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ART — A PROGRAM FOR THE TREATMENT OF REACTOR THERMA TRANSIENTS ON THE IBM-704

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BETTIS ATOMIC POWER LABORATORY, PITTSBURGH, PA.,
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A description is given of a program by which the behavior of a nuclear reactor during various thermal transients may be studied. The program is written for a 32,000-word IBM-704 computer with six tape units. It is designed to predict the behavior of a water-cooled and moderated reactor with flat plate fuel elements during transients which are slower than a prompt excursion and during which the reactor flow, inlet temperature, and control rod motion may be specified as a function of time.

ART—A PROGRAM FOR THE TREATMENT OF REACTOR THERMAL TRANSIENTS ON THE IBM-704

J. E. Meyer, R. B. Smith, H. G. Gelbard,
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I. INTRODUCTION AND THEORY

The designer of a nuclear power reactor must be able to predict the characteristics and safety of the reactor over a wide range of transient situations. These situations include cases of very fast transients with prompt excursions and, at the other extreme, slow changes in reactor plant power demand. The ART program* is designed to predict the behavior of a water-cooled and moderated reactor during transients which are of an intermediate speed.

First-pass inlet temperature, reactor flow, and control rod motion are assumed to be known functions of time. This has permitted the omission of calculations describing the behavior of the remainder of the reactor plant. During transients of long duration, ** the interrelation between the reactor and other components may, therefore, necessitate supplementary analysis or experiment. The exclusion of extremely rapid accidents† has suggested simplifications which permit an efficient calculational procedure for transients of intermediate speed. The major simplifications are:

1) The use of a single mass flowrate for all points in any given reactor coolant channel.

2) The use of a single node point in the water at each axial level (a one-dimensional hydrodynamic model). In the case of rapid transients, the heat transfer in the water normal to the direction of fluid flow cannot be neglected.

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*ART is a program for handling Accidents and other Reactor Transients on the IBM-704. It replaces ATBAC (Ref 1), an earlier Bettis code for reactor transient evaluation. Major changes have been made to obtain greater flexibility and simplified input preparation. Other features have been added, such as calculations for steady-state hot channel flow, and provision for extracting fluid properties and empirical correlations from a property tape.

**Those in which the significant power and temperature transient is of longer duration than the time for transport of water around the loop.

†Those in which the time for transit of water through the core is long compared to the time for large power excursions or large changes in inlet flow.

3) Similarly, the use of a single node point for representation of fuel element temperature is justified only for those transients in which the shape of the temperature profile across the plate is not altered drastically.

It is to be noted that the dividing line between fast and intermediate speed transients is quite broad and the restrictions given in the preceding paragraph should be kept in mind in considering the use of ART. It should also be noted that in cases in which the flow tends to have "chugging" or oscillatory behavior (usually when a large quantity of steam is present in the channel), the change of mass velocity with position is undoubtedly quite important and the single mass velocity assumption of ART is inappropriate.

The reactor model considered in the ART code is of either one or two passes and is illustrated in Fig. 1. The reactor is operating initially in a steady-state condition. It may then be subjected to variations in one or more of the following quantities which are considered to be known functions of time:

1) Flowrate through the reactor.
2) First-pass inlet temperature.
3) Reactivity introduction due to control rod motion.

This combination permits analyses of transients such as those caused by loss of flow, rod withdrawal, and cold water insertion.

The heat generation rate is assumed to be separable in space and time. Reactor kinetics calculations are performed to determine core power as a function of time.* Temperature induced reactivity effects are included. The temperature coefficient is assumed to be a known function of position in the reactor.

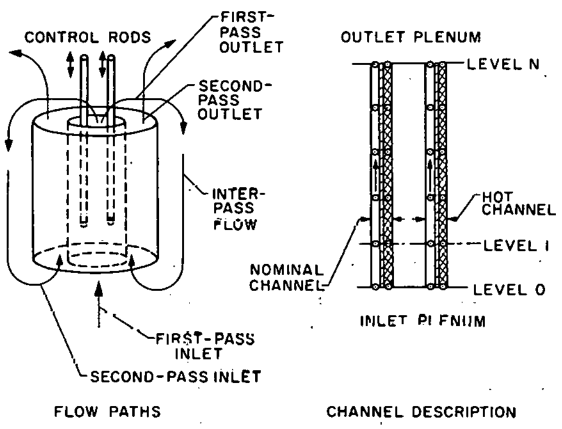

Fig. 1 Reactor Model

A single coolant channel through the core is used to represent the nominal behavior of each pass. Thermal calculations are performed for from one to four additional channels in each pass. The additional channels may be used as hot channels to represent possible extremes in dimensions, pressure drop, and heat input. The hot channels then serve to assess reactor safety during the transient under consideration.

A flat plate fuel element is assumed (Fig. 2). The treatment of fluid flow and convective heat removal in each of the several channels is based on a one-dimensional transient model in which variations in fluid velocity and fluid properties in directions transverse to the flow path are neglected.

The code output includes pointwise water, surface and plate temperatures, pointwise heat fluxes, core power and individual channel flowrate as a function of time. In addition, at each time in the transient and at each point, the heat flux required for DNB (departure from nucleate boiling) is calculated. The minimum ratio of DNB flux to local flux is also determined and included as part of the output.

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* By option, core power as a function of time may be requester specified and the reactor kinetics calculations bypassed.

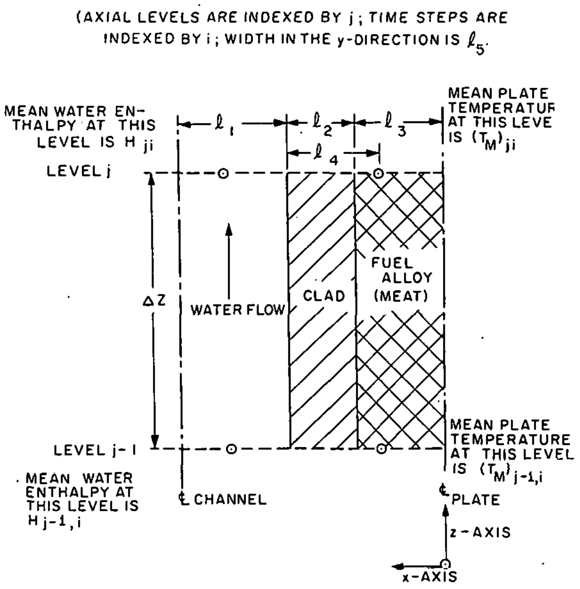

Fig. 2 Geometry of a Typical Channel Section

Typical machine time is 360 seconds per second of real time. Approximately 40 seconds of this total is associated with evaluation of reactor kinetics, 280 in thermal calculations, and 40 seconds for writing output on tape.

The following paragraphs contain a description of the differential equations which are handled in ART and of the major assumptions which are made in deriving them.

A. Conservation Laws in the Water

The conservation laws for treatment of each of these several channels may be written as follows:

Conservation of Mass

$$\frac{\partial}{\partial t}\,(1/v) + \frac{\partial G}{\partial z} = 0 \tag{1.1}$$

Conservation of Momentum

$$\frac{\partial G}{\partial t} + \frac{\partial}{\partial z}\,(vG^2) = -\frac{\partial p}{\partial z} - \left(\frac{f}{2D_h}\right)(vG^2) - \left(\frac{g}{v}\right) \tag{1.2}$$

Conservation of Energy

$$\frac{\partial H}{\partial t} + (vG)\,\frac{\partial H}{\partial z} = v\left[\frac{\partial p}{\partial t} + (vG)\,\frac{\partial p}{\partial z}\right] + v\left[\frac{\phi + rq}{\ell_1}\right] + \left(\frac{f}{2D_h}\right)\,(vG)^3 \tag{1.3}$$

These conservation laws may be combined with the following:

Equation of State

$$T_W = T_W(H, p) \quad v = v(H, p) \tag{1.4}$$

The following assumptions have been applied in the derivation of Eqs (1.1) through (1.4) (also see Figs. 1 and 2):

1) Consistent units are used and the Eulerian point of view is adopted (i.e., for example, $H = H(z, t)$, $G = G(z, t)$, etc.). Symbols are defined in Appendix I.

2) The flow is parallel to the positive z-direction. The channel is of constant half thickness ℓ_1 in the x-direction (the direction normal to the plate). All variations in fluid properties and velocity in the y-direction may be neglected. The fluid velocity profile has a zero value at the wall but very rapidly approaches a uniform nonzero value equal to vG at a small distance from the wall. In the case of two-phase flow, it is assumed that the phases are well mixed and are moving with the same velocity (fog or homogeneous flow). There is no transfer of heat or fluid across the channel centerline.

3) Conduction of heat in the z-direction is neglected.

4) The equations of state are taken from conditions of thermal equilibrium. Therefore, for example, voids introduced by the presence of steam bubbles coming from the wall into a subcooled liquid are not included in the specific volume calculation.

The equations solved in ART are a greatly simplified version of Eqs (1.1) through (1.4). The first and probably one of the most limiting assumptions is that the amount of fluid in any section of the channel does not change rapidly with time. Therefore, the derivative of specific volume in

Eq (1.1) may be neglected, and the conservation of mass can be rewritten* as

$$\frac{\partial G}{\partial z} = 0 \quad \text{or} \quad G = G(t) \quad . \tag{1.5}$$

With the use of Eq (1.5) the conservation of momentum may be readily integrated over the length of the channel to get the behavior of mass velocity with time. Thus,

$$\frac{dG}{dt} = \left[\frac{p_o - p_n}{L}\right] - \left[\frac{v_n - v_o}{L}\right] G^2 - \left(\frac{G^2}{2D_h L}\right) \int_0^L (fv)\, dz - \left(\frac{1}{L}\right) \int_0^L (g/v)\, dz \quad , \tag{1.6}$$

where z = 0 and the subscript "o" refer to the position just inside the channel inlet, and where z = L and the subscript "n" denote the position just inside the channel exit.

The energy equation has also been simplified by neglecting the effect of the last term (i.e., the dissipation term) and the effect of pressure changes in both time and distance. Thus;

$$\frac{\partial H}{\partial t} = \frac{v}{\ell_1} \left[(\phi + rq) - G\ell_1 \frac{\partial H}{\partial z}\right] \quad . \tag{1.7}$$

In addition, all properties are considered to be evaluated at some mean pressure. With this assumption, the equations of state may be rewritten as

$$T_w = T_w(H) \qquad v = v(H) \quad . \tag{1.8}$$

It may be noted that Eq (1.6) gives the conservation of momentum in terms of the pressure at the position just inside the channel inlet and just inside the channel exit. The relationships between these values and the pressures p_I and p_E in the inlet and exit plenums are given by

$$p_o = p_I - \left[\frac{K_c + 1 - \sigma_o^2}{2}\right] \left(v_o\, G^2\right) \tag{1.9}$$

and

$$p_n = p_E + \left[\frac{K_e - 1 + \sigma_n^2}{2}\right] \left(v_n\, G^2\right) \quad , \tag{1.10}$$

where the coefficients K_c and K_e represent the unrecoverable portions of the pressure loss at channel entrance and exit, and where the remainder of the pressure change is the result of either acceleration or deceleration of the fluid upon changing area (σ_o and σ_n are the ratios at the inlet and exit of channel area to the plenum area associated with that particular channel). Assumptions similar to that leading to Eq (1.7) indicate that the enthalpy just inside the channel inlet is identical to that in the inlet plenum; thus,

$$H_o = H_I \quad . \tag{1.11}$$

In the ART treatment, the nominal channel mass velocity G^{NC} is a known function of time (obtained from experiment or other analysis). Therefore, Eqs (1.6), (1.9), and (1.10) may be applied in that channel, at any time, to determine the pressure difference from inlet to exit plenum. It is then assumed that this nominal channel pressure drop** may be applied across all of the hot channels in that particular pass. This permits an application of Eqs (1.6), (1.9), and (1.10) in each hot channel to determine G^{HC} as a function of time.

---

*Note that it is important that the left-hand side of Eq (1.3) is not written as $v[\partial/\partial t\ (H/v) + \partial/\partial z\ (GH)]$ after this assumption has been made. This derivative would then depend on the reference point used for enthalpy.

** There is some adjustment made for channel-to-channel variations in pressure drop.

The inlet plenum temperature [and hence enthalpy by Eq (1.8)] is also supplied as a function of time (obtained from experiment or other analysis) for the first-pass hot and nominal channels. Therefore, the use of Eq (1.11) permits the bulk water conditions just inside the channel inlet to be determined as a function of time. The conditions in the second-pass inlet plenum as a function of time cannot usually be specified, however, since they do depend on a knowledge of the first-pass exit conditions at some earlier time in the transient. In ART it is assumed that, at any time, the enthalpy of perfectly mixed first-pass exit water, $H_n^{AC}(t)$, is linearly related to the exit enthalpy of the nominal channel by*

$$H_n^{AC}(t) = H_o^{NC} + F_a \left[H_n^{NC}(t) - H_o^{NC} \right] . \tag{1.12}$$

The factor F_a is assumed to be constant and is normally less than one because the leakage flow** which mixes with the nominal channel exit water is usually cooler than that water. Since the first-pass exit water is not perfectly mixed before arriving at the second-pass inlet, the following adjustment is made. A constant factor B_m is supplied for each second-pass channel, and the unmixed exit water that leaves the first pass at time t, arriving at the second-pass inlet at some later time, is assumed to have an enthalpy $H_{ex}(t)$ given by†

$$H_{ex}(t) = H_o^{NC} + F_a(1 + B_m) \left[H_n^{NC}(t) - H_o^{NC} \right] . \tag{1.13}$$

It may be seen that the perfect mixing value is obtained by setting B_m to zero. The mixing coefficients B_m and F_a are requester specified and must be obtained from some other analysis or test. The transport time to the second-pass inlet is variable, in general, since reactor flow may be changing with time. This variable transport delay problem is handled in ART by storing first-pass exit enthalpies as a function of time. The rate of volume expulsion of water from the first pass is assumed proportional to $(G^{NC} v_{ex})$ where v_{ex} is the specific volume corresponding to H_{ex}. The interpass water is then considered incompressible and is moved toward the second-pass inlet at a velocity proportional to $G^{NC}(t)\ v_{ex}(t)$. This approach enables the inlet enthalpy for each second-pass channel to be determined as a function of time.

This analysis of both mixed first-pass exit enthalpy and of the interpass mixing and transport problem is subject to the following restrictions:

1) The time for transport of leakage water through the first pass has been chosen to be identical to the transport time for nominal channel water.
2) The time for transport of water to the second pass is assumed to be identical for all streams of fluid leaving the first pass.
3) No heat transfer to structural members is permitted in the interpass region.
4) The effect of changes in temperature of interpass water is assumed to be negligible in reactivity calculations.

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* This relation only applies if first-pass inlet enthalpy is constant with time. An equivalent expression for the case of variable first-pass inlet enthalpy is given by Eqs (2.54) and (2.55).

** The active core flow is normally considered to be only that flow passing adjacent to the fuel alloy. The flow which is mixed with the active core flow in the exit plenum is called "leakage flow," and consists of water which is beyond the end of the fuel alloy (the end in the y-direction), flow which cools structural members and control rods, and flow which passes through clearances between core components. The leakage flow is usually cooler than the active core flow. It is assumed that the exit enthalpy of the nominal channel is identical to the mean exit enthalpy of the active core flow.

† This equation applies only for fixed first-pass inlet enthalpy. An equivalent expression for the variable case is given by Eqs (2.54) and (2.55).

In the simultaneous solution of Eqs (1.6) through (1.10), the quantities L, D_h, g, ℓ_1, r, K_c, σ_o, K_e, and σ_n are considered to be constant with time. The specific volume v is a known function of enthalpy [Eq (1.8)], and the friction factor f is a known function of mass velocity, enthalpy, and heat flux. The heat flux ϕ must be obtained from a knowledge of both the bulk water temperature, Eq (1.8), and the temperature in the fuel plate. The heat generation rate q is obtained from reactor kinetics calculations.

B. The Plate Energy Balance

The heat flow internal to the plate and clad is assumed to be one-dimensional and normal to the plate surface (in the x-direction—see Fig. 2). If it is assumed that the heat is generated in the fuel alloy (meat) only and uniformly inside that volume, then the following equations may be utilized to describe the plate energy balance:

$$(\rho C)_m \frac{\partial T}{\partial t} = \lambda_m \frac{\partial^2 T}{\partial x^2} + \frac{(1 - r) q}{\ell_3} \tag{1.14}$$

from $x = 0$ to $x = \ell_3$, and

$$(\rho C)_c \frac{\partial T}{\partial t} = \lambda_c \frac{\partial^2 T}{\partial x^2} \tag{1.15}$$

from $x = \ell_3$ to $x = \ell_2 + \ell_3$.

The first of these equations is subjected to the boundary conditions that $\partial T/\partial x = 0$ at $x = 0$ (that is, there is no heat conduction across the plate centerline to an adjacent channel). Continuity of T and $-\lambda(\partial T/\partial x)$ across the interface between meat and clad is also assumed. The surface temperature is denoted by T_s, and the heat flux ϕ at the plate surface is given by

$$\phi = - \left(\lambda_c \frac{\partial T}{\partial x}\right) \quad , \tag{1.16}$$

where the function in parentheses is evaluated at the position $x = \ell_2 + \ell_3$. Again, the problem solved in ART is a simpler one-point approximation to Eqs (1.14) through (1.16). If Eqs (1.14) and (1.15) are integrated from $x = 0$ to $x = \ell_2 + \ell_3$,

$$(\rho C)_m \int_0^{\ell_3} \left(\frac{\partial T}{\partial t}\right) dx + (\rho C)_c \int_{\ell_3}^{\ell_2 + \ell_3} \left(\frac{\partial T}{\partial t}\right) dx = - \phi + (1 - r) q \quad . \tag{1.17}$$

The one-point ART approximation is made by using a single temperature T_m in the plate and by choosing a length ℓ_4 which gives an approximate energy balance from

$$\left[(\rho C)_m \ell_3 + (\rho C)_c \ell_2\right] \frac{dT_m}{dt} = - \phi + (1 - r) q \tag{1.18}$$

and

$$\phi = \frac{\lambda_c (T_m - T_s)}{\ell_4} \quad . \tag{1.19}$$

C. Heat Transfer from Plate to Water

The relationship between bulk water temperature T_w, surface temperature T_s, and heat flux ϕ, is assumed, in the case of no local boiling, to be

$$\phi = h(T_s - T_w) \quad , \tag{1.20}$$

where h is considered to be proportional to $G^{0.8}$. In the case of local boiling, the Jens-Lottes correlation is used [i.e., $T_s = T_c$ of Eq (2.9) —also see Ref 2].

D. Use of Empirical Correlations

Several forms of correlations for boiling pressure drop and for the heat flux required for DNB are available. These are based on forms which have been in use at the Bettis Atomic Power Laboratory for steady-state thermal design purposes. Note that, in evaluation of the friction factor, the change in viscosity with temperature is neglected.

E. Heat Generation Rate

The heat generation q is obtained by assuming separability in space and time. The spatial power distribution is supplied for each channel as an approximate axial step function. The power level as a function of time is determined by a solution of the reactor kinetics equations [Eqs (2.40) and (2.41)], including temperature induced reactivity feedback [Eq (2.46)].

F. Summary of Equations

In the ART Program, a simultaneous solution is obtained for the water energy balance [Eqs (1.7) and (1.11)], water momentum balance [Eqs (1.6), (1.9), and (1.10)], interpass mixing and transport delay [Eqs (1.12) and (1.13)], the plate energy balance [Eqs (1.18) and (1.19)], the heat transfer from plate to water [Eq (1.20)], and the reactor kinetics equations [Eqs (2.40) and (2.41)]. An explicit forward extrapolation technique has been employed in obtaining time derivatives. The explicit technique does cause limitations [Eqs (5.1) through (5.6)] in time-step length in order to obtain difference equation stability.* Such limitations also have made it desirable to solve the reactor kinetics equations with a finer time mesh than that used in the thermal calculations.

The detailed techniques for dividing the channels into sections and for obtaining difference approximations are discussed in Section II.

II. CALCULATIONAL PROCEDURE

This section contains a description of the detailed calculational procedure used in ART. Reference should be made to Section I for a discussion of simplifying assumptions, to Section V for a description of the preparation of input quantities, and to Appendix I for a complete list of nomenclature.

Equations are written with a consistent set of units. However, input is supplied in more conventional units, and conversion to consistent units is made prior to computation.

Each reactor coolant channel to be considered is divided into n sections of equal length Δz in the z-direction. A typical geometry is shown in Fig. 2. The j^{th} section contains the material which, in the x-direction, lies between the centerline of the water channel and the centerline of the plate and, in the z-direction, between the axial level j-1 and j. Level j = 0 is the position just inside the channel inlet, and level j = n is located just inside the channel exit. Time steps are indexed by i, and i = 0 refers to conditions during steady-state operation.

A. Energy Balance

The heat generation rate in plate and water in the j^{th} axial section, at time i, is denoted by $q_{ji} \Delta z \ell_5$. Therefore, q_{ji} is the total heat generation per unit area normal to the x-axis. A fraction r of this heat generation occurs directly in the water; the remainder occurs in the plate. The total heat flow passing from plate to water is denoted by $\phi_{ji} \Delta z \ell_5$. The heat capacity of the plate** is

$$\Delta z \, \ell_5 \left[(\rho C)_c \, \ell_2 + (\rho C)_m \, \ell_3 \right] ,$$

---

*The use of an implicit scheme to obtain larger allowable time steps has been assessed as unprofitable because of the strong and highly nonlinear coupling between the various equations.

**This full capacity is available only if the entire plate is changing temperature at the same rate. See Section V-B for a discussion of the choice of $(\rho C)_c$, $(\rho C)_m$, and ℓ_4.

where $(\rho C)_c$ and $(\rho C)_m$ are the heat capacity per unit volume of clad and meat, respectively. The rate of change of mean plate temperature in the j^{th} axial section is approximated by the rate of change of mean plate temperature at level j (the section exit), so that the energy balance for the j^{th} section of the plate can be expressed by

$$\left[(\rho C)_c\,\ell_2 + (\rho C)_m\,\ell_3\right] \frac{dT_{mj}}{dt} = -\phi_j + q_j(1 - r) \quad , \tag{2.1}$$

or written* in finite difference form (to advance from conditions at time i to conditions at time i + 1, a time increment Δt_i later) as

$$(T_m)_{j,\,i+1} = (T_m)_{ji} - \frac{\Delta t_i}{\left[(\rho C)_c\,\ell_2 + (\rho C)_m\,\ell_3\right]} \left[\phi_{ji} - q_{ji}(1 - r)\right] \quad . \tag{2.2}$$

The energy balance for the water contained in the j^{th} axial section must include not only the heat input from the plate, $\phi_{ji}\,\Delta z\,\ell_5$, and the heat generation directly in the water, $rq_{ji}\,\Delta z\,\ell_5$, but also the heat convected away by water flow, $G_i\,\ell_5\ell_1\,(H_{ji} - H_{j-1,\,i})$. In this expression, G_i is the mass velocity** through the section, and H_{ji} denotes the mean water enthalpy at level j. If the heat storage rate in the water is also related to the rate of exit enthalpy rise, the energy balance for the j^{th} section of water can be expressed by

$$\left[\frac{\Delta z\,\ell_1}{v_j}\right] \frac{dH_j}{dt} = \Delta z(\phi_j + rq_j) - G\ell_1(H_j - H_{j-1}) \quad ; \tag{2.3}$$

or in finite difference terms by†

$$H_{j,\,i+1} = H_{ji} + \frac{v_{ji}\,\Delta t_i}{\ell_1} \left[(\phi_{ji} + rq_{ji}) - \frac{G_i\,\ell_1}{\Delta z}\,(H_{ji} - H_{j-1,\,i})\right] \quad , \tag{2.4}$$

where v_{ji} denotes the specific volume of the fluid at level j and is a known function of enthalpy H_{ji}. The heat flux for the j^{th} section ϕ_{ji} is evaluated for section exit conditions; i.e., for heat transfer from a plate with mean plate temperature $(T_m)_{ji}$ to a fluid with mean enthalpy H_{ji}. It is assumed that this heat must be transferred through an equivalent conduction path of length ℓ_4 and of thermal conductivity λ_c inside the plate, and through some film drop at the plate surface. The heat flux is taken to be the greater of the following two expressions:

$$\phi_{ji} = U_i\left[(T_m)_{ji} - (T_w)_{ji}\right] \tag{2.5}$$

or

$$\phi_{ji} = \frac{\lambda_c}{\ell_4}\left[(T_m)_{ji} - (T_c)_{ji}\right] \quad , \tag{2.6}$$

where $(T_w)_{ji}$ is the bulk fluid temperature corresponding to the enthalpy H_{ji}; where the over-all heat transfer coefficient U_i is given by††

---

*Instability may occur if the time steps are not sufficiently small. See Eqs (5.3) and (5.4) in Section V.

**At any time, a single average value for mass velocity is used for all points in a given channel. See Eq (1.5).

†See Eqs (5.1) and (5.2) of Section V for a discussion of stability.

††The parameter h^* is a film coefficient evaluated at G^*, a reference mass velocity. For each nominal channel, G^* is equal to the steady-state mass velocity. For hot channels, G^* is the first guess of the steady-state mass velocity. The fluid properties used in this evaluation of h^* should represent some average of the values to be encountered during the transient.

$$U_i = \frac{1}{\frac{\ell_4}{\lambda_c} + \frac{1}{h_i}} \tag{2.7}$$

and

$$h_i = h^* \left[\frac{G_i}{G^*} \right]^{0.8} \quad ; \tag{2.8}$$

and where $(T_c)_{ji}$ is the local boiling surface temperature predicted from

$$(T_c)_{ji} = \left\{ \begin{array}{ll} T_{sat} + K_{cr} \left[\frac{\phi_{j,i-1}}{10^6} \right]^{0.25} & \phi_{j,i-1} > 0 \\ T_{sat} & \phi_{j,i-1} \le 0 \end{array} \right\} . \tag{2.9}$$

The fluid saturation temperature is denoted by T_{sat}. Note that the assumption has been made that the local boiling surface temperature T_c can be evaluated at time i from the heat flux at time i-1.

The actual surface temperature $(T_s)_{ji}$ is given by

$$(T_s)_{ji} = (T_m)_{ji} - \frac{\ell_4 \phi_{ji}}{\lambda_c} \quad ; \tag{2.10}$$

and as a result of Eqs (2.5), (2.6), and (2.10), it may be seen that, for all positive values of K_{cr},

$$(T_s)_{ji} = (T_w)_{ji} + \frac{\phi_{ji}}{h_i} \text{ if } \phi_{ji} \le 0 \quad .$$

B. Pressure Drop

The pressure drop for a given channel, from a point just below the channel entrance to another point just above the channel exit, can be broken into four parts. The loss term resulting from entrance and exit losses and from friction drop within the channel is denoted by $(\Delta p_f)_i$. The pressure drop resulting from change in elevation is $(\Delta P_{e\ell})_i$. The pressure drop from spatial acceleration (density variation with position in the channel at any time, plus the velocity changes experienced by fluid entering and leaving the channel) is given by $(\Delta p_{a2})_i$. The transient acceleration drop resulting from mass velocity changes with time is denoted by $(\Delta p_{a1})_i$. The total pressure drop Δp_i for any channel is then given by

$$\Delta p_i = (\Delta p_f)_i + (\Delta p_{e\ell})_i + (\Delta p_{a1})_i + (\Delta p_{a2})_i \quad . \tag{2.11}$$

The individual terms can be evaluated by

$$(\Delta p_f)_i = K_c \left(v_{oi} G_i^2/2 \right) + K_e (v_{ni} G_i^2/2) + \left[(f_{oi} v_{oi})/2 + \sum_{j=1}^{n-1} f_{ji} v_{ji} + (f_{ni} v_{ni})/2 \right] \left[\left(G_i^2 \Delta z \right) / (2D_h) \right] , \tag{2.12}$$

$$(\Delta p_{e\ell})_i = g \Delta z \left[\frac{1}{2} (1/v_{oi}) + \sum_{j=1}^{n-1} 1/v_{ji} + \frac{1}{2} (1/v_{ni}) \right] , \tag{2.13}$$

$$(\Delta p_{a1})_i = n \Delta z \, (G_{i+1} - G_i)/\Delta t_i \quad , \tag{2.14}$$

and

$$(\Delta p_{a2})_i = - \left(1 + \sigma_o^2 \right) \left(v_{oi} G_i^2/2 \right) + \left(1 + \sigma_n^2 \right) \left(v_{ni} G_i^2/2 \right) \quad . \tag{2.15}$$

In these expressions, the following notation applies:

K_c, K_e are the unrecoverable entrance and exit loss coefficients,

D_h is the channel hydraulic diameter,

f_{ji} is the friction factor at the j^{th} axial level,

g is the acceleration of gravity acting toward the minus z-direction,

σ_o, σ_n are the area ratios (inside to outside) at the entrance and exit.

The friction factor f_{ji} is given by

$$f_{ji} = (f_{iso})_i \, (f/f_{iso})_{ji} \qquad H_{ji} < H_f \tag{2.16}$$

for subcooled liquid, or

$$f_{ji} = (f_{iso})_i \, (v_f/v_{ji}) \, \left(\phi^2_{L0}\right)_{ji} \qquad H_{ji} \geq H_f \tag{2.17}$$

for steam-water mixtures. The specific volume of saturated liquid is denoted by v_f and the enthalpy of saturated liquid by H_f. In both of these expressions, the isothermal friction factor $(f_{iso})_i$ is a known input function† of Reynolds' number $(N_R)_i$, and

$$(N_R)_i = (G_i \, D_h)/\bar{\mu} \ , \tag{2.18}$$

where D_h is the hydraulic diameter and $\bar{\mu}$ is a mean viscosity for the liquid.

Subcooled Region Pressure Drop

The function $(f/f_{iso})_{ji}$ for the subcooled region is set equal to one at all points for which the heat flux is less than or equal to zero. If $\phi_{ji} > 0$, then $(f/f_{iso})_{ji}$ is given (for the first kind of subcooled pressure drop correlation) by

$$\left.\begin{aligned}(f/f_{iso})_{ji} &= 1 \text{ if } (T_w)_{ji} < T_1 \\ &= 1 \text{ if } (T_w)_{ji} \geq T_1 \text{ and } \theta_{ji} = \theta^*_{ji} \\ &= 1 + f_1 \left[\frac{(T_w)_{ji} - T_1}{T_{sat} - T_1}\right] \text{ if } \theta_{ji} > 0^*_{ji}\end{aligned}\right\} \tag{2.19}$$

If the second kind of subcooled pressure drop correlation is used, then

$$(f/f_{iso})_{ji} = F_H \left[1 + f_5 \ \frac{1 - (\theta^*_{ji}/\theta_{ji})}{(G_i/10^6)^{f6}}\right] , \tag{2.20}$$

where F_H is the smaller of $f_4(1 - f_3 0^*_{ji})$ and 1.0. The quantities f_1, T_1, f_3, f_4, f_5, and f_6 are input constants. The quantity θ^*_{ji} is defined as the smaller of $(T_c)_{ji} - (T_w)_{ji}$ and θ_{ji}, where

$$\theta_{ji} = \phi_{ji}/(h_f)_i \ . \tag{2.21}$$

The film coefficient for pressure drop calculations $(h_f)_i$ is given by

$$(h_f)_i = (h_f/h) \, h_i \ , \tag{2.22}$$

where h_i is obtained from Eq (2.8) with (h_f/h) an input constant.

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†This input function is a group of up to three equations of the form $(f_{iso})_i = a(N_R)_i^{-b}$, each applicable over a range of Reynolds' numbers, with a and b known constants. The various a and b values are determined during code operation from requester supplied (N_R, f_{iso}) coordinate pairs.

Saturation Region Pressure Drop

In the saturation region ($H_{ji} \geq H_f$), the function $(\phi^2_{L0})_{ji}$ of Eq (2.17) is assumed to be a known function of mass velocity G_i and quality X_{ji}, where

$$X_{ji} = \frac{H_{ji} - H_f}{H_g - H_f} \ . \tag{2.23}$$

This input function is given in terms of a five-segment straight line fit of ϕ^2_{L0} vs quality for up to four different mass velocities. Linear interpolation on the basis of quality and $(1/G_i)$ is used to find ϕ^2_{L0}. That is, if G_i is between G_a and G_b, then

$$\phi^2_{L0} = \left(\phi^2_{L0}\right)_a + \left[\frac{(1/G_i) - (1/G_a)}{(1/G_b) - (1/G_a)}\right]\left[\left(\phi^2_{L0}\right)_b - \left(\phi^2_{L0}\right)_a\right] \ .$$

Linear extrapolation is provided for values of mass velocity outside of the input range. If only a single value of G is supplied, the ϕ^2_{L0} vs X relationship is used for all mass velocities.

Hot-Channel Flow

Since the mass velocity is given as a function of time for the nominal channel, all pressure drop terms, including the transient acceleration term, are known at any time i for the nominal channel. For each hot channel in parallel with the nominal channel,* it is assumed that the total hot-channel pressure drop $(\Delta p)^{HC}_i$ is related to the nominal channel pressure drop by

$$(\Delta p)^{HC}_i = K^{HC}_{pf} (\Delta p_f)^{NC}_i + K^{HC}_{pa}\left[(\Delta p_{a1})^{NC}_i + (\Delta p_{a2})^{NC}_i\right] + (\Delta p_{e\ell})^{NC}_i \ , \tag{2.24}$$

where K^{HC}_{pf} and K^{HC}_{pa} are plenum distribution factors for pressure loss and acceleration terms, respectively. These factors are used to account for channel-to-channel variations in pressure drop.

For each hot channel, all pressure drop terms are known, with the exception of the transient acceleration term. This term, $(\Delta p_{a1})^{HC}_i$, may be found by combining Eqs (2.11) and (2.24). The mass velocity G^{HC}_{i+1} may then be obtained from Eq (2.14) as

$$G^{HC}_{i+1} = G^{HC}_i + \frac{\Delta t_i}{n\Delta z}(\Delta p_{a1})^{HC}_i \ .$$

C. Fluid Properties

The specific volume v and the bulk temperature (T_w) must be specified as an input function of enthalpy H. This is done by supplying up to six, but not less than three, values of enthalpy in increasing order, with the last two being H_f and H_g, respectively. The temperatures for these enthalpies are then supplied, with the last two equal to T_{sat}. Finally, the specific volumes for these enthalpies are given, the last two being v_f and v_g. Linear interpolation, on the basis of either temperature or enthalpy, is used to find fluid properties.

For temperatures or enthalpies below the smallest entry in the table described in the previous paragraph, the temperature vs enthalpy relationship is obtained by linear extrapolation, and the specific volume is taken to be equal to the table entry corresponding to the smallest enthalpy. For enthalpies above the largest in the table, the problem is discontinued.

D. Departure from Nucleate Boiling Calculations

The energy balance and pressure drop calculations are based on average mass velocities and average heat fluxes in the hot channel. However, in the calculation of the DNB ratio, local mass

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*All first-pass hot channels are considered to be in parallel with the first-pass nominal channel and, similarly, second-pass hot channels with the second-pass nominal channel.

velocities and local heat fluxes are used, which are given by the relationships

$$\phi^L_{ji} = (\phi^L/\phi)\,\phi_{ji} \tag{2.25}$$

and

$$G^L_i = (G^L/G)\;G_i\;. \tag{2.26}$$

The local correction factors (ϕ^L/ϕ) and (G^L/G) are specified for each channel. If (ϕ^L/ϕ) is set equal to zero, all DNB calculations are bypassed for that channel. It is possible to obtain DNB ratios for the nominal as well as the hot channels.

The DNB ratio B_{ji} is calculated by

$$B_{ji} = \left[(F_c)_j\;(\phi_{BO})_{ji}\right]/\phi^L_{ji}\;, \tag{2.27}$$

where $(F_c)_j$ is a correction factor used to account for the distance from the channel inlet and for the fact that the heat input profile is not sectionwise constant. If $\phi^L_{ji} \le 0$, Eq (2.27) is bypassed and B_{ji} is set equal to zero. DNB is considered to take place for $B_{ji} \le B_u$, the latter supplied as an input quantity for each channel. The minimum nonzero DNB ratio of each channel for which $(\phi^L/\phi) \ne 0$ is selected and printed as output. When DNB occurs, all DNB ratios are printed beginning at that time for the particular channel.

The DNB heat flux $(\phi_{BO})_{ji}$ is a function of bulk fluid conditions and mass velocity. For the first kind of DNB correlation, the following is used for $(T_w)_{ji} \le T_2$:

$$\frac{(\phi_{BO})_{ji}}{10^6} = B_1\left[G^L_i/10^6\right]^{r_1}\left[T_{sat} - (T_w)_{ji}\right]^{m_1}$$

and, for $(T_w)_{ji} > T_2$, the smaller of either

$$\frac{(\phi_{BO})_{ji}}{10^6} = B_2\left[G^L_i/10^6\right]^{r_2}\left[H_{ji}/10^3\right]^{-m_2} \tag{2.28}$$

or

$$\frac{(\phi_{BO})_{ji}}{10^6} = B_3\left[H_{ji}/10^3\right]^{-m_3}$$

is used.

For the second kind of DNB correlation, the following equations are used:

$$\frac{(\phi_{BO})_{ji}}{10^6} = B_4\left[H_{ji}/10^3\right]^{-m_4} \qquad G^L_i < G_1$$

and

$$\frac{(\phi_{BO})_{ji}}{10^6} = B_5\left[C_1 + D_1\left(G^L_i/10^6\right)\right]^{r_5}\left[H_{ji}/10^3\right]^{-m_5} \qquad G^L_i \ge G_1\;. \tag{2.29}$$

E. Steady-State Determination

The ART transient is assumed to start at t = 0 from steady-state reactor operation. This section is devoted to the determination of the steady-state conditions prior to entering the transient calculations. It is assumed that the steady-state nominal channel mass velocity is known, that the first-pass inlet temperatures are given, and that the heat generation q_{jo} for all channels can be calculated from input parameters by

$$q_{jo} = F_j \; (q/q^*) \, q_o^* \quad j = 0, 1, 2 \ldots, n \quad , \tag{2.30}$$

where F_j is an input power factor for the j^{th} axial section; q_o^* is an input reference heat generation rate per unit heat transfer area; and (q/q^*) is an all-point multiplier for the heat generation which accounts for engineering hot-channel factors, pass power sharing, etc., and has a value for each channel. Since steady-state operation is postulated, the energy balance relationships become:

$$\phi_{jo} = q_{jo}\,(1 - r) \tag{2.31}$$

$$H_{jo} = H_{j-1,o} + (q_{jo}\Delta z)/(G_o \ell_1) \tag{2.32}$$

$$(T_s)_{jo} = \min \left[(T_c)_{jo},\; (T_w)_{jo} + (\phi_{jo}/h_o) \right] \tag{2.33}$$

$$(T_m)_{jo} = (T_s)_{jo} + (\ell_4 \phi_{jo}/\lambda_c) \quad . \tag{2.34}$$

All other parameters are determined from the same relationships as are used in transient operation, with the exception of hot-channel mass flow. Hot-channel mass flow is determined by first solving Eq (2.32) for the fluid conditions in the nominal channel. Then, the terms on the right-hand side of Eq (2.24) are evaluated for the nominal channel, except that (Δp_{a1}) is taken as zero.* The left-hand side of Eq (2.24) is then the steady-state hot channel pressure drop $(\Delta p)_s^{HC}$. The steady-state, hot-channel mass velocity G_o^{HC} is obtained by iteration. The k^{th} iteration** is conducted as follows:

1) Hot-channel fluid properties are determined from Eq (2.32), with G_o set equal to the k^{th} iteration value $G_o^{(k)}$.

2) Hot-channel steady-state pressure drop is determined from Eqs (2.11) through (2.15), but with (Δp_{a1}) set equal to zero. The resulting total pressure drop is denoted by $(\Delta p)_s^{(k)}$.

3) The iterative process is stopped if the following inequality is satisfied, or if k = 30:

$$\left| \frac{(\Delta p)_s^{(k)} - (\Delta p)_s^{HC}}{(\Delta p)_s^{HC}} \right| < \epsilon \quad . \tag{2.35}$$

   If the inequality is satisfied, the final value of $G_o^{(k)}$ is considered to be the steady-state mass velocity for this channel, and $(\Delta p)_s^{(k)}$ is taken to be the steady-state pressure drop. If k = 30, the channel concerned is identified, the values of $(\Delta p)_s^{HC}$, $G_o^{(30)}$, and $(\Delta p)_s^{(30)}$ are printed and the problem is discontinued.

4) If the iteration is to proceed, the next mass velocity $G_o^{(k+1)}$ is found by

$$G_o^{(k+1)} = G_o^{(k)} \left[(\Delta p)_s^{HC} / (\Delta p)_s^{(k)} \right]^{1/2} \quad . \tag{2.36}$$

Equations (2.31), (2.33), and (2.34) are then used in conjunction with other pertinent relationships to find the steady-state hot channel temperature, DNB ratios, etc.

F. Heat Generation and Reactivity Feedback

The heat generation at any point within the reactor is assumed to be proportional to a single power-coastdown function (P/P_o). That is, the heat generation rate q_{ji} is given by

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*However, during the zeroth time-step (i.e., from i = 0 to i = 1), $(\Delta p_{al})_o^{NC}$ and $(\Delta p_{al})_o^{HC}$ will, in general, not be equal to zero.

**For k = 0, $G_o^{(k)}$ is set equal to G^* for that channel.

$$q_{ji} = q_{jo} \, (P/P_o)_i = F_j \, (q/q^*) \; q_o^* \, (P/P_o)_i \; . \tag{2.37}$$

Heat Generation with Reactor Kinetics

If the power coastdown is to be determined by the reactor kinetics equations, then

$$(P/P_o)_i = \alpha_o \, (\alpha/\alpha_o)_i + (1 - \alpha_o) \, N_i \; , \tag{2.38}$$

where the first term on the right-hand side is a decay heat contribution; the second is the neutron power contribution. The steady-state fraction of power produced by decay heat is α_o.

The decay-heat coastdown function $(\alpha/\alpha_o)_i$ is taken equal to one until a scram occurs, i.e., until $t = t_3$. After scram occurs, $(\alpha/\alpha_o)_i$ is obtained by a linear interpolation in the following table (fitted from information in Ref 3 for a reactor operating an infinite time at the same power level prior to $t = t_3$):

$t \quad t_3$	(α/α_o)
0	1.0
1.5	0.848
8.0	0.690
30.0	0.535

(2.39)

When $t - t_3 > 30.0$, the problem is stopped.

The neutron power coastdown function N_i is found from a solution of the reactor kinetics equations:

$$\frac{dN}{dt} = \left[\frac{\delta K - \bar{\beta}}{\ell^*} \right] N + \sum_{d=1}^{d_\ell} \frac{\bar{\beta}_d \, \chi_d}{\ell^*} \tag{2.40}$$

and

$$\frac{d \, \chi_d}{dt} = \lambda_d \, (N - \chi_d) \; , \tag{2.41}$$

where d indexes the delayed neutron group; d_ℓ (from 1 to 7) is the total number of delayed neutron groups; ℓ^* is the prompt neutron lifetime; λ_d and $\bar{\beta}_d$ are, respectively, decay constants and effective delayed neutron fractions;

$$\bar{\beta} = \sum_{d=1}^{d_\ell} \bar{\beta}_d \; ;$$

δK denotes reactivity; and $N = \chi_d = 1$ at $t = 0$.

The reactivity δK is composed of two parts, that resulting from rod motion, δK_r, and that resulting from nominal channel temperature changes δK_t. The reactivity does, in general, vary with time. Since the prompt neutron lifetime ℓ^* is so small, the time increment Δt_r used in solving the reactor kinetics equation must be smaller than that used in the thermal portion of the code. Denoting the value of N at a time $k\Delta t_r$ after time i by N_i^k, the equations† for neutron power are given by

$$(\chi_d)_i^{k+1} = (\chi_d)_i^k + \lambda_d (\Delta t_r)_i \left[N_i^k - (\chi_d)_i^k \right] \tag{2.42}$$

and

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†See Eqs (5.5) and (5.6) of Section V for a discussion of stability.

$$N_i^{k+1} = \frac{N_i^k \left[1 + \frac{(\Delta t_r)_i}{2\ell^*}\left(\delta K_i^k - \bar{\beta}\right)\right] + \frac{(\Delta t_r)_i}{2\ell^*} \sum_{d=1}^{d_\ell} \bar{\beta}_d \left[(\chi_d)_i^{k+1} + (\chi_d)_i^k\right]}{\left[1 - \frac{(\Delta t_r)_i}{2\ell^*}\left(\delta K_i^k - \bar{\beta}\right)\right]} , \tag{2.43}$$

where

$$\delta K_i^k = (\delta K_r)_i^k + (\delta K_t)_i \tag{2.44}$$

and

$$(\Delta t_r)_i = \left\{ \begin{array}{l} \frac{1}{10} (\Delta t)_i \text{ if } (\delta K_r)_i^{(o)} = 0 \\ \\ \frac{1}{25} (\Delta t)_i \text{ if } (\delta K_r)_i^{(o)} \neq 0 \end{array} \right\} . \tag{2.45}$$

Note that $N_{i+1} = N_i^{(10)}$ when $(\delta K_r)_i^{(o)} = 0$, and $N_{i+1} = N_i^{(25)}$ when $(\delta K_r)_i^{(o)} \neq 0$. In both cases $N_i^{(o)} = N_i$.

The temperature-dependent portion of the reactivity [Eq (2.44)] is constant between i and i + 1, and is given by

$$(\delta K_t)_i = \frac{\partial(\delta K)}{\partial T_w} \left\{ \sum_{j=1}^{n} a_j \left[(T_w)_{ji} - (T_w)_{jo}\right]_{\text{pass 1}}^{\text{NC}} + \sum_{j=1}^{n} a_j \left[(T_w)_{ji} - (T_w)_{jo}\right]_{\text{pass 2}}^{\text{NC}} \right\} , \tag{2.46}$$

where $\partial(\delta K)/\partial T_w$ is the temperature coefficient of reactivity, and the a_j's are the temperature coefficient weighting factors, chosen so that

$$\sum_{j=1}^{n} (a_j)_{\text{pass 1}} + \sum_{j=1}^{n} (a_j)_{\text{pass 2}} = 1 .$$

The rod motion portion of the reactivity $(\delta K_r)_i^k$ is considered to be constant at an input value δK_1, for times between t = 0 and t = t_3. The scram time t_3 is determined from input scram settings S_f and S_p and from input delay times τ_f and τ_p (the subscripts f and p denote power to flow ratio and core power, respectively). During the calculation of a problem, the time at which $(P/P_o)_i/(G/G_o)_i^{NC}$ becomes greater than or equal to S_f is determined and denoted by t_f. The time at which $(P/P_o)_i$ becomes greater than or equal to S_p is determined and denoted by t_p. Then, the scram time t_3 is determined by:

$$t_3 = \min \left\{ \begin{array}{l} t_f + \tau_f \\ \\ t_p + \tau_p \end{array} \right. . \tag{2.47}$$

Note that either S_p or S_f, or both, may be set less than one; in which case, the corresponding values t_p or t_f, or both, would be set equal to zero, permitting the specification of a fixed scram time. After t = t_3, the reactivity $(\delta K_r)_i^k$ is found by a linear interpolation in an input table of two to five pairs of values of t - t_3 and δK_r:

$t - t_3$	δK_r
0	X
X	X
X	X
X	X
X	X

(2.48)

For times greater than the last time entry in the table, the last reactivity entry in the table will be maintained.

Heat Generation without Reactor Kinetics

The reactor kinetics portion of the code may be bypassed, and a series of up to 25 time values and values of P/P_o must be supplied with linear interpolation used to calculate $(P/P_o)_i$. For values of time in excess of the table, the last value is held constant. The tabular form for t vs (P/P_o) is

t	(P/P_o)
0	1.0
X	X
X	X
X	X
⋮	⋮

(2.49)

G. Flow Coastdown

The nominal channel mass velocity is found as a function of time by linear interpolation in an input table of (G/G_o) and by use of the equation

$$(G_i) = G_o\,(G/G_o)_i\ . \qquad (2.50)$$

The steady-state mass velocity G_o may be different for the two passes of the core, but the (G/G_o) function is considered to be the same. The following table consists of up to 35 time values and values of (G/G_o):

t	(G/G_o)
0	1.0
X	X
X	X
⋮	⋮

(2.51)

For times greater than the last time entry in the table, the last velocity entry applies.

H. First Pass Inlet Temperature

The first-pass inlet temperature $(T_w)_{oi}$ is found as a function of time by linear interpolation in an input table of up to 30 time values and the corresponding values of $(T_w)_{oi}$ for the first-pass nominal channel and the first-pass hot channels:

t	$(T_w)_{oi}^{NC}$	$(T_w)_{oi}^{HC}$
0	X	X
X	X	X
X	X	X
⋮	⋮	⋮

(2.52)

For times greater than the last time entry in the table, the last temperature entries in the table are assumed to apply. The same inlet temperature relation is used for all first-pass hot channels.

I. Second-Pass Inlet Temperature

The second-pass inlet temperature depends on the first-pass outlet temperature; however, the first-pass outlet temperature must be evaluated at some earlier time because of the time for transport of water to the second-pass inlet. During steady-state, the first-pass outlet temperature with appropriate mixing corrections is the second-pass inlet temperature. If a single-pass core is under consideration, all calculations of this section are bypassed.

Mixed First-Pass Outlet Enthalpy: Fixed First-Pass Inlet Temperature

If the first-pass inlet temperature (or enthalpy) is constant, the mixed first-pass exit enthalpy $(H_{ex})_i$ could be evaluated* from

$$(H_{ex})_i = (H_{oi})^{NC} + F_a(1 + B_m) \left[(H_{ni})^{NC} - (H_{oi})^{NC} \right] , \qquad (2.53)$$

where $(H_{oi})^{NC}$ and $(H_{ni})^{NC}$ are, respectively, the inlet and exit enthalpies of the first-pass nominal channel. The factor F_a equals the fraction of first-pass flow through the active core. The factor B_m accounts for imperfect mixing in the exit water; two values of B_m are supplied, one which applies to the second-pass nominal channel (usually zero) and the other which is used for all second-pass hot channels. Therefore, there is available, for each time i, a value of $(H_{ex})_i$ to be applied to the second-pass nominal channel at some later time, and a value to be applied to the second-pass hot channels at this later time.

Mixed First-Pass Outlet Enthalpy—Variable First-Pass Inlet Temperature

If the first-pass inlet temperature is a variable, then Eq (2.53) no longer applies. To handle this case, the exit temperature of an imaginary average channel is calculated by applying heat balance Eq (2.4) to each of n sections of this average channel, using the assumptions

$$\left.\begin{aligned} (H_{oi})^{AC} &= (H_{oi})^{NC} , \\ (v_{ji})^{AC} &= (v_{ji})^{NC} , \\ (G_i)^{AC} &= (G_i)^{NC} , \\ (\phi_{ji} + rq_{ji})^{AC} &= F_a(\phi_{ji} + rq_{ji})^{NC} , \\ \text{and} \qquad (\ell_1)^{AC} &= (\ell_1)^{NC} , \end{aligned}\right\} \qquad (2.54)$$

where NC refers to the first-pass nominal channel and AC to this average channel. These assumptions are equivalent to the calculation of average channel exit enthalpy by completely mixing the nominal channel exit water at any time with a stream of nonheated leakage water. This leakage stream has a mass flowrate proportional to that for the nominal channel, and has a transport time from bottom to top plenum equal to the nominal channel transport time. If this model is required to reduce to Eq (2.53) in the case of constant inlet temperature, then Eq (2.53) may be rewritten as

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*Equation (2.55) is actually used for this evaluation in the case of fixed first-pass inlet temperature. Equation (2.53) is written only to show a form which may be more easily recognized.

$$(H_{ex})_i = (H_{ni})^{AC} + \frac{B_m F_a}{(1 - F_a)} \left[(H_{ni})^{NC} - (H_{ni})^{AC} \right] , \qquad (2.55)$$

where the comments under Eq (2.53) also apply.

Second-Pass Inlet Enthalpy

By denoting the interpass delay time during steady-state as K_o, an equivalent interpass length L_{ex} and an elapsed length L_i can be calculated from

$$L_{ex} = (v_{ex})_o \, G_o^{NC} \, K_o \qquad (2.56)$$

and

$$L_i = \sum_0^{i-1} \left[G_i^{NC} \, (v_{ex})_i \, \Delta t_i \right] , \qquad (2.57)$$

where $(v_{ex})_i$ is the specific volume corresponding to the enthalpy $(H_{ex})_i$ of Eq (2.53) or (2.55) when B_m has its value for the second-pass nominal channel. The mass velocity G_i^{NC} is for the first-pass nominal channel. The elapsed length L_i is a measure of how far the water that was leaving the first pass at the beginning of the transient has traveled at any later time.

The first-pass exit enthalpies $(H_{ex})_i$ for the second-pass nominal and hot channels are retained along with values of L_i as follows:

$$\left. \begin{array}{lll} L_1 & (H_{ex})_o^{NC} & (H_{ex})_o^{HC} \\ L_2 & (H_{ex})_1^{NC} & (H_{ex})_1^{HC} \\ L_3 & (H_{ex})_2^{NC} & (H_{ex})_2^{HC} \\ \vdots & \vdots & \vdots \end{array} \right\} \qquad (2.58)$$

Provision is made for retaining 1350 rows of this table. The second-pass inlet enthalpy H_{oi} is found from

$$\left. \begin{array}{ll} H_{oi} = (H_{ex})_o & L_i - L_{ex} < L_2 \\ \quad = (H_{ex})_1 & L_1 \le L_i - L_{ex} < L_2 \\ \quad = (H_{ex})_2 & L_2 \le L_i - L_{ex} < L_3 \;, \\ \quad \vdots & \end{array} \right\} \qquad (2.59)$$

If $L_{1350} \le L_i - L_{ex}$, then $H_{oi} = (H_{ex})_{1349}$.

III. INPUT FORMAT

ART-02 problems are of three types—parent, one-shot, and continuation. This option is to allow information generated during a parent problem to be written on tape at some specified time during the transient. The parent problem then proceeds to its completion. This tape may be used to initiate one or more continuation problems from the advanced point in the transient, with attendant advantages in machine time. The one-shot problem is used when no such tape is required.

An input deck for ART-02 must consist of an identification card, followed by the necessary data and terminated by a blank card. Specifications for each of three types of problems are listed separately, with the exception of the identification card which must have the same format for all problems.

The identification card consists of an eight-digit problem number in columns 1-8, a variable field for comments in columns 9-65, problem type in column 66, column 67 blank, and ART02 in columns 68-72. The problem type, column 66, must be P for parent, C for continuation, or blank for one-shot. A continuation problem must have the same problem number as its associated parent problem.

All data cards must contain, as the first number on the card, a series number, followed by a comma. The data must be listed immediately following this number. Successive numbers must be separated by commas, with no intervening blank columns. The last number on a card must not be followed by a comma. Floating point numbers, designated by F, must contain a decimal point. Fixed point numbers, designated by X, must not contain a decimal point. If additional cards are needed for any section, they must be numbered sequentially in the units position of the series number from 2-9. Card numbers must be in ascending order.

The following tables contain the series number, card format, item identification, and units used for various quantities. A discussion of each input quantity and of some of the decisions leading to its choice is given in Section V.

A. Parent Problem

Control Information

Time Increments: 1011, F_{11}, X_1, F_{12}, F_{21}, X_2, F_{22}, . . . , F_{n1}, X_n, F_{n2} $(1 \le n \le 5)$

F_{i1} is a time-step increment	sec
X_i is the number of time-steps per printout	
F_{i2} is the interval end time	sec

The sequence $\{F_{i2}\}$ must be in ascending order. One of the F_{i2} numbers must equal the continuation time (F_8, series 1061). The interval end time F_{n2} denotes the final problem stop.

Problem Size: 1021, X_1, X_2, X_3, X_4

$X_1 = n$ $(2 \le n \le 30)$, the number of axial sections

$X_2 = 1$ or 2, the number of passes

X_3 = the number of first-pass hot channels, $0 \le X_3 \le 4$

X_4 = the number of second-pass hot channels, $0 \le X_4 \le 4$

Property Tape: 1031, X_1, X_2, X_3, X_4, X_5,

X_1 is the data file requested, $0 \le X_1 \le 99$,

$X_2 = \begin{Bmatrix} 0 \text{ card} \\ 1 \text{ tape} \end{Bmatrix}$ input, subcooled pressure drop

$X_3 = \begin{Bmatrix} 0 \text{ card} \\ 1 \text{ tape} \end{Bmatrix}$ input, saturation region pressure drop

$X_4 = \begin{Bmatrix} 0 \text{ card} \\ 1 \text{ tape} \end{Bmatrix}$ input, fluid properties

$X_5 = \begin{Bmatrix} 0 \text{ card} \\ 1 \text{ tape} \end{Bmatrix}$ input, DNB information

If $X_1 = 0$, then $X_2 = X_3 = X_4 = X_5 = 0$.

Input Options: 1041, X_1, X_2, X_3

$X_1 = \begin{Bmatrix} 1 \text{ first} \\ 2 \text{ second} \end{Bmatrix}$ kind, subcooled pressure

$X_2 = \begin{Bmatrix} 1 \text{ first} \\ 2 \text{ second} \end{Bmatrix}$ kind, DNB correlation

$$X_3 = \left\{ \begin{array}{l} 1 \text{ reactor kinetics and scram} \\ 2 \text{ reactor kinetics only} \\ 3 \text{ power coastdown} \end{array} \right\}, \text{ type of heat generation}$$

Output Options: 1051, $X_{11}, X_{12}, \ldots, X_{16}, X_{21}, X_{22}, \ldots, X_{26}$

$$X_{11} \ldots X_{16} \text{ are } \left\{ \begin{array}{l} 0 \text{ no printout} \\ 1 \text{ printout} \end{array} \right\} \text{ for nominal channel results:}$$

X_{11} controls $(T_w)_{ji}$, bulk fluid temperature

X_{12} controls $(T_m)_{ji}$, mean plate temperature

X_{13} controls $(T_s)_{ji}$, surface temperature

X_{14} controls $(T_c)_{ji}$, surface temperature for local boiling

X_{15} controls ϕ_{ji}, heat fluxes

X_{16} controls B_{ji}, DNB ratios after DNB occurs

Hot channel results are specified by $X_{21} \ldots X_{26}$. If no hot channels are requested ($X_3 = X_4 = 0$, series 1021), omit $X_{21} \ldots X_{26}$.

Over-all Conditions: 1061, $F_1, F_2, F_3, F_4, F_5, F_6, F_7, F_8$

$F_1 = p_o$, operating pressure	psi
$F_2 = q_o^*$, reference heat generation	10^6 Btu/ft^2-hr
$F_3 = K_{cr}$, parameter in Jens-Lottes treatment of nucleate boiling film coefficient	mixed units
$F_4 = g$, component of acceleration of gravity acting in the negative z-direction	ft/sec^2
$F_5 = \epsilon$, steady-state convergence criterion	
$F_6 = \Delta z$, axial mesh increment	in.
F_7 = problem stop after DNB	sec
F_8 = continuation time	sec

The operating pressure F_1 must be an integer value; F_8 must equal an interval end time of series 1011, and F_8 must not be included for a one-shot problem.

Individual Channel Characteristics

The following data must be supplied for each channel requested. The second digit of the series number denotes the channel and must be 0 for the first-pass nominal channel; 1, 2, 3, 4 as needed for the first-pass hot channels; 5 for the second-pass nominal channel; 6, 7, 8, 9 as needed for the second-pass hot channels. Data must not be supplied for unused channels.

Dimensions: 2_11, F_1, F_2, F_3, F_4

$F_1 - \ell_1$, channel half-thickness	in.
$F_2 = \ell_2$, clad thickness	in.
$F_3 = \ell_3$, meat half-thickness	in.
$F_4 = \ell_4$, equivalent plate conduction length	in.

Metal Properties: 2_21, F_1, F_2, F_3

$F_1 = (\rho C)_c$, clad heat capacity	Btu/ft^3-°F
$F_2 = (\rho C)_m$, meat heat capacity	Btu/ft^3-°F
$F_3 = \lambda_c$, plate conductivity	Btu/ft-hr-°F

Flow Characteristics: 2_31, F_1, F_2, F_3, F_4, F_5, F_6, F_7, F_8, F_9, F_{10}, F_{11}, F_{12}, F_{13}

$F_1 = B_u$, DNB ratio at which DNB takes place

$F_2 = G^*$, reference mass velocity $10^6 \, lb_m/ft^2$-hr

$F_3 = h^*$, reference film coefficient Btu/ft^2-hr-°F

$F_4 = D_h$, hydraulic diameter in.

$F_5 = \bar{\mu}$, mean viscosity lb_m/ft-hr

$F_6 = K_c$, entrance unrecoverable loss coefficient

$F_7 = K_e$, exit unrecoverable loss coefficient

$F_8 = \sigma_o^2$, entrance area ratio squared

$F_9 = \sigma_n^2$, exit area ratio squared

$F_{10} = K_{pf}$, plenum distribution factor on pressure loss terms

$F_{11} = K_{pa}$, plenum distribution factor on acceleration terms

$F_{12} = h_f/h$, pressure drop film coefficient conversion factor

$F_{13} = G^L/G$, local correction factor on mass velocity

Note that $F_{10} = F_{11} = 1.0$ for nominal channels.

Friction Factors: 2_41, F_{11}, F_{12}, F_{21}, F_{22}, . . . , F_{n1}, F_{n2} $(2 \leq n \leq 4)$

$F_{i1} = N_R$, Reynolds' number

$F_{i2} = f_{iso}$, isothermal friction factor

The sequence $\{F_{i1}\}$ must be in ascending order.

Heat Generation: 2_51, F_1, F_2, F_3

$F_1 = q/q^*$, reference heat flux multiplier

$F_2 = r$, fraction of heat generated directly in the water

$F_3 = \phi^L/\phi$, local heat flux correction factor

Input Power Factor: 2_61, F_0, F_1, F_2, . . . , F_j, . . . , F_n where F_j is the power factor for section j, and n is the number of axial sections. Note that n + 1 factors must be supplied.

DNB Correction Factor: 2_71, F_0, F_1, F_2, . . . , F_j, . . . , F_n where F_j is the correction factor for section j, and n is the number of axial sections. Note that n + 1 factors must be supplied. This series must be omitted for any channel with $F_3 = \phi^L/\phi = 0$, series 2_51.

Pressure Drop Correlations

Subcooled Pressure Drop (First Kind): 3011, F_1, F_2

$F_1 = f_1$, correlation parameter mixed units

$F_2 = T_1$, correlation temperature °F

This series must be omitted if input is from the property tape or if second kind is specified.

Subcooled Pressure Drop (Second Kind): 3021, F_1, F_2, F_3, F_4

$F_1 = f_3$, correlation parameter 1/°F

$F_2 = f_4$, correlation parameter

$F_3 = f_5$, correlation parameter

$F_4 = f_6$, correlation parameter

This series must be omitted if input is from the property tape or if first kind is specified.

Saturation Region Pressure Drop (Quality): 3031, F_1, $F_2, \ldots, F_i, \ldots, F_n$ $(2 \le n \le 6)$ where F_i is quality and F_1 must equal zero. The sequence $\{F_i\}$ must be in ascending order. This series must be omitted if input is from the property tape.

Saturation Region Pressure Drop (G, ϕ^2_{LO}):

3041, $F_{11}, F_{12}, \ldots, F_{1m}$ (m = n+1, series 3031)

3042, $F_{21}, F_{22}, \ldots, F_{2m}$ (m = n+1, series 3031)

3043, $F_{31}, F_{32}, \ldots, F_{3m}$ (m = n+1, series 3031)

3044, $F_{41}, F_{42}, \ldots, F_{4m}$ (m = n+1, series 3031)

where

$F_{i1} = G_i$ mass velocity 10^6 lb_m/ft^2-hr

$F_{i2}, \ldots, F_{im} = \phi^2_{LO}$, values associated with quality, series 3031. Series 3042, 3043, and 3044 may be omitted. The sequence $\{F_{i1}\}$ must be in ascending order with $F_{11} > 0$. This series must be omitted if input is from the property tape.

Fluid Properties

Enthalpy: 4011, F_1, $F_2, \ldots, F_i, \ldots, F_n$ $(3 \le n \le 6)$

$F_i = H$, enthalpy Btu/lb_m

$F_{n-1} = H_f$, enthalpy of saturated liquid Btu/lb_m

$F_n = H_g$, enthalpy of saturated vapor Btu/lb_m

The sequence $\{F_i\}$ must be in ascending order. This series must be omitted if input is from the property tape.

Temperature: 4021, F_1, $F_2, \ldots, F_i, \ldots, F_m$ (m = n, series 4011)

$F_i = T$, temperatures associated with the enthalpies of series 4011 °F

$F_{m-1} = T_{sat}$, saturation temperature °F

$F_m = T_{sat}$, saturation temperature °F

The sequence $\{F_i\}$ must be in ascending order, and the series omitted if input is from the property tape.

Specific Volume: 4031, F_1, $F_2, \ldots, F_i, \ldots, F_m$ (m = n, series 4011)

$F_i = v$, specific volumes associated with the enthalpies of series 4011 ft^3/lb_m

$F_{m-1} = v_f$, specific volume of saturated liquid ft^3/lb_m

$F_m = v_g$, specific volume of saturated vapor ft^3/lb_m

The sequence $\{F_i\}$ must be in ascending order, and the series omitted if input is from the property tape.

DNB Correlations

First Kind: 5011, F_1, F_2, F_3, F_4, F_5, F_6, F_7, F_8, F_9

$F_1 = B_1$, parameter mixed units

$F_2 = m_1$, correlation exponent

$F_3 = r_1$, correlation exponent

$F_4 = T_2$, correlation temperature °F

$F_5 = B_2$, parameter mixed units

$F_6 = m_2$, correlation exponent

$F_7 = r_2$, correlation exponent

$F_8 = B_3$, parameter mixed units

$F_9 = m_3$, correlation exponent

This series must be omitted if input is from the property tape.

Second Kind: 5021, F_1, F_2, F_3, F_4, F_5, F_6, F_7, F_8

$F_1 = B_4$, correlation parameter mixed units

$F_2 = m_4$, correlation exponent

$F_3 = G_1$, correlation mass velocity 10^6 lb_m/ft^2-hr

$F_4 = r_5$, correlation exponent

$F_5 = B_5$, correlation parameter mixed units

$F_6 = m_5$, correlation exponent

$F_7 = C_1$, correlation constant

$F_8 = D_1$, correlation constant ft^2 hr/lb_m

This series must be omitted if input is from the property tape.

Reactor Kinetics

This section must be omitted if power coastdown is specified.

Constants: 6011, F_1, F_2, F_3, F_4

$F_1 = \alpha_o$, steady-state decay heat power fraction

$F_2 = \ell^*$, prompt neutron lifetime sec

$F_3 = \delta K_1$, rod motion portion of reactivity before scram

$F_4 = \frac{\partial(\delta K)}{\partial T_w}$, reactivity temperature coefficient 1/°F

$\bar{\beta}_d$, λ_d: 6021, F_{11}, F_{12}, F_{21}, F_{22}, . . . , F_{i1}, F_{i2}, . . . , F_{n1}, F_{n2} $(1 \le n \le 7)$

$F_{i1} = \bar{\beta}_d$, effective delayed neutron fraction

$F_{i2} = \lambda_d$, decay constant 1/sec

First-Pass Nominal Channel Weighting Factors: 6031, F_1, F_2, . . . , F_j, . . . , F_n (n = No. of axial sections) where $F_j = a_j$, the temperature coefficient weighting factor for the j^{th} axial section. Note that n factors must be supplied.

Second-Pass Nominal Channel Weighting Factors: 6041, F_1, F_2, . . . , F_j, . . . , F_n (n = No. of axial sections) where $F_j = a_j$, the temperature coefficient weighting factor for the j^{th} axial section. Note that n factors must be supplied. The sum of all a_j, first and second passes, must equal one (any sum between .999 and 1.003 will be accepted). If one pass is specified, omit series 6041.

Scram

Data of this section must be supplied only if scram is specified.

Scram Constants: 7011, F_1, F_2, F_3, F_4, F_5

$F_1 = S_f$, power-to-flow ratio scram setting

$F_2 = \tau_f$, power-to-flow ratio scram delay time sec

$F_3 = S_p$, power scram setting

$F_4 = \tau_p$, power scram delay time sec

F_5 = problem stop after scram sec

Time and Reactivity: 7021, F_{11}, $F_{12}, \ldots, F_{i1}$, $F_{i2}, \ldots, F_{n1}$, F_{n2} $(2 \le n \le 5)$

$F_{i1} = (t - t_3)$, time elapsed after scram sec

$F_{i2} = (\delta K)_r$, reactivity resulting from control rod motion

The sequence $\{F_{i1}\}$ must be in ascending order and F_{11} must be zero.

Power Coastdown

This section must be omitted if reactor kinetics are specified.

Time Increments: 8011, X_1, F_1, X_2, $F_2, \ldots, X_i$, $F_i, \ldots, X_n$, F_n $(1 \le n \le 10)$

X_i is the number of intervals and the F_i's are the interval end times. The intervals are assumed to begin at time zero. The sequence $\{F_i\}$ must be in ascending order. Either one of the F_i's must equal the continuation time, or F_n must be less than the continuation time. The $\Sigma X_i \le 24$ and $X_i \neq 0$.

Power Coastdown Function: 8021, F_0, $F_1, \ldots, F_i, \ldots, F_n$ $(n = \Sigma X_i$, series 8011)

$F_0 = 1.0$

$F_i = (P/P_0)_i$ for the times specified in series 8011.

Flow Coastdown

Time Increments: 9011, X_1, F_1, X_2, $F_2, \ldots, X_i$, $F_i, \ldots, X_n$, F_n $(1 \le n \le 10)$

X_i is the number of intervals and the F_i's are the interval end times. The intervals are assumed to begin at time zero. The sequence $\{F_i\}$ must be in ascending order. Either one of the F_i's must equal the continuation time, or F_n must be less than the continuation time. The $\Sigma X_i \le 34$ and $X_i \neq 0$.

Mass Velocity Coastdown Function: 9021, F_0, $F_1, \ldots, F_i, \ldots, F_n$ $(n = \Sigma X_i$, series 9011)

$F_0 = 1.0$

$F_i = (G/G_o)_i$ for the times given in series 9011.

First-Pass Inlet Temperatures

Time Increments: 10011, X_1, F_1, X_2, $F_2, \ldots, X_i$, $F_i, \ldots, X_n$, F_n $(1 \le n \le 10)$ This series is similar to series 9011 except that $\Sigma X_i \le 29$.

Nominal Channel Inlet Temperature: 10021, F_0, F_1, $F_2, \ldots, F_i, \ldots, F_n$ $(n = \Sigma X_i$, series 10011). $F_i = (T_w)_{oi}$ for the times given in series 10011.

Hot Channel Inlet Temperature: 10031, F_0, F_1, $F_2, \ldots, F_i, \ldots, F_n$ $(n = \Sigma X_i$, series 10011). This series has the same significance for hot channels that series 10021 has for nominal channels. If this series is omitted, series 10021 will be used for any hot channels.

Second-Pass Inlet Temperatures: 11011, F_1, F_2, F_3, F_4. Data of this section must be supplied only if two passes have been specified.

$F_1 = F_a$, fraction of first-pass core through the active core

$F_2 = K_o$, steady-state interpass delay time sec

$F_3 = B_m^{NC}$, nominal channel interpass mixing factor

$F_4 = B_m^{HC}$, hot channel interpass mixing factor

Note that F_4 must be omitted if no second-pass hot channels are specified.

B. One-Shot Problems

The specifications for a one-shot problem are the same as those for a parent problem, with the exception that the continuation time of series 1061 is omitted. This removes the restrictions on series 1011, 8011, 9011, and 10011 which pertain to the continuation time.

C. Continuation Problem

The following sections are the only sections which may be changed by a continuation problem, subject to the following restrictions:

In time-dependent tables (series 1011, 8011, 9011, and 10011) only those entries greater than the continuation time of the parent problem may be changed. The scram delay times τ_f and τ_p, series 7011, may be changed only if scram has not occurred prior to the continuation time. Care should be taken when changing τ_f and τ_p. If the delay times are shortened and if this causes either $(t_f + \tau_f)$ or $(t_p + \tau_p)$ to be less than the continuation time, then the problem output will be based on a reactivity δK_1 between t_3 and the continuation time, rather than a reactivity found from the scram table. Only the series 1011, 7011, 8011, 8021, 9011, 9021, 10011, 10021, and 10031 may be changed. The time dependent tables are modified in the following manner. A search is made for the continuation time. All entries prior to that time are retained. New entries are added to the table from that time forward. Care should be taken to assure that the number of entries retained plus the number of entries added do not exceed the table size as given in the specifications for a parent problem.

Time Increments: 1011, F_{11}, X_1, $F_{12}, \ldots, F_{n1}$, X_n, F_{n2} where n plus the number of triplets retained does not exceed five. The left-hand end time, not specified, is assumed to be the continuation time.

Scram Constants: 7011, F_1, F_2 where $F_1 = \tau_f$ and $F_2 = \tau_p$. If a change is desired in either value, both must be supplied.

Power Coastdown

Time Increments: 8011, X_1, F_1, X_2, $F_2, \ldots, X_n$, F_n where the ΣX_i plus the number of entries retained must not exceed 25. The left-hand end time, not specified, is assumed to be the continuation time of the parent problem.

Power Coastdown Function: 8021, F_0, F_1, $F_2, \ldots, F_i, \ldots, F_m$ $(m = \Sigma X_i$, series 8011) where $F_0 = (P/P_o)$ at the continuation time, and $F_i = (P/P_o)_i$ for the times specified in series 8011.

Flow Coastdown

Time Increments: 9011, X_1, F_1, X_2, $F_2, \ldots, X_i$, $F_i, \ldots, F_n$ where the ΣX_i, plus the number of entries retained, must not exceed 35. The left-hand end time, not specified, is assumed to be the continuation time of the parent problem.

Mass Velocity Coastdown Function: 9021, F_0, F_1, $F_2, \ldots, F_i, \ldots, F_m$ $(m = \Sigma X_i$, series 9011) where $F_0 = (G/G_o)$ at the continuation time, and $F_i = (G/G_o)_i$ for the times specified in series 9011.

First-Pass Inlet Temperature

If the data of this section are changed, then series 10011, 10021, and 10031 must be changed. The replacement of series 10031 with 10021 is not performed on continuation problems.

Time Increments: 10011, X_1, F_1, X_2, F_2, . . . , X_i, F_i, . . . , X_n, F_n where the ΣX_i, plus the number of entries retained, must be less than or equal to 29.

Nominal Channel Inlet Temperatures: 10021, F_0, F_1, . . . , F_i, . . . , F_m ($m = \Sigma X_i$, series 10011) where $F_0 = (T_w)$ at the continuation time, and $F_i = (T_w)_i$ for the times specified in series 10011.

Hot Channel Inlet Temperatures: 10031, F_0, F_1, . . . , F_i, . . . , F_m ($m = \Sigma X_i$, series 10011) where $F_0 = (T_w)$ at the continuation time, and $F_i = (T_w)_i$ for the times specified in series 10011.

D. Problem Stops

There are various ways to terminate the computations of a given problem. A specified time delay, after either scram or DNB, and the last time value of the time triplets are considered to be the only direct means for terminating the calculations. However, there are six indirect means by which a problem will be discontinued or rejected. Each exit from the calculations is appropriately identified. The six indirect exits are:

1) If the enthalpy exceeds Hg, calculations are ceased.
2) If the quality range of the pressure drop correlations is exceeded, calculations are ceased.
3) If the problem stop after scram is more than 30 seconds and the decay heat coastdown function is exceeded, calculations are ceased.
4) If more than 30 iterations are required for hot-channel steady-state pressure drop convergence, calculations are ceased.
5) The appearance of negative or extremely large numbers can cause a problem to be discontinued. Stops of this type are generally the result of the violation of a stability criterion (see Eqs 5.1 through 5.5). The most frequent stop is of the type x^y, where $x \leq 0$. This is identified by the print out of "X** Y ERROR" and the location in memory, where the subroutine was entered to perform the evaluation.
6) Input data inconsistencies, if present, are identified and the problem is rejected.

E. Estimation of Machine Time

An approximation of the over-all machine time required for a given problem may be obtained from the expression

$$S \times C \times N \times 6 \times 10^{-4} \text{ minutes,}$$

where S is the number of time steps, C is the number of channels, and N is the number of axial sections. This estimate includes the time required to print periodic results. Five to six seconds are required to prepare a full page of output for off line printing. The time in milliseconds to perform the thermal calculations for a given channel may be approximated by 118 + 20(N), where N is the number of axial sections. The DNB calculations are a substantial portion of this time and may be approximated by 18.9 + 6.8(N). The reactor kinetics calculations may be approximated by $0.5(P)(N) + [2.46 + 0.97(d_\ell)](k)$, where P is the number of passes, N is the number of axial sections, d_ℓ is the number of delayed neutron groups, and k is either 10 or 25.

It may be seen that the process of preparing transient results for off-line printing requires substantially more time than the actual calculation of a single time-step. Therefore, some consideration should be given to the frequency at which printed transient results are requested.

IV. OPERATING INSTRUCTIONS

The ART code is designed to operate on an IBM-704 computer having a core storage of 32,768 words, an on-line card reader, an on-line 716 printer, an on-line card punch, and from two to six tape units. One logical drum is required if the dump routine is used. Since dumping is a manual operation, the logical drum is not an essential requirement. In addition, an off-line 717 printer is required and an off-line 714 card reader may be used.

The on-line card punch is used only for punching cards when a tape check sum or redundancy error is indicated. This feature may be omitted by modification of the tape control program.

A. Tape and Sense Switch Outline

1) On-line printer board: GLOUT2.

2) Tape Logic

Tape Logic	Remarks
1	ART program tape.
2	ART property tape—this tape is not required if all data is supplied by card input.
3	BCD input—this tape is not required if all data is read via the on-line card reader. An end-of-file condition indicates the completion of all problems.
4	Operator restart tape—this tape must be blank and provided if sense switch 4 is up. A restart record is written after every 500 time steps.
5	BCD output—this tape should be blank or contain previous output for off-line printing. No rewind or end-of-file instruction is given to the tape.
6	Continuation tape—this tape is used only if the problem is one of continuation. A parent problem requires this tape to be blank and all continuation problems require the tape written by the associated parent problem.
10	Core dumps produced by manual operations for off-line printing.

3) Sense Switches

1	Up	Normal.
	Down	Bypass incorrect continuation tape on logic 6.
2	Up	Normal.
	Down	Restart problem with data from tape logic 4.
3	Up	Normal.
	Down	On-line card input. Tape logic 3 is not required.
4	Up	Normal.
	Down	Bypass the periodic writing of restart data on tape logic 4. If down, restarts by means of switch 2 should not be attempted.

5	Up	Normal
	Down	Process problem input and prepare the input edit. The steady-state and transient calculations are not executed.
6	Up	Normal.
	Down	Rewind tape logic 1 and load tape to dump core on tape logic 10. The dump uses drum logic 1. The code uses this switch internally as a debugging aid.

After providing the proper printer board, tape, and sense switch settings, push the CLEAR and LOAD TAPE buttons to commence processing problems. An end-of-file condition indicates the termination of all ART-02 problems. The input tape, if used, is not rewound. A manual end-of-file should be written on the output tape before it is removed.

Only location $(110)_8$ is programmed as a stop, i.e., HTR 1, 1. All comments to and requests of the operator are printed on-line before the machine stops at $(110)_8$.

If a tape read-write check stop occurs at location $(325)_8$, a manual transfer to location $(111)_8$ will attempt to bypass the trouble. Any stop other than $(110)_8$ or $(325)_8$ indicates possible machine malfunction. The stop should be recorded, a blank tape placed in ready status on logic 10, tape logic 1 rewound, switch 6 depressed, and a load tape executed. The dump program prints on-line when completed and stops at location 4.

Any stop other than (4) which is less than $(110)_8$ indicates trouble in a loading routine.

B. Preparation of the ART Program Tape

The program tape consists of eight records. The first record selects the main program if neither a dump nor restart is requested by means of the switch settings. The second through fifth records are a modification of the GK DS2 core dump program. The sixth record is a copy of the WB TSB2 self-loading routine, and the seventh and eighth records are the main body of the ART program. The ninth record is an end of file.

The procedure for writing the program tape is as follows: Ready a blank tape on logic 1, ready the binary deck in the card reader, clear memory, and load cards. After the program tape has been written, the computer stops at location $(343)_8$.

C. SHARE Distributed Programs

The references below are to programs and subroutines used in the code which have been made available through the SHARE Distribution Agency. The references are identified by the SHARE label, name, author, organization, date, and distribution numbers.

1) AS AS03, Floating Point Exponential, R. J. Dinsmore, Aerojet-General Corporation, Sacramento, Calif., March 27, 1957, Dist. Nos. 224 and 437.

2) EL TEST, Logical Switch Subroutine, W. R. Couch, IBM, Endicott, N.Y., March 27, 1957, Dist. No. 220.

3) GK DS2, Octal Core Dump Program, D. B. MacMillan, Knolls Atomic Power Laboratory, General Electric Co., Schenectady, N. Y., Jan. 22, 1958, Dist. No. 434.

4) GL OUT2, General Purpose Output Program, E. R. Clark, Lockheed Aircraft Corp., Georgia Division, Marietta, Georgia, May 24, 1956, Dist. Nos. 84, 93, and 117.

5) LA S820, Floating Natural Logarithm, I. Cherry, University of California, Los Alamos Laboratory, Feb. 21, 1956, Dist. Nos. 69 and 171.

6) WB CTB2, Absolute Binary Card to Tape Loader, W. H. Guilinger and G. E. Crane, Westinghouse Electric Corp., Bettis Atomic Power Laboratory, Pittsburgh, Pa., Jan. 20, 1958, Dist. No. 425.

7) WB TSB2, Tape to Storage Binary Loader, W. H. Guilinger and G. E. Crane, Westinghouse Electric Corp., Bettis Atomic Power Laboratory, Pittsburgh, Pa., June 20, 1958, Dist. No. 425.

8) WB RWT4, Binary Read-Write Tape Routine, R. B. Smith, Westinghouse Electric Corp., Bettis Atomic Power Laboratory, Pittsburgh, Pa., Feb. 1958, Dist. Nos. 425 and 494.

9) UA SQR3, Square Root Subroutine, W. P. Melcher, United Aircraft Corp., East Hartford, Conn., Oct. 24, 1955, Dist. No. 4.

10) UA CSB1, Absolute Binary Loader, W. P. Melcher, United Aircraft Corp., East Hartford, Conn., April 12, 1956, Dist. No. 66.

11) UA CSH2, BCD Tape or Card Reader Subroutine, R. Nutt and W. P. Melcher, United Aircraft Corp., East Hartford, Conn., April 26, 1956, Dist. No. 73.

12) UA DBC1, Decimal, Octal, BCD Loader Subroutine, R. Nutt and W. P. Melcher, United Aircraft Corp., East Hartford, Conn., April 23, 1956, Dist. Nos. 73 and 89.

13) UA SAP3, SHARE Symbolic Assembly Program, W. P. Melcher, United Aircraft Corp., East Hartford, Conn., Sept. 26, 1957, Dist. Nos. 347, 431, and 457.

V. PREPARATION OF INPUT FOR A SAMPLE PROBLEM

This section contains a discussion of some of the decisions leading to the choice of ART input quantities. The discussion is based on the analysis of a fictitious two-pass core sustaining a complete loss of flow accident without scram. All input cards for this problem and selected portions of output are listed in Appendix II.

The problem input is prefaced by a card which may be used to title the problem. In this case the problem was described as a "sample problem for WAPD-TM-156," given an identification number "XXXXXXXX," and was further denoted as a one-shot ART-02 problem by the blank in column 66 and the information in columns 68-72.

A. Control Information: Cards 1011-1061

Time Increments: Card 1011

The information on this card (.02, 10, 1.8) implies that a time step of length 0.02 seconds is to be used throughout this problem of total length no longer than 1.8 seconds. A printout is to occur every 10 time steps or at t = 0, 0.2, 0.4, . . . , 1.8.

Two factors influence the choice of time increments:

1) Are the difference equations stable? That is, do errors introduced in the solution at one time step tend to grow with succeeding time steps?

2) How closely do the difference equations approximate the differential equations?*

The second question is by far the most difficult to answer, and can often only be examined by solving the problem several times, each time with a different time increment and observing the

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* A stable difference treatment in no way guarantees an acceptable approximation to the solution of the differential equation.

behavior of the solution. Although this approach offers some insight into the answer to this question, it is not clear that a smaller time step will give a difference solution that is any closer to the solution of the differential equation, unless Δz is also reduced. In fact, in certain instances,[†] it may be shown that with a given Δz, the closest approach to the solution of the differential equation may be obtained by choosing the largest time step permitted by the stability criteria of the following paragraphs. (This would also involve changing the time step during the solution.)

The question of stability may be examined by the methods of Ref 4 if changes of fluid properties during a time step and the interaction between reactor kinetics and energy balance equations are neglected. The difference equations of ART may then be shown to be stable if the following conditions[††] are satisfied (consistent units must be used):

1) The water energy balance Eq (2.4) gives

$$\Delta t_i \le \frac{1}{\left(\frac{v_{ji} U_i}{\ell_1 c_p}\right) + \left(\frac{G_i v_{ji}}{\Delta z}\right)} \tag{5.1}$$

$$\Delta t_i < \frac{1}{\left(\frac{G_i v_{ji}}{\Delta z}\right)} , \tag{5.2}$$

as criteria for no local boiling and for local boiling, respectively, where c_p is the specific heat $\partial H/\partial T$ and is infinite if the water is in the saturation region.

2) The plate energy balance Eq (2.2) gives

$$\Delta t_i \le \frac{(\rho C)_c \ell_2 + (\rho C)_m \ell_3}{U_i} \tag{5.3}$$

and

$$\Delta t_i \le \frac{(\rho C)_c \ell_2 + (\rho C)_m \ell_3}{(\lambda_c/\ell_4)} \tag{5.4}$$

as criteria for no local boiling and for local boiling, respectively.

3) Reactor kinetics neutron level Eq (2.43) gives the criterion

$$\Delta t_i \le \frac{m \ell^*}{\bar{\beta} - \delta K_i^k} , \tag{5.5}$$

where this equation is only applicable when $\delta k \le 0$ and where $m = 10$ if $(\delta K_r)_i^o = 0$, and $m = 25$ if $(\delta K_r)_i^o \neq 0$.

4) Reactor kinetics precursor Eq (2.42) gives the criterion

$$\Delta t_1 \le \left(\frac{m}{\lambda_d}\right) , \tag{5.6}$$

where m has the same significance as in Eq (5.5).

[†] If the conditions of (5.2) through (5.4) are violated during the operation of the ART problem, a warning will be printed out. It has been noted that a slight violation of condition (5.1) during a few time steps of a problem is often not detrimental to the solution if this stability criterion is afterwards satisfied because of flow coastdown.

[††] An unpublished investigation by N. J. Curlee and J. V. Reihing of the frequency response of outlet temperature to sinusoidal variations in inlet temperature.

For the sample problem, the following values have been used to check stability. Most of these correspond to the beginning of the coastdown. However, the beginning of the problem, generally, will not be the worst time for stability behavior, and other than beginning-of-problem conditions must be considered.

The assumed numbers for the sample problem are:

$v_{ji} \sim 0.020\ \text{ft}^3/\text{lb}_m$; $G_i \sim 4 \times 10^6\ \text{lb}_m/\text{ft}^2\text{-hr} \sim 1100\ \text{lb}_m/\text{ft}^2\text{-sec}$

$\Delta z = 6.2$ in. ~ 0.52 ft; $c_p \sim 1.2\ \text{Btu/lb}_m\text{-}^\circ\text{F}$; $\ell_1 = 0.0485$ in. ~ 0.0040 ft

$h = 8170\ \text{Btu/ft}^2\text{-hr-}^\circ\text{F} \sim 2.30\ \text{Btu/ft}^2\text{-sec-}^\circ\text{F}$; $\lambda_c = 8.1\ \text{Btu/ft-hr-}^\circ\text{F} \sim 0.0022\ \text{Btu/ft-sec-}^\circ\text{F}$

$\ell_4 = 0.018$ in. ~ 0.0015 ft; $(\rho C)_c = 0$; $(\rho C)_m = 33.2\ \text{Btu/ft}^3\text{-}^\circ\text{F}$

$\ell_2 = 0.0180$ in. ~ 0.0015 ft; $\ell_3 = 0.042$ in. ~ 0.0035 ft

average core temperature rise = 20°F; $\frac{\partial(\delta K)}{\partial T} = -2.5 \times 10^{-4}\ (1/^\circ\text{F})$

$\bar{\beta} = \sum_d \bar{\beta}_d = 0.0079$; $\ell^* = 3.2 \times 10^{-5}$ sec; largest $\lambda_d = 1.507\ \text{sec}^{-1}$; m = 10 because of no scram.

The derived quantities are:

$U_i \sim 0.90\ \text{Btu/ft}^2\text{-sec-}^\circ\text{F}$; $(\lambda_c/\ell_4) \sim 1.47\ \text{Btu/ft}^2\text{-sec-}^\circ\text{F}$

$(\rho C)_c \ell_2 + (\rho C)_m \ell_3 \sim 0.116\ \text{Btu/ft}^2\text{-}^\circ\text{F}$; $\delta K_i^k \sim 0.0050$.

The stability criteria are:

$\Delta t_i \leq 0.022$ sec for Eq (5.1)
0.024 sec for Eq (5.2)
0.129 sec for Eq (5.3)
0.077 sec for Eq (5.4)
0.050 sec for Eq (5.5)
6.6 sec for Eq (5.6)

By examining these stability criteria, it appears that the chosen time step of 0.020 sec satisfies all stability criteria.

The selection of 0.2 sec for the printout interval gives a reasonably clear picture of the variation of quantities in this particular problem without burdening the requester with a great volume of output. In addition, the machine time needed for printout is not negligible (approximately six seconds for every 50 lines of output, whether the lines are filled or not).

Problem Size: Card 1021

Six axial sections per channel have been chosen here. Note that this is a most important point in machine time considerations. A smaller number of sections reduces the machine time spent per time step, and also, in many cases, increases the allowable time step length [Eqs (5.1) and (5.2)]. A higher number of sections may be needed to obtain more detailed output or to permit a more detailed input power shape. However, acceptable results may often be obtained with a smaller number of sections, which should be given especially serious consideration for long slow accidents. In such cases a few detailed steady-state problems (which run quite rapidly) may be used for interpreting the results of much less detailed transient problems.

A two-pass core with one nominal channel per pass has also been specified on this card. If the limiting hot channel occurs in one pass or the other, one of these could be eliminated. On the other hand, one of these passes may contain a hot channel with high heat input at the bottom and low heat input at the top. It may also contain a channel with somewhat lower peak heat input but with a greater total input. If it is not clear which is controlling thermally, then both channels may be run as hot channels in that pass.

Property Tape: Card 1031

As indicated on this card, needed fluid properties, DNB, and pressure drop correlations were extracted from file two of the property tape. It is essential, of course, that data at the required pressure and of the requested types are available in this file. A system has been in operation at Bettis by which a tape containing an up-to-date edit of property tape contents is retained in the computing center. This edit tape may be printed on request.

Input Options: Card 1041

This card indicates the use of the second kind of both subcooled pressure drop and DNB correlations. The proper type will be extracted from tape. For a discussion of these types, see comments under cards 3011, 3021, 5011, and 5021. A choice to use reactor kinetics with no scram is also indicated on this card.

Output Options: Card 1051

A choice of output desired is indicated on this card. Note that the DNB ratio printout is begun for a given channel only after a DNB ratio less than or equal to B_u has been determined for that channel.

Over-all Conditions: Card 1061

p_o is the operating pressure, and is used only for extracting information from the property tape, but must be supplied even if the property tape is not used; 2000 psi data were chosen here.

$q_o{}^*$ is a reference heat flux, arbitrarily chosen as 100,000 Btu/ft^2-hr and, therefore, supplied as 0.1 in the input units of 10^6 Btu/ft^2-hr. This quantity is a common multiple for the heat generation in all channels. Thus, only this number needs to be changed if one reactor is to be examined at several power levels. Further discussion of this quantity is included under card 2051.

K_{cr} is a parameter for determination of nucleate boiling characteristics. The following correlation by Jens and Lottes (Ref 2) may be used to predict surface temperature under nucleate boiling conditions:

$$T_c = T_{sat} + \frac{60\ (\phi/10^6)^{1/4}}{e^{p_o/900}} , \qquad (5.7)$$

where ϕ is in units of Btu/ft^2-hr and p_o is in psia.

By comparison with Eq (2.9),*

$$K_{cr} = \frac{60}{e^{(p_o/900)}} = \frac{60}{e^{(2000/900)}} = 6.51 .$$

g is the component of acceleration due to gravity in the negative z-direction. In the assumed case of vertical upflow, g = +32.17 ft/sec^2. Other values could be supplied for a core with downflow, for a core with a list, or for an examination of the effect of neglecting elevation terms.

ϵ is a convergence criterion on the hot channel pressure drop balance in steady-state, defined by Eq (2.35). It is used in the sample problem as 0.005, requiring that the hot channel pressure drop $(\Delta p)_s^{(k)}$ be within 1/2% of the value of $(\Delta p)_s^{HC}$ desired. In this case, with no local or bulk

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*K_{cr} was supplied erroneously as 7.21 in the input for the sample problem.

boiling in steady-state, the convergence is quite rapid. However, there are two possibilities of convergence difficulties in a steady-state boiling situation that must be considered (also see the discussion of G^*, card 2031):

1) Discontinuities in pressure drop correlations and the use of a finite number of mesh points can introduce multiple discontinuities in the relationship between the calculated pressure drop for the hot channel and the hot channel flow. These discontinuities may be larger than a very tight convergence criterion and may preclude any steady-state solution within such a criterion.

2) The hot channel pressure drop vs flow relation in the boiling region may reach a minimum value at a pressure drop above that sought, or the solution may be multiple valued. Finally, the pressure drop curve may be quite flat so that convergence may be slow.

Δz is the axial mesh increment. A 37.2 in. channel is considered here. Therefore, Δz = length/n = (37.2 in./6) = 6.2 in. Note that in ART, the heated length is assumed to be equal to the length for pressure drop considerations. If it is desired to include a pressure drop contribution for a short unheated length at each end of the channel,

1) $n\Delta z$ should be set equal to the total plate length and suitable reductions made in heat generation figures, or

2) $n\Delta z$ should be set equal to the heated length and the losses in these end positions included in the unrecoverable entrance and exit loss coefficients K_c and K_e (card 2031).

Problem Stop after DNB: Since the film boiling heat transfer is not handled in ART, this input entry permits the problem to be stopped after DNB has occurred (i.e., after $B_{ji} \leq B_u$ for some channel).

Continuation Time: Eliminated here since a one-shot problem is considered.

B. Individual Channel Characteristics: Cards 2011-2671

Only first-pass nominal channel cards will be discussed here, but the comments will apply to the cards for other channels as well.

Dimensions: Card 2011

ℓ_1, ℓ_2, and ℓ_3 = 0.0485, 0.018, and 0.042, respectively. The nominal channel considered here is assumed to have a 97-mil channel gap between plates and to have fuel plates with a total thickness of 120 mils, composed of two 18-mil clads and an 84-mil fuel alloy.

ℓ_4 is the equivalent conduction length into the plate. The combination of ℓ_4, λ_c, $(\rho C)_c$, and $(\rho C)_m$ is used to define a one-lump treatment which approximates the transient behavior of the plate. It should be noted that the behavior of the temperature T_m probably does not adequately represent the temperature at any single point but gives a good over-all energy balance between plate and water in slow thermal transients. A comparison of the one-lump approach with a many-section treatment on other digital codes is suggested for evaluating choices of the parameters ℓ_4, λ_c, $(\rho C)_m$. The best values probably depend on the type of transient considered. For example, if the surface temperature is to rise and the heat generation is to remain constant, the best choice would be expected to be different than in the inverse situation. In addition, the relative sizes and properties of clad and meat must be considered. A condition examined by E. V. Somers* suggests that ℓ_4 should be set equal to ℓ_2 (the clad thickness); that λ_c should equal the clad conductivity; that $(\rho C)_m$ should be given its full value; and that $(\rho C)_c$ be set

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*Westinghouse Research Laboratories, work done on the basic equations describing energy flow and pressure drop relationships for transient coolant flow conditions in a non-homogeneous reactor (July, 1956).

somewhere between zero and its full value. This approximation, with $(\rho C)_c$ set equal to zero, was incorporated into the ATBAC Code (Ref 1) and into the sample problem considered here. Additional studies† for another typical geometry, using the clad value for λ_c and full values for $(\rho C)_m$ and $(\rho C)_c$, have indicated that the best choice for the ratio $[\ell_4/\ell_2 + \ell_3]$ may vary between 0.4 and 0.5.

Metal Properties: Card 2021

$(\rho C)_c$, $(\rho C)_m$, and λ_c = 0, 33.2 Btu/ft^3-°F, and 8.1 Btu/ft-hr-°F, respectively. The discussion under card 2011 indicates the basis for the choice of zero for the first number. Values for the other numbers were chosen arbitrarily.

Flow Characteristics: Card 2031

B_u = 1.5. This is the DNB ratio at which it is assumed that departure from nucleate boiling occurs. It is designated as other than one because of uncertainties in the DNB correlations and their application to this transient situation. (See Ref 5, pp 57-60 for a discussion of the DNB uncertainty factor.)

G^* = 3.0. This quantity is given in units of 10^6 lb$_m$/ft^2-hr, and is defined as the steady-state value of mass velocity for nominal channels and as the first estimate of steady-state mass velocity for all hot channels. Its value for nominal channels is obtained from a knowledge of total system flow and the amount of this flow which bypasses the active heat transfer surfaces. The bypass flow determination is based on a pressure drop balance for all flow paths in parallel for a given pass. The first estimate for hot channel flow is generally not important in a nonboiling situation and may, for convenience, be chosen equal to G^* for the nominal channel. In a boiling situation there is the possibility of multiple solutions or slow convergence (see discussion of ϵ, card 1061), so that the choice of G^* is much more important; several steady-state problems should probably be run with different choices of G^* when the requester is confronted with an unfamiliar situation.

h^* = 6486 Btu/ft^2-hr-°F, which is the film coefficient corresponding to the mass velocity G^*. The value here was determined by the use of the following empirical relationship:

$$h^* = 0.019\left(\frac{k_w}{D_h}\right)\left(\frac{G^* D_h}{\bar{\mu}}\right)^{0.8}\left(\frac{c_p \bar{\mu}}{k_w}\right)^{0.4} , \qquad (5.8)$$

with k_w = 0.36 Btu/ft-hr-°F, $\bar{\mu}$ = 0.26 lb$_m$/ft-hr; c_p = 1.16 Btu/lb$_m$-°F, D_h = 0.1944 in. = 0.0162 ft, and G^* = 3 x 10^6 lb$_m$/ft^2-hr. The coefficient 0.019 is reduced from a Colburn coefficient of 0.023, in order to represent a reasonable lower limit of experimental data (Ref 2, p 14). For hot channels it is suggested that the values of D_h and G^* be based on average and not local tolerances, since the film coefficient is used in over-all energy balance and pressure drop calculations and, therefore, should be correct on an average basis for the channel.

D_h = 0.1944 in. The hydraulic diameter is here computed for a thin rectangular channel as $4\ell_1$. Note that either D_h or the f_{iso} table may be used to consider possible flow restriction caused by warping of the fuel plates. D_h is used in Eqs (2.12) and (2.18); f_{iso} in Eqs (2.12), (2.16), and (2.17).

$\bar{\mu}$ is the viscosity to be used in Reynolds' number evaluation for determination of f_{iso}, chosen here as 0.26 lb$_m$/ft-hr.

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† Unpublished memo by R. G. Fasiczka.

K_c and K_e are the unrecoverable contraction and expansion loss coefficients for entrance and exit losses. These have been arbitrarily assigned a value of 0.5, but are generally obtained from test results (Ref 6). These coefficients may also be used to include losses in orifices located at the channel entrance and exit, or may be increased for hot channels as an alternate to K_{pf} and K_{pa} as a method for describing non-uniformities of flow pattern.

σ_o^2 and σ_n^2 are equal to the square of the area ratio at entrance and exit, or

$$\left(\frac{\text{area inside channel}}{\text{area in plenum region}}\right)^2 .$$

These quantities are used to calculate the recoverable spatial acceleration portion of the pressure drop at entrance and exit, and are arbitrarily assigned a value of one here.

K_{pf} and K_{pa} are the plenum distribution factors for friction drop and for acceleration. The nominal channel friction drop is multiplied by K_{pf} before being applied to the hot channels in parallel with it. Acceleration terms are multiplied by K_{pa}. Both values must be supplied as one for nominal channels and have been arbitrarily chosen here as 0.925 for all hot channels. The value in actual design situations can best be obtained from experimental measurements of channel-to-channel differences in pressure drop.

h_f/h is an empirical coefficient used in evaluating local boiling pressure drop. For example, the empirical approach of Ref 7, p 19 suggests that local boiling pressure drop is related to a temperature θ, computed by

$$\theta = 0.766 \frac{\phi}{h_{D-B}} , \tag{5.9}$$

where ϕ is the surface heat flux and h_{D-B} is a film coefficient computed using 0.023 rather than 0.019 in Eq (5.8). Therefore, in order to use the approach of Ref 7, in conjunction with a film coefficient calculated using 0.019,

$$(h_f/h) = \frac{(0.023)}{(0.766)(0.019)} = \frac{0.030}{0.019} = 1.58 .$$

However, this quantity has been arbitrarily assigned a value of one for the sample problem.

$G^L/G = 0.9$. Since local wide spots in a channel will cause lower local mass velocities and since such changes can affect the heat flux required for DNB, an adjustment in mass velocities is permitted for use in DNB calculations only. It is assumed here that local mass velocities may be as small as 90% of the average mass velocity. The ratio is calculated by (average channel area/maximum local channel area).

Friction Factors: Card 2041

In order to supply the empirical relationship between the isothermal friction factor and Reynolds' number (for example, see Ref 8, Fig. 1), the input on this card consists of pairs of N_R, f_{iso} coordinates. In the sample problem, values of f_{iso} at N_R = 30,000 and at 250,000 are taken to be 0.0241 and 0.0162, respectively. Additional input points are permitted for wider flow variations and a more exact description of the empirical curve. Linear interpolation on a log-log plot between sets of data is used. A linear log-log extrapolation is performed, if necessary, beyond both extremes of Reynolds' numbers. Note that, since a different f_{iso} vs N_R curve is permitted for each channel, surface roughness variations may be accounted for in the preparation of this table.

Heat Generation: Card 2051

$q/q^* = 1.0$. It is assumed that if a nuclear analysis indicates a uniform power density distribution and if all channels have nominal characteristics, then the core under consideration would have a uniform heat generation value per unit area of 100,000 Btu/ft^2-hr (Ref 9, pp 46-47). However, a nuclear analysis does predict a non-uniform power distribution, which is represented here by the F_j factors, and which may be derived directly from nuclear data. For example, the second-pass hot channel distribution is shown as an approximate step function in Fig. 3 from the more continuous distribution taken from JET output. The example shown is the power traverse at row 2, column 17 of the example in the PROP-JET report (Ref 9, p 93).

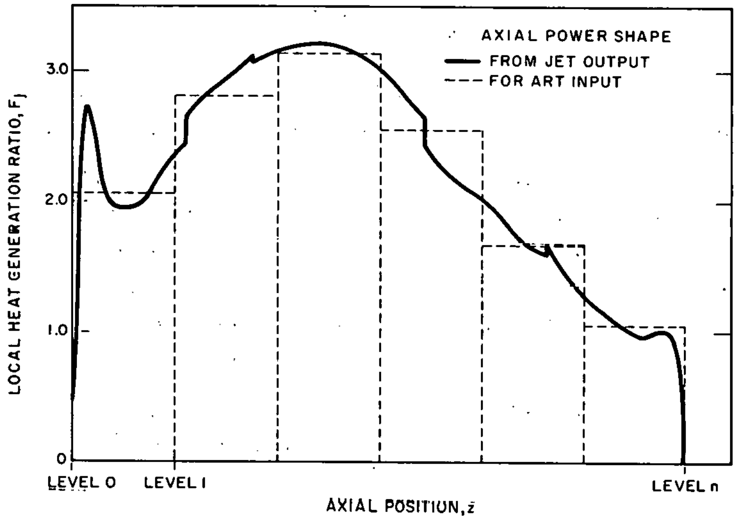

Fig. 3 Sample Axial Power Distribution

Since these JET output power values are for average mesh rectangle and not vertex power, it is appropriate here that this entire shape be multiplied by 1.15. In addition, all channels in the core are not uniform, so that some engineering hot channel factors must be added. As in Ref 9, p 47, it is assumed that the average engineering hot channel factor total heat addition to the channel is 1.2. Therefore, for channel 6, the value of q/q^* has been taken to be $1.2 \times 1.15 = 1.38$. This value appears on card 2651. Since, for nominal channels, all pointwise variations are the result of nuclear considerations, and since these are included in the F_j factors, a multiplier of q/q^* equal to one is used for nominal channels.

r is the fraction of the power which is generated in the water. It is chosen arbitrarily as 0.024. The heat generation in the water depends chiefly on the energy release by slowing neutrons and by gamma radiation absorbed in the water. (See Ref 10, p 24 for a discussion of methods in which energy is released.) The tabulation of Ref 10 indicates that thermalizing fission neutrons amount to approximately 2-1/2% of the total fission power, and total gamma release amounts to approximately 9-1/2%. However, water, other than that adjacent to the plates, thermalizes many neutrons and absorbs gamma rays. In addition, fuel plates and structural material are much more effective in absorbing gamma rays than the water. An examination of the relative slowing down and gamma absorption rates in various materials must be made for each core in order to determine r.

ϕ^L/ϕ is set to zero if no DNB calculations are needed for a specific channel. Since DNB calculations require a fairly large amount of machine time, it is recommended that they be bypassed whenever possible. When this value is nonzero, it is applied because DNB is a localized phenomena; therefore, the DNB ratio should be based on local tolerances of heat fluxes. Here, it is assumed that the local hot channel factor is 1.4 compared to an average hot channel factor of 1.2 Therefore, $\phi^L/\phi = 1.4/1.2 = 1.167$ for all hot channels.

Input Power Factor: Card 2061

F_j—see the discussion under card 2051 for the normalization of F_j chosen here. These values are taken directly from nuclear data in which the average core power is one, and in which no engineering tolerances are considered (see Fig. 3). Note that F_j is the average core power between level j-1 and level j. Note that F_o is used for DNB calculations for the first half-section of the channel. It is not used in any energy balance calculations. The value of F_o is arbitrarily assumed here to be the same as that at station one. A zero value for this quantity is permitted.

DNB Correction Factors: Card 2071

$(F_c)_j$—the DNB correction factor combines two effects. First, it contains the entrance effect on DNB heat flux. That is, the heat flux required to cause a departure from nucleate boiling is a function of channel position, in addition to enthalpy and mass velocity. Second, the $(F_c)_j$ factor is used to define the difference between the actual power shape and the step approximation. For the most recent Bettis DNB correlations, the first contribution has the form $e^{-0.0012L/S}$, where L = the distance from the inlet and S = the channel thickness (Ref 5, p 47). However, for the sample problem, this contribution to $(F_c)_j$ was assumed to have a value of 0.8 at channel 6, level 2, and other values elsewhere. The power shape contribution to the DNB correction factor was determined from examining Fig. 3. It is noted that the block approximation gives an F_j value of 2.81 for level 2. However, the detailed shape shows a value of 3.17 at the same point. Therefore, for channel 6, level 2:

$$(F_c)_2 = \frac{\text{entrance effect multiplier on DNB}}{\text{detailed power shape/block power shape}} \tag{5.10}$$

$$= \frac{0.8}{(3.17)/(2.81)} \quad .$$

Input Cards for Other Channels

Cards 2111 to 2171, 2511 to 2561, and 2611 to 2671 are quite similar to the corresponding 2000 series cards. (See the comments under the cards with the same last two digits in the 2011 to 2071 range.)

C. Pressure Drop Correlations: Cards 3011-3044

Subcooled Pressure Drop, First Kind: Card 3011

This card is eliminated here since the second kind of subcooled pressure drop correlation is used. The use of the first type of correlation is discussed in Ref 8, p 12. Note that f/f_{iso}, by this form, is always one when no local boiling is predicted (using the coefficient h_f). When local boiling is predicted, the value is either one or a value obtained by linear interpolation in temperature between one at a bulk temperature T_1 and $(1 + f_1)$ at saturation temperature.

Subcooled Pressure Drop, Second Kind: Card 3021

This card is eliminated here since the data are taken from the property tape. The development of this type of correlation is discussed in Ref 7, pp 18-22; the values which have been extracted from tape correspond to the upper limit equations given on page 22 of that report which are:

$$f/f_{iso} = F_H \left[1 + 1.2\ (0.76) \left(\frac{10^6}{G}\right)^{2/3} \psi \right] , \tag{5.11}$$

where

$$F_H = \text{smaller of } 1.05\,(1-.0025\ \theta^*) \text{ and } 1.0$$

and

$$\psi = 1 - (\theta^*/\theta) \quad .$$

Then, by comparison with Eq (2.20),

$f_3 = 0.00250,$

$f_4 = 1.05,$

$f_5 = (1.2)(0.76) = 0.912,$

and

$f_6 = 2/3 = 0.666,$

which is identical to the data extracted from the property tape.

Saturation Region Pressure Drop: Cards 3031 to 3044

These data were omitted since they were taken from the property tape. However, if supplied by cards, they would be given the following form:

3031, 0, .02, .05, .1, .2, .4

3041, .6, 1.1, 1.71, 2.45, 3.58, 5.59, 9.02

3042, 1., 1.1, 1.45,...

3043, 2., 1.1, 1.28,...

3044, 5.,...

For example, for a mass velocity of 0.6 x 10^6 lb_m/ft^2-hr and for a quality of 0.02, ϕ_{LO}^2 would be extracted from this table as 1.71. Any interpolation needed is linear in (1/G) and in quality. An extrapolation on (1/G) for mass velocities outside of the range of this table is performed. No extrapolations on quality are done, however. The values given in the preceding table are 10% above the values given in Fig. 17 of Ref 7. The factor 1.1 is chosen to obtain an upper limit for these pressure drop correlations.

D. Fluid Properties: Cards 4011 to 4031

These cards are omitted because the data were taken from the property tape. Note that if the enthalpy is below the range of this table, linear extrapolation for temperature is used. Specific volume is held constant. However, if enthalpy values exceed the maximum in this table, then saturated or superheated steam exists and the problem is stopped.

E. DNB Correlations: Cards 5011 and 5021

First Kind: Card 5011

The correlation for DNB heat flux is taken from the following Bettis design equations for 2000 psia (exclusive of inlet correction and in units of 10^6 Btu/ft^2-hr) (see Ref 5, p 39). For less than 20°F subcooling, the smaller of

$$0.60 \left(\frac{G}{10^6}\right)^{0.7} \left(\frac{H}{10^3}\right)^{-0.8} \qquad (5.12)$$

or

$$0.30 \left(\frac{H}{10^3}\right)^{-3.0} \qquad (5.13)$$

is used.

For greater than 20° subcooling,

$$0.445 \left(\frac{G}{10^6}\right)^{0.5} (T_s - T_w)^{0.22} \qquad (5.14)$$

is used where G = mass velocity (lb_m/ft^2-hr), H = bulk water enthalpy at DNB point, T_s = saturation temperature, and T_w = bulk water temperature.

By comparison with Eq (2.28),

$B_1 = 0.445$, $m_1 = 0.22$, $r_1 = 0.5$, $T_2 = T_{sat} - 20°F = 616°F$ at 2000 psia

$B_2 = 0.60$, $m_2 = 0.8$, $r_2 = 0.7$

$B_3 = 0.30$, $m_3 = 3.0$

Second Kind: Card 5021

This card is omitted since the data were taken from the property tape. This form of correlation for DNB heat flux is taken from the newer Bettis design equations for 2000 psia (exclusive of inlet correction and in units of 10^6 Btu/ft^2-hr) (Ref 5, p 47).

For $1.6 \times 10^6 \leq G \leq 5.0 \times 10^6$ lb/ft^2-hr,

$$0.240\left(\frac{H}{10^3}\right)^{-2.5}\left(1 + \frac{G}{10^7}\right)^2 \tag{5.15}$$

is used.

For $0.2 \times 10^6 \leq G \leq 1.6 \times 10^6$,

$$0.325\left(\frac{H}{10^3}\right)^{-2.5} \tag{5.16}$$

is used.

By comparison with Eq (2.29),

$B_4 = 0.325$ $\quad m_4 = 2.5$ $\quad G_1 = 1.6$

$r_5 = 2.0$ $\quad B_5 = 0.240$ $\quad m_5 = 2.5$

$C_1 = 1.0$ $\quad D_1 = 0.1$

For lower pressures, it is recommended in Ref 5, p 55 that no velocity-dependent values be used. This can be accomplished easily by setting G_1 to some very high number. The quantities r_5, B_5, m_5, C_1, and D_1 are still needed as input, and may be supplied as a value of 1.0.

F. Reactor Kinetics: Cards 6011-6041

Constants: Card 6011

α_0 is the fraction of steady-state power produced by fission product decay and is chosen here as 0.07. (See Ref 3 and Ref 10, p 24 for a discussion of fission product decay.) As is shown in Ref 3, the pre-shutdown value for fission product energy release (Mev/fission) from gamma rays is given as follows:

Mev/fission	After the following operation
5.8	one hour
6.4	10 hours
6.8	100 days
7.1	infinite operation

If it is assumed that there is, essentially, infinite operation of the reactor, that the release from beta rays is approximately equal to the gamma release, and that the total energy release of instantaneous plus decay power is 197.5 Mev per fission, then, $\alpha_0 = 2 \times 7.1/197.5 = 0.072$. The power coastdown form of the decay contribution is taken from the infinite operation curve of Ref 3, p 14. It is based on constant power for an infinite time prior to the beginning of the transient and until the scram time t_3 is reached. At time t_3, an instantaneous drop to the zero fission rate is assumed. It may be seen, in the sample problem, that the decay contribution will remain constant since there is no scram. In problems in which t_3 is used to begin withdrawal of rods, then the decay portion of the power should not be decreasing and it is suggested that α_0 be set to zero.

ℓ^* is the mean neutron lifetime, and is chosen here as 3.2×10^{-5} sec. (For details on calculating this parameter, see Refs 11 and 12.)

δK_1 is the value of reactivity resulting from control rod motion which will be maintained from the beginning of the problem up to $t = t_3$ (the scram time). Here no rod influence is desired, therefore, $\delta K_1 = 0$.

$\frac{\partial(\delta K)}{\partial T_w}$ is the temperature coefficient of reactivity. This number may be determined by the methods of Ref 12 and has been chosen here to be -2.5×10^{-4} $(°F)^{-1}$.

Neutron Precursor Constants: Card 6021, 6022

The basic information on which the choice of these delayed neutron parameters may be based is summarized in the following table:

Delayed Group No.		1	2	3	4	5	6
Keepin 1955	Rel Abund	0.036	0.210	0.192	0.409	0.135	0.018
(β = 0.0070) *	Decay Const (sec^{-1})	0.01277	0.0319	0.1181	0.318	1.507	5.33
Keepin 1958	Rel Abund	0.038	0.213	0.188	0.407	0.128	0.026
(β = 0.0065) **	Decay Const (sec^{-1})	0.0127	0.0317	0.115	0.311	1.40	3.87

---

*Ref 13
**Ref 14

The decay constant λ may be selected directly from this table. The effective yield of neutrons $\bar{\beta}_d$ in the particular group may be calculated as the product of the relative abundances in the table and the value of β listed on the left-hand side. In addition, $\bar{\beta}_d$ must be multiplied by a ratio describing the effectiveness of group d neutrons in producing fissions in a given reactor:

$$\bar{\beta}_d = \beta \text{ (relative abundance)}_d \text{ (effectiveness)}_d \quad . \tag{5.17}$$

The data from Keepin 1955 were used in the sample problem. For example, in group 4, λ is seen to be 0.318 sec^{-1} and the effectiveness of group 4 was chosen as 1.143; thus $\bar{\beta}_4 = (0.0070)\ (0.409)\ (1.143) \approx 0.003272$. Note that only the first five groups of precursors were used in the sample problem to enable the comparison of results with a similar ATBAC problem. However, there is no reason why the sixth group should not also be included, if the stability criterion mentioned under card 1011 is satisfied. Also, if temperature coefficient and rod worth are obtained from experiment, care should be taken so that the delayed neutron data and effectiveness corrections used in reducing experimental data are consistent with those used for analyzing transients. (A discussion of calculating effectiveness values is contained in Refs 11 and 12.)

Temperature Coefficient Weighting Factors: Cards 6031 and 6041

These quantities are best calculated by either an adjoint integration over various portions of the core or by running nuclear design problems with individual sections of the core increased in temperature. Care should be taken because the temperature coefficient used here is not as measured at zero power when the reflector and leakage water also change temperature. Here, only a temperature coefficient resulting from changes in the temperature of the water adjacent to the plates is desired.

In the sample problem, the second pass has arbitrarily been chosen as 1.5 times as important reactivity-wise as the first pass, and a uniform axial distribution of temperature coefficient in each pass has been assumed. Therefore, $a_j = 1/15$ for each first-pass node and 1/10 for each second-pass node point. It can be seen that these values do sum to one.

Note that only n values are given for each pass. The inlet temperature has no temperature coefficient associated with it.

G. Scram: Cards 7011 and 7021

Scram Constants: Card 7011

This card is not included since scram is not desired. If the requester desires to specify the start of scram at a particular time in a transient, the value of S_f or S_p should be set at a value less than one and the corresponding delay time should be set equal to the time of the desired entry into the scram table.

Scram Table: Card 7021

This card is not included since scram is not desired. Linear interpolation is used in this table and δK is considered positive for rod withdrawal and negative for rod insertion. If it is desired that δK should be continuous, then the first entry must be set equal to δK_1. If the last time in this table is exceeded, then the last reactivity value is maintained over the remainder of the problem.

H. Power Coastdown: Cards 8011 and 8021

This information was omitted since reactor kinetics were used. (See the next section for a discussion of the method of input.) If this table is exceeded, the power is held constant at the value of the last entry.

I. Flow Coastdown: Cards 9011-9022

Since a flow coastdown which is quite rapid at first and then decreases more slowly is being considered, the values are supplied at 0.05 sec intervals up to 0.5 sec and at 0.1 sec intervals up to 1.8 sec. This is specified by giving 10, 0.5, 13, and 1.8 on card 9011. If a parent problem is considered, the continuation time must either equal one of the end times in the table or must be greater than all end times. The flow coastdown values are calculated by $G/G_o = 1/1 + 3t$ and are also shown in Fig. 4.

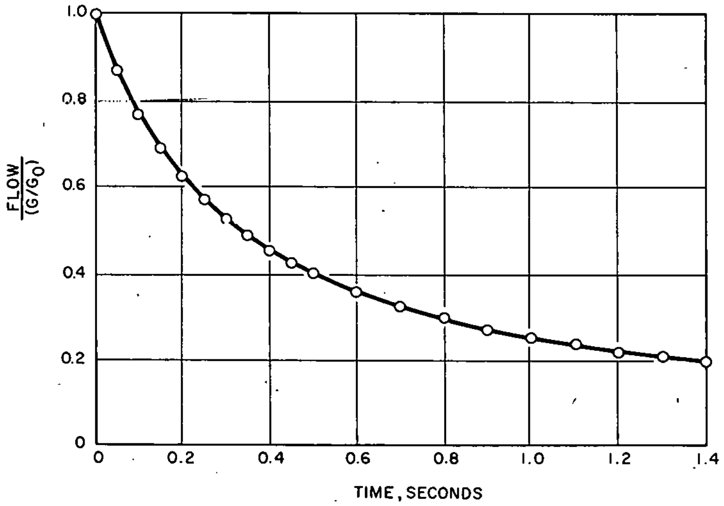

Fig. 4 Sample Forcing Function

In the general case, this flow coastdown must be calculated considering the nominal core pressure drop characteristics and also the characteristics of pump coastdown and primary-loop pressure drop.

If the table listed on card 9022 is exceeded, the last value will be used for the remainder of the problem.

J. First-Pass Inlet Temperatures: Cards 10011 and 10021

Since the first-pass inlet temperature is to be held constant, only one increment is used on card 10011, accompanied with any nonzero value for end time (subject to the same parent problem restrictions as listed under card 9011).

Two values of 500°F are given on card 10021 to indicate that this value remains constant throughout the problem. When this table is exceeded, its last entry is used throughout the remainder of the problem.

K. Second-Pass Inlet Temperatures: Card 11011

This card is used only if there is a second pass. Only 1350 first-pass exit enthalpies are stored, and after all of these have been used, the second-pass inlet temperature is held constant, again limiting the usefulness of the code to those problems of relatively short duration.

F_a is the quantity defined as the fraction of first-pass flow through the active core. It is assumed here that the average channel is used to represent the perfect mixing enthalpy of all water leaving the first pass, and that the nominal channel exit represents the average enthalpy of all water except leakage flow. Then, a more precise definition of F_a is

$$F_a = \frac{\text{(total heat release to water leaving first pass/rate water leaves first pass)}}{\text{(total heat release to nominal channel water/nominal channel flowrate)}} \quad . \tag{5.18}$$

The value chosen is 0.848. Note that this value should never be chosen equal to one, since it appears in the denominator of Eq (2.55) in such a way as to make the denominator zero.

K_o is the interpass transport time in steady-state. This value depends on core configuration and is chosen here as 4 sec.

$(B_m)_{NC}$ = o. It is assumed here that the second-pass nominal channel sees perfect mixing of the first-pass exit water. Therefore, this value is set equal to zero.

$(B_m)_{HC}$ is the quantity used to show the effect of imperfect mixing on second-pass hot channel inlet temperatures. The imperfect mixing is accounted for in ART by comparing the exit enthalpy of the nominal channel with the exit enthalpy of the average channel, and by increasing the perfect mixing value by an amount proportional to the difference of these two exit enthalpies and also proportional to B_m. Considering the two options of "mixing factor" and "crossover option" of the PROP-JET code (Ref 9), B_m can be shown to have the following forms:

Mixing Factor Option

$$(B_m)_{HC} = \frac{(F_\Delta - F_a)(1 - F_m)}{F_a} \tag{5.19}$$

where F_a is the quantity given in Eq (5.18),

$$F_\Delta = \frac{\text{(heat input first-pass hot channel/flow first-pass hot channel)}}{\text{(heat input first-pass nominal channel/flow first-pass nominal channel)}} \quad ,$$

and F_m is the mixing factor (a value of one holds for perfect mixing).

Crossover Option

If it is assumed that some limited region of the first pass has the same flow as the average channel but has a higher heat input, and if the exit water from this region goes to the inlet of the second-pass hot channel, then,

$$(B_m)_{HC} = \frac{\text{average power in limited region - average power first pass}}{\text{average power in first pass}} \quad . \tag{5.20}$$

In the sample problem, the mixing factor option was used with a mixing factor $F_m = 0.8$.

Then,

$$\frac{\text{heat input first-pass hot channel}}{\text{heat input first-pass nominal channel}} = \frac{(q/q^*)_{HC} \left\{ \sum_{j=1}^{n} F_j \right\}_{HC}}{(q/q^*)_{NC} \left\{ \sum_{j=1}^{n} F_j \right\}_{NC}}$$

$$= \frac{(1.38)\ (9.20)}{(1.0)\ (5.42)} = 2.34, \text{ and}$$

$$\frac{\text{flow first-pass nominal channel}}{\text{flow first-pass hot channel}} = \frac{(G_o)_{NC}\ (\ell_1)_{NC}}{(G_o)_{HC}\ (\ell_1)_{HC}}$$

$$= \frac{(3.0)\ (0.0485)}{(2.5)\ (0.0450)} = 1.293 \ .$$

Therefore,

$$F_\Delta = (2.34)\ (1.293) = 3.03$$

and

$$B_m = \frac{(3.03 - 0.848)\ (1 - 0.8)}{0.848} = 0.515 \ .$$

Note that (G_o) for the hot channel used in these calculations is an estimate of the first-pass hot channel flow and not the value which was obtained by the ART code in steady-state iterations. In addition, the sum of the axial power values must exclude F_o.

L. Discussion of Output

The output for the sample problem is given in Appendix II. A printout of input cards is also supplied there.

Input Print

Pages 1-5 of the output contain a printout of all input quantities as they are accepted by the machine. Any information which has been extracted from the property tape is also presented on these pages.

Steady-State Flow

The results of iterations for steady-state flow in the hot channels are given on the next page of problem output. For example, in channel 6, an initial guess for the mass velocity in steady state was 4×10^6 lb_m/ft^2-hr and the required pressure drop, considering the second-pass nominal channel, was 11.69 psi. After three iterations, a result of 3.108×10^6 for steady-state mass velocity yielded a pressure drop of 11.70 psi, which is within the required convergence criterion, permitting calculations to proceed. Since there is no iteration required for nominal channel flows, there is no change from the input value.

Transient Results

The remaining pages of problem output contain transient results. Some of these are also given in Figs. 5 and 6. The information for a given time step is begun at the start of a page. The time, power-to-flow ratio, and power are given as a preface to the remainder of the output. Scram setting information is also supplied. Following this over-all information, the output for each of the channels is given, including the flow for that channel, the pressure drop, and the minimum DNB ratio. In addition, if that particular channel has bulk boiled or has burned out, such information is supplied. Point-by-point values of water temperature, metal temperature, surface temperature, heat flux, and DNB ratio are then listed if they have been requested. Under each of these headings, point zero is listed on a separate line. The next line lists points 1 through 10, then 11 through 20, etc.

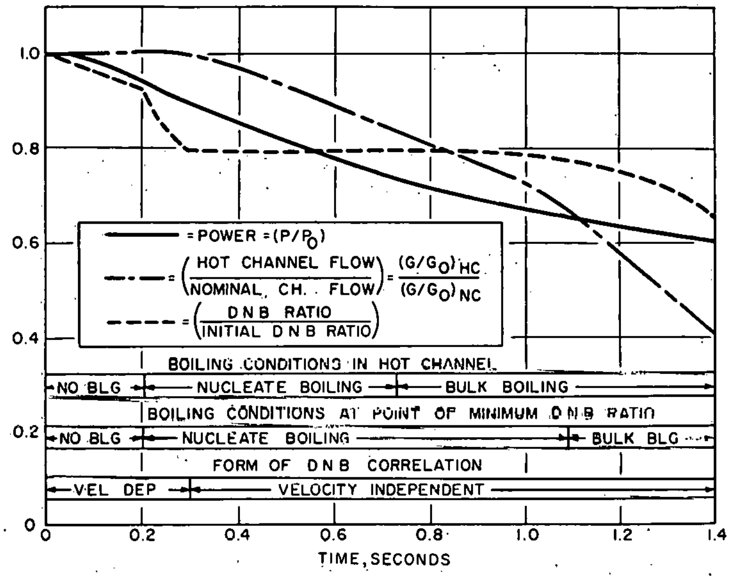

Fig. 5 Sample Output, Flow and Power Coastdown and Safety Evaluation

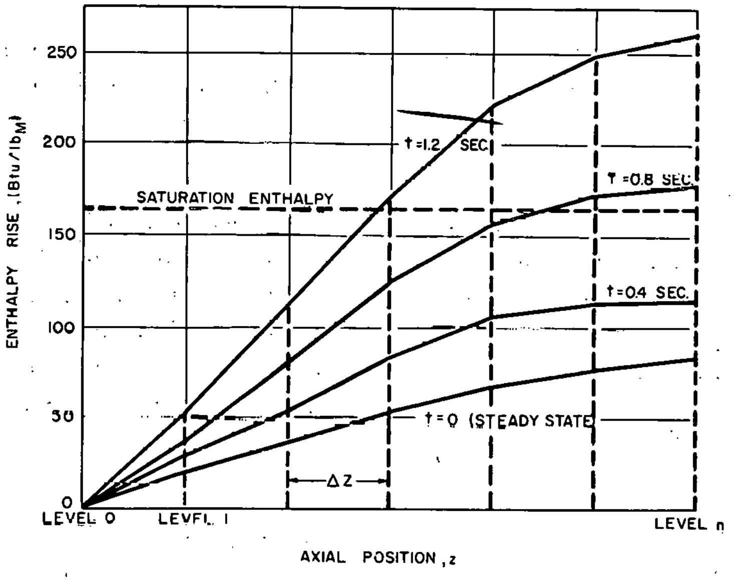

Fig. 6 Sample Output, Enthalpy Profile

VI. PROPERTY TAPE PREPARATION

The ART-01 code provides for the preparation, updating, and printing of the property tape which may be used with the ART-02 code. The user may specify that specific portions of the input data required for a problem be taken from the property tape. The property tape is basically a library of fixed data which may be requested, thereby reducing the amount of data which must be supplied with each problem.

Each file of the property tape contains six records of the following information:

Record	Information
1	Subcooled pressure drop (first kind)
2	Subcooled pressure drop (second kind)
3	Saturation region pressure drop
4	Fluid properties
5	DNB correlations (first kind)
6	DNB correlations (second kind)

No provision is made for more than one property tape. The physical length of the tape is the only restriction on the number of files which the property tape may contain.

Two sample card files are shown in Appendix III. The information was assembled by R. Pyle and P. Heiser.

A. Input Preparation

The input data deck must consist of an identification card, option control card, and as many card files as desired. Each card file terminates with a blank card. The input deck is terminated by an end-of-file condition on the computer.

The identification card must contain ART PROPERTY TAPE in columns 1 through 17, ART01 in columns 68 through 72, and columns 18 and 67 blank. Column 71 must be zero. The remaining columns may contain any additional alpha-numeric identification desired.

B. Option Control Card

The option control card is identified as 1001, comma, option specification, comma, and, in specific cases, a file number N. Where file numbers are supplied, they must not contain a decimal point.

1) 1001, 1

Option one writes an original property tape. All acceptable card files are written on tape, a duplicate copy of the tape is made, and all files on the tape are prepared on the output tape for off-line printing.

2) 1001, 2

Option two provides for updating the current property tape with additions of files of data. All acceptable card files are written on tape beginning with the appropriate file number in sequence, a duplicate copy is prepared, and the files which have been added are prepared for off-line printing.

3) 1001, 3, N

Option three is the same as option two, except that N specifies the file number for commencing the update operation.

4) 1001, 4

Option four provides for making a copy of the property tape.

5) 1001, 5, N_1, N_2, . . . , N_n $(n \le 99)$

Option five provides for preparing the specified N_i files for off-line printing. The files requested must be in ascending order. To prepare the entire tape for printing, the option specification must be as follows: 1001, 5, 0.

6) 1001, 6, N_1, N_2, . . . , N_n $(n \le 99)$

Option six provides the combined specifications of options four and five. Thus, the property tape is copied and the specified files are prepared for off-line printing.

For either options five or six the additional cards necessary to specify up to 99 files must begin with 1002, 1003, etc., but must not exceed 1100.

The control card or cards for options four, five, and six, followed by one blank card, constitute a complete input deck; whereas, the control card for options one, two, and three must be followed by the additional card files to be written on tape. Each card within a card file must contain, in columns 1 through 5, a series identification number followed by a comma. These series numbers must appear in ascending order in a file. The data must be listed immediately following the series number with a comma separating each number. Every data entry must contain a decimal point. The first blank column terminates the card. The last number on each card must not be followed by a comma.

In the following outline, the first entries of a series are typical formats for the cards, indicating the quantities which must be supplied with each pressure value. Each series must contain from two through 100 pressure values, along with their associated sets of data. Appendix III contains a brief discussion of input preparation for a sample property tape.

C. Subcooled Pressure Drop: First Kind

2001, F_{11}, F_{12}, F_{13}, F_{21}, F_{22}, F_{23}, . . . , F_{i1}, F_{i2}, F_{i3}

2002, $F_{i+1,1}$, $F_{i+1,2}$, $F_{i+1,3}$, . . . , F_{n1}, F_{n2}, F_{n3} $(2 \le n \le 100)$

⋮

where

F_{i1} = p, the i^{th} pressure psi

F_{i2} = f_1, correlation parameter

F_{i3} = T_1, correlation parameter

This series may be omitted if series 3001 is supplied. The pressure p must be an integer value, and successive values must be in ascending order.

D. Subcooled Pressure Drop: Second Kind

3001, F_{11}, F_{12}, F_{13}, F_{14}, F_{15}, . . .

3002, . . . , F_{n1}, F_{n2}, F_{n3}, F_{n4}, F_{n5} $(2 \le n \le 100)$

where

F_{i1} = p the i^{th} pressure psi

$$\left.\begin{aligned} F_{i2} &= f_3 \\ F_{i3} &= f_4 \\ F_{i4} &= f_5 \\ F_{i5} &= f_6 \end{aligned}\right\}\ \text{correlation parameters}$$

This series may be omitted if series 2001 is supplied. The pressure must be an integer value, and successive values must be in ascending order.

E. Saturation Region Pressure Drop

4001, p_1, F_1, F_2, . . . , F_n $(2 \le n \le 6)$

4002, G_{11}, $(\phi^2_{LO})_1$, . . . , $(\phi^2_{LO})_n$

4003, G_{12}, $(\phi^2_{LO})_1$, . . . , $(\phi^2_{LO})_n$

4004, G_{13}, $(\phi^2_{LO})_1$, . . . , $(\phi^2_{LO})_n$

4005, G_{14}, $(\phi^2_{LO})_1$, . . . , $(\phi^2_{LO})_n$

4011, p_2, F_1, F_2, . . . , F_n

4012 . . .

$\vdots$

where p is the pressure associated with the F_i's, which are quality values. The mass velocity G is the other index for ϕ^2_{LO}, the pointwise fit to the saturation region pressure drop function. The quality values must be in ascending order, starting with zero. There must be from one through four G values, and for each mass velocity, as many ϕ^2_{LO} values as there are quality values. The mass velocities must be nonzero and in ascending order.

All succeeding pressure groupings must contain the same number of quality and mass velocity values as supplied for the first pressure, p_1. Note that each grouping begins with the series number increased by one in the tens position. The series number for the last permissible group is 4991.

F. Fluid Properties

5001, p_1, H_1, H_2, . . . , H_n $(3 \le n \le 6)$

5002, T_1, T_2, . . . , T_n

5003, v_1, v_2, . . . , v_n

5011, p_2, H_1, H_2, . . . , H_n

5012, T_1, T_2, . . . , T_n

5013, v_1, v_2, . . . , v_n

$\vdots$

where p is the pressure value, H is the enthalpy, T is the water temperature, and v is the specific volume. All values must be in ascending order, with the exception that $T_{n-1} = T_n = T_{sat}$. The last two values of H are H_f and H_g, respectively. Similarly, the last two values of v are v_f and v_g.

All successive groupings must contain the exact number of entries as supplied with the first pressure. Each group begins with the series number increased in the tens position.

G. DNB Correlations: First Kind

6001, F_{11}, F_{12}, . . . , $F_{1,10}$

6011, F_{21}, F_{22}, . . . , $F_{2,10}$

$\vdots$

where

$F_{i1} = p$, pressure psi

$F_{i2} = B_1$, parameter mixed units

$F_{i3} = m_1$, correlation exponent

$F_{i4} = r_1$, correlation exponent

$F_{i5} = T_2$, correlation temperature °F

$F_{i6} = B_2$, parameter mixed units

$F_{i7} = m_2$, correlation exponent

$F_{i8} = r_2$, correlation exponent

$F_{i9} = B_3$, parameter mixed units

$F_{i10} = m_3$, correlation exponent

This series may be omitted if series 7001 is supplied.

H. DNB Correlations: Second Kind

7001, $F_{11}, F_{12}, \ldots, F_{19}$

7011, $F_{21}, F_{22}, \ldots, F_{29}$

⋮

where

$F_{i1} = p$, pressure psi

$F_{i2} = B_4$, parameter mixed units

$F_{i3} = m_4$, correlation exponent

$F_{i4} = G_1$, correlation mass velocity $10^6 lb_m/ft^2$-hr

$F_{i5} = r_5$, correlation exponent

$F_{i6} = B_5$, parameter mixed units

$F_{i7} = m_5$, correlation exponent

$F_{i8} = C_1$, correlation constant

$F_{i9} = D_1$, correlation constant ft^2-hr/lb_m

This series may be omitted if series 6001 is supplied.

I. Operating Instructions

1) On-line printer board: GLOUT2

2)

Tape Logic	Remarks
2	Blank for option 1; current ART property tape for options 2 through 6.
3	BCD input tape.
4	Blank. Will be a duplicate of logic 2 for options 1, 2, 3, 4, and 6.
5	BCD output tape. No rewind or end-of-file instruction is given for this tape.

3) Sense switches: Only switch 3 is used. If switch 3 is down, data should be supplied via the on-line card reader. If 3 is up, input is via tape logic 3.

4) The program operates only from binary cards; UA CSB 1 should be used to load the program deck of binary cards. When the proper printer board, tapes, and switch settings have been provided, ready the card reader and push the CLEAR and LOAD CARD buttons to begin.

5) Stops: A stop at $(7777)_8$ indicates the end of the problem. A stop at $(1111)_8$ indicates that operator intervention is requested. The on-line printer specifies the exact request. Stops below $(110)_8$ are in UA CSB 1. A $(16602)_8$ stop is in UA DBC 1 for out of range decimal data. A $(17063)_8$ stop is in UA CSH 2 for illegal punch detection.

6) Remove all tapes on the completion of a problem and label logic 2 as the ART property tape, logic 4 as a duplicate, and print tape 5 on the off-line printer.

APPENDIX I: NOMENCLATURE

Dimensions of each quantity are denoted by M = mass, L = length, θ = time, T = temperature, $F = ML/\theta^2$ = force, and $H = FL = ML^2/\theta^2$ = energy. All equations in the text are written in terms of a consistent set of units; input and output will be in mixed units.

Symbol	Description	Defining Equation	Dimensions	Input Card
a	Used in footnote explaining Eq (2.18)	--	--	--
a_j	Temperature coefficient weighting factors	(2.46)	--	6031, 6041
B_{ji}	The DNB ratio at the j^{th} axial level	(2.27)	--	--
B_m	An interpass mixing factor	(1.13), (2.53), (5.19), (5.20)	--	11011
B_u	The DNB ratio at which DNB takes place	--	--	2 x 31
B_1 to B_5	Parameters in DNB calculations	(2.28), (2.29), (5.12) - (5.16)	Mixed	5011, 5021
b	Used in footnote explaining Eq (2.18)	--	--	--
C_1	Constant in DNB correlation	(2.29), (5.15)	--	5021
c_p	Specific heat of water	(5.1)	H/MT	--
D_h	The channel hydraulic diameter	(2.12), (2.18)	L	2 x 31
D_1	Constant in DNB correlation	(2.29), (5.15)	$L^2\theta/M$	5021
DNB	Term for departure from nucleate boiling	--	--	--
F	Symbol used with subscripts to denote floating point number when describing input	Sections III and IV	--	--
F_H	Heating contribution to subcooled pressure drop	(2.20), (5.11)	--	--
F_a	Fraction of first-pass flow through the active core	(1.13), (2.53), (2.55), (5.18)	--	11011
$(F_c)_j$	Entrance effect and local power correction for DNB heat flux	(2.27), (5.10)	--	2 x 71

Symbol	Description	Defining Equation	Dimensions	Input Card
F_j	Section j power factor	(2.30), (2.37)	--	2 x 61
F_m	Mixing factor	(5.19)	--	--
F_Δ	Total hot-channel factor on enthalpy rise for first-pass hot channel	(5.19)	--	--
f	A friction factor used to predict frictional resistance to fluid flow	(2.12), (2.16) (2.17)	--	--
$(f/f_{iso})_{ji}$	Function to fit subcooled nonisothermal pressure drop	(2.19), (2.20)	--	--
$(f_{iso})_i$	Isothermal friction factor	(2.18)	--	2 x 41
f_1 to f_6	Subcooled pressure drop correlation parameters	(2.19), (2.20) (5.11)	Mixed	3011, 3021
G^*	Reference mass velocity, which equals the first estimate of steady-state hot channel mass velocity or equals the steady-state nominal channel mass velocity	(2.8)	$M/L^2\theta$	2 x 31
G	Mass velocity	(2.4)	$M/L^2\theta$	--
G_i^L	Local mass velocity	(2.26)	$M/L^2\theta$	
$(G/G_o)_i$	Mass velocity coastdown function	(2.50), (2.51)	--	9021
(G^L/G)	Local correction factor on mass velocity	(2.26)	--	2 x 31
C_1	Mass velocity in DNB correlation	(2.29), (5.15)	$M^2/L^2\theta$	5021
g	The component of the acceleration of gravity acting in the negative z-direction	(2.13)	L/θ^2	1061
H_f	Enthalpy of saturated liquid	--	H/M	4011
H_g	Enthalpy of saturated vapor	--	H/M	4011
H	Fluid enthalpy	(2.4)	H/M	--
h^*	Reference film coefficient evaluated at the mass velocity G^*	(2.8), (5.8)	$H/L^2\theta T$	2 x 31
h_{D-B}	A film coefficient used in local boiling pressure drop calculations	(5.9)	$H/L^2\theta T$	

Symbol	Description	Defining Equation	Dimensions	Input Card
h	Film coefficient	(2.8)	$H/L^2\theta T$	--
$(h_f)_i$	Film coefficient used in pressure drop calculations	(2.21), (2.22) (5.9)	$H/L^2\theta T$	--
(h_f/h)	Factor for conversion to pressure drop film coefficient	(2.22), (5.9)	--	2 x 31
K_c, K_e	Unrecoverable loss coefficients for entrance and exit	(2.12)	--	2 x 31
K_{cr}	Parameter in Jens-Lottes treatment of nucleate boiling film coefficients	(2.19), (5.7)	Mixed	1061
K_{pa}	A plenum distribution factor on acceleration terms	(2.24)	--	2 x 31
K_{pf}	A plenum distribution factor on pressure loss terms	(2.24)	--	2 x 31
K_o	The interpass transport time in steady state	(2.56)	θ	11011
k_w	Fluid thermal conductivity	(5.8)	$H/L\theta T$	--
L_{ex}	Equivalent interpass length	(2.56)	L	--
L_i	Elapsed interpass length	(2.57)	L	--
ℓ^*	Prompt neutron lifetime	(2.40), (2.43)	θ	6011
ℓ_1	Channel half-thickness	Fig. 2	L	2 x 11
ℓ_2	Clad thickness	Fig. 2	L	2 x 11
ℓ_3	Meat half-thickness	Fig. 2	L	2 x 11
ℓ_4	Equivalent plate conduction length	Fig. 2	L	2 x 11
ℓ_5	Active channel width	Fig. 2	L	--
m	Number in stability equations	(5.5), (5.6)	--	--
m_1 to m_5	Exponents in DNB correlations	(2.28), (2.29)	--	5011, 5021
N_i	Neutron power coastdown function	(2.38), (2.43)	--	--
$(N_R)_i$	Reynolds' Number	(2.18)	--	2 x 41
n	Number of axial sections	--	--	1041
$(P/P_o)_i$	Power coastdown function	(2.37), (2.38) (2.49)	--	8021
p	Fluid pressure	--	F/L^2	--
p_o	The reactor operating pressure	--	F/L^2	1061

Symbol	Description	Defining Equation	Dimensions	Input Card
(q/q^*)	Multiplier on reference	(2.30), (2.37)	--	2 x 51
q	Total heat generation rate in the j^{th} axial section per unit heat transfer area	(2.1), (2.37)	$H/L^2\theta$	--
q_{jo}	Steady-state total heat generation per unit heat transfer area	(2.30)	$H/L^2\theta$	--
q_o^*	Reference heat generation per unit heat transfer area	(2.30), (2.37)	$H/L^2\theta$	1061
r	Fraction of heat generated directly in the water	(2.1)	--	2 x 51
r_1, r_2, r_5	Exponents in DNB correlations	(2.28), (2.29), (5.12) - (5.16)	--	5011, 5021
S_f	Power-to-flow scram setting	(2.47)	--	7011
S_p	Power scram setting	(2.47)	--	7011
T_c	Local boiling surface temperature	(2.6), (2.9), (5.7)	T	--
T_m	Mean plate temperature	(1.18), (1.19), (2.1)	T	--
T_w	Bulk fluid temperature	(2.5)	T	--
T_s	Surface temperature	(2.10)	T	--
T_{sat}	Saturation temperature	--	T	4021
T_1	Temperature in subcooled pressure drop correlation	(2.19)	--	3011
T_2	Temperature in DNB correlation	(2.28), (5.14)	T	5011
t	Time from start of transient	--	θ	--
t_f	Time at which power-to-flow scram setting is reached	(2.47)	θ	--
t_p	Time at which power scram setting is reached	(2.47)	θ	
t_3	Time of scram	(2.47)	θ	--
U_i	Over-all heat transfer coefficient	(2.5), (2.7)	$H/L^2\theta T$	--
v_f	Specific volume of saturated liquid	--	L^3/M	4031

Symbol	Description	Defining Equation	Dimensions	Input Card
v_g	Specific volume of saturated vapor	--	L^3/M	4031
v	Fluid specific volume	(2.4)	L^3/M	--
X	Symbol used with subscripts to denote fixed point number when describing input	Section III	--	--
X_{ji}	Quality in the saturation region	(2.23)	--	--
z	Coordinate position measured relative to the channel inlet and directed toward the channel exit.	Fig. 2	L	--
α_o	Steady-state decay heat power fraction	(2.38)	--	6011
(α/α_o)	Decay power coastdown function	(2.38), (2.39)	--	--
$\overline{\beta}$	Total effective delayed neutron fraction	(2.40)	--	--
$\overline{\beta}_d$	Effective delayed neutron fraction, Group d	(2.40), (5.17)	--	6021
Δp_i	Total channel pressure drop	(2.11)	F/L^2	--
$(\Delta p)_s^{HC}$	Steady-state hot channel pressure drop	(2.35), (2.36)	F/L^2	--
$(\Delta p_{a1})_i$	Transient acceleration pressure drop	(2.14)	F/L^2	--
$(\Delta p_{a2})_i$	Spatial acceleration pressure drop	(2.15)	F/L^2	--
$(\Delta p_{e\ell})_i$	Elevation pressure drop	(2.13)	F/L^2	--
$(\Delta p_f)_i$	Pressure loss (friction loss plus expansion and contraction losses)	(2.12)	F/L^2	--
Δt_i	The time increment between time i and time i + 1	(5.1) - (5.6)	θ	1101
$(\Delta t_r)_i$	Time increment in the reactor kinetics equation	(2.45)	θ	--
Δz	Axial mesh increment	Fig. 1	L	1061
$(\delta K)_i$	Total excess reactivity	(2.44)	--	--
$(\delta K_r)_i$	Excess reactivity resulting from rod motion	(2.44), (2.48)	--	7021

Symbol	Description	Defining Equation	Dimensions	Input Card
$(\delta K_t)_i$	Excess reactivity resulting from temperature change	(2.44), (2.46)	--	--
δK_1	Excess reactivity prior to scram	(Para. before 2.47)	--	6011
$\partial(\delta K)/\partial T_w$	Temperature coefficient of reactivity	(2.46)	$1/T$	6011
ϵ	Convergence criterion on steady-state hot-channel pressure drop	(2.35)	--	1061
θ or θ_{ji}	Film drop used in pressure drop calculations based on the film coefficient $(h_f)_i$	(2.20), (5.9), (5.11)	T	--
θ^* or θ^*_{ji}	Actual film drop as used in pressure drop calculations	(2.19), (2.20), (5.11)	T	--
λ_c, λ_m	Conductivity of clad and meat	(1.14), (1.15), (2.6), (2.7)	H/L0T	2 x 21
λ_d	Decay constant in the dth delayed group	(2.42)	$1/\theta$	6021
$\bar{\mu}$	Mean viscosity	(2.18)	$(M/L\theta)$	2 x 31
$(\rho C)_c$	Clad heat capacity, volume basis	(2.1)	H/L^3T	2 x 21
$(\rho C)_m$	Meat heat capacity, volume basis	(2.2)	H/L^3T	2 x 21
σ_o, σ_n	Area ratios at channel entrance and exit (plenum area over channel area)	(2.15)	--	2 x 31
τ_f	Power-to-flow ratio scram delay time	(2.47)	θ	7011
τ_p	Power scram delay time	(2.47)	θ	7011
$(\phi_{BO})_{ji}$	DNB heat flux	(2.27), (2.28), (2.29)	$H/L^2\theta$	--
ϕ	Heat flux from plate to water	(2.1)	$H/L^2\theta$	--
ϕ^L_{ji}	Local heat flux	(2.25)	$H/L^2\theta$	--
$(\phi^2_{LO})_{ji}$	Function to fit saturation region pressure drop	(2.17)	--	3041
(ϕ^L/ϕ)	Local correction factor on heat flux	(2.25)	--	2 x 51
$(x_d)_i$	Normalized concentration of precursors of the dth delayed neutron group	(2.41), (2.42)	--	--

Symbol	Description	Defining Equation	Dimensions	Input Card
ψ	Parameter in subcooled pressure drop correlation	(5.11)	--	--
Superscripts:				
AC	Average channel	--	--	--
NC	Nominal channel	--	--	--
HC	Hot channel	--	--	--
(k)	Denotes the k^{th} iteration for steady-state mass velocities or the k^{th} iteration in the reactor kinetics equation	(2.35), (2.43)	--	--
Subscripts:				
a, b	Subscripts used in interpolation discussion following Eq (2.23)	--	--	--
c	Clad	--	--	--
d	Delayed neutron group number	--	--	--
ex	Conditions used in interpass mixing and transport calculations	(2.53) - (2.58)	--	--
E	Conditions in exit plenum	(1.10)	--	--
I	Conditions in inlet plenum	(1.9), (1.11)	--	--
i	Denotes conditions at the beginning of time step i (i.e., at $t = t_i = \sum_{0}^{i-1} \Delta t_i$); if i = 0, steady state is implied.	--	--	--
j	Denotes conditions at the j^{th} axial level (i.e., at $z = j\Delta z$); it is also used for the section between level j-1 and level j.	Fig. 1	--	--
m	Meat or average plate	--	--	--
n	j=n refers to conditions just inside the channel exit	--	--	--
o	i=0 refers to the conditions at the start of the transient. j=0 refers to conditions just inside the channel inlet	--	--	--

APPENDIX II: INPUT AND OUTPUT FOR A SAMPLE PROBLEM

The following pages contain a listing of input cards from the sample problem of Section V. In addition, the majority of the IBM-704 output for this problem is given.

Pages 1-5 of the output give a complete listing of input quantities as accepted by the machine, including that information extracted from property tape. Page 6 gives steady-state results and pages 7, 10, and 13 give results for three different times during the transients. As is noted in the input, additional transient output was printed for times 0.2, 0.4, 0.8, 1.0, and 1.4 seconds. This particular problem stopped when point 6 in channel 6 reached a quality of 41% at time = 1.46 sec. Since this quality is out of the range of the specified saturation region pressure drop data, the problem was discontinued at that time. Further discussion of the output to this problem is given in Section V.

```
XXXXXXXX   SAMPLE PROBLEM FOR WAPD-TM-156                               ART02CARD 001
1011,.02,10,1.8                                                              CARD 002
1021,6,2,1,1                                                                 CARD 003
1031,2,1,1,1,1                                                               CARD 004
1041,2,2,2                                                                   CARD 005
1051,1,0,0,0,1,0,1,1,1,1,1,1                                                 CARD 006
1061,2000.,.1,7.21,32.17,.005,6.2,.4                                         CARD 007
2011,.0485,.018,.042,.018                                                    CARD 008
2021,0,33.2,8.1                                                              CARD 009
2031,1.5,3.,5486.,.1944,.26,.5,.5,1.,1.,1.,1.,1.,.9                          CARD 010
2041,3E4,.0241,2.5E5,.0162                                                   CARD 011
2051,1.,.024.0                                                               CARD 012
2061,.82,.82.1.09,1.18,1.06,.79,.48                                          CARD 013
2111,.0450,.015,.043,.015                                                    CARD 014
2121,0,33.2,8.1                                                              CARD 015
2131,1.5,3.,6587.,.180,.26,.6025,.6025,1.,1.,.925,.925,1.,.9                 CARD 016
2141,3E4,.0252,2.5E5,.0175                                                   CARD 017
2151,1.38,.024,1.167                                                         CARD 018
2161,1.39,1.39,1.8,1.98,1.8,1.38,.85                                         CARD 019
2171,.783,.783,.714,.8,.87,.75,.625                                          CARD 020
2511,.0485,.018,.042,.018                                                    CARD 021
2521,0,33.2,8.1                                                              CARD 022
2531,1.5,4.0,8170.,.1944,.26,.5,.5,1.,1.,1.,1.,1.,.9                         CARD 023
2541,3E4,.0241,2.5E5,.0162                                                   CARD 024
2551,1.,.024,0                                                               CARD 025
2561,1.16,1.16,1.48,1.62,1.23,.77,.45                                        CARD 026
2611,.045,.015,.043,.015                                                     CARD 027
2621,0,33.2,8.1                                                              CARD 028
2631,1.5,4.,8297.,.180,.26,.6851,.6851,1.,1.,.925,.925,1.,.9                 CARD 029
2641,3E4,.0252,2.5E5,.0175                                                   CARD 030
2651,1.38,.024,1.167                                                         CARD 031
2661,2.06,2.05,2.81,3.14,2.55,1.66,1.05                                      CARD 032
2671,.75,.75,.708,.525,1.025,.759,.632                                       CARD 033
6011,.07,3.2E-5,0,-2.5E-4                                                    CARD 034
6021,.000288,.01277,.01650,.03190,.001535,.1181,.003272,.318                 CARD 035
6022,.001080,1.507                                                           CARD 036
6031,.0667,.0666,.0667,.0667,.0666,.0667                                     CARD 037
6041,.1,.1,.1..1,.1,.1                                                       CARD 038
9011,10,.5,13.1.8                                                            CARD 039
9021,1.00,.870,.769,.690,.625,.571,.526,.488,.454,.426                       CARD 040
9022,.400,.357,.323,.294,.270,.250,.233,.217,.204,.192                       CARD 041
9023,.182,.172,.164,.156                                                     CARD 042
10011,1,.02                                                                  CARD 043
10021,500.,500.                                                              CARD 044
11011,.848,4.0,0,.515                                                        CARD 045
                                                                             CARD 046
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                                    XXXXXXXX   SAMPLE PROBLEM FOR WAPD-TM-156                          ART02  PAGE    1


   A. CONTROL INFORMATION

        TIME INCREMENTS  .020  10  1.80

           PROBLEM SIZE   6 SECTIONS   2 PASS(ES)   1 HOT CHANNEL(S) 1ST PASS   1 HOT CHANNEL(S) 2ND PASS

              DATA TAPE  FILE  2, SUB DELTA P(TAPE) SAT DELTA P(TAPE) FL PROP(TAPE) BO COR(TAPE)

          INPUT OPTIONS  DELTA P KIND 2, BCR KIND 2, HEAT GEN TYPE 2

         OUTPUT OPTIONS     WATER TEMP/QUAL  METAL TEMP  SURF TEMP  CRIT TEMP  HEAT FLUX  BO RATICS
                         NC      YES               NO          NO          NO          YES       NO
                         HC      YES               YES         YES         YES         YES       YES

     OVERALL CONDITIONS  P.0=2000  Q*.0=.1000  K.CR= 7.21  G=32.17  EPS=.005  DELTA Z= 6.200  PBS=  .40
```

```
                              XXXXXXXX   SAMPLE PROBLEM FOR WAPD-TM-156                        ART02  PAGE    2
  B. INDIVIDUAL CHANNEL CHARACTERISTICS
                CHANNEL  0
             DIMENSIONS  L.1=.0485  L.2=.0180  L.3=.0420  L.4=.0180
       METAL PROPERTIES  RHOC.C=  .00  RHOC.M=33.20  LAMDA.C= 8.10
         FLOW CHARACTER  B.U=1.500  G*=3.000  H*= 6486  D.H=.1944  MUBAR=.260
                         K.C= .500  K.E= .500  SIGSQ.0=1.000  SIGSQ.N=1.000  K.PF=1.000  K.PA=1.000
                         H.F/H=1.000  GL/G= .900
       FRICTION FACTORS  (N.R, F.ISO)   30000, .0241  250000, .0162
        HEAT GENERATION  Q/Q*=1.000  R=.024  PHIL/PHI= .000
                    F.J   .820
                          .820  1.090  1.180  1.060   .790   .480
                CHANNEL  1
             DIMENSIONS  L.1=.0450  L.2=.0150  L.3=.0430  L.4=.0150
       METAL PROPERTIES  RHOC.C=  .00  RHOC.M=33.20  LAMDA.C= 8.10
         FLOW CHARACTER  B.U=1.500  G*=3.000  H*= 6587  D.H=.1800  MUBAR=.260
                         K.C= .602  K.E= .602  SIGSQ.0=1.000  SIGSQ.N=1.000  K.PF= .925  K.PA= .925
                         H.F/H=1.000  GL/G= .900
       FRICTION FACTORS  (N.R, F.ISO)   30000, .0252  250000, .0175
        HEAT GENERATION  Q/Q*=1.380  R=.024  PHIL/PHI=1.167
                    F.J  1.390
                         1.390  1.800  1.980  1.800  1.380   .850
                   FC.J   .783
                          .783   .714   .800   .870   .750   .625
```

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                                    XXXXXXXX   SAMPLE PROBLEM FOR WAPD-TM-156                 ART02  PAGE    3

          CHANNEL  5

       DIMENSIONS  L.1=.0485  L.2=.0180  L.3=.0420  L.4=.0180

 METAL PROPERTIES  RHOC.C=  .00  RHOC.M=33.20  LAMDA.C= 8.10

   FLOW CHARACTER  B.U=1.500  G*=4.000  H*= 8170  D.H=.1944  MUBAR=.260

                   K.C= .500  K.E= .500  SIGSQ.0=1.000  SIGSQ.N=1.000  K.PF=1.000  K.PA=1.000

                   H.F/H=1.000  GL/G= .900

 FRICTION FACTORS  (N.R, F.ISO)   30000, .0241  250000, .0162

  HEAT GENERATION  Q/Q*=1.000  R=.024  PHIL/PHI= 1.000

              F.J  1.160
                   1.160  1.480  1.620  1.230   .770   .450

          CHANNEL  6

       DIMENSIONS  L.1=.0450  L.2=.0150  L.3=.0430  L.4=.0150

 METAL PROPERTIES  RHOC.C=  .00  RHOC.M=33.20  LAMDA.C= 8.10

   FLOW CHARACTER  B.U=1.500  G*=4.000  H*= 8297  D.H=.1800  MUBAR=.260

                   K.C= .685  K.E= .685  SIGSQ.0=1.000  SIGSQ.N=1.000  K.PF= .925  K.FA= .925

                   H.F/H=1.000  GL/G= .900

 FRICTION FACTORS  (N.R, F.ISO)   30000, .0252  250000, .0175

  HEAT GENERATION  Q/Q*=1.380  R=.024  PHIL/PHI=1.167

              F.J  2.060
                   2.060  2.810  3.140  2.550  1.660  1.050

             FC.J   .750
                    .750   .708   .825  1.026   .759   .632
```

```
                                      XXXXXXXX   SAMPLE PROBLEM FOR WAPD-TM-156                          ART02  PAGE    4
  C. PRESSURE DROP CORRELATIONS

   SUBCOOLED DELTA P, 2ND KIND   F.3=.00250  F.4=1.050  F.5= .912  F.6= .666

    SATURATION DELTA P    G   X= .000     .020     .050     .100     .200     .400
                        .600     1.10     1.71     2.45     3.58     5.59     9.02
                       1.000     1.10     1.45     1.86     2.45     3.42     4.95
                       2.000     1.10     1.28     1.49     1.76     2.15     2.64
                       5.000     1.10     1.21     1.31     1.43     1.58     1.78

  D. FLUID PROPERTIES

               ENTHALPY  377.0    474.6    552.7    630.9    671.7   1135.1

            TEMPERATURE  400.0    489.0    554.0    611.0    635.8    635.8

        SPECIFIC VOLUME  .01844   .01992   .02156   .02385   .02567   .18780

  E. BURNOUT CORRELATIONS

     BURNOUT, 2ND KIND    B.4      M.4     G.1      R.5      B.5      M.5     C.1      D.1
                          .325    2.500   1.600    2.000     .240    2.500   1.000     .100

  F. HEAT GENERATION (REACTOR KINETICS, NO SCRAM)

       REACTOR KINETICS  .0700   .0000320    .000000   -.000250

               BETA BAR  .000288   .001680   .001536   .003272   .001080

                  LAMDA   .01277    .03190    .11810    .31800   1.50700

          1ST PASS A.J   .0667   .0666   .0667   .0667   .0666   .0667

          2ND PASS A.J   .1000   .1000   .1000   .1000   .1000   .1000

  G. FLOW COASTDOWN

          FLOW    TIME     .000     .050     .100     .150     .200     .250     .300     .350     .400     .450
                 G/G.0   1.0000    .8700    .7690    .6900    .6250    .5710    .5260    .4880    .4540    .4260

                  TIME     .500     .600     .700     .800     .900    1.000    1.100    1.200    1.300    1.400
                 G/G.0    .4000    .3570    .3230    .2940    .2700    .2500    .2330    .2170    .2040    .1920

                  TIME    1.500    1.600    1.700    1.800
                 G/G.0    .1820    .1720    .1640    .1560
```

```
                                   XXXXXXXX   SAMPLE PROBLEM FOR WAPD-TM-156                         ART02  PAGE     5
   H. INLET TEMPERATURES

        PASS ONE   TIME     .000     .020
               T.IN NC  500.0    500.0
               T.IN HC  500.0    500.0

        PASS TWO          F.A= .848  K.0=4.000  B.M(NC)=.000  B.M(HC)=.515
```

```
                           XXXXXXXX   SAMPLE PROBLEM FOR WAPD-TM-156                        ART02  PAGE    6
STEADY STATE FLOW

            CHANNEL  G.*     G.0    NR ITER  DELTA P.S  ITER P.S
               0     3.C00   3.000              7.679      7.679
               1     3.000   2.631     3        7.182      7.193
               5     4.000   4.000             12.554     12.[illegible]
               6     4.000   3.408     3       11.690     11.[illegible]


TRANSIENT RESULTS START ON NEXT PAGE
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                                   XXXXXXXX   SAMPLE PROBLEM FOR WAPD-TM-156                           ART02  PAGE    7
TIME=  .000  P/F=  1.000  P=  1.000  P/F SET AT T=        P SET AT T=        SCRAM SET AT T=T.3=
   CHANNEL 0  G/G.0= 1.0000  G= 3.000  DELTA P=  6.229 BOR=        AT J=    BULK BOIL AT T=        BURNOUT AT T=

     WATER TEMP-QUAL  500.00
                      502.91   506.77   510.95   514.72   517.52   519.22
           HEAT FLUX   .0800
                       .0800    .1064    .1152    .1035    .0771    .0468
   CHANNEL 1  G/G.0= 1.0000  G= 2.631  DELTA P=  5.840 BOR=  4.721 AT J= 3  BULK BOIL AT T=        BURNOUT AT T=

     WATER TEMP-QUAL  500.00
                      508.36   519.19   531.10   541.92   550.22   555.17
          METAL TEMP  560.46
                      568.82   597.48   617.22   620.22   610.25   592.14
        SURFACE TEMP  531.57
                      539.93   560.07   576.07   582.81   581.57   574.48
           CRIT TEMP  640.56
                      640.56   640.88   541.00   640.88   640.55   640.01
           HEAT FLUX   .1872
                       .1872    .2424    .2667    .2424    .1859    .1145
   CHANNEL 5  G/G.0= 1.0000  G= 4.000  DELTA P= 10.621 BOR=        AT J=    BULK BOIL AT T=        BURNOUT AT T=

     WATER TEMP-QUAL  516.30
                      519.39   523.32   527.53   530.90   532.95   534.15
           HEAT FLUX   .1132
                       .1132    .1444    .1581    .1200    .0752    .0439
   CHANNEL 6  G/G.0= 1.0000  G= 3.408  DELTA P=  9.902 BOR=  2.891 AT J= 3  BULK BOIL AT T=        BURNOUT AT T=

     WATER TEMP-QUAL  524.69
                      534.26   547.31   560.91   571.28   578.03   582.30
          METAL TEMP  605.53
                      615.09   657.57   684.12   671.34   643.17   623.51
        SURFACE TEMP  562.71
                      572.28   599.17   613.86   618.34   608.67   601.68
           CRIT TEMP  641.05
                      641.05   641.48   641.63   641.34   640.78   640.24
           HEAT FLUX   .2775
                       .2775    .3785    .4229    .3435    .2236    .1414
```

```
                                    XXXXXXXX   SAMPLE PROBLEM FOR WAPD-TM-156                        ART02  PAGE   10
TIME=  .600  P/F=  2.193  P=   .783  P/F SET AT T=           P SET AT T=          SCRAM SET AT T=T.3=
   CHANNEL 0  G/G.0=  .3570  G= 1.071  DELTA P=  1.839 BOR=         AT J=    BULK BOIL AT T=         BURNOUT AT T=

     WATER TEMP-QUAL  500.00
                      505.62  512.64  519.72  525.44  528.88  529.98
           HEAT FLUX   .0601
                       .0585   .0763   .0810   .0707   .0502   .0276

   CHANNEL 1  G/G.0=  .3651  G=  .960  DELTA P=  1.779 BOR=  5.334 AT J= 3  BULK BOIL AT T=         BURNOUT AT T=

     WATER TEMP-QUAL  500.00
                      515.57  534.41  553.70  567.70  576.54  579.62
          METAL TEMP  574.25
                      587.51  625.50  651.70  654.99  640.61  615.50
        SURFACE TEMP  552.71
                      566.54  599.07  623.27  629.66  622.02  605.09
           CRIT TEMP  640.24
                      640.20  640.47  640.55  640.42  640.08  639.51
           HEAT FLUX   .1396
                       .1352   .1713   .1842   .1641   .1204   .0675

   CHANNEL 5  G/G.0=  .3570  G= 1.428  DELTA P=  2.477 BOR=         AT J=    BULK BOIL AT T=         BURNOUT AT T=

     WATER TEMP-QUAL  516.30
                      522.48  530.00  537.80  543.04  545.51  546.14
           HEAT FLUX   .0864
                       .0846   .1062   .1143   .0838   .0489   .0251

   CHANNEL 6  G/G.0=  .3166  G= 1.079  DELTA P=  2.368 BOR=  2.311 AT J= 3  BULK BOIL AT T=         BURNOUT AT T=

     WATER TEMP-QUAL  524.69
                      544.29  570.14  596.40  614.90  623.00  623.99
          METAL TEMP  624.66
                      641.02  687.86  693.93  683.77  668.18  655.77
        SURFACE TEMP  593.69
                      611.05  641.17  641.34  641.06  640.52  639.87
           CRIT TEMP  640.66
                      640.62  641.17  641.34  641.06  640.52  639.87
           HEAT FLUX   .2007
                       .1942   .3025   .3408   .2768   .1793   .1030
```

```
                              XXXXXXXX   SAMPLE PROBLEM FOR WAPD-TM-156                     ART02  PAGE   13

TIME= 1.200  P/F=  2.941  P=   .638  P/F SET AT T=         P SET AT T=        SCRAM SET AT T=T.3=

   CHANNEL 0  G/G.0=  .2170  G=  .651  DELTA P=  1.355 BOR=          AT J=    BULK BOIL AT T=         BURNOUT AT T=

     WATER TEMP-QUAL  500.00
                      507.67  517.29  527.04  534.94  539.71  541.22
            HEAT FLUX  .0494
                       .0482   .0629   .0567   .0582   .0411   .0222

   CHANNEL 1  G/G.0=  .2100  G=  .552  DELTA P=  1.331 BOR=  4.988 AT J= 3  BULK BOIL AT T=         BURNOUT AT T=

     WATER TEMP-QUAL  500.00
                      521.33  547.04  574.64  596.60  610.29  610.87
           METAL TEMP 582.80
                      601.45  648.47  667.27  664.74  658.74  646.48
         SURFACE TEMP 565.58
                      584.79  627.38  640.48  640.37  640.08  639.08
            CRIT TEMP 640.00
                      639.95  640.21  640.48  640.37  640.08  639.21
            HEAT FLUX  .1116
                       .1080   .1367   .1736   .1579   .1209   .0480

   CHANNEL 5  G/G.0=  .2170  G=  .868  DELTA P=  1.598 BOR=          AT J=    BULK BOIL AT T=         BURNOUT AT T=

     WATER TEMP-QUAL  516.30
                      524.69  534.94  545.64  552.91  556.16  557.04
            HEAT FLUX  .0708
                       .0694   .0873   .0941   .0690   .0407   .0210

   CHANNEL 6  G/G.0=  .1253  G=  .429  DELTA P=  1.555 BOR=  2.167 AT J= 5  BULK BOIL AT T=  .720  BURNOUT AT T=

     WATER TEMP-QUAL  524.59
                      560.84  603.26   .0235   .1329   .1904   .2121
           METAL TEMP 652.52
                      668.16  678.94  683.55  675.30  662.76  654.02
         SURFACE TEMP 629.95
                      640.51  640.91  641.05  640.79  640.28  639.80
            CRIT TEMP 640.30
                      640.51  640.91  641.05  640.79  640.28  639.80
            HEAT FLUX  .1463
                       .1791   .2465   .2734   .2237   .1456   .0922
```

APPENDIX III: SAMPLE ART PROPERTY TAPE

The input to a sample ART property tape is listed on the following pages. In addition, a listing of the data as accepted and as labeled by the IBM-704 is also presented. Two files of data have been prepared in this sample problem. The first contains information needed for analyzing problems below 1850 psia. The second contains data for 1850 psia and above. Since some of the data is identical in both files, several pages of output have not been reproduced here. Note that data file 2 was used for the sample problem listed in Appendix II.

A. Subcooled Pressure Drop: First Kind

The data of file 1 from 1100 to 1850 psi are taken from Ref 8, pp 12-13. The results for lower pressures are determined by setting $T_1 = T_{sat} - 76°F$ and requiring that $1 + f_1$ = the Martinelli-Nelson value (Ref 17) of ϕ^2_{LO} at 4.2% quality. This latter technique is discussed in Ref 16. File 2 contains no subcooled pressure drop correlation of the first kind.

B. Subcooled Pressure Drop: Second Kind

File 1 contains no data for this kind of pressure drop correlation. File 2 contains the upper limit equations of Ref 8, p 11. The development of this form of correlation is discussed in Ref 7.

C. Saturation Region Pressure Drop

File 1 contains the velocity-independent values presented by Martinelli and Nelson in Ref 17. These values, however, have been multiplied by 1.3 to attempt to account for uncertainties in this correlation (since the hotter channels are the only ones boiling, this alteration tends to be conservative). File 2 contains the velocity-dependent values of Shcr (Ref 7). These values have been multiplied by 1.1 to account for uncertainties in the correlation. The values listed for 1850 psia are the 2000 psia values of Ref 7 multiplied by the ratio of Martinelli-Nelson values at the two pressures and at corresponding qualities. This procedure is as recommended in Ref 8.

D. Fluid Properties

Identical information on fluid properties has been supplied for file 1 and file 2 and was obtained from Keenan and Keyes (Ref 18). The values for v_g, H_f, H_g, and T_{sat} vs pressure were obtained directly from tabulated values of Keenan and Keyes. The v_f was obtained from Eq (18), p 21 of Ref 18. The relationship between specific volume and temperature in the subcooled region was obtained by using a graph of the quantity $v - v_f$ from the compressed liquid table of Ref 18, p 74 and by using the v_f obtained from Eq (18) on p 21 of Ref 18. The relationship between enthalpy and temperature was obtained from the graph $H - H_f$, also from the compressed liquid table of Ref 18, combined with the H_f values of the steam table tabulation.

To obtain an optimized fit in the subcooled region, the following technique was used. For each pressure, some convenient low end point in temperature (either 200°F, 300°F, or 400°F) was chosen. The enthalpy vs temperature and specific volume vs temperature relationships were then fit by a least squares technique using a single straight line over the entire range of temperature from this lower end point up to the saturation temperature. The deviations from this straight line were then plotted vs temperature for both enthalpy and specific volume, and three convenient breakpoints for further straight line fits were determined by eye. The choice of these three intermediate temperatures between the lowest temperature and the saturation temperature defined four regions for a straight line fit by a least squares technique. The intersection of these subregion straight lines were then used as the input for the ART property tape. Some small adjustments were needed so that both enthalpy and specific volume lines intersect at the same temperature.

E. DNB Correlations: First Kind

Both file 1 and file 2 contain the values of B_1, m_1, and r_1 obtained from the correlation by Jens and Lottes (Ref 2) of UCLA DNB data of Ref 15. Also see page 52 of Ref 2. The value of T_2 was chosen at 20° subcooling as in Ref 5, p 39. The values of B_2 through m_3 are as used in the former Bettis design equation for 2000 psia (Eq V-2, V-3 in Ref 5, p 39).

F. DNB Correlations: Second Kind

The quantities B_4 and m_4 were obtained from Ref 5, Eq VI-13, and include pressure corrections to the quantities obtained from that reference. G_1 is set at 10.0 to prevent operation of the velocity-dependent part of the DNB correlations. The remaining values are therefore arbitrary, but have been set at the 2000 psia values of Ref 5, Eq VI-6. The high pressure correlations of file 2 have been taken directly from the design Eqs VI-5 and VI-6 of Ref 5, p 47.

```
ART PROPERTY TAPE        JULY 24, 1958       FILES 1 AND 2.          ART01 ID CARD
1001,1                                                                     OP CARD
2001,05E2,3.348,391.01                                                    FILE1001
2002,06E2,2.804,410.21                                                    FILE1002
2003,07E2,2.420,427.10                                                    FILE1003
2004,08E2,2.117,442.23                                                    FILE1004
2005,09E2,1.677,455.98                                                    FILE1005
2006,10E2,1.638,468.61                                                    FILE1006
2007,11E2,1.493,480.31                                                    FILE1007
2008,12E2,1.319,491.22                                                    FILE1008
2009,13E2,1.169,501.46                                                    FILE1009
2010,14E2,1.070,511.10                                                    FILE1010
2011,15E2,0.981,520.23                                                    FILE1011
2012,16E2,0.880,528.90                                                    FILE1012
2013,17E2,0.790,537.15                                                    FILE1013
2014,18E2,0.738,545.00                                                    FILE1014
2015,1849.,.719,548.81                                                    FILE1015
4001,100.,0,.05,.2,.4,.8,1.                                               FILE1016
4002,1.,1.3,18.2,66.95,144.3,274.3,198.9                                  FILE1017
4011,250.,0,.05,.2,.4,.8,1.                                               FILE1018
4012,1.,1.3,10.14,34.58,65.,115.7,85.67                                   FILE1019
4021,5E2,0,.05,.2,.4,.8,1.                                                FILE1020
4022,1.,1.3,6.24,20.02,36.27,62.4,44.2                                    FILE1021
4031,750.,0,.05,.2,.4,.8,1.                                               FILE1022
4032,1.,1.3,4.68,13.76,24.83,42.77,29.12                                  FILE1023
4041,1E3,0,.05,.2,.4,.8,1.                                                FILE1024
4042,1.,1.3,3.8,10.34,18.33,31.20,21.06                                   FILE1025
4051,1250.,0,.05,.2,.4,.8,1.                                              FILE1026
4052,1.,1.3,3.25,8.06,13.78,22.75,16.12                                   FILE1027
4061,15E2,0,.05,.2,.6,.9,1.                                               FILE1028
4062,1.,1.3,2.86,6.37,14.04,16.9,12.61                                    FILE1029
4071,1750.,0,.05,.2,.6,.9,1.                                              FILE1030
4072,1.,1.3,2.5,5.08,10.53,12.61,10.21                                    FILE1031
4081,1849.,0,.05,.2,.6,.9,1.                                              FILE1032
4082,1.,1.3,2.39,4.73,9.59,11.57,9.4                                      FILE1033
5001,1E2,168.15,200.38,243.02,270.68,298.40,1187.2                        FILE1034
5002,200.,232.,275.,301.,327.81,327.81                                    FILE1035
5C03,.0166257,.0168532,.017209,.0174538,.0177375,4.432                    FILE1036
5011,150.,168.29,212.63,259.45,301.77,330.51,1194.1                       FILE1037
5012,200.,244.,290.,331.,358.42,358.42                                    FILE1038
5013,.0166237,.0169441,.0173443,.0177658,.0180898,3.015                   FILE1039
5021,2E2,269.79,290.44,311.24,332.24,355.36,1198.4                        FILE1040
5022,3E2,320.,340.,360.,381.79,381.79                                     FILE1041
5023,.017439,.0176443,.0178664,.0181055,.0183871,2.288                    FILE1042
5031,250.,269.89,290.51,321.78,353.51,376.,1201.1                         FILE1043
5032,3E2,320.,350.,380.,400.95,400.95                                     FILE1044
5033,.0174329,.0176376,.0179765,.018357,.0186517,1.8438                   FILE1045
5041,3E2,269.99,302.02,332.39,365.35,393.84,1202.8                        FILE1046
5042,3E2,331.,360.,391.,417.33,417.33                                     FILE1047
5043,.017429,.0177501,.0180915,.0185006,.0188947,1.5433                   FILE1048
5051,350.,270.09,295.95,343.05,385.88,409.69,1203.9                       FILE1049
5052,3E2,326.0,370.0,410.0,431.72,431.72                                  FILE1050
5053,.0174259,.0176940,.0182133,.0187729,.0191222,1.3260                  FILE1051
5061,4E2,270.19,319.95,364.38,394.66,424.0,1204.5                         FILE1052
5062,3E2,348.0,390.0,418.0,444.59,444.59                                  FILE1053
5063,.0174219,.0179365,.0184753,.0188879,.0193379,1.1613                  FILE1054
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5071,450.,270.29,319.02,365.55,396.86,437.2,1204.6                       FILE1055
5072,3E2,347.0,391.0,420.0,456.28,456.28                                FILE1056
5073,.0174179,.0179216,.0184828,.0189115,.0195450,1.0320                FILE1057
5081,5E2,270.39,319.1,366.69,407.85,449.4,1204.4                        FILE1058
5082,3E2,347.0,392.0,430.0,457.01,467.01                                FILE1059
5083,.0174140,.0179175,.0184919,.0190662,.0197452,.9278                 FILE1060
5091,6E2,270.57,323.43,383.99,432.46,471.6,1203.2                       FILE1061
5092,3E2,351.0,408.0,452.0,486.21,486.21                                FILE1062
5093,.0174060,.0179551,.0187115,.0194359,.0201306,.7698                 FILE1063
5101,7E2,270.75,323.59,388.43,450.66,491.5,1201.2                       FILE1064
5102,3E2,351.0,412.0,468.0,503.10,503.10                                FILE1065
5103,.0173999,.0179462,.0137601,.0197242,.0205026,0.6554                FILE1066
5111,8E2,375.59,410.33,457.5,487.8,509.7,1198.6                         FILE1067
5112,4E2,432.0,474.0,500.0,518.23,518.23                                FILE1068
5113,.0185731,.0190645,.0198303,.0204043,.0208665,0.5687                FILE1069
5121,9E2,375.71,408.25,454.1,492.5,526.6,1195.4                         FILE1070
5122,4E2,430.0,471.0,504.0,531.98,531.98                                FILE1071
5123,.0185621,.0190197,.0197578,.0204879,.0212266,0.5006                FILE1072
5131,1E3,375.83,428.0,477.1,527.1,542.4,1191.8                          FILE1073
5132,4E2,448.0,491.0,533.0,544.61,544.61                                FILE1074
5133,.0185511,.0193127,.0201617,.0212211,.0215861,0.4456                FILE1075
5141,1050.,375.87,427.0,477.1,525.1,550.0,1189.9                        FILE1076
5142,4E2,447.0,491.0,531.0,550.57,550.57                                FILE1077
5143,.0185461,.0192883,.0201537,.0211620,.0217665,0.4218                FILE1078
5151,11E2,375.92,427.61,478.20,526.4,557.4,1187.8                       FILE1079
5152,4E2,448.0,492.0,532.0,556.31,556.31                                FILE1080
5153,.0185421,.0193007,.0201669,.0211662,.0219475,0.4001                FILE1081
5161,12E2,375.07,449.5,499.6,547.8,571.7,1183.4                         FILE1082
5162,4E2,467.0,510.0,549.0,567.22,567.22                                FILE1083
5163,.0185311,.0196340,.0205592,.0216573,.0223131,0.3619                FILE1084
5171,13E2,376.17,430.9,497.1,550.2,585.4,1178.6                         FILE1085
5172,4E2,451.0,508.0,551.0,577.46,577.46                                FILE1086
5173,.0185206,.0193241,.0204880,.0216698,.0226853,0.3293                FILE1087
5181,14E2,375.32,430.9,501.8,576.3,598.7,1173.4                         FILE1088
5182,4E2,451.0,512.0,571.0,587.10,587.10                                FILE1089
5183,.0185101,.0193051,.0205613,.0223200,.0230658,0.3012                FILE1090
5191,15E2,376.42,431.9,497.0,555.3,611.6,1167.9                         FILE1091
5192,4E2,452.0,508.0,555.0,596.23,596.23                                FILE1092
5193,.0184961,.0193059,.0204435,.0217390,.0234573,0.2765                FILE1093
5201,16E2,376.52,451.6,521.1,578.7,624.1,1162.1                         FILE1094
5202,4E2,469.0,528.0,573.0,604.9,604.9                                  FILE1095
5203,.0184861,.0195995,.0209263,.0223635,.0233620,0.2548                FILE1096
5211,17E2,376.62,452.6,522.2,582.5,636.3,1155.9                         FILE1097
5212,4E2,470.0,529.0,576.0,613.15,613.15                                FILE1098
5213,.0184761,.0195988,.0209310,.0224504,.0242820,0.2354                FILE1099
5221,18E2,376.74,471.3,545.7,605.5,648.3,1149.4                         FILE1100
5222,4E2,486.0,548.0,593.0,621.03,621.03                                FILE1101
5223,.0184631,.0198952,.0214498,.0231130,.0247207,0.2179                FILE1102
5231,19E2,376.87,451.5,525.7,605.1,660.1,1142.4                         FILE1103
5232,4E2,469.0,532.0,595.0,628.58,628.58                                FILE1104
5233,.0184531,.0195435,.0209592,.0230520,.0251818,0.2021                FILE1105
5241,20E2,376.97,474.6,552.7,630.9,671.7,1135.1                         FILE1106
5242,4E2,489.0,554.0,611.0,635.82,635.82                                FILE1107
5243,.0184421,.0199218,.0215638,.0238509,.0256689,0.1878                FILE1108
5251,21E2,377.07,471.3,551.1,630.3,683.3,1127.4                         FILE1109
5252,4E2,486.0,553.0,611.0,642.77,642.77                                FILE1110
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5253,.0184331,.0198412,.0214772,.0237939,.0261864,0.1746                 FILE1111
5261,22E2,372.67,471.5,551.0,632.7,694.8,1119.2                          FILE1112
5262,4E2,486.0,553.0,613.0,649.46,649.46                                 FILE1113
5263,.0184211,.0198259,.0214420,.0238293,.0267411,0.1625                 FILE1114
5271,23E2,377.37,471.5,551.0,636.5,706.5,1110.4                          FILE1115
5272,4E2,485.0,553.0,616.0,655.91,655.91                                 FILE1116
5273,.0184031,.0198042,.0214002,.0239161,.0273409,0.1513                 FILE1117
5281,24E2,377.47,492.7,574.9,662.4,718.4,1101.1                          FILE1118
5282,4E2,504.0,572.0,633.0,662.12,662.12                                 FILE1119
5283,.0183901,.0201584,.0219611,.0248834,.0279942,0.1407                 FILE112C
5291,25E2,377.67,491.9,575.7,664.8,730.6,1091.1                          FILE1121
5292,4E2,504.0,573.0,635.0,668.13,668.13                                 FILE1122
5293,.0183881,.0201384,.0219545,.0249542,.0287178,0.1307                 FILE1123
6001,05E2,.817,.22,.1600,447.01,.60,.8,.7,.3,3.                          FILE1124
6011,06E2,.755,.22,.1826,466.21,.60,.8,.7,.3,3.                          FILE1125
6021,07E2,.715,.22,.2053,483.10,.60,.8,.7,.3,3.                          FILE1126
6031,08E2,.680,.22,.2280,498.23,.60,.8,.7,.3,3.                          FILE1127
6041,09E2,.650,.22,.2506,511.98,.60,.8,.7,.3,3.                          FILE1128
6051,10E2,.626,.22,.2733,524.61,.60,.8,.7,.3,3.                          FILE1129
6061,11E2,.600,.22,.2960,536.31,.60,.8,.7,.3,3.                          FILE1130
6071,12E2,.580,.22,.3186,547.22,.60,.8,.7,.3,3.                          FILE1131
6081,13E2,.560,.22,.3413,557.46,.60,.8,.7,.3,3.                          FILE1132
6091,14E2,.540,.22,.3640,567.10,.60,.8,.7,.3,3.                          FILE1133
6101,15E2,.522,.22,.3866,576.23,.60,.8,.7,.3,3.                          FILE1134
6111,16E2,.505,.22,.4093,584.90,.60,.8,.7,.3,3.                          FILE1135
6121,17E2,.438,.22,.4320,593.15,.60,.8,.7,.3,3.                          FILE1136
6131,18E2,.472,.22,.4546,601.00,.60,.8,.7,.3,3.                          FILE1137
6141,19E2,.458,.22,.4773,608.58,.60,.8,.7,.3,3.                          FILE1138
6151,20E2,.445,.22,.5000,615.82,.60,.8,.7,.3,3.                          FILE1139
7001,500.,.325,2.5,10.,2.,.24,2.5,1.,.1                                  FILE1140
7011,800.,.325,2.5,10.,2.,.24,2.5,1.,.1                                  FILE1141
7021,1E3,.3575,2.5,10.,2.,.24,2.5,1.,.1                                  FILE1142
7031,12E2,.390,2.5,10.,2.,.24,2.5,1.,.1                                  FILE1143
7041,1600.,.3575,2.5,10.,2.,.24,2.5,1.,.1                                FILE1144
7051,1849.,.3370,2.5,10.,2.,.24,2.5,1.,.1                                FILE1145
                                                                         FILE1146
3001,1850.,.0025,1.05,1.003,.666                                         FILE2001
3002,2000.,.0025,1.05,0.912,.666                                         FILE2002
4001,1850.,0,.02,.05,.1,.2,.4                                            FILE2003
4002,.6,1.1,1.80,2.62,4.01,6.26,10.64                                    FILE2004
4003,1.,1.1,1.52,1.99,2.74,3.83,5.84                                     FILE2005
4004,2.,1.1,1.34,1.59,1.97,2.41,3.12                                     FILE2006
4005,5.,1.1,1.27,1.40,1.60,1.77,2.10                                     FILE2007
4011,2000.,0,.02,.05,.1,.2,.4                                            FILE2008
4012,.6,1.1,1.71,2.45,3.58,5.59,9.02                                     FILE2009
4013,1.,1.1,1.45,1.86,2.45,3.42,4.95                                     FILE2010
4014,2.,1.1,1.28,1.49,1.76,2.15,2.64                                     FILE2011
4015,5.,1.1,1.21,1.31,1.43,1.58,1.78                                     FILE2012
5001,1E2,168.15,200.38,243.02,270.68,298.40,1187.2                       FILE2013
5002,200.,232.,275.,301.,327.81,327.81                                   FILE2014
5003,.0166257..0168532,.017209,.0174538,.0177375,4.432                   FILE2015
5011,150.,168.29,212.63,259.45,301.77,330.51,1194.1                      FILE2016
5012,200.,244.,290.,331.,358.42,358.42                                   FILE2017
5013,.0166237,.0169441,.0173443,.0177658,.0180898,3.015                  FILE2018
5021,2E2,269.79,290.44,311.24,332.24,355.36,1198.4                       FILE2019
5022,3E2,320.,340.,360.,381.79,381.79                                    FILE2020
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5023,.017439,.0176443,.0178664,.0181055,.0183871,2.238            FILE2021
5031,250.,269.89,290.51,321.78,353.51,376.,1201.1                FILE2022
5032,3E2,320.,350.,380.,400.95,400.95                             FILE2023
5033,.0174329,.0176376,.0179769,.018357,.0186517,1.8438           FILE2024
5041,3E2,269.99,302.02,332.39,365.35,393.84,1202.8                FILE2025
5042,3E2,331.,360.,391.,417.33,417.33                             FILE2026
5043,.017429,.0177501,.0180915,.0185006,.0188947,1.5433           FILE2027
5051,350.,270.09,296.95,343.05,385.88,409.69,1203.9               FILE2028
5052,3E2,326.0,370.0,410.0,431.72,431.72                          FILE2029
5053,.0174259,.0176940,.0182133,.0187729,.0191222,1.3260          FILE2030
5061,4E2,270.19,319.95,364.38,394.66,424.0,1204.5                 FILE2031
5062,3E2,348.0,390.0,418.0,444.59,444.59                          FILE2032
5063,.0174219,.0179385,.0184755,.0188879,.0193379,1.1613          FILE2033
5071,450.,270.29,319.02,365.55,396.86,437.2,1204.5                FILE2034
5072,3E2,347.0,391.0,420.0,456.28,456.23                          FILE2035
5073,.0174179,.0179216,.0184828,.0189115,.0195450,1.0320          FILE2036
5081,5E2,270.39,319.1,366.69,407.85,449.4,1204.4                  FILE2037
5082,3E2,347.0,392.0,430.0,467.01,467.01                          FILE2038
5083,.0174140,.0179175,.0184919,.0190662,.0197452,.9278           FILE2039
5091,6E2,270.57,323.43,383.99,432.46,471.6,1203.2                 FILE2040
5092,3E2,351.0,408.0,452.0,486.21,486.21                          FILE2041
5093,.0174060,.0179551,.0187115,.0194359,.0201306,.7698           FILE2042
5101,7E2,270.75,323.59,388.43,450.66,491.5,1201.2                 FILE2043
5102,3E2,351.0,412.0,458.0,503.10,503.10                          FILE2044
5103,.0173999,.0179462,.0187601,.0197242,.0205026,0.6554          FILE2045
5111,8E2,375.59,410.33,457.5,487.8,509.7,1198.6                   FILE2046
5112,4E2,432.0,474.0,500.0,518.23,518.23                          FILE2047
5113,.0185731,.0190645,.0198303,.0204043,.0208665,0.5687          FILE2048
5121,9E2,375.71,408.25,454.1,492.5,526.6,1195.4                   FILE2049
5122,4E2,430.0,471.0,504.0,531.98,531.98                          FILE2050
5123,.0185621,.0190197,.0197578,.0204879,.0212266,0.5006          FILE2051
5131,1E3,375.83,428.0,477.1,527.1,542.4,1191.8                    FILE2052
5132,4E2,448.0,491.0,533.0,544.61,544.61                          FILE2053
5133,.0185511,.0193127,.0201617,.0212211,.0215861,0.4456          FILE2054
5141,1050.,375.87,427.0,477.1,525.1,550.0,1189.9                  FILE2055
5142,4E2,447.0,491.0,531.0,550.57,550.57                          FILE2056
5143,.0185461,.0192883,.0201537,.0211620,.0217665,0.4218          FILE2057
5151,11E2,375.92,427.61,478.20,526.4,557.4,1187.8                 FILE2058
5152,4E2,446.0,492.0,532.0,556.31,556.31                          FILE2059
5153,.0185421,.0193007,.0201669,.0211662,.0219475,0.4001          FILE2060
5161,12E2,375.07,449.5,499.6,547.8,571.7,1183.4                   FILE2061
5162,4E2,467.0,510.0,549.0,567.22,567.22                          FILE2062
5163,.0185311,.0196340,.0205592,.0216573,.0223131,0.3619          FILE2063
5171,13E2,376.17,430.9,497.1,550.2,585.4,1178.6                   FILE2064
5172,4E2,451.0,508.0,551.0,577.46,577.46                          FILE2065
5173,.0185206,.0193241,.0204880,.0216698,.0226853,0.3293          FILE2066
5181,14E2,376.32,430.9,501.8,576.3,598.7,1173.4                   FILE2067
5182,4E2,451.0,512.0,571.0,587.10,587.10                          FILE2068
5183,.0185101,.0193051,.0205618,.0223200,.0230658,0.3012          FILE2069
5191,15E2,376.42,431.9,497.0,555.3,611.6,1167.9                   FILE2070
5192,4E2,452.0,508.0,555.0,596.23,596.23                          FILE2071
5193,.0184961,.0193059,.0204435,.0217590,.0234573,0.2765          FILE2072
5201,16E2,376.52,451.6,521.1,578.7,624.1,1162.1                   FILE2073
5202,4E2,469.0,526.0,573.0,604.9,604.9                            FILE2074
5203,.0184861,.0195995,.0209263,.0223635,.0238620,0.2548          FILE2075
5211,17E2,376.62,452.0,522.2,582.5,636.3,1155.9                   FILE2076
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5212,4E2,470.0,529.0,576.0,613.15,613.15                                FILE2077
5213,.0184761,.0195988,.0209310,.0224504,.0242820,0.2354                FILE2078
5221,18E2,376.74,471.3,545.7,605.5,648.3,1149.4                         FILE2079
5222,4E2,486.0,548.0,593.0,621.03,621.03                                FILE2080
5223,.0184631,.0198952,.0214498,.0231130,.0247207,0.2179                FILE2081
5231,19E2,376.87,451.5,525.7,605.1,660.1,1142.4                         FILE2082
5232,4E2,469.0,532.0,593.0,628.58,628.58                                FILE2083
5233,.0184531,.0195435,.0209592,.0230520,.0251818,0.2021                FILE2084
5241,20E2,376.97,474.6,552.7,630.9,671.7,1135.1                         FILE2085
5242,4E2,489.0,554.0,611.0,635.82,635.82                                FILE2086
5243,.0184421,.0199218,.0215638,.0233509,.0256689,0.1578                FILE2087
5251,21E2,377.07,471.3,551.1,630.3,683.3,1127.4                         FILE2088
5252,4E2,486.0,553.0,611.0,642.77,642.77                                FILE2089
5253,.0184331,.0198412,.0214772,.0237939,.0261864,0.1746                FILE2090
5261,22E2,372.67,471.5,551.0,632.7,694.8,1119.2                         FILE2091
5262,4E2,486.0,553.0,613.0,649.46,649.46                                FILE2092
5263,.0184211,.0198259,.0214420,.0238290,.0267411,0.1625                FILE2093
5271,23E2,377.37,471.5,551.0,636.5,706.5,1110.4                         FILE2094
5272,4E2,486.0,553.0,616.0,655.91,655.91                                FILE2095
5273,.0184081,.0198042,.0214002,.0239161,.0273409,0.1513                FILE2096
5281,24E2,377.47,492.7,574.9,662.4,718.4,1101.1                         FILE2097
5282,4E2,504.0,572.0,633.0,662.12,662.12                                FILE2098
5283,.0183981,.0201584,.0219611,.0248834,.0279942,0.1407                FILE2099
5291,25E2,377.67,491.9,575.7,664.8,730.6,1091.1                         FILE2100
5292,4E2,504.0,573.0,635.0,668.13,668.13                                FILE2101
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6001,05E2,.817,.22,.1600,447.01,.60,.8,.7,.3,3.                         FILE2103
6011,06E2,.755,.22,.1826,466.21,.60,.8,.7,.3,3.                         FILE2104
6021,07E2,.715,.22,.2053,483.10,.60,.8,.7,.3,3.                         FILE2105
6031,08E2,.680,.22,.2280,498.23,.60,.8,.7,.3,3.                         FILE2106
6041,09E2,.650,.22,.2506,511.98,.60,.8,.7,.3,3.                         FILE2107
6051,10E2,.626,.22,.2733,524.61,.60,.8,.7,.3,3.                         FILE2108
6061,11E2,.600,.22,.2960,536.31,.60,.8,.7,.3,3.                         FILE2109
6071,12E2,.580,.22,.3186,547.22,.60,.8,.7,.3,3.                         FILE2110
6081,13E2,.560,.22,.3413,557.46,.60,.8,.7,.3,3.                         FILE2111
6091,14E2,.540,.22,.3640,567.10,.60,.8,.7,.3,3.                         FILE2112
6101,15E2,.522,.22,.3866,576.23,.60,.8,.7,.3,3.                         FILE2113
6111,16E2,.505,.22,.4093,584.90,.60,.8,.7,.3,3.                         FILE2114
6121,17E2,.488,.22,.4320,593.15,.60,.8,.7,.3,3.                         FILE2115
6131,18E2,.472,.22,.4546,601.00,.60,.8,.7,.3,3.                         FILE2116
6141,19E2,.458,.22,.4773,608.58,.60,.8,.7,.3,3.                         FILE2117
6151,20E2,.445,.22,.5000,615.82,.60,.8,.7,.3,3.                         FILE2118
7001,1850.,.325,2.5,1.6,2.,.24,2.5,1.,.1                                FILE2119
7011,2000.,.325,2.5,1.6,2.,.24,2.5,1.,.1                                FILE2120
                                                                        FILE2121
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ART PROPERTY TAPE       JULY 24, 1958      FILES 1 AND 2.         ART01                FILE   1            PAGE    1

SUBCOOLED PRESSURE DROP FIRST KIND

         P          F1          T1

  1     500       3.348       391.0
  2     600       2.804       410.2
  3     700       2.420       427.1
  4     800       2.117       442.2
  5     900       1.877       456.0
  6    1000       1.638       463.6
  7    1100       1.493       480.3
  8    1200       1.319       491.2
  9    1300       1.169       501.5
 10    1400       1.070       511.1

 11    1500        .981       520.2
 12    1600        .880       528.9
 13    1700        .790       537.1
 14    1800        .738       545.0
 15    1849        .719       548.8
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AIRT PROPERTY TAPE        JULY 24, 1958       FILES 1 AND 2.         ART01                    FILE   1            PAGE    3

SATURATION REGION PRESSURE DROP

       P

  1    100    G     X=   .000  X=   .050  X=   .200  X=   .400  X=   .800  X= 1.000
            1.000         1.30      18.20      66.95     144.30     274.30     198.90

  2    250    G     X=   .000  X=   .050  X=   .200  X=   .400  X=   .800  X= 1.000
            1.000         1.30      10.14      34.58      65.00     115.70      85.67

  3    500    G     X=   .000  X=   .050  X=   .200  X=   .400  X=   .800  X= 1.000
            1.000         1.30       6.24      20.02      36.27      62.40      44.20

  4    750    G     X=   .000  X=   .050  X=   .200  X=   .400  X=   .800  X= 1.000
            1.000         1.30       4.68      13.78      24.83      42.77      29.12

  5   1000    G     X=   .000  X=   .050  X=   .200  X=   .400  X=   .800  X= 1.000
            1.000         1.30       3.80      10.34      18.33      31.20      21.06

  6   1250    G     X=   .000  X=   .050  X=   .200  X=   .400  X=   .800  X= 1.000
            1.000         1.30       3.25       8.06      13.78      22.75      16.12

  7   1500    G     X=   .000  X=   .050  X=   .200  X=   .600  X=   .900  X= 1.000
            1.000         1.30       2.86       6.37      14.04      16.90      12.61

  8   1750    G     X=   .000  X=   .050  X=   .200  X=   .600  X=   .900  X= 1.000
            1.000         1.30       2.50       5.08      10.53      12.61      10.21

  9   1849    G     X=   .000  X=   .050  X=   .200  X=   .600  X=   .900  X= 1.000
            1.000         1.30       2.39       4.73       9.59      11.57       9.40
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ART PROPERTY TAPE       JULY 24, 1958      FILES 1 AND 2.         ART01                  FILE   1            PAGE    4

FLUID PROPERTIES

          P

   1     100    ENTHALPY     168.1      200.4      243.0      270.7      298.4     1187.2
                    TEMP     200.0      232.0      275.0      301.0      327.8      327.8
                  SP VOL    .01663     .01685     .01721     .01745     .01774    4.43200

   2     150    ENTHALPY     168.3      212.6      259.4      301.8      330.5     1194.1
                    TEMP     200.0      244.0      290.0      331.0      358.4      358.4
                  SP VOL    .01662     .01694     .01734     .01777     .01809    3.01500

   3     200    ENTHALPY     269.3      290.4      311.2      332.2      355.4     1198.4
                    TEMP     300.0      320.0      340.0      360.0      381.8      381.8
                  SP VOL    .01744     .01764     .01787     .01811     .01839    2.28800

   4     250    ENTHALPY     269.9      290.3      321.8      353.5      376.0     1201.1
                    TEMP     300.0      320.0      350.0      380.0      400.9      400.9
                  SP VOL    .01743     .01764     .01798     .01836     .01865    1.84380

   5     300    ENTHALPY     270.0      302.0      332.4      365.3      393.8     1202.8
                    TEMP     300.0      331.0      360.0      391.0      417.3      417.3
                  SP VOL    .01743     .01775     .01809     .01850     .01889    1.54330

   6     350    ENTHALPY     270.1      296.9      343.0      385.9      409.7     1203.9
                    TEMP     300.0      326.0      370.0      410.0      431.7      431.7
                  SP VOL    .01743     .01769     .01821     .01877     .01912    1.32600

   7     400    ENTHALPY     270.2      319.9      364.4      394.7      424.0     1204.5
                    TEMP     300.0      348.0      390.0      418.0      444.6      444.6
                  SP VOL    .01742     .01794     .01848     .01889     .01934    1.16130

   8     450    ENTHALPY     270.3      319.0      365.5      396.9      437.2     1204.6
                    TEMP     300.0      347.0      391.0      420.0      456.3      456.3
                  SP VOL    .01742     .01792     .01848     .01891     .01954    1.03200

   9     500    ENTHALPY     270.4      319.1      366.7      407.8      449.4     1204.4
                    TEMP     300.0      347.0      392.0      430.0      467.0      467.0
                  SP VOL    .01741     .01792     .01849     .01907     .01975     .92780

  10     600    ENTHALPY     270.6      323.4      384.0      432.5      471.6     1203.2
                    TEMP     300.0      351.0      408.0      452.0      486.2      486.2
                  SP VOL    .01741     .01796     .01871     .01944     .02013     .76980

  11     700    ENTHALPY     270.8      323.6      388.4      450.7      491.5     1201.2
                    TEMP     300.0      351.0      412.0      468.0      503.1      503.1
                  SP VOL    .01740     .01795     .01876     .01972     .02050     .65540

  12     800    ENTHALPY     375.6      410.3      457.5      487.8      509.7     1198.6
                    TEMP     400.0      432.0      474.0      500.0      518.2      518.2
                  SP VOL    .01857     .01906     .01983     .02040     .02087     .56870

  13     900    ENTHALPY     375.7      408.3      454.1      492.5      526.6     1195.4
                    TEMP     400.0      430.0      471.0      504.0      532.0      532.0
                  SP VOL    .01856     .01902     .01976     .02049     .02123     .50060

  14    1000    ENTHALPY     375.8      428.0      477.1      527.1      542.4     1191.8
                    TEMP     400.0      448.0      491.0      533.0      544.6      544.6
                  SP VOL    .01855     .01931     .02016     .02122     .02159     .44560
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ART PROPERTY TAPE        JULY 24, 1958      FILES 1 AND 2.           ART01                    FILE   1             PAGE    5

 15    1050    ENTHALPY    375.9     427.0     477.1     525.1     550.0    1189.9
                   TEMP    400.0     447.0     491.0     531.0     550.6     550.6
                 SP VOL   .01855    .01929    .02015    .02116    .02177    .42180

 16    1100    ENTHALPY    375.9     427.6     478.2     526.4     557.4    1187.8
                   TEMP    400.0     448.0     492.0     532.0     556.3     556.3
                 SP VOL   .01854    .01930    .02017    .02117    .02195    .40010

 17    1200    ENTHALPY    375.1     449.5     499.6     547.8     571.7    1183.4
                   TEMP    400.0     467.0     510.0     549.0     567.2     567.2
                 SP VOL   .01853    .01963    .02056    .02166    .02231    .36190

 18    1300    ENTHALPY    376.2     430.9     497.1     550.2     585.4    1178.6
                   TEMP    400.0     451.0     508.0     551.0     577.5     577.5
                 SP VOL   .01852    .01932    .02049    .02167    .02269    .32930

 19    1400    ENTHALPY    376.3     430.9     501.8     576.3     598.7    1173.4
                   TEMP    400.0     451.0     512.0     571.0     587.1     587.1
                 SP VOL   .01851    .01931    .02056    .02232    .02307    .30120

 20    1500    ENTHALPY    376.4     431.9     497.0     555.3     611.6    1167.9
                   TEMP    400.0     452.0     508.0     555.0     596.2     596.2
                 SP VOL   .01850    .01931    .02044    .02174    .02346    .27650

 21    1600    ENTHALPY    376.5     451.6     521.1     578.7     624.1    1162.1
                   TEMP    400.0     469.0     528.0     573.0     604.9     604.9
                 SP VOL   .01849    .01960    .02093    .02236    .02386    .25480

 22    1700    ENTHALPY    376.6     452.6     522.2     582.5     636.3    1155.9
                   TEMP    400.0     470.0     529.0     576.0     613.1     613.1
                 SP VOL   .01848    .01960    .02093    .02245    .02428    .23540

 23    1800    ENTHALPY    376.7     471.3     545.7     605.5     648.3    1149.4
                   TEMP    400.0     486.0     548.0     593.0     621.0     621.0
                 SP VOL   .01846    .01990    .02145    .02311    .02472    .21790

 24    1900    ENTHALPY    376.9     451.5     525.7     605.1     660.1    1142.4
                   TEMP    400.0     469.0     532.0     593.0     628.6     628.6
                 SP VOL   .01845    .01954    .02096    .02305    .02518    .20210

 25    2000    ENTHALPY    377.0     474.6     552.7     630.9     671.7    1135.1
                   TEMP    400.0     489.0     554.0     611.0     635.8     635.8
                 SP VOL   .01844    .01992    .02156    .02385    .02567    .18780

 25    2100    ENTHALPY    377.1     471.3     551.1     630.3     683.3    1127.4
                   TEMP    400.0     486.0     553.0     611.0     642.8     642.8
                 SP VOL   .01843    .01984    .02148    .02379    .02619    .17460

 27    2200    ENTHALPY    372.7     471.5     551.0     632.7     694.8    1119.2
                   TEMP    400.0     466.0     553.0     613.0     649.5     649.5
                 SP VOL   .01842    .01983    .02144    .02383    .02674    .16250

 28    2300    ENTHALPY    377.4     471.5     551.0     636.5     706.5    1110.4
                   TEMP    400.0     486.0     553.0     616.0     655.9     655.9
                 SP VOL   .01841    .01980    .02140    .02392    .02734    .15130

 29    2400    ENTHALPY    377.5     492.7     574.9     662.4     718.4    1101.1
                   TEMP    400.0     504.0     572.0     633.0     662.1     662.1
                 SP VOL   .01840    .02016    .02196    .02488    .02799    .14070
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ART PROPERTY TAPE        JULY 24, 1958      FILES 1 AND 2.        ART01                    FILE   1             PAGE    6

 30    2500    ENTHALPY    377.7     491.9     575.7     664.3     730.6    1091.1
                   TEMP    400.0     504.0     573.0     635.0     668.1     668.1
                 SP VOL   .01839    .02014    .02195    .02495    .02872    .13070
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ART PROPERTY TAPE        JULY 24, 1958       FILES 1 AND 2.         ART01                    FILE   1              PAGE    7
BURNOUT CORRELATIONS FIRST KIND

          P          B1         M1         R1         T2         B2         M2         R2         B3         M3

   1     500       .817       .220       .160      447.0       .600       .800       .700       .300      3.000
   2     600       .755       .220       .183      466.2       .600       .800       .700       .300      3.000
   3     700       .715       .220       .205      483.1       .600       .800       .700       .300      3.000
   4     800       .680       .220       .228      498.2       .600       .800       .700       .300      3.000
   5     900       .650       .220       .251      512.0       .600       .800       .700       .300      3.000
   6    1000       .626       .220       .273      524.6       .600       .800       .700       .300      3.000
   7    1100       .600       .220       .296      536.3       .600       .800       .700       .300      3.000
   8    1200       .580       .220       .319      547.2       .600       .800       .700       .300      3.000
   9    1300       .560       .220       .341      557.5       .600       .800       .700       .300      3.000
  10    1400       .540       .220       .364      567.1       .600       .800       .700       .300      3.000

  11    1500       .522       .220       .387      576.2       .600       .800       .700       .300      3.000
  12    1600       .505       .220       .409      584.9       .600       .800       .700       .300      3.000
  13    1700       .488       .220       .432      593.1       .600       .800       .700       .300      3.000
  14    1800       .472       .220       .455      601.0       .600       .800       .700       .300      3.000
  15    1900       .450       .220       .477      608.6       .600       .800       .700       .300      3.000
  16    2000       .445       .220       .500      615.8       .600       .800       .700       .300      3.000
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ART PROPERTY TAPE       JULY 24, 1958      FILES 1 AND 2.          ART01                FILE   1             PAGE    8

BURNOUT CORRELATIONS SECOND KIND

         P         B4        M4        G1        F5        B5        M5        C1        D1

  1     500      .325     2.500    10.000     2.000      .240     2.500     1.000      .100
  2     800      .325     2.500    10.000     2.000      .240     2.500     1.000      .100
  3    1000      .357     2.500    10.000     2.000      .240     2.500     1.000      .100
  4    1200      .390     2.500    10.000     2.000      .240     2.500     1.000      .100
  5    1600      .357     2.500    10.000     2.000      .240     2.500     1.000      .100
  6    1849      .337     2.500    10.000     2.000      .240     2.500     1.000      .100
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ART PROPERTY TAPE       JULY 24, 1958      FILES 1 AND 2.        ART01                FILE   2            PAGE   10

SUBCOOLED PRESSURE DROP SECOND KIND

         P          F3          F4        F5         F6

  1    1850      .00250      1.050     1.003       .666
  2    2000      .00250      1.050      .912       .666
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ART PROPERTY TAPE       JULY 24, 1958      FILES 1 AND 2.        ART01                     FILE   2             PAGE   11

SATURATION REGION PRESSURE DROP

          P

   1    1850   G    X=  .000   X=  .020   X=  .050   X=  .100   X=  .200   X=  .400
             .600       1.10       1.80       2.62       4.01       6.25      10.64
            1.000       1.10       1.52       1.99       2.74       3.83       5.84
            2.000       1.10       1.34       1.59       1.97       2.41       3.12
            5.000       1.10       1.27       1.40       1.60       1.77       2.10

   2    2000   G    X=  .000   X=  .020   X=  .050   X=  .100   X=  .200   X=  .400
             .600       1.10       1.71       2.45       3.58       5.59       9.02
            1.000       1.10       1.45       1.86       2.45       3.42       4.95
            2.000       1.10       1.28       1.49       1.76       2.15       2.64
            5.000       1.10       1.21       1.31       1.43       1.58       1.78
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ART PROPERTY TAPE       JULY 24, 1958      FILES 1 AND 2.        ART01                FILE   2            PAGE   16
BURNOUT CORRELATIONS SECOND KIND
          P          B4        M4        G1        R5        B5        M5        C1        D1

  1     1850       .325     2.500     1.600     2.000      .240     2.500     1.000      .100
  2     2000       .325     2.500     1.600     2.000      .240     2.500     1.000      .100
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