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# ALARM-B1 : A COMPUTER PROGRAM FOR BOILING WATER REACTOR BLOWDOWN ANALYSIS

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# A Computer Program for Boiling Water Reactor Blowdown Analysis

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The digital computer program ALARM-B1 written in FORTRAN-IV for FACOM 230-75 is for analyzing thermodynamic and thermal-hydraulic phenomena of BWR during a large breake LOCA. The outputs are pressure, core inlet flow and enthalpy which affect core heat transfer during transients. In ALARM-B1, the heat transfer from core to coolant during transients is not calculated, but it is given as inputs. ALARM-B1 solves integral forms of fluid conservation and state equations for user-defined volumes (nodes) which are treated as one-dimensional homogeneous elements with interconnecting flow paths (junctions). The numbers of nodes and junctions and their initial fluid conditions are given as inputs. The program is of a variable dimension so there are no limits to the numbers of nodes and junctions.

# 沸騰水型原子炉ブローダウン解析コード：ALARM－B1

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ALARM－B1 は沸騰水型動力炉の冷却料喪失事故，特に一次冷却系配管の大破断に伴う熱力学的，熱水力学的過渡現象を解析するための，FORTRAN－Ⅳ で書かれた，FACOM 230－75 用の計算プログラムである。この計算プログラムの主なる出力データは，事故後の炉心の熱除去に大きく影響を与える圧力容器圧力，炉心入口流量，及びエンタルピー等である。この計算プログラムは炉心の熱伝達現象を計算せず流体への伝熱量はあらかじめ評価して，入力データとして与えられる。

ALARM－B1は，流体の保存式を積分型で解く，いわゆるノード・ジャンクションモデルを採用している。計算される体系のノード・ジャンクション数，及びそれらの流体の初期条件は入力データによって与えられる。ALARM－B1は可変デイメンジョンのプログラムなのでノード・ジャンクションの数に対しては特に制限はない。

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## I. Introduction

A series of computer codes to evaluate the performance core cooling system (ECCS) during a postulated LOCA in light water nuclear reactors has been developed in Japan Atomic Energy Research Institute (JAERI). Postulating various modes of pipe breake such as gillotine and split break 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.

ALARM-B1 computer code which is one of BWR's code series calculates thermo-hydraulic and thermodynamic, phenomena in the pressure vessel and the primary coolant loop during transient of the large breake of the recirculation line. The ALARM-B1 does not calculate heat transfer to the coolant during transient but it is given as input data. Therefore the main outputs of the ALARM-B1 are core inlet flow, enthalpy and pressure transient which significantly affect the heat transfer in the core during the blowdown. Once the behavior of these variable is determined, the variables serve as input into the computer code HYDY-B1 which determine heat transfer conditions in the core. In the near future, the modification of the ALARM-B will be made by combining the ALARM-B1 with the HYDY-B1. A few analytical models prepared in the ALARM-B1 are not completely in compliance with the required feature in the safety evaluation for the ECCS recommended by Japanese Atomic Energy Commission. These models will be also improved in the coming version ALARM-B2.

In this report, fundamental features of the program, analytical models and the program organization will be described.

## II. Fundamental Features of the ALARM-B1 Program

The Fundamental features of the blowdown code ALARM-B1 are summarized as follows;

(1) Node and Junction model

The primary system is divided into a number of saptial volume elements called "node". The fluid condition for each node is assumed to be uniform and the state value of each node such as thermodynamic pressure is also assumed to be represented as a point value. Hypothetical ducts "junctions", connect adjacent nodes according to the problem geometry. The mass and energy balance is solved in each node at each time step during the transient. A momentum balance is applied to the junction with appropriate assumptions.

(2) Assumption of phase equilibrium

The fluid contained in the nodes consists of only liquid in a sub-cooled state, liquid and/or vapor in saturated equilibrium, or only vapor in a superheated state as determined by the energy and mass balances at any given time. It is not permitted that more than one fluid states exist in a node at the same time.

(3) Homogeneous two phase model and two-phase separation model

If the fluid condition contained a node is two phase mixture, two options concerning two phase flow are available. One is the homogeneous two phase model in which the steam and liquid move always in the same direction with the same velocity. The other option is two-phase separation model in which the upward relative movement of steam void is taken into account by giving a gradient factor of the vapor distribution and the relative velocity at the mixture surface[1]. Therefore this separation region is assumed to be heterogeneous in enthalpy and is assumed to have no spatial variation in thermodynamic pressure. For two axially connected nodes, the following option is also provided. When the mixture level in the upper node has become below the bottom of the node, the volume mass and energy are added to the lower node. The mixture level and vapor distribution calculations are now extended into the lower node. Inversely, the quantities of lower node can also be added to upper node when the mixture level in lower node reaches the bottom of the node. Though the selection of the above models is quite optional, usually the downcommer region is represented by the separate model.

(4) Core region heat transfer

The heat transferred from the fuel to the coolant during blowdown is given by input data. Thus no heat transfer problem is treated in core by ALARM-B1. The detailed thermohydraulics are treated in another code HYDY which determines the heat transfer coefficients during blowdown according to the boundary conditions given by ALARM-B1.

(5) Recirculation pump model

The behavior of the recirculation pump is calculated by the homologous low using a set of input characteristic curves. Required characteristic curves are Q-H, n-H, n-T, Q-T relations at the rating and the reversal flow and rotation conditions. Another option is also provided for recirculation pump behavior using a suction flow quality and heat correlation for only normal flow.

(6) Jet pump model

For the jet pump behavior the momentum equation is solved for the four cases according to whether the drive, suction, and throat flow are in normal or reversal flow condition respectively. The jet pump flow path is as a junction in which momentum flux due to cross-sectional area change and momentum mixing are incorporated but compressibility of fluid is ignored. An option is provided for jet pump behavior neglecting the temporal change of the suction flow momentum for convenience of comparing the results with other analysis.

(7) Subnode model for core region

The nodes with heat input such as the core and core bypass nodes are optionally subdivided into a number of common pressure subnodes. This permits calculation of fluid enthalpy within the core and bypass nodes where the fluid enthalpy varies with distance through the core.

## III. Analytic Equations to be Solved

### 3.1 Node Conservation Equations

Fluid condition in each constant volume node can be specified by the conservation equations of mass and energy assuming that the flow and fluid properties are constant during a time step. The mass and energy equations are

$$\frac{dM_i}{dt} = \Sigma W_{ij} \quad , \tag{1}$$

$$\frac{d}{dt}(M_i h_i) - V_i \frac{dP_i}{dt} = \Sigma W_{ij} h_{ij} + Q_i \quad , \tag{2}$$

where
$M_i$ = total mass in node i ,
$W_{ij}$ = flow rate into volume i through junction j ,
$h_{ij}$ = enthalpy of flowing fluid ,
$h_i$ = average enthalpy in node i ,
$V_i$ = volume in node i ,
$P_i$ = thermodynamic pressure in node i ,
$Q_i$ = heat input to node i .

To obtain the direct solution for the pressure rate $\dot{P}$, the conservation of volume is considered and since each node is a constant volume,

$$\frac{dV_i}{dt} = \frac{dV_i}{dt} v_i + \frac{dv_i}{dt} M_i = 0 \quad , \tag{3}$$

where $v_i$ is specific volume of fluid in node i. From equation of state, $v_i$ is given as a function of pressure $P_i$ and enthalpy $h_i$:

$$v_i = v_i(P_i,\ h_i) \quad . \tag{4}$$

A combination of above equations (1), (2), (3) and (4) yields the pressure rate equation:

$$\frac{dP_i}{dt} = \frac{-[\dot{M}_i v_i + (\frac{\partial v}{\partial h})_p \{\Sigma W_{ij} h_{ij} + Q_i + \dot{M}_i h_i\}]}{M_i (\frac{\partial v}{\partial p})_h + V_i (\frac{\partial v}{\partial h})_p} \quad , \tag{5}$$

where, for subcooled fluid and superheated fluid:

$$(\frac{\partial v}{\partial h})_h = f_1(p,h) \qquad \text{fluid compressibility} \tag{6}$$

$$(\frac{\partial v}{\partial h})_p = f_2(p,h) \qquad \text{fluid thermal expansion} \tag{7}$$

and for saturated fluid:

$$(\frac{\partial v}{\partial p})_h = \frac{dv_{gi}}{dp} - \frac{v_{fg}}{h_{fg}} \frac{dh_{fi}}{dp} + x \{\frac{dv_{gi}}{dp} - \frac{v_{fg}}{h_{fg}} \frac{dh_{gi}}{dp_i} - \frac{dv_{gi}}{dp_i} + \frac{v_{fg}}{h_{fg}} \frac{dh_{fi}}{dp_i}\}, \quad (8)$$

$$(\frac{\partial v}{\partial h})_p = \frac{v_{fg}}{h_{fg}} \quad , \quad (9)$$

$$v = v_f + xv_{fg} \quad , \quad (10)$$

$$x = \frac{h - h_f}{h_g - h_f} \quad , \quad (11)$$

where $v_f$ = specific volume of saturated liquid ,
$v_g$ = " of " vapor ,
$h_f$ = enthalpy of saturated liquid ,
$h_g$ = " of " vapor ,
$h_{fg} = h_g - h_f$ ,
$v_{fg} = v_g - v_f$ .

The state volumes and their derivatives in Eq. (5) are calculated by linear interpolation of the value in the steam tables for ALARM-B1 with pressure and enthalpy as independent variables.

## 3.2 Two-phase Separation Model[1)]

The two-phase separation model used in ALARM-B1 is almost the same as used in RELAP-3. It is a semiempirical fit to a number of experimental results. 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 the mixture surface. The assumed bubble distribution is

$$\alpha(Z) = m \frac{Z}{Z_m} + b \quad , \quad (12)$$

where $\alpha(Z)$ = void fraction at Z,
m,b = time dependent slope and intercept,
Z = height above the bottom of the volume,
$Z_m$ = time-dependent height of mixture interface.

The slope and intercept of Eq. (12) are evaluated by the assumed gradient factor and the average void fraction within the two-phase mixture. For an average void fraction less than 0.5, the distribution of the void fraction is given by

$$\alpha(Z) = 2(Co-1)\ \alpha_o \frac{Z}{Z_m} + (2-Co)\alpha_o, \quad 0 \leq \alpha_o \leq 0.5, \tag{13}$$

where $\alpha_o$ = average void fraction within the mixture,

$Co$ = assumed gradient factor ,

and for average void fractions between 0.5 and 1:

$$\alpha(Z) = 2(Co-1)\ [1-\alpha_o] \frac{Z}{Z_m} + 1 - Co(1-\alpha_o), \ 0.5 \leq \alpha \leq 1. \tag{14}$$

The constant Co, which must be limited between 1.0 and 2.0, determines the maximum bubble gradient. If the Co of unity is chosen, the mixture is homogeneous; if 2.0, the bubble gradient is maximum within the permissible physical constrains. In the persent version of ALARM-B1, Co is input and kept constant during transient.

An average void fraction within the mixture and the mixture level during transient is estimated by applying conservation of mass in the node. Steam can be added to a node either through a junction or by flashing of liquid within the mixture. On the other hand when condensation due to pressure rise during transient occurs, it is assumed that the steam within the mixture and steam region are uniformly changed into liquid. The differential equation describing the bubble mass balance in a node is

$$\frac{dM_{gbi}}{dt} = \frac{dM_{vi}}{dt} - W_v - \Sigma\ C_{ij} x_{ij} W_{ij} \quad , \tag{15}$$

where $M_{gbi}$ = mass of steam entrained in the mixture,

$M_{vi}$ = total mass of steam within the node,

$C_{ij}$ = 0.0 if the junction j contracts the mixture region,

= 1.0 if " does not contact the mixture region,

$x_{ij}$ = quality of junction flow,

$W_v$ = bubble mass flow rate at mixture surface,

$W_{ij}$ = flow into or out of the node at junction j.

In current BWR plant, the steam separator is provided at the top of upper plenum to separate steam and water effectively. An option for calculating the steam flow at the separator outlet is permitted. Since a separator outlet actually consists of two flow paths, the upward separated steam flow which leads to the steam done and the downward liquid flow must be estimated. These two flow paths are treated as a single junction and the upward separated steam flow is obtained by using separator efficiency specified as a function of the mixture level elevation. This steam flow is

$$W_s = \eta \, x_{ij} \, W_{ij} \qquad , \tag{16}$$

where $W_s$ = separated steam flow to the steam region,

$\eta$ = separator efficiency as function of the mixture level elevation,

$x_{ij}$ = quality of separator junction,

$W_{ij}$ = flow into the separation region.

Since the volume of the mixture region is known at all times during the transient by solving Eq. (15), the height of the mixture level can be calculated from the node geometry, which is given in a form of a data table of height versus node cross-sectional area. The average void fraction change during transient is also calculated by use of $M_{gb}$ in Eq. (15) and above mixture region volume.

Another option is available for expressing continuous change of the mixture level between axially adjacent two nodes. After the mixture level in upper node arrives at the bottom of upper node, the volume, mass and energy are added to the lower node and the mixture level and vapor distribution calculations are performed for new extended node connecting upper and lower node. In this model, the conversation of momentum for two nodes is ignored but the conversation of energy is considered. This model can eliminate some unphysical results appearing in other codes like RELAP3, such that the two phase mixture region is floating in the steam. This option may be applied to axially connected nodes within the system to be calculated.

### 3.3 Momentum Balance

The one dimensional momentum equation is integrated in the volume element between the midpoints of two adjacent nodes. This integration with some simplifications gives

$$\frac{1}{g_c}\left(\frac{\ell}{A}\right)_{ij} \frac{dW_{ij}}{dt} = P_i - P_j - \frac{g}{g_c}\int_{Z_i}^{Z_j} \rho(z)dz - R_{ij}\,\frac{|W_{ij}|W_{ij}}{\rho_{ij}} + \Delta P_m + \Delta P_p \quad , \tag{17}$$

where $g_c$ = gravitational conversion constant ,

$g$ = gravitational acceleration,

$(\frac{\ell}{A})_{ij}$ = junction inertia,

$W_{ij}$ = average flow from node i to noide i+1,

$P_i - P_j$ = thermodynamic pressure differential across the fluid contained in flow volume,

$\int_{Z_i}^{Z_j} \rho(z)dz$ = gravitational head,

$R_{ij}$ = loss coefficient,

$\Delta P_m$ = momentum flux term for area change,

$\Delta P_p$ = pump head.

The momentum flux term on the right hand of Eq. (17) is not explicitly treated in the present version of ALARM-B1 except for jet pump junction. This omission of the momentum flux term would not affect the final results in most of BWR-LOCA conditions*.

The integration of gravitational head is performed with consideration density distribution as defined by the two-phase separation model.

At the user's option, the junction flow can be limited by Moody's two-phase choked flow model to be described in 3.5. In this case, the flow through the junction is chosen as the smaller of the inertia flow calculated by Eq. (17) or the choked flow.

## 3.4 Frictional Pressure Drip

Frictional pressure drop is given by the fourth term on the right hand of Eq. (17). The loss coefficient $R_{ij}$ for the steady state is calculated from intial balance with input pressure distribution and given by

$$R_{ij} = \frac{\{(P_i + P_{grav,i}) - (P_j + \Delta P_{grav,j}) + \Delta P_m + \Delta P_p\}}{W_{ij}|W_{ij}|} \rho_{ij}$$

This loss coefficient $R_{ij}$ includes Fanning friction factor, and other loss coefficient such as expansion or contraction loss coefficient for the actual flow path. Thus $R_{ij}$ can be represented by

$$R_{ij} = \frac{1}{2g_c A^2} \frac{f\Phi^2 L}{D} + K_{ij} \text{ other},$$

where $A$ = junction flow area,

$f$ = Fanning friction factor,

* This term will be incorporated into ALARM-B in the near future.

$\phi^2$ = two-phase multiplier,

L = equivalent flow path length,

D = equivalent diameter,

$K_{ij}$= loss coefficient except for Fanning friction factor.

$K_{ij\ other}$ for steady state is obtained from $R_{ij}$ and Fanning friction factor which is determined by

$$f = 0.316\ Re^{-0.25}.$$

If the junction flow is initially two-phase, Fanning friction factor is first calculated as saturated liquid. Two-phase multiplier $\Phi^2$ is next calculated by using Thom[3] and Martinelli's[4] correlations provided as a built-in data table in the ALARM-B1 program. These correlations are functions of the junction pressure and quality. The junction pressure is estimated in terms of algebraic mean for two adjacent node pressures with gravity head, and junction quality is set equal to the quality for the upstream node.

The loss coefficient in transients is obtained in the same manner as in the steady state except that $K_{ij\ other}$ is assumed to be constant during transients.

Usually it is difficult to estimate equivalent diameter, equivalent length and flow area for actual complicated flow paths. Accordingly, ALARM-B1 provides another option for the loss coefficient. This option does not consider $K_{ij\ other}$ but considers two-phase multiplier for the lumped loss coefficient $R_{ij}$. If the junction flow is initially two-phase, the single-phase loss coefficient corresponding to total mass flow rate is

$$R_{ijo} = R_{ij}/\Phi^2,$$

where $R_{ijo}$ = initial single phase loss coefficient corresponding to total mass flow rate,

$\Phi^2$ = initial two-phase multiplier.

For the calculation of two-phase pressure drop during transient, the single-phase frictional pressure drop for total mass flow rate as saturated liquid is first calculated by using the loss coefficient $R_{ijo}$ for steady state. The two-phase pressure drop is then obtained by multiplying the single-phase value by multiplier estimated by the transient junction pressure and quality.

If the reverse loss coefficient is significantly different from the normal, the user may input a valve for it. For the junction with no initial flow, a valve for $R_{ij}$ must be specified by input.

## 3.5 Leak and Fill Systems

The leak and fill systems specify the time dependent boundary condition for the system to be calculated. Water may be injected into any node by means of fill junctions. On the other hand, not only the leak junctions limited by choking but also the another type leak junctions, in which transient leak flow rate is specified tabular input, can be set up at user's option. Initiation of flow through these junctions may be controlled by many different trip signals.

(1) The following three options can be selected as fill data a set:

(i) fill flow rate vs. time.

(ii) " vs. pressure of the node injected,

(iii) " vs. pressure d ifference between the node, pressure and reserver pressure.

Temperature or enthalpy is also specified as input data to determine injected fluid energy.

(2) The following two options can be selected as leak data set:

(i) leak flow limited by choking,

(ii) Leak flow rate given by tabular input,

a) leak flow rate vs. time,

b) " vs. pressure of the node assigning the junction.

In (i) above, the mass flow rate is limitted by Moody's[5),6)] two phase choked flow model

$$W_{choke} = A \cdot Cd \cdot G(P_o, h_o), \tag{22}$$

where $W_{choke}$ = maximum junction flow,

$A$ = time dependent flow area,

$G$ = mas velocity as a function of stagnation pressure $P_o$ and stagnation enthalpy $h_o$,

$Cd$ = multiplies to Moody's choked flow rate.

The stagnation conditions are assumed to be the thermodynamic conditions in the node to which the leak junction in connected. The flow rate through the junction is chosen as the smaller of the inertia flow calculated by orifice equation and the choked flow. Moody's model also gives the throat pressure as a function of $P_O$ and $h_O$. The sink pressure must be less than the throat pressure for choking to occur in a leak junction.

This Moody's choked flow model is optionally applied to any junctions except for fill junctions such as jut pump drive nozzle with constant flow area.

### 3.6 Reactor Core Model[2)]

The core is assumed to be uniform pressure but is divided into a number of subnodes to determine enthalpy rise. The flow rate for core inlet and outlet is determined by Eq. (17). On the other hand, inter-subnode flow is approximated by following manner:

$$W_i = W_i \qquad \bar{h}_i < h_f, \tag{23}$$

$$W_{i+1} = W_i + \delta W \qquad \bar{h}_i > h_f, \tag{24}$$

where $W_i, W_{i+1}$ = inter-subnode flow,
$\delta W = (W_O - W_I)/(\text{Number of boiling subnodes})$,
$W_I$ = core inlet flow,
$W_O$ = core outlet flow,
$\bar{h}_i$ = subnode average enthalpy,
$\bar{h}_f$ = saturated fluid-enthalpy.

The conservation of energy for i-th subnodes is

$$\frac{d}{dt}(R_i h_{i+1}) = W_i(h_i - h_{i+1}) + Q_i + \frac{dp}{dt} V_i, \tag{25}$$

where $R_i$ = mass in subnode,
$h_i$ = subnode interface enthalpy,
$Q_i$ = heat added to subnode,
$V_i$ = subnode volume.

The subnode mass $R_i$ is normalized by total core mass calculated by Eq. (1) and subnode thermodynamic condition. As mentioned previously, no calculation is made for $Q_i$, but is given by as a function of time.

The reactor core model described in this section is essentially the same as in the LAMB code developed by the General Electric Company. The reason why the same model is provided in ALARM-B1 is to compare with other computational results. Since the heat transfer from the fuel to the coolant is dependent on the hydraulic conditions, and the core hydraulics is affected by the heat added to the fluid, it is obvious that this model is not correct. Indeed this is especially true when the fluid is predicted to be superheated steam in a subnode. Actually the core thermohydraulics are recalculated in somewhat more rigorous manner by another code HYDY according to the core inlet and/or outlet hydraulic condition determined by the ALARM-B1. This feature will be improved in the comming version, ALARM-B2.

## 3.7 Jet Pump Model

ALARM-B1 provides three analytical models for jet pump behavior. The options being available consist of conbining some of these methods according to the mixture level change in downcommer region during transient and each method.

### (1) Model 1

For the jet pump behavior, the momentum equation is solved for each flow path with flow direction and momentum flux change.

The characteristic magnitude of jet pump is shown in Fig. 1. This model is simplified under the following assumption.

i) Pressure $P_1$, $P_2$, $P_3$ are constant over the cross section.

ii) The compressibility of fluid is ignored.

iii) Mass flow $W_S$ and $W_D$ are completely intermixed at the end of the mixing pipe between plane 1 and 2 shown in Figure 1.

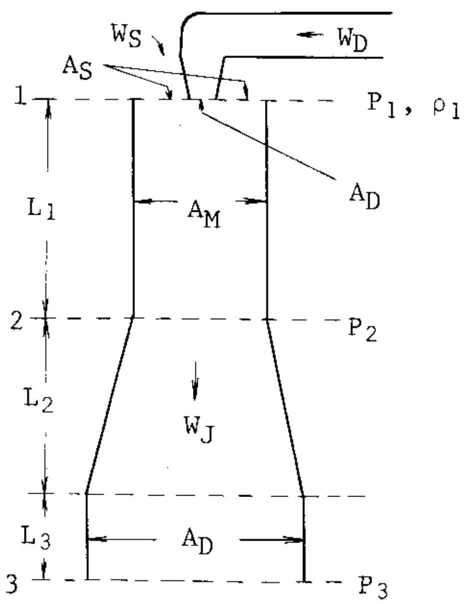


Fig. 1 Characteristic Magnitude of the jet pump

In ALARM-B1 the jet pump flow paths are treated as the junctions and the momentum equations are applied to the junction between inlet of suction flow path and cross section 1, drive flow path and cross section 1, and cross section 1 and throat flow path, respectively. The pressure $P_1$ is calculated from the conservations of mass and momentum with the above assumptions.

The momentum equations for three junctions are given by

$$\frac{1}{g_c}\left(\frac{\ell}{A}\right)_J \frac{\partial W_J}{\partial t} = P_1 - P_L + \Delta P_{Jm} - \frac{W_J^{\,2}}{2g_c\rho_J}\left\{\frac{1}{2}\left(\frac{1}{A_M^2} - \frac{1}{A_{Lower}^2}\right) - \frac{1}{A_M^2}\right\} + \Delta P_{Jg} - \Delta P_{Jf} \,, \tag{26}$$

$$\frac{1}{g_c}\left(\frac{\ell}{A}\right)_S \frac{\partial W_S}{\partial t} = P_S - P_1 + \Delta P_{Sm} + \Delta P_{Sg} - \Delta P_{Sf} \,, \tag{27}$$

and

$$\frac{1}{g_c}\left(\frac{\ell}{A}\right)_D \frac{\partial W_P}{\partial t} = P_D - P_1 + \Delta P_{Dm} + \Delta P_{Dg} - \Delta P_{Df} \,, \tag{28}$$

where
$A_S$ = suction inlet flow area ,
$A_D$ = drive " ,
$A_M$ = mixing region " ,
$A_{Lower}$ = lower plenum flow area ,
$P_L$ = " pressure ,
$P_S$ = down conner " ,
$P_O$ = drive pipe " ,
$W_D$ = drive mass flow rate ,
$W_S$ = suction ,
$W_J$ = throat " ,
$\Delta P_{Jm}$ = throat momentum flux ,
$\Delta P_{Dm}$ = drive " ,
$\Delta P_{Sm}$ = suction " ,
$\Delta P_{Jg}$ = throat gravitation head ,
$\Delta P_{Dg}$ = drive " ,
$\Delta P_{Sg}$ = suction " ,
$\Delta P_{Jf}$ = throat frictional pressure drop ,
$\Delta P_{Df}$ = drive " ,
$\Delta P_{Sf}$ = suction " .

The gravitational head and the frictional pressure drop for three junctions are calculated in the same manner in 3.2 and 3.3. The momentum flux terms are derived from the force balance with appropriate assumptions. For the four cases according to whether the drive, suction and throat in normal or reversal flow, terms for the momentum flux are given as follows:

(i) $W_D > 0, \quad W_S > 0, \quad W_J > 0,$

$$\Delta P_{Jm} = \frac{1}{g_c P_1 A_M} \left(\frac{W_S{}^2}{A_S} + \frac{W_D{}^2}{A_O}\right), \tag{29}$$

$$\Delta P_{Dm} = \frac{W_D^2}{2g_c\rho_D} \left(\frac{1}{A^2_{pipe}} - \frac{1}{A_D^2}\right), \tag{30}$$

$$\Delta P_{Sm} = \frac{W_S{}^2}{2g_c\ S} \left(\frac{1}{A^2_{down}} - \frac{1}{A_S{}^2}\right), \tag{31}$$

$$\rho_1 = \rho_1(P_1, H_1), \tag{32}$$

$$H_1 = (W_S H_S + W_D H_D)/W_J, \tag{33}$$

$$\rho_J = W_J/\left(\frac{W_S}{\rho_S} + \frac{W_D}{\rho_D}\right), \tag{34}$$

where $A_{pipe}$ = drive pipe flow area,
$A_{down}$ = down commer flow area,
$\rho_S$ = suction fluid density,
$\rho_D$ = drive " ,
$\rho_J$ = throat " ,
$\rho_1$ = fluid density at the cross section 1,
$P_1$ = pressure over the cross section 1,
$H_1$ = enthalpy,

(ii) $W_D < 0, \quad W_S > 0, \quad W_J < 0$ and $W_D > 0, \ W_S < 0, \quad W_J > 0,$

$$\Delta P_{Jm} = \frac{W_J{}^2}{2g_c\rho_1 A_M A_{Jet}}, \quad A_{Jet} = A_S\left|\frac{W_J}{W_S}\right|, \tag{35}$$

$$\Delta P_{Dm} = \frac{1}{2g_c\rho_S} \left(\frac{1}{A^2_{pipe}} - \frac{1}{A^2_{drive}}\right), \ A_{drive} = A_S\left|\frac{W_D}{W_S}\right|, \tag{36}$$

$$\Delta P_{Sm} = \frac{1}{2g_c\rho_S} \left(\frac{1}{A^2_{down}} - \frac{1}{A_S{}^2}\right), \tag{36}$$

$$\rho_1 = \rho_1(P_1, H_1), \tag{37}$$

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

$$H_1 = (W_J H_S - W_J H_J)/-W_D, \tag{38}$$

$$\rho_D = W_D/(\frac{W_J}{\rho_J} - \frac{W_S}{\rho_S}), \tag{39}$$

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

$$H_1 = H_D, \tag{40}$$

$$\rho_J = \rho_D, \tag{41}$$

$$\rho_S = \rho_D, \tag{42}$$

where $H_S$ = suction flow enthalpy,
$H_D$ = drive flow enthalpy,

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

$$\Delta P_{Jm} = \frac{W_J{}^2 A_{Jet}}{g_c \rho_1 A_M A_S{}^2} \quad , \quad A_{Jet} = A_S \left|\frac{W_J}{W_S}\right|, \tag{43}$$

$$\Delta P_{Dm} = \frac{W_D{}^2}{2g_c \rho_D} \left(\frac{1}{A^2_{pipe}} - \frac{1}{A^2_{drive}}\right), \tag{44}$$

where if $|W_D| < |W_S| \dfrac{A_D}{A_S}$ , $A_{drive} = A_D$,

if except for above condition, $A_{drive} = A_S \left|\dfrac{W_D}{W_S}\right|$,

$$\Delta P_{Sm} = \frac{W_S{}^2}{2g_c\ S} \left(\frac{1}{A^2_{down}} - \frac{1}{A_S{}^2}\right), \tag{45}$$

$$\rho_1 = \rho_1(P_1, H_1), \tag{46}$$

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

$$H_1 = H_S, \tag{47}$$

$$\rho_J = \rho_S, \tag{48}$$

$$\rho_D = \rho_S, \tag{49}$$

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

$$H_1 = (W_D H_D - W_J H_J)/-W_S \,, \tag{50}$$

$$\rho_S = W_S/(\frac{W_J}{\rho_J} - \frac{W_D}{\rho_D}), \tag{51}$$

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

$$\Delta P_{Jm} = \frac{W_J{}^2}{g_c \rho_1 A_M{}^2} \,, \tag{52}$$

$$\Delta P_{Dm} = \Delta P_{Dm} \text{ in Eq. (30)}, \tag{53}$$

$$\Delta P_{Sm} = \Delta P_{Sm} \text{ in Eq. (31)}, \tag{54}$$

$$\rho_1 = \rho_1(P_1, H_1), \tag{55}$$

$$H_1 = H_J, \tag{56}$$

$$\rho_S = \rho_J, \tag{57}$$

$$\rho_D = \rho_D, \tag{58}$$

where $A_M = A_D + A_S$.

The two phase multipliers for these junctions are calculated by the same method as described in 3.4 with the pressure of $P_1$, $P_L$, $P_S$ and $P_D$ and quality at the cross section 1.

Under the assumption (ii), the conservation of mass at the cross section 1 is given by

$$W_S + W_D = W_J, \tag{59}$$

and differentiating both sides of Eq. (59) by time gives

$$\dot{W}_S + \dot{W}_D = \dot{W}_J. \tag{60}$$

The pressure $P_1$ is obtained by solving Eq. (26), Eq. (27), Eq. (28) and Eq. (60) with an iterative manner.

The mass flow at the drive junction may be in a critical flow condition sometime after the occurrence of break, and Eq. (28) can no longer be applied. To determine the critical mass flow, the similar method as shown in 3.5 is applied. The stagnation conditions for the drive junction in a reversal critical flow condition are assumed to be thermodynamic conditions at the cross section 1. For other three cases. They are given by

i) $W_S > 0,\ W_D < 0,\ W_J > 0,$

$$H_0 = H_S ,$$

$$P_0 = P_1 + \frac{W_S^{\,2}}{2g_c\rho_1 A_S^{\,2}},$$

ii) $W_S > 0,\ W_D < 0,\ W_J > 0,$

$$H_0 = \frac{W_S H_S + |W_J| H_J}{|W_D|},$$

$$P_0 = P_1 + \frac{W_D^{\,2}}{2g_c\rho_1 (A_M + A_S)^2},$$

and iii) $W_S < 0,\ W_D < 0,\ W_J < 0,$

$$H_0 = H_J ,$$

$$P_0 = P_1 + \frac{W_J^{\,2}}{2g_c\rho_1 A_M^{\,2}},$$

where $H_0$ = stagnation enthalpy ,
$P_0$ = " pressure .

The temporal change of the momentum is approximated to be zero when the flow is in a critical flow condition. For example, if the drive junction is critical, it follows that

$$W_S + W_{D\ crit} = W_J , \tag{61}$$

$$W_S = W_J . \tag{62}$$

In above condition, the pressure $P_1$ is calculated by substituting Eq. (61) and Eq. (62) for Eq. (59) and Eq. (60).

(2) Model 2

The model to be described in this section is similar to that in the LAMB code. In this model temporal change of the suction flow momentum is ignored during transient, therefore the pressure $P_1$ over the cross section 1 is directly obtained from Eq. (27) putting zero to the left hand side. Eq. (26) and Eq. (28) are subsequently solved for the drive flow $W_D$ and throat flow $W_J$ respectively,. and the suction flow is obtained by using the new drive flow $W_D$ and throat flow $W_J$ from mass balance in the jet pump.

(3) Model 3

For the jet pump junctions, momentum flux terms are ignored, and only gravitational head and frictional pressure drop are considered. This model may be applied when the mixture level in the down commer region is below the elevation of the jet pump suction nozzle.

## 3.8 Recirculation Pump Model

Two models are provided to analyse the behavior of the recirculation pump. In one model, the hydraulic torque and head are calculated for all combinations of flow and speed using the homologous relationships. Another model is a simpler model by which the head is calculated from the suction flow quality for only normal flow conditions.

These two models are described more in detail in the following.

(1) Pump model using homologous relations for head and torque

The dimensionless homologous relations can be expressed[8] by

$$h/n^2 = \text{const.} \quad q/n = \text{const.}, \tag{61}$$

$$h/q^2 = \text{const.} \quad n/q = \text{const.}, \tag{62}$$

$$t/n^2 = \text{const.} \quad q/n = \text{const.}, \tag{63}$$

$$t/q^2 = \text{const.} \quad n/q = \text{const.}, \tag{64}$$

where $h = H/H_o$ normalized head,
$q = Q/Q_o$ normalized volumetric flow,
$n = N/N_o$ normalized speed,
$t = T/T_o$ normalized torque.

The head and torque are derived from the following set of pump characteristic curves specified as tabular input data:

(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) $|q| < |n|$,
if $n \geq 0$, (A) and (E) are used,
if $n < 0$, (B) and (F) are used.

(ii) $|q| > |n|$,
if $q > 0$ , (C) and (G) are used,
if $q < 0$ , (D) and (H) are used.

For example, in the case of $|q| < |n|$ and $n \geq 0$, 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 suquare of the normalized speed according to the equations (61) and (63). In the case of using the curves at rated flow, the similar procedures are performed.

As the hydraulic torque found in the calculations above is for the fluid conditions at normal operation, it must be modified when the fluid density to changed. The modification relation is,

$$T_h = T_o \, t \, \rho/\rho_o , \tag{65}$$

where $T_h$ = hydraulic torque,
$T_o$ = rated torque,
$t$ = the normalized torque by homologous law,
$\rho_o$ = rated fluid density,
$\rho$ = fluid density.

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

$$\Delta P_p = H_o h \rho, \tag{66}$$

where $H_o$ = rated head,

$h$ = the normalized head by homologous law.

When cavitation is expected, the pump pressure and hydraulic torque are again modified by the following cavitation model.[9]

$$\Delta P_p' = \Delta P_p - \sigma x_e, \tag{67}$$

$$T_h' = T_h - \sigma x_e W/\omega\rho, \tag{68}$$

where $\Delta P_p'$ = cavitated pump pressure rise,

$T_h'$ = cavitated,

$\sigma$ = cavitation constant (input data),

$x_e$ = quality at impeller eye,

$W$ = mass flow rate,

$\omega$ = angular velocity.

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

$$P_{eye} = P_{up} - \Delta P_{NPSH}, \tag{69}$$

where $P_{eye}$ = eye pressure,

$P_{up}$ = pump suction pressure,

$\Delta P_{NPSH}$ = required suction pressure (tabular input as 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 on the pump rotor. In the completely cavitated condition, the pump impeler will be insulated from the fluid because of the discharge of steam bubbles. The value of quality to produce complete cavitation is estimated from the maximum head loss which would be that required to drop the pump head to zero at rated flow and zero speed:

$$x_{e,max} \cdot \sigma = H_{max}\, n^2 \cdot \rho, \tag{70}$$

where $x_{e,max}$ = maximum quality,

$H_{max}$ = maximum head loss,

this value is at rated flow and zero speed in the characteristic curves, or is optionally specified as input,

$n$ = normalized speed ratio.

In ALARM-B1 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 resistance, and the loss coefficient for the stalled rotor is added to the flow path form loss factor. The pump speed during transient is found by setting the hydraulic pump torque equal to the rate of change of angular momentum:

$$\frac{I}{g_c}\frac{d\omega}{dt} = T_{ho} - T_h(t), \tag{71}$$

where $I$ = inertia moment of the rotating member,

$\omega$ = angular velocity of the pump,

$t$ = time after transient,

$T_h$ = hydraulic torque exerted by the pump impeler,

$T_{ho}$ = steady state hydraulic torque " .

When the pump is tripped by the pump trip logic provided in the program, the steady state torque, which is calculated from the volumetric flow rate and angular velocity for the steady state condition, is set to zero

(2) Pump model using head and quality correlation[2)]

Another model is such that the pump head is estimated for only normal suction flow by using the suction flow quality and head correlation and for other flow condition, the pump is assumed to be locked. The form of correlation for rated rotating pump is given by

$$\Delta P = f(w,x), \tag{72}$$

where $\Delta P$ = normalized pressure difference across the pump,

$w$ = normalized suction mass flow rate,

$x$ = quality at suction inlet.

The value for the correlation is specified as tabular input data.

Pump Coastdown equation with assumption of complete pump efficiency is given by

$$\frac{I}{g_c}\frac{d\omega}{dt} = -\{F\omega + \frac{\Delta P_p S_S}{\rho_S w}\}, \tag{73}$$

where $I$ = inertia moment,

$w$ = angular velocity of the pump,

$F$ = constant for the frictional torque,

$\Delta P_p$= pressure difference across the pump,

$W_S$ = suction mass flow rate,

$\rho_S$ = suction fluid density.

The pressure difference across the pump; $\Delta P_p$ is calculated by using tabular input correlation and rated conditions with homologous relations. The pump rotor is however assumed to be completely stolled when the transient condition for the pump become beyond the range of tabular input correlation.

The momentum inertia is calculated from the initial conditions and input pump time constant for the coastdown. This is

$$\frac{I}{g_c}\frac{w_o}{T_o} = \lambda_{const}, \tag{74}$$

where $\lambda_{const}$ = input pump time constant,

$T_o = \frac{W_o \Delta P_{po}}{\rho_{So}\omega_o}$ steady state hydraulic torque,

subscript; 0 refers to the steady state conditions.

3.9 Hypothetical Valves

Hypothetical valves may be placed, at the user's option, in any junction. Two types of such valves are available. Type 1 is an initially open valve which instantaneously closes under trip control logic provided in the program. Type 2 is reverse to Type 1. These valves are used to simulate the transient action for the system such as the onset of the double-ended pipe break.

# IV. ALARM-B1 Program Organization

## 4.1 Problem Dimension

Since the ALARM-B1 is programmed by the use of variable dimensioning, the program permits the optimum use of available storage and there are no particular restrictions on the numbers of nodes and junctions, etc.

The integer data required for the dimensioning are read immediately following the title card. After all data are read in, the required core memories are compared with available storage for the ALARM-B1. If the required core memories exceed available storage the computation stops. The required size of the core is calculated in the program by

IEND = 6 × NTSC + 6 × NTRIP + 9 × NEDIT + 61 × NVOL
+ 2 × NSUB + 70 × NJUN + 17 × NJET + 27 × NPUMP
+ 4 × NLK + 4 × NFILL + 12 × NSUB + 10 × NTSUB
9 × NJEGRP + 100
+ Geometry Data for volume
+ Pump Characteristic curve Data
+ Leak Data
+ Fill Data
+ Subnode Data
+ Separator Data

where, descriptions for the above variables and data will appear in Appendix A.

## 4.2 Restart and Dump Option

The restart and dump option is provided against the failure of a ALARM-B1 calculation due to time step size being too large and the probability of a computer failure during a very long run, and for the detailed data check except printed data. Virtually all informations of the computations prior to a job termination are dumped on FORTRAN unit 1 for each frequency specified by the input. And if desired, the problem can be continued with a new sequence of time steps. The data required for the restart are only those included the Time Step Data Card and the Edit Data Variable Card.

## 4.3 Editting and Plotting

ALARM-B1 provides two kinds of edits, which are similar to those in RELAP3, An edit is a fixed format and another allows the user to choose for frequent printout without restriction on the number of calculated variables. The amount of edited information to be printed are controlled by two integer data on the Time Step Data Card (refer to Appendix A).

On the other hand, the variables for plotting are stored on the FORTRAN unit 2 and 3. This edit also allows the user to chose for frequent store, without restriction on the number of the variables to be ploted. Plotting is performed in final portion of a computation and if desired, only a plotting job can be performed for selected variables from a number of privous variables to be ploted.

### 4.4 Control Options

Control parameters are usually required to simulate a reactor system. For instance, the pump trip may be initiated at the time when the electric power is lost. These parameters may be described through the trip-control data cards.

Trips can be controlled by elapsed time, node pressure, mixture level, water temperature, or junction flow. One such controlling variable can control as many 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 condition is satisfied, the trip action is generated after a specified delay time.

## V. Acknowledgment

The author expresses his thanks to K. Sato of Reactor Safety Codes Development Laboratory at JAERI for his valuable suggestions and critical reading of this report. He is also grateful to T. Shimooke of Reactor Safety Evaluation Laboratory at JAERI for his examination of a huge amount of test result and to the members of Reactor Safety Codes Development Laboratory at JAERI for their valuable discussions.

## VI. References

1) W. H. Retting, et al., RELAP3 A Computer Program for Reactor Blowdown Analysis, IN-1321 (June 1970).

2) Bruce C. Slifer and J. E. Honch, Loss of Coolant Accident and Emergency Core Cooling Modesl for General Electric Boiling Water Reactors NEDO-10329 (April 1971).

3) J.R.S. Thom, Prodiction of Pressure Drop during Forced Circulation Boiling Water Int. J. Heat Mass Transfer Vol.7, pp.709-724, Pergamon Press 1964.

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4) Martinelli, R. C. and D. B. Nelson, Prediction of Pressure Drop during Forced Circulation Boiling of Water Trans. ASME70, 695-702 (1948).

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7) F. Steinhoff, BRUJET A Blowdown Program for Boiling Water Reactos with Water Jet Pumps, Translated for the U.S.A.E.C., AEC-TR-7363 (Sept. 1971).

8) Victor, L. Streeter, and E. Benjamin Wyle, Hydraulic Transient pp150-159 McGraw-Hill 1967.

9) Redirect and Rebuttal Testimony of DR. Donald H. Roy on Behalf of Babcock & Wilcox (Docket NO. RM-50-1 Oct. 1972).

# APPENDIX A Input Data Requirements

## 1. REAG Input Routine

All input data are read into the ALARM-B1 program in free format via a generalized subroutine REAG. Subroutine REAG for FACOM 230-75 converts BCD information to integer or floating point binary information; three conversion types, i.e. type of reading N floating numbers, type of reading N interger numbers and mixed type of reading $4*N_1$ characters, $N_2$ integers and $N_3$ floating point numbers, respectively, are allowed by corresponding subroutines.

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

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

The subroutine will convert BCD number 105 and 108 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 0.0015. Data punched on a card may be delimited by blank colum or comma. The slash (/) indicates the end of the BCD field to be converted. If no slash is present, 72 colums of a card are scanned and next card is read.

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 therefor 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 the user's guide of "The subroutine to read the data in free format" is referred to for more detailed information.

## 2. Data Card Summary

In the following descriptions of the data cards, the user must specify the card number, which indicates the descriptive title of the data contained on the following cards. This card number, which is 1 to 15, must be punched in the field from the 1st to 72nd column, and remaining columns may be used for comment. Respective data are punched on cards following the descriptive title card. Except for the Title Card and the Problem Dimension Card, the order of the descriptive title cards may be arbitrary, but the data cards next to the descriptive title card must be in the specified sequence.

The each descriptive title card number is as follows;

| Descriptive Title | Card Number |
|---|---|
| Title Card | No Number |
| Problem dimension Card | 1 |
| Edit Variable Data Cards | 2 |
| Time Step Data Cards | 3 |
| Trip Control Data Cards | 4 |
| Volume Data Cards | 5 |
| Bubble Data Cards | 6 |
| Junction Data Cards | 7 |
| Jet Pump Data Cards | 8 |
| Jet Pump Geometry Data Cards | 9 |
| Recirculation Pump Data Cards | 10 |
| Leak Table Data Card | 11 |
| Fill Table Data Card | 12 |
| Sub-node Data Card | 13 |
| Steam Separator Data Card | 14 |
| Plot Variable Data Card | 15 |

## 2.1 Title Card (one card)

The information punched in the first colum to 72nd of a card will be printed at the top of page of out put.

## 2.2 Problem Dimension Card

Number of entries are 16 integer data

NREST Restart control

0 = Calculation starts at initial steady state

0>= " restarts at NREST-th time step by using restart information on FORTRAN unit 1

-1= Only plotting is performed by using previous plot information on FORTRAN unit 2 and unit 3

-2 = Store restart information on FORTRA unit 1

-3 = Store restart and plot information on FORTRAN unit 1, unit 2 and unit 3

| | |
|---|---|
| NEDIT | Number of edit variables specified by edit vanable data cards. |
| NTSC | Number of time step data cards |
| NTRIP | Number of trip control data cards |
| NVOL | Number of volumes |
| NBUB | Number of bubble-parameter sets |
| NJUN | Number of junctions |
| NPUMP | Number of pump data sets |
| NLK | Number of leak system data sets |
| NFILL | Number of fill system data sets |
| NSUB | Number of sub-node data sets |
| NTSUB | Total number of sub-node |
| NJETP | Number of jet pump data sets |
| NJEGRP | Number of jet pump geometry data sets |
| NEDITP | Number of plot variables |
| NBUF | Number of core memories to be used for one plot variable data |

## 2.3 Edit Variable Data Cards

The number of the variables to be edited is NEDIT. The specification is made by using the following symbols.

Variables with reference to volume

Variable

| | | |
|---|---|---|
| AP | Average Pressure | $(kg/m^2)$ |
| TM | Total Mass | (kg) |
| AT | Average Temperature | (°C) |
| AD | Average Density | $(kg/m^3)$ |
| AE | Average Enthalpy | (kcal/kg) |
| AQ | Average Quality | |
| SM | Steam Mass | (kg) |
| ZM | Water Level | (m) |
| LV | Specific volume of saturated water | $(m^3/kg)$ |
| GV | Specific volume of saturated gas | $(m^3/kg)$ |
| LE | Specific Enthalpy of saturated water | (kcal/kg) |
| GE | Specific Enthalpy of saturated gas | (kcal/kg) |
| ST | Saturated Temperature | (°C) |

| | | |
|---|---|---|
| SP | Saturated Pressure | (kg/m$^2$) |
| LM | Liquid Mass | (kg) |

Variables with reference to Sub-node

| | | |
|---|---|---|
| FW | Mass Flow Rate | (kg/sec) |
| EN | Enthalpy | (kcal/kg) |
| QF | Heat generation rate | (kcal/sec) |

Variables with reference to junction

| | | |
|---|---|---|
| JF | Mass Flow Rate | (kg/sec) |
| JQ | Junction Quality | |
| FPL | Function Pressure Drop | (kg/m$^2$) |
| PPL | Pump | (kg/m$^2$) |
| JE | Junction Enthalpy | (kcal/kg) |
| TPL | Total Pressure Drop | (kg/m$^2$) |
| GPL | Gravity Pressure Drop | (kg/m$^2$) |

Variables with reference to the system balance

| | | |
|---|---|---|
| TEB | Energy Balance | (kcal) |
| TMB | Mass Balance | (kg) |
| TEN | Total Heat added during transient | (kcal) |
| TML | Total Mass Leaked | (kg) |
| TEL | Total Energy Leaked | (kcal) |

Symbols of available region number identification are as follows;

| | |
|---|---|
| Volume Data | N1, N2, etc. |
| Junction Data | J1, J2, etc. |
| Sub-Node Data | S1, S2, etc. |
| System Balance Data | T |

example:

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | Column |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | P | | | N | 1 | | | J | Q | | | J | 1 | 0 | | |

2.4 Time Step Data Cards

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

N1 Number of time steps per edit specified by 2.3

N2 Number of edits specified by 2.3 per detailed edit

N3 Number of detailed edits per restara information edit

N4 Number of time steps per plot information edit

X1 Time step size (sec)

X2 End of current time step data (sec)

## 2.5 Trip Control Data Cards

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

IDACT Action to be taken $|IDACT| \leqq 20$

1 = End of Problem

2 = Open leak

3 = Trip pump

4 = Start fill

5 = Dummy

$6 \leq |IDACT| \leq 20$ Open (or close) valve

$|IDACT| = |IVALVE|$ IVALVE is a variable contained in junction valve will be closed, and if IDACT > 0, junction valve will be open.

If $-5 < IDACT < 0$, end of Action 1 to Action 4 e.g. if IDACT = -2, all leak will stop.

If user wants to control each system data set such as 1st fill data set, two-digit-interger number which consists of data set number and IDACT, can be read in e.g., if IDACT = 28, the leak from junction with 8th leak data set will start.

IDSIG Signal being compared

1 = Elasped time (sec)

2 = Pressure ($kg/m^2$)

3 = Mixture level (m)

4 = Water Temperature (°C)

5 = Dummy

6 = Inter-node flow (kg/sec)

If IDSIG > 0, the action will start when the signal exceeds the signal set point during transient.

If IDSIG < 0, the action will start when the signal drops below the signal set point during transient.

IDVOL Node or junction index

The node or junction number checked as signal.

IDOPT Optional node or junction index

If IDOPT > 0, the absolute difference value for IDVOL and IDOPT is checked as signal.

SETPT Signal set p·int

DELAY Delay time for initiation of action after reaching setpoint.

2.6 Volume Data Card

NVOL data sets are required. Each data set consists of 5 integer entries and 7 floating point number entries and tabular input data are optionally required.

IBUB Bubble data index

If two-phase separation model is not applied to the node, set IBUB = 0

IMOV Upper node number

IMOV indicates the upper node number to be connected, when the mixture level of this node reaches the bottom of this node.

If this option is not required, set IMOV = 0

IMLO Lower volume number

IMLO indicates the lower node number to be connected, when the mixture level of this node reaches the bottom of this node.

If this option is not required, set IMLO = 0

The progrom does not permit both IMOV ≠ 0 and IMLO ≠ 0 at the same time.

ISUB Sub-node data index

If the node has no sub-nodes, set ISUB = 0

IZ Number of data points for the table of the node cross-section vs. the node height from the bottom. If there is no cross-section change, set IZ = 0

P Node pressure ($kg/m^2$)

TEMP Node temperature, enthalpy or quality

If TEMP > 1. TEMP is average temperature (°C)

If 0 ≤ TEMP ≦ 0 TEMP is average quality of mixture

If TEMP < 0 TEMP is average enthalpy (kcal/kg)

V Volume ($m^3$)

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

ZM Mixture level from the bottom (m)

ELEV Elevation at the bottom of the node (m)

QAV Steady state heat addition to the fluid (kcal/sec)
If ISUB $\neq$ 0, set QAV = 0.

If IZ > 1, the following data are required. This data block consists of $2 \times$ IZ floating point number entries for table of the node cross-section vs. node height. Data must be arranged as follows; volume height $Z_1$, corss-section $S_1$, volume height $Z_2$, corss-section $S_2$ ........ volume height $Z_{IZ}$, cross-section $S_{IZ}$. Above data bock must punch on refreshed cards.

## 2.7 Bubble Data Cards

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

ALPHA Bubble-gradient parameter
$1 \leq$ ALPHA $\leq 2.$

VBUB Bubble velocity (m/sec)
$0. <$ VBUB

## 2.8 Junction Data Cards

NJUN data blocks are required. Each data block consists of 4 integer entries and 9 floating point number entries.

IN Volume index at junction inlet

OUT Volume index at junction outlet
If the junction is leak junction, OUT < 0.
If " is fill " , IN < 0.
If the junction is suctior, drive of jet pump, OUT = 0.
If the junction is throat of jet pump, IN = 0.

IPUMP For IN $\geq$ 0, OUT $\geq$ 0 (normal junction), IPUMP is recirculation pump data set number and if there is no pump, set IPUM = 0.
For IN > 0, OUT < 0 (leak junction), IPUMP is leak data set number.
For IN < 0, OUT > 0 (fill junction), IPUMP is fill data set number.

IVALVE Valve index $|\text{IVALVE}| \geq 6$
If IVALVE $\geq$ 6, initial open valve
If IVALVE $\leq$ -6, initial close valve

WP Initial junction mass flow rate (kg/sec)

AJUNC Minimum flow area for chocked flow calculation $(m^2)$

(a) For IN ≥ 0, OUT ≥ 0 (normal junction)

if AJUNC ≤ 0., no chocked flow calculation

if AJUNC > 0., minimum flow area for chocked flow calculation.

(b) For IN > 0, OUT < 0 (leak junction)

(i) If time dependent leak flow area; A given in the Leak Data Sets is negative, AJUNC must be zero.

(ii) If time dependent leak flow area; A > 0 and AJUNC < 0, AJUNC is not used.

(iii) If time dependent leak flow area; A > 0 and AJUNC > 0, AJUNC*A is used for chocke flow calculation.

(c) For IN < 0, OUT > 0 (fill junction)

AJUNC must be zero.

DJUNC Junction equivalent diameter (m)

DJUNC is used only for frictional pressrue drop calculation.

If DJUNC = 0, the loss coefficient is RJUNC or calculated from initial balance.

If IN < 0 or OUT < 0, set DJUNC = 0

FJUNC Junction flow area $(m^2)$

FJUNC is used only for Fanning friction factor calculation.

If DJUNC = 0, set FJUNC = 0.

LJUNC Junction equivalent length (m)

LJUNC is used only for frictional pressure drop calculation.

If DJUNC = 0, set LJUNC = 0

INERTIA Junction effective L/A $(m^{-1})$

If IN < 0, or OUT < 0, set INERTIA = 0

RJUNC Steady state loss coefficient $(sec^2kgf/m^5kgm)$

If RJUNC = 0, and DJUNC = 0, the loss coefficient is calculated from initial balance.

If IN < 0, or OUT < 0 set RJUNC = 0

RNJUNC Steady state loss coefficient for reverse flow $(sec^2kgf/m^5kgm)$

If RNJUNC = 0, the reversal loss coefficient is the same as for normal flow condition.

## 2.9 Jet Pump Data Cards

NJEGRP data blocks are required. Each data block consists of 5 integer entries and 1 floating point number entry.

| | |
|---|---|
| JMOPT | Jet pump model option (see section 3.7)<br>=1, uses Method 1<br>=2, uses Method 2<br>=3, uses Method 1 & Method 3<br>=4, uses Method 2 & Method 3 |
| IJOPT | Jet pump geometry data set number |
| JETGRP(1) | Suction junction number |
| JETGRP(2) | Drive junction number |
| JETGRP(3) | Jet pump throat junction |
| PIN | Outlet pressure of jet pump suction flow ($kgf/m^2$)<br>If the loss coefficients for jet pump junctions are entered, set PIN = 0.<br>If PIN < 0, \|PIN\| indicates steady state frictional pressure drop for suction flow. |

2.10 Jet Pump Geometry Data Cards

NJETP data blocks are required. Each data block consists of 11 floating point number entries.

| | |
|---|---|
| AS | Suction inlet flow area ($m^2$) |
| AD | Drive nozzle flow area ($m^2$) |
| AT | Throat flow area ($m^2$) |
| ADIF | Diffuser outlet flow area ($m^2$) |
| DL1 | Flow path length for mixing section (m) |
| DL2 | Flow path length for diffuser section (m) |
| DL3 | Flow path length from diffuser outlet to lower plenum inlet (m) |
| DL4 | Dummy, set, DL4 = 0 |
| AJS | Downcommer flow area ($m^2$) |
| AJD | Jet pump drive pipe flow area ($m^2$) |
| AJJ | Lower plenum flow area ($m^2$) |

2.11 Recirculation Pump Data Cards

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

(1) Data set for the pump model using homologous law (see Section 3.8).

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

| | | | |
|---|---|---|---|
| N1 | Number of data points for | (A) | characteristic curve |
| N2 | " | (B) | " |
| N3 | " | (C) | " |

| | | | |
|---|---|---|---|
| N4 | Number of data points for | (D) | characteristic curve |
| N5 | " | (E) | " |
| N6 | " | (F) | " |
| N7 | " | (G) | " |
| N8 | " | (H) | " |
| N9 | Number of data points for NPSH9m) vs. mass flow rate (kg/sec) | | |

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

| | | |
|---|---|---|
| HLOSX | Maximum head loss (see Eq. ( )) | (m) |
| | If HLOSX = 0, calculated in the program. | |
| | If HLOSX = -1., another pump model is used. | |
| CABC | Cavitation constant | $(kg/m^2)$ |
| RHO | Rated fluid density | $(kg/m^3)$ |
| HO | Rated pump head | (m) |
| QO | Rated volumetric flow rate | $(m^3/sec)$ |
| NO | Rated pump speed | (rad/sec) |
| TO | Rated hydraulic torque | $(kg_f \cdot m/rad)$ |
| 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) Each data block from the third to the eleventh is 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 real value. Data must be arranged as follows;

independent variable $X_1$, dependent variable $Y_1$, ..........
........ independent $X_n$, dependent variable $Y_n$

(2) Pump model using head and quality correlation (see Section 3.8)

(i) The first data block has 9 integer data entries. Each entry indicates that number of data points for W-H curve at given quality plus one.

(ii) The second data block has 9 floating point data entries.

| | | |
|---|---|---|
| HOPT | Set HOPT = -1.0 | |
| TCONST | Time constant for calculating inertia moment (sec) | |
| FHT | Frictional torque constant $(kg_m \cdot m/rad^2)$ | |
| HO | Pump head at mass flow rate W = 0 | $(kg/m^2)$ |

| | | |
|---|---|---|
| QO | Mass flow rate at pump head H = 0 | (kg/sec) |
| NO | Pump speed at steady state | (rad/sec) |
| TO | Set TO = 0. | |
| I | Set I = 0. | |
| KSR | Loss coefficient of stalled rotor | ($kg_f \cdot sec^2/kg_m \cdot m^5$) |

(iii) Each data block from the third to the eleventh has twice the total number of data points. Data must be arranged as follow; the third data the third data block is

quality x = 0, 0.0, normalized mass flow $W_1$, normalized heat $H_1$

.......... normalized mass flow $W_N$, normalized head $H_N$

the fourth data block is

quality x = $x_1$, 0.0, normalized mass flow $W_1$, normalized head $H_1$

.......... normalized mass flow $W_N$, normalized head $H_N$

⋮

## 2.12 Leak Table Data Cards

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

(1) The first data block

| | |
|---|---|
| NAREA | Number of data points for leak table |
| ICHOKE | Leak type<br>If ICHOKE ≤ 0, no liquid phase choking.<br>If ICHOKE > 0, liquid phase choking is allowed. |
| SINK | Sink pressure ($kg/m^2$) |
| CONCO | Multiplier for choked flow calculation |

(2) The second data block has 2*NAREA floating points data entries. Data must be arranged as follows;

time $t_1$, flow area $A_1$, time $t_2$, flow area $A_2$, ..............

.......... time $t_{NAREA}$, flow area $A_{NAREA}$.

If flow area A ≤ 0, the value of A is mass flow rate (kg/sec).

If flow area A > 0, see section 2.6 in Appendix A.

## 2.13 Fill Table Data Cards

NFILL data sets are required. Each data set consists of a data block having 2 integers and 2 floating point entries and tabular input.

(1) The first data block

| | |
|---|---|
| IFILL | Number of data points for fill table |
| IX | Independent variable |
| | If IX = 0, time (sec) |
| | If IX > 0, node pressure ($kg/m^2$) |
| | If IX < 0, differential pressure of node and fill reserver ($kg/m^2$) |
| FILPRS | Pressure in fill reserver (kg/m ) |
| FILTEM | Temperature in fill reserver |
| | If $0 \leq \lvert FILTEM \rvert \leq 1$, reserver quality |
| | If 1 < FILTEM , " temperature (°C) |
| | If FILTEM < 0, " enthalpy (kcal/kg) |

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

## 2.14 Sub-node Data Cards

NSUB data sets are required.

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

NOSUB Number of sub-nodes

(2) The second data block has NOSUB integer entries. Number of data points for power vs. time table (time, $Q_{ij}$) is specified to each subnode.

(3) The third data block has NOSUB floating point entries. Volume of each sub-node is given.

(4) For each sub-node, power (kcal/sec) vs. time (sec) table data are given with refreshed card every sub-node. Therefore NOSUB blocks are required. Data arrangement is the same as in the Leak Table Data Cards.

## 2.15 Steam Separator Data Cards

Two data blocks are required.

(1) The first block has 2 integer entries.

NSEP Node number feeding the steam separator
If this option is not required, set NSEP = 0

NIITA Number of data points for table of steam separator efficiency vs. mixture level elevation (m)

(2) The second block has 2*NIITA floating point number entries. Data arrangement is the same as in the Leak Table Data Card.

## 2.16 Plot Variable Data Cards

(1) The first block has 2 floating point number

X1 Length of x-axis

X2 Length of y-axis

(2) The second blocks has NEDITP*2 alphanumeric entries. Data arrangement is the same as in the Edit Variable Data Cards.

## 2.17 Data Termination Card

The user must punch a "0" sign in the first column. This card indicates termination of data sets. After this card is read in, a computation starts and if the computation normally ends, the program requires the data sets for next job, for which only data sets to modify the previous data spts may be entered.

## 2.18 Job Termination Card

The user must punch a "END" word in the first three columns. Wherever the program meets this data cards, the job stops at once.

# APPENDIX B Steam Table for ALARM-B1

## 1. Preparation of Steam Table

The STG-ALARM computer program generates tables of water properties and writes these tables on a data set in the proper format for ALARM-B1. Properties stored in the tables as functions of pressure and enthalpy include entropy, specific volume, temperature, thermal expansion, and compressibility. The properties of water calculated by using the 1976 IFC formulation for industrial use of the properties of steam[1] as coded in the ASTEM[2] package.

The independent variables of the canonical function in the IFC formulation are pressure and temperature. On the other hand, the tables for ALARM-B1 requires pressure and enthalpy as independent variable. Thus the water properties for ALARM-B1 are calculated by using the STEAMV package and some thermodynamic relations. Temperature of single phase water corresponding to given pressure and enthalpy is obtained by iterative technique with isopiestic heat capacity, and other water properties are calculated with given pressure and obtained temperature. Thermal expansion and compressibility for ALARM-B1 is found by thermodynamic variable transformation. For single phase water, these relations are

$$\left(\frac{\partial v}{\partial h}\right)_P = \frac{v\beta}{C_p}, \qquad \text{(B-1)}$$

$$\left(\frac{\partial v}{\partial h}\right)_P = -\left(\frac{C_v}{C_p}\kappa + \frac{v\beta}{C_p}\right)\cdot v, \qquad \text{(B-2)}$$

where $P$ = pressure, $C_p = \left(\frac{h}{T}\right)_P$,
$v$ = specific volume,
$h$ = enthalpy, $C_v = C_p - \frac{vT\beta^2}{\kappa^2}$,
$\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_P$,
$\kappa = -\frac{1}{v}\left(\frac{\partial v}{\partial P}\right)_T$,

and for saturated liquid and vapor, they are

$$\frac{dh}{dp} = C_p \frac{v_g - v_f}{h_g - h_f} T + (v - vT\beta), \qquad \text{(B-3)}$$

$$\frac{dv}{dp} = -v\cdot\kappa + v\beta \frac{v_g - v_f}{h_g - h_f}\cdot T, \qquad \text{(B-4)}$$

where, the various quantities on right hand are in the saturated condition.

The pressure, liquid enthalpy and vapor enthalpy as the arry dat are entered in the STG-ALARM program and the tables shown in the next section are generated.

## 2. Structure of Steam Table

Eleven tables of thermodynamic properties of water are provided. The first one table contains saturation properties as a function of the pressure. Five tables from the second are subcool tables for each property as a function of the enthalpy and the pressure specified in the first table. Remaining five tables contain superheat properties as a function of the enthalpy and the pressure in the first table. The array for each table is as follows;

(1) Saturation properties

PS(I,1) : P

PS(I,2) : $S_f$

PS(I,3) : $S_g$

PS(I,4) : T

PS(I,5) : $h_f$

PS(I,6) : $v_f$

PS(I,7) : $h_g$

PS(I,8) : $v_g$

PS(I,9) : $\frac{dv_f}{dp}$

PS(I,10): $\frac{dh_f}{dp}$

PS(I,11): $\frac{dv_g}{dp}$

PS(I,12): $\frac{dh_g}{dp}$

where PS(I,J) is an array symbol and index I(=1∿30) refers to pressure. The pressure, the range of which is $10^3 \leq$ PS(I,1) $\leqq 2.4 \times 10^6$ kg/m$^2$, in increasing order are stored in PS(1,1) through PS(30,1).

(2) Subcool liquid properties

For each pressure PS(I,1), and given liquid enthalpy, the tables of water temperature, specific volume, thermal expansion, compressibility are arranged as follows;

PHL(I,K) ; given liquid enthalpy; h

PTL(I,K) ; T

PD (I,K) ; v

PDD(I,K) ; $(\frac{\partial v}{\partial h})_P$

PDP(I,K) ; $(\frac{\partial v}{\partial p})_h$

where, index K (=1∿20) refers to given liquid enthalpy. The liquid enthalpy, the range of which is 10. $\leq$ PHL(I,K) $\leq$ 440. (kcal/kg), in increasing order are stored in PHL(I,1) through PHL(I,K). If the PHL(I,K) is greater than the saturated liquid enthalpy; PS(I,5) corresponding to the pressure PS(I,1), PHL(I,K) is set to the saturation liquid enthalpy.

(3) Superheat steam properties

The tables for superheat steam properties are arranged by the same scheme in the subcool liquid tables.

PHG(I,L) ; given vapor enthalpy h

PTG(I,L) ; T

PV (I,L) ; v

PGD(I,L) : $(\frac{\partial v}{\partial h})_p$

PGP(I,L) ; $(\frac{\partial v}{\partial p})_h$

where, L(=1,30) refers to given steam enthalpy. The range of the steam enthalpy 567. $\leq$ PHG(I,L) $\leq$ 933.. If the PHG(I,L) is less than the saturated steam enthalpy; PS(I,7) corresponding to the pressure PS(I,1), PHG(I,L) is set to the saturated steam enthalpy.

## 3. References

1. JSME Steam Tables pp99-116 (1968).
2. K. V. Moore, ASTEM -- A Collection of Fortran Subroutines to Evaluate the 1976 ASME equations of State for Water/Steam and Derivatives of These Equations ANCR-1026 (Oct. 1971).

JAERI-M 6968 Errata

| Page | Line | Printed | To be corrected |
|---|---|---|---|
| Japanese Abstract | ↓5 | の冷却料喪失事故 | の冷却材喪失事故 |
| 2 | ↑4 | are now extended | are new extended |
| 4 | ↑10 | $= \frac{dVi}{dt}Vi + \frac{dVi}{dt}Mi$ ... (3) | $= \frac{dMi}{dt}Vi + \frac{dVi}{dt}Mi$ ... (3) |
| 5 | ↑15 | The state volumes | The state values |
| 8 | ↑8 | Rij = | Rij = ... (18) |
| 8 | ↑4 | Rij = | Rij = ... (19) |
| 9 | ↓7 | f = | f = ... (20) |
| 9 | ↑10 | Rijo = | Rijo = ... (21) |
| 11 | ↓1 | the leak junction in connected | the leak junction is connected |
| 22 | ↓1 | $= - \{ F\omega + \frac{\Delta P_p S_s}{\rho_s w} \}$ ... (73) | $= - \{ F\omega + \frac{\Delta P_p W_s}{\rho_s \omega} \}$ ... (73) |
| 22 | ↓3 | w = angular | ω = angular |
| 32 | ↑17 | and 9 floating | and 8 floating |
| 35 | ↓8 | (See Eq.( )) (m) | (See Eq.(70)) (m) |
| 38 | ↓10 | X-axis | X-axis (mm) |
| 38 | ↓11 | Y-axis | Y-axis (mm) |