)
= 8 Cladding surface temperature (°C)
= 9 Metal temperature (°C)
=10 Junction flow

IDSIG > 0 ----- Trip limit HIGH
IDSIG < 0 ----- " LOW

IX1 Node or junction index
The node or junction number checked as signal

IX2 Optional node or junction index
If IX2>0, the absolute difference value for IX1 and IX2 is checked as signal.

SETPT Signal set point

DELAY Delay time for initiation of action after reaching setpoint

2.6 Volume Data Cards

NVOL data sets are required. Each data set consists of 2 integer entries and 10 floating point number entries.

IBUB Buble data index ($0 \leq IBUB \leq NBUB$)
If two-phase separation model is not applied to the volume, set IBUB = 0

NPUMP Pump number index ($0 \leq NPUMP \leq NPMP$)
If the volume contains no pump, set NPUMP = 0

P Node pressure (kg/m^2)

TEMP Node temperature (°C) or enthalpy (kcal/kg)
TEMP > 0.----- temperature (0. < TEMP < 800.)
TEMP $\leq$ 0.----- enthalpy |TEMP| (kcal/kg)

HORX Quality or humidity ($0. \leq HORX \leq 1.$)
If the volume contains subcooled liquid, HORX < 0..

V Volume (m^3)

ZVOL Volume height from the bottom to the top (m)

ZM Mixture level from the bottom (m) ($0. \leq ZM \leq ZVOL$)

FLOWA Flow area of volume (m^2)

DIAMV Equivalent diameter of flow area (m)
If DIAMV = 0., set DIAMV = $2.*\sqrt{FLOWA/\pi}$.
Used only for Fanning friction calculation.

ELEV Elevation at bottom of volume (m)

FLOWL Flow length of volume (m)
If FLOWL = 0., set FLOWL = V/FLOWA.
Used only for Fanning friction calculation.

The following data is required only if NPUMP > 0 and this data block must be refreshed.

XN Initial pump speed (rad/sec)

2.7 Bubble Data Cards

NBUB data blocks are required. Each data block consists of two floating point number entries.

ALPH Bubble gradient parameter (0. ≤ ALPH ≤ 1.)

VBUB Bubble velocity (0. < VBUB) (m/sec)
Set Number (ALPH = 0. VBUB = 0.) is built-in.

2.8 Pump Curve Data Cards

NPMPC data sets are required. Each data set consists of two data blocks and tabular input data.

(i) The first data block consists of 9 integer data entries

N1	Number of data points for	(A)	characteristic curve
N2	"	(B)	"
N3	"	(C)	"
N4	"	(D)	"
N5	"	(E)	"
N6	"	(F)	"
N7	"	(G)	"
N8	"	(H)	"

N9 Number of data points for NPSH (kg_f/m^2)
vs. mass flow rate (kg/sec)

(ii) The second data block consists of 9 floating point number entries

HLOSM Maximum head loss (m)
If HLOSM = 0., calculated in the code.

CAVCON Cavitation constant (kg_f/m^2)

ROHO Rated fluid density (kg_m/m^3)

HO Rated pump head (m)

QO Rated volumetric flow rate (m^3/sec)

NO Rated pump speed (rad/sec)

TO Rated hydraulic torque (kg_f.m/rad)

I Inertia moment ($kg_m \cdot m^2/rad^2$)

KSR Loss coefficient of stalled rotor ($kg_f \cdot sec^2/kg_m \cdot m^5$)

(iii) The third data block to the 11-th data block are tabular input. Entries for each block are twice the number of data points. For each pump characteristic curve, normalized values are used. On the other hand, for NPSH curve tabular data are given by realistic value. Data must be arranged as follows;

independent variable X_1, dependent variable Y_1, ----------
--------,independent Xn, dependent Yn.

2.9 Junction Data Cards

NJUN data blocks are required. Each data block consists of 6 integer entries and 9 floating point number entries.

IW(1) Volume index at junction inlet ($0 \leq IW(1) \leq NVOL$)

IW(2) Volume index at junction outlet ($0 \leq IW(2) \leq NVOL$)

IPUMP
(a) (IW(1) > 0, IW(2) > 0) Pump index
($0 \leq |IPUMP| \leq NPMP$)
IPUMP > 0 ----- Discharge side junction
IPUMP < 0 ----- Suction side junction
(b) (IW(1) > 0, IW(2) = 0) Leak index
($0 \leq IPUMP \leq NLK$)
(c) (IW(1) = 0, IW(2) > 0) Fill index
($0 \leq IPUMP \leq NFLL$)

IVALVE Valve index ($0 \leq IVALVE \leq NCKV$)
IVALVE = 0 ----- No valve
IVALVE > 0 ----- Check valve

IANGL Mixing junction index
= 0 No momentum mixing junction
= 1 Momentum mixing junction
= 2 No momentum flux calculation

JENTH Junction enthalpy index
= 0
= 1
= 2
= 3
Refer to §3.1.5 in detail

WP Junction mass flow rate (kg_m/sec)

AJUN — Junction flow area (m^2) (AJUN > 0.)
For leak junction, AJUN is full leak area.

ZJUN — Junction elevation (m)

INERTA — Junction effective L/A (1/m)

(a) IW(1) > 0, IW(2) > 0
INERTA ≥ 0.

(b) IW(1) = 0 or IW(2) = 0
INERTA = 0.

If IW(1) > 0, IW(2) > 0 and INERTA = 0., INERTA is calculated from one-half of the length of each adjacent volume divided by the volume flow area where volume length is FLOWL.

FRIFF — Form loss coefficient for forward flow

FRIFR — Form loss coefficient for reverse flow
Form loss coefficient is a dimensionless positive number due to geometric changes within flow control volume, if any.
Form loss coefficient is used as following form:

$$K \frac{v^2}{2}$$

where K is FRIFF or FRIFR and v is based on the junction area.If both FRIFF and FRIFR are zero, calculated in the code.

ANGLE — Cross angle for momentum mixing junction
(0.≤ ANGL < 90°.)
If IANGL ≠ 1, set ANGL = 0..

ZACOEF — Coefficient for subcooled critical flow calculation of normal junction (IW(1) > 0, IW(2) > 0) by Zaloudek's equation (0.is interpreted as 0.9)

MDCOEF — Contraction coefficient for critical flow calculation of normal junction (IW(1) > 0, IW(2) > 0) by Moody's equation (0.is interpreted as 1.0)
If MDCOEF < 0., critical flow check is not performed for nromal junction.

2.10 Valve Data Cards

NCKV data blocks are required. Each data block consists of one integer entry and 4 floating point number entries.

ITCV — Type of valve
= 0 Type 0 (without hysteresis)
= 1 Type 1 (with hysteresis)
$-N \leq ITCV \leq -6$ a closed valve to open under trip control
$6 \leq ITCV \leq N$ an open valve to close under trip control

PBACK — Back pressure for closure (kg_f/m^2)

FRICF — Forward flow friction coefficient ($kg_f \cdot sec^2/kg_m \cdot m^5$)

FRICRO — Reverse flow friction coefficient ($kg_f \cdot sec^2/kg_m \cdot m^5$) (valve open)

FRICRC — Reverse flow friction coefficient ($kg_f \cdot sec^2/kg_m \cdot m^5$) (valve closed)
If ITCV $\neq$ 0, or $\neq$ 1, set PBACK, FRICF, FRICRO and FRICRC are zero.

2.11 Leak Table Data Cards

NLK data sets are required. Each data set consists of a data block having 2 integer and 3 floating point number entries and tabular input.

(i) The first data block

ILAORF — Type of leak table data
= 1 ----- Leak flow area vs. time
= 2 ----- Leak mass flow rate vs. time

NAREAF — Number of data points

SINK — Sink pressure

CONCO — Contraction coefficient for critical flow calculation by Moody's equation

C2 — Coefficient for subcooled critical flow calculation by Zaloudek's equation ($0.5 \leq C2 < 1.0$)

(ii) The second data block has 2*NAREAF floating point number entries. Data must be arranged as follows;

time t_1, normalized flow area A_1 (or mass flow rate),
time t_2, normalized flow area A_2 (or mass flow rate),
----------,time t_{NAREAF}, normalized flow area A_{NAREAF} (or mass flow rate).

2.12 Fill Table Data Cards

NFLL data sets are required. Each data set consists of a data block having 2 integer and 2 floating point number entries and tabular input.

(i) The first data block

NFILL Number of data points

IX Independent variable
IX = 0 ------- time (sec)
IX > 0 ------- pressure (kg_f/m^2) ($P_{vol} + P_{grav}$)
IX < 0 ------- differential pressure (kg_f/m^2)
($P_{fill} - P_{vol} - P_{grav}$)

FILPRS Pressure in fill reservoir (kg_f/m^2)

FILTEM Temperature, quality or enthalpy in fill reservoir
1.0 < FILTEM ------- temperature (°C)
0. ≦ FILTEM ≦ 1.0 -- quality
0. > FILTEM -------- |FILTEM| enthalpy ($kcal/kg_m$)

(ii) The second data block has 2*NFILL floating point number entries. Data arrangement is the same as in the Leak Table Data Cards;

independent variable t_1, mass flow rate w_1, independent variable t_2, mass flow rate w_2, ----------, independent variable t_{NFILL}, mass flow rate w_{NFILL}.

2.13 Kinetics Constants Data Cards

Required only if NOCOR > 0. Data set consists of following three parts.

(i) The first block has 2 integer entries and 2 floating point number entries.

IPCT Normalized power (P(t)/P(0)) calculation indicator
= 0 -- One prompt neutron group plus six groups of delayed neutrons plus eleven fission gamma emitters

= 1---P(t)/P(0) vs. time table

ITBL Kinetics parameter indicator
= 0---use built-in data
= 1---use input data for decay constants and yields of both delayed neutron groups and fission gamma emitters

BETABL Effective delayed neutron fraction over mean lifetime (sec^{-1})

REAC0 Initial reactivity ($)

(ii) The second data set required only if IPCT = 1

(a) one integer entry

NTVSNP Number of data points for power vs. time table

(b) 2*NTVSNP floating point number entries

Data arrangement is as follows:

time t_1, normalized power ($P(t_1)/P(0)$), time t_2, normalized power ($P(t_2)/P(0)$), ----------,time t_{NTVSNP}, normalized power ($P(t_{NTVSNP})/P(0)$).
Time values are in ascending order.

(iii) The third data set is required only if IPCT = 0 and ITBL = 1

(a) 6 floating point number entries
Normalized effective delayed neutron fraction (β_{ieff}/β_{eff})

(b) 6 floating point number entries
Decay constants of delayed neutron groups (λ_i) (sec^{-1})

(c) 12 floating point number entries
Energy Fraction of fission gamma groups and total fraction (α_i, $\Sigma\alpha_i$)

(d) 11 floating point number entries
Decay constants of fission gamma groups (λ_{Dj}) (sec^{-1})

(e) One floating point number entry
Energy fraction of actinide decay heat (α_{act})

2.14 Scram Table Data Cards

Required only if NOCOR > 0 and IPCT = 0

This data set consists of following two blocks.

(i) The first data block has one integer entry

NSCRAM Number of data points for scram data table

(ii) The second data block has 2*NSCRAM floating point number entries. Data arrangement is as follows:

time t_1, reactivity ρ_1 ($), time t_2, reactivity ρ_2 ($),----------, time t_{NSCRAM}, reactivity ρ_{NSCRAM} ($).

2.15 Density Reactivity Table Data Cards

Required only if NOCOR > 0 and IPCT = 0

This data set consists of four parts.

(i) The first data block has one integer entry

INWDOP Density reactivity calculation indicator
= 1---option 1 (calculated weighting factors in core regions)
= 2---option 2 (input weighting factor)

(ii) The second data block is required if INWDOP = 1 and has 3 floating point number entries. These entries are the coefficients in polynominal fitting equation; $\delta k\rho = AROH\cdot\rho + \frac{1}{2} BROH\cdot\rho^2 + \frac{1}{3} CROH\cdot\rho^3$ for density reactivity feedback.

AROH Coefficient in fitting equation
BROH Coefficient in fitting equation
CROH Coefficient in fitting equation

(iii) The third data block is required if INWDOP = 2

(a) One integer entry and NOCOR floating point number entries

NROARO Number of data points for reactivity data table
WROH(1) Reactivity weighting factor for the first core region
WROH(2)
⋮
WROH(NOCOR)

(iv) The fourth data block is required if INWDOP = 2 and has 2*INWDOP floating point number entries. Data arrangement is as follows:

density ρ_1 (kg/m^3), reactivty $A\rho_1$ ($), density ρ_2, reactivity $A\rho_2$, ----------,density ρ_{NROARO}, reactivity $A\rho_{NROARO}$.

Density values are in ascending order.

2.16 Doppler Table Data Cards

Required only if NOCOR > 0 and IPCT = 0

This data set consists of following four parts.

(i) The first data block has one integer entry.

IDOPOP Doppler reactivity calculation indicator
= 1---option 1 (use fitting equation for Doppler reactivity)
= 2---option 2 (use Doppler table data)

(ii) The second data block is required if IDOPOP = 1, and has one floating point number entry

RFT Constant in fitting equation for Doppler feedback reactivity (RFT < 0.)

(iii) The third data block is required if IDOPOP = 2, and has one integer entry and NOCOR floating point number entries.

NTEREA Number of data points for Doppler table data
WFT(1) Doppler reactivity weighting factor for the first core region
WFT(2)
⋮
WFT(NOCOR)

(iv) The fourth data block is required if IDOPOP = 2, and has 2*NTEREA floating point number entries. Data arrangement is as follows:

temperature T_1(°C), Doppler reactivity R_{ft_1}($),----------
---------,Temperature T_{NTEREA}, Doppler reactivity $R_{ft_{NTEREA}}$

Temperature values are in asccending order.

2.17 Heat Slab Data Cards

NSLB data sets are required

(i) The first data block has 3 integer entries and 5 floating point number entries.

IVSL Volume number at left slab surface
(-1 ≦ IVSL ≦ NVOL)

IVSR Volume number at right slab surface
(-1 ≦ IVSR ≦ NVOL)
A zero value for either IVSL or IVSR means that the slab surface does not conduct heat.
A -1 value for either IVSL or IVSR means that there is a constant heat sink on the -1 side.

For this case, two more input quantities are needed: a constant heat transfer coefficient and a removal fraction of the total power initially generated. At least one of the quantities IVSL or IVSR must be greater than zero if a heat slab is a core section, IVSL must be zero.

IGOM Geometry index ($1 \leqq IGOM \leqq NGOM$)

AHTL Heat transfer area at left slab surface (m^2)

AHTR Heat transfer area at right slab surface (m^2)

VOLS Volume of heat slab (m^3)

HDML Left side hydraulic diameter (m)
If IVSL > 0 and HDML = 0., HDML will be set equal to DIAMV (on 2.6 volume data)

HDMR Right side hydraulic diameter (m)
If IVSR > 0, and HDMR = 0., HDMR will be set equal to DIAMV (on 2.6 volume data)

(ii) The second data block is required if either IVSL or IVSR equal to -1, and has 2 floating point number entries.

PFR Removal fraction of the total power initially generated

HTC Constant heat transfer coefficient ($kcal/m^2$-sec-°C)

2.18 Core Section Data Cards

NOCOR data sets are required if NOCOR > 0. This data set has one integer entry and 3 floating point number entries.

ISLB Slab number ($1 \leqq ISLB \leqq NSLB$)

CHANL Channel length (CHANL > 0.) (m)

HEDIA Heated equivalent diameter (HEDIA > 0.) (m)

POWFR Fraction of power generated in core section
($0. \leqq POWFR \leqq 1.0$) $\sum_{1}^{NOCOR} POWFR_i = 1.0$

2.19 Slab Geometry Data Cards

NGOM data sets are required and this data set consists of following two parts.

(i) The first data block has 5 integer entries and 3 floating point number entries.

JGOM Geometry type
= 1 -- Rectangular
= 2 -- Cylindrical

NREG Number of region (1 ≦ NREG)

IHTMOD Heat conduction calculation indicator
= 0--Heat conduction model
= 1---Point heat transfer model

IMATID(1) Material index of the first region
(1 ≦ IMATID ≦ NMAT)

ISPST(1) Number of space step for the first region (1 ≦ ISPST)

WREG(1) Region width of the first region (m)
Negative region width is also permitted.

POFRRG(1) Fraction of slab power generated in the first region

RDLFT Radial distance to left surface (m)
RDLFT = 0. for a solid rod
If WREG(1) < 0., RDLFT means outer radius

(ii) The second data set is required if NREG ≧ 2. These data must be set for the second region to NREG-th region. Data for each region have 3 integer entries and 2 floating point number entries.

IGAP(J) Gap indicator
= 0--no gap region
= 1--gap region

IMATID(J) Material index (1 ≦ IMATID(J) ≦ NMAT)

ISPST(J) Number of space step (1 ≦ ISPST(J))

WREG(J) Region width (m)

POFRRG(J) Fraction of slab power generated

2.20 Thermal Property Data Cards

NMAT data sets are required. Each data set consists of following 6 data blocks.

(i) one integer entry

NTATK Number of data points for thermal conductivity

(ii) 2*NTATK floating point number entries

Data arrangement is as follows:

temperature T_1 (°C), thermal conductivity k_1 (kcal/m-sec-°C),

----------,temperature T_{NTATK}, thermal conductivity k_{NTATK}
Temperature values are in ascending order.

(iii) one integer entry

NTAHC Number of data points for volumetric heat capacity

(iv) 2*NTAHC floating point number entries

Data arrangement is as follows:
temperature T_1 (°C), volumetric heat capacity ρc_{p_1} (kcal/m^3-°C),
---------,temperature T_{NTAHC}, volumetric heat capacity $\rho c_{p_{NTAHC}}$
Temperature values are in ascending order.

(v) one integer entry

NTAGAP Number of data points for gap conductance

(vi) 2*NTAGAP floating point number entries

Data arrangement is as follows:
temperature T_1 (°C), gap conductance G_{gap1}(kcal/m^2-sec-°C), -----
---------, temperature T_{NTAGAP}, gap conductance $G_{gapNTAGAP}$

2.21 Heat Exchanger Data Cards

NHTX data sets are required. Each data set consists of following 5 data blocks.

(i) 3 integer entries

JVOL Volume number of primary side ($1 \leqq JVOL \leqq NVOL$)

JHEAT Heat exchanger model indicator
= 0 --static model
= 1-- transient heat conduction model

JVOLS Volume number of secondary side ($1 \leqq JVOLS \leqq NVOL$)

(ii) This data block is required if JHEAT = 0, and has 5 floating point number entries.

ASG Heat transfer area of primary side (m^2)

HTSCD Constant heat transfer coefficient of secondary when heat flows from secondary to primary (kcal/m^2-sec-°C)

XQHED Equivalent heated diameter of primary side (m)

XQHDM Equivalent hydraulic diameter of primary side (m)

XQL Channel length of primary side (m)
Used for CHF calculation

(iii) 4 integer entries

JSLB Slab number ($1 \leqq JSLB \leqq NSLB$)

JHTCOM Heat transfer coefficient calculation indicator
= 0--input heat transfer coefficients of both primary and secondary side
= 1--calculates heat transfer coefficients of both primary and secondary side in the code

NTAHT1 Number of data points for primary heat transfer coefficient vs. time table
NTAHT1 $\geqq$ 1 if JHTCOM = 0, NTAHT1 = 0 if JHTCOM = 1

NTAHT2 Number of data points for secondary heat transfer coefficient vs. time table
NTAHT2 $\geqq$ 1 if JHTCOM = 0, NTAHT2 = 0 if JHTCOM = 1

(iv) This data block is required if both JHEAT = 1 and JHTCOM = 0, and has 2*NTAHT1 floating point number entries. Data arrangement is as follows:

time t_1, primary heat transfer coefficient h_{p1} (kcal/m^2-sec-°C),
--------, time t_{NTAHT2}, primary heat transfer coefficient $h_{pNTAHT1}$
Time values are in ascending order.

(v) This data block is required if both JHEAT = 1 and JHTCOM = 0, and has 2*NTAHT2 floating point number entries.
Data arrangement is as follows:

time t_1 (sec), secondary heat transfer coefficient h_{s1} (kcal/m^2-sec-°C),
--------- time, t_{NTAHT2}, secondary heat transfer coefficient $h_{sNTAHT2}$.
Time values are in ascending order.

3. Input for Restarting

An old restart data tape to be used must be mounted on FORTRAN Unit 2 and a blank tape must be mounted on Unit 3. The following input for restarting are required.

3.1 Title Card

The information punched in the first column to the 72nd of a card will be printed at the top of the page of out put. The information on this card must be identical to the title of the previous case.

3.2 Problem Dimensions Data Card

Number of entries are 17 integers and one floating point number.

LDMP — N the restart number of the old problem where restart is to begin.

NEDI — Number of minor edit variables
NEDI must be less than or equal to that of the old problem.

NTC — Number of time step data cards
NTC must be less than or equal to that of the old problem.

NTRP — Number of trip control data cards
NTRP must be less than or equal to that of the old problem.

The following 13 integer entries (NVOL, NBUB, NJUN, NPMP, NPMPC, NCKV, NLK, NFLL, NSLB, NOCOR, NGOM, NMAT, NHTX) and a floating point number entry (POWER0) must be equal to those of the old problem.

3.3 Edit Variable Data Cards

NEDI variables are to be editted, and the same rules apply as for the original problem. The quantities being edited on the new run need not have any relation to those of the original run.

3.4 Time Step Data Cards

NTC data blocks must be entered. The same rules apply as for the original problem.

3.5 Trip Control Data Cards

NTRP data blocks are required. Data blocks for any trips to remain actuated once the signals are received, must be reentered with the same specifications as for the old problem, while for a trip not yet actuated, the specifications which is not same as for the old problem may be entered.

APPENDIX B

PREEDIT --- A Editting Program for ALARM-P1 Plot Data File

The PREEDIT program edits plot information in one new file from some ALARM-P1 plotter files produced by some sequential runs as well as that with new time width for plotting. Newly editted file is used as input file of the plotting program PLOTR4[2] which is plotting routine for the RELAP4 program.

Figure B-1 presents a function of PREEDIT. Sequence of input logical unit number must be corresponding to that of calculated physical time.

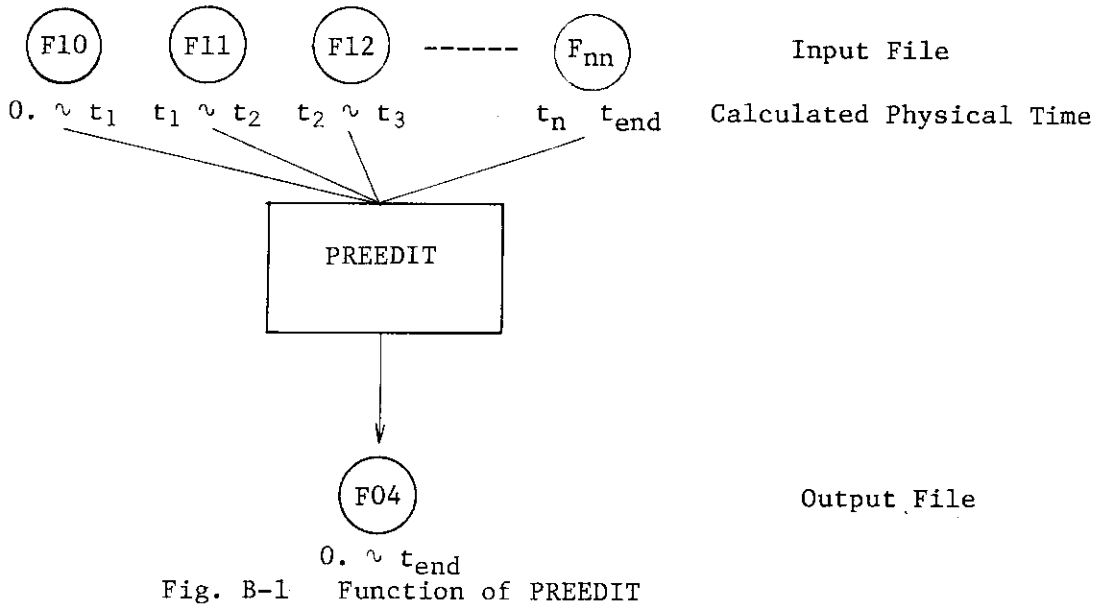

Fig. B-1 Function of PREEDIT

Input Data of PREEDIT

(1) Title Card (20A4)

Information of this data card must be identical to the old problem.

(2) Number of Input File Card (I10)

NTAPE Number of input files

(3) Editting Data Cards (4X, I6, 3(F10.0))

NTAPE card are required

ID FORTRAN logical unit number of input file

ST Start time to be editted on this file

ET End time to be editted on this file

DT Time width

APPENDIX C Sample Input Data List

```
/*                                                                      ISP50001
/*          LOFT(L1-4) ANALYSIS  BY  ALARM-P1                           ISP50002
/*                                                                      ISP50003
     CSNI STANDARD PROBLEM NO.5  BY  ALARM-P1(MOD1)                     ISP50004
/*                                                                      ISP50005
/*   PROBLEM DIMENSION                                                  ISP50006
/*                                                                      ISP50007
      -3  18  6  9  31  1  35  2  1  3  0  2  1  0  1  1  0  0,0       ISP50008
/*                                                                      ISP50009
/*   EDIT VARIABLE                                                      ISP50010
/*                                                                      ISP50011
AP  N1  AP  N10 AP  N15 AP  N21 AP  N22 AR  N1  AR  N10 AR  N15 AR  N21 ISP50012
AP  N14 AP  N11 AP  N9  JW  J31 JW  J11 JW  J10 JW  J12 AP  N28 AP  N30 ISP50013
/*                                                                      ISP50014
/*   TIME STEP CONTROL                                                  ISP50015
/*                                                                      ISP50016
       500      10     1      1000     0.00001          0,05           ISP50017
       200      30     1       200     0.00005          0,30           ISP50018
       500      20     1       100     0,0001           1,00           ISP50019
       200      10     1        20     0.0005           5,00           ISP50020
       500      10     1        10     0,001           20,00           ISP50021
       500      20     1        10     0,001           80,00           ISP50022
/*   TRIP  CONTROL                                                      ISP50023
/*                                                                      ISP50024
     1    1     0   0        60,0      0,0                             ISP50025
     1   -4     1   0         1,899E4  0,0                             ISP50026
/*           ( TWO PUMPS )                                             ISP50027
    41    1     0   0         0,0      0,0                             ISP50028
    42    1     0   0         0,0      0,0                             ISP50029
/*           ( LPIS INJECTION --- FILL SYSTEMS )                       ISP50030
    51    1     0   0        36,0      0,0                             ISP50031
/*           ( HPIS INJECTION --- FILL SYSTEMS )                       ISP50032
    52    1     0   0        22,0      0,0                             ISP50033
/*           ( ACC  INJECTION --- FILL SYSTEMS )                       ISP50034
     6   -4    28   0        43,14E4   0,0                             ISP50035
     7    1     0   0         0,0      0,0                             ISP50036
     8    1     0   0         0,0      0,0                             ISP50037
/*                                                                      ISP50038
/*   VOLUME DATA                                                        ISP50039
/*                                                                      ISP50040
    0      0 160,7172995E+4 279,444   -1,0   0,13933   0,2840736       ISP50041
      0,2840736       0,06342     0,2840736     -0,1420368          0,0 ISP50042
    0      0 160,6821378E+4 280,000   -1,0   0,06853   0,2840736       ISP50043
      0,2840736       0,06342     0,2840736     -0,1420368          0,0 ISP50044
    0      0 160,5977496E+4 280,556   -1,0   0,16567   0,384048        ISP50045
      0,384048        0,06342     0,2840736     -0,1420368          0,0 ISP50046
    1      0 160,3516174E+4 280,000   -1,0   0,70517   3,429           ISP50047
      3,429           0,15107     0,0102108      0,0950976          3,56 ISP50048
    0      0 159,8593530E+4 279,444   -1,0   0,70517   3,429           ISP50049
      3,429           0,15107     0,0102108      0,0950976          3,56 ISP50050
    0      0 159,7046413E+4 278,889   -1,0   0,17473   1,685544        ISP50051
      1,685544        0,06342     0,2840736     -1,4121384          0,0 ISP50052
```

```
      0      1 160,6962025E+4 279,444   -1.0   0,19413   1,5200376          ISP50053
        1.5200376       0.06342     0.2840736     -1,4121384          0.0  ISP50054
        177,437                                                            ISP50055
      0      1 160,6962025E+4 279,444   -1.0   0.22755   1,5200376          ISP50056
        1,5200376       0,06342     0.2840736     -1,4121384          0,0  ISP50057
        177,437                                                            ISP50058
      0      0 161,3853727E+4 279,444   -1.0   0,11385   0,2840736          ISP50059
        0,2840736       0,06342     0.2840736     -0,1420368          0.0  ISP50060
      0      0 161,3502109E+4 279,444   -1.0   0,14981   0,2840736          ISP50061
        0.2840736       0,06342     0.2840736     -0,1420368          0.0  ISP50062
      1      0 161,4064697E+4 280,556   -1.0   0,94306   5,1703224          ISP50063
        5.1703224       0,18236     0,0493776     -4,255008           0,0  ISP50064
      0      0 161,4978902E+4 280,556   -1.0   0,64315   0,8238744          ISP50065
        0.8238744       0,78055     0.9970008     -4,988052           0,0  ISP50066
      0      0 161,2587904E+4 280.000   -1.0   0,91474   3,5317176          ISP50067
        3,5317176       0,25901     0,5742432     -4,1641776          0,0  ISP50068
      1      0 160,8438818E+4 279,444   -1.0   0,30869   1,5325344          ISP50069
        1,5325344       0,23067     0,5419344     -0,63246            0,0  ISP50070
      0      0 160,7172995E+4 279,444   -1.0   0,16406   0,2840736          ISP50071
        0.2840736       0,06342     0.2840736     -0,1420368          0,0  ISP50072
      0      0 160,6118143E+4 279,444   -1.0   0,01269   0,7690104          ISP50073
        0,7690104       0,00836     0,1033272     -0,0515112          0,0  ISP50074
      0      0 160,5063291E+4 276,667   -1.0   0,33672   2,8882848          ISP50075
        2,8882848       0,10563     0,3666744      0,7174992          0,0  ISP50076
      0      0 160,7172995E+4 276,667   -1.0   0,33672   2,8882848          ISP50077
        2,8882848       0,10563     0,3666744      0,7174992          0,0  ISP50078
      0      0 160,9353023E+4 273,889   -1.0   0,04996   2,07264            ISP50079
        2,07264         0,02564     0,1807464     -1,354836           0,0  ISP50080
      0      0 160,7172995E+4 272,222   -1.0   0,01575   1,2643104          ISP50081
        1,2643104       0,00836     0,10333       -1,2643104          0,0  ISP50082
      0      0 161,3502109E+4 280,556   -1.0   0,13857   0,2840736          ISP50083
        0,2840736       0,06342     0,2840736     -0,1420368          0,0  ISP50084
      1      0 160,5344585E+4 342,778    0,0   0,96288   1,703344           ISP50085
        1,1454384       0,56520     0,847344       1,1539728          0,0  ISP50086
      0      0 160,6469760E+4 300,000   -1.0   0,00634   1,0308336          ISP50087
        1,0308336       0,00145     0,0429768      0,1420368          0,0  ISP50088
      0      0 160,6540084E+4 276,667   -1.0   0,16576   0,8619744          ISP50089
        0,8619744       0,03883     0,2221992     -0,11113008         0,0  ISP50090
      0      0 161,2869198E+4 276,667   -1,0   0,19235   0,6074664          ISP50091
        0,6074664       0,03883     0,2221992      0,1420368          0,0  ISP50092
      0      0 159,3811533E+4 272,222   -1.0   0,00408   0,10320528         ISP50093
    0,10320528   0,00836   0,10320528   -0,0515112   0,0                   ISP50094
      0      0 160,5907172E+4 320,000   -1.0   0,00634   0,2023872          ISP50095
    0,2023872    0,00144   0,042672       1,1298936   0,0                   ISP50096
/*    ECCS                                                                 ISP50097
/*   (VOL=28)  ACC LINE NEAR COLD-LEG                                      ISP50098
      0      0 161,3375359E+4 254,444   -1.0   0,03398   0,04443984         ISP50099
        0,04443984      0,006207    0,08890        0,1420368          0,0  ISP50100
/*   (VOL=29)  ACC LINE NEAR ACC TANK (CONTAINS STANDPIPE )                ISP50101
      0      0  43,1364276E+4  33,333   -1,0   0,3285    0,7705344          ISP50102
        0,7705344       0,006207    0,08890        0,18647664         0,0  ISP50103
/*   (VOL=30)  ACC TANK                                                    ISP50104
      1      0  43,1364276E+4  33,333    0,0   3,6816    2,919984           ISP50105
        1,999           1,2607      1,267          0,18647664         0,0  ISP50106
```

```
      0      0   1,0407876E+4  83,889     0,0 104,809      4,9054512          ISP50107
        2,871216       21,367        5,21208        -4,13004            0,0   ISP50108
/*                                                                            ISP50109
/*    BUBBLE DATA                                                             ISP50110
/*                                                                            ISP50111
         0,8      0,9144                                                      ISP50112
/*                                                                            ISP50113
/*    PUMP DATA                                                               ISP50114
/*                                                                            ISP50115
      11  12  13  17  11   7  10  17  2                                       ISP50116
      0,0   1,0E-5  620,775  124,648  0,3154  369,661 10,232  0,363  0,0ISP50117
/*                                                                            ISP50118
/*    HEAD                                                                    ISP50119
/*                                                                            ISP50120
   -1,0       2,4722   -0,80574   2,0474   -0,6069   1,831                   ISP50121
   -0,40683   1,624    -0,200171  1,4705    0,0      1,4036                  ISP50122
    0,19061   1,3636    0,38963   1,3186    0,59396  1,2328                  ISP50123
    0,7902    1,1336    1,0       1,0078                                     ISP50124
/*                                                                            ISP50125
   -1,0      -1,0      -0,80     -0,63     -0,60     -0,30                   ISP50126
   -0,40     -0,05     -0,20      0,15      0,0       0,25                   ISP50127
    0,20      0,28      0,40      0,34      0,4118    0,2768                  ISP50128
    0,59763   0,4584    0,763467  0,6992    1,0       0,9465                  ISP50129
/*                                                                            ISP50130
   -1,0      -1,0      -0,80     -0,97     -0,60     -0,95                   ISP50131
   -0,40     -0,88     -0,20     -0,80      0,0      -0,67                   ISP50132
    0,20     -0,50      0,40     -0,25      0,57554   0,0                    ISP50133
    0,74432   0,2583    0,77348   0,3778    0,86313   0,6326                 ISP50134
    1,0       1,0078                                                         ISP50135
/*                                                                            ISP50136
   -1,0       2,4722   -0,82297   1,9968   -0,63332  1,5897                  ISP50137
   -0,45534   1,3279   -0,27109   1,1949   -0,17716  1,0605                  ISP50138
   -0,09073   1,0156    0,0       0,934279  0,091099 0,9229                  ISP50139
    0,186509  0,8963    0,271762  0,875     0,455872 0,8433                  ISP50140
    0,574406  0,8355    0,740576  0,8466    0,766619 0,8469                  ISP50141
    0,871471  0,8838    1,0       0,9465                                     ISP50142
/*                                                                            ISP50143
/*    TORQUE                                                                  ISP50144
/*                                                                            ISP50145
   -1,0       1,9843   -0,80096   1,394    -0,60638  1,0975                  ISP50146
   -0,40686   0,822    -0,19928   0,6648    0,0      0,6032                  ISP50147
    0,1930    0,6325    0,393     0,7369    0,59552  0,8331                  ISP50148
    0,79782   0,9229    1,0       0,9672                                     ISP50149
/*                                                                            ISP50150
   -1,0      -1,0      -0,30     -0,90     -0,10     -0,50                   ISP50151
    0,0      -0,45      0,40     -0,25      0,50      0,0                    ISP50152
    1,0       0,3569                                                         ISP50153
/*                                                                            ISP50154
   -1,0      -1,0      -0,25     -0,90     -0,08     -0,80                   ISP50155
    0,0      -0,67      0,40     -0,25      0,50      0,15                   ISP50156
    0,737255  0,526586  0,768049  0,606594  0,86723   0,74366                ISP50157
    1,0       0,9672                                                         ISP50158
/*                                                                            ISP50159
   -1,0       1,9843   -0,82234   1,8308   -0,63371  1,6824                  ISP50160
```

```
   -0,45853  1,557     -0,267023  1,4362    -0,176107 1,3879                ISP50161
   -0,08931  1,3481     0,0       1,23361    0,090643 1,1965                ISP50162
    0,188569 1,1096     0,27347   1,0416     0,458669 0,8958                ISP50163
    0,57448  0,7807     0,73816   0,6134     0,76852  0,5849                ISP50164
    0,870057 0,4877     1,0       0,3569                                    ISP50165
/*                                                                          ISP50166
    0,0      0,0        1,E+8     0,0                                       ISP50167
/*                                                                          ISP50168
/*    JUNCTION  DATA                                                        ISP50169
/*                                                                          ISP50170
     1    2    0   0   0   1   268,400   0,06342     0,0          0,0      ISP50171
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50172
     2    3    0   0   0   1   268,400   0,06342     0,0          0,0      ISP50173
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50174
     3    4    0   0   0   1   268,400   0,05169     0,2420112    0,0      ISP50175
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50176
     4    5    0   0   0   1   268,400   0,15143     3,057144     0,0      ISP50177
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50178
     5    6    0   0   0   1   268,400   0,05169     0,2734056    0,0      ISP50179
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50180
     6    7   -1   0   0   1   134,200   0,06342    -1,2701016    0,0      ISP50181
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50182
     6    8   -2   0   0   1   134,200   0,06342    -1,2701016    0,0      ISP50183
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50184
     7    9    1   0   0   1   134,200   0,03661     0,0          0,0      ISP50185
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50186
     8    9    2   0   0   1   134,200   0,03661     0,0          0,0      ISP50187
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50188
     9   10    0   0   0   1   268,400   0,06342     0,0          0,0      ISP50189
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50190
    10   11    0   0   0   1   268,400   0,06342     0,0          0,0      ISP50191
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50192
    11   12    0   0   0   1   268,400   0,17094    -4,255008     0,0      ISP50193
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50194
    12   13    0   0   0   1   268,400   0,26254    -4,1641776    0,0      ISP50195
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50196
    13   14    0   0   0   1   268,400   0,04779    -0,63246      0,0      ISP50197
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50198
    14    1    0   0   0   1   268,400   0,06342     0,0          0,0      ISP50199
                   1,0E-5   1,0E-5   0,0   0,85   0,0                      ISP50200
    14   15    0   0   0   1     0,0     0,06342     0,0          0,0      ISP50201
                   0,0      0,0      0,0   0,85   0,0                      ISP50202
    24   15    0   0   0   1     0,0     0,03880     0,0          0,0      ISP50203
                   0,5      0,5      0,0   0,85   0,0                      ISP50204
    15   16    0   0   0   1     0,0     0,00836     0,0          0,0      ISP50205
                   0,0      0,0      0,0   0,85   0,0                      ISP50206
    16   17    0   0   0   1     0,0     0,00836     0,7174992    0,0      ISP50207
                   1,52     1,09     0,0   0,85   0,0                      ISP50208
    17   18    0   0   0   1     0,0     0,01914     3,4222944    0,0      ISP50209
                 7,02     7,02   0,0   0,85   0,0                         ISP50210
    18   19    0   0   0   1     0,0     0,00836     0,7174992    0,0      ISP50211
                 1,09     1,52   0,0   0,85   0,0                         ISP50212
    19   20    0   0   0   1     0,0     0,00836    -1,2127992    0,0      ISP50213
                17,10    17,10   0,0   0,85   0,0                         ISP50214
```

```
    20   31   0   2   0   1      0,0      0,00836      0,0          0,0     ISP50215
                0,0   0,0   0,0   0,85     0,60                             ISP50216
    11   21   0   0   0   1      0,0      0,06342      0,0          0,0     ISP50217
                0,0   0,0   0,0   0,85     0,0                              ISP50218
    25   21   0   0   0   1      0,0      0,03880      0,1420368    0,0     ISP50219
                0,5   0,5   0,0   0,85     0,0                              ISP50220
    21   26   0   0   0   1      0,0      0,00836      0,0          0,0     ISP50221
                0,0   0,0   0,0   0,85     0,0                              ISP50222
    22   27   0   0   0   1      0,0      0,00468      1,2743688    0,0     ISP50223
                0,0   0,0   0,0   0,85     0,60                             ISP50224
    23    2   0   0   0   1      0,0      0,00145      0,1420368    0,0     ISP50225
                0,95  0,44  0,0   0,85     0,60                             ISP50226
    26   31   0   3   0   1      0,0      0,00836      0,0          0,0     ISP50227
                0,0   0,0   0,0   0,85     0,60                             ISP50228
    27   23   0   0   0   1      0,0      0,00145      1,1515344    0,0     ISP50229
                9,00  9,00  0,0   0,85     0,60                             ISP50230
/*    ECC WATER INLET JUNCTION  (J=31)                                       ISP50231
    28   10   0   0   2   1      0,0      0,00599      0,1420368    0,0     ISP50232
          1,0   1,0   0,0    0,85   -1,0                                    ISP50233
/*    ( ACC CHECK VALVE )  (J=32)                                            ISP50234
    29   28   0   1   0   1      0,0      0,00599      0,18647664   0,0     ISP50235
              34,20 34,20 0,0   0,85   -1,0                                 ISP50236
/*     TOP OF STANDPIPE  (J=33)                                            ISP50237
    30   29   0   0   0   1      0,0      0,00621      0,95701104   0,0     ISP50238
              38,50 38,50 0,0   0,85   -1,0                                 ISP50239
/*    LPIS FILL JUNCTION (J=34)                                            ISP50240
     0   28   1   0   0   1      0,0      0,00599      0,1642567    0,0     ISP50241
              1,00  1,0   0,0   0,85     0,60                             ISP50242
/*    HPIS FILL JUNCTION (J=35)                                            ISP50243
     0   28   2   0   0   1      0,0      0,00599      0,1642567    0,0     ISP50244
              1,00  1,0   0,0   0,85     0,60                             ISP50245
/*                                                                         ISP50246
/*                                                                         ISP50247
/*    CHECK VALVE DATA                                                     ISP50248
/*                                                                         ISP50249
    -6      0,0    0,0    0,0   0,0                                       ISP50250
    -7      0,0    0,0    0,0   0,0                                       ISP50251
    -8      0,0    0,0    0,0   0,0                                       ISP50252
/*                                                                         ISP50253
/*       FILL TABLE DATA                                                   ISP50254
/*       ( LPIS INJECTION )                                                ISP50255
       8    1    7,03E+4   26,0                                           ISP50256
         0,0   10,81   28124,0   10,0   56248,0  8,861                    ISP50257
     84372,0    7,541 112496,0    5,719 140620,0 2,954                    ISP50258
    160307,0    0,0   100,E+4     0,0                                      ISP50259
/*       ( HPIS INJECTION )                                                ISP50260
     2    1    7,03E+4   26,0                                             ISP50261
       70,31  1,081       2109300,0    1,081                              ISP50262
/*                                                                         ISP50263
/*    HEAT SLAB DATA                                                       ISP50264
/*                                                                         ISP50265
     0   11  1    0,0   76,206    13,6644    0,0   0,0                    ISP50266
/*                                                                         ISP50267
/*    SLAB GEOMETRY DATA                                                   ISP50268
```

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/*                                                                      ISP50269
      1   1  0  1   5    0.2560   0.0   0.0                            ISP50270
/*                                                                      ISP50271
/*    MATERIAL THERMAL PROPERTY DATA                                    ISP50272
/*                                                                      ISP50273
/*    SS304  THERMAL CONDUCTIVITY                                       ISP50274
/*                                                                      ISP50275
      2                                                                 ISP50276
      100.0    3.95725E-3     1300.0     7.97485E-3                    ISP50277
/*                                                                      ISP50278
/*    SS304  HEAT CAPACITY                                              ISP50279
/*                                                                      ISP50280
      13                                                                ISP50281
      76.667    712.1265   121.111  710.0256   204.444   712.5495      ISP50282
     315.556    727.0415   426.667  751.3452   537.778   782.2920      ISP50283
     648.889    816.7132   760.000  851.4400   871.111   883.3040      ISP50284
     982.222    909.1364  1093.333  925.7688  1204.444   930.0322      ISP50285
    1315.556    918.7580                                               ISP50286
/*                                                                      ISP50287
/*    GAP CONDUCTANCE  DATA                                             ISP50288
/*                                                                      ISP50289
      2                                                                 ISP50290
      0.0   0.0    1000.0   0.0                                        ISP50291
/*                                                                      ISP50292
/*    END  OF DATA                                                      ISP50293
```

JAERI-M 8004 Errata

Page	Line	Printed	To be corrected
vi	↓ 11	adjacent Gap	adjacent to Gap
2	↓ 11	calculations[7)],	calculations[35)],
6	↓ 3	eqations	equations
6	↓ 10	$+\frac{\partial Q_e}{\partial}$	$+\frac{\partial Q_e}{\partial x}$
7	↓ 7	stateproperty	state property
7	↑ 4	$\frac{\bar{W}_i^2}{\bar{\rho}_i}) \sum_j W_{ij}$	$\frac{\bar{W}_i^2}{\bar{\rho}_i}) + \sum_j W_{ij}$
7	↑ 1	arrange	average
9	↑ 6	specific	specified
12	↑ 8	and 0.0<X<1.0	and $0.0 \leq X < 1.0$
13	↓ 7	constan of air (2.87 Joule/°C•Kgm)	constant of air (287.0 Joule/K•Kgm)
13	↓ 13	(7.18 Joule/°C•Kgm)	(718.4 Joule/K•Kgm)
14	↓ 5	bellow	below
16	↓ 1	horizontaly	horizontally
16	↓ 2	ALARM-P1 however allows	ALARM-P1, however, allows
21	↑ 1	fanning	Fanning
22	↓ 4	difined	defined
25	↑ 3	P_{flux}	ΔP_{flux}
27	↑ 5	superheat	superheated
28	↑ 5	breake	break
30	↑ 9	STH2o	STH2O
30	↑ 5	interating	iterating
31	↓ 3	valve	value
32	↓ 3	power and the decay	power, the decay