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ART-04 - A MODIFICATION OF THE ART PROGRAM FOR THE TREATMENT OF REACTOR THERMAL TRANSIENTS ON THE IBM-704

July 1960
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PITTSBURGH, PENNSYLVANIA

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J. E. Meyer and W. D. Peterson

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This report describes several recent modifications of the ART program for the study of the behavior of a nuclear reactor during various thermal transients. The program requires a 32,000-word IBM-704 computer with six tape units. The basic ART program is described elsewhere (WAPD-TM-156). The major modifications are provision for a slip flow model and for void reactivity contribution.

ART-04 - A MODIFICATION OF THE ART PROGRAM FOR THE TREATMENT OF REACTOR THERMAL TRANSIENTS ON THE IBM-704

J. E. Meyer and W. D. Peterson

I. INTRODUCTION

The ART program is designed to predict the thermal behavior of a water-cooled and moderated reactor during transients which are of an intermediate speed, i.e., faster than a normal operational transient and slower than a prompt excursion. The basic program and the problem solved are described in detail in WAPD-TM-156 (Ref 1), and the present report contains a description of recent changes in the basic program.

The assumption of fog or homogeneous flow was made for the hydrodynamic treatment of the previous ART versions. The modification of ART-04 includes the provision for slip flow, that is, flow in which the vapor velocity is different from that of the liquid. The temperature-induced reactivity in previous versions included only a fixed temperature coefficient for each point in the core nominal channel. The revision includes also a density coefficient for points in both nominal and hot channels which may be used to introduce reactivity effects due to boiling. The program is intended for cores which are predominantly nonboiling, and therefore should be used with caution when this condition is not met.

A further modification provides for a reactivity versus time table for control-rod-induced reactivity changes which is completely independent of the present table for scram. The present scram table permits the insertion of reactivity following some scram time determined during the problem solution.

The added reactivity table provides a simpler means of inserting reactivity when the entire time behavior is known prior to the start of the problem. The combined use of the new and old tables permits a rod withdrawal followed by a rod insertion at some scram time determined during the problem solution. The latest forms for subcooled pressure drop and DNB correlations have also been added.

The following numbering system applies to the various versions of the ART program:

ART-01 - The program for property tape preparation (Ref 1).

ART-02 - The program for treatment of reactor thermal transients using a homogeneous or fog flow model (Ref 1).

ART-03 - A program for evaluation of core frequency response (used to obtain the frequency responses in Ref 2).

ART-04 - The present modification for treatment of reactor thermal transients. By option, ART-04 may be used exactly as ART-02.

II. THEORY

A. Slip Flow Considerations

The basic model used here for separated or slip flow is that proposed by Martinelli and Nelson (Refs 3 and 4). In that treatment the vapor fraction, R, is assumed to be a known function of quality in the saturation region. The average vapor velocity is considered to be different from that of liquid (slip flow). However, it is also assumed here that the vapor is well dispersed and that the vapor fraction is a continuous function of position. Therefore, slug or annular flow patterns would not be handled properly.

Conservation Laws

The conservation laws (mass, momentum, and energy) for the fluid may be developed using the integral form of Liepmann and Roshko (Ref 5, Eqs 7-8, 7-12, and 7-17) and may be written as follows:

$$\frac{\partial}{\partial t}\left[\rho_f(1-R) + \rho_g R\right] + \frac{\partial}{\partial z}\left[\rho_f(1-R)V_f + \rho_g R V_g\right] = 0 \; , \tag{2.1}$$

$$\frac{\partial}{\partial t}\left[\rho_f(1-R)V_f + \rho_g R V_g\right] + \frac{\partial}{\partial z}\left[\rho_f(1-R)V_f^2 + \rho_g R V_g^2\right] = - \frac{\partial p}{\partial z} - \frac{(fv)G^2}{2D_h} - \left[\rho_f(1-R) + \rho_g R\right] g \; , \tag{2.2}$$

and $$\frac{\partial}{\partial t}\left[\rho_f(1-R)H_f + \rho_g R H_g\right] + \frac{\partial}{\partial z}\left[\rho_f(1-R)V_f H_f + \rho_g R V_g H_g\right] = \frac{\phi + rq}{\ell_1} \; . \tag{2.3}$$

The following assumptions apply:

a. Consistent units are used and the Eulerian point of view is adopted. Symbols are defined in Appendix I.

b. The assumptions following Eqs (1.1)-(1.4) of WAPD-TM-156 (Ref 1) apply here also. The use of slip flow, of course, replaces that of fog or homogeneous flow.

c. In the saturation region, the fv product in Eq (2.2) is replaced in the Martinelli-Nelson treatment by a triple product $f_{iso}\phi_{LO}^2 v_f$ where f_{iso} and v_f are evaluated at saturated liquid conditions and ϕ_{LO}^2 is a function of quality only. It may be noted that Bettis additions (see Ref 6) to this treatment have considered ϕ_{LO}^2 to be a function of both quality and mass velocity. Provision is made for this alteration in both ART-02 and ART-04.

d. In the energy equation (2.3) all mechanical work and kinetic energy terms have been neglected, as have the effect of pressure changes with both space and time.

e. In portions of the channel which are subcooled ($H \leq H_f$), R is taken to be zero and ρ_f is replaced by the subcooled water density.

<u>Definitions and Simplifications</u>

The above equations may be simplified by defining several macroscopic quantities. In all cases in the subcooled region, R is taken to be zero and ρ_f is replaced by the subcooled water density. The volume-weighted mean density, $\bar{\rho}$, at any channel position is given by

$$\bar{\rho} = \rho_f(1-R) + \rho_g R \ ; \tag{2.4}$$

and the total mass flow per unit flow area, G, is seen to be

$$G = \rho_f(1-R)V_f + \rho_g R V_g \ . \tag{2.5}$$

The quality, X, is defined as the mass flow of vapor divided by the mass flow of both liquid and vapor. This definition reduces to the more conventional one of the mass fraction of vapor in the case of no slip. With this definition of quality, it may be seen that the phase velocities V_g and V_f may be replaced by

$$V_g = \left(\frac{XG}{R\rho_g}\right) , \tag{2.6}$$

and

$$V_f = \frac{(1-X)G}{(1-R)\rho_f} \ . \tag{2.7}$$

Therefore, the slip ratio V_g/V_f is seen to be given by

$$(V_g/V_f) = \frac{\rho_f X(1-R)}{\rho_g R(1-X)} \ . \tag{2.8}$$

The enthalpy, H, is defined by

$$H = (1-X)H_f + XH_g \ , \tag{2.9}$$

and an effective specific volume for spatial acceleration is given by

$$v' = \frac{(1-X)^2}{(1-R)} v_f + \frac{X^2}{R} v_g \ . \tag{2.10}$$

It may be seen on close examination of the energy balance that there is a change in heat capacity due to the presence of slip flow. This is here represented by a parameter, ψ, which is given by

$$\psi = \left[\rho_f X(1-R)\right] - \left[\rho_g R(1-X)\right] \ . \tag{2.11}$$

This parameter is seen to go to zero if a slip ratio of one is used and is greater than zero for all slip ratios greater than one. It also goes to zero at (X=0, R=0) and at (X=1, R=1).

With these definitions the equations for conservations of mass, momentum, and energy may be rewritten:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial G}{\partial z} = 0 , \tag{2.12}$$

$$\frac{\partial G}{\partial t} + \frac{\partial}{\partial z} (v'G^2) = - \frac{\partial p}{\partial z} - \frac{(fv)G^2}{2D_h} - \bar{\rho} g , \tag{2.13}$$

and

$$\bar{\rho} \frac{\partial H}{\partial t} - H_{fg} \frac{\partial \Psi}{\partial t} + G \frac{\partial H}{\partial z} = \frac{\phi + rq}{\ell_1} . \tag{2.14}$$

The following state and slip flow equations are used and correspond to the simplified Eq (1.8) of Ref 1:

$$v = v(H) , T_w = T_w(H) ,$$
$$R = \begin{cases} 0 & \text{for } H \leq H_f \\ R(X) & \text{for } H_f < H \leq H_g \end{cases} . \tag{2.15}$$

The product fv appearing in Eq (2.13) is the parameter correlated in the saturation region so that no distinction need be made concerning which specific volume is to be used in this term. Equation (2.12) has been multiplied by H and subtracted from Eq (2.3) in order to obtain Eq (2.14). This latter operation is quite important in view of the assumption of spatially constant G which is made in Eq (2.16). If it is not done, the energy balance becomes dependent on the reference condition used for zero enthalpy. The energy balance should, of course, be independent of such an arbitrary reference.

The assumption is made in ART-04 as in ART-02 that the amount of fluid in any section of the channel does not change rapidly with time so that the derivative of average density in Eq (2.12) is assumed to be zero. The conservation of mass may then be rewritten as

$$\frac{\partial G}{\partial z} = 0 \text{ , or as } G = G(t) \text{ .} \qquad (2.16)$$

With this assumption, the conservation of momentum equation may be readily integrated over the length of the channel to obtain the behavior of mass velocity with time. This behavior may be found from

$$\frac{dG}{dt} = \left[\frac{p_o - p_n}{L}\right] - \left[\frac{v'_n - v'_o}{L}\right] G^2 - \frac{G^2}{2D_h L} \int_0^L (fv) dz - \frac{1}{L} \int_0^L (\bar{\rho} g) dz \text{ .} \qquad (2.17)$$

The conditions at inlet and exit are expressed by the following:

$$p_o = p_I - \left[\frac{K_c + 1 - \sigma_o^2}{2}\right] v_o G^2 \text{ ,} \qquad (2.18)$$

$$p_n = p_E + \left[\frac{K_e - 1 + \sigma_n^2}{2}\right] v_n G^2 \text{ ,} \qquad (2.19)$$

and

$$H_o = H_I \text{ .} \qquad (2.20)$$

It may be noted that Eqs (2.18)-(2.20) are exactly the same as Eqs (1.9)-(1.11) of Ref 1. The specific volume, v, based on the quality present is used in these equations rather than the specific volume v' used in the momentum Eq (2.17). This procedure is based on the recommendations of B. W. LeTourneau of the Bettis Thermal and Hydraulics Engineering Section.

Interpass Mixing and Transport Calculations

The conditions in the second pass inlet plenum as a function of time cannot usually be specified since they do depend on the first pass exit conditions at some earlier time. The previous ART versions included an interpass mixing treatment which depends on the nominal channel exit enthalpy behavior as a function of time and on user-specified mixing parameters. The only change which is included in this calculation in ART-04 is in the case of a first-pass nominal channel which is boiling. If this is the case, any model for the interpass mixing calculations would be open to question. However, the ART-04 calculations are based on the following requirements:

a. that they reduce to the ART-02 interpass calculations if no boiling is present in the nominal channel or if the slip ratio is equal to one;

b. that they give back the nominal channel behavior if the leakage flow parameter F_a is equal to one.[†]

The remaining phases of the calculations are exactly as in ART-02. The rate of movement of interpass water is assumed proportional to the rate of volume efflux of fluid from the first-pass nominal channel. This efflux rate may be shown to be proportional to the following quantity in the case of two-phase flow:

$$(1-R)V_f + RV_g = G\left[(1-X)v_f + Xv_g\right] . \qquad (2.21)$$

B. Void Reactivity Contribution[††]

If we consider at time zero that the core under consideration is operating at steady state (i.e., $\delta K = 0$), then the reactivity at any time in the transient may be given by

$$\delta K = \delta K_r + \int_V k_t\left[T_w - (T_w)_o\right]dV + \int_V k_v(\bar{\rho} - \bar{\rho}_o)dV , \qquad (2.22)$$

where the term δK_r refers to the reactivity introduced by control rod motion, the first integral over the core volume represents effects due to water temperature changes, and the final integral represents effects due to fluid density changes. The reactivity introduced by changes in fuel and structure temperature is neglected in the above expressions. In the ART treatment it is first assumed that functions k_t and k_v are known functions of space only and not of time or temperature. In addition, the k_t is allowed to be nonzero only for water contained in nominal channels. The k_v is permitted to be nonzero in both nominal and hot channels. There is no contribution for reactivity effects in leakage or interpass water.

[†] The parameter F_a may not be supplied as unity due to the form of Eq (2.55) of Ref 1.

[††] This information is based on request for ART code modifications prepared by S. G. Margolis, A. S. Rathbun, and J. A. Redfield.

Equation (2.22) may be written as

$$\delta K = \delta K_r + \delta K_t + \delta K_v , \qquad (2.23)$$

where the δK_t represents the effect of the temperature change of nominal channel water, and δK_v represents the effect of the density change of nominal channel and hot channel water. The density changes caused by the presence of bubbles during local boiling are neglected in these calculations.

It should be noted that there are some very real difficulties in defining the thermal characteristics of the hot channels used in these calculations. The problem is aggravated if the channels begin boiling and have the attendant large density changes. Hot channels which have dimensions and heat generation rates determined by extremes in engineering tolerances and extremes in core power peaking probably would give an unrealistically high shutdown mechanism. Some average dimensions and average heat generation rates over regions of the core in which boiling is expected appear to be appropriate for inclusion of void effects. Some ART hot channels can be used with extremes of dimensions and heat input for evaluation of core safety but with a zero density coefficient; other more typical channels may be used for introduction of (boiling) void reactivity.

A limitation on this entire void procedure is the assumption in the ART program that the heat generation is separable in space and time. Changes in the spatial power shape caused by the boiling are neglected but could conceivably be quite important.

III. CALCULATIONAL PROCEDURE

A. Slip Flow Considerations

Input and Input Edit

The vapor volume, R, is input in the ART-04 program as a multiple straight line function of quality. That is, the void fraction is assumed to be a function of quality and pressure only (and not of mass velocity). Since all properties are evaluated in ART at a single mean pressure, this relationship reduces to a function of quality only. It is required of the input that at zero quality the vapor fraction is also zero and at $X = 1$, $R = 1$.

In order that the user may assess the accuracy of his vapor-fraction input, the slip ratio (Eq 2.8) and the energy slip parameter (Eq 2.11) are calculated both for the input quality points and for the midpoints between the input quantities. The slip ratios are not used in any calculation directly but serve only to check the input data. It may be noted that the energy slip parameter, ψ, is a piecewise quadratic in quality (see Eq 2.11) and that the slip ratio is a rational fraction which becomes indeterminate at quality values of zero and one (see Eq 2.8); for these values, the slip ratios are found by

$$(V_g/V_f) = \frac{(\rho_f/\rho_g)}{\left(\frac{dR}{dX}\right)_{X=0}} \qquad \text{at } X=0 \; , \tag{3.1}$$

and

$$(V_g/V_f) = (\rho_f/\rho_g)\left(\frac{dR}{dX}\right)_{X=1} \quad \text{at } X=1 \; . \tag{3.2}$$

Water Energy Balance

The water energy balance relationship, Eq (2.14), is evaluated by a differencing technique employing backward space differences and forward or explicit time differences to get the following as a substitute for Eq (2.4) of Ref 1:

$$H'_{j,i+1} = H_{ji} - \frac{H_{fg}\,\psi_{ji}}{\bar{\rho}_{ji}} + \frac{\Delta t_i}{\ell_1 \bar{\rho}_{ji}} \left[(\phi_{ji} + rq_{ji}) - \frac{G_i \ell_1}{\Delta z} (H_{ji} - H_{j-1,i}) \right] \; , \tag{3.3}$$

where

$$H'_{j,i+1} = H_{j,i+1} - \frac{H_{fg}\,\psi_{j,i+1}}{\bar{\rho}_{ji}} \; . \tag{3.4}$$

Fluid conditions and heat transfer rates may be assumed to be known at time i. Therefore, Eq (3.3) may be applied to determine the parameter H' at each point at time i+1. For values of H' greater than H_f, the right-hand side of Eq (3.4) is a known piecewise quadratic function of quality (see Eqs 2.9 and 2.11). The quality at time i+1 may therefore be determined† by

†It is quite important in applying Eq (3.4) that $\bar{\rho}_{ji}$ is held constant at its value at time i. This may be seen in Eq (2.14) where we note that $\bar{\rho}$ is a multiplier of $\partial H/\partial t$, and is not differentiated with respect to time.

a solution of the quadratic equations. For values of H' less than or equal to H_f, the parameter, ψ, is considered to be zero and Eq (3.4) reduces to that used in ART-02. Since Eq (3.4) is a piecewise quadratic relation in the saturation region, there is a possibility of multiple roots. This is checked during calculations and a problem stop occurs if multiple roots exist. It is expected that the only cause for multiple roots would be a nonphysical R versus quality relationship.

The same type of numerical stability analysis that leads to Eq (5.2) in Ref 1 yields the following stability criterion for the energy balance equation in the saturation region ($H_{ji} \geq H_f$):

$$\Delta t_i \leq \frac{\Delta z \left[\bar{\rho}_{ji} - \left(\frac{d\psi}{dX}\right)_{ji} \right]}{G_i} . \tag{3.5}$$

Once quality or enthalpy is known for the advanced time, the following quantities may be determined:

	Subcooled Region $H' \leq H_f$	Saturation Region $H_f < H' \leq H_g$
Average Density ($\bar{\rho}$)	$\bar{\rho} = (1/v)$, v from Eq (2.15)	Eq (2.4)
Enthalpy (H)	$H' = H$	Eq (2.9)
Energy Slip Parameter (ψ)	$\psi = 0$	Eq (2.11)
Effective Specific Volume for Acceleration (v')	$v' = v$, v from Eq (2.15)	Eq (2.10)

Pressure Drop

In order to obtain a pressure balance between hot and nominal channels and to determine the mass velocity at the advanced time in each hot channel, the following equations are used to replace Eqs (2.12)-(2.15) of Ref 1:

$$(\Delta p_f)_i = K_c(v_{oi}G_i^2/2) + K_e(v_{ni}G_i^2/2)$$
$$+ \left[(f_{oi}v_{oi})/2 + \sum_{j=1}^{n-1} (f_{ji}v_{ji}) + (f_{ni}v_{ni})/2\right](G_i^2\,\Delta z/2D_h) , \quad (3.6)$$

$$(\Delta p_{e\ell})_i = g\Delta z \left[\frac{1}{2}\,\bar{\rho}_{oi} + \sum_{j=1}^{n-1} \bar{\rho}_{ji} + \frac{1}{2}\,\bar{\rho}_{ni}\right] , \quad (3.7)$$

$$(\Delta p_{a1})_i = n\Delta z\ (G_{i+1} - G_i)/\Delta t_i , \quad (3.8)$$

and

$$(\Delta p_{a2})_i = (1 - \sigma_o^2)(v_{oi}G_i^2/2) + (v'_{ni} - v'_{oi})\,G_i^2 - (1 - \sigma_n^2)(v_{ni}G_i^2/2) . \quad (3.9)$$

As mentioned following Eq (2.3), the correlation of saturation region pressure drop is in terms of the product $(f_{ji}v_{ji})$:

$$(f_{ji}v_{ji}) = (f_{iso})_i\ v_f(\phi_{LO}^2)_{ji} , \quad (3.10)$$

which is independent of the specific volume used in Eq (3.6) for calculating the frictional terms. This last equation corresponds to Eq (2.17) of Ref 1.

Interpass Mixing Calculations

The requirements for interpass mixing discussed in the paragraph preceding Eq (2.21) are satisfied if Eq (2.53) and Eqs (2.55) through (2.59) of Ref 1 are retained and if Eq (2.54) of Ref 1 is replaced by the following:

$$(H_{oi})^{AC} = (H_{oi})^{NC} ,$$
$$(\bar{\rho}_{ji})^{AC} = (\bar{\rho}_{ji})^{NC} ,$$
$$G_i^{AC} = G_i^{NC} , \quad (3.11)$$
$$(\phi_{ji} + rq_{ji})^{AC} = F_a(\phi_{ji} + rq_{ji})^{NC} ,$$

and

$$\ell_1^{AC} = \ell_1^{NC} .$$

The energy balance used in the average channel is identical with Eq (3.3). The length of the table of interpass mixing values has been increased so that it now contains 2000 rather than 1350 rows.

B. Void Reactivity Contributions

The temperature coefficient in ART-04 applies for the nominal channel only and is calculated as in Eq (2.46) of Ref 1. This equation may be rewritten as

$$(\delta K_t)_i = \alpha_t \left\{ \sum_{\substack{j=1 \\ m=0,5}}^{n} a_{mj} \left[(T_w)_{ji} - (T_w)_{jo} \right]_m \right\}, \tag{3.12}$$

where m denotes the channel number and is zero for the first pass nominal channel, 1-4 for the first pass hot channels, 5 for the second pass nominal channel, and 6-9 for the second pass hot channels. The coefficients $a_{mj} = 0$ for m = 1-4 and 6-9, and the symbol α_t has been substituted for $\partial(\delta K)/\partial T_w$. The reactivity contribution due to density changes $(\delta K_v)_i$ has been added in ART-04 where

$$(\delta K_v)_i = \alpha_v \left\{ \sum_{m=0}^{9} \sum_{j=0}^{n} b_{mj} \left[\bar{\rho}_{ji} - \bar{\rho}_{jo} \right]_m \right\}. \tag{3.13}$$

It may be noted that the summation on m is over all channels. That is, b_{mj} may be nonzero for any point in any of the channels 0 through 9. In addition, the sum over points in the channel is from point 0 through point n. That is, a reactivity introduction by inlet density change is permitted. The omission of point zero from reactivity contribution is retained in the temperature coefficient, however.

It should be noted that for the nominal channels, the temperature coefficient now has a different significance if a nonzero density coefficient is supplied. The revised temperature coefficient may be interpreted as the effect on reactivity at a constant water density of a change in the temperature of the moderator. The density coefficient is interpreted as the effect on reactivity at a constant water temperature of a change in the water density.

Care must be taken if the user specifies only a nominal channel coefficient and intends that the change of temperature coefficient with temperature be represented by density coefficients. Since the fluid property tables in the subcooled region are multiple straight line fits, the derivative of density with respect to temperature actually has a sawtooth behavior and so gives a sawtooth-shaped temperature coefficient. This problem has been alleviated somewhat by permitting the user to supply up to 15 points in fluid property fits (six were permitted in ART-02). An illustration of this effect is supplied in Section VI.F.

An interpretation of the weighting constants a_{mj} and b_{mj} in terms of the functions of Eq (2.22) is that

$$\alpha_t a_{mj} = \int_{V_{mj}} k_t \, dV , \tag{3.14}$$

and

$$\alpha_v b_{mj} = \int_{V_{mj}} k_v \, dV , \tag{3.15}$$

where V_{mj} is the portion of the core water volume associated with point j in channel m. It is important that the integration be taken only over water which has roughly the same density and temperature behavior as the water in the channel under consideration and not, for example, over leakage water or that beyond the end of the fuel in the y-direction.

C. Revised Local Boiling Pressure Drop Forms

Change in Second Kind

Two forms of subcooled pressure drop correlations are available in ART-02. In the second kind of pressure drop correlation (Eq 2.20 of Ref 1), the function F_H is given as the smaller of $f_4(1-f_3\theta_{ji}^{*})$ and unity. The revised second kind retains the use of Eq (2.20) of Ref 1 but the function F_H is redefined as

$$F_H = \begin{cases} 1.0, & \text{if } 1 \le f_4(1-f_3\theta_{ji}^{*}), \\ f_4(1-f_3\theta_{ji}^{*}), & \text{if } f_7 < f_4(1-f_3\theta_{ji}^{*}) < 1, \text{ and} \\ f_7, & \text{if } f_4(1-f_3\theta_{ji}^{*}) \le f_7 . \end{cases} \tag{3.16}$$

If no value is supplied for the parameter f_7, it is set equal to zero.

Addition of a Third Kind of Subcooled Pressure Drop Correlation

Using the definition of θ_{ji} and θ_{ji}^{*} that precedes Eq (2.21) in WAPD-TM-156 (Ref 1), the subcooled region pressure drop form of WAPD-TH-410 (Ref 6) is given as

$$(f/f_{iso})_{ji} = \begin{cases} \max\left[(1-f_8\theta_{ji}^{*}),\ f_9\right], & \text{if } \theta_{ji} = \theta_{ji}^{*}, \text{ and} \\ 1 + f_{10}\left[\dfrac{(T_w)_{ji} - (T_{LB}^{*})_{ji}}{T_{sat} - (T_{LB}^{*})_{ji}}\right], & \text{if } \theta_{ji} > \theta_{ji}^{*}, \end{cases} \tag{3.17}$$

where $(T_{LB}^{*})_{ji}$ is defined by

$$(T_{LB}^{*})_{ji} = (T_c)_{ji} - \theta_{ji}\ , \tag{3.18}$$

with $(T_c)_{ji}$ given by Eq (2.9) and θ_{ji} by Eq (2.21) of Ref 1.

D. Addition of a Third Kind of DNB Correlation

Two forms of DNB correlations are available in ART-02. The following form for predicting DNB heat flux has been added to ART-04:

$$\frac{(\phi_{BO})_{ji}}{10^6} = B_6\, e^{-C_2 L_j}\left[H_{ji}/10^3\right]^{-(C_3+C_4L_j)}\ , \tag{3.19}$$

where

$$L_j = \begin{cases} \max\ (L_1,\ j\Delta z), & \text{if } H_{ji} > H_1, \text{ and} \\ L_1, & \text{if } H_{ji} \le H_1\ . \end{cases} \tag{3.20}$$

E. An Independent Reactivity Versus Time Table

In ART-04 the rod motion portion of the reactivity is divided into two portions:

$$\delta K_r = \delta K_{r1} + \delta K_{r2}\ . \tag{3.21}$$

The δK_{r1} is as given in Eq (2.48) of WAPD-TM-156:

$$\delta K_{r1} = \begin{cases} \delta K_1, & \text{for } 0 \leq t < t_3, \text{ and} \\ \text{Linear interpolation in Scram Table,} & \text{for } t_3 \leq t \end{cases} \quad (3.22)$$

where t_3 is the scram time determined during the course of the problem by Eq (2.47) of WAPD-TM-156 (Ref 1). The second reactivity portion δK_{r2} is given by

$$\delta K_{r2} = \begin{cases} \text{A value obtained by linear interpolation in an independent reactivity table for } 0 \leq t \leq \text{ last time} \\ \text{entry in table, or by the last reactivity in the table for times greater than the last time in the table.} \end{cases} \quad (3.23)$$

The independent reactivity versus time table should be useful in cases in which the reactivity introduction is known prior to the start of the problem, and in cases in which a rod withdrawal is followed by a rod insertion at a time t_3 determined by scram conditions.

F. First Pass Inlet Enthalpy

First pass inlet enthalpy (H_{oi}) may now, as an option, be specified as a function of time. When this option is exercised, an input enthalpy specification table replaces the inlet temperature specification of Eq (2.52) of Ref 1:

t	H_{oi}^{NC}	H_{oi}^{HC}
0	X	X
X	X	X
X	X	X
⋮	⋮	⋮

(3.24)

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

G. Additional Edit Information

Wherever the input format (Section IV) has been changed from the ART-02 format, additional entries will be printed in the input edit of all problems; these entries appear as zero if unused. Where series have been added, the entries involved are printed only when the appropriate options are chosen.

In the steady-state edit, the pressure drop for each channel is broken down into Δp_f, $\Delta p_{e\ell}$, and Δp_{a2} ($\Delta p_{a1} = 0$). In addition, hot channel flow and pressure drop are printed from iteration 21 until convergence, or until the problem is stopped after iteration 30.

The transient edit for a reactor kinetics problem includes the printing of $(\delta K)_i$, $(\delta K_r)_i$, $(\delta K_t)_i$, and $(\delta K_v)_i$ for $t_i > 0$. In all problems, $(\Delta p_f)_i$, $(\Delta p_{e\ell})_i$, $(\Delta p_{a1})_i$, and $(\Delta p_{a2})_i$ as well as $(\Delta p)_i$ are printed for every channel. The transient edit also includes the enthalpy of the exit section of each channel (H_{ni}). This value appears in the right-hand margin whenever water temperature-quality is printed.

At each time-step, a stability test is made for the water energy balance, plate energy balance, neutron level and precursor level equations. If a given test fails, the time at which it failed, the required time-step size, and the actual step size are printed at the head of the next transient edit, and that test is discontinued. As an aid to spotting these comments, the same information and the time are printed on the on-line monitor sheet.

If a problem is discontinued between transient printouts, a final edit will be made. The resultant information will be a mixture from the old and new time-steps. The channel which caused the problem to be discontinued is identified. If the problem is not discontinued in channel 0, then all entries in the time-step heading may be considered up to date, as are the results of earlier channels. The quantities δK_t and δK_v (if printed) will not have been changed since the previous time-step, but are up to date in the sense that they have been used to find the value of $(\delta K)_i$ in the neutron level equation. If the problem is discontinued in channel 0, the type of stop would determine which parts of the time-step heading have been updated. In general, one should assume that no changes have been made.

IV. INPUT FORMAT

An ART identification card may have ART04 or ART02 in columns 68-72. Column 66 may be P, C, or blank.

The input format for ART02 problems is that contained in Ref 1, with a minor optional change. The input format for ART04 problems is the ART02 format with the changes and additions contained herein. The following table summarizes the series which are modified, and the input formats affected. No changes in property tape have been made. Input sections which have been added must be supplied by card input. All changes and additions are optional.

Series		ART04	ART02
1041	changed	X	
3021	changed	X	
3025	added	X	
4011, 4021, 4031	changed	X	X
4041, 4051	added	X	
5031	added	X	
6011	changed	X	
6051	added	X	
61_1	added	X	
10021	changed	X	
10031	changed	X	

A. Parent Problems

Control Information

Input Options: 1041, X_1, X_2, X_3, X_4

$$X_1 = \left\{ \begin{array}{l} 1 \text{ first} \\ 2 \text{ second} \\ 3 \text{ third} \end{array} \right\} \text{kind, subcooled pressure drop.}$$

$$X_2 = \begin{Bmatrix} 1 \text{ first} \\ 2 \text{ second} \\ 3 \text{ kind} \end{Bmatrix} \text{kind, DNB correlation.}$$

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

$$X_4 = \begin{Bmatrix} 1 \text{ temperature} \\ 2 \text{ enthalpy} \end{Bmatrix}, \text{ specified for first pass inlet.}$$

If X_4 is omitted, the program assumes that temperatures are supplied.

Pressure Drop Correlations

Subcooled Pressure Drop - Second Kind: 3021, F_1, F_2, F_3, F_4, F_5

$F_5 = f_7$, correlation parameter.

If F_5 is omitted, $f_7 = 0$. If tape input is specified, card 3021 will be permitted with one floating point number, f_7. This series must be omitted if first or third kind is specified.

Subcooled Pressure Drop - Third Kind: 3025, F_1, F_2, F_3

$F_1 = f_8$, correlation parameter. $1/^{o}F$

$F_2 = f_9$, correlation parameter.

$F_3 = f_{10}$, correlation parameter.

This series may be supplied only from cards, which must be omitted if first or second kind is specified.

Fluid Properties

Enthalpy: 4011, F_1, F_2,...,F_i,....,F_n (card: $3 \leq n \leq 15$; tape: $3 \leq n \leq 6$)

This implies a similar increase in size of temperature (4021) and specific volume (4031) when input is from cards.

Vapor Volume Fractions

Quality: 4041, F_1, F_2,....,F_i,....,F_n ($1 \leq n \leq 5$)

$F_i = X$, quality

F_o (not supplied) is set to zero. The sequence $\{F_i\}$ must be in ascending order. If this series is omitted, the fog flow model will be used.

Vapor Volume Fraction: 4051, F_1, F_2,...,F_i,...,F_m (m=n, series 4041)

F_i = R, vapor fraction associated with quality, series 4041.

F_o (not supplied) is set to zero. If $F_n = 1.0$, series 4041, then F_m should also be 1.0. This series must be omitted if series 4041 is omitted.

DNB Correlations

Third Kind: 5031, F_1, F_2, F_3, F_4, F_5, F_6

$F_1 = B_6$, correlation parameter.	mixed units
$F_2 = C_2$, correlation parameter.	(1/in.)
$F_3 = C_3$, correlation parameter.	
$F_4 = C_4$, correlation parameter.	(1/in.)
$F_5 = L_1$, correlation length.	in.
$F_6 = H_1$, correlation enthalpy.	Btu/lb_m

This series may be supplied only from cards, which must be omitted if first or second kind is specified.

Reactor Kinetics

Constants: 6011, F_1, F_2, F_3, F_4, F_5

$F_5 = \alpha_v$ ft^3/lb_m

If F_5 is omitted, $\alpha_v = 0$. If a nonzero F_5 is supplied, the density coefficients (series 61_1) are required.

Rod Motion Reactivity: 6051, F_{11}, F_{12},...,F_{i1}, F_{i2},...,F_{n1}, F_{n2} $(2 \leq n \leq 6)$

F_{i1} = t, time. seconds

$F_{i2} = \delta K_{r2}$, reactivity.

F_{11} must be zero, and the sequence $\{F_{i1}\}$ must be in ascending order. If reactor kinetics is specified and this series is omitted, $\delta K_{r2} = 0$.

Density Coefficients: 61_1, F_o, F_1,...,F_j,...,F_n (n = number of axial sections)

$F_j = b_{mj}$, the density coefficient weighting factor for the j-th axial section.

One set of coefficients must be supplied for each channel used if $\alpha_v \neq 0$ (F_5, series 6011), the channel number appearing in the tens position of the card number. This series must be omitted when $\alpha_v = 0$. Note that n+1 numbers must be supplied for each channel.

First-Pass Inlet Enthalpies: Cards 10021 and 10031

If $X_4 = 2$ on the input options card, 1041, then the values on cards 10021 and 10031 will be interpreted as enthalpies (Btu/lb_m) rather than temperatures. The input format and limitations are unchanged.

B. One-Shot Problems

All changes and additions to parent problems are also allowed for one-shot problems.

C. Continuation Problems

ART04 continuation problems are run exactly as in ART-02. Parent problems may contain the above changes, but no alteration in this data is allowed when the continuation problem is run.

D. Estimation of Machine Time

Continue to use the methods of Section III.E of Ref 1 for estimating machine time.

V. OPERATING INSTRUCTIONS

The operating instructions contained in Ref 1 are essentially unchanged. The remarks concerning sense switch 2 should be amended to read "Down - Restart problem with data from logical tape 4 if the comment RESTART TAPE AVAILABLE has been printed on-line."

VI. PREPARATION OF INPUT FOR A SAMPLE PROBLEM

This section contains a discussion of some of the decisions leading to the choice of ART-04 input quantities. The discussion is based on the analysis of a fictitious two-pass reactor core sustaining a complete loss-of-flow accident without scram. The reactor core is considered to have the same geometry as the sample core of WAPD-TM-156 (Ref 1, p 29). However, in the present problem, the core is operated at 1250 psia rather than 2000 psia and has a somewhat lower inlet temperature. The ART-04 provision for slip flow and void reactivity effects are included. All input cards for this problem and selected portions of the output are listed in Appendix II. The sample problem of WAPD-TM-156 will be referred to as problem XX, the present problem as YY. The present discussion is limited to those portions of input which have been changed from problem XX. A discussion of the remaining input quantities may be found in WAPD-TM-156, Section V. Symbols are defined in Appendix I of this report and Appendix I of WAPD-TM-156.

A. Control Information: Cards 1011-1061

Time Increments: Card 1011

The same type of numerical stability analysis that leads to Eq (5.2) in WAPD-TM-156 (Ref 1) yields the following stability criterion for the energy balance equations in the saturation region ($H_{ji} \geq H_f$) in the case that the slip flow option is utilized:

$$\Delta t_i \leq \frac{\Delta z \left[\bar{\rho}_{ji} - \left(\frac{d\Psi}{dX}\right)_{ji} \right]}{G_i} . \tag{6.1}$$

In the sample problem, the flow has been reduced sufficiently by the time that bulk boiling takes place to warrant the use of the same time-step (0.02 sec) as in problem XX.

If a large amount of reactivity is introduced by density coefficients, care must be taken that the stability criterion of Eq (5.5) in WAPD-TM-156 (Ref 1) is satisfied. This equation is given incorrectly in Ref 1, and should be

$$\Delta t_i \leq \frac{2m\ell^*}{\bar{\beta} - \delta K_i^k} ,$$

where the equation is applicable only when $\delta K_i^k \leq 0$ and where m=10 if $(\delta K_r)_i^o = 0$, and m=25 if $(\delta K_r)_i^o \neq 0$. Note that if this criterion is not met in a problem with $(\delta K_r) = 0$, a suggested procedure involves setting (δK_r) to some extremely small number (say 10^{-20}). The solution is then obtained with m=25, permitting a larger basic time-step.

Problem Size: Card 1021

It is assumed that the thermally limiting core hot channel is located in the second pass. Therefore, no first-pass hot channel is used. The geometry and hydraulic characteristics of the thermally limiting hot channel are ascribed to channel 6 (the first hot channel in the second pass). Void reactivity effects are assumed to be important only in the hotter region of the second pass. All such void reactivity contributions are assigned to channel 7 (the second hot channel in the second pass). This input card, therefore, indicates a two-pass core with six axial sections, no first-pass hot channel, and two second-pass hot channels.

Property Tape: Card 1031

The necessary DNB and fluid property information is obtained from file 1 of the property tape. This file is used at Bettis for lower pressure information (i.e., below 1850 psia).

Input Options: Card 1041

The third kind of subcooled pressure-drop correlation is used for this lower pressure operation.

Over-all Conditions: Card 1061

The parameters p_o and K_{cr} have been changed on this card to correspond to the 1250 psia operation. The calculation of K_{cr} is by Eq (5.7) of WAPD-TM-156.

B. Individual Channel Characteristics: Cards 2011-2671

There have been only slight changes in the information supplied for channels 0, 5, and 6. The quantity (h/h_f) has been modified to correspond to the design recommendations of WAPD-TH-410 (Ref 6). These recommendations include the use of a film coefficient h_f based on a coefficient of 0.023 rather than 0.019 in Eq (5.8) of WAPD-TM-156. Therefore,

$$(h_f/h) = \left(\frac{0.023}{0.019}\right) = 1.21 \quad . \qquad (6.2)$$

In addition, the quantity (q/q^*) has been altered in channel 5. Since two channels (5 and 7) have been used in reactivity calculations as opposed to the single second-pass nominal channel of problem XX, and since channel 7 has a higher heat flux, the heat flux of channel 5 must be reduced. Channel 5 now represents the behavior of a group of channels of lower average heat output than in problem XX. In order to have the same total heat generation in the second pass,

$$\begin{aligned}&\begin{bmatrix}\text{Heat transfer area associ-}\\\text{ated with channel 5}\end{bmatrix}\left[(q/q^*)\left(\sum_{j=1}^{n} F_j\right)\right]_{\text{ch 5}}\\&+\begin{bmatrix}\text{Heat transfer area associ-}\\\text{iated with channel 7}\end{bmatrix}\left[(q/q^*)\left(\sum_{j=1}^{n} F_j\right)\right]_{\text{ch 7}}\\&=\begin{bmatrix}\text{Total second pass heat}\\\text{transfer area}\end{bmatrix}\left[(q/q^*)\left(\sum_{j=1}^{n} F_j\right)\right]_{\substack{\text{pass}\\\text{two}}},\end{aligned} \tag{6.3}$$

where pass two denotes the second-pass nominal channel of problem XX. If it is assumed that all F_j for the present channel 5 are identical to those used in problem XX,† and that the heat transfer area associated with channel 7 is 7% of the total second-pass heat transfer area, then by Eq (6.3)

$$(q/q^*)_{\text{ch }5} = \frac{1}{(6.71)(.93)}\left[(6.71) - (13.27)(0.07)\right] = 0.926 ,$$

where $$\sum_{j=1}^{n} F_j = \begin{Bmatrix} 6.71 \text{ for ch 5 and pass two} \\ 13.27 \text{ for ch 7} \end{Bmatrix},$$

and $$(q/q^*) = 1 \text{ for ch 7 and pass two .}$$

C. Characteristics for Channel 7: Cards 2711-2761

It is quite important that the dimensions, hydraulic characteristics, and heat generation rate of any channel used to supply void reactivity contributions be typical of the region represented by that channel. They should not be extremes such as are used in hot channel computations for

† The difference in axial power shape between the pass-two nominal channel and channel 7 would presumably cause a shift in F_j values also. This shift in power shape has been neglected.

reactor safety. Most of the dimensional and hydraulic characteristics of channel 7 were taken to be equal to those for the nominal channel (channel 5). The F_j power factors were obtained directly from nuclear calculations (Ref 7 and Ref 1, p 36) and are identical to those used in channel 6. However, channel 6 also utilizes an increase in heat generation by 38% ($q/q^* = 1.38$ on card 2651) resulting from engineering tolerances (1.2) and from the local nuclear predictions of heat generation rate (1.15). Since channel 7 is to be averaged over a larger nuclear region and since engineering tolerances are to be neglected, q/q^* is set equal to one.

D. Pressure Drop Correlations

Subcooled Pressure Drop, Third Kind: Card 3025

A design recommendation for use of the third kind of subcooled pressure drop correlation is presented in WAPD-TH-410 (Ref 6, p 2). For best fit, this gives (assuming that a value of .030 is used for calculation of h_f):

$$f_8 = .001 \left(\frac{.030}{.023}\right) = .0013 \ ,$$

f_9 is not specified in WAPD-TH-410,[†]

and $$f_{10} = (f/f_{iso})_{sat} - 1 \ ,$$

where $(f/f_{iso})_{sat}$ = Martinelli-Nelson value of ϕ_{LO}^2 at 4.2% quality.

For the correlation upper limit (assuming that a value of .023 is used for calculation h_f):

$$f_8 = 0 \ ,$$

$$f_9 = 0 \ ,$$

and $$f_{10} = (f/f_{iso})_{sat} - 1 \ .$$

The correlation upper limit has been used in the sample problem.

[†] This value is used to set a lower boundary on (f/f_{iso}) in the heating region. For example, it may be set equal to zero to avoid obtaining negative values.

Saturation Region Pressure Drop: Cards 3031-3044

The saturation region pressure drop information was chosen for the sample problem to approximate the upper limit recommendations of WAPD-TH-410 (Ref 6, p 3). Care was taken to avoid obtaining ϕ_{LO}^2 values under 1.1 for conditions of low quality and high mass velocities.

E. Vapor Volume Fractions: Cards 4041-4051

The multiple straight-line fit of Martinelli-Nelson vapor fractions information is shown in Fig. 1. It should be noted that small differences in the points chosen for fitting can make a relatively large difference in some of the quantities derived from the R(X) fit. The adequacy of the R(X) fit is discussed in the following paragraphs and means for testing the adequacy are developed. The ψ and V_g/V_f functions which are part of the input edit of problem YY are shown in Fig. 2 and are there compared to the same information determined directly from the smooth curves. On the average, the multiple straight-line fit gives the proper behavior, but locally, fairly large differences arise.

In the bulk boiling region there are four quantities with units of density which are used in the ART calculations. These are: $\bar{\rho}$ which is used for evaluation of elevation pressure drop, $(1/v')$ used for spatial acceleration effects, $[\bar{\rho} - d\psi/dX]$ used in the energy equation,† and (1/v) used for homogeneous flow:where

$$\bar{\rho} = R\rho_g + (1-R)\rho_f \; , \qquad (6.4)$$

$$(1/v') = \frac{1}{\left[\frac{X^2}{R} v_g + \frac{(1-X)^2}{(1-R)} v_f\right]} \; , \qquad (6.5)$$

$$\bar{\rho} - \frac{d\psi}{dX} = \left(\frac{v}{v_f v_g}\right) \frac{dR}{dX} \; , \qquad (6.6)$$

†This quantity may be obtained from the first two terms in the energy equation (since ψ is a function of H only):

$$\bar{\rho}\,\frac{\partial H}{\partial t} - H_{fg}\frac{\partial \psi}{\partial t} = \left[\bar{\rho} - H_{fg}\frac{d\psi}{dH}\right]\frac{\partial H}{\partial t} = \left[\bar{\rho} - \frac{d\psi}{dX}\right]\frac{\partial H}{\partial t} \; .$$

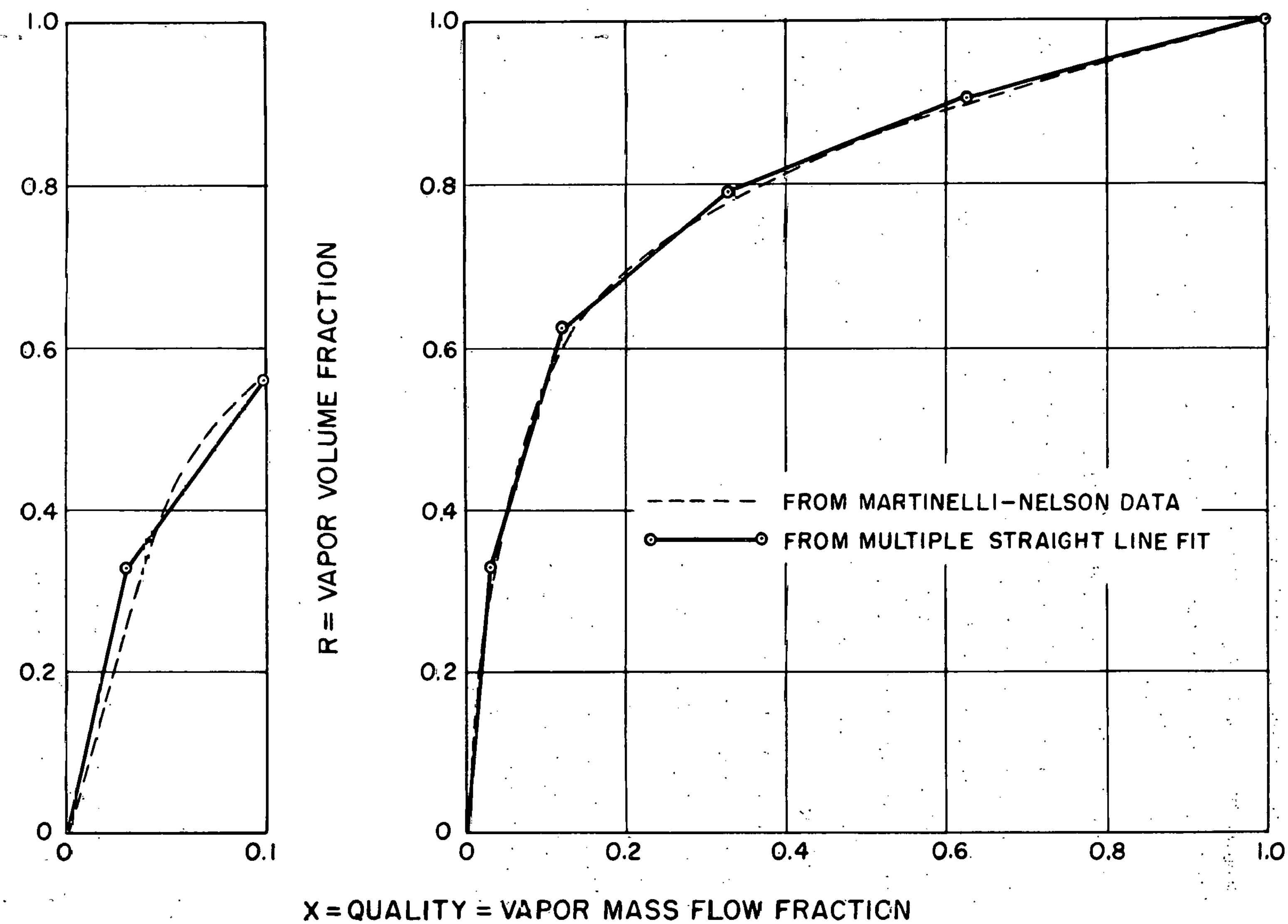

Fig. 1 - Multiple Straight Line Fit of Vapor Fractions at 1250 Psia

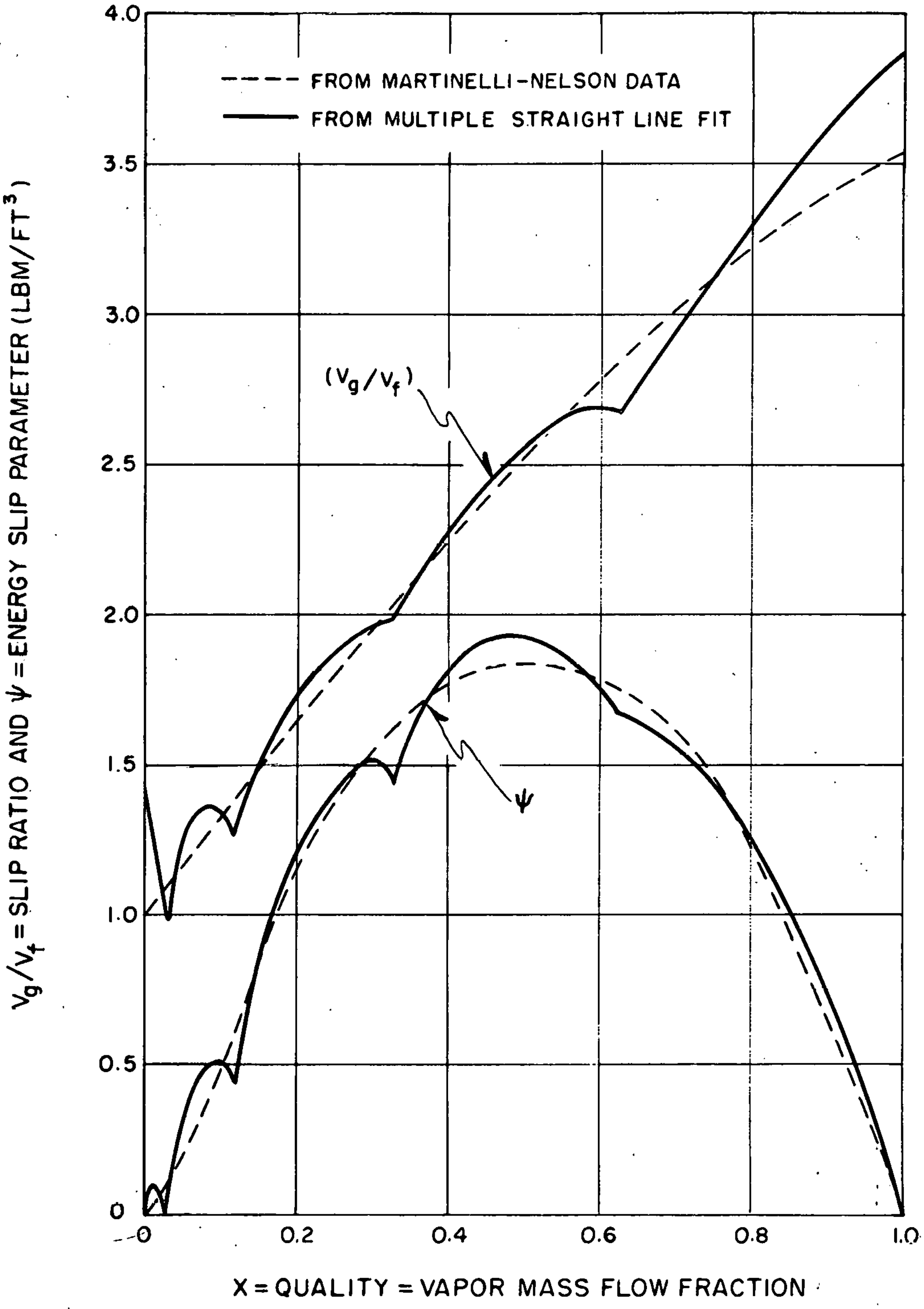

Fig. 2 - Slip Ratio and the Energy Slip Parameter at 1250 Psia

and $$(1/v) = \frac{1}{Xv_g + (1-X)v_f} \,. \qquad (6.7)$$

These densities as determined for the sample problem are shown in Figs. 3 and 4 as a function of quality. Values determined by graphical methods directly from the Martinelli-Nelson data are also shown. It may be seen that locally the multiple straight-line fit used in ART can be a fairly poor approximation to the smoother graphically-determined curves. However, since in the saturation region

$$\bar{\rho}\,\frac{\partial H}{\partial t} - H_{fg}\,\frac{\partial \psi}{\partial t} = \left[\bar{\rho} - \frac{d\psi}{dX}\right]\frac{\partial H}{\partial t} = H_{fg}\,\frac{\partial}{\partial t}\int_0^X \left[\bar{\rho} - \frac{d\psi}{dX}\right] dX \;, \qquad (6.8)$$

the behavior of the function $\int_0^X \left[\bar{\rho} - \frac{d\psi}{dX}\right] dX$ will give an indication of the effect of the multiple straight-line fitting on energy balance. This function is presented in Fig. 5. It is seen that the behavior of this function is approximately correct. A plot of this type is probably the best measure of the adequacy of the particular R(X) values which have been supplied.

F. Reactor Kinetics: Cards 6011, 6031, 6041, and 6171

The determination of temperature coefficient is discussed in WAPD-TM-156 (Ref 1, p 40). The choices of temperature coefficient and weighting have, however, been made arbitrarily in the present sample problem and are described in the following paragraphs.

This core, operating at lower pressure, is also assumed to have a lower inlet temperature (450°F) than that of problem XX (500°F). The temperature coefficient of problem XX (-2.5×10^{-4}) is changed in YY (-2.2×10^{-4}) because of this reduction in core temperature. The pass-wise split of temperature coefficient is assumed to remain the same, 2/5 of the total or $-.88 \times 10^{-4}$ being associated with the first-pass and 3/5 of the total or -1.32×10^{-4} with the second pass. Of the second-pass coefficient, -1.2×10^{-4} is associated with the region represented by the second-pass nominal channel and -0.12×10^{-4} is associated with the channel 7. No reactivity contribution from channel 6 is considered because it is used to represent extremes in dimensions, pressure drop, and heat input.

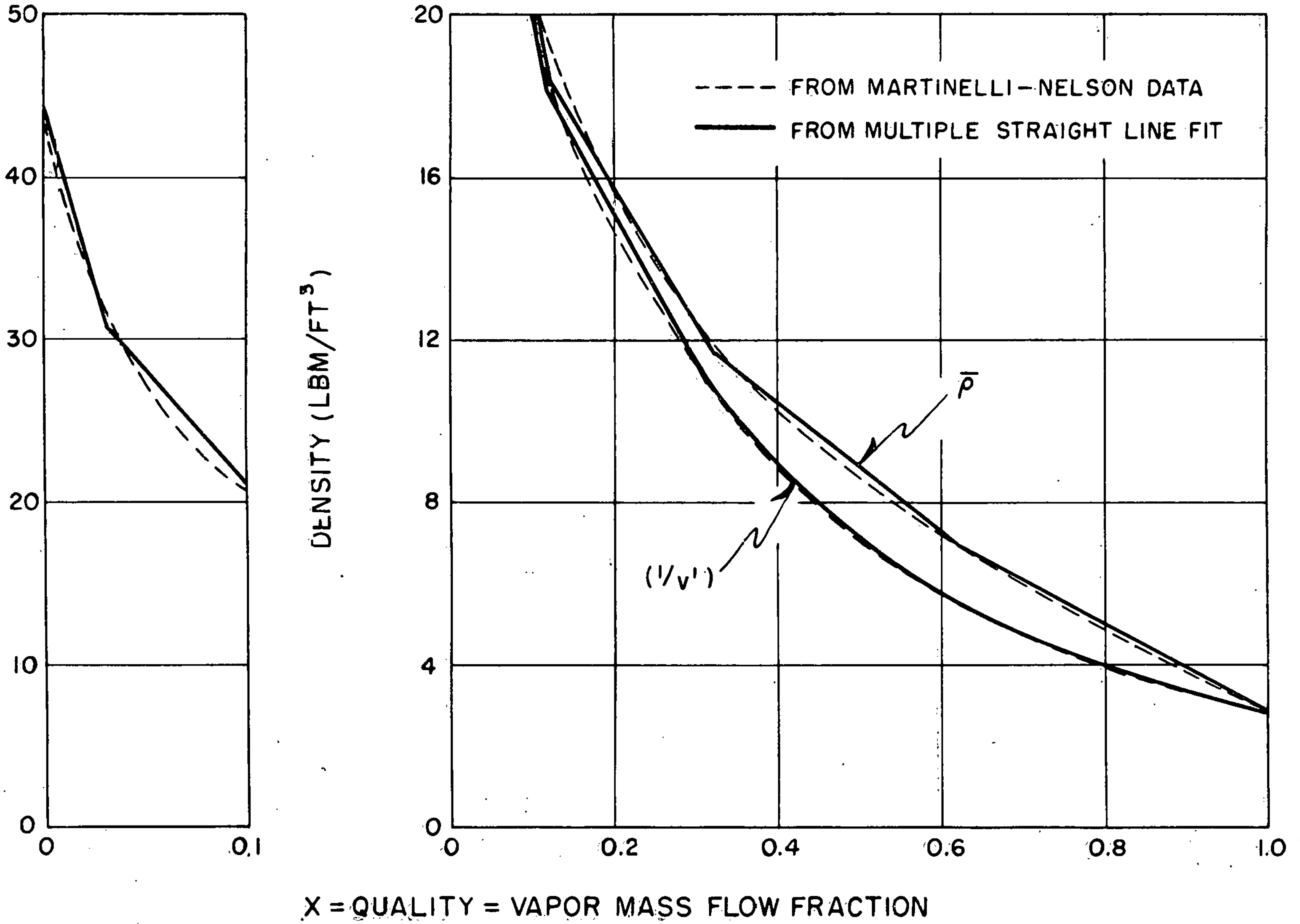

Fig. 3 - Densities at 1250 Psia for Use in Mass and Momentum Considerations

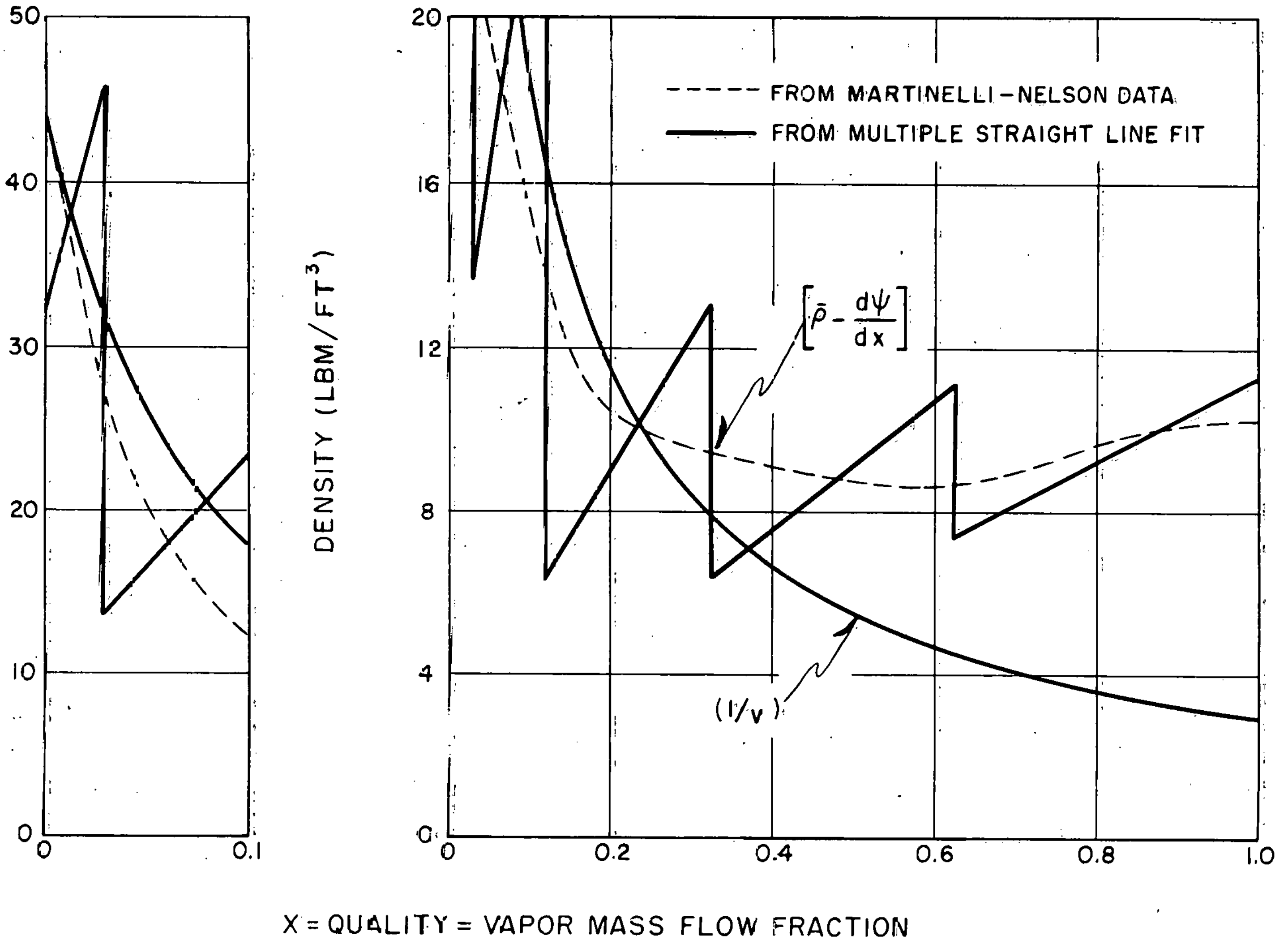

Fig. 4 - Homogeneous Density and Density for Use in Energy Considerations: 1250 Psia

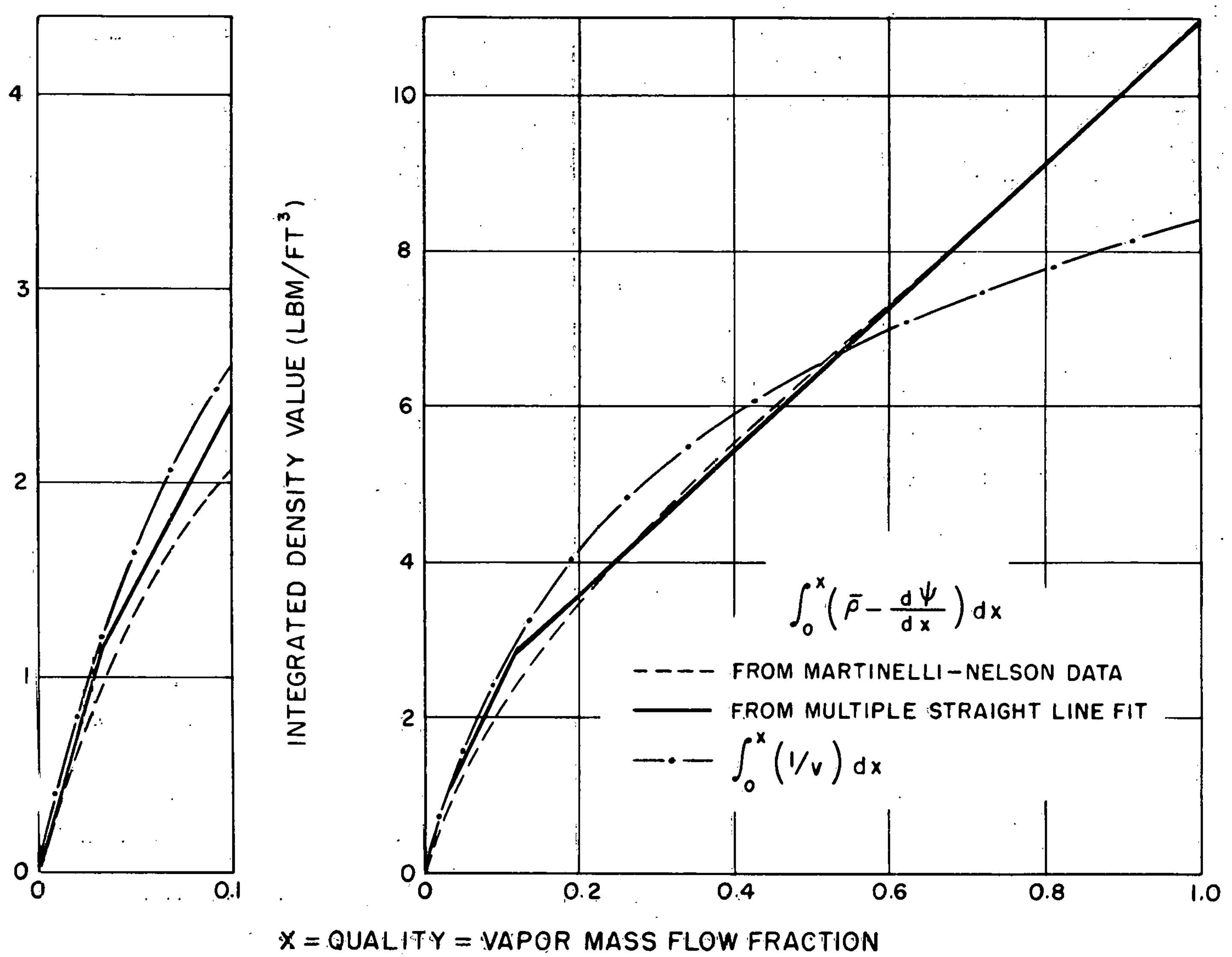

Fig. 5 - Important Density Integrals for Energy Calculations at 1250 Psia

The option is available to represent the nominal channel reactivity by a combination of temperature and density effects. That is, the reactivity may be considered to be made up of a portion due to temperature change with water density held constant (effect due to changes in thermal neutron cross sections, Doppler broadening, etc.), and a portion due to changes in density with temperature held constant (any changes in water number density affecting neutron thermalization, core leakage, and absorptions in the water). However, in the ART code, density is an explicit function of temperature, so that the portion due to density changes in the subcooled region may be considered as an effective temperature coefficient that varies with temperature:

$$\left.\frac{\partial(\delta K)}{\partial T_w}\right|_{\text{effective}} = \frac{\partial(\delta K)}{\partial \bar{\rho}} \frac{d\bar{\rho}}{dT_w} .$$

The scaling function $d\bar{\rho}/dT_w$ for this effective coefficient is shown in Fig. 6 as a function of temperature. An effective temperature coefficient thus obtained would have a discontinuity everywhere that $d\bar{\rho}/dT_w$ does. The effective reactivity scaling function $\bar{\rho}$ is shown in Fig. 7 as a function of temperature. Figure 6 shows that if temperature changes are over a relatively small range, a constant temperature coefficient is probably a better approximation than the sawtooth curve obtained by using a multiple straight fit.† For this reason, the reactivity effects of the nominal channels have been assumed to be entirely concentrated in temperature effects. Therefore, for the nominal channels, with the assumption of a uniform axial temperature coefficient:

$$\alpha_T = -.88 \times 10^{-4} - 1.2 \times 10^{-4} = -2.08 \times 10^{-4}/^{\circ}F .$$

The expression,

$$a_{mj} = \frac{1}{n}\left[\text{Fraction of } \alpha_T \text{ associated with channel } m\right] \text{ gives}$$

†A better fit can, of course, be obtained by using more points in the fitting procedure, with some attendant machine time increases.

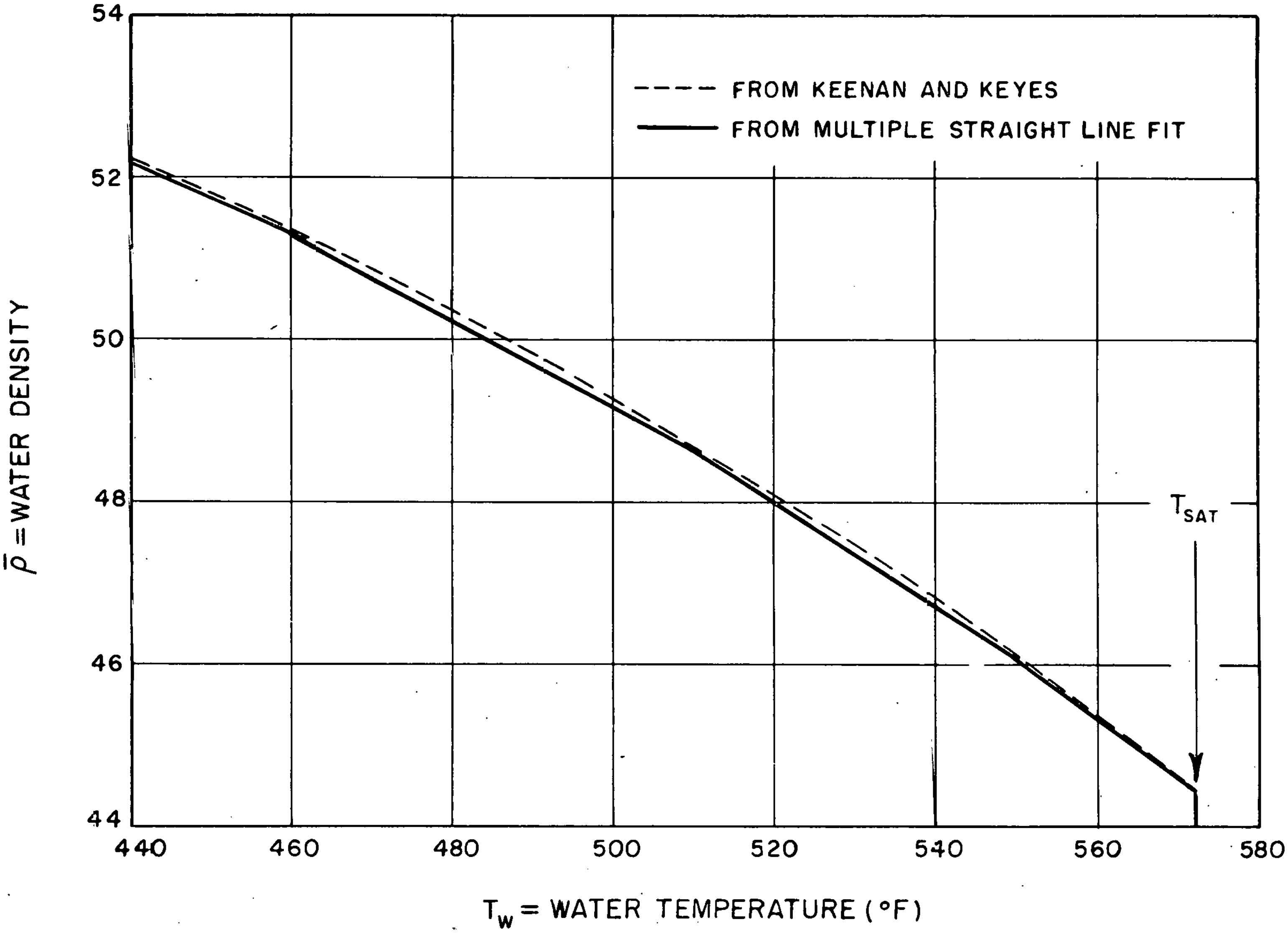

Fig. 6 - Water Density Derivative at 1250 Psia

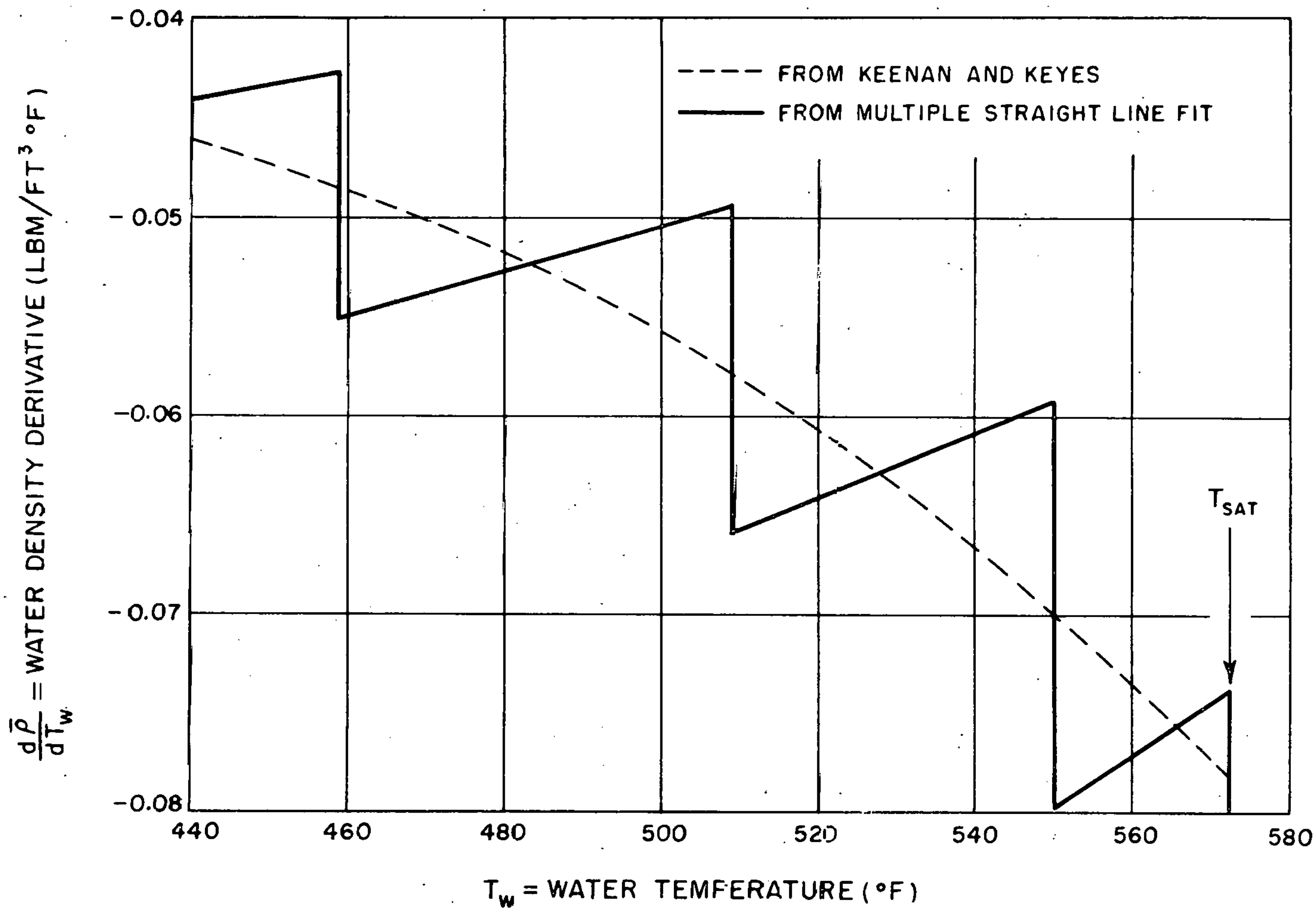

Fig. 7 - Water Density at 1250 Psia

$$a_{0j} = \frac{1}{6}\left[.88/2.08\right] = .0705 \text{ for channel 0 , and}$$

$$a_{5j} = \frac{1}{6}\left[1.2/2.08\right] = .0962 \text{ for channel 5 .}$$

Note that in the input, two of the a_{5j} numbers have been given as .0961 in order that the a_{mj} sum to one.

In the hot channel, the temperature change is over a much larger range, so that the density coefficient gives an adequate description of reactivity effects resulting from density changes (see Fig. 7). If it is assumed that the reactivity introduced by a uniform channel 7 temperature change from 450^oF to 500^oF is to be $-(.12 \times 10^{-4}/^oF) \times 50^oF = -6 \times 10^{-4}$, then

$$\alpha_v = \frac{\delta K}{\bar{\rho}_{500} - \bar{\rho}_{450}}$$

$$= \frac{-6 \times 10^{-4}}{49.17 \text{ lb}_m/\text{ft}^3 - 51.72 \text{ lb}_m/\text{ft}^3} = +2.35 \times 10^{-4} \text{ ft}^3/\text{lb}_m ,$$

where the densities have been evaluated by the straight-line fit used during code operation. In order to represent a uniform axial weighting, the b_{mj} values for channel 7 have been chosen as 1/12 for points 0 and 6, and as 1/6 for points 1 through 5. It should be noted that the b_{mj} weighting factors are given for n+1 points while a_{mj} factors are given for n points only.

G. Problem Input and Output

A print of the input cards and selected portions of the sample problem output are given in Appendix II. The results of the problem are similar in nature to the sample problem of WAPD-TM-156.

APPENDIX I: NOMENCLATURE

Dimensions 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 are in mixed units. Nomenclature not given here may be found in Appendix I of WAPD-TM-156 (Ref 1).

Symbol	Description	Defining Equation	Dimensions	Input Card
a_{mj}	Temperature coefficient weighting factors	(3.12),(3.14)	-----	6031, 6041
B_6	DNB correlation parameter	(3.19)	Mixed	5031
b_{mj}	Density coefficient weighting factors	(3.13),(3.15)	-----	61ml
$C_2 - C_4$	DNB correlation parameters	(3.19)	Mixed	5031
$f_7 - f_{10}$	Subcooled pressure drop correlation parameters	(3.16),(3.17)	Mixed	3021, 3025
H_{fg}	Latent heat of vaporization	-----	H/M	-----
H'	Parameter used in water energy balance calculations	(3.4)	H/M	-----
H_1	Enthalpy used in DNB correlation	(3.20)	H/M	5031
k_t	Local temperature coefficient of reactivity, volume basis	(2.22)	$(1/TL^3)$	-----
k_v	Local density coefficient of reactivity, volume basis	(2.22)	(1/M)	-----
L_j, L_1	Lengths used in DNB correlation	(3.19),(3.20)	L	5031
R	Volume fraction of vapor phase	(2.4)	-----	4041, 4051
V	Core volume	(2.22)	L^3	-----
V_f	Velocity of the liquid phase	(2.7)	(L/θ)	-----
V_g	Velocity of the vapor phase	(2.6)	(L/θ)	-----

Symbol	Description	Defining Equation	Dimensions	Input Card
V_{mj}	Portion of the core volume associated with point j in channel m	(3.14),(3.15)	L^3	-----
v'	Effective specific volume for spatial acceleration	(2.10)	(L^3/M)	-----
α_t	Over-all temperature coefficient of reactivity	(3.12),(3.14)	1/T	6011
α_v	Over-all density coefficient of reactivity	(3.13),(3.15)	(L^3/M)	6011
δK_r	Excess reactivity due to rod motion	(3.21)	-----	-----
δK_{r1}	Portion of reactivity due to rod motion from scram table	(3.22)	-----	6011, 7021
δK_{r2}	Portion of reactivity due to rod motion from independent reactivity table	(3.23)	-----	6051
δK_t	Excess reactivity due to temperature changes	(3.12)	-----	-----
δK_v	Excess reactivity due to water density changes	(3.13)	-----	-----
$\bar{\rho}$	Average water density	(2.4)	(M/L^3)	-----
ρ_f	Density of saturated liquid	-----	(M/L^3)	-----
ρ_g	Density of saturated vapor	-----	(M/L^3)	-----
ψ	Energy slip parameter	(2.11)	(M/L^3)	-----

Subscripts

E	Exit plenum
I	Inlet plenum
m	Channel number (0 = first pass NC, 1 to 4 = first pass HC, 5 = second pass NC, 6 to 9 = second pass HC). Also used for meat or average plate.

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, a portion of the IBM-704 output for this problem is given. Pages 1-5 of the output give a complete listing of the input quantities as accepted by the machine. Page 6 gives steady-state results and pages 7, 13, and 19 give results for three different times during the transient. As is noted in the input, additional transient output was printed during the transient but is not included here. This particular problem stopped when point 6 in channel 6 reached a quality of 100% at time = 1.58 sec. Since no calculations are performed in the superheat region, the problem was then discontinued.

```
YYYYYYYY   SAMPLE PROBLEM FOR WAPD-TM-202                                      ART04CARD0001
1011,.02,5,1.8                                                                      CARD0002
1021,6,2,0,2                                                                        CARD0003
1031,1,0,0,1,1                                                                      CARD0004
1041,3,2,2                                                                          CARD0005
1051,1,0,0,0,1,0,1,1,1,1,1,1                                                        CARD0006
1061,1250.,.1,15.0,32.17,.005,6.2,.4                                                CARD0007
2011,.0485,.018,.042,.018                                                           CARD0008
2021,0,33.2,8.1                                                                     CARD0009
2031,1.5,3.,6486.,.1944,.26,.5,.5,1.,1.,1.,1.,1.21,.9                               CARD0010
2041,3E4,.0241,2.5E5,.0162                                                          CARD0011
2051,1.0,.024,0                                                                     CARD0012
2061,.82,.82,1.09,1.18,1.06,.79,.48                                                 CARD0013
2511,.0485,.018,.042,.018                                                           CARD0014
2521,0,33.2,8.1                                                                     CARD0015
2531,1.5,4.,8170.,.1944,.26,.5,.5,1.,1.,1.,1.,1.21,.9                               CARD0016
2541,3E4,.0241,2.5E5,.0162                                                          CARD0017
2551,.926,.024,0                                                                    CARD0018
2561,1.16,1.16,1.48,1.62,1.23,.77,.45                                               CARD0019
2611,.045,.015,.043,.015                                                            CARD0020
2621,0,33.2,8.1                                                                     CARD0021
2631,1.5,4.,8297.,.18,.26,.6581,.6581,1.,1.,.925,.925,1.21,.9                       CARD0022
2641,3E4,.0252,2.5E5,.0175                                                          CARD0023
2651,1.38,.024,1.167                                                                CARD0024
2661,2.06,2.06,2.81,3.14,2.55,1.66,1.05                                             CARD0025
2671,.75,.75,.708,.825,1.026,.759,.632                                              CARD0026
2711,.0485,.018,.042,.018                                                           CARD0027
2721,0,33.2,8.1                                                                     CARD0028
2731,1.5,4.,8170.,.1944,.26,.5,.5,1.,1.,1.,1.,1.21,.9                               CARD0029
2741,3E4,.0241,2.5E5,.0162                                                          CARD0030
2751,1.,.024,0                                                                      CARD0031
2761,2.06,2.06,2.81,3.14,2.55,1.66,1.05                                             CARD0032
3025,0,0,1.25                                                                       CARD0033
3031,0,.1,.5,.77,.93,1.                                                             CARD0034
3041,.125,2.09,8.36,26.5,36.5,36.5,26.                                              CARD0035
3042,.45,1.87,7.48,23.8,32.3,32.8,23.2                                              CARD0036
3043,1.927,1.1,4.4,14.,19.2,19.2,13.6                                               CARD0037
3044,5.,1.1,3.75,11.9,16.4,16.4,11.7                                                CARD0038
4041,.030,.12,.325,.625,1.                                                          CARD0039
4051,.33,.625,.79,.905,1.                                                           CARD0040
6011,.07,3.2E-5,0,-2.08E-4,2.35E-4                                                  CARD0041
6021,2.88E-4,.01277,16.8E-4,.0319,15.36E-4,.1181,32.72E-4,.318                      CARD0042
6022,10.8E-4,1.507,1.44E-4,5.33                                                     CARD0043
6031,.0705,.0705,.0705,.0705,.0705,.0705                                            CARD0044
6041,.0961,.0962,.0962,.0962,.0962,.0961                                            CARD0045
6101,0,0,0,0,0,0,0                                                                  CARD0046
6151,0,0,0,0,0,0,0                                                                  CARD0047
6161,0,0,0,0,0,0,0                                                                  CARD0048
6171,.0833,.1667,.1667,.1666,.1667,.1667,.0833                                      CARD0049
9011,10,.5,13,1.8                                                                   CARD0050
9021,1.,.87,.769,.69,.625,.571,.526,.488,.454,.426                                  CARD0051
9022,.4,.357,.323,.294,.27,.25,.233,.217,.204,.192                                  CARD0052
9023,.182,.172,.164,.156                                                            CARD0053
10011,1,.02                                                                         CARD0054
10021,450.,450.                                                                     CARD0055
11011,.848,4.,0,.515                                                                CARD0056
                                                                                    CARD0057
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                              YYYYYYYY   SAMPLE PROBLEM FOR WAPD-TM-202                         ART04  PAGE    1

A. CONTROL INFORMATION

     TIME INCREMENTS  .0200   5  1.800

        PROBLEM SIZE   6 SECTIONS   2 PASS(ES)   0 HOT CHANNEL(S) 1ST PASS   2 HOT CHANNEL(S) 2ND PASS

           DATA TAPE  FILE  1, SUB DELTA P(CARD) SAT DELTA P(CARD) FL PROP(TAPE) BO COR(TAPE)

       INPUT OPTIONS  DELTA P KIND 3, BOR KIND 2, HEAT GEN TYPE 2

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

  OVERALL CONDITIONS  P.0=1250  Q*.0=.1000  K.CR=15.00  G=32.17  EPS=.005  DELTA Z= 6.200  PBS=  .40
```

```
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=1.210  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  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=1.210  GL/G= .900
  FRICTION FACTORS  (N.R, F.ISO)   30000, .0241  250000, .0162
   HEAT GENERATION  Q/Q*= .926  R=.024  PHIL/PHI= .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.J=1.500  G*=4.000  H*= 8297  D.H=.1800  MUBAR=.260
                   K.C= .658  K.E= .658  SIGSQ.0=1.000  SIGSQ.N=1.000  K.PF= .925  K.PA= .925
                   H.F/H=1.210  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   .835  1.026   .759   .632
          CHANNEL  7
       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=1.210  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  2.060
                   2.060  2.810  3.140  2.550  1.660  1.050
```

YYYYYYYY SAMPLE PROBLEM FOR WAPD-TM-202

C. PRESSURE DROP CORRELATIONS

SUBCOOLED DELTA P, 3RD KIND F.8= .000000 F.9= .000 F.10= 1.250

SATURATION DELTA P G	X= .000	.100	.500	.770	.930	1.000
.125	2.09	8.36	26.50	36.50	36.50	26.00
.450	1.87	7.43	23.80	32.80	32.80	23.20
1.927	1.10	4.40	14.00	19.20	19.20	13.60
5.000	1.10	3.75	11.90	16.40	16.40	11.70

D. FLUID PROPERTIES

ENTHALPY	375.6	440.2	498.3	549.0	578.5	1181.0
TEMPERATURE	400.0	459.0	509.0	550.0	572.3	572.3
SPECIFIC VOLUME	.01853	.01948	.02052	.02166	.02250	.34560

X	.0000	.0150	.0300	.0750	.1200	.2225	.3250	.4750	.6250	.8125	1.0000
R(X)	.0000	.1650	.3300	.4775	.6250	.7075	.7900	.8475	.9050	.9525	1.0000
VG/VF	1.3964	1.1838	.9645	1.3628	1.2568	1.8173	1.9660	2.5008	2.6874	3.3194	3.8913
PSI(X)	.000	.086	-.033	.464	.409	1.301	1.490	1.932	1.657	1.199	.000

E. BURNOUT CORRELATIONS

BURNOUT, 2ND KIND	B.4	M.4	G.1	R.5	B.5	M.5	C.1	D.1
	.386	2.500	10.000	2.000	.240	2.500	1.000	.100

F. HEAT GENERATION (REACTOR KINETICS, NO SCRAM)

REACTOR KINETICS .0700 .0000320 .000000 -.000208 .000235

BETA BAR	.000288	.001680	.001536	.003272	.001080	.000144
LAMDA	.01277	.03190	.11810	.31800	1.50700	5.33000

A.0J	.0705	.0705	.0705	.0705	.0705	.0705
A.5J	.0961	.0962	.0962	.0962	.0962	.0961
B.0J	.0000					
	.0000	.0000	.0000	.0000	.0000	.0000
B.5J	.0000					
	.0000	.0000	.0000	.0000	.0000	.0000
B.6J	.0000					
	.0000	.0000	.0000	.0000	.0000	.0000
B.7J	.0833					
	.1667	.1667	.1666	.1667	.1667	.0833

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	.3220	.2940	.2700	.2500	.2330	.2170	.2040	.1920
	TIME	1.500	1.600	1.700	1.800						
	G/G.0	.1820	.1720	.1640	.1560						

H. INLET TEMPERATURES

PASS ONE	TIME	.000	.020
	T.IN NC	450.0	450.0

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

STEADY STATE FLOW

CHANNEL	G.*	G.O	NR ITER	DELTA P.S	ITER P.S	= P.F.	+ P.EL	+ P.A2
0	3.000	3.000		7.417	7.417	6.257	1.102	.057
5	4.000	4.000		12.031	12.031	10.852	1.084	.095
6	4.000	3.363	3	11.210	11.227	9.899	1.043	.285
7	4.000	3.949	1	12.031	12.083	10.815	1.062	.206

TRANSIENT RESULTS START ON NEXT PAGE

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                                     YYY~YYYY   SAMPLE PROBLEM FOR WAPD-TM-202                         ART04  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=  5.967 BOR=         AT J=    BULK BOIL AT T=         BURNOUT AT T=
                            DELTA P.F =   6.257, DELTA P.EL =   1.102, DELTA P.A1 =  -1.450, DELTA P.A2 =    .057
     WATER TEMP-QUAL  450.00
                      453.19   457.44   461.85   465.73   468.63   470.39                                        453.444
            HEAT FLUX   .0800
                        .0800    .1064    .1152    .1035    .0771    .0468
   CHANNEL 5  G/G.0= 1.0000  G= 4.000  DELTA P= 10.098 BOR=         AT J=    BULK BOIL AT T=         BURNOUT AT T=
                            DELTA P.F =  10.352, DELTA P.EL =   1.084, DELTA P.A1 =  -1.933, DELTA P.A2 =    .095
     WATER TEMP-QUAL  467.37
                      470.32   474.09   478.21   481.34   483.30   484.44                                        469.791
            HEAT FLUX   .1048
                        .1048    .1338    .1464    .1112    .0696    .0407
   CHANNEL 6  G/G.0= 1.0000  G= 3.363  DELTA P=  9.422 BOR=  3.554 AT J= 3  BULK BOIL AT T=         BURNOUT AT T=
                            DELTA P.F =   9.899, DELTA P.EL =   1.043, DELTA P.A1 =  -1.806, DELTA P.A2 =    .285
     WATER TEMP-QUAL  476.04
                      486.06   499.72   514.53   526.30   533.90   538.71                                        535.050
          METAL TEMP  557.28
                      567.30   610.53   638.46   625.87   599.37   580.12
        SURFACE TEMP  514.46
                      524.48   552.13   573.20   573.86   564.86   558.29
           CRIT TEMP  583.23
                      583.23   584.11   584.44   583.82   582.65   581.54
           HEAT FLUX    .2775
                        .2775    .3785    .4229    .3435    .2236    .1414
   CHANNEL 7  G/G.0= 1.0000  G= 3.949  DELTA P= 10.098 BOR=         AT J=    BULK BOIL AT T=         BURNOUT AT T=
                            DELTA P.F =  10.815, DELTA P.EL =   1.062, DELTA P.A1 =  -1.986, DELTA P.A2 =    .206
     WATER TEMP-QUAL  476.04
                      481.73   489.60   498.34   505.43   509.99   512.74                                        502.973
          METAL TEMP  538.14
                      543.87   574.30   593.98   582.30   560.03   544.39
        SURFACE TEMP  500.90
                      506.64   523.51   536.23   536.21   530.02   525.41
           CRIT TEMP  582.38
                      582.38   583.20   583.50   582.93   581.86   580.83
           HEAT FLUX    .2011
                        .2011    .2743    .3065    .2489    .1620    .1025
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                         YYYYYYYY   SAMPLE PROBLEM FOR WAPD-TM-202                           ART04  PAGE   13
TIME=  .600  P/F=  2.232  P=   .797  P/F SET AT T=          P SET AT T=        SCRAM SET AT T=T.3=
                    DEL K = -.002085 =  .000000 (ROD) + -.001852 (TEMP) + -.000233 (VOID)

   CHANNEL 0  G/G.0=  .3570  G= 1.071  DELTA P=  1.850 BOR=          AT J=    BULK BOIL AT T=        BURNOUT AT T=

                    DELTA P.F =     .935, DELTA P.EL =    1.093, DELTA P.A1 =   -.190, DELTA P.A2 =    .012

     WATER TEMP-QUAL  450.00
                      456.21   463.65   470.96   476.81   480.29   481.34                              466.184
           HEAT FLUX   .0609
                       .0591    .0772    .0819    .0714    .0507    .0278

   CHANNEL 5  G/G.0=  .3570  G= 1.428  DELTA P=  2.461 BOR=          AT J=    BULK BOIL AT T=        BURNOUT AT T=

                    DELTA P.F =   1.619, DELTA P.EL =    1.075, DELTA P.A1 =   -.253, DELTA P.A2 =    .020

     WATER TEMP-QUAL  467.37
                      473.34   480.57   488.04   493.02   495.32   495.83                              483.028
           HEAT FLUX   .0811
                       .0793    .0995    .1071    .0784    .0457    .0233

   CHANNEL 6  G/G.0=  .2324  G=   .781  DELTA P=  2.357 BOR=  3.176 AT J= 3  BULK BOIL AT T=  .440  BURNOUT AT T=

                    DELTA P.F =   1.731, DELTA P.EL =     .827, DELTA P.A1 =   -.445, DELTA P.A2 =    .245

     WATER TEMP-QUAL  476.04
                      499.46   534.26   567.59    .0501    .0754    .0871                              631.011
          METAL TEMP  586.46
                      604.66   631.40   637.39   626.76   610.48   598.94
        SURFACE TEMP  558.03
                      577.58   583.55   583.87   583.29   582.18   581.10
           CRIT TEMP  582.23
                      582.12   583.55   583.87   583.29   582.18   581.10
           HEAT FLUX   .1842
                       .1755    .3100    .3468    .2817    .1834    .1156

   CHANNEL 7  G/G.0=  .3552  G= 1.403  DELTA P=  2.461 BOR=          AT J=    BULK BOIL AT T=        BURNOUT AT T=

                    DELTA P.F =   1.618, DELTA P.EL =    1.041, DELTA P.A1 =   -.246, DELTA P.A2 =    .048

     WATER TEMP-QUAL  476.04
                      487.68   502.80   518.28   529.30   534.89   536.89                              532.800
          METAL TEMP  548.79
                      558.80   598.28   623.45   612.17   585.65   565.99
        SURFACE TEMP  520.02
                      530.67   560.51   581.85   579.39   565.57   554.48
           CRIT TEMP  581.78
                      581.72   582.44   582.69   582.09   580.97   579.85
           HEAT FLUX   .1554
                       .1519    .2039    .2246    .1770    .1084    .0622
```

```
TIME= 1.200  P/F=  2.991  P=   .649  P/F SET AT T=        P SET AT T=        SCRAM SET AT T=T.3=
                DEL K = -.004007 =  .000000 (ROD) + -.003492 (TEMP) + -.000515 (VOID)
   CHANNEL 0  G/G.0=  .2170  G=  .651  DELTA P=  1.394 BOR=        AT J=    BULK BOIL AT T=        BURNOUT AT T=
                DELTA P.F =    .375, DELTA P.EL =   1.085, DELTA P.A1 =   -.073, DELTA P.A2 =    .006
     WATER TEMP-QUAL  459.00
                      458.53   468.61   478.75   486.91   491.77   493.19                            479.958
           HEAT FLUX   .0504
                       .0490   .0640    .0678    .0590    .0416    .0223
   CHANNEL 5  G/G.0=  .2170  G=  .868  DELTA P=  1.630 BOR=        AT J=    BULK BOIL AT T=        BURNOUT AT T=
                DELTA P.F =    .649, DELTA P.EL =   1.068, DELTA P.A1 =   -.097, DELTA P.A2 =    .010
     WATER TEMP-QUAL  467.37
                      475.53   485.46   495.80   502.73   506.09   506.91                            495.922
           HEAT FLUX   .0668
                       .0654   .0822    .0835    .0649    .0378    .0191
   CHANNEL 6  G/G.0=  .0645  G=  .217  DELTA P=  1.588 BOR=  1.533 AT J= 3  BULK BOIL AT T=  .440  BURNOUT AT T=
                DELTA P.F =   1.052, DELTA P.EL =    .412, DELTA P.A1 =   -.025, DELTA P.A2 =    .149
     WATER TEMP-QUAL  476.04
                      547.52   .1798    .4234    .5849    .6733    .6988                             999.543
          METAL TEMP  510.59
                      510.60   621.73   626.57   617.89   604.58   595.15
        SURFACE TEMP  582.18
                      582.18   582.98   583.27   582.72   581.67   580.66
           CRIT TEMP  582.18
                      582.18   582.98   583.27   582.72   581.67   580.66
           HEAT FLUX   .1841
                       .1842   .2511    .2806    .2279    .1485    .0940
   CHANNEL 7  G/G.0=  .1891  G=  .747  DELTA P=  1.630 BOR=        AT J=    BULK BOIL AT T=        BURNOUT AT T=
                DELTA P.F =    .733, DELTA P.EL =   1.015, DELTA P.A1 =   -.141, DELTA P.A2 =    .023
     WATER TEMP-QUAL  476.04
                      492.82   515.29   539.09   556.50   565.17   566.85                            571.283
          METAL TEMP  556.24
                      570.86   615.34   620.24   612.63   600.89   591.59
        SURFACE TEMP  533.53
                      548.75   582.11   582.44   581.93   580.95   579.84
           CRIT TEMP  581.24
                      581.18   582.11   582.44   581.93   580.95   579.84
           HEAT FLUX   .1227
                       .1194   .1795    .2041    .1658    .1077    .0635
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