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STEAMFREQ-I, A MODEL FOR DYNAMIC STABILITY ANALYSIS OF STEAM GENERATORS WITH IMPOSED HEAT FLUX DISTRIBUTIONS

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PREPARED FOR
SANDIA LABORATORIES
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ABSTRACT

This report presents the results of analysis to develop an advanced computer model, STEAMFREQ-I, for the investigation of density-wave instabilities in steam generators with imposed heat flux. The key model features include a drift flux flow model in the boiling region, spatial variation of heat flux, wall dynamics, and variable steam properties in the superheat region. Stability predictions for STEAMFREQ-I are compared with those from two other codes. In addition, stability predictions are compared with data representing unstable and stable conditions obtained from a solar receiver panel test and with stability threshold data from a sodium-heated steam generator test.

1. INTRODUCTION

The computer code STEAMFREQ-I represents a model for the investigation of density-wave instabilities in a steam generator with imposed heat flux conditions. The basic approach used in STEAMFREQ-I is similar to that of NUFREQ[1], previously developed to investigate instabilities in boiling systems. Major new features of STEAMFREQ-I include:

a. Arbitrary spatial variation of the imposed heat flux throughout the channel length;

b. Consideration of wall dynamics resulting in time-dependent heat transfer coefficients and heat flux throughout the channel length;

c. Use of a drift-flux flow model in the boiling region to take into account the relative velocities between the phases; and

d. Consideration of variable steam properties in the superheat region.

Analysis leading to the governing conservation equations is presented in Section 2. The computational method leading to a solution is described in Section 3. Stability predictions are compared with those obtained with two other codes and with experimental data in Section 4.

2. ANALYTICAL MODEL

A schematic representation of a boiling loop is shown in Figure 1. The loop is modeled in STEAMFREQ-I with the following components:

a. heated single-phase region,
b. heated two-phase boiling region,
c. heated superheat region,
d. outlet resistance and adiabatic riser,
e. unheated single-phase inlet region and inlet resistance,
f. circulation pump.

Any region that is not present in a system can be eliminated either through input options or by internal logic.

The loop is modeled with the governing mass and energy conservation equations in each region. These equations are coupled locally (in the radial direction) with the wall temperature perturbations. The equations are solved by linearizing and Laplace-transforming methods. The response of the system to a sinusoidal inlet velocity oscillation is subsequently obtained. The amplitude and phase change of the pressure drop response in each region are calculated from the linearized momentum equation.

The boundary conditions for the pressure drop provide the stability criteria for the system. For parallel channel analysis, instability for a certain (the "hottest") channel occurs when:

$$\delta(\Delta P_{1\phi,ch}) + \delta(\Delta P_{2\phi+s,ch}) = 0 \tag{1}$$

For analysis of the entire loop, instability occurs when:

$$\delta(\Delta P_{1\phi,\ell}) + \delta(\Delta P_{2\phi+s,\ell}) = 0 \tag{2}$$

It is convenient to evaluate system stability in terms of a Nyquist plot. The variable to be plotted can be arbitrarily selected and for our case, a logical choice is:

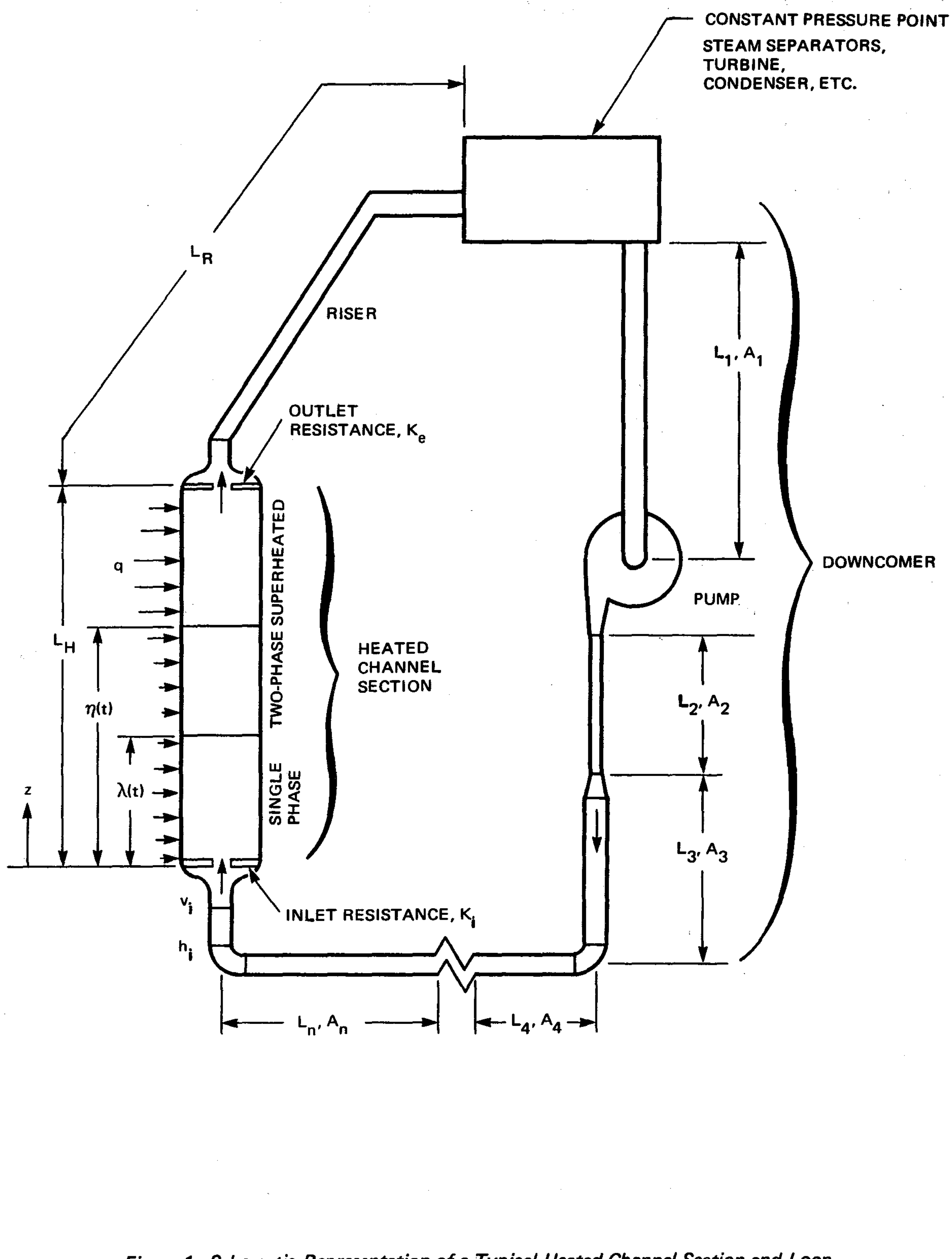

Figure 1. Schematic Representation of a Typical Heated Channel Section and Loop

$$\frac{\delta(\Delta P_{2\phi} + s)}{\delta(\Delta P_{1\phi})}$$

The system is unstable when the Nyquist locus intercepts the real axis to the left of the -1 point.

2.1 Heated Single-Phase Region

The mass and energy conservation equations for the single-phase region can be written as:

$$v^+ = v(t) \tag{3}$$

$$\frac{\partial T_w^+}{\partial t} + v^+ \frac{\partial T_w^+}{\partial z} = \frac{q_1^+ P_h}{\rho c A} \tag{4}$$

where the superscript + indicates variables having both spatial and time dependence. The density ρ is assumed constant and equal to the average density based on the inlet conditions and the liquid phase at the boiling boundary $z = \lambda$. By specifying the heat flux at discrete nodes, as illustrated in Figure 2, we can define a distance Z as:

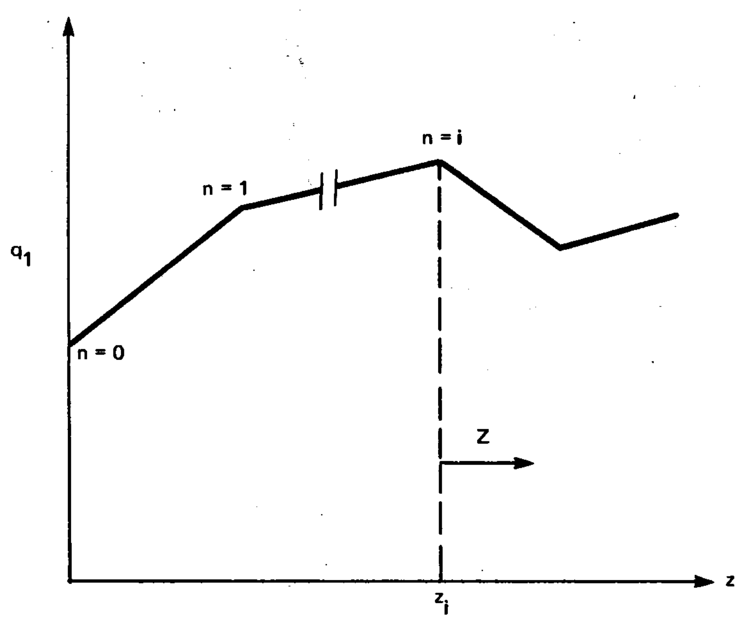

Figure 2. Heat Flux Distribution Along the Channel

$$Z = z - z_i \tag{5}$$

At steady-state $\frac{\partial}{\partial t} = 0$ and Equations 4 and 5 yield:

$$\frac{dT_w}{dZ} = \frac{q_1 P_h}{\rho v C A} \tag{6}$$

By utilizing the heat flux gradient, f', for a segment, the heat flux can be separated into two parts as follows:

$$q_1 = q + f' Z \tag{7}$$

Substituting Equation 7 into Equation 6 and integrating yields:

$$T_w = T_{wi} + \frac{P_h}{\rho v c A} (q Z + f' \frac{Z^2}{2}) \tag{8}$$

Starting from the inlet temperature, Equation 8 can be used for each segment until bulk boiling occurs.

Perturbing and Laplace-transforming Equations 3 and 4 yields:

$$\delta v = \delta v_i \tag{9}$$

and

$$\frac{d\delta T_w}{dz} + \frac{s}{v} \delta T_w = \frac{q_i P_h}{\rho c V A} \left(\frac{\delta q_i}{q_i} - \frac{\delta V}{V}\right) \tag{10}$$

where s is the Laplace-transform variable and δ(.) is the Laplace-transformed perturbation of the variable (.). The external heat flux (constant in time) is imposed on the outer wall. The heat input from the inner wall to the fluid is variable during flow oscillations because of the variation of the heat transfer coefficient and tube wall temperature. Assuming that this coupling between the wall and the fluid depends only on local conditions, the heat flux perturbation, δq_1, can be expressed as a function of the fluid temperature perturbation and the heat transfer coefficient perturbation as follows:

$$\delta q_1 = \alpha_1 \left[\delta T_w + \frac{\delta H}{H} (T_w - T_1)\right] \quad (11)$$

Here, α_1 is a constant which depends on the tube geometry and thermal conductivity. The derivation of Equation 11 for the cases of cylindrical and flat-plate geometry is presented in Appendix A. The perturbation δH depends on the heat transfer correlation used. For the single-phase region where a Dittus-Boelter type correlation is commonly used, δH becomes:

$$\frac{\delta H}{H} = a_1 \frac{\delta v}{v} \quad (12)$$

where a_1 is the Reynolds number exponent, with values around 0.8.

Substituting Equations 11, 12 and the heat transfer relationship

$$q_1 = H(T_1 - T_w) \quad (13)$$

into Equation 10, we obtain:

$$\frac{d\delta T_w}{dz} + \alpha_2 \, \delta T_w = - \alpha_3 q_1 \quad (14a)$$

where

$$\alpha_2 \equiv \frac{s}{v} - \frac{P_h \alpha_1}{\rho c v A} \quad (14b)$$

$$\alpha_3 \equiv \frac{P_h}{\rho v c A} \frac{\delta v}{v} \left(1 + \frac{\alpha_1 a_1}{H}\right) \quad (14c)$$

Using Equation 7 for q_1 in each segment, Equation 14a is integrated to yield:

$$\delta T_w = \{\delta T_{wi} + \frac{\alpha_3}{\alpha_2}(q - \frac{f'}{\alpha_1})\} e^{-\alpha_2 Z} - \alpha_3\{\frac{f'Z + q}{\alpha_2} - \frac{f'}{\alpha_2^2}\} \quad (15)$$

Starting with $\delta T_{wi} = 0$ at the channel inlet, Equation 15 is used to determine δT_w at each node up to the steady-state boiling boundary, where the temperature perturbation is transformed into a boiling-boundary perturbation $\delta\lambda$. Figure 3 shows the water temperature near the boiling boundary at two different times t' and t". An increase in δT_w from time t' to time t" results in a decrease in $\delta\lambda$. Therefore, the boiling boundary perturbation is to a first order:

$$\delta\lambda = - \frac{\delta T_w(\lambda)}{\frac{\partial T_w}{\partial z}\Big|_\lambda} \quad (16)$$

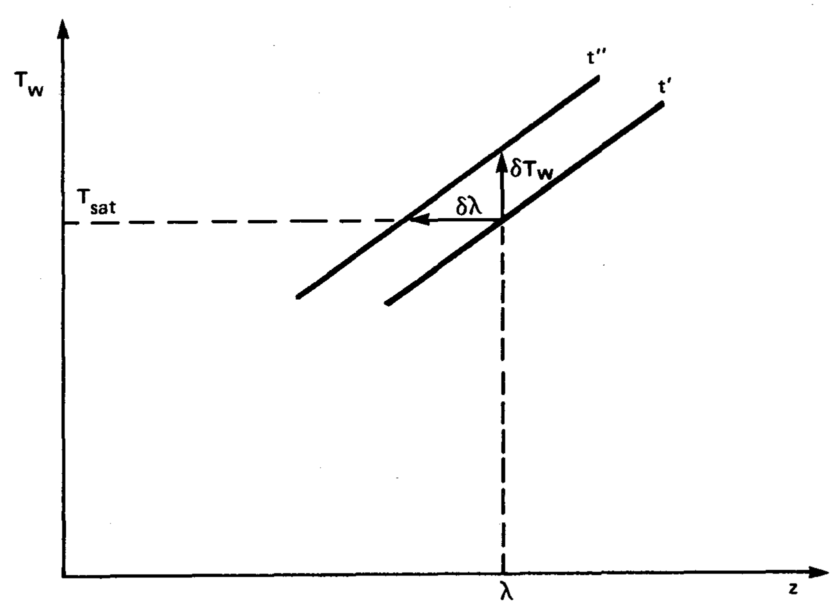

Figure 3. Water Temperature Near the Boiling Boundary (to First-Order Approximation) at Two Different Times t' and t"

Combining Equations 6 and 16 yields:

$$\delta\lambda = -\frac{\rho vcA}{q_1 P_h} \delta T_w(\lambda) \tag{17}$$

The momentum equation for the single-phase region can be written as:

$$-\frac{\partial P^+}{\partial z} = \rho \frac{D_v v^+}{Dt} + \frac{f\rho v^{+2}}{2D_H} + C_g g \rho \tag{18}$$

The steady-state pressure drop can be obtained by setting $\frac{\partial}{\partial t} = 0$ and integrating from Z = 0 to Z = λ:

$$\Delta P_{1\phi} = \frac{f\rho v_i^2}{2D_H} \lambda + C_g g \rho \lambda + K_i \frac{\rho v_i^2}{2} \tag{19}$$

The K_i term is included to account for pressure drop due to inlet orificing.

Equation 18 is perturbed, Laplace-transformed, and integrated from Z = 0 to Z = λ + δλ to yield:

$$\delta(\Delta P_{1\phi}) = \int_0^\lambda \left(\rho \frac{D_v \delta v}{Dt} + \frac{f\rho v\delta v}{D_H}\right)dz + K_i \rho v_i \delta v_i + \left(\frac{f\rho v_i^2}{2D_H} + C_g g \rho\right)\delta\lambda \tag{20}$$

The first term in the integral can be simplified as follows:

$$\frac{D_v \delta v}{Dt} = \frac{\partial \delta v}{\partial t} + v \frac{\partial \delta v}{\partial z} = s\, \delta v_i$$

where the second term on the right hand side is zero from Equation 9. Equation 20 then becomes:

$$\delta(\Delta P_{1\phi}) = \left(s\rho\lambda + \frac{f\rho v_i \lambda}{D_H} + K_i \rho v_i\right) \delta v_i + \left(\frac{f\rho v_i^2}{2D_H} + C_g g \rho\right)\delta\lambda \tag{21}$$

2.2 Boiling Region

Conservation equations for a two-phase mixture can be formulated in a number of equivalent ways[2]. The formulation that takes into account the vapor-liquid drift velocity and is most suitable for this analysis is that of the drift-flux model by Zuber et al[3]. The continuity equations of the vapor and liquid phases are transformed into a continuity equation for the volumetric flux density, j:

$$\frac{dj^+}{dz} = \Omega^+ \tag{22}$$

where

$$\Omega^+ \equiv \frac{\Gamma_g^+(\rho_f - \rho_g)}{\rho_f \rho_g} \tag{23}$$

and Γ_g^+ is the vapor generation rate,

$$\Gamma_g^+ \equiv \frac{q_1^+ P_h}{A h_{fg}} \tag{24}$$

and a density propagation equation:

$$\frac{\partial \rho^+}{\partial t} + C_k^+ \frac{\partial \rho^+}{\partial z} = - \rho'^+ \Omega^+ \tag{25}$$

where

$$C_k^+ \equiv j^+ + V'^+_{gj} + \alpha^+ \frac{\partial V^+_{gj}}{\partial \alpha} \tag{26}$$

$$\rho'^+ \equiv \rho_f + C_o (\rho_f - \rho^+) \tag{27}$$

$$V'^+_{gj} \equiv (C_o - 1) j^+ + V^+_{gj} \tag{28}$$

The derivation of these equations can be found in Reference 4. The term Ω is usually referred to as the "reaction frequency," with C_k as the "kinetic wave velocity," ρ the average mixture density, and V^+_{gj} representing the drift velocity of the vapor phase with respect to the volumetric flux. The average mixture density is defined as:

$$\rho = \alpha\rho_g + (1-\alpha)\rho_f \tag{29a}$$

The drift velocity is usually represented as:

$$V^+_{gj} = (\text{constant})\ (1-\alpha^+)^n \tag{29b}$$

The exponent n ranges from 0 to 1.5. The drift flux model correlation parameter, C_o, is defined as:

$$C_o \equiv \frac{\int_A (\alpha j)dA}{(\int_A (\alpha)dA)(\int_A (j)dA)} \tag{30}$$

The variable ρ^+ is transformed into a dimensionless density function, ϕ^+, by using the following definition:

$$\phi^+ = \frac{1}{C_o} \ln \frac{\rho'^+}{\rho_f} \tag{31}$$

Substituting Equation 31 into Equation 25 yields:

$$\frac{\partial\phi^+}{\partial t} + C_k{}^+ \frac{\partial\phi^+}{\partial z} = -\Omega^+ \tag{32}$$

At steady-state, the governing differential equations, Equations 22 and 32, become:

$$\frac{dj}{dz} = \Omega \tag{33a}$$

$$\frac{d\phi}{dz} = - \frac{\Omega}{C_k} \qquad (33b)$$

They are integrated numerically along the boiling channel until the average mixture density ρ reaches the saturated vapor density. The boundary conditions are:

$$j = v_w \text{ at } z = \lambda \qquad (34)$$

$$\phi = 0 \text{ at } z = \lambda \qquad (35)$$

Knowing j and ϕ, we obtain ρ from Equations 27 and 31 and, defining the average mixture velocity v^+ as

$$v^+ \equiv \frac{G^+}{\rho^+}, \qquad (36)$$

we arrive at the following relationship between v^+ and j^+:

$$v^+ = j^+ - (\frac{\rho_f}{\rho^+} - 1)\, V'_{gj}{}^+ \qquad (37)$$

The mixture velocity will be used later in the momentum equation.

Perturbing and Laplace-transforming Equations 22 and 32 yields:

$$\frac{d\delta j}{dz} = \delta\Omega \qquad (38)$$

$$\frac{d\delta\phi}{dz} = - s\,\frac{\delta\phi}{C_k} - \frac{\delta\Omega}{C_k} + \frac{\Omega\delta C_k}{C_k{}^2} \qquad (39)$$

To integrate Equations 38 and 39, $\delta\Omega$ and δC_k must be specified. Utilizing Equations 23, 24, and Equation A.7 of Appendix A, we obtain the following relationship for $\delta\Omega$:

$$\delta\Omega = \frac{P_h(\rho_f-\rho_g)}{Ah_{fg}\rho_f\rho_g}\,\delta q_1$$

$$= \frac{P_h(\rho_f-\rho_g)}{Ah_{fg}\rho_f\rho_g}\,\alpha_1\,\frac{\delta H}{H}\,(T_w - T_1) \tag{40a}$$

Here, we have used the identity:

$$\delta T_w \equiv \delta T_{sat} \equiv 0 \tag{40b}$$

From Equations 26 and 28 we obtain:

$$\delta C_k = C_o\ \delta j + \delta V_{gj} + \delta(\alpha\,\frac{\partial V_{gj}}{\partial\alpha}) \tag{41}$$

The term $\delta(\alpha\,\frac{\partial V_{gj}}{\partial\alpha})$ in Equation 41 is generally small in most boiling systems and will be neglected to simplify the algebra.

The terms, δH and δV_{gj} are obtained from the correlations used for H and V_{gj}. In general, δH is evaluated from:

$$\delta H = \frac{\partial H}{\partial v}\,\delta v + \frac{\partial H}{\partial T_1}\,\delta T_1 + \frac{\partial H}{\partial\rho}\,\delta\rho \tag{42a}$$

and δV_{gj} from

$$\delta V_{gj} = \frac{\partial V_{gj}}{\partial\alpha}\,\frac{d\alpha}{d\rho}\,\delta\rho \tag{42b}$$

Using Equation 29 and the identity

$$\alpha \equiv \frac{\rho_f-\rho}{\rho_f-\rho_g} \tag{42c}$$

we obtain:

$$\delta V_{gj} = (\text{constant})\ (\frac{n}{\rho_f-\rho_g})\ (1-\alpha)^{n-1}\ \delta\rho \tag{42d}$$

The perturbed conservation Equations 38 and 39 can now be integrated along the boiling channel. The integration limits are the steady-state boiling boundary, λ, and the steady-state superheat boundary, η. That is, the integration is performed in fixed-space coordinates, without following the movement of the boiling and superheat boundaries. However, the effect of these movements is taken into account, as discussed in the following paragraphs.

Referring to Figure 4, the boundary conditions are obtained as follows. The true velocity must be continuous at the instantaneous location of the boiling boundary, $\lambda + \delta\lambda$. Therefore,

$$v^{+}_{\lambda + \delta\lambda} = j^{+}_{\lambda + \delta\eta} \tag{43}$$

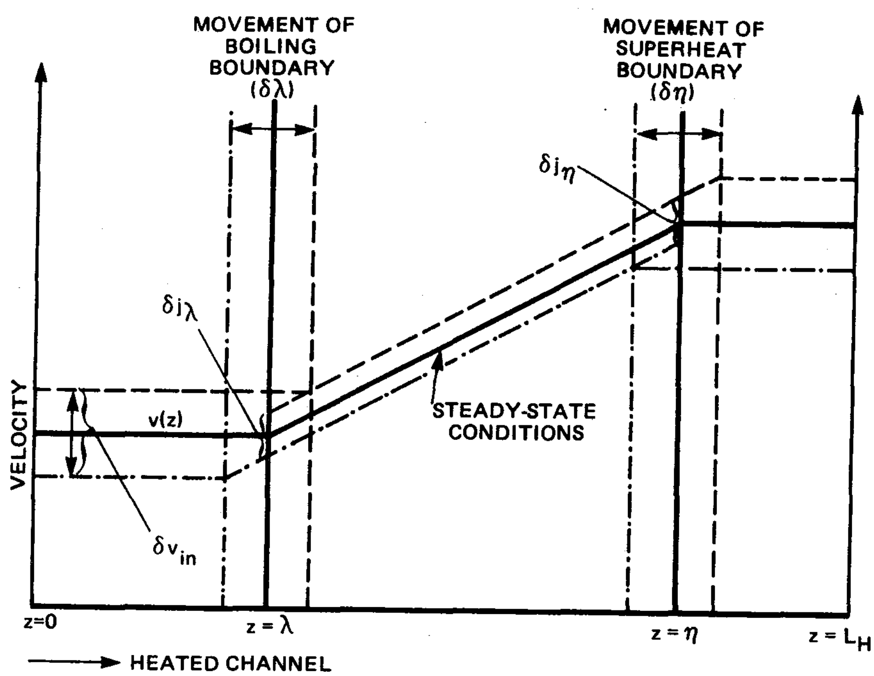

Figure 4. Perturbed Velocity Profile Along the Heated Channel

Expanding both sides and approximating the time-dependent gradients of v^+ and j^+ at λ by their steady-state values yields:

$$v_\lambda^+ + \frac{dv^+}{dz}\Big|_\lambda \delta\lambda = j_\lambda^+ + \frac{dj^+}{dz}\Big|_\lambda \delta\lambda = j_\lambda^+ + \Omega_\lambda \delta\lambda \qquad (44)$$

The second term on the left hand side is zero, since the velocity does not vary along the single-phase region. Thus, writing the time-dependent velocities in terms of a steady-state part and a perturbed part:

$$v_\lambda + \delta v_\lambda = j_\lambda + \delta j_\lambda + \Omega_\lambda \delta\lambda \qquad (45)$$

Cancelling v_λ with j_λ and rearranging terms, we obtain:

$$\begin{aligned} \delta j_\lambda &= \delta v_\lambda - \Omega_\lambda \delta\lambda \\ &= \delta v_w - \Omega_\lambda \delta\lambda \end{aligned} \qquad (46)$$

The latter equality results because all the velocity perturbations in the single-phase region are equal to δv_w. Equation 46 is the boundary condition for Equation 38.

The boundary condition for Equation 39 is obtained by using Equation 33:

$$\begin{aligned} \delta\phi &= -\frac{\partial\phi}{\partial z}\Big|_\lambda \delta\lambda \simeq \frac{d\phi}{dz}\Big|_\lambda \delta\lambda \\ &= \frac{\Omega_\lambda}{C_{k\lambda}} \delta\lambda \qquad \text{at } z = \lambda \end{aligned} \qquad (47)$$

The momentum equation for the boiling region of the water channel is:

$$-\frac{\partial P^+}{\partial z} = \rho^+ \frac{D_v v^+}{Dt} + \frac{C_f f_{fo}}{D_H} \frac{G^{+2}}{2\rho_f} \phi_{fo}^2 + C_g g \rho^+ + \frac{\partial}{\partial z}\left[\frac{\rho_f - \rho^+}{\rho^+ - \rho_g} \frac{\rho_f \rho_g}{\rho^+} V_{gj}'^{+2}\right] \qquad (48)$$

where ϕ_{fo}^2 is the two-phase frictional pressure-drop multiplier and f_{fo} is the two-phase friction factor based on all liquid flow.

At steady-state, Equation 48 can be integrated numerically from the boiling boundary ($z = \lambda$) to the superheat boundary ($z = \eta$). The first term on the right hand side can be integrated analytically, since

$$\int_\lambda^\eta \rho \frac{D_v v}{Dt} dz = \int_\lambda^\eta \frac{\partial v}{\partial z} dz$$

$$= G \int_\lambda^\eta dv \qquad (49)$$

$$= G (v_\eta - v_\lambda)$$

The last term containing V'_{gj} goes to zero at the integration limits. The gravity and frictional terms are integrated numerically.

Equation 48 is now perturbed, Laplace-transformed and integrated from the instantaneous location of the boiling boundary to the instantaneous superheat boundary. The different terms on the right hand side can be grouped together as follows:

$$\delta(\Delta P_{2\phi}) = \delta(\Delta P_{2\phi})_\eta - \delta(\Delta P_{2\phi})_\lambda + \delta(\Delta P_{2\phi})_{acc} + \delta(\Delta P_{2\phi})_g + \delta(\Delta P_{2\phi})_f + \delta(\Delta P_{2\phi})_{dr} \qquad (50)$$

The terms on the right hand side represent the pressure drop perturbations due to the movement of superheat and boiling boundaries, acceleration, gravity, friction and vapor-liquid drift, respectively. The first two terms of Equation 50 are given by:

$$\delta(\Delta P_{2\phi})_\eta = (\frac{C_f f \rho_g v_\eta^2}{2D_H} + g\rho_g + \rho v_\eta \frac{\partial v}{\partial z}|_\eta)\delta\eta$$

$$= (\frac{C_f f \rho_g v_\eta^2}{2D_H} + g\rho_g + \rho v_\eta \Omega_\eta)\delta\eta \qquad (51)$$

and $$\delta(\Delta P_{2\phi})_\lambda = \left(\frac{f\rho_f v_\lambda^2}{2D_H} + g\rho_f + \rho v_\lambda \frac{\partial v}{\partial z}\Big|_\lambda\right)\delta\lambda$$

$$= \left(\frac{f\rho_f v_\lambda^2}{2D_H} + g\rho_f + \rho v_\lambda\ \Omega_\lambda\right)\delta\lambda \tag{52}$$

The superheat boundary perturbation, $\delta\eta$, is obtained in a similar manner to the boiling boundary perturbation. Figure 5 shows the average mixture density near the superheat boundary (to first-order approximation) at two different times t' and t". The superheat boundary is defined as the position where ρ equals ρ_g. We observe from Figure 5 that an increase in $\delta\rho$ causes an increase in $\delta\eta$. Therefore, the superheat boundary perturbation is:

$$\delta\eta = \frac{-\delta\rho}{\frac{\partial\rho}{\partial z}\Big|_\eta} \simeq \frac{-\delta\rho}{\frac{d\rho}{dz}\Big|_\eta} \tag{53}$$

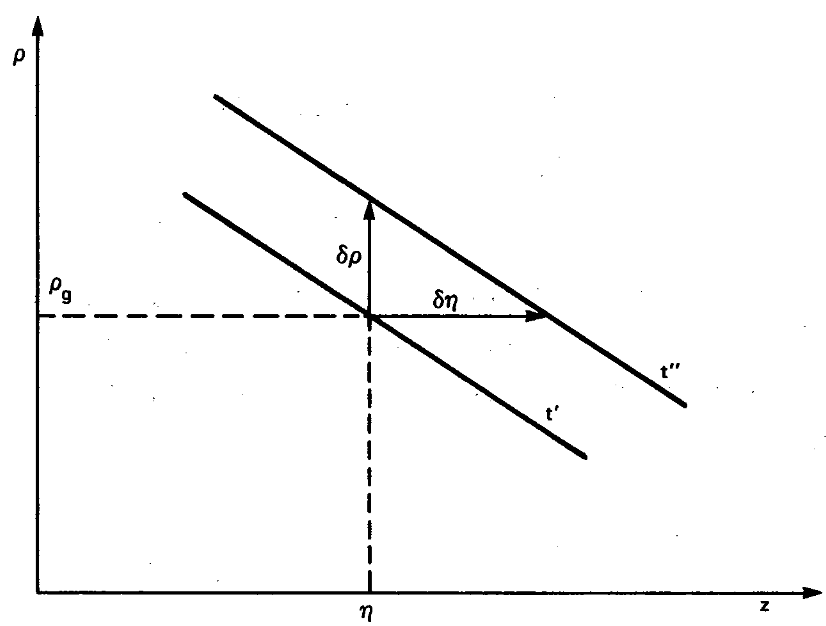

Figure 5. Average Water-Steam Mixture Density Near the Superheat Boundary (to a First-Order Approximation) at Two Different Times t' and t''

Utilizing Equations 25 and 27, we obtain:

$$\delta\eta = -\frac{C_{k\eta}}{\rho g \Omega_\eta}\,\delta\rho \tag{54}$$

The acceleration pressure drop perturbation is obtained as follows

$$\begin{aligned}\delta(\Delta P_{2\phi})_{acc} &= {}_\lambda\!\int^\eta \{\delta[\rho\frac{\partial v}{\partial t} + \rho v\,\frac{\partial v}{\partial z}]\}\ dz \\ &= {}_\lambda\!\int^\eta (\rho\,\frac{\partial \delta v}{\partial t})\ dz + \delta\ {}_\lambda\!\int^\eta \rho v\,\frac{\partial v}{\partial z}\,dz \\ &= I_1 + I_2\end{aligned} \tag{55}$$

where

$$I_1 = {}_\lambda\!\int^\eta s\rho\ \delta v\ dz$$

and I_2 is obtained through integration by parts as

$$I_2 = \delta[\rho v^2|_\lambda^\eta - {}_\lambda\!\int^\eta v\,\frac{\partial}{\partial z}\,(\rho v)\ dz] \tag{56}$$

The last term is modified using the continuity equation:

$$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial z}\,(\rho v) = 0 \tag{57}$$

Equation 56 now becomes:

$$\begin{aligned}I_2 &= \delta[\rho v^2|_\lambda^\eta + {}_\lambda\!\int^\eta \frac{\partial\rho}{\partial t}\,v\ dz] \\ &= v_\eta^2\ \delta\rho_\eta - v_\lambda^2\ \delta\rho_\lambda + 2[\rho_\eta v_\eta \delta v_\eta - \rho_\lambda v_\lambda \delta v_\lambda] + s\ {}_\lambda\!\int^\eta v\delta\rho\ dz\end{aligned} \tag{58}$$

The remaining terms of Equation 50 are:

$$\delta(\Delta P_{2\phi})_f = \frac{C_f f_{fo}}{D_H}\,\frac{G_w}{\rho_f}\,{}_\lambda\!\int^\eta \Phi_{fo}^2\ (v\delta\rho + \rho\delta v)\ dz \tag{59}$$

$$\delta(\Delta P_{2\phi})_g = C_g \, g \, {}_\lambda\!\int^n \delta\rho \, dz \tag{60}$$

$$\delta(\Delta P_{2\phi})_{dr} = \delta \, {}_\lambda\!\int^n \frac{d}{dz} [(\frac{\rho_f}{\rho^2} - \frac{1}{\rho}) \rho_f \rho_g V'^{\,2}_{gj}] \, dz \tag{61}$$

$$= [(-\frac{2\rho_f}{\rho^3} + \frac{1}{\rho^2}) \rho_f \rho_g V'^{\,2}_{gj} \delta\rho + (\frac{\rho_f}{\rho^2} - \frac{1}{\rho}) \rho_f \rho_g 2V'_{gj} \delta V'_{gj}]^n_\lambda$$

The above quantities can all be calculated once δv and $\delta\rho$ are known at all nodal points. The transformation of δj to δv is obtained by perturbing Equation 36:

$$\delta v = \delta j - (\frac{\rho_f}{\rho} - 1) \delta V'_{gj} + \frac{\rho_f V'_{gj}}{\rho^2} \delta\rho \tag{62}$$

The relationship between $\delta\phi$ and $\delta\rho$ is provided by Equations 27 and 31:

$$\delta\rho = \rho' \, \delta\phi \tag{63}$$

2.3 Superheat Region

The specific volume-enthalpy relationship for steam at constant pressure can be approximated very well with a straight line of slope k_o. This is the basis of the formulation adopted for the superheat region, and leads to equations that are similar to those obtained in the two-phase region assuming homogeneous flow.

Defining a fictitious superheated "quality", x_s, by

$$x_s \equiv \frac{h_s - h_g}{h_{fg}} \tag{64}$$

the specific volume of superheat steam (at constant pressure) becomes:

$$V_s = V_g + k_o (h_s - h_g) \tag{65}$$

Further, defining

$$V_{gs} \equiv k_o h_{fg} \tag{66}$$

Equations 64 and 65 become:

$$V_s = V_g + V_{gs}\, x_s \tag{67}$$

This relationship is similar to the one valid for the two-phase specific volume in homogeneous flow.

Although V_{gs} and k_o are assumed to be constants in the following derivation, they are calculated from steam tables and allowed to vary along the superheat region.

The mass and energy conservation equations for the superheat region are:

$$\frac{D_v \rho_s^+}{Dt} + \rho_s^+ \frac{\partial v_s^+}{\partial z} = 0 \tag{68}$$

and $$\rho_s^+ \frac{D_v h_s^+}{Dt} = \frac{q_1^+ \rho}{A} \tag{69}$$

We want to transform these Equations into Equations in terms of x_s. Thus

$$\frac{D_v \rho_s^+}{Dt} = \frac{D_v (1/V_s^+)}{Dt}$$

$$= - \frac{1}{V_s^{+2}} \frac{D_v V_s^+}{Dt}$$

$$= - \frac{1}{V_s^{+2}} k_o \frac{D_v h_s^+}{Dt} \qquad \text{(from Equation 65)}$$

$$= -\frac{1}{V_s^+} k_o \frac{q_1^+ P_h}{A} \qquad \text{(from Equation 69)}$$

$$= -\frac{\Omega_s^+}{V_s^+} \tag{70}$$

where we have defined

$$\Omega_s^+ \equiv \frac{k_o q_1^+ P_h}{A} \tag{71}$$

Substituting Equation 70 into Equation 68 yields:

$$\frac{\partial v_s^+}{\partial z} = \Omega_s^+ \tag{72}$$

This is the superheat velocity propagation equation, similar to Equation 22 for the boiling region.

Substituting Equation 64 into 69 yields:

$$\rho_s^+ h_{fg} \frac{D_v x_s^+}{Dt} = \frac{q_1^+ P_h}{A} \tag{73}$$

But from Equation 67

$$\rho_s^+ = \frac{1}{V_g^+ + x_s^+ V_{gs}} \tag{74}$$

Substituting Equation 74 into Equation 73 we get:

$$\frac{D_v x_s^+}{Dt} - \Omega_s^+ x_s^+ = \Omega_s^+ \frac{V_g^+}{V_{gs}} \tag{75}$$

This last equation is the superheat "quality" (density) propagation equation.

At steady-state, Equations 66, 67 and 71 yield:

$$\frac{dx_s}{dz} = \frac{\Omega_s(x_s+V_g/V_{gs})}{V_s}$$
$$= \frac{q_1 P_h}{GAh_{fg}} \tag{76}$$

Integration of Equations 72 and 75 from the superheat boundary to the heated section exit will give the steady-state solutions.

Perturbing and Laplace-transforming Equations 72 and 75, we obtain:

$$\frac{d\delta v_s}{dz} = \delta\Omega_s \tag{77}$$

$$\frac{d\delta x_s}{dz} = \frac{\Omega_s - s}{v_s}\,\delta x_s + \frac{x_s+V_g/V_{gs}}{V_s}\,\delta\Omega_s - \frac{q_1 P_h}{GAv_s h_{fg}}\,\delta v_s \tag{78}$$

From Equation 71

$$\delta\Omega_s = \frac{k_o P}{A}\,\delta q_1 \tag{79}$$

where δq_1 is obtained from Equation A.7 of Appendix A.

We now need a relationship between the variables δx_s, δT_s and $\delta\rho_s$. From Equation 74,

$$\delta\rho_s = -\rho_s^2\, V_{gs}\, \delta x_s \tag{80}$$

and from Equation 64

$$\delta x_s = \frac{\delta h_s}{h_{fg}} = \frac{C_{ps}}{h_{fg}}\,\delta T_s \tag{81}$$

The momentum equation for the superheat region can be written as

$$-\frac{\partial P^+}{\partial z} = \rho_s^+ \frac{D_v v_s^+}{Dt} + \frac{C_{fs} f \rho_s^+ v_s^{+2}}{2D_H} + C_{gs}\, g\, \rho_s^+ \tag{82}$$

The steady-state pressure drop is obtained by integrating from the superheat boundary ($z = \eta$) to the heated channel exit ($z = L_H$). The first term results in

$$\int_{\eta}^{L_H} \rho_s v_s \frac{\partial v_s}{\partial z} dz = G \int_{\eta}^{L_H} dv_s$$

$$= G\,(v_{sL_H} - v_{s\eta}) \qquad (83)$$

and the other two terms on the right hand side are evaluated by a straight-forward numerical integration.

The perturbed pressure drop is obtained by perturbing, Laplace-transforming and integrating Equation 82 from $z = \eta^+$ to $z = L_H$:

$$\delta(\Delta P_s) = \delta(\Delta P_s)_{acc} + \delta(\Delta P_s)_f + \delta(\Delta P_s)_g - \delta(\Delta P_s)_\eta \qquad (84)$$

These terms are evaluated by methods similar to those used for the boiling region and, therefore, only the results are shown here:

$$\delta(\Delta P_s)_{acc} = s \int_{\eta}^{L_H} (v_s\,\delta\rho_s + \rho_s\,\delta v_s)\,dz + v_{sL_H}^2\,\delta\rho_{sL_H} - v_{s\eta}^2\,\delta\rho_{s\eta} + 2\,G\,[\delta v_{sL_H} - \delta v_{s\eta}] \qquad (85)$$

$$\delta(\Delta P_s)_f = \frac{C_{fs} f}{2D_H} \int_{\eta}^{L_H} (v_s^2\,\delta\rho_s + 2\rho_s\,v_s\,\delta v_s)\,dz \qquad (86)$$

$$\delta(\Delta P_s)_g = C_{gs}\,g \int_{\eta}^{L_H} \delta\rho_s\,dz \qquad (87)$$

$$\delta(\Delta P_s)_\eta = \left(\frac{C_f f \rho_g v_{g\eta}^2}{2D_H} + g\,\rho_g + \rho_g\,v_g\,\Omega_{s\eta}\right)\delta\eta \qquad (88)$$

2.4 Outlet Resistance and Riser

In the adiabatic riser, the fundamental conservation equations reduce to:

$$\frac{\partial v_r^+}{\partial z} = 0 \tag{89}$$

$$\frac{\partial \rho_r^+}{\partial t} + v_r^+ \frac{\partial \rho_r^+}{\partial z} = 0 \tag{90}$$

At steady-state, the solutions are:

$$v_r = \frac{A}{A_r} v_{ex} \tag{91}$$

$$\rho_r = \rho_{ex} \tag{92}$$

Perturbing and Laplace-transforming Equations 89 and 90 yields:

$$\frac{d\delta v_r}{dz} = 0 \tag{93}$$

$$s\ \delta\rho_r + v_r \frac{d\delta\rho_r}{dz} = 0 \tag{94}$$

Combining Equations 91 and 93 yields:

$$\delta v_r = \frac{A}{A_r} \delta v_{ex} \tag{95a}$$

Integrating Equation 94 for the length of the riser (from $z = L_H$ to $z = L_H + L_r$) yields:

$$\delta\rho_r = \delta\rho_{ex}\ e^{-s \frac{z-L_H}{v_r}} \tag{95b}$$

For a system with two-phase mixture in the riser, Equations 89 and 90 are replaced by:

$$\frac{\partial j^+}{\partial z} = 0 \tag{96a}$$

$$\frac{\partial \rho^+}{\partial t} + C_k^+ \frac{\partial \rho^+}{\partial z} = 0 \tag{96b}$$

Following the same steps as above, Equations 95a and 96b become:

$$\delta j_r = \frac{A}{A_r} = \delta j_{ex} \tag{96c}$$

$$\delta \rho_r = \delta \rho_{ex}\ e^{-s \frac{z-L_H}{C_k}} \tag{96d}$$

At the exit of the heated section, void fraction is generally quite high (> 0.5) and so $V_{gj} \to 0$. Therefore, from Equations 26 and 37, we have

$$C_k^+ \approx j^+ \approx v^+$$

and Equations 96(c) and 96(d) can be approximated by Equations 95(a) and 95(b).

The momentum equation for the riser is:

$$-\frac{\partial P^+}{\partial z} = \rho_r \frac{D_v v_r^+}{Dt} + \frac{C_{fr} f \rho_r^+ v_r^{+2}}{2D_H} + C_{gr}\ g\ \rho_r^+ \tag{97}$$

Integrating over the riser length, the steady-state pressure drop is:

$$(\Delta P_r) = \left(\frac{C_{fr} f \rho_r v_r^2}{2D_H} + C_{gr}\ g\ \rho_r\right) L_r + K_{ex} \frac{\rho_{ex} v_{ex}^2}{2} \tag{98}$$

where the K_{ex} term is included to account for any flow resistance at the heated channel exit.

The perturbed solution yields the following terms

$$\delta(\Delta P)_r = \delta\ (\Delta P_r)_{acc} + \delta(\Delta P_r)_f + \delta(\Delta P_r)_g + K_{ex}\ \rho_{ex}\ v_{ex}\ \delta v_{ex} + K_{ex}\ v_{ex}^2\ \delta \rho_{ex}/2 \tag{99}$$

For this region, analytical evaluation of the integrals is possible. First, we need to evaluate the integral

$$\int_{L_H}^{L_H+L_r} \delta\rho_r \, dz = \int_{L_H}^{L_H+L_r} \delta\rho_{ex} \, e^{-s\frac{Z-L_H}{v_r}} \, dz$$

$$= \frac{v_r}{s} \delta\rho_{ex} [1-e^{-\frac{sL_r}{v_r}}] \tag{100}$$

and then the terms on the right hand side of Equation 97 are evaluated as follows:

$$\delta(\Delta P_r)_{acc} = \int_{L_H}^{L_H+L_r} \rho_r \, \delta \left(\frac{D_v v_r}{Dt}\right) dz$$

$$= \int_{L_H}^{L_H+L_r} \rho_r \left[\frac{\partial \delta v_r}{\partial t} + \delta\{v_r \frac{\partial v_r}{\partial z}\}\right]dz$$

$$= s \, \rho_r \, \delta v_r \, L_r \tag{101}$$

$$\delta(\Delta P_r)_f = \frac{C_f f}{2D_H} \int_{L_H}^{L_H+L_r} [v_r^2 \, \delta\rho_r + 2v_r\rho_r\delta v_r]dz$$

$$= \frac{C_f f}{2D_H} \left[\frac{v_r^3}{s} \delta\rho_{ex} \, (1-e^{-\frac{sL_r}{v_r}}) + 2v_r\rho_r L_r \delta v_r\right] \tag{102}$$

$$\delta(\Delta P_r)_g = C_{gr} \, g \int_{L_H}^{L_H+L_r} \delta\rho_r \, dz$$

$$= C_{gr} \, g \, \frac{v_r}{s} \delta\rho_{ex} [1-e^{-\frac{sL_r}{v_r}}] \tag{103}$$

2.5 Single-Phase Loop

This region includes all unheated single-phase components, i.e., the piping, pumps, and any inlet orificing. The only conservation equation that needs to be considered in this region is the momentum equation:

$$- \frac{\partial P^+}{\partial z} = \rho \frac{dv_i^+}{dt} + \frac{f \rho v_i^{+2}}{2D_H} + g\rho C_g \qquad (104)$$

The density ρ is evaluated at the heated test section inlet conditions.

The steady-state pressure drop is obtained by integrating Equation 104 over all sections of the unheated length:

$$\Delta P_\ell = (\sum_j \frac{f_j L_j}{D_{Hj} A_j^2}) \frac{\rho A^2 v_i 2}{2} - \rho g (C_{gH} L_H + C_{gr} L_r) - \Delta P_{pump} \qquad (105)$$

The coefficients C_{gH} and C_{gr} are included to account for non-vertical lengths of the heated section (L_H) and the riser (L_r), respectively. The summation over the various lengths of different cross-sectional flow areas (A_j) are required since all velocities are referenced to the heated-region flow area A, so that only v_i needs to be computed.

Equation 104 is now perturbed and Laplace-transformed to yield:

$$- \frac{d\delta\rho}{dz} = s\rho \; \delta v_i + \frac{f \rho v_i}{2D_H} \delta v_i \qquad (106)$$

Integrating Equation 106 over the unheated lengths gives:

$$\delta(\Delta P_\ell) = \rho A (\sum_j \frac{L_j}{A_j}) \; s \; \delta v_i + \rho A^2 v_i (\sum_j \frac{f_j L_j}{D_{Hj} A_j^2}) \delta v_i - \delta (\Delta P)_{pump} \qquad (107)$$

The last term on the right hand side represents the transformed perturbation of the pump head and can be obtained from the pump characteristics. In the case of a centrifugal pump, the relationship is

$$\delta (\Delta P_{pump}) = \zeta \; A \; \delta v_i \qquad (108)$$

where ζ is the slope of the operational head-flow characteristic in suitable units.

3. COMPUTATIONAL METHOD

The governing conservation equations are summarized in Table 1. These equations are in the form of analytical expressions for the single-phase region and the riser, and in the form of initial-value ordinary differential equations for the boiling and superheater regions. Euler's forward difference method is used for solving the differential equations numerically and the user has the option of using the Richardson Extrapolation Method to improve the numerical accuracy. The continuity and energy equations are decoupled from the momentum equation so that computations proceed from left to right across Table 1, and then, from top to bottom. Stability plots are generated using the pressure-drop perturbations which are evaluated with the perturbed momentum equations given on the last line of Table 1.

STEAMFREQ-I is programmed in FORTRAN and it requires a central memory of 62K words on a CDC-6400 or 42K on a Honeywell H-6000 computer system. Typical running time with 400 nodes each for the boiling and superheat regions and 29 oscillation periods is 83s on the CDC-6400 and 97s on the H-6000.

Table 1. Summary of Conservation Equations[1] Programmed in STEAMFREQ-I

		Heated Single-phase Region	Two-phase Region	Superheat Region	Riser
Computational Method		Analytical	Numerical	Numerical	Analytical
Steady-State Equations	Continuity and energy	3[2] 8	33a 33b	72[2] 76	91 92
	Momentum	19	48[2]	82[2]	98
Perturbed Equations	Continuity and energy	9 15	38 39	77 78	93 94
	Momentum	21	50	84	99

[1] Equation numbers refer to numbers used in text.

[2] Equations at steady-state conditions are obtained by setting $\frac{\partial}{\partial t} = 0$

4. MODEL VERIFICATION

Stability analysis methodology, heat transfer correlations, comparison of stability predictions from STEAMFREQ-I, NUFREQ2 and NUFREQ3, and comparison of predictions from STEAMFREQ-I and two sets of experimental data are presented in this section.

4.1 Stability Analysis

Two types of density-wave instabilities are possible in steam generator tubes and are determined by the respective boundary conditions. The most common type of instability in steam generators is parallel channel instability. Only those few tubes which happen to receive a slightly higher heat flux or lower flow rate in any particular panel oscillate, or the tubes oscillate out of phase in such a manner that the constant-pressure boundaries are now the receiver panel inlet and exit. In this case the piping upstream and downstream of the panel headers does not participate and has no effect on the dynamics of the system. The occurrence of density-wave oscillations within one or several "hot" channels may be undetected since the individual tubes are generally not instrumented. The tube material may then deteriorate by thermal fatigue, ultimately leading to tube failures.

The pressure drop across a single individual tube is nearly a constant due to the large by-pass effect from the rest of the tubes. The boundary condition is therefore

$$\delta(\Delta P_{1\phi,ch}) + \delta(\Delta P_{2\phi+s,ch}) = 0$$

In the second mode of instability, all the tubes in a particular panel oscillate in phase. In this case the rest of the loop (i.e., the inlet piping from a selected constant pressure point to the boiler panel inlet and the exit piping from the boiler panel exit to the constant pressure point) participates in the dynamics of the system and, therefore, should be included in the mathematical model. The constant pressure points in this case are selected as the inlet and exit of a large mixing chamber. For this mode of oscillation the actual resistance of the piping is important.

These density-wave instabilities involving the entire loop can cause severe problems in predicting system performance and in system control, and should therefore be avoided by designers. Generally, thresholds for loop instabilities are higher than those for parallel-channel instabilities due to the stabilizing effect of the large single-phase pressure drop in the piping, pump, and inlet orificing. Occasionally, the loop can be more unstable than an individual channel if the system has long piping or components containing a two-phase mixture or superheated vapor. For loop instability analysis, the pressure is continuous around the closed loop and the boundary condition is therefore

$$\delta(\Delta P_{2\phi,\ell}) + \delta(\Delta P_{2\phi+s,\ell}) = 0$$

Instability data obtained from two different steam generator tests, described in the following subsections, represent parallel channel instabilities. Predictions with STEAMFREQ-I, which are compared with the data, are based on parallel channel stability analysis.

4.2 Thermal-Hydraulic Correlations

The thermal-hydraulic correlations used in STEAMFREQ-I are summarized in Table 2. The heat transfer correlations are based on uniform circumferential heating. The correlations are contained in program subroutines to facilitate the addition of improved correlations and, thereby, improve the analytical model.

4.3 Comparison of Stability Predictions from Several Computer Codes

Nyquist plots for channel stability predictions from NUFREQ2, NUFREQ3, and STEAMFREQ-I are presented in Figures 6 through 10. The tube geometry, thermal-hydraulic conditions and stability predictions are summarized in Table 3.

NUFREQ2 is a stability code, modified from NUFREQ[1], which takes into account axial variation of heat flux in the single-phase liquid region, and

Table 2. List of Correlations Used in STEAMFREQ-I

Single-Phase (Water) Heat Transfer	$Nu = 0.023\, Re^{.8} Pr^{.4}$ Dittus-Boelter Correlation [5]
Nucleate Boiling Heat Transfer	$T_{wall} - T_{sat} = 0.072\, q''^{0.5} \exp(-\frac{p}{1260})$ T in °F q in $Btu/hr \cdot ft^2$ p in psia Thom, et al. [6]
CHF Quality	$x_c = \frac{0.78\,(1 - \frac{p}{3208})^{1.054}}{(\frac{G}{10^6})^{0.625}} (\frac{D_H}{0.394})^{0.15}$ G in $lbm/h \cdot ft^2$, D_H in in., P in psia Wolf, et al. [7]
Post-Dryout Heat Transfer	$Nu = 0.0193\, Re^{0.8} Pr^{1.23} [x + 1(1-x)\frac{\rho_g}{\rho_f}]^{0.68} (\frac{\rho_g}{\rho_f})^{0.068}$ Bishop, et al. [8]
Superheat Steam Heat Transfer	$Nu = 0.0133\, Re^{0.84} Pr^{0.33}$ Heinemann [9]
Drift Flux Model Correlation Parameter, C_o	$C_o = \beta[1 + (\frac{1}{\beta} - 1)^b]$ where $\beta = \frac{j_g}{j}$; $b = (\frac{\rho_g}{\rho_f})^{0.1}$ Dix [10]
Drift Velocity, V_{gj}	$V_{gj} = 1.53\, [\frac{\sigma g(\rho_f - \rho_g)}{\rho_f^2}]^{0.25} (1-\alpha)^{1.5}$ Zuber, et al. [11]
Two-Phase Pressure Drop	Martinelli-Nelson Correlation [12]

Table 3. Channel Stability Comparison for 40% Power, South Panel, Solar Central Receiver

Tube Geometry and Material

Inside diameter	6.83 mm (0.269 in.)
Outside diameter	12.70 mm (0.50 in.)
Heated length	12.50 m (41 ft)
Unheated inlet length	5.49 m (18 ft)
Unheated outlet length	0.43 m (1.4 ft)
Material	Incoloy 800

Thermal-Hydraulic Condition

Pressure	10.8 MPa (1565 psia)
Inlet temperature	288 C (550 F)
Outlet temperature	516 C (960 F)
Flow rate per tube	23.8 kg/h (52.4 lb/h)
Mass flux	183 $kg/s{\cdot}m^2$ (0.135×10^6 $lb/h{\cdot}ft^2$)
Incident power per tube	7.16 kW
Absorbed power per tube	4.85 kW
Max. incident heat flux	0.0575 MW/m^2
Max. absorbed heat flux	0.0420 MW/m^2

Stability Predictions

CODE	NUFREQ2	NUFREQ3	STFR-I
K_{or} = 0 Condition			
State	Unstable	Stable	Unstable
Transit time, s	60.6	60.6	64.1
Osc. period, s	64, 26.6	--	14
Stability threshold			
K_{or}	>1430	--	105

RUN 19.1

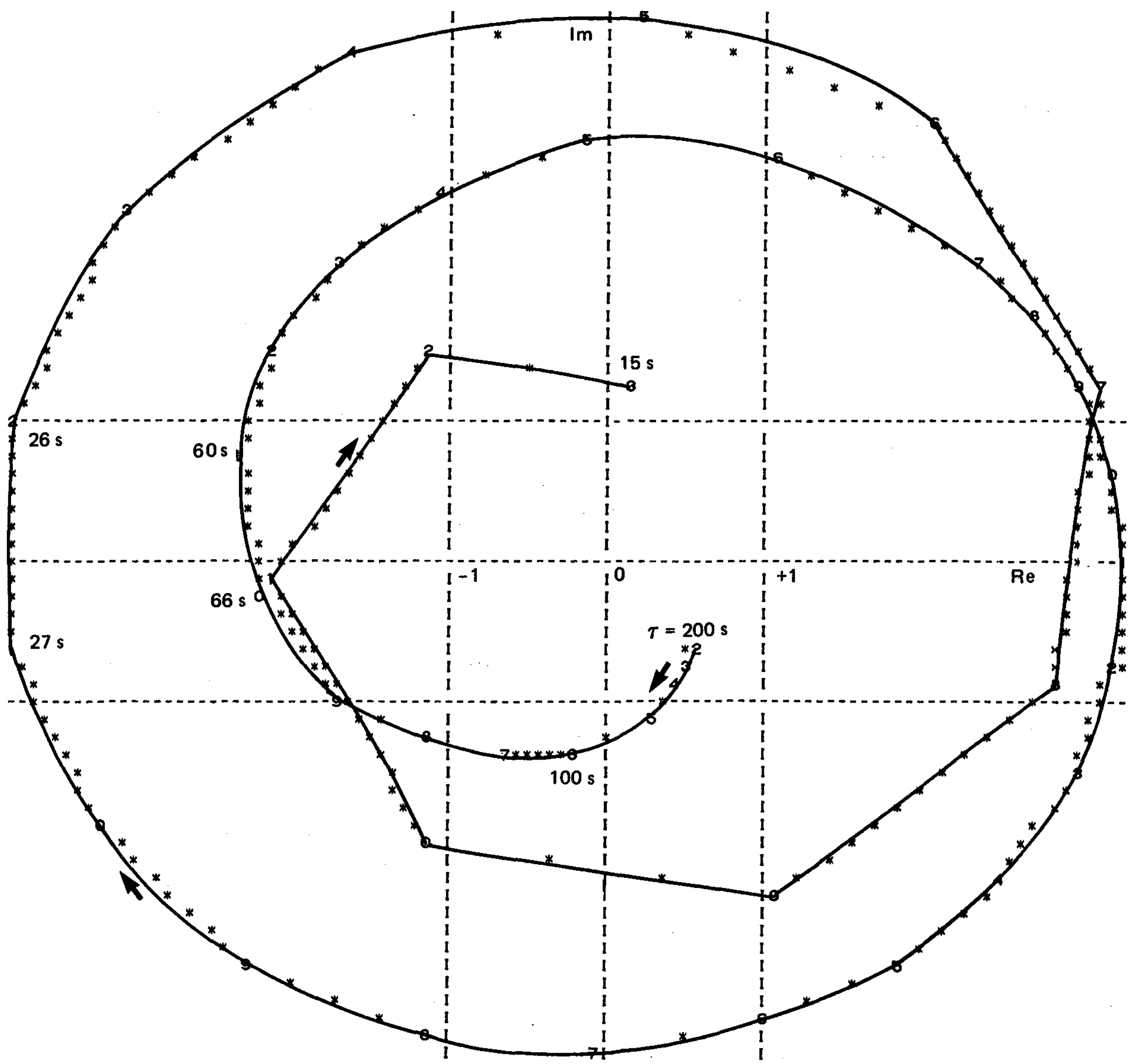

Figure 6. Nyquist Plot from NUFREQ2 for Table 3 Conditions with $K_{or} = 0$

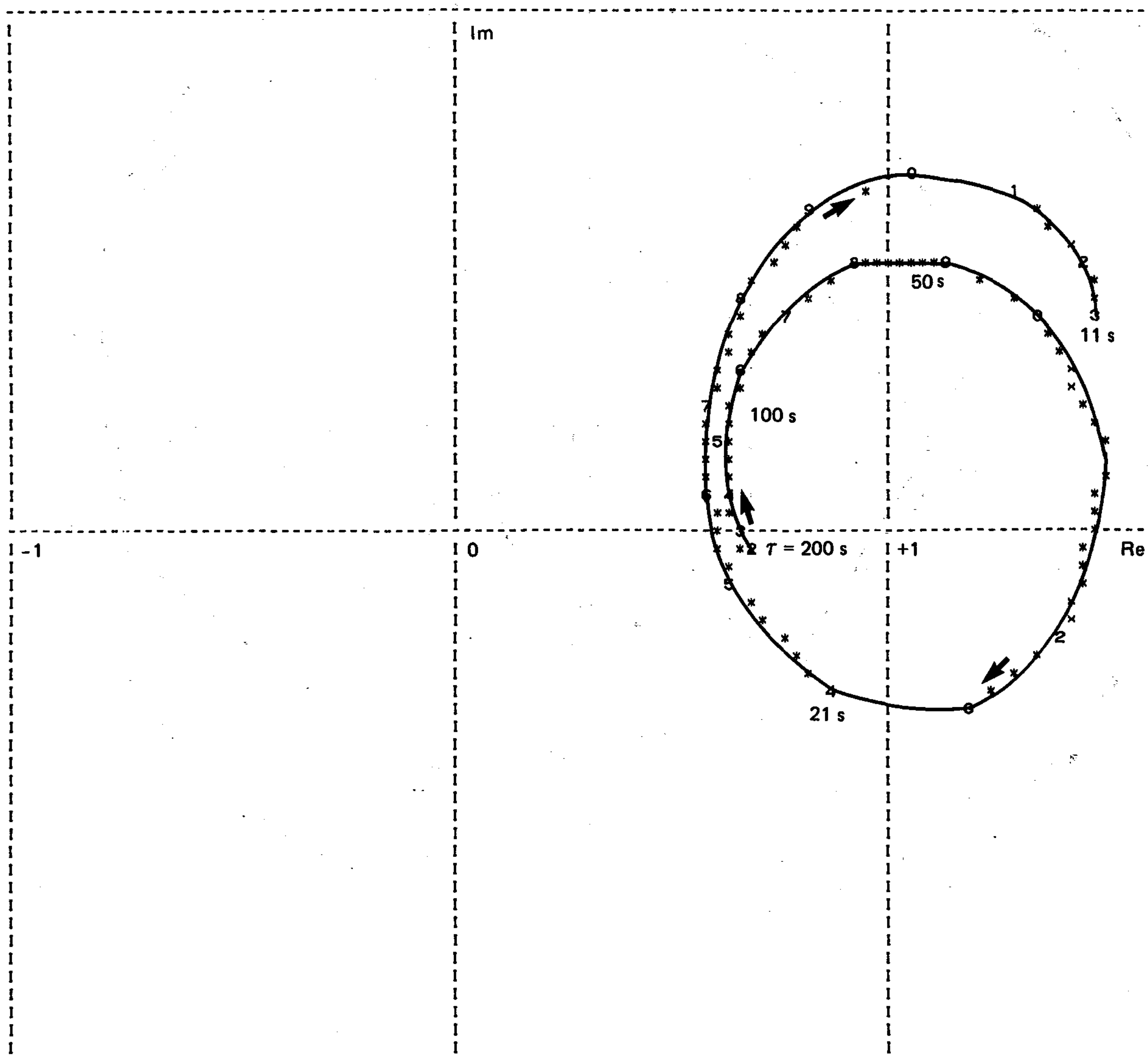

Figure 7. Nyquist Plot from NUFREQ3 for Table 3 Conditions with $K_{or} = 0$

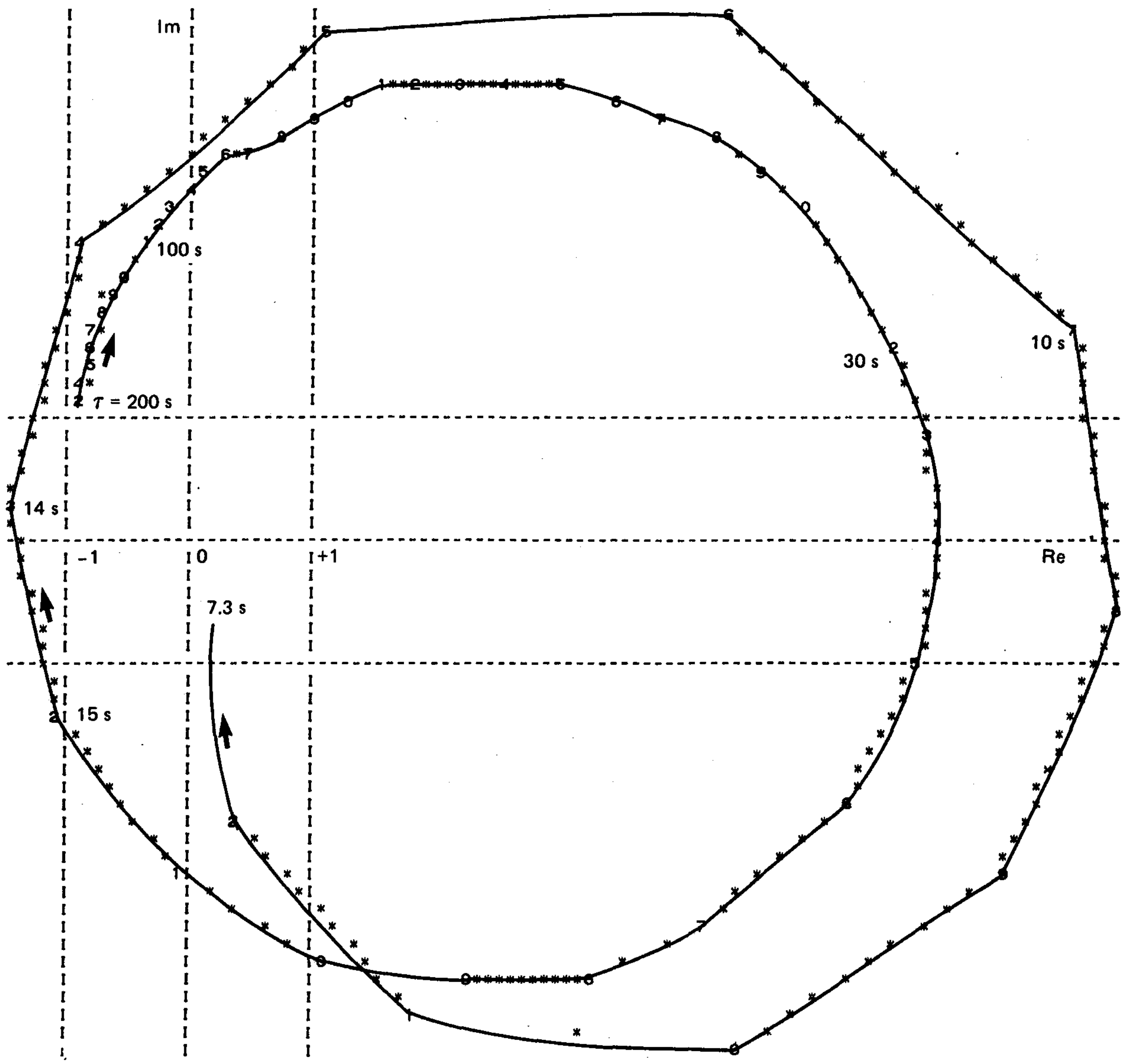

Figure 8. Nyquist Plot from STEAMFREQ-I for Table 3 Conditions with $K_{or} = 0$

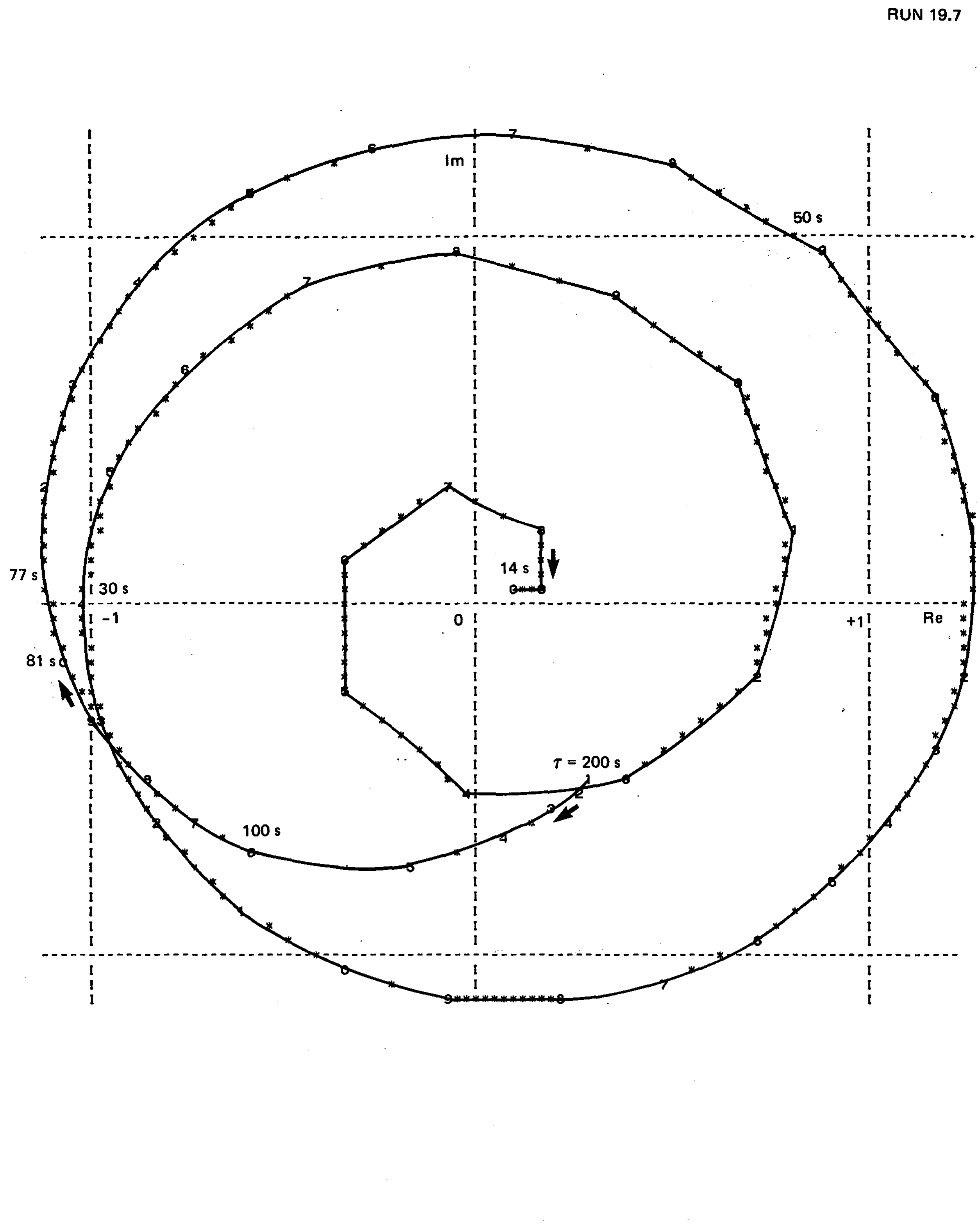

Figure 9. Nyquist Plot from NUFREQ2 for Table 3 Conditions with K_{or} = 1430

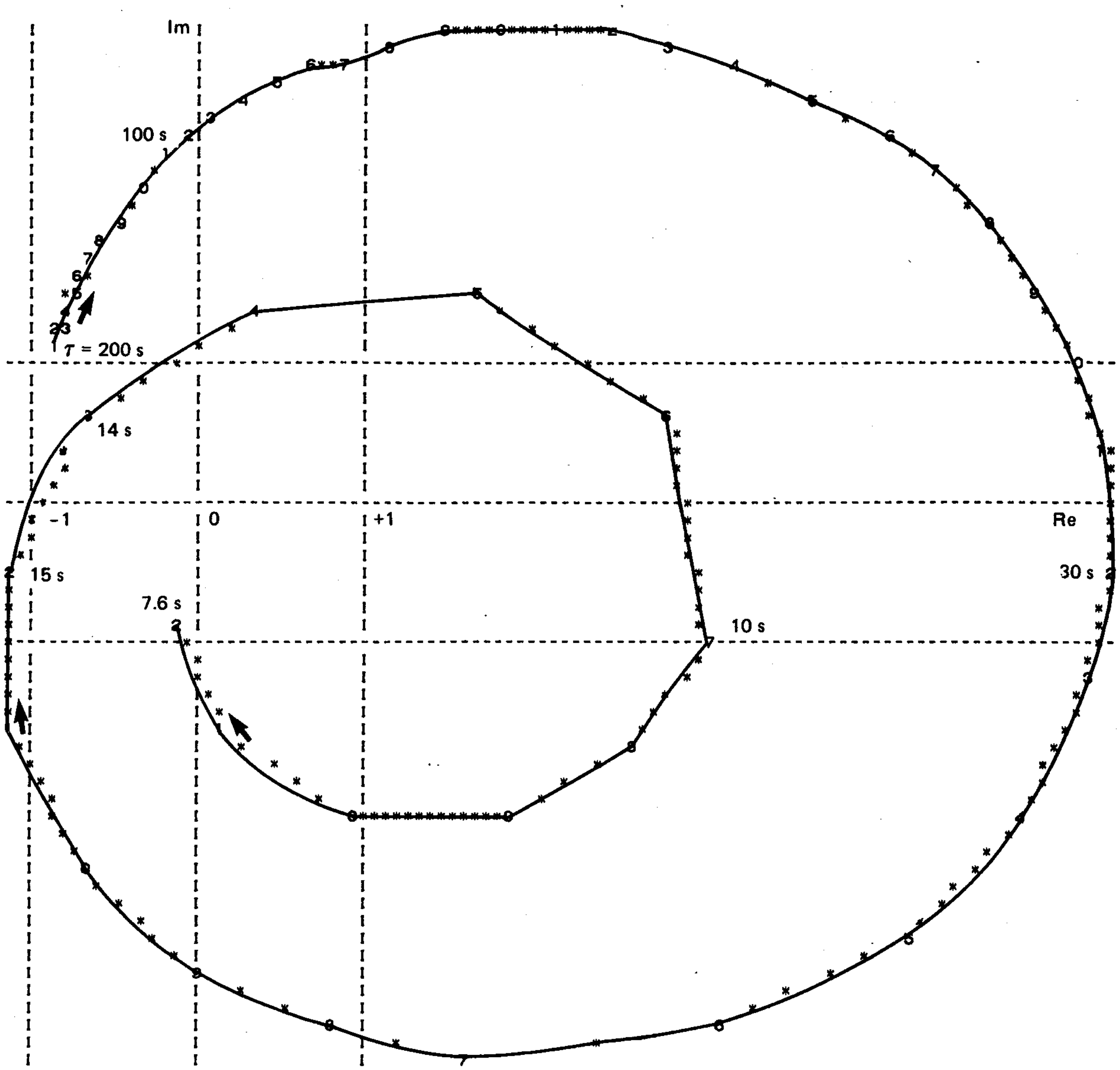

Figure 10. Nyquist Plot from STEAMFREQ-I for Table 3 Conditions with K_{or} = 105

includes a superheat steam region [13]. NUFREQ3 is a further modification to include the time dependence of the single-phase region transit time when wall dynamics in the single-phase region are considered.

The geometry and condition selected for comparison corresponds to a 40% power condition for a south panel of a central receiver for a proposed solar electric plant. The Nyquist plots for tubes without inlet orificing are presented in Figures 6 through 8. Both NUFREQ2 and STEAMFREQ-I predict unstable conditions, while NUFREQ3 predicts no instabilities. The degree of instability predicted by NUFREQ2 and STEAMFREQ-I was examined by increasing the loss coefficient, K_{or}, for a tube inlet orifice, thereby increasing the inlet pressure drop. NUFREQ2 still predicts a slight instability even when K_{or} is increased to 1430 as illustrated in Figure 9. On the other hand, STEAMFREQ-I predicts a stable condition when $K_{or} = 105$ as illustrated in Figure 10.

4.4 Comparison of Stability Predictions with Data from a Solar Receiver Panel Test

Dynamic stability test data have recently become available from a solar receiver panel test. The test panel consists of 70 tubes connected to common inlet and outlet manifolds as shown in Figure 11. The tube id = 6.83 mm, od = 12.70 mm, and the heated length is 12.5 m. The panel is installed with a vertical orientation of the heated length in a 5-MW Central Receiver Test Facility [14]. The panel absorbs solar radiation reflected from a heliostal field. The test instrumentation and test plan have been previously described [15]. Temperatures at the outlet of eight tubes were monitored. Two of these tubes, tubes 30 and 40, also had near-central pressure taps located 8.23 m from the active heated tube inlet plane, i.e., z = 12.80 m. Pressures were measured from the inlet manifold to the central tap and from the central tap to a tap near the outlet manifold.

Data from test day 194 illustrate both unstable and stable conditions with superheated outlet steam. Data for an unstable region with substantial systematic outlet temperature and pressure oscillations for tubes 30 and 40 at 10.3 MPa (1500 psia) pressure and 410 $kg/s{\cdot}m^2$ (0.302×10^6 $lb/h{\cdot}ft^2$) mass flux are presented in Figures 12 through 14. A data time span

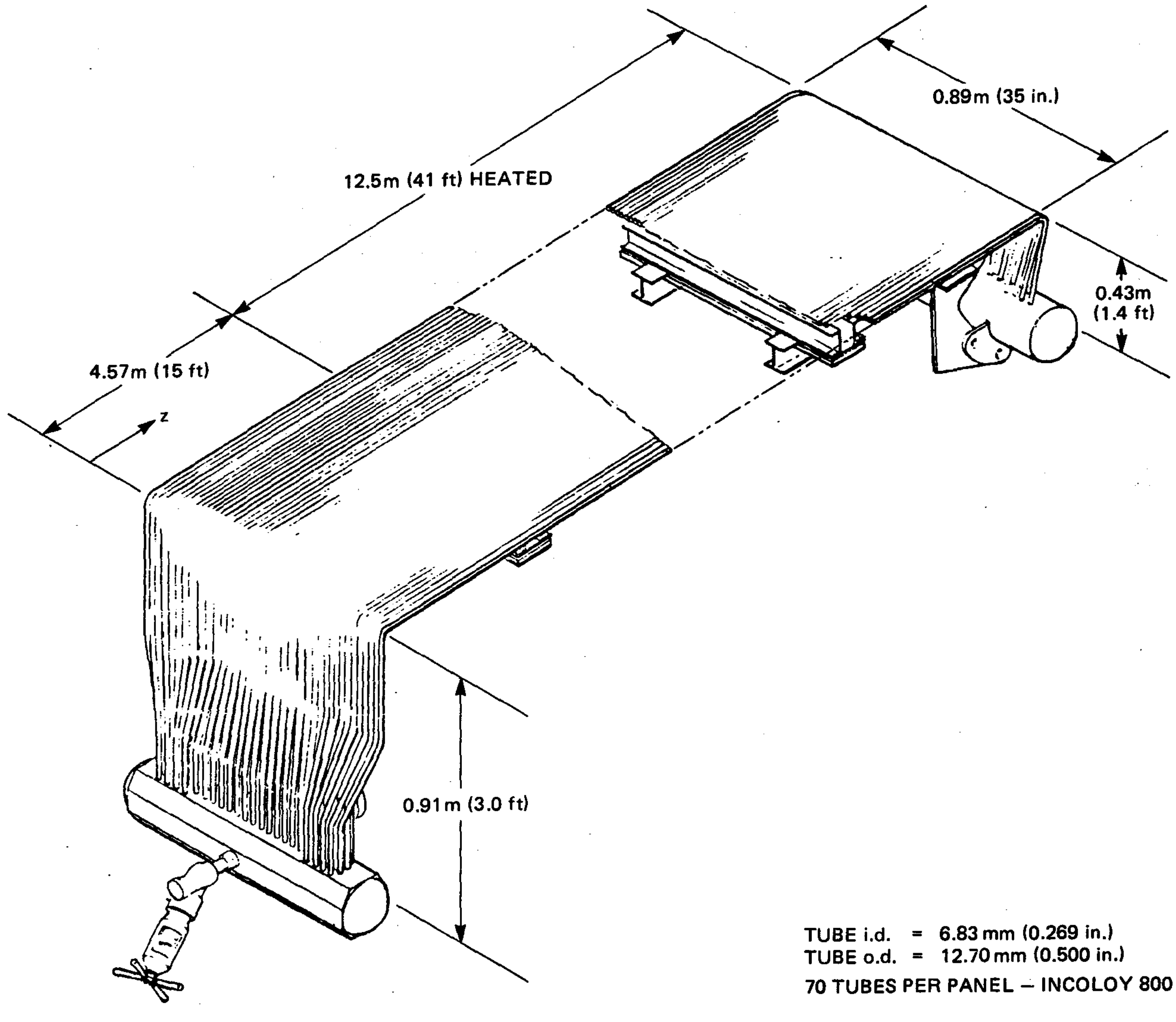

Figure 11. Solar Receiver Test Panel

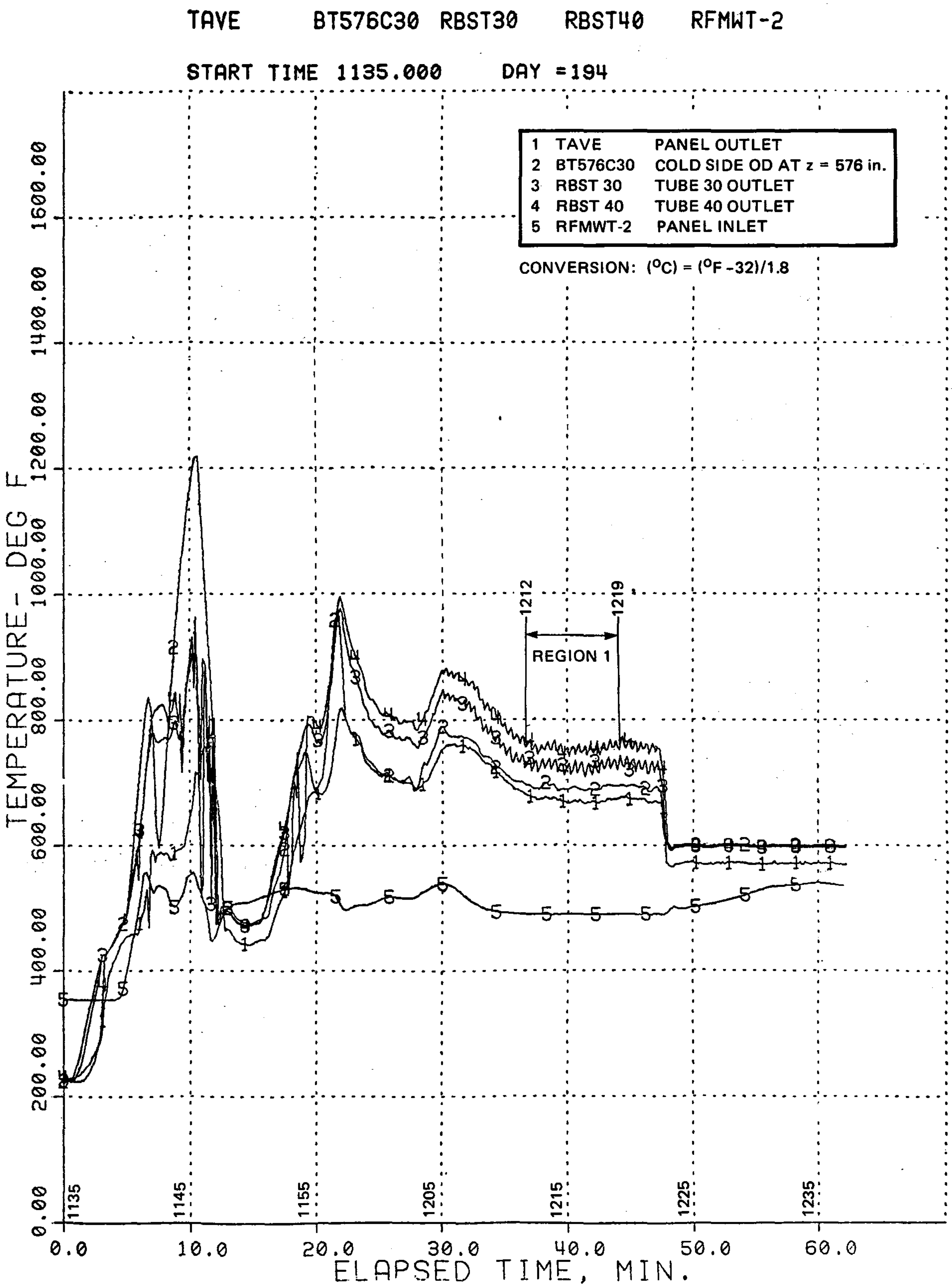

Figure 12. Measured Temperature Profiles for Solar Receiver Test Panel

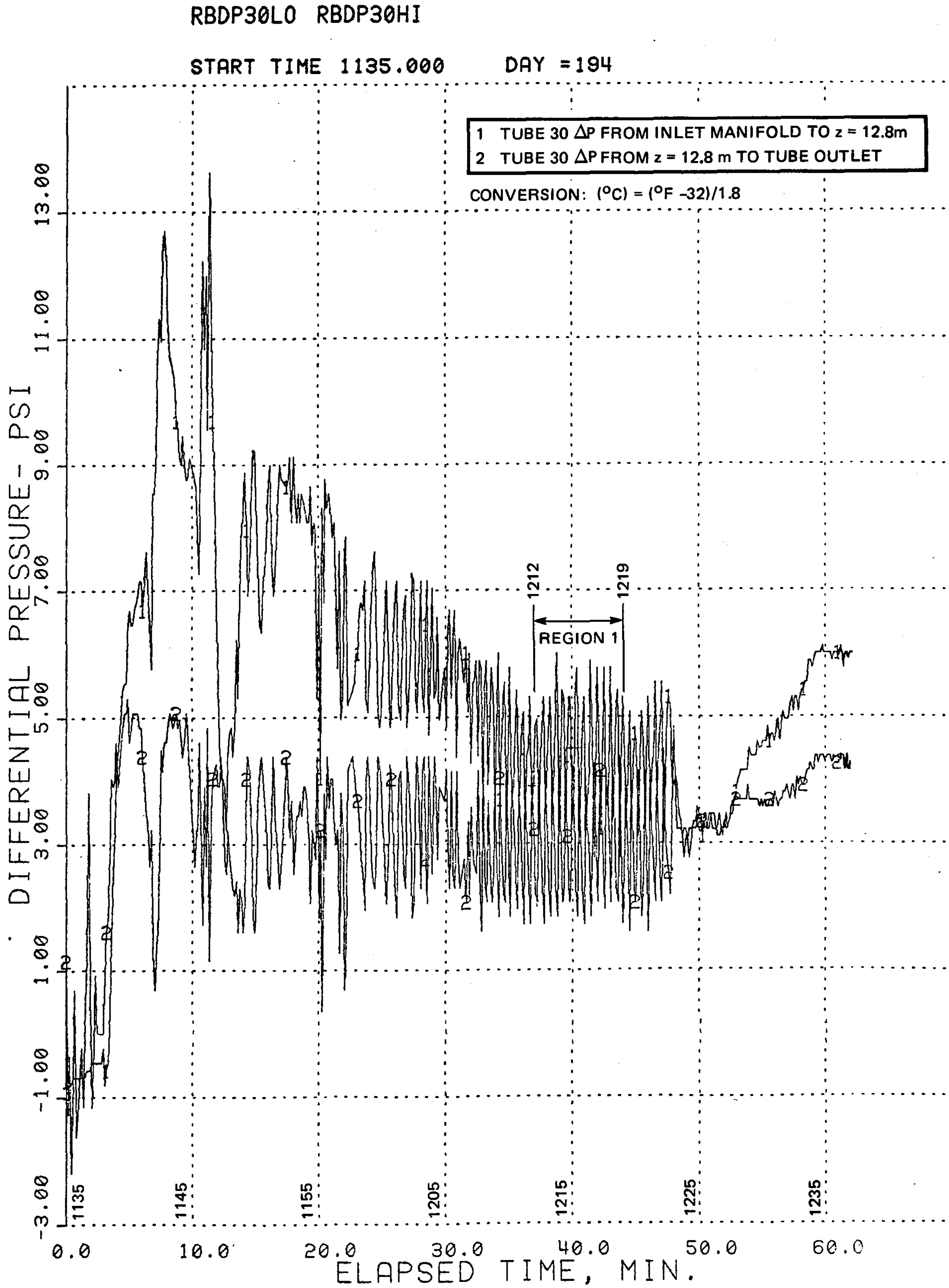

Figure 13. Pressure Drop Profiles for Tube 30, Solar Receiver Test Panel

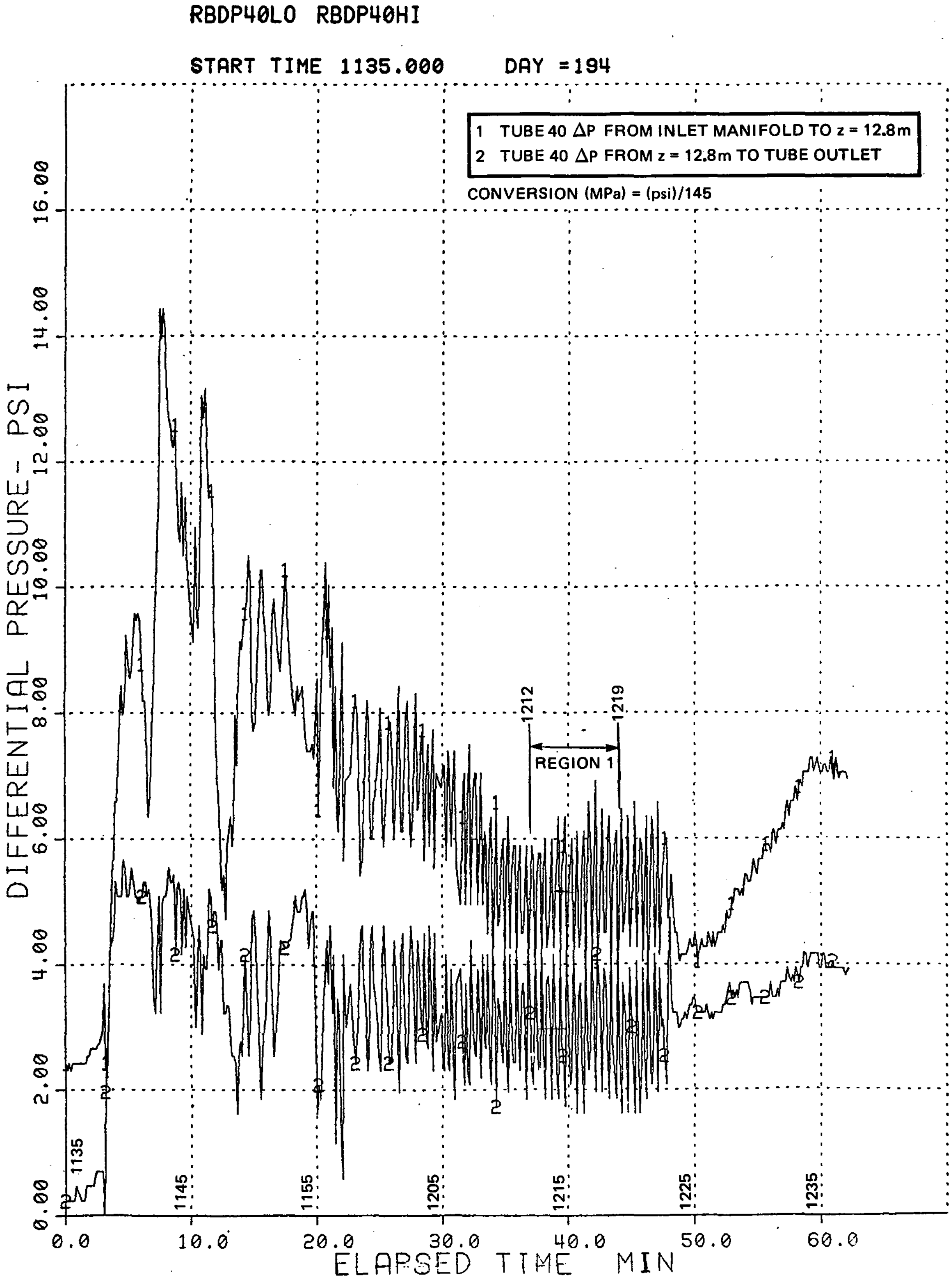

Figure 14. Measured Pressure Drop Profiles for Tube 40, Solar Receiver Test Panel

identified as Region 1, from 1212 to 1219, has been selected for analysis. Region 1 data is presented on an expanded scale in Figures 15 through 17. The outlet temperature oscillations and the pressure oscillations have amplitudes of $\pm$ 4.4 C (8 F) and $\pm$ 6.9 kPa (1 psi), respectively. The periods of both oscillations for both tubes 30 and 40 are 6.5s.

Data for a stable region at 9.93 MPa (1440 psia) pressure and 100 $kg/s \cdot m^2$ (0.74×10^6 $lb/h \cdot ft^2F$) are identified as Region 2 in Figure 18. There is a slight variation in operating conditions during Region 2. Consequently, conditions corresponding to time 1323 were selected for analysis. The data for both Regions 1 and 2 are summarized in Table 4.

The outlet temperatures of tubes 30 and 40 for both Region 1 and 2 conditions varied from the average panel outlet temperature, and, also, from each other. This temperature variation results from a transverse variation of heat flux across the panel.

The analysis was conducted to determine the dynamic stability of both tubes 30 and 40, contained within the 70-tube test panel. Both the GE Solar Thermal Analysis Program, STAP [13], and the new stability code STEAMFREQ-I were used. The steady-state conditions were first simulated by using STAP. The mass flux, outlet pressure, and inlet temperature, were prescribed and the incident heat flux was varied until the experimental tube outlet temperatures were matched. The absorbed heat flux from STAP along with appropriate temperature, pressure and mass flux conditions were then used in STEAMFREQ-I to predict the dynamic stability.

The results of the analysis are summarized in Table 4, and Nyquist plots are presented in Figures 19 and 20 for Region 1, and in Figures 21 and 22 for Region 2, for tube numbers 30 and 40, respectively. The predictions agree with the experimental results, with both tubes unstable for Region 1 and stable for Region 2. For Region 1 the oscillation periods for tube numbers 30 and 40 are predicted at 3.2 and 3.0s, respectively, compared with an experimental value of 6.5s.

STEAMFREQ-I can also be used to determine the amplitude ratio of the experimental pressure oscillations to flow oscillations. Utilizing the

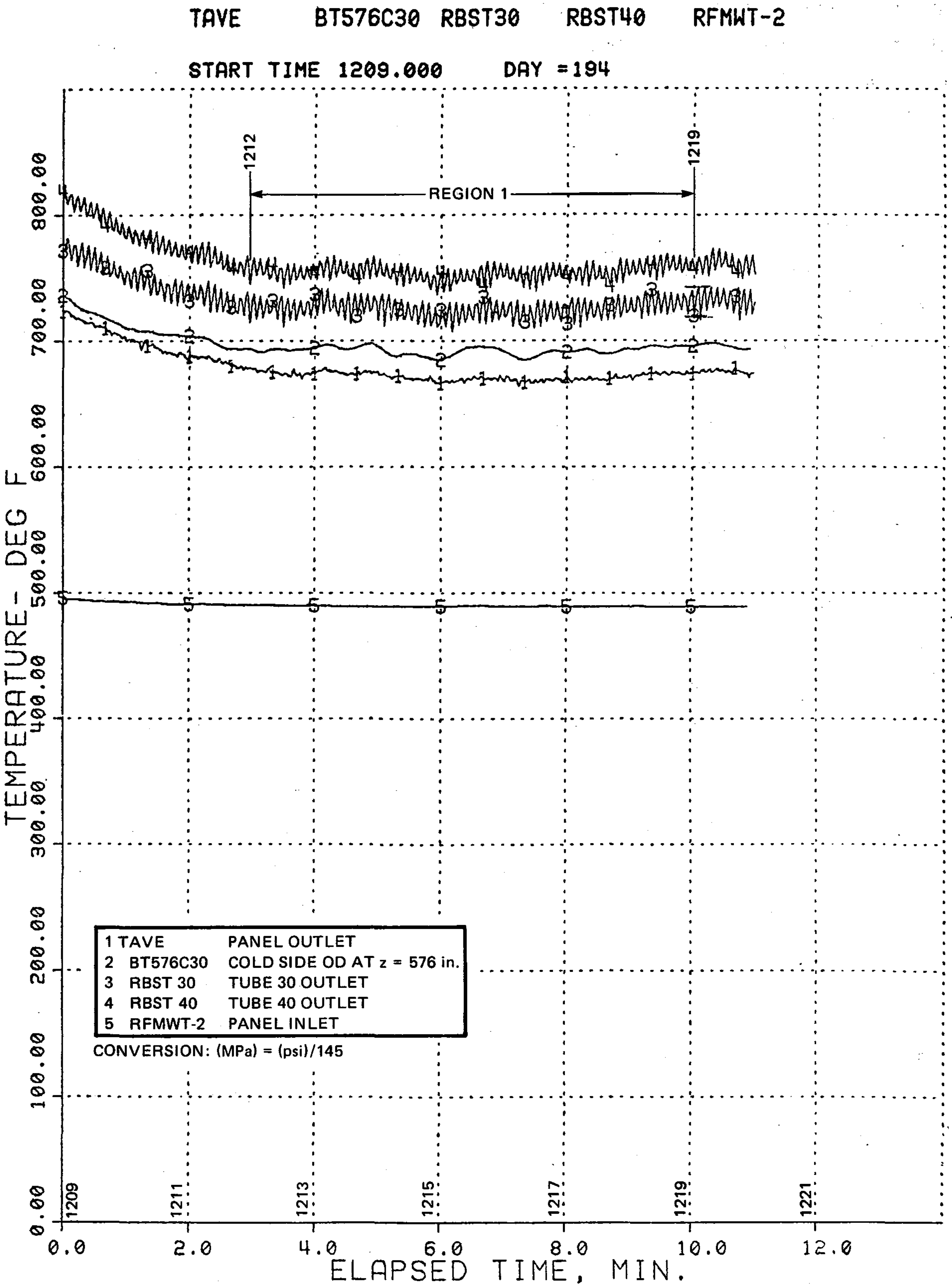

Figure 15. Measured Temperature Profiles for Solar Receiver Test Panel, with 5X Resolutions

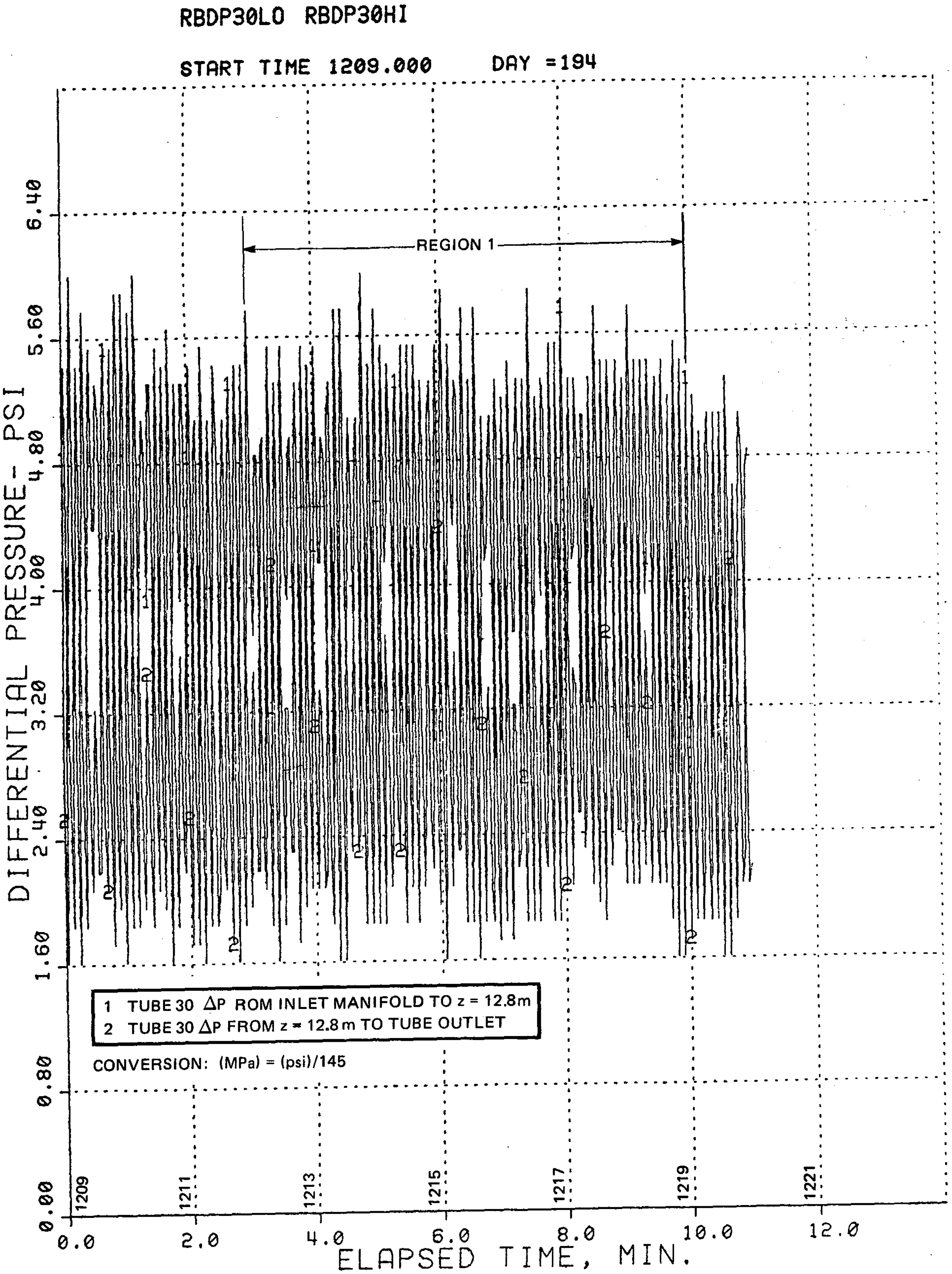

Figure 16. Measured Pressure Drop Profiles for Tube 30, Solar Receiver Test Panel, with 5X Resolutions

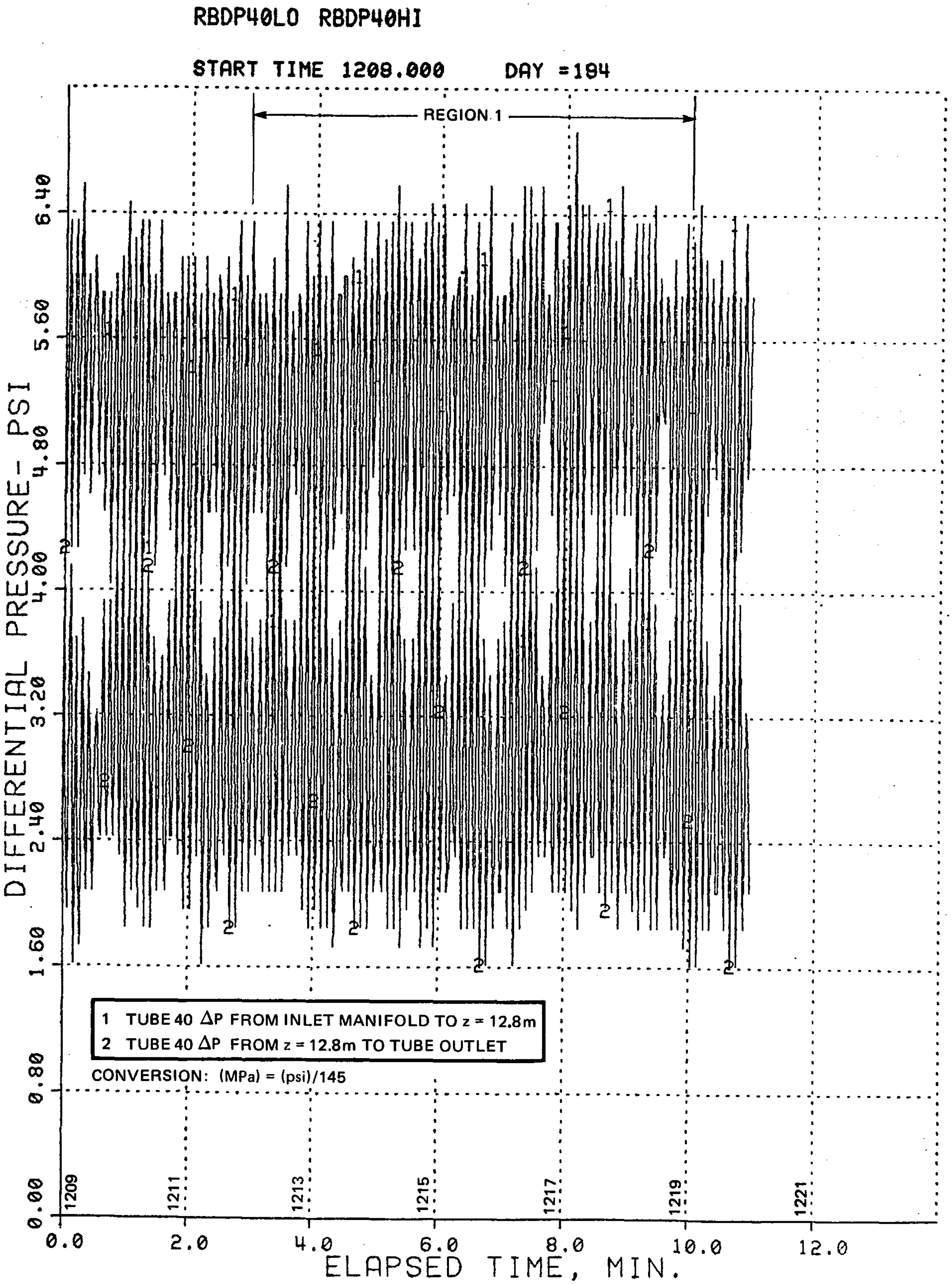

Figure 17. Measured Pressure Drop Profiles for Tube 40, Solar Receiver Test Panel, with 5X Resolutions

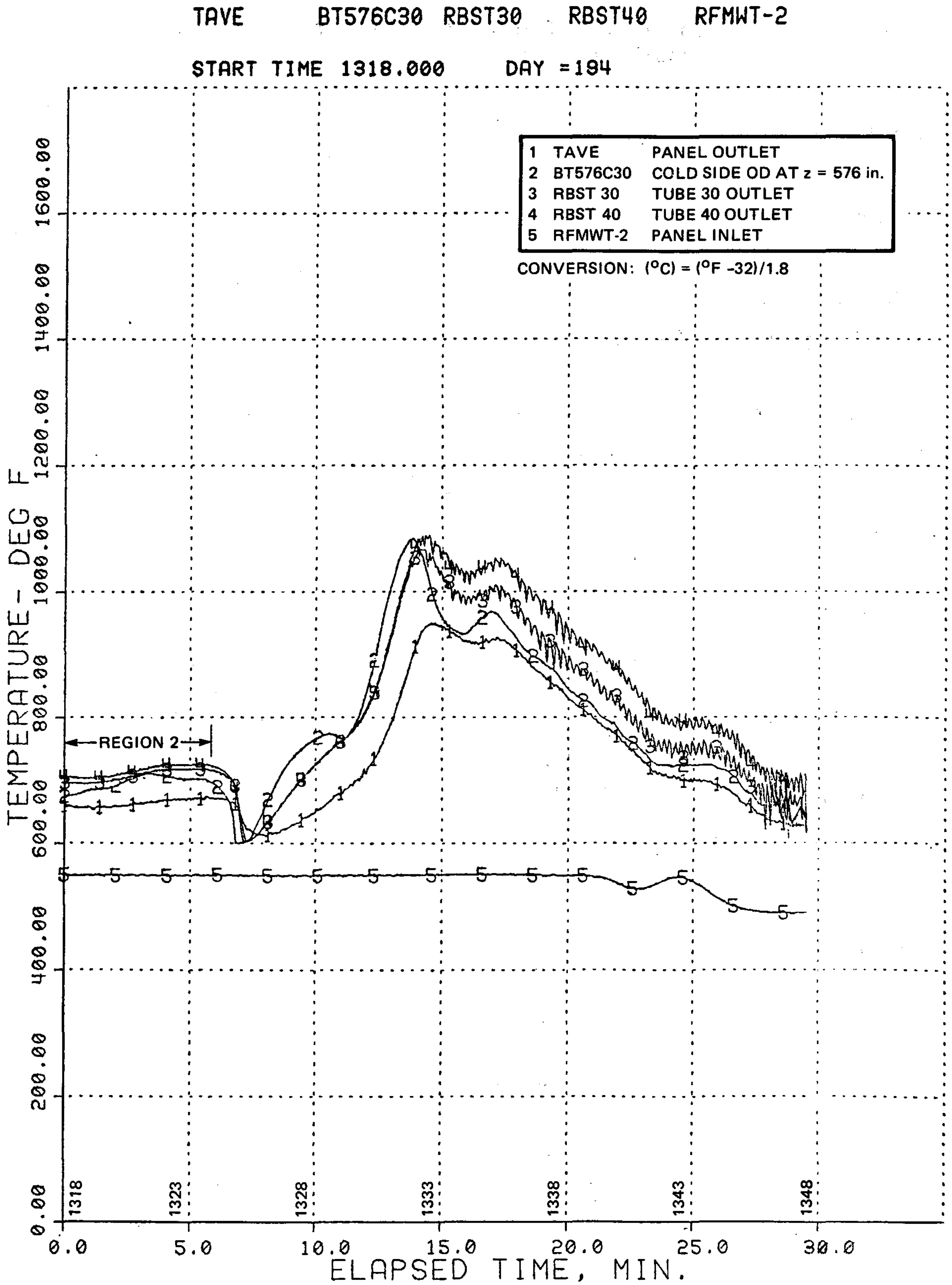

Figure 18. Measured Temperature Profiles for Solar Receiver Test Panel

Table 4. Comparison of Solar Receiver Panel Experimental Stability Results and Predictions from STEAMFREQ-I

Experimental				
Day	194		194	
Time	1212-1219		1323	
Panel Condition				
Outlet pressure, MPa	10.3 (1500)		9.93 (1440)	
Inlet temperature, C	254 (490)		550 (288)	
Flow rate per tube, kg/h	54.1 (119)		13.4 (29.4)	
Mass flux, $kg/s{\cdot}m^2 (10^6 lb/h{\cdot}ft^2)$	410 (.302)		100 (0.74)	
Inlet velocity, m/s (ft/s)	.525 (1.72)		.136 (.447)	
Absorbed power, MW	1.97		0.40	
Absorbed power per tube, kW	28.1		5.71	
Tube Condition				
Tube No.	30	40	30	40
Exit temperature, C (F)	385 (725)	399 (750)	381 (718)	386 (726)
Exit quality	1.25	1.28	1.24	1.25
Pressure drop, kPa (psi)	116 (16.9)	112 (16.2)	--	--
ΔP_{osc}, kPa (psi)	6.9 (1.0)	6.9 (1.0)	Stable	Stable
τ, s	6.5	6.5	Stable	Stable
Prediction				
Run No.	31.8	31.7	36.3	36.4
Heated section transit time, s	8.7	8.5	31.0	30.9
$\Delta V_{i,osc}/V_i$	0.52	0.52	Stable	Stable
Osc. period, s	3.2	3.0	Stable	Stable

RUN 31.8

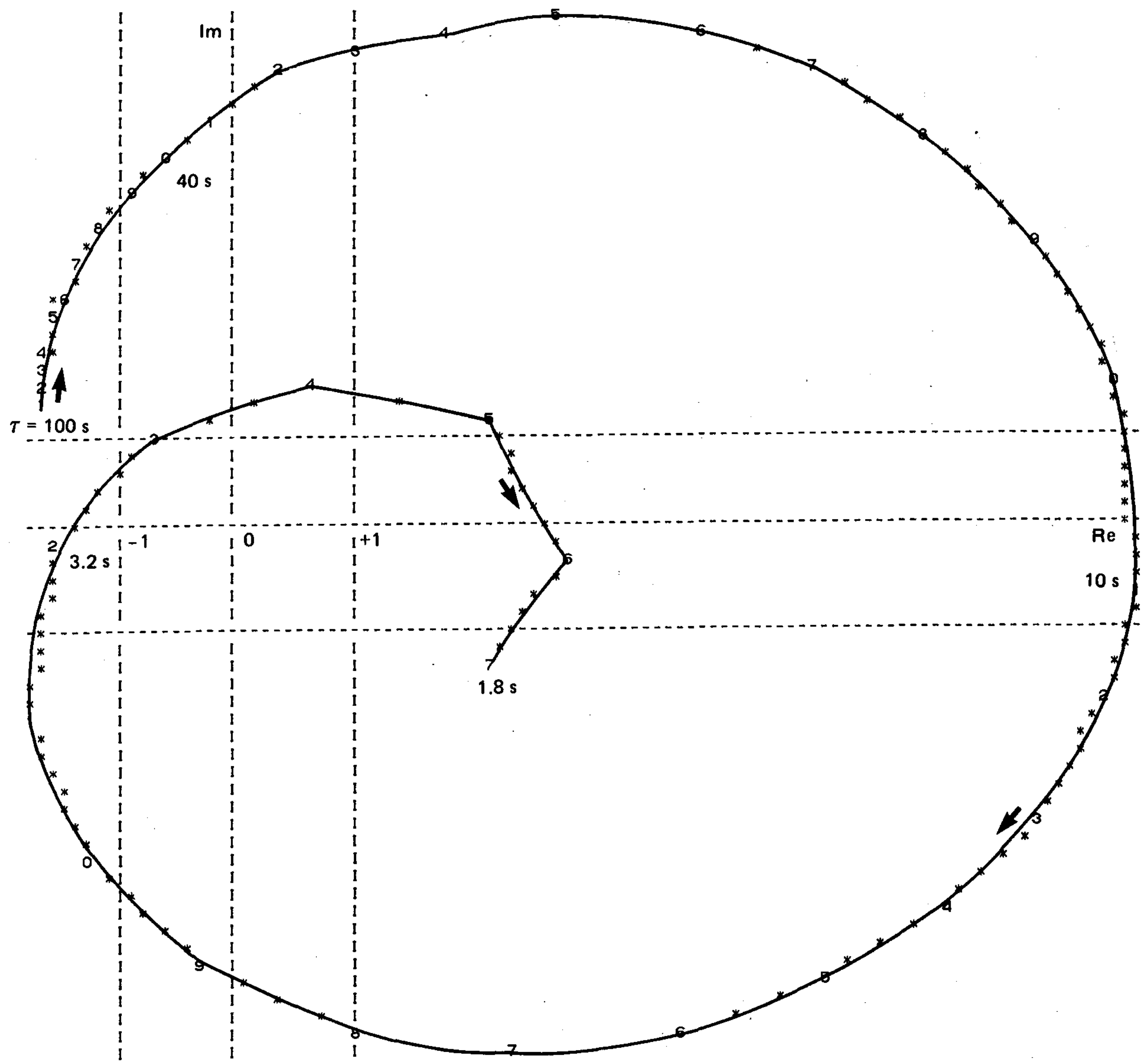

Figure 19. Nyquist Plot from STEAMFREQ-I for Solar Receiver Test Panel, D194: 1212–1219, Region 1, Tube 30

RUN 31.7

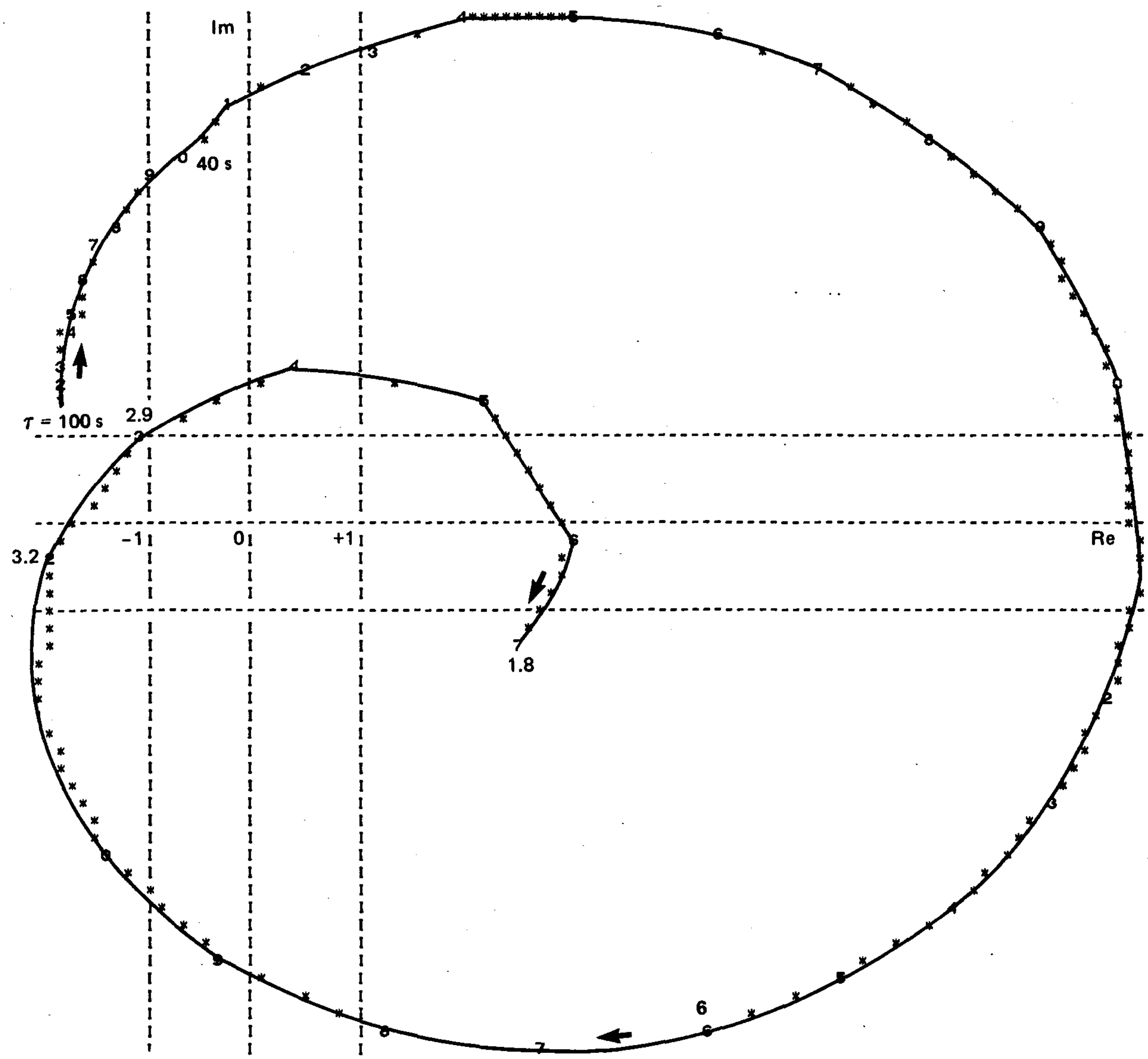

Figure 20. Nyquist Plot from STEAMFREQ-I for Solar Receiver Test Panel, D194: 1212–1219, Region 1, Tube 40

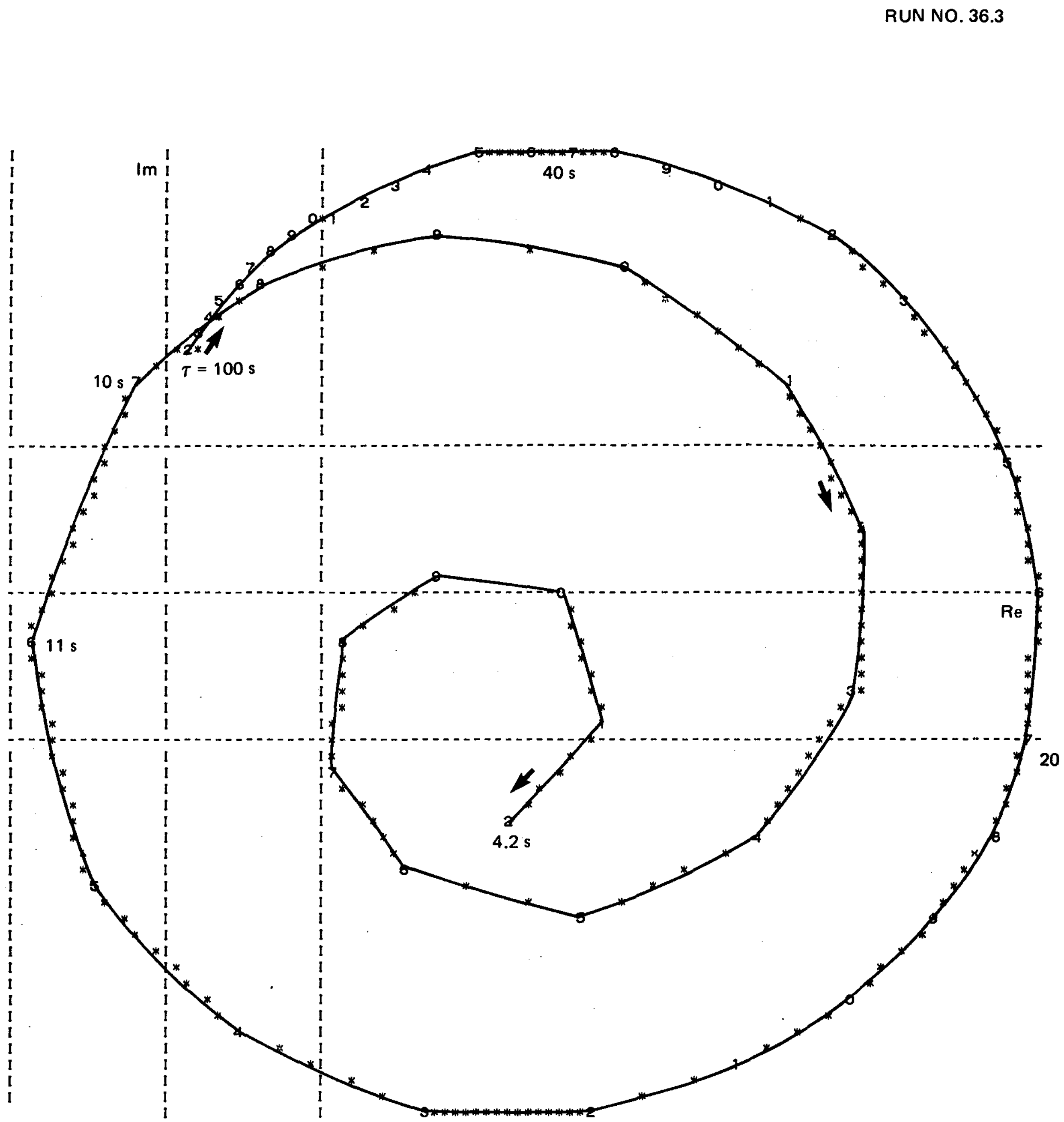

Figure 21. Nyquist Plot from STEAMFREQ-I for Solar Receiver Test Panel, D194: 1323, Tube 30

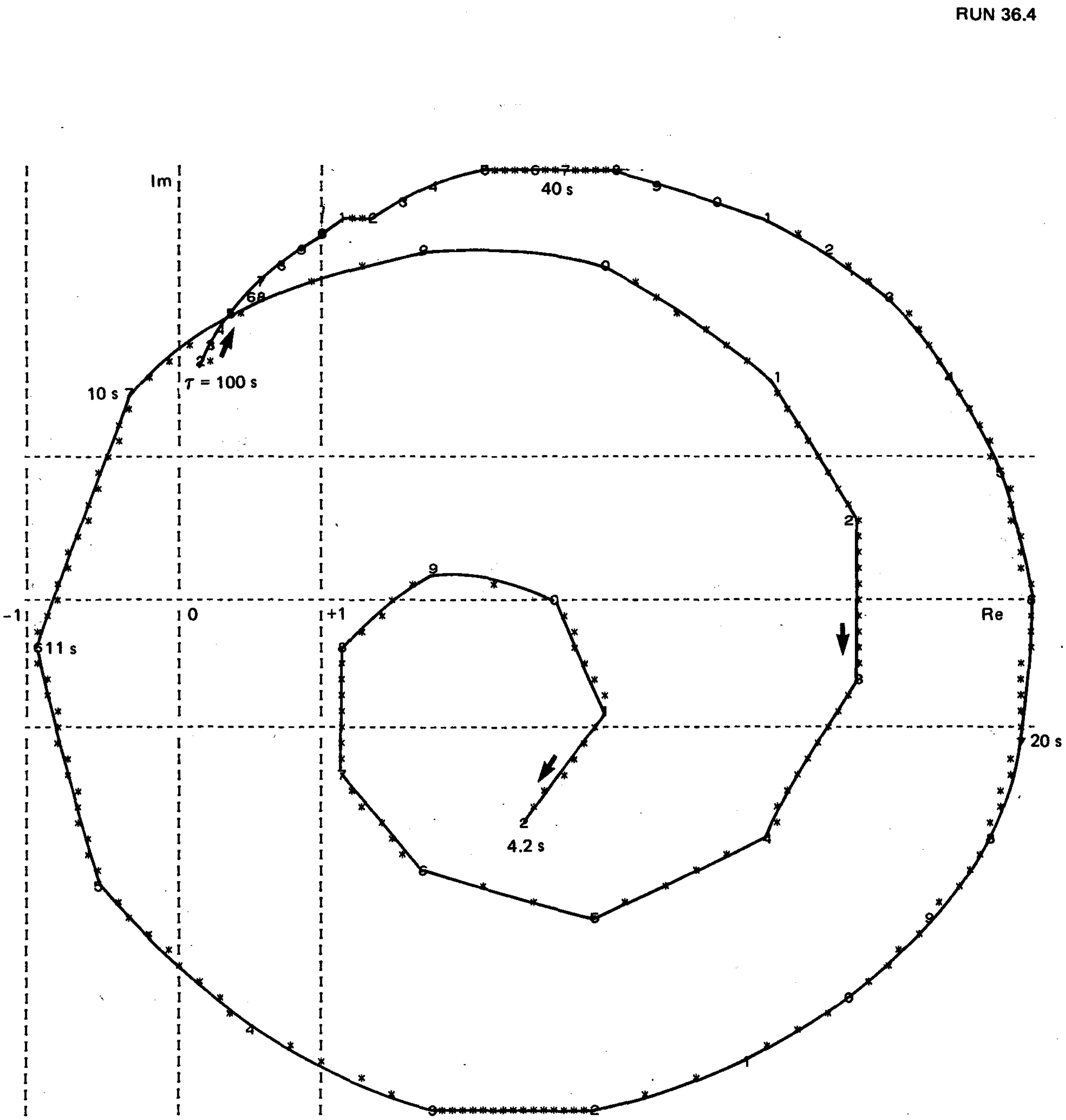

Figure 22. Nyquist Plot from STEAMFREQ-I for Solar Receiver Test Panel, D194:1323, Tube 40

experimental pressure oscillation of ± 6.7 kPa (1 psi), the code predicts an inlet flow oscillation of ± 52%.

4.5 Comparison of Stability Predictions With Data From a Sodium-Heated Steam Generator Test

Threshold dynamic stability data have recently been obtained by France [16] and co-workers at Argonne National Laboratories. The test article and the test facility have been previously described [7, 17]. The test article consists of a 2-1/4 Cr-1 Mo steel tube with an inside diameter of 10.0 mm and a wall thickness of 2.90 mm. Water flows vertically upward in the tube and is heated by sodium which flows countercurrent in a surrounding annulus. The tubes are held in concentricity by support spacers. The active heat transfer length between centerlines of the sodium nozzles is 13.1 m.

The test tube is installed in the 1-MW Steam Generator Test Facility (SGTF). The test section inlet and exit piping are schematically presented in Figure 23. A test section bypass circuit permits up to 100 times the test tube flow rate to bypass the test tube. The bypass simulates a large number of tubes in parallel with the test tube and imposes constant pressure boundaries at the beginning of the inlet piping and the end of outlet piping.

The test tube flow rate was measured with a turbine-type flow meter. The pressure drops across the inlet and outlet piping were monitored. The outlet flow resistance was increased by step-wise closure of an exit throttle valve until instability was detected.

Data showing the initiation of substantial systematic flow rate oscillations are presented in Figures 24 and 25 for superheated outlet steam at 15.8 MPa (2290 psia) pressure and 421 $kg/s{\cdot}m^2$ (0.310×10^6 $lb/h{\cdot}ft^2$) mass flux. These oscillations are characteristic of dynamic channel instability. The average time period of the flow oscillations is 4.3s. The experimental conditions are summarized in Table 5.

The steady-state operating conditions have a 2.7% energy imbalance between the sodium and water sides. This imbalance is assumed to arise from errors in the water mass flux and the sodium-side power values.

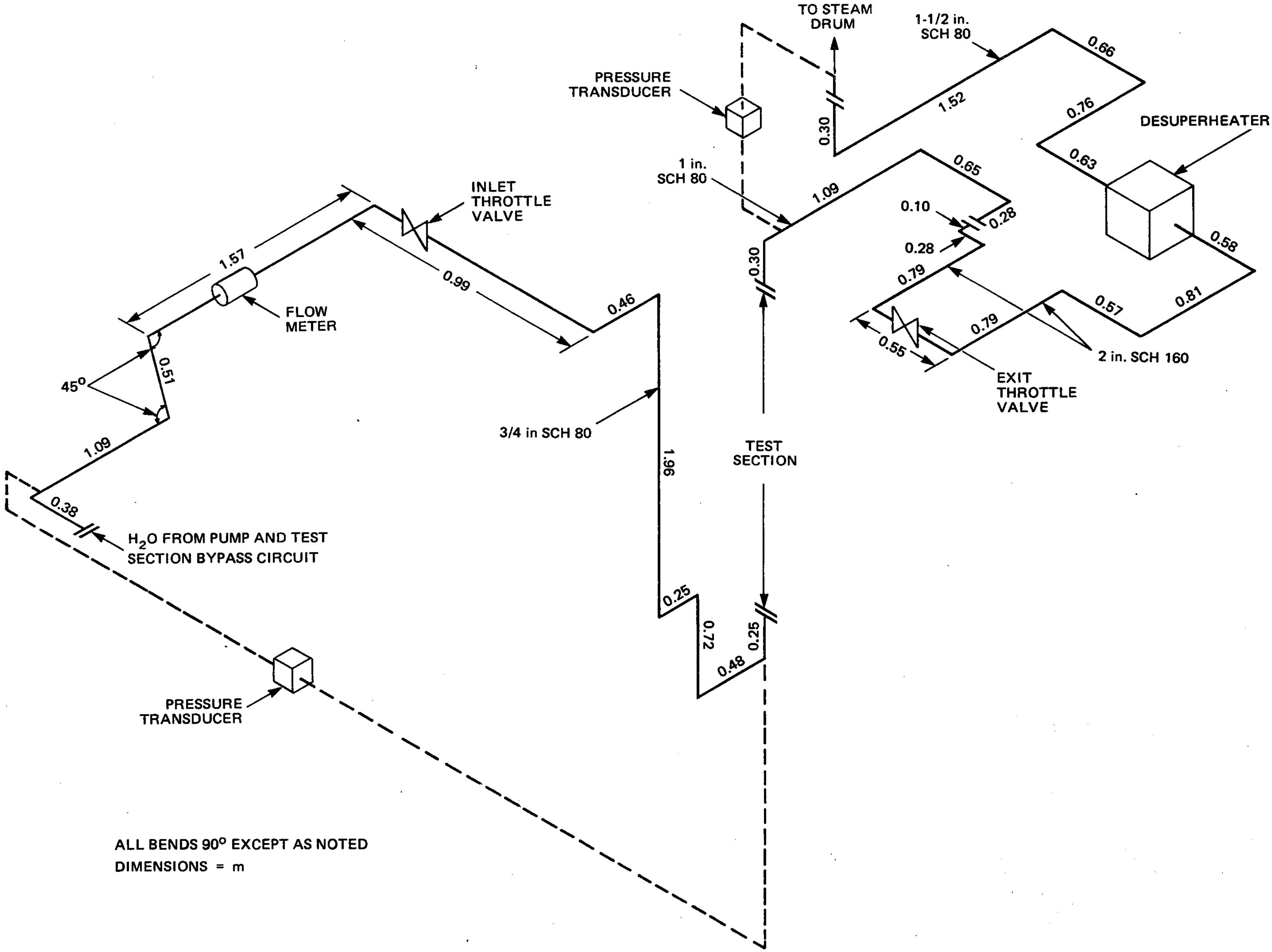

Figure 23. SGTF Test Section Inlet and Exit Piping, Reference 16

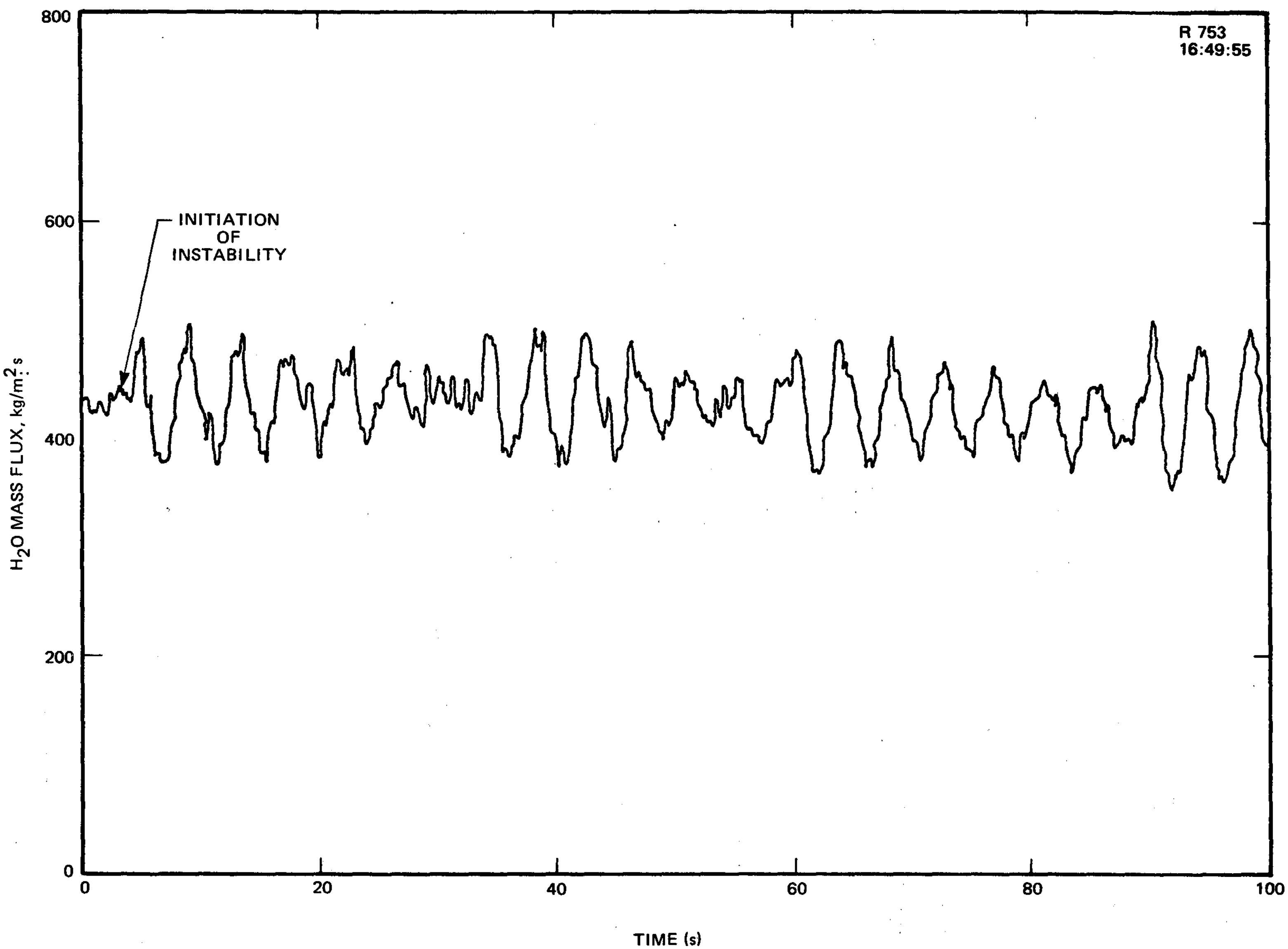

Figure 24. Water Mass Flux Oscillations at Instability Threshold for Sodium-Heated Tube, Reference 16

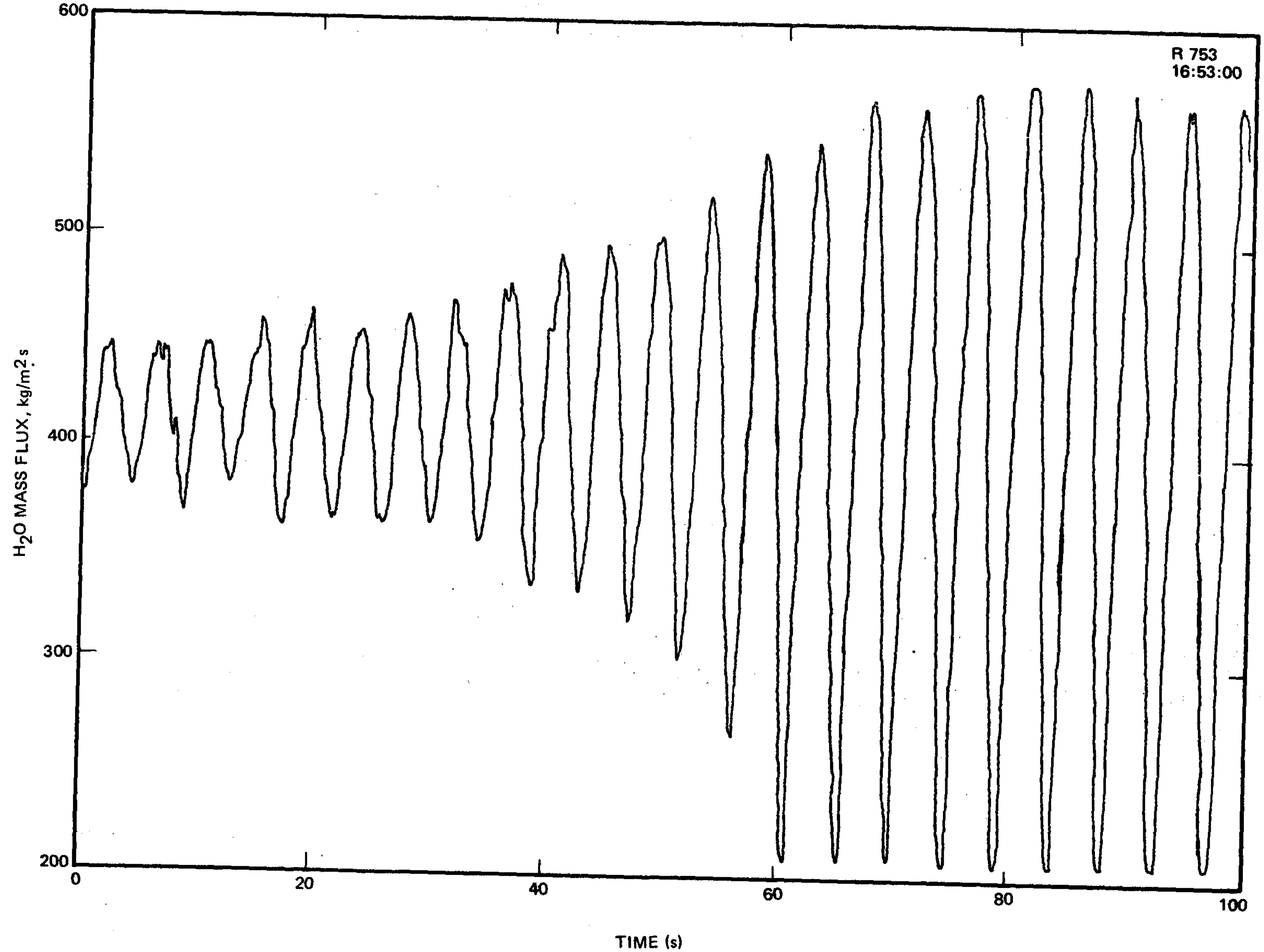

Figure 25. Water Mass Flux Oscillations Far into the Instability, Reference 16

Table 5. Comparison of Sodium-Heated Steam Generator Experimental Results and Predictions from STEAMFREQ-I at Instability Thresholds

Experimental

Run	817
System pressure	15.80 MPa (2290 psia)
Inlet temperature	239.2 C (462 F)
Exit temperature	441.1 C (826 F)
Exit quality[(1)]	1.553
Water flow rate, W	0.0331 kg/s (263 lb/h)
Water mass flux, G	421.2 kg/s·m^2 (0.310 x 10^6 lb/h·ft^2)
$\Delta P_{i,f}$	1.4 kPa (0.2 psi)
$\Delta P_{o,f}$	62. kPa (9.0 psi)
Power,[(2)] Q	67.5 kW
τ	4.3 s

Prediction

Condition	Set I			Set II		
Run	43.6	45.4	45.8	44.7	46.4	46.3
Exit quality	1.553	1.708	1.669	1.553	1.686	1.646
G/G_{exp}	1.00	1.00	0.95	0.973	0.973	0.934
Q/Q_{exp}	1.027	1.099	1.027	1.00	1.06	1.00
$\Delta P_{o,f}/\Delta P_{o,f,exp}$	2.11	1.00	1.00	1.67	1.00	1.00
Heated section transit time, s	9.6	9.2	9.8	9.9	9.5	10.0
Osc. period, s	4.1	3.7	4.0	4.2	3.8	4.1

1. Based on measured exit temperature
2. Based on sodium-side conditions

The stability predictions with STEAMFREQ-I were conducted with two sets of conditions simulating the data. In the first set, designated as Set 1, power was considered dependent and varied until a heat balance was obtained. In the second set, designated as Set 2, mass flux was considered dependent and, in turn, was varied until a heat balance was obtained. Three series of runs were, subsequently, made with each set of conditions to predict the instability. In the first series the outlet pressure drop was systematically increased until an instability was predicted; in the second series the power was increased, and in the third series the mass flux was decreased.

Results for the final run in each series are summarized in Table 5, and corresponding Nyquist plots are presented in Figures 26 and 27 for Set 1 and Figures 28 and 29 for Set 2. The results show good agreement between the predicted oscillation periods of 3.7 to 4.2s and the experimental period of 4.3s. The predicted mass flux and power to obtain instability are within 6.6 and 6.0% of the experimental values, respectively. The largest disagreement occurs between the predicted and experimental outlet pressure drops, corresponding to ratios of 2.11 and 1.67 for Sets 1 and 2, respectively.

The difference between the predicted and the experimental stability threshold conditions may be due to several experimental features which are not precisely modeled in STEAMFREQ-I. The location of the outlet flow resistance imposed by the outlet throttle valve is only approximately modeled. The code assumes that the valve flow resistance is in the outlet plane of the test section. The test outlet piping in Figure 23 shows that the valve and its associated flow resistance is located substantially farther downstream. STEAMFREQ-I also uses an imposed heat flux as specified input and, consequently, the effects of primary-secondary heat flux-flow coupling are neglected. Because of the complicated interactions between flow, heat flux, wall dynamics, and geometry, it is not possible to state whether the lack of precise modeling should be stabilizing or destabilizing. Improved modeling in these areas should provide better agreement.

RUN 43.6

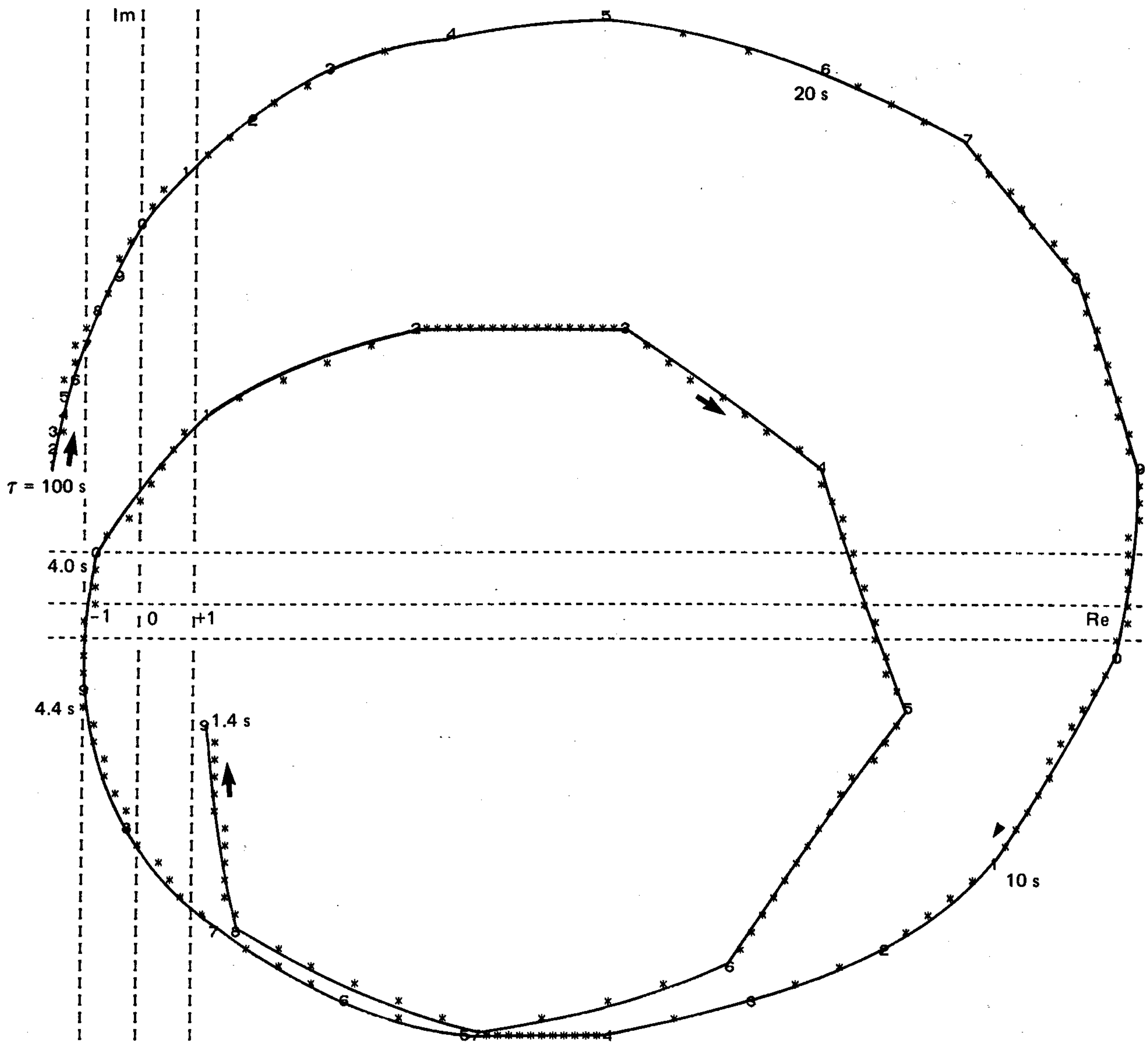

Figure 26. Nyquist Plot from STEAMFREQ-I for Sodium-Heated Tube at Instability Threshold, Conditions Set I, Run 43.6

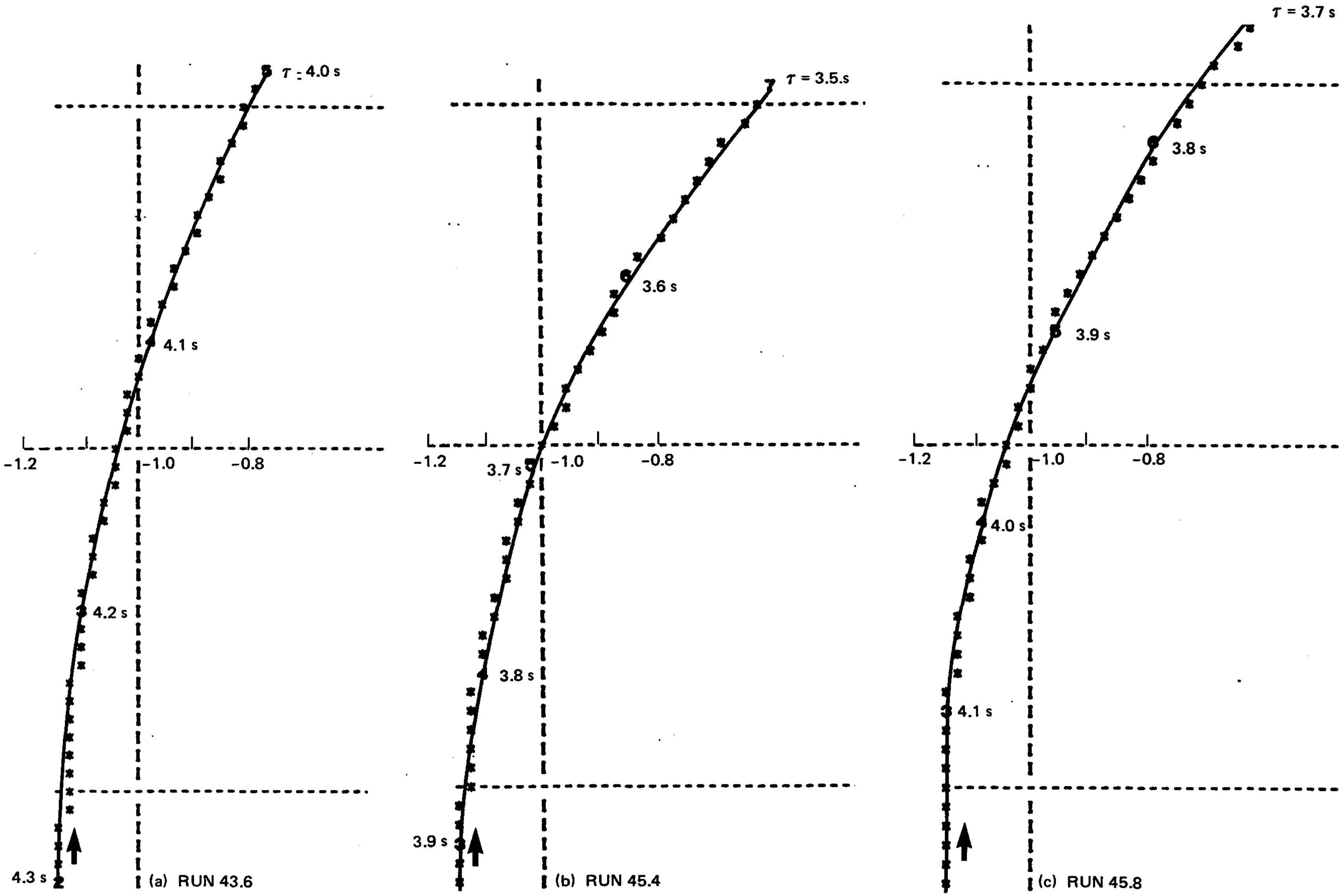

Figure 27. Partial Nyquist Plots from STEAMFREQ-I for Sodium-Heated Tube at Instability Threshold, Condition Set I

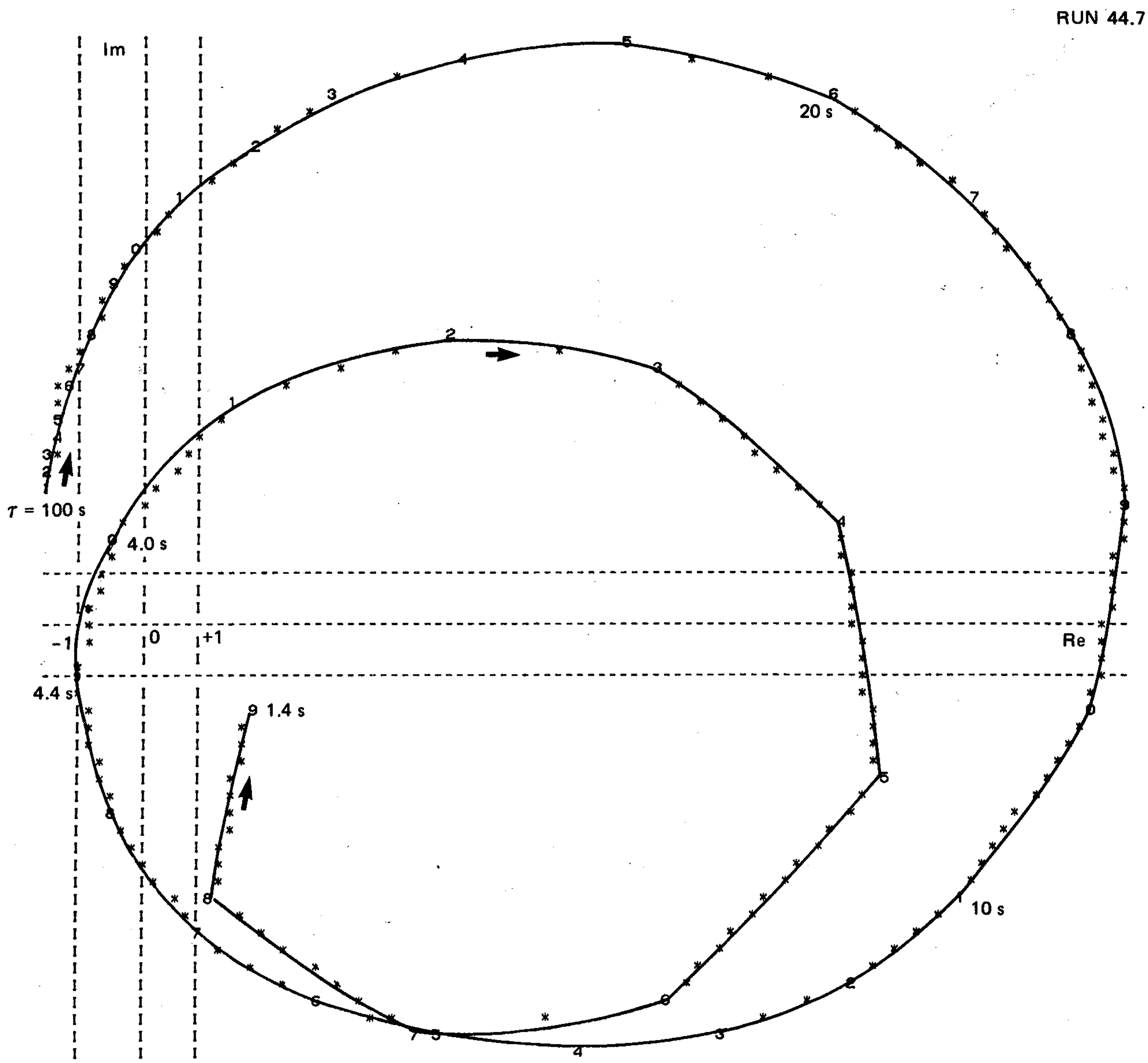

Figure 28. Nyquist Plot from STEAMFREQ-I for Sodium-Heated Tube at Instability Threshold, Condition Set II, Run 44.7

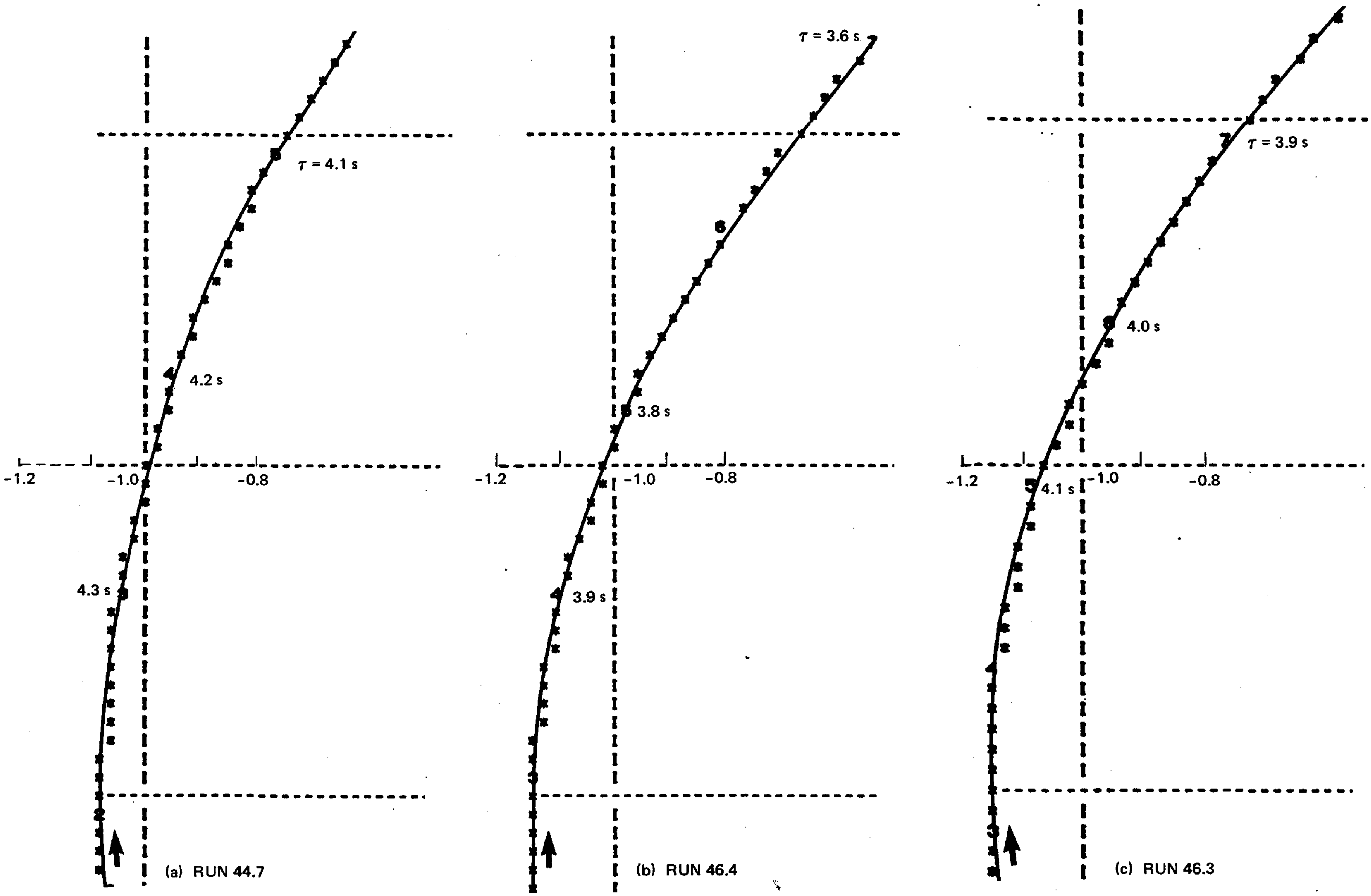

Figure 29. Partial Nyquist Plots from STEAMFREQ-I for Sodium-Heated Tube at Instability Threshold, Condition Set II

5. SUMMARY AND CONCLUSIONS

Analysis to develop an advanced model for the investigation of density-wave instabilities has yielded the following principal results:

a. An analytical model has been formulated for the investigation of density-wave instabilities in steam generators with imposed heat flux. The model utilizes a drift flux flow model in the boiling region, permits spatial variation of imposed heat flux, and includes wall dynamics and variable steam properties in the superheat region.

b. The governing conservation equations of the model are solved numerically in a FORTRAN program, STEAMFREQ-I.

c. Stability results in the form of Nyquist plots are presented for predictions from NUFREQ2, NUFREQ3 and STEAMFREQ-I. Results from STEAMFREQ-I are between those from NUFREQ2 and NUFREQ3.

d. Unstable and stable conditions predicted with STEAMFREQ-I agree with unstable and stable experimental conditions obtained from a solar receiver panel test.

e. Predictions of stability thresholds from STEAMFREQ-I are compared with experimental data from a sodium-heated steam generator test. The predicted mass-flux and power to obtain instability are within 6.6 and 6.0% of the experimental values, respectively.

ACKNOWLEDGEMENTS

This work was performed under GE-Sandia Contract No. 18-2969 managed by E. T. Cull of Sandia Laboratories.

K. R. Callis and R. B. Butler are acknowledged for computer analysis support.

NOMENCLATURE

a	Parameter defined when introduced
a_1	Reynolds number exponent in single-phase heat transfer correlation
A	Cross-sectional flow area of heated tube
b	Tube wall thickness
c	Specific heat
C_f	Adjustment factor for frictional pressure drop
C_g	Adjustment factor for gravitational pressure drop
C_o	Drift flux model correlation parameter
C_k	Kinematic velocity
D_H	Hydraulic diameter
f	Friction factor (Moody type)
f'	Axial gradient of the heat flux
f_{fo}	Two phase friction factor based on the total flow being all liquid
g	Acceleration of gravity
G	Mass flux
h	Enthalpy
h_{fg}	Latent heat of vaporization
H	Heat transfer coefficient
j	Volumetric flux density
k	Thermal conductivity
k_o	Constant introduced in Equations 65 and 66
K_{ex}	Exit pressure drop coefficient
K_i	Inlet pressure drop coefficient
K_{or}	Inlet orifice pressure drop coefficient
L_H	Heated channel length

L_r	Riser Length
P	Pressure
P_h	Heated perimeter
$\Delta P_{i,f}$	Frictional inlet pressure drop
$\Delta P_{o,f}$	Frictional outlet pressure drop
ΔP_{osc}	Amplitude of measured pressure oscillation
q	Heat flux
Q	Power
r	Radial coordinate
s	Laplace-transform variable
t	Time
T	Temperature
v	Velocity
V_g	Specific volume of the vapor at saturation conditions
V_{gs}	Fictitious specific volume defined in Equation 66
V_s	Specific volume of the superheated vapor
ΔV	Velocity oscillation amplitude
V_{gj}	Drift velocity of the vapor with respect to j (drift flux model)
W	Flow rate
x	Radial coordinate in flat-plate geometry
x_s	Superheat quality defined in Equation 64
z	Axial coordinate (in flow direction)

<u>Greek Letters</u>

α	Void fraction
$\alpha_1\ \alpha_2\ \alpha_3$	Constants defined when introduced

Γ_g	Vapor generation rate
ζ	Slope of pump characteristic
κ	Thermal diffusivity
η	Superheat boundary
λ	Boiling boundary
ρ	Density
τ	Oscillation period
ϕ	Dimensionless density function
ϕ_{fo}	Two-phase frictional pressure drop multiplier
Ω	Reaction frequency
Ω_s	Parameter defined in Equation 71

Superscripts

+	Designates variables with both space and time dependence.

Steady-state values are shown without subscripts or superscripts, while the perturbations are denoted by δ. Thus for a variable y function of z and t: $y^+(z,t) = y(z) + \delta y(z,t)$. The Laplace transform of $\delta y(z,t)$, $\delta y(z,s)$ is also denoted as δy to simplify the notations.

Subscripts

1	Inner wall surface
2	Outer wall surface
1ϕ	Single-phase
2ϕ	Two-phase
ch	Channel
ex	Heated channel exit
exp	Experimental

f	Liquid phase at saturation
g	Vapor phase at saturation
i	Inlet conditions
ℓ	Unheated loop
r	Riser
s	Superheat
t	Tube wall
w	Water
η	Superheat boundary
λ	Boiling boundary

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APPENDIX A

DETERMINATION OF HEAT FLUX PERTURBATION AT THE INNER WALL

Since the heat flux is imposed externally on the outer wall*, the heat input into the fluid (q_1^+) is variable during flow oscillations. Assuming that the heat flux perturbation depends only on the local flow conditions and the local wall temperature, we can relate these as follows:

$$\delta q_1 = H\,(\delta T_1 - \delta T_w) + \delta H\,(T_1 - T_w) \tag{A.1}$$

On the outer wall,

$$\delta q_2 = 0 \tag{A.2}$$

The wall temperature perturbation is obtained from the solution of the perturbed conduction equation of the tube wall. Consider the case of cylindrical geometry first. Referring to Figure A.1, the time dependent conduction equation for the tube wall in the radial direction is:

$$\frac{\partial T_t}{\partial t} = \kappa \frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{\partial T_t}{\partial r}\right) \tag{A.3}$$

The boundary conditions are:

$$k\,\frac{\partial T_t}{\partial r}\bigg|_{r_1} = q_1 \tag{A.3a}$$

$$k\,\frac{\partial T_t}{\partial r}\bigg|_{r_2} = q_2 \tag{A.3b}$$

Perturbing and Laplace-transforming Equation A.3 and the boundary conditions yields:

*The solution for the perturbation in the case of a wall with constant and radially uniform internal heat generation is identical to the one considered here.

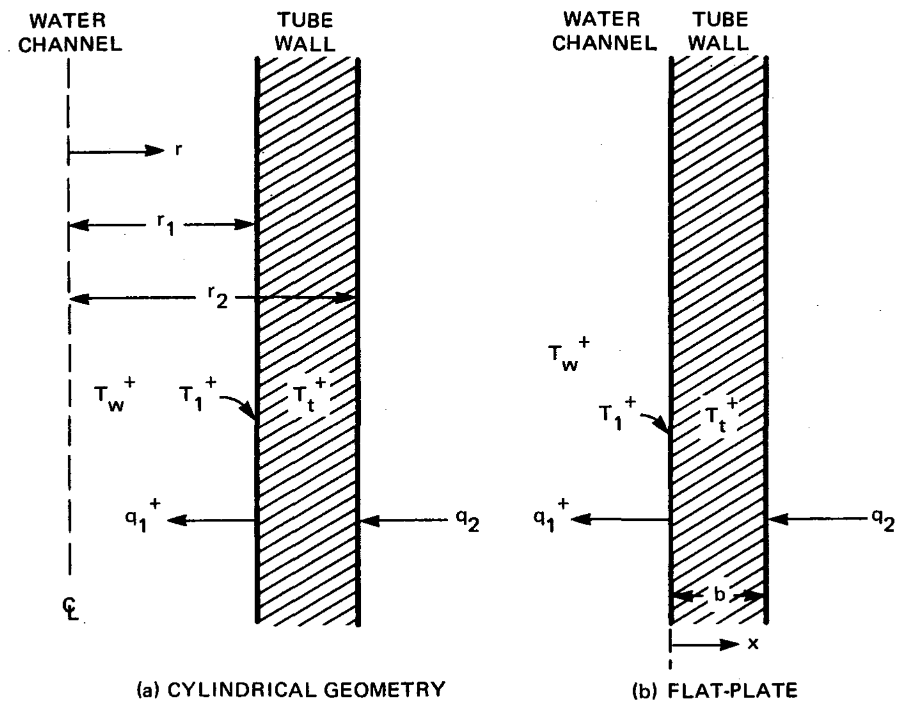

Figure A-1. Channel Geometry Section

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\delta T_t}{dr}\right) = \frac{s}{\kappa}\,\delta T_t \tag{A.4}$$

$$k\left.\frac{\partial \delta T_t}{\partial r}\right|_{r_1} = \delta q_1 \tag{A.4a}$$

$$k\left.\frac{\partial \delta T_t}{\partial r}\right|_{r_2} = \delta q_2 \tag{A.4b}$$

Equation A.4 is a Bessel-type ordinary differential equation with the following solution:

$$\delta T_t = A_1\, I_o\,(ar) + A_2\, K_o\,(ar) \tag{A.5}$$

where

$$a \equiv \sqrt{\frac{s}{\kappa}}$$

and $I_o(ar)$ and $K_o(ar)$ are the modified Bessel functions of the first kind. The constants A_1 and A_2 are obtained from the boundary conditions A.4a and A.4b and Equations A.1 and A.2. δT_1 is determined by setting $r=r_1$ in Equation A.5:

$$\delta T_1 = A_1 I_o(ar_1) + A_2 K_o(ar_1) \tag{A.6}$$

Substituting back into Equation A.1 we obtain

$$\delta q_1 = \alpha_1\,[\delta T_w + \frac{\delta H}{H}(T_w - T_1)] \tag{A.7}$$

where

$$\alpha_1 \equiv \frac{-1}{\frac{1}{H} + \left(\frac{I_o(ar_1)K_1(ar_2) + I_1(ar_2)K_o(ar_1)}{I_1(ar_2)K_1(ar_1) - I_1(ar_1)K_1(ar_2)}\right)\frac{1}{ka}} \tag{A.8}$$

Equation A.7 is the heat flux perturbation at the inner wall expressed in terms of perturbations of the fluid temperature and the heat transfer coefficient.

The procedure for obtaining δq_1 in the case of flat-plate geometry is similar to the cylindrical geometry case. Referring to part (b) of Figure A.1, the wall conduction equation now becomes

$$\frac{\partial T_t}{\partial t} = \kappa \frac{\partial^2 T_t}{\partial x^2} \qquad \text{(A.9a)}$$

The boundary conditions are:

$$k \left.\frac{\partial T_t}{\partial x}\right|_{x=0} = q_1 \qquad \text{(A.9b)}$$

$$k \left.\frac{\partial T_t}{\partial x}\right|_{x=} = q_2 \qquad \text{(A.9c)}$$

Perturbing and Laplace-transforming Equation A.9a and following the same procedure as that for cylindrical geometry, δq_1 is obtained in the same form as Equation A.7, except that the constant α_1 is now defined as:

$$\alpha_1 \equiv \frac{-1}{\frac{1}{H} + \frac{1}{ka} \frac{(e^{ab} + e^{-ab})}{(e^{ab} - e^{-ab})}} \qquad \text{(A.10)}$$

where b is the tube wall thickness.

APPENDIX B
STEAMFREQ-I LISTING

FILE FS0227/STFR-I; PAGE 1
11/27/79 AT 19.91335

```
C
C
C      STEAMFREQ-I IS A PROGRAM TO STUDY DENSITY WAVE OSCILLATIONS IN
C     STEAM GENERATORS WITH IMPOSED HEAT FLUX
C******************
C    -INPUT DESCRIPTION----------------------
C
C     .......INPUT FOR NAMELIST $SYSTEM
C
C     P = SYSTEM PRESSURE (PSIA)
C      TSAT = SATURATION TEMPERATURE CORRESPONDING TO P (F)
C      TLIMIT = ESTIMATED EXIT STEAM TEMPERATURE FOR GENERATION OF STEAM
C               TABLE. SET IT EQUAL TO 100 - 200 DEGREES FARENHEIT
C                 ABOVE ESTIMATION  (DEFAULT = 1400. )
C      IPRES = 0  -  MARTINELLI-NELSON CORRELATION IS USED FOR TWO-PHASE
C                        PRESSURE-DROP CALCULATIONS
C             = 1  -  USER SPECIFY TWO-PHASE PRESSURE-DROP CORRELATION
C                        THROUGH INPUT, PROGRAM INTERPOLATES THE DATA
C                        SUPPLIED BY USER.
C
C      ........INPUT VALUES OF TWO-PHASE PRESSURE-DROP MULTIPLIERS IF
C               IPRES=1 WAS SPECIFIED IN $SYSTEM
C               INPUT MULTIPLIERS STARTING FROM QUALITY=0 TO QUALITY=1.
C               IN INTERVALS OF .1 (11 VALUES ALTOGETHER) USING
C               FORMAT (8F10.5)
C
C      $SYSTEM (AND PRESSURE-DROP CORRELATIONS, IF SPECIFIED) NEED TO
C      BE INPUTED  ONLY ONCE AND WILL BE USED THROUGHOUT THE PROGRAM RUN
C
C      .........INPUT ONE LINE FOR COMMENTS
C
C      ........INPUT FOR NAMELIST $INPT
C
C      R1 = INNER RADIUS OF THE HEATED CHANNEL (FT)
C      R2 = OUTER RADIUS OF THE HEATED CHANNEL (FT)
C      ALHEAT = LENGTH OF HEATED CHANNEL (FT)
C      RISER = LENGTH OF ADIABATIC RISER (FT)
C      DRISE = HYDRAULIC DIAMETER OF RISER (FT)
C      ARISE = CROSS-SECTIONAL AREA OF RISER (FT2)
C          (DEFAULT...RISER=0.0 AND ARISE, DRISE NEED NOT BE SPECIFIED)
C      VINLET = STEADY-STATE WATER VELOCITY AT INLET OF HEATED SECTION
C               (FT/SEC)
C      TWIN = INLET WATER TEMPERATURE (F)
C      NODE = NUMBER OF FINITE DIFFERENCE MESH TO BE DIVIDED IN THE BOIL-
C             ING REGION  (DEFAULT = MAXIMUM OF 400)
C      NODZS = NUMBER OF FINITE DIFFERENCE MESH TO BE DIVIDED IN THE
C               SUPERHEAT REGION (DEFAULT = MAXIMUM OF 400)
C      NODQ = NUMBER OF POINTS  WHERE HEAT FLUX IS TO BE SPECIFIED
C             ALONG THE HEATED CHANNEL. NODQ MUST BE .LE. 50
C
```

```
C     A1 = REYNOLD"S NUMBER EXPONENT FOR SINGLE -PHASE REGION
C          (DEFAULT = 0.8)
C     VGJN = EXPONENT FOR ZUBER-FINDLAY DRIFT VELOCITY CORRELATION
C        (DEFAULT = 1.5 )
C     RHOWL = DENSITY OF WALL MATERIAL (LBM/FT3)
C     SPHTWL = HEAT CAPACITY OF WALL MATERIAL (BTU/LBM/F)
C     CONDUC = THERMAL CONDUCTIVITY OF WALL MATERIAL (BTU/FT-SEC-F)
C
C     DELT = INLET WATER TEMPERATURE PERTURBATIONS
C     DELV = INLET WATER VELOCITY PERTURBATIONS
C     ( DEFAULT.... DELT=0.0, DELV=1.0 )
C     EITHER DELV OR DELT HAS TO BE SPECIFIED TO START CALCULATIONS
C     FOR STABILITY TESTS , SPECIFY DELV=1.0, DELT=0.0 )
C
C     NUCLEATE BOILING HEAT TRANSFER COEFF. CORRELATIONS......
C     IHTNB = 1   THOM"S CORRELATION FOR NUCLEATE BOILING REGIME
C             2  JENS-LOTTES CORRELATION FOR NICLEATE BOILING REGIME
C             3     CONSTANT HEAT TRANSF. COEFF. FOR NUCLEATE BOILING
C                    MUST THEN SPECIFY   CHTNB = NUCLEATE BOILING
C                                                HEAT TRANS. COEFF.
C          (DEFAULT....  IHTNB=2  )
C
C
C     SLOOP = SUM OF (LI/AI) FOR I = 1,N, EQUIVALENT INERTIA OF LOOP
C           (FT-1) (DEFAULT = 0.0)
C     SFLOOP = SUM OF FI*LI/(DHI*AI**2) FOR I = 1,N, EQUIVALENT FRICTION
C           RESISTANCE OF LOOP   (FT-4)
C           LI = SEGMENT LENGTH, AI = SEGMENT FLOW AREA, FI = SEGMENT
C           FRICTION FACTOR, DHI = SEGMENT HYDRAULIC DIAMETER
C           (DEFAULT = 0.0)
C     AA = SLOPE OF PUMP CURVE (LBF/FT2/LBM/SEC) (GIVE ABSOLUTE VALUE)
C          (DEFAULT = 0.0)
C     IF LOOP FEEDS  N  HEATED CHANNELS IN PARALLEL, MULTIPLY SLOOP
C     AND AA BY  N  AND SFLOOP BY N**2
C
C     FRIC = MOODY TYPE FRICTION FACTOR  (HEATED REGION AND RISER)
C               (DEFAULT = 0.02243 )
C     FINLET = LOSS COEFFICIENT AT INLET OF HEATED CHANNEL (DEFAULT = 0.
C     FEXIT = LOSS COEFFICIENT AT EXIT OF HEATED CHANNEL (DEFAULT=0.0)
C     FINLET AND FEXIT ARE BASED ON WATER DENSITY AND VELOCITY AT IN
C
C     CORF2 = CORRECTION FACTOR TO ADJUST FRICTIONAL PRESSURE DROP IN
C          HEATED SECTION OF TWO/PHASE REGION  (DEFAULT = 1.0 )
C     CORFS = CORRECTIONAL FACTOR TO ADJUST FRICTIONAL PRESSURE DROP IN
C          SUPERHEAT REGION (DEFAULT = 1.0 )
C     CORFR = CORRECTIONAL FACTOR TO ADJUST FRICTIONAL PRESSURE DROP IN
C          THE RISER ( DEFAULT = 1.0 )
C     GRC = ACCELERATION OF GRAVITY ( DEFAULT = 32.17 FT/SEC2 FOR
C          UPWARD FLOW )
C     CORG2 = CORRECTIONAL FACTOR TO ADJUST GRAVITATIONAL PRESSURE
C             DROP IN TWO-PHASE AND SUPERHEAT REGION (DEFAULT = 1.0)
C      CORGR = CORRECTION FACTOR TO ADJUST GRAV. PRES. DROP IN RISER
```

```
C          (DEFAULT =1.0)
C
C     WINT = FIRST VALUE OF THE CIRCULAR FREQUENCY TO BE USED (RAD/S)
C          (DEFAULT VALUE = 0.0785 WHERE PERIOD=80.0 SEC  )
C     WFIN = LAST VALUE OF THE CIRCULAR FREUQUENCY TO BE USED (RAD/S)
C          DEFAULT VALUE = 6.28 WHERE PERIOD =1 SEC )
C     XMULT = MULTIPLIER FOR ADVANCING VALUES OF FREQUENCY
C         DEFAULT VALUE = 1.2
C     IREQ = SET EQUAL TO 1 IF VALUE OF XMULT IS NOT TO BE MODIFIED
C             INTERNALLY  WHEN PLOTTING NYQUIST PLOTS (DEFAULT = 0)
C
C     IL = 0   OR 1   FOR HEATED  CHANNEL WITH CONSTANT PRESSURE DROP
C           B.C. OR ENTIRE LOOP (DEFAULT = 1)
C     IR = 1   OR 0   FOR RISER OR NO RISER (DEFAULT = 1)
C     IPRINT = 0  OR 1   SET EQUAL TO 1 IF DETAILED OUTPUT AT EACH
C             FREQUENCY IS NEEDED  (DEFAULT = 0)
C     ICALC = 0  CALCULATES STEADY STATE CONDITIONS ONLY
C     ICALC = 1  CALCULATES PERTURBED PRESSURE DROP FOR OSCILLATOR TESTS
C                   ONLY
C              2  DOES NYQUIST PLOT IN ADDITION TO ABOVE
C       (DEFAULT ICALC = 2 )
C     IRUN ..... SET IRUN = 0 IF ONLY AN APPROXIMATE SOLUTION IS NEEDED
C         (DEFAULT ... IRUN = 1 AND THE PROGRAM WILL DO A RICHARDSON
C              EXTRAPOLATION FOR A HIGHER NUMERICAL ACCURACY,
C                GENERALLY TO LESS THAN TWO PERCENT )
C     IRICHN = MULTIPLICATIVE FACTOR FOR RICHARDSON EXTRAPOLATION
C      ( DEFAULT = 2 *******NO NEED TO SPECIFY IF IRUN SET  EQUAL TO 0 )
C
C     IHTNB  SPECIFIES CHOICE FOR NUCLEATE BOILING HEAT TRANSFER CORRELA
C     IHTNB = 1      THOM CORRELATION
C              2   JENS-LOTTES CORRELATION
C              3   CONSTANT  (MUST SPECIFY CHTNB = CONSTANT HEAT TRANSFER
C                            COEFFICIENT IN BTU/FT2-SEC-F )
C         (DEFAULT = 2 )
C
C     IMVBB,IFLOW,IDP,IDPFLW
C           SET EQUAL TO 1 IF BODE PLOTS OF THE FOLLOWING QUANTITIES
C     ARE NEEDED -
C                   MOVEMENT OF THE BOILING BOUNDARY(IMVBB)
C                   INLET TO EXIT FLOW TRANSFER FUNCTION(IFLOW)
C                   TOTAL PRESSURE DROP(IDP)
C                   PRESSURE DROP TO EXIT FLOW T.F.(IDPFLW)
C
C     IHFLUX = MODE OF SPECIFICATION OF HEAT FLUX
C     IHFLUX=0 ... NORMALIZED HEAT FLUX IS TO BE SPECIFIED AT EACH NODE
C                    HFLUXA = AVERAGE HEAT FLUX (BTU/SEC-FT2. HAS TO BE
C                             SPECIFIED
C     IHFLUX=1 ... DIMENSIONAL HEAT FLUX IS TO BE SPECIFIED AT EVERY
C                  NODE (NO NEED TO SPECIFY HFLUXA)
C     IHFLUX = 2 ... SPECIFY ONLY HFLUXA, HEAT FLUX DISTRIBUTION
C                     TAKEN FROM PREVIOUS INPUT
C
```

```
C     NSTOP = SET EQUAL TO 1 TO STOP CALCULATIONS
C                   (DEFAULT VALUES = 0)
C
C
C     INCLUDE THE FOLLOWING HEAT FLUX DISTRIBUTION NEXT IF IHFLUX=0 OR 1
C     Z1 - ARRAY OF THE ABSCISSAS OF NODES (FT)
C          FORMAT(8F10.4)
C     HFLUX = ARRAY OF VALUES OF HEAT FLUX AT LIMITS OF NODES. PROGRAM
C          INTERPOLATES LINEARLY IN BETWEEN   FORMAT(8F10.4)
C     NUMBER OF THE ABOVE ARRAY INPUT MUST BE EQUAL TO NODQ SPECIFIED
C     ABOVE IN $INPT
C
C
C     EXTERNAL FUNCTIONS REQUIRED . . . . . . . . . . . . . . . . . . . .
C
C     HL(P,T) - LIQUID ENTHALPY
C     HFSAT(P) - SATURATED LIQUID ENTHALPY (BTU/LBM)
C     FHFG(P) - LATENT HEAT OF WATER (BTU/LBM)
C     MUTL(T) -  LIQUID VISCOSITY  (LBM/HR FT)
C     COND(T) - THERMAL CONDUCTIVITY OF SATURATED LIQUID (BTU/HR FT F)
C     DENS(P,T,*) - DENSITY OF THE LIQUID
C     VISCST(T,RHO) - VISCOSITY OF SUPERHEATED STEAM (LBM/SEC-FT)
C     CONDST(T,RHO) - THERMAL CONDUCTIVITY OF SUPERHEATED STEAM
C                        (BTU/SEC-FT-F)
C
C     HT1P(COND,D,RE,PR) - CORRELATION FOR SINGLE-PHASE HEAT TRANSFER
C                           COEFFICIENT
C     FHTNB(Q,H,P,IHTNB,CHTNB) - CORRELATION FOR NUCLEATE BOILING HEAT
C               TRANSFER COEFFICIENT
C     XDO(Q,GO,P,D) - CORRELATION FOR DRYOUT POINT
C     HTDO(COND,D,RE,PR,X,ROGROF) - CORRELATION FOR POST-DRYOUT
C               HEAT TRANS. COEFF.
C     HTS(COND,D,RE,PR) - CORRELATION FOR SUPERHEAT STEAM HEAT
C                          TRANSFER COEFF.
C
C     FDHNU (H,T1TS,DELT1) -
C          CORRELATION FOR HEAT TRANSFER COEFFICIENT PERTURBATIONS
C          IN NUCLEATE BOILING REGION
C     FDHDO(H,X,RHO,VEL,ROGROF,VFG,DELVEL,DELRHO) -
C          CORRELATION FOR HEAT TRANSFER COEFFICIENT PERTURBATIONS
C          IN POST-DRYOUT REGION
C     FDHS(H,RHO,VEL,DELRHO,DELVEL) -
C        CORRELATION FOR HEAT TRANSFER COEFFICIENT PERTURBATIONS IN
C          SUPERHEAT REGION
C
      DIMENSION COMMEN(20)
      NAMELIST/SYSTEM/P,TSAT,IPRES,TLIMIT
      NAMELIST/INPT/R1,R2,ALHEAT,VINLET,
     1              FRIC,          FINLET, FEXIT, NODE, NODQ, GRC, A1,
     2         RHOWL, SPHTWL, DELT, DELV,        TWIN,     CONDUC
     3              , NSTOP,      CORF2, CORG2, CORFS,CORFR,CORGR
     4      ,IL, IREQ, XMULT, SLOOP, SFLOOP, IR, RISER,AA,NODZS,IPRINT
```

```
      5     ,WINT, WFIN, HFLUXA, IHFLUX, ARISE, DRISE, ICALC
      6     ,IRUN, IMVBB, IFLOW, IDP, IDPFLW,VGJN,IRICHN,IHTNB,CHTNB
       COMPLEX DELVIN, DELTWI, S, DELZBB, DELRHO, DELVW, DELPHI, DELP1T,
      1       DELP2T, DELVA, DELV1
       COMMON/WATRPR/ PHW, ALHEAT, VINW, HFG, SPHTW, AW, RHOF, RHOG,
      1      TSAT, R1, R2, GRC, GC, DH, VRCAW, A1, CONDUC,      AKAPPA,
      2      DELZ, PI,RHOFG, ARISE, RISER, HF, RHOI, ROMUFG
      3      ,RHOA, VINA,VINLET, RHO1, ROGROF, NODEDO, SPHTST, VGJN
       COMMON/TWDIST/ NODQ, TWIN, NODE, NOD1, NODBB, SIGMA
       COMMON/TRFCN/ S, DELVIN, DELZBB, DELTWI, DELVA,DELV1
       COMMON/SS/ ZBB,ZBOIL
       COMMON/SSSOLN/ VELW(401), CK(401),VGJ(401),RHO(401), X(401),
      1      Z(401),HFLUX2(401)
       COMMON/PERTSN/ DELRHO(401),DELVW(401),DELPHI(401)
       COMMON/HTINPT/Z1(50),HFLUX(50),HGRAD(50)
       COMMON/VAR1/ GO, VGSAT,      IL,                        DELZS
      1      ,NODZS,NODZS1, NODN1,PAH, IR, VEXIT, RHOEXT, AA,P,ZSUPER
      2     ,ISUPER,VRISE,IHTNB,CHTNB
       COMMON/VAR6/IBP(4),IRUN,IRICHN
       COMMON/PRESUR/IPRES,PRESCR(11)
       COMMON/FRICT/ FRIC,FINLET,FEXIT,CORF2,CORG2,CORFS,CORFR,CORGR
      1    , SLOOP, SFLOOP,DRISE, IPRINT
       COMMON/FREQ1/XMULT, WINT, WFIN, IREQ, PERIOD, W1, WMUL
       EQUIVALENCE (IBP(1),IMVBB),(IBP(2),IFLOW),(IBP(3),IDP),(IBP(4),
      1    IDPFLW)
       FSIGMA(T)=.16642*(1.047515-.001485*T)**1.2
C      . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
C      DEFAULT VALUES. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
C      . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
       DATA NODE,NODZS/2*400/
       DATA DELV,DELT /1.,0./
       DATA IHTNB,CHTNB/2,1./
       DATA IRICHN/2/
       DATA PI,GC,GRC,NSTOP/ 3.1415926, 2*32.17, 0/
       DATA IL,IR,TLIMIT,AA/2*1,1400.,0.0/
       DATA CORF2,CORG2,CORFS,CORFR,CORGR/5*1.0/
       DATA IRUN, IMVBB, IFLOW, IDP, IDPFLW/1,4*0/
       DATA FINLET,FEXIT,SLOOP,SFLOOP,FRIC/4*0.0,.02243/
       DATA ICALC,A1,RISER,IPRES/2,0.8,0.0,0/
       DATA IREQ, IPRINT, IHFLUX/3*0/
       DATA WINT, WFIN, XMULT/.0785,6.25, 1.2 /
       DATA VGJN/1.5/
       READ (5,SYSTEM)
C      . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
C      SETS UP STEAM TABLE FOR SYSTEM PRESSURE
C      . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
       SIGMA=FSIGMA(TSAT)
       CALL TABLE (P,TSAT,TLIMIT)
       CALL SATVAP(P,TSAT,EDUMMY,SVD)
       CALL ENTHTP(P,EDUMMY,T,GASCON,SPHTST)
       RHOG=1./SVD
       IF (IPRES.EQ.1) READ 5,(PRESCR(I),I=1,11)
```

```
 1    READ (5,2) COMMEN
 2    FORMAT (20A4)
      WRITE (6,3) COMMEN
 3    FORMAT (1H1,25X,20A4 ///)
      READ (5,INPT)
      IF (NSTOP.EQ.1) STOP
      NODN1=NODQ-1
      IF (IHFLUX.EQ.2) GOTO 8
      READ 5,(Z1(I),I=1,NODQ)
      READ 5,(HFLUX(I),I=1,NODQ)
 5    FORMAT (8F10.4)
C     . . . . . . . . . . . . . . . . . . . . . . .
C     CONVERSION OF NORMALISED HEAT FLUX OR AVERAGE HEAT FLUX INTO
C     DIMENSIONAL HEAT FLUX
C
      HFLUXS=0.0
      DO 6 I=1,NODN1
 6    HFLUXS=(HFLUX(I)+HFLUX(I+1))*(Z1(I+1)-Z1(I))+HFLUXS
      HFLUXS=HFLUXS/ALHEAT/2.
      IF (IHFLUX.EQ.1) HFLUXA=HFLUXS
 8    DO 7 I=1,NODQ
 7    HFLUX(I)=HFLUX(I)*HFLUXA/HFLUXS
      HFLUXS=HFLUXA
      IF (IRUN.EQ.1) NODE=NODE*(IRICHN-1)/IRICHN
      NOD1=NODE+1
      IF (IRUN.EQ.1) NODZS=NODZS*(IRICHN-1)/IRICHN
      NODZS1=NODZS+1
      HF=HFSAT(P)
      HFG=FHFG(P)
      TAVE=(TWIN+TSAT)/2.
C
C     THREE DIFFERENT WATER DENSITIES ARE NEEDED .....
C     RHOI = WATER DENSITY AT INLET TEMP
C     RHOA = WATER DENSITY AT AVERAGE SINGLE-PHASE TEMP
C     RHOF = WATER DENSITY AT SATURATION TEMP
C
      RHOI=DENS(P,TWIN,DUMMY)
      RHOA=DENS(P,TAVE,DUMMY)
      RHOF=DENS(P,TSAT,DUMMY)
      GO=RHOI*VINLET
      VINW=GO/RHOF
      VINA=GO/RHOA
      ENTHI=HL(P,TWIN)
      ENTHS=HFSAT(P)
      SPHTW=(ENTHS-ENTHI)/(TSAT-TWIN)
C
C     CALCULATES HEAT FLUX GRADIENTS
      DO 10 I=1,NODN1
C
 10   HGRAD(I)=(HFLUX(I+1)-HFLUX(I))/((Z1(I+1)-Z1(I))+1.E-12)
      VGSAT=1./RHOG
      PHW=2.*PI*R1
```

```
      AW=PI*R1*R1
      GOHR=GO*3600.
      DH=2.*R1
      RHOFG=RHOF-RHOG
      VRCAW=GO       *SPHTW*AW
      AKAPPA=CONDUC/RHOWL/SPHTWL
C
      WRITE (6,SYSTEM)
      WRITE (6,INPT)
      WRITE (6,90)  P, TWIN, TSAT, HFLUXA,VINLET,GOHR, R1, R2, AW, PHW,
     1      ARISE, CONDUC, SPHTWL, RHOWL, SLOOP, AA
 90   FORMAT(   "      SYSTEM PARAMETERS",//," SYSTEM PRESSURE(PSIA) = "
     1      ,F10.2,/," INLET TEMPERATURE (F) = ",F8.2,/,
     2      " SATURATION TEMP CORRESPONDING TO SYSTEM PRESSURE (F) = "
     3      F8.2,/," AVERAGE HEAT FLUX (BTU/FT2/SEC) = ",F10.4,/,
     4      " STEADY STATE INLET VELOCITY (FT/SEC) = ",F8.3,/,
     5      " MASS FLUX (LBM/HR/FT2) = ",F10.1,/,
     7      " INNER WALL RADIUS (FT) = ",F8.5,/," OUTER WALL RADIUS (FT)
     8 = ",F8.5,/," HEATED CHANNEL FLOW AREA (FT2) = ",F10.6,/,
     9      " HEATED CHANNEL PERIMETER (FT) = ",F8.5,/,
     1      " RISER CROSS-SECTIONAL AREA (FT2) = ",F9.6,/,
     1      " THERMAL CONDUCTIVITY OF WALL MATERIAL (BTU/FT/SEC/DEG F) =
     2 ",F10.5,/," HEAT CAPACITY OF WALL MATERIAL (BTU/LBM/DEG F) = "
     3      ,F10.5,/," DENSITY OF WALL MATERIAL (LBM/FT3) = ",F8.2,/,
     5      " LOOP INERTIA (SUM L/A, FT-1) = ",F10.3,/,
     6      " PUMP SLOPE (LBF/FT2 PER LBM/SEC) = ",F6.2,//)
      WRITE (6,900)
 900  FORMAT (///" DISTANCE       HEAT FLUX",/,"       FT       BTU/FT2/SEC
     1",/)
      WRITE (6,901) (Z1(I),HFLUX(I),I=1,NODQ)
 901  FORMAT(1X,2F10.5)
      IF (IPRES.EQ.1)  WRITE (6,902) (PRESCR(I),I=1,11)
 902  FORMAT (///," VALUES OF TWO-PHASE PRESSURE-DROP MULTIPLIERS",/,
     1    " QUALITY     MULTIPLIER",/,"       0.0       ",F8.3,/,
     2    "        0.1       ",F8.3,/,"      0.2       ",F8.3,/,
     2    "        0.3       ",F8.3,/,"      0.4       ",F8.3,/,
     2    "        0.5       ",F8.3,/,"      0.6       ",F8.3,/,
     2    "        0.7       ",F8.3,/,"      0.8       ",F8.3,/,
     2    "        0.9       ",F8.3,/,"      1.0       ",F8.3,/)
      DELV1=CMPLX(DELV,0.0)
      DELVA=DELV1*RHOI/RHOA
      DELVIN=DELV1*RHOI/RHOF
      DELTWI=CMPLX(DELT,0.0)
C
C     CALCULATES STEADY STATE HEATED CHANNEL FLOW CONDITIONS
      CALL STEDST
C
C     CALCULATES STEADY STATE PRESSURE DROP
      CALL DP(0)
      IF (ICALC.EQ.0) GOTO 1
C
C     DO PERTURBED CALCULATIONS
```

```
      CALL FREQ(ICALC,VINLET,IPRINT)
      GOTO 1
      END
      SUBROUTINE STEDST
C     THIS SUBROUTINE DOES ALL STEADY STATE FLOW CALCULATIONS
C
      REAL MUTL
      COMMON/WATRPR/ PHW, ALHEAT, VINW, HFG, SPHTW, AW, RHOF, RHOG,
     1      TSAT, R1, R2, GRC, GC, DH, VRCAW, A1, CONDUC,     AKAPPA,
     2      DELZ, PI,RHOFG, ARISE, RISER, HF, RHOI, ROMUFG
     3      ,RHOA, VINA,VINLET, RHO1, ROGROF, NODEDO, SPHTST, VGJN
      COMMON/HTCOEF/H1,H2(401),H3(401)
      COMMON/FRICT/ FRIC,FINLET,FEXIT,CORF2,CORG2,CORFS,CORFR,CORGR
     1     , SLOOP, SFLOOP,DRISE, IPRINT
      COMMON/TWDIST/ NODQ, TWIN, NODE, NOD1, NODBB, SIGMA
      COMMON/SS/ ZBB,ZBOIL
      COMMON/SSSOLN/ VELW(401), CK(401),VGJ(401),RHO(401), X(401),
     1      Z(401),HFLUX2(401)
      COMMON/HTINPT/Z1(50),HFLUX(50),HGRAD(50)
      COMMON/VAR1/ GO, VGSAT,     IL,                     DELZS
     1      ,NODZS,NODZS1, NODN1,PAH, IR, VEXIT, RHOEXT, AA,P,ZSUPER
     2     ,ISUPER,VRISE,IHTNB,CHTNB
      COMMON/VAR2/ RHOS(401),VELWS(401), XS(401), ZS(401), CPG(401),
     1      VGS(401),           HFLUX3(401)
      COMMON/VAR5/CO1(401),RHOPR(401),VGJC
      COMMON/VAR6/IBP(4),IRUN,IRICHN
      DATA TIMES,TIMER/2*0.0/
      ZSUPER=0.0
      ISUPER=0
      NODEDO=NODE
      ROGROF=RHOG/RHOF
      B1=ROGROF**.1
      PAH=PHW/AW/HFG
      VGJC=1.53*(SIGMA*GRC*(RHOF-RHOG)/RHOF/RHOF)**.25*CORG2
      RHO1=(RHOF-RHOG)/RHOF/RHOG
      TWOLD=TWIN
C
C     EVALUATING LIQUID AND VAPOR PROPERTIES
C
      VISCL=MUTL(TSAT)/3600.
      CONDL=COND(TSAT)/3600.
      VISCV=VISCST(TSAT,RHOG)
      CONDV=CONDST(TSAT,RHOG)
      REL=GO*DH/VISCL
      PRL=SPHTW*VISCL/CONDL
      REV=GO*DH/VISCV
      PRV=SPHTST*VISCV/CONDV
      ROMUFG=ROGROF**.5*(VISCL/VISCV)**.1
C
C     CALCULATE SINGLE-PHASE HEAT TRANSFER COEFF.
C
      H1=HT1P(CONDL,DH,REL,PRL)
```

```
C
C     CALCULATES STEADY STATE BOILING BOUNDARY
C
      DO 10 I=1,NODN1
      TW=TWOLD+(HFLUX(I)+HFLUX(I+1))*(Z1(I+1)-Z1(I))/2.*PHW/VRCAW
      IF (TW.GT.TSAT) GOTO 20
   10 TWOLD=TW
      WRITE (6,11)
   11 FORMAT (//," NO BOILING OCCURS IN HEATED CHANNEL")
      STOP
   20 K=I
      IF (ABS(HGRAD(I)).LT.1.E-10) GOTO 25
      B=SQRT((HFLUX(K)/HGRAD(K))**2+2.*(TSAT-TWOLD)*VRCAW/HGRAD(K)/PHW)
      IF (HGRAD(K).GE.0.0) ZBB=Z1(K)-HFLUX(K)/HGRAD(K)+B
      IF (HGRAD(K).LT.0.0) ZBB=Z1(K)-HFLUX(K)/HGRAD(K)-B
      GOTO 26
   25 ZBB=Z1(K)+(TSAT-TWOLD)*VRCAW/PHW/HFLUX(K)
   26 NODBB=K+1
      VRAW=VRCAW/SPHTW
C
C     CALCULATES STEADY STATE SUPERHEAT BOUNDARY
C
      HFLUXB=HFLUX(K)+HGRAD(K)*(ZBB-Z1(K))
      HFG1=0.0
      HFG2=(HFLUXB+HFLUX(K+1))*(Z1(K+1)-ZBB)/2.*PHW/VRAW
      IF (HFG2.GT.HFG) GOTO 35
      HFG1=HFG2
      DO 30 I=NODBB,NODN1
      HFG2=HFG1+(HFLUX(I)+HFLUX(I+1))*(Z1(I+1)-Z1(I))/2.*PHW/VRAW
      IF (HFG2.GT.HFG) GOTO 35
   30 HFG1=HFG2
C
C     DISCRETIZATION OF THE BOILING REGION AND THE EVALUATION OF HEAT
C     FLUX AT EACH NODE
C
      ZBOIL=ALHEAT-ZBB
      GOTO 38
   35 ISUPER=1
      K=I
      HFLUXB=HFLUX(K)
      Z1B=Z1(K)
      IF ((K+1).EQ.NODBB) Z1B=ZBB
      IF ((K+1).EQ.NODBB)  HFLUXB=HFLUX(K)+HGRAD(K)*(ZBB-Z1(K))
      NODSB=I+1
      IF (ABS(HGRAD(K)).LT.1.E-10) GOTO 36
      B=SQRT((HFLUXB/HGRAD(K))**2+2.*(HFG-HFG1)*VRAW/HGRAD(K)/PHW)
      IF (HGRAD(K).GE.0.0) ZSB=Z1B-HFLUXB/HGRAD(K)+B
      IF (HGRAD(K).LT.0.0) ZSB=Z1B-HFLUXB/HGRAD(K)-B
      GOTO 37
   36 ZSB=Z1B+(HFG-HFG1)*VRAW/PHW/HFLUXB
   37 ZBOIL=ZSB-ZBB
   38 DELZ=ZBOIL/FLOAT(NODE)
```

```
      K=NODBB-1
      DO 22 I=1,NOD1
      Z(I)=ZBB+DELZ*FLOAT(I-1)
      IF (Z(I).GT.Z1(K+1))GOTO 24
      HFLUX2(I)=HGRAD(K)*(Z(I)-Z1(K))+HFLUX(K)
      GOTO 22
   24 K=K+1
      HFLUX2(I)=HFLUX(K)
   22 CONTINUE
C
C     INITIAL VALUES FOR TWO-PHASE REGION
C
      RHO(1)=RHOF
      VELW(1)=VINW
      H2(1)=H1
      CO1(1)=FCO1(0.,B1)
      RHOPR(1)=RHOF
      X(1)=0.0
      CK(1)=VINW*CO1(1)+FVGJ(VGJC,X(1),VGJN)
      PHI=0.0
      VFLUX=VINW
      VGJ(1)=(CO1(1)-1.)*VFLUX+FVGJ(VGJC,X(1),VGJN)
C
C     INTEGRATING THE VOLUMETRIC FLUX AND DENSITY WAVE PROPAGATION EQS
C
      DO 40 I=1,NODE
      GAMG=(HFLUX2(I)+HFLUX2(I+1))*PHW/AW/HFG/2.
      OMEGA=GAMG*RHO1
      VFLUX=VFLUX+OMEGA*DELZ
      PHI=PHI-OMEGA/CK(I)*DELZ*CO1(I)
      RHOPR(I+1)=RHOF*EXP(PHI)
      RHO(I+1)=(RHOPR(I)+(CO1(I)-1.)*RHOF)/CO1(I)
      IF (RHO(I+1).LE.RHOG)  RHO(I+1)=RHOG
      ALPHA=(RHOF-RHO(I+1))/RHOFG
      VGJO=FVGJ(VGJC,ALPHA,VGJN)
      X(I+1)=ALPHA*RHOG*(CO1(I)/RHOF+VGJO/GO)/(1.+CO1(I)*ALPHA*(ROGROF
     1     -1.))
      IF (X(I+1).LE.0.) X(I+1)=1.E-5
      IF (X(I+1).GE.1.) X(I+1)=1.-1.E-15
      IF (I.GT.NODEDO) GOTO 28
      XDRYOT=XDO(HFLUX2(I),GO,P,DH)
      IF (X(I+1).GT.XDRYOT) NODEDO=I
   28 BETA=X(I+1)/(X(I+1)+ROGROF*(1.-X(I+1)))
      CO1(I+1)=FCO1(BETA,B1)
      VGJ(I+1)=VGJO+(CO1(I+1)-1.)*VFLUX
      CK(I+1)=VFLUX+VGJ(I+1)+ALPHA*DVGJDA(VGJC,ALPHA,VGJN)
      VELW(I+1)=VFLUX     -(RHOF/RHO(I+1)-1.)*VGJ(I+1)
C
C     EVALUATION OF HEAT TRANSFER COEFFS
C
      IF (I.GE.NODEDO) GOTO 15
      H2(I+1)=FHTNB(HFLUX2(I+1),H2(I),P,IHTNB,CHTNB)
```

```
      GOTO 16
   15 H2(I+1)=HTDO(CONDV,DH,REV,PRV,X(I+1),ROGROF)
   16 CONTINUE
   40 CONTINUE
      QUAL=X(NOD1)
      VEXIT=VELW(NOD1)
      RHOEXT=RHO(NOD1)
C
C     SUMMATION OF THE RECIPRICAL OF THE AVERAGE TWO-PHASE VELOCITY FOR
C     USE LATER IN CALCULATING TWO-PHASE TRANSIT TIME
C
      VELW2R=.5*(1./VELW(1)+1./VELW(NOD1))
      DO 45 I=2,NODE
   45 VELW2R=VELW2R+1./VELW(I)
      VELW2R=VELW2R/FLOAT(NODE)
C
      ENTHEX=HF+X(NOD1)*HFG
      CALL SATVAP (P,TSAT,EHGSAT,SVD)
      ENG=EHGSAT
      CALL ENTHTP(P,ENG,T,GASCON,CPG(1))
      IF (ISUPER.EQ.0) GOTO 110
      XS(1)=0.0
      ZSUPER=ALHEAT-ZSB
      DELZS=ZSUPER/FLOAT(NODZS)
      ZS(1)=ZSB
      K=NODSB-1
C
C     DISCRETISATION OF THE SUPERHEAT REGION AND THE CALCULATION OF HEAT
C     AT EACH NODE
C
      DO 91 I=1,NODZS1
      ZS(I)=ZSB+(I-1)*DELZS
      IF (ZS(I).GT.Z1(K+1)) GOTO 92
      HFLUX3(I)=HFLUX(K)+HGRAD(K)*(ZS(I)-Z1(K))
   90 CONTINUE
   91 CONTINUE
      GOTO 93
   92 K=K+1
      HFLUX3(I)=HFLUX(K)
      GOTO 90
C
C     INITIAL CONDITIONS FOR THE SUPERHEAT REGION
C
   93 RHOS(1)=RHOG
      VELWS(1)=CK(NOD1)
      VGS(1)=GASCON*HFG
      H3(1)=H2(NOD1)
      SV=VGSAT
C
C     INTEGRATION OF FLOW CONDITIONS FOR SUPERHEAT REGION
C
      DO 100 I=1,NODZS
```

```
      ENG=ENG+(HFLUX3(I)+HFLUX3(I+1))*PHW*DELZS/VRAW/2.
      XS(I+1)=(ENG-EHGSAT)/HFG
      CALL ENTHTP(P,ENG,T,GASCON,CPG(I+1))
      VGS(I+1)=GASCON*HFG
C
C     EVALUATION OF HEAT TRANSFER COEFF
      H3(I+1)=HTS(CONDV,DH,REV,PRV)
      SV=SV+VGS(I)*(XS(I+1)-XS(I))
      RHOS(I+1)=1./SV
  100 VELWS(I+1)=GO/RHOS(I+1)
      VEXIT=VELWS(NODZS1)
      RHOEXT=RHOS(NODZS1)
      QUAL=1.
      ENTHEX=ENG
C
C     SUMMATION OF THE RECIPRICAL OF THE VELOCITY IN THE SUPERHEAT
C     REGION FOR USE LATER IN THE CALCULATION OF TRANSIT TIME
C
      VELSR=.5*(1./VELWS(1)+1./VELWS(NODZS1))
      DO 105 I=2,NODZS
  105 VELSR =VELSR +1./VELWS(I)
      VELSR =VELSR /FLOAT(NODZS)
C
C     EVALUATIONS OF TRANSIT TIMES
C
      TIMES=ZSUPER*VELSR
  110 TIME1=ZBB/VINA
      TIME2=ZBOIL*VELW2R
      IF (IR.EQ.1) VRISE=VEXIT*AW/ARISE
      IF (IR.EQ.1) TIMER=RISER/VRISE
      TIMEHT=TIME1+TIME2+TIMES
      TIMET=TIMEHT+TIMER
      TOTLEN=ALHEAT+RISER
      IF (IRUN.EQ.1) RETURN
C
      WRITE(6,993)ZBB,TIME1,ZBOIL,TIME2,ZSUPER,TIMES,RISER,TIMER,
     1      ALHEAT, TIMEHT, TOTLEN, TIMET, QUAL, ENTHEX, VEXIT
  993 FORMAT (20X,"LENGTH(FT)  TRANSIT TIME(SEC)",/,
     1   " SINGLE PHASE       ",F10.5,2X,F10.5,/,
     1   " TWO PHASE          ",F10.5,2X,F10.5,/,
     1   " SUPERHEAT REGION   ",F10.5,2X,F10.5,/,
     1   " RISER              ",F10.5,2X,F10.5,/,
     1   " TOTAL              ",F10.5,2X,F10.5,/,
     1   " TOTAL TEST SECTION ",F10.5,2X,F10.5,/,
     2      " EXIT QUALITY = ",F8.5,/,
     3      " EXIT ENTHALPY (BTU/LBM) = ",F10.3,/,
     4      " EXIT AVERAGE VELOCITY (FT/SEC) = ",F10.4,//)
      RETURN
      END
      SUBROUTINE FREQ(ICALC,VINLET ,IPRINT)
C
C     THIS SUBROUTINE DOES THE FOLLOWING.........
```

```
C     1. DETERMINES THE PERTURBED FREQUENCY
C     2. CALCULATES TRANSFER FUNCTIONS BY CALLING SUBROUTINE TRNFCN
C     3. CALCULATES PERTURBED PRESSURE DROPS BY CALLING SUBROUTINE DP
C     4. DO RICHARDSON"S EXTRAPOLATION IF SPECIFIED
C     5. CALLS A SUBROUTINE TO STORE PLOTTING VARIABLES
C     6. DO BODE PLOTS AND NYQUIST PLOT
C
      COMMON/TWDIST/ NODQ, TWIN, NODE, NOD1, NODBB, SIGMA
      COMMON/CBODE/BODE(100,9),DPREAL(100),DPIMAG(100)
      COMMON/VAR1/ GO, VGSAT,      IL,                    DELZS
     1      ,NODZS,NODZS1, NODN1,PAH, IR, VEXIT, RHOEXT, AA,P,ZSUPER
     2     ,ISUPER,VRISE,IHTNB,CHTNB
      COMMON/VAR6/IBP(4),IRUN,IRICHN
      COMMON/TRFCN/ S, DELVIN, DELZBB, DELTWI, DELVA, DELV1
      COMMON/DELP1/DEL(14),DELPEX,DELP2B,DELTS
      COMPLEX DEL, OLDRAT, S, RATIO, DELVIN, DELZBB, DELTWI,DELVA,DELV1
     1     ,DELPEX,DELP2B,DELSAV,DELTS
      DIMENSION NAME(4) ,DELSAV(100,5)
      DIMENSION XREA(100),YIMA(100),PER(100),AMRAT(100), ARRAT(100)
      COMMON/FREQ1/XMULT, WINT, WFIN, IREQ, PERIOD, W1, WMUL
      DATA XLIMIT,YLIMIT,ISIG,ISI/1.05,1.25,1,2/
      DATA (NAME(I),I=1,4)/ 6HBB MVT, 6HEX FLO ,  6HTOT DP,
     1      6HDP EXF  /
      DATA PI/3.1415926/
      WMUL=XMULT
      ICOUNT=1
      W1=WINT
      RATIO=CMPLX(0.0,0.0)
      GOTO 10
    5 W1=W1*WMUL
   10 IF (W1.GT.WFIN) GOTO 50
      OLDRAT=RATIO
C
C     CALCULATES THE NEXT PERIOD, ROUNDED TO 2 SIGNIFICANT FIQURES
C
      PERIOD=2.*PI/W1
      NPER=INT(ALOG10(PERIOD))
      IF (PERIOD.LE.1.0) ISIG=ISI
      PERIOD=AINT(10.**ISIG*PERIOD/(10.**NPER))*10.**(NPER-ISIG)
      PER(ICOUNT)=PERIOD
      W1=2.*PI/PERIOD
      S=CMPLX(0.0,W1)
C
C     CALCULATES TRANSFER FUNCTIONS
      CALL TRNFCN
C
C     CALCULATES PERTURBED PRESSURE DROPS
      CALL DP(1)
      IF (IRUN.EQ.0) CALL FNPLOT(PERIOD,IPRINT,ICOUNT,VINLET)
      IF (IRUN.EQ.0) GOTO 20
C
C     SAVE RESULTS IF RICHARDSON"S EXTRAPOLATION IS USED (I.E., IRUN=1)
```

```
C
      DELSAV(ICOUNT,1)=DEL(6)
      DELSAV(ICOUNT,2)=DEL(8)
      DELSAV(ICOUNT,3)=DEL(9)
      DELSAV(ICOUNT,4)=DEL(10)
      DELSAV(ICOUNT,5)=DEL(14)
   20 RATIO=(DEL(6)+DEL(8)+DEL(10)+DELPEX)/(DEL(2)+DEL(3))
C
      DRAT=CABS(OLDRAT-RATIO)
      XREA(ICOUNT)=REAL(RATIO)
      YIMA(ICOUNT)=AIMAG(RATIO)
      AMRAT(ICOUNT)=CABS(RATIO)
      ARRAT(ICOUNT)=ANGL(RATIO)
      ICOUNT=ICOUNT+1
      IF (ICOUNT.GT.100) GOTO 50
      IF (IREQ.EQ.1) GOTO 5
      IF (AMRAT(ICOUNT-1).LE.1.E-3) GOTO 5
      DRAREL=DRAT/AMRAT(ICOUNT-1)
C
C     ADJUSTING MULTIPLIER FOR THE NEXT FREQUENCY
C
      IF(DRAREL.GT.0.4) WMUL=SQRT(WMUL)
      IF (DRAREL.LE.0.1) WMUL=WMUL**2
      IF (WMUL.LT.XLIMIT) WMUL=XLIMIT
      IF (WMUL.GT.YLIMIT) WMUL=YLIMIT
      GOTO 5
   50 ICOUNT=ICOUNT-1
      IF (IRUN.EQ.0) GOTO 40
C
C     DECREASE STEP SIZE BY ONE-HALF AND REPEAT CALCULATIONS 2 AND 3
C     CORRECTIONS BY RICHARDSON"S EXTRAPOLATION
C
      NODE=NODE*IRICHN/(IRICHN-1)
      NOD1=NODE+1
      NODZS=NODZS*IRICHN/(IRICHN-1)
      NODZS1=NODZS+1
      IRUN=0
      CALL STEDST
      IRUN=1
      DO 60 I=1,ICOUNT
      PERIOD=PER(I)
      W1=2.*PI/PERIOD
      S=CMPLX(0.0,W1)
      CALL TRNFCN
      CALL DP(1)
      DEL(6)=DEL(6)*FLOAT(IRICHN)-DELSAV(I,1)*FLOAT(IRICHN-1)
      DEL(8)=DEL(8)*FLOAT(IRICHN)-DELSAV(I,2)*FLOAT(IRICHN-1)
      DEL(9)=DEL(9)*FLOAT(IRICHN)-DELSAV(I,3)*FLOAT(IRICHN-1)
      DEL(10)=DEL(10)*FLOAT(IRICHN)-DELSAV(I,4)*FLOAT(IRICHN-1)
      DEL(14)=DEL(14)*FLOAT(IRICHN)-DELSAV(I,5)*FLOAT(IRICHN-1)
      DEL(7)=DEL(6)-DELP2B+DEL(8)-DEL(9)
      CALL FNPLOT(PERIOD,IPRINT,I      ,VINLET)
```

```
C
C     DEL(13) = RATIO OF TWO-PHASE TO SINGLE-PHASE PRESSURE DROP PERTUR-
C               BATIONS
C             = NUQUIST PLOT VARIABLE
C
      XREA(I      )=REAL(DEL(13))
      YIMA(I      )=AIMAG(DEL(13))
      AMRAT(I      )=CABS(DEL(13))
   60 ARRAT(I      )=ANGL(DEL(13))
C
C     DO BODE PLOTS IF SPECIFIED
C
   40 WRITE (6,80)
   80 FORMAT (1H1,   "   PERIOD",15X,"NYQUIST PLOT"15X,"BOIL.BOUND.MOVEM
     1NT  EXIT/INLT FLOW   TOT PRESSURE DROP  DP-TO-EXIT-FLOW",/,
     2"        SEC           REAL        IMAG        MOD       ARG       MOD
     1   ARG       MOD       ARG       MOD       ARG       MOD       ARG")
      WRITE (6,81) (I,PER(I),XREA(I),YIMA(I),AMRAT(I),ARRAT(I),
     1      (BODE(I,J),J=2,9),I=1,ICOUNT)
   81 FORMAT (/,(I4,F7.1,    2E11.3,1X,5(E11.3,F7.1)))
C
      DO 100 KP=1,4
      IF (IBP(KP).EQ.0) GOTO 110
      CALL PRTPL4 (NAME(KP),      ICOUNT,100,100,9,2*KP-1,1.0   )
      CALL PRTPL4 (NAME(KP),      ICOUNT,100,100,9,2*KP   ,180.0)
  110 CONTINUE
  100 CONTINUE
      IF (ICALC.EQ.1) RETURN
C
C     DO NYQUIST PLOT
C
      WRITE (6,90)
   90 FORMAT (1H1,50X,16HNYQUIST DIAGRAM   )
      CALL POLPLT(XREA,YIMA,ICOUNT)
      RETURN
      END
      SUBROUTINE FNPLOT(PERIOD,IPRINT,ICOUNT,VINLET)
C
C     THIS SUBROUTINE STORES THE PLOTTING VARIABLES FOR BODE AND
C     NUQUIST PLOTS AND ALSO PRINTS OUT THESE VARIABLES FOR EACH FREQUEN
C
      DIMENSION          AMDEL(14),ARDEL(14)
      COMMON/DELP1/DEL(14),DELPEX,DELP2B,DELTS
      COMMON/CBODE/BODE(100,9),DPREAL(100),DPIMAG(100)
      COMPLEX DEL,DELPEX,DELP2B, DUMMY,DELTS
      W1=6.2831853/PERIOD
      DEL(11)=DEL(3)+DEL(6)+DEL(8)
      DEL(12)=DEL(5)+DEL(6)+DEL(8)+DEL(10)+DELPEX
      DEL(13)=(DEL(6)+DEL(8)+DEL(10)+DELPEX)/(DEL(2)+DEL(3))
      DO 10 I=1,14
      AMDEL(I)=CABS(DEL(I))
   10 ARDEL(I)=ANGL(DEL(I))
```

```
C
C     BODE(ICOUNT,N) IS THE ARRAY OF VARIABLES FOR BODE PLOTS
C
      BODE(ICOUNT,1)=PERIOD
      BODE(ICOUNT,2)=AMDEL(1)
      BODE(ICOUNT,3)=ARDEL(1)
      BODE(ICOUNT,4)=AMDEL(14)
      BODE(ICOUNT,5)=ARDEL(14)
      BODE(ICOUNT,6)=AMDEL(12)
      BODE(ICOUNT,7)=ARDEL(12)
      BODE(ICOUNT,8)=144.*AMDEL(14)/(AMDEL(12)*VINLET)
      BODE(ICOUNT,9)=ARDEL(14)-ARDEL(12)
      DUMMY=DEL(12)
      DPREAL(ICOUNT)=REAL(DUMMY)/AMDEL(12)
      DPIMAG(ICOUNT)=AIMAG(DUMMY)/AMDEL(12)
      IF (IPRINT.EQ.0) RETURN
      AMDTS=CABS(DELTS)
      ARDTS=ANGL(DELTS)
C
      WRITE(6,910) W1,PERIOD,(DEL(I),AMDEL(I),ARDEL(I),I=1,13),
     1 DELTS,AMDTS,ARDTS
  910 FORMAT(///," PERTURBATIONS WITH OSCILLATING INLET VELOCITY--",/,
     1      " FREQUENCY = ",F8.4," RAD/SEC        PERIOD = ",F8.3,
     2      " SEC "                                ,/,
     4      35X,"REAL",10X,"IMAG",10X,"MOD",10X,"ARG",/,
     5      " MOVEMENT OF BOILING BOUNDRY(FT)",3(E12.4,2X),F8.2,/,
     5      " --PRESSURE DROPS (LBF/FT2) --",/,
     6      " UNHEATED SINGLE PHASE           ",3(E12.4,2X),F8.2,/,
     7      " HEATED SINGLE PHASE             ",3(E12.4,2X),F8.2,/,
     7      "  (W/O CONSIDER BB MOVEMENT)     ",3(E12.4,2X),F8.2,/,
     8      " TOTAL SINGLE PHASE              ",3(E12.4,2X),F8.2,/,
     9      " HEATED TWO PHASE                ",3(E12.4,2X),F8.2,/,
     9      "  (W/O CONSIDER BB AND SB MOVMNT",3(E12.4,2X),F8.2,/,
     1      " SUPERHEAT                       ",3(E12.4,2X),F8.2,/,
     1      "  (W/O CONSIDER SB MOVEMENT)     ",3(E12.4,2X),F8.2,/,
     2      " RISER                           ",3(E12.4,2X),F8.2,/,
     3      " TOTAL HEATED LENGTH             ",3(E12.4,2X),F8.2,/,
     4      " TOTAL                           ",3(E12.4,2X),F8.2,/,
     5      " NYQUIST PLOT                    ",3(E12.4,2X),F8.2,/,
     6      " EXIT TEMPERATURE (F)            ",3(E12.4,2X),F8.2,/)
      RETURN
      END
      SUBROUTINE TRNFCN
C     THIS SUBROUTINE CALUCLATES THE TRANSFER FUNCTIONS
C
      COMPLEX FDHNU,FDHDO,FDHS
      COMPLEX ARGU, ARGU1, ARGU2, IOR1, I1R1, KOR1, K1R1, IOR2, I1R2,
     1      KOR2, K1R2, CO, C1, C2, C3, DELTW1,DELJ, DELQ, DELOM, DELCK
      COMPLEX DELVIN, DELTWI, S, DELZBB, DELRHO, DELVW, DELPHI
      COMPLEX DELXS, DELROS, DELVS, DELHS, DELTS, DDXSDZ, DELVEX, DELZSB
     1     ,DELREX, DELH1, DELVA, DELV1,DVGJ, DELT1, DVGJ1
      COMMON/WATRPR/ PHW, ALHEAT, VINW, HFG, SPHTW, AW, RHOF, RHOG,
```

```
     1       TSAT, R1, R2, GRC, GC, DH, VRCAW, A1, CONDUC,     AKAPPA,
     2       DELZ, PI,RHOFG, ARISE, RISER, HF, RHOI, ROMUFG
     3       ,RHOA, VINA,VINLET, RHO1, ROGROF, NODEDO, SPHTST,VGJN
      COMMON/TWDIST/ NODQ, TWIN, NODE, NOD1, NODBB, SIGMA
      COMMON/TRFCN/ S, DELVIN, DELZBB, DELTWI, DELVA, DELV1
      COMMON/SS/ ZBB,ZBOIL
      COMMON/SSSOLN/ VELW(401), CK(401),VGJ(401),RHO(401), X(401),
     1       Z(401),HFLUX2(401)
      COMMON/HTINPT/Z1(50),HFLUX(50),HGRAD(50)
      COMMON/PERTSN/ DELRHO(401),DELVW(401),DELPHI(401)
      COMMON/VAR1/ GO, VGSAT,      IL,                      DELZS
     1       ,NODZS,NODZS1, NODN1,PAH, IR, VEXIT, RHOEXT, AA,P,ZSUPER
     2      ,ISUPER,VRISE,IHTNB,CHTNB
      COMMON/VAR2/ RHOS(401),VELWS(401), XS(401), ZS(401), CPG(401),
     1       VGS(401),            HFLUX3(401)
      COMMON/VAR3/DELVS(401),DELROS(401)
      COMMON/VAR4/DELZSB,DELREX,DELVEX, DVGJ,DVGJ1
      COMMON/VAR5/CO1(401),RHOPR(401),VGJC
      COMMON/HTCOEF/H1,H2(401),H3(401)
      DVGC=VGJC*VGJN/RHOFG**VGJN
      ARGU=CSQRT(S/AKAPPA)
      ARGU1=ARGU*R1
      ARGU2=ARGU*R2
C
CALCUL ATING SINGLE-PHASE TEMPERATURE PERTURBATIONS
C
      DELTW1=DELTWI
      DO 10 I=2,NODBB
      CALL FUNCCO(CO,H1,ARGU1,ARGU2,CONDUC,ARGU)
      C1=S/VINA-PHW*CO/VRCAW
      C2=PHW*DELVA *(1.+CO*A1/H1)/VRCAW/VINA
      C3=DELTW1+C2/C1*(HFLUX(I-1)-HGRAD(I-1)/C1)
      IF (I.EQ.NODBB) GOTO 11
   10 DELTW1=C3*CEXP(C1*(Z1(I-1)-Z1(I)))-C2*((HGRAD(I-1)*(Z1(I)-Z1(I-1))
     1      +HFLUX(I-1))/C1-HGRAD(I-1)/C1/C1)
   11 DELTW1=C3*CEXP(C1*(Z1(I-1)-ZBB   ))-C2*((HGRAD(I-1)*(ZBB  -Z1(I-1))
     1      +HFLUX(I-1))/C1-HGRAD(I-1)/C1/C1)
C
C     INITIAL VALUES FOR THE TWO-PHASE REGION
C
      DELZBB=-DELTW1*RHOA*AW*VINA*SPHTW/HFLUX2(1)/PHW
      DELT1=CMPLX(0.,0.)
      OMEGA1=RHOFG*PHW/RHOF/RHOG/AW/HFG
      OMEGA=OMEGA1*HFLUX2(1)
      DELJ=DELVIN-OMEGA*DELZBB
      DELRHO(1)=DELZBB*HFLUX2(1)*PHW*RHOFG/AW/HFG/RHOG/CK(1)
      DVGJ1=DVGJDR(DVGC,RHO(1),RHOG,VGJN)*DELRHO(1)
      DELVW(1)=DELJ+DVGJ1*RHOF/RHO(1)/RHO(1)
      DELPHI(1)=DELRHO(1)*CO1(1)/RHOPR(1)
      DELCK=DELJ*CO1(1)+DVGJ1
C
C     INTEGRATION OF PERTURBED VOLUMETRIC FLUX AND DENSITY PROPAGATION
```

```
C      EQUATIONS
C
       DO 20 I=2,NOD1
       OMEGA=OMEGA1*HFLUX2(I-1)
       IF (I.GE.NODEDO) GOTO 15
C
C      CALCULATING HEAT FLUX PERTURBATIONS IN NUCLEATE BOILING REGION
C
       TWTS=HFLUX2(I)/H2(I)
       DELH1=FDHNU(H2,TWTS,DELT1,IHTNB)
       GOTO 16
C
C      CALCUL ATING HEAT FLUX PERTURBATIONS IN POST-DRYOUT REGION
C
 15    DELH1=FDHDO(H2(I-1),X(I-1),RHO(I-1),VELW(I-1),ROGROF,RHO1,DELVW
      1     (I-1),DELRHO(I-1))
 16    CALL FUNCCO(CO,H2(I-1),ARGU1,ARGU2,CONDUC,ARGU)
       DELQ=CO*(-HFLUX2(I-1))*DELH1/H2(I-1)/H2(I-1)
       DELT1=(DELQ-DELH1*HFLUX2(I-1)/H2(I-1))/H2(I-1)
       DELOM=OMEGA1*DELQ
       DVGJ=DVGJDR(DVGC,RHO(I-1),RHOG,VGJN)*DELRHO(I-1)
       IF (I.EQ.2) DVGJ1=DVGJ+(CO1(1)-1.)*DELJ
       DELJ=DELJ+DELZ*DELOM
       DELCK=DELJ*CO1(I-1)+DVGJ
       DELPHI(I)=DELPHI(I-1)-DELZ*(S*DELPHI(I-1)/CK(I-1)+DELOM/CK(I-1)
      1    *CO1(I)-OMEGA*DELCK/CK(I-1)/CK(I-1)*CO1(I))
       DELRHO(I)=DELPHI(I)*RHOPR(I)/CO1(I)
 20    DELVW(I)=DELJ*(CO1(I)+(1.-CO1(I))*RHOF/RHO(I))-(RHOF/RHO(I)-1.)
      1     *DVGJ+RHOF/RHO(I)*VGJ(I)*DELRHO(I)/RHO(I)
       DVGJ=(CO1(NOD1)-1.)*DELJ+DVGJDR(DVGC,RHO(NOD1),RHOG,VGJN)
      1    *DELRHO(NOD1)
       DELREX=DELRHO(NOD1)
       DELVEX=DELVW(NOD1)
       DELTEX=CMPLX(0.0,0.0)
       IF (ISUPER.EQ.0) RETURN
C
C      INITIAL VALUES FOR THE SUPERHEAT REGION
C
       DELZSB=DELRHO(NOD1)/( HFLUX2(NOD1)*PHW*RHOFG/AW/HFG/RHOF/CK(NOD1))
       OMEGAS=HFLUX3(1)*PAH*VGS(1)
       DELROS(1)=DELRHO(NOD1)*OMEGAS/OMEGA
       DELXS=-DELROS(1)/RHOS(1)**2/VGS(1)
       DELVS(1)=DELVW(NOD1)-DELZSB*(OMEGAS-OMEGA)
C
C      INTEGRATING PERTURBED EQUATIONS FOR THE SUPERHEAT REGION
C
       DO 30 I=2,NODZS1
       OMEGAS=HFLUX3(I-1)*PAH*VGS(I-1)
C
C     CALCULATING HEAT FLUX PERTURBATIONS IN THE SUPERHEAT REGION
C
       DELHS=FDHS(H3(I-1),RHOS(I-1),VELWS(I-1),DELROS(I-1),DELVS(I-1))
```

```
      CALL FUNCCO(CO,H3(I-1),ARGU1,ARGU2,CONDUC,ARGU)
      DELTS=DELXS*HFG/CPG(I-1)
      TST1=-HFLUX3(I-1)/H3(I-1)
      DELQ=CO*(DELTS+DELHS*TST1/H3(I-1))
      DELOM=DELQ*VGS(I-1)*PAH
      DELVS(I)=DELVS(I-1)+DELZS*DELOM
      DDXSDZ=DELXS*(OMEGAS-S)+DELOM*(VGSAT/VGS(I-1)+XS(I-1))-DELVS(I-1)
     1      *HFLUX3(I-1)*PAH/GO
      DELXS=DELXS+DELZS*DDXSDZ/VELWS(I-1)
   30 DELROS(I)=-(RHOS(I)**2)*VGS(I)*DELXS
      DELREX=DELROS(NODZS1)
      DELVEX=DELVS(NODZS1)
      DELTEX=-HFG/(CPG(NODZS1)*RHOS(NODZS1)**2*VGS(NODZS1))*DELREX
      RETURN
      END
      SUBROUTINE DP(MODE)
C
C     THIS SUBROUTINE DOES THE PRESSURE DROP CALCULATIONS
C     MODE = 0  CALCULATES STEADY-STATE PRESSURE DROP
C     MODE = 1  CALCULATES PERTURBED PRESSURE DROPS
C
      COMMON/DELP1/DEL(14),DELPEX,DELP2B,DELTS
      COMPLEX S,DELVIN,DELZBB,DELTWI,DELRHO,DELVW,DELPHI,DEL,
     1       DELP1T,DELP2T,DRHOSM,DFRISM,DACCSM ,CMO,DELZSB, DELPIN,
     2      DELP1A,DELP1F,DELP1B,DELPEX, DELP2A,DELP2F,DELP2G,DELP2D,
     3      DELP2B,EXL,DELPRG,DELPRF,DELPRA,DRHOSS,DFRISS,DACCSS,DELPSC,
     5      DELPSA,DELPSF,DELPSG,DELVRS, DELVA, DELV1, DELPSB
      COMPLEX DELTEX,DELROS,DELVS,DELREX,DELVEX,DVGJ,DVGJ1,DELTS
      COMMON/WATRPR/ PHW, ALHEAT, VINW, HFG, SPHTW, AW, RHOF, RHOG,
     1      TSAT, R1, R2, GRC, GC, DH, VRCAW, A1, CONDUC,     AKAPPA,
     2      DELZ, PI,RHOFG, ARISE, RISER, HF, RHOI, ROMUFG
     3      ,RHOA, VINA,VINLET, RHO1, ROGROF, NODEDO, SPHTST, VGJN
      COMMON/TWDIST/ NODQ, TWIN, NODE, NOD1, NODBB, SIGMA
      COMMON/TRFCN/ S, DELVIN, DELZBB, DELTWI, DELVA, DELV1
      COMMON/SS/ ZBB,ZBOIL
      COMMON/SSSOLN/ VELW(401), CK(401),VGJ(401),RHO(401), X(401),
     1      Z(401),HFLUX2(401)
      COMMON/PERTSN/ DELRHO(401),DELVW(401),DELPHI(401)
      COMMON/VAR1/ GO, VGSAT,      IL,                       DELZS
     1      ,NODZS,NODZS1, NODN1,PAH, IR, VEXIT, RHOEXT, AA,P,ZSUPER
     2     ,ISUPER,VRISE,IHTNB,CHTNB
      COMMON/VAR2/ RHOS(401),VELWS(401), XS(401), ZS(401), CPG(401),
     1      VGS(401),           HFLUX3(401)
      COMMON/VAR3/DELVS(401),DELROS(401)
      COMMON/VAR4/DELZSB,DELREX,DELVEX, DVGJ,DVGJ1,DELTEX
      COMMON/FRICT/ FRIC,FINLET,FEXIT,CORF2,CORG2,CORFS,CORFR,CORGR
     1    , SLOOP, SFLOOP,DRISE, IPRINT
      COMMON/FREQ1/XMULT, WINT, WFIN, IREQ, PERIOD, W1, WMUL
      DATA CONVER/144.0/
      CMO=CMPLX(0.0,0.0)
      IF (MODE.EQ.1) GOTO 200
      DPACCS=0.0
```

```
      DPFRIS=0.0
      DPGRVS=0.0
      DPFRIR=0.0
      DPGRVR=0.0
C
C     STEADY STATE PRESSURE DROP ACROSS SINGLE-PHASE REGION
C
      DPFRI1=FRIC *RHOA*VINA*VINA*ZBB/2./GC/DH/CONVER
      DPGRV1=GRC*RHOA*ZBB/GC/CONVER*CORG2
      DPINLT=FINLET*RHOI*VINLET*VINLET/2./GC/CONVER
      DPLOOP=GO*AW**2*VINLET*SFLOOP/GC/2./CONVER*FLOAT(IL)
      DPACC1=0.0
      DP1P=DPFRI1+DPACC1+DPGRV1
C
C     STEADY-STATE PRESSURE DROP ACROSS TWO-PHASE REGION
C
      DPACC2=RHOF*VINW*(VELW(NOD1)-VINW)/GC/CONVER
      DPDRFT=RHO(1)/RHO(NOD1)*(RHO(1)/RHO(NOD1)-1.)*RHOG*VGJ(NOD1)**2/GC
     1     /CONVER
      DPEXIT=FEXIT*GO*VEXIT/2./GC/CONVER
       RHOSUM=.5*(RHO(1)+RHO(NOD1))
       FRISUM=.5*(VELW(1)*VELW(1)*RHO(1)+VELW(NOD1)*VELW(NOD1)*RHO(NOD1))
       DO 30  I=2,NODE
       RHOSUM=RHOSUM+RHO(I)
       XTT=((1.-X(I))/X(I))**.9*ROMUFG
       PHIFT2=FPHI(XTT,X(I),P)
 30    FRISUM=FRISUM+            GO **2*PHIFT2/RHOF
       DPGRV2=GRC*RHOSUM*ZBOIL/GC/FLOAT(NODE)*CORG2/CONVER
       DPFRI2=FRIC *FRISUM*ZBOIL/2./DH/GC/FLOAT(NODE)*CORF2/CONVER
       DP2P=DPACC2+DPFRI2+DPGRV2+DPDRFT
       IF (IR.EQ.0) GOTO 90
C
C      STEADY-STATE PRESSURE DROP ACROSS RISER
C
       DPFRIR=FRIC*CORFR*RHOEXT*VRISE**2/2./GC/DRISE*RISER/CONVER
       DPGRVR=GRC*CORGR*RHOEXT*RISER/CONVER/GC
 90    DPRS=DPFRIR+DPGRVR
       IF (ISUPER.EQ.0) GOTO 100
C
C      STEADY-STATE PRESSURE DROP ACROSS SUPERHEATER
C
       DPACCS=RHOG*VELW(NOD1)*(VELWS(NODZS1)-VELW(NOD1))/GC/CONVER
       RHOSSM=.5*(RHOS(1)+RHOS(NODZS1))
       FRISSM=.5*(VELWS(1)**2*RHOS(1)+VELWS(NODZS1)**2*RHOS(NODZS1))
       DO 130 I=2,NODZS
       RHOSSM=RHOSSM+RHOS(I)
 130   FRISSM=FRISSM+VELWS(I)**2*RHOS(I)
       DPGRVS=GRC*CORG2*RHOSSM*ZSUPER/GC/FLOAT(NODZS)/CONVER
       DPFRIS=FRIC*CORFS*FRISSM*ZSUPER/2./DH/GC/FLOAT(NODZS)/CONVER
 100       DPSP=DPGRVS+DPFRIS+DPACCS
C
       DPHEAT=DP1P+DP2P+DPSP
```

```
      DPTT=DPHEAT+DPRS+DPINLT+DPEXIT
      DPFRIT=DPINLT+DPFRI1+DPFRI2+DPFRIS+DPFRIR+DPEXIT+DPLOOP
      DPGRVT=DPGRV1+DPGRV2+DPGRVS+DPGRVR-(ALHEAT*CORG2+RISER*CORGR)
     1       *RHOI/144.
      DPACCT=DPACC2+DPACCS
      DPTL=DPFRIT+DPGRVT+DPACCT
C
      WRITE (6,900) DPINLT,DPINLT,DP1P,DPFRI1,DPGRV1,DP2P,DPFRI2,FRIC,
     1     CORF2,DPGRV2,CORG2,DPACC2,DPSP,DPFRIS,FRIC,CORFS,DPGRVS,
     2     CORG2,DPACCS,DPRS,DPFRIR,FRIC,CORFR,DPGRVR,CORGR,DPEXIT,
     3     DPEXIT,DPLOOP,DPLOOP,SFLOOP,DPHEAT,DPTT,DPTL,DPFRIT,DPGRVT,
     4     DPACCT
  900 FORMAT(///," STEADY STATE PRESSURE DROP (PSI)",/,35X,
     1    " TOTAL",10X,"FRICTION (MOODY FACTOR X CORRT)  GRAVITY (CORRT
     3FACTOR)  ACCELERATION",/,
     3    " INLET LOSS",19X,F10.3,5X,F10.3,/,
     5    " HEATED SINGLE PHASE REGION   ",F10.3,5X,F10.3,26X,F10.3,/,
     6    " HEATED TWO PHASE REGION      "
     7  F10.3,5X,F10.3,"  F=" ,F8.5,"X",F8.5,5X,F10.3,"  G=" ,F8.5,5X,
     8    F10.3,/," SUPERHEAT REGION",13X,
     9  F10.3,5X,F10.3,"  F=" ,F8.5,"X",F8.5,5X,F10.3,"  G=" ,F8.5,5X,
     1    F10.3,/," RISER " ,23X,
     9  F10.3,5X,F10.3,"  F=" ,F8.5,"X",F8.5,5X,F10.3,"  G=" ,F8.5,5X,
     1         /," EXIT LOSS",20X,F10.3,5X,F10.3,/,
     4    " FRICTION IN REST OF LOOP     ",F10.3,5X,F10.3,10X,"SUM(F*L/D
     5*A2) = ",E13.4,/," TOTAL HEATED REGION",10X,F10.3,/,
     6    " TOTAL TEST SECTION",11X,F10.3,/,
     8   " TOTAL LOOP",19X,F10.3,5X,F10.3,26X,F10.3,17X,F10.3,/)
      RETURN
C
C     PERTURBED PRESSURE DROP IN SINGLE-PHASE REGION
C
  200 DELPIN=FINLET*RHOI*VINLET*DELV1 /GC
      DELP1A  =RHOA*ZBB*S*DELVA /GC
      DELP1F  =FRIC *RHOA*VINA*ZBB*DELVA /GC/DH
      DELP1B  =(FRIC *RHOA*VINA**2/2./GC/DH+GRC*RHOA/GC)*DELZBB
      DELPSA=CMO
      DELPSB=CMO
      DELPSF=CMO
      DELPSG=CMO
      DELPRA=CMO
      DELPRF=CMO
      DELPRG=CMO
C
C     PERTURBED PRESSURE DROP IN TWO-PHASE REGION
C
      OMEGA1=HFLUX2(1)*PAH*RHO1
      OMEGA2=HFLUX2(NOD1)*PAH*RHO1
      DELP2T=(VELW(NOD1)**2*DELRHO(NOD1)-VELW(1)**2*DELRHO(1)+
     1     2.*(RHO(NOD1)*VELW(NOD1)*DELVW(NOD1)-RHOF*VELW(1)*DELVW(1))
     2     -OMEGA1*DELZBB*GO)/GC
      DRHOSM=.5*(DELRHO(1)+DELRHO(NOD1))
```

```
      DFRISM=.5*(VELW(1)*(VELW(1)*DELRHO(1)+2.*RHO(1)*DELVW(1))
     1        +VELW(NOD1)*(VELW(NOD1)*DELRHO(NOD1)+2.*RHO(NOD1)*DELVW(NOD1
     2   )))
      DACCSM=.5*(RHO(1)*DELVW(1)+RHO(NOD1)*DELVW(NOD1)+VELW(1)*DELRHO
     1      (1)+VELW(NOD1)*DELRHO(NOD1))
      DO 40 I=2,NODE
      DRHOSM=DRHOSM+DELRHO(I)
      XTT=((1.-X(I))/X(I))**.9*ROMUFG
      PHIFT2=FPHI(XTT,X(I),P)
      DFRISM=DFRISM+VELW(I)*(VELW(I)*DELRHO(I)+2.*RHO(I)*DELVW(I))
     1      *RHO(I)/RHOF*             PHIFT2
   40 DACCSM=DACCSM+RHO(I)*DELVW(I)+VELW(I)*DELRHO(I)
      DELPEX  =FEXIT*((VELW(NOD1))**2*DELRHO(NOD1)+2.*RHO(NOD1)
     1        *VELW(NOD1)*DELVW(NOD1))/2./GC
      DELP2A  =DACCSM*S*ZBOIL/GC/FLOAT(NODE)+DELP2T
      DELP2F  =FRIC *DFRISM*ZBOIL/2./GC/DH/FLOAT(NODE)*CORF2
      DELP2G  =GRC/GC*DRHOSM*ZBOIL/FLOAT(NODE)*CORG2
      DELP2D =RHOF*RHOG/GC*((1.-2.*RHOF/RHO(NOD1))*VGJ(NOD1)**2*DELRHO
     1      (NOD1)/RHO(NOD1)**2-(1.-2.*RHOF/RHO(1))*VGJ(1)**2*DELRHO(1)
     2      /RHO(1)**2+2.*(RHOF/RHO(NOD1)-1.)*VGJ(NOD1)*DVGJ/RHO(NOD1)
     3      -2.*(RHOF/RHO(1)-1.)*VGJ(1)*DVGJ1/RHO(1))
      DELP2B=-DELP1B
      IF (IR.EQ.0) GOTO 150
C
C     PERTURBED PRESSURE DROP IN RISER
C
          EXL=CEXP(-S*RISER/VRISE)-1.
      DELVRS=DELVEX*AW/ARISE
      DELPRG=-GRC*CORGR*VRISE*EXL*DELREX/S/GC
      DELPRF=FRIC*CORFR/2./GC/DRISE*VRISE*(2.*RHOEXT*RISER*DELVRS-VRISE
     1    **2*DELREX/S*EXL)
      DELPRA=                      S*RISER*RHOEXT*DELVRS/GC
  150 IF (ISUPER.EQ.0) GOTO 170
C
C     PERTURBED PRESSURE DROP IN SUPERHEATER
C
      DELTS=DELTEX
      DRHOSS=.5*(DELROS(1)+DELROS(NODZS1))
      DFRISS=.5*(VELWS(1)*(VELWS(1)*DELROS(1)+2.*RHOS(1)*DELVS(1))+
     1  VELWS(NODZS1)*(VELWS(NODZS1)*DELROS(NODZS1)+2.*RHOS(NODZS1)
     2     *DELVS(NODZS1)))
      DACCSS=.5*(RHOS(1)*DELVS(1)+VELWS(1)*DELROS(1)+
     1     RHOS(NODZS1)*DELVS(NODZS1)+VELWS(NODZS1)*DELROS(NODZS1))
      DO 160 I=2,NODZS
      DRHOSS=DRHOSS+DELROS(I)
      DFRISS=DFRISS+VELWS(I)*(VELWS(I)*DELROS(I)+2.*RHOS(I)*DELVS(I))
  160 DACCSS=DACCSS+RHOS(I)*DELVS(I)+VELWS(I)*DELROS(I)
      OMEGAS=HFLUX3(1)*PAH*VGS(1)
      DELPSC=(VEXIT**2*DELREX+2.*GO*(DELVEX-DELVS(1))
     1   -VELWS(1)**2*DELROS(1)-GO*(OMEGAS-OMEGA2)*DELZSB)/GC
      DELPSA=DELPSC+DACCSS*S*ZSUPER/GC/FLOAT(NODZS)
      DELPSF=FRIC*CORFS*DFRISS*ZSUPER/2./GC/DH/FLOAT(NODZS)
```

```
      DELPSG=GRC/GC*DRHOSS*ZSUPER*CORG2/FLOAT(NODZS)
      DELPSB=(FRIC*CORF2*RHOG*VELW(NOD1)**2/2./GC/DH+GRC*CORG2*RHOG/GC)
     1      *DELZSB
  170 DEL(1)=DELZBB
C
C     SUMMATION OF THE DIFFERENT COMPONENTS OF PRESSURE DROPS TO BE USED
C     LATER
C
      DEL(2)=         (SLOOP*RHOI*AW*S/GC+SFLOOP*AW**2*GO/GC-AA*AW)
     1        *DELV1 *FLOAT(IL)
      DEL(3)=DELP1A+DELP1F+DELP1B+DELPIN
      DEL(4)=DEL(3)-DELP1B
      DEL(5)=DEL(3)+DEL(2)
      DEL(6)=DELP2A+DELP2F+DELP2G+DELP2D+DELP2B+DELPSB
      DEL(7)=DEL(6)-DELP2B-DELPSB
      DEL(8)=DELPSA+DELPSF+DELPSG-DELPSB
      DEL(9)=DEL(8)+DELPSB
      DEL(10)=DELPRA+DELPRF+DELPRG
      IF ( REAL(DELVIN).LT.1.E-10) GOTO 190
      DEL(14)=(DELVEX*RHOEXT+DELREX*VEXIT)/DELVIN/RHOF
      GOTO 191
  190 DEL(14)=CMO
  191 CONTINUE
      RETURN
      END
      FUNCTION HL(P,T)
CHL          LIQUID ENTHALPY  0-P-2120 PSIA
      HL     = 0.001618*P-47.62+(0.965566-4.982E-6*P)*T
     1 +(8.2445*P-8843.4)/(802.-T) + (6.6612*P-20392.)/(T-750.)
      RETURN
      END
      FUNCTION DENS(P,T,HPT)
CDENS     LIQUID DENSITY     0-P-2120 PSIA
      HPT = HL(P,T)
      IF(HPT .GE. 280.)     GO TO 100
      DENS = 2.14E-4*P +62.4 +(1.438E-9*P- 8.73E-5)*HPT**2
     1 + (2.32E-10 - 6.2E-15*P)*HPT**4
      RETURN
  100 DENS = 5.761E-4*P+92.924 + (1.6386*P+39440.2)/(HPT-(0.035704*P
     1 + 1377.35))
      RETURN
      END
      FUNCTION HFSAT(P)
      HFSAT=323.9128+0.2964306*P-0.944149E-4*P**2
     C      + 0.165674E-07*P**3
      RETURN
      END
      FUNCTION FHFG(P)
C     LATENT HEAT OF VAPORIZATION OF WATER (BTU/LBM)
C
      FHFG= 883.6608 - 0.2911105*P + 0.743325E-04*P**2
     C        - 0.165592E-07*P**3
```

```
      RETURN
      END
      SUBROUTINE TABLE (P,TSAT,TEND)
C
C     SETS UP STEAM TABLE VAPTAB,  OF THE FOLLOWING FORM.......
C     TG(I) = TEMPERATURE
C     HG(I) = ENTHALPY
C     SV(I) = SPECIFIC VOLUME
C
      COMMON/VAPTAB/TG(100),HG(100),SV(100)
      DELT=(TEND-TSAT)/99.
      DO 10 I=1,100
      TG(I)=TSAT+DELT*FLOAT(I-1)
   10 CALL SATVAP(P,TG(I),HG(I),SV(I))
      RETURN
      END
      SUBROUTINE SATVAP (P,TEMP,HG,SV)
C
C     STEAM TABLE FUNCTIONS.........
C     ..... INPUT .....
C     P = PRESSURE (PSIA)
C     T = TEMPERATURE (F)
C     ..... OUTPUT .....
C     HG = ENTHALPY (BTU/LBM)
C     SV = SPECIFIC VOLUME (FT3/LBM)
C     ............................
C     REF - STELTZ AND SILVESTRI "THE FORMULATION OF STEAM PROPERTIES
C                 FOR DIGITAL COMPUTER APPLICATION", TRANS ASME, VOL. 80
C                 , 1958, P. 967.
C
      REAL J,K,L,M,N,M1,M2,M3,L1,L2,L3,KP
      TC=(TEMP-32.)*5./9.
       PINT=P/14.696
      DATA A,B,C,D,E /1.89,2641.62,10.,80870.,82.546/
      DATA F,G,H,J,K      /1.6246E+5,.21828,1.2697E+5,3.635E-4,6.768E-8/
      DATA L,M,N,Q,R,U /1.472,7.5566E-4,47.8365,.101325,4.55504,.43/
      DATA V,W,Y,C1,HP,KP,SP/.23888888,-698.65,.0160185,14.6959,2502.36,
     1    273.16,-1.48847/
      TAU=1./(KP+TC)
      ALPHA=B*C**(D*TAU*TAU)
      BETA=D*ALOG(C)*TAU*TAU
      GAMMA=ALPHA*(1.+2.*BETA)
      DELTA=E-F*TAU
      EPS=G-H*TAU*TAU
      RHO=J-K*(1000.*TAU)**24.
      B0=A-TAU*ALPHA
      B3=B0*B0*B0
      B4=B3*B0
      B12=B4*B4*B4
      B13=B12*B0
      M1=PINT*PINT/2.
      M2=(TAU*PINT)**4./4.
```

```
      M3=(TAU*PINT)**13./13.
      L1=BO*BO*TAU*TAU*(3.*DELTA-F*TAU)-DELTA*TAU**3.*2.*BO*GAMMA
      L2=B4    /TAU*(4.*EPS-2.*H*TAU*TAU)-EPS*4.*B3    *GAMMA
      L3=-B13    /TAU*(13.*RHO-24.*K*(1000.*TAU)**24.)+RHO*13.*B12*
     CGAMMA
      HG   =((PINT*(A-2.*TAU*ALPHA*(1.+BETA))+L1*M1+L2*M2+L3*M3)*Q
     1+L/TAU+.5*M/TAU/TAU-N*ALOG(TAU)+W+HP)*U
      SV=(R/PINT/TAU+BO+BO*BO*TAU*TAU*DELTA*PINT+B4*(TAU*PINT)**3.*EPS
     1       -B13*(TAU*PINT)**12.*RHO)*Y
      RETURN
      END
      SUBROUTINE ENTHTP (P,ENG,T,GASCON,CPG)
C     THIS SUBROUTINE INTERPOLATES THE FOLLOWING STEAM TABLE OUTPUTS
C     WITH INPUT ENTHALPY (ENG), USING THE TABLE VAPTAB
C     ..... INPUT .....
C     ENG = ENTHALPY
C     .....  OUTPUT .....
C     T = TEMPERATURE
C     GASCON = GRADIENT OF SPECIFIC HEAT/STEAM ENTHALPY
C     CPG = SPECIFIC HEAT OF STEAM
C
      COMMON/VAPTAB/TG(100),HG(100),SV(100)
      DO 10 I=2,100
   10 IF (ENG.LE.HG(I)) GOTO 20
      WRITE (6,30)
   30 FORMAT (//," ENTHALPY TABLE OUTSIDE LIMIT")
      STOP
   20 T=TG(I-1)+(TG(I)-TG(I-1))*(ENG-HG(I-1))/(HG(I)-HG(I-1))
      GASCON=(SV(I)-SV(I-1))/(HG(I)-HG(I-1))
      CPG=(HG(I)-HG(I-1))/(TG(I)-TG(I-1))
      RETURN
      END
      FUNCTION ANGL(COMP)
C     ANGL = ANGLE OF THE COMPLEX VARIABLE (COMP)
C
      COMPLEX COMP
      FIMAG=AIMAG(COMP)
      DREAL=REAL(COMP)
      SREAL=DREAL**2
      SQMOD=FIMAG**2+DREAL**2
      IF(SREAL.LE.1.0E-30) GO TO 93
      ANGL=57.296*ATAN2(FIMAG,DREAL)
      RETURN
   93 ANGL=90.0
      IF(FIMAG.LE.0.0) ANGL=-90.0
      IF(SQMOD.LE.1.0E-30) ANGL=0.0
      RETURN
      END
      FUNCTION VISCST(T,RHO)
C     VISCOSITY OF SUPERHEATED STEAM 212 F - 1292 F (LBM/SEC-FT)
C     INPUT - T(F) AND RHO(LBM/FT3)
C     REF - ASME STEAM TABLE P. 74
```

```
C
      TC=.55555556*(T-32.)
      RHOC=RHO/62.43
      VISSAT=.407*TC+80.4
      IF (TC.GT.375.) GOTO 10
      VISCST=VISSAT-RHOC*(1858.-5.9*TC)
      GOTO 20
   10 VISCST=VISSAT+RHOC*353.+676.5*RHOC*RHOC+102.1*RHOC**3
   20 VISCST=VISCST*.0671969E-6
      RETURN
      END
      FUNCTION CONDST(T,RHO)
C     THERMAL CONDUCTIVITY OF SUPERHEATED STEAM 212 F - 1292 F (
C             BTU/SEC-F-FT)
C     INPUT - T(F) AND RHO(LBM/FT3)
C     R EF - ASME STEAM TABLE P. 77
C
      TC=.555555556*(T-32.)
      RHOC=RHO/62.43
      CONSAT=17.6+.0587*TC+1.04E-4*TC*TC-4.51E-8*TC**3
      CONDST=(103.51+.4198*TC-2.771E-5*TC*TC)*RHOC+2.1482E+14*RHOC*RHOC
     1     /TC**4.2+CONSAT
      CONDST=.1605E-6*CONDST
      RETURN
      END
      REAL FUNCTION MUTL(T)
C     VISCOSITY OF SATURATED LIQUID WATER IN RANGE 32 TO 572 DEG. F
C     VISCOSITY IN LBM/HR -FT  --  TEMPERATURE IN DEG. F
C     REF - ASME STEAM TABLES, PAGE 74
      MUTL  = 0.0584*10.0**(446.04/(207.6+T))
      RETURN
      END
      FUNCTION COND(T)
C     THERMAL CONDUCTIVITY OF SATURATED WATER IN RANGE 32 TO 662 DEG. F
C     KF IN BTU/HR-FT-DEG.F  --    TEMPERATURE IN DEG. F
      DATA A0, A1, A2, A3, A4 /-0.53299, 1.6406,  -1.0404, 0.30378,
     1     -0.042433/
      TT = (T+459.67)/491.67
      COND = A0 + A1*TT + A2*TT*TT + A3*TT**3 + A4*TT**4
      RETURN
      END
      FUNCTION FPHI(XTT,X,P)
      REAL MATNEL
      DIMENSION MATNEL(11,5)
      COMMON/PRESUR/IPRES,PRESCR(11)
      DATA  MATNEL   /1.,5.6,8.5,11.5,14.5,17.,19.,21.,22.,21.5,14.,
     1     1.,3.5,5.,6.9,8.4,9.9,11.,12.,13.,13.,8.2,
     2    1.,2.5,3.3,4.0,4.8,5.7,6.3,7.0,7.7,7.8,5.8,
     3      1.,1.7,2.2,2.7,3.0,3.2,3.7,4.0,4.3,4.35,3.6,
     4       1.,1.4,1.5,1.65,1.8,1.95,2.1,2.25,2.4,2.5,2.1/
      IF (IPRES.EQ.1) GOTO 10
      I=INT(X*10.)+1
```

```
      J=INT(P/500.)-1
      F1=MATNEL(I,J)+(X-FLOAT(I-1)*.1)*(MATNEL(I+1,J)-MATNEL(I,J))/.1
      F2=MATNEL(I,J+1)+(X-FLOAT(I-1)*.1)*(MATNEL(I+1,J+1)-MATNEL(I,J+1))
     1    /.1
      FPHI=F1+(P-FLOAT(500+500*J))*(F2-F1)/500.
      RETURN
   10 I=INT(X*10.)+1
      FPHI=PRESCR(I)+(PRESCR(I+1)-PRESCR(I))*(X*10.-FLOAT(I-1))
      RETURN
      END
      FUNCTION HT1P(COND,D,RE,PR)
C     SINGLE-PHASE HEAT TRANSFER COEFF  (BTU/SEC-FT2-F)
C     DITTUS-BOELTER CORRELATION
C
      HT1P=COND*.023/D*RE**.8*PR**.4
      RETURN
      END
      SUBROUTINE FUNCCO(CO,H,ARGU1,ARGU2,CONDUC,ARGU)
C     THIS SUBROUTINE CALCULATES CO, WHICH RELATES THE WALL GEOMETRY
C     DYNAMICS TO THE FLUID DYNAMICS
C     THE FOLLOWING ROUTINE USES A FLAT-PLATE GEOMETRY
C
      COMPLEX CO,ARGU1,ARGU2,ARGU,C1,C2
      C1=CEXP(-2.*ARGU1)
      C2=CEXP(-2.*ARGU2)
      CO=-1./(1./H+1./CONDUC/ARGU*(C1+C2)/(C1-C2))
      RETURN
      END
      FUNCTION FHTNB(Q,H,P,IHTNB,CHTNB)
C
C     CORRELATION FOR NUCLEATE BOILING HEAT TRANSFER COEFFICIENT(BTU/FT2
C       -SEC-F)
C     IHTNB = 1   THOM CORRELATION
C             2   JENS-LOTTES CORRELATION
C             3   CONSTANT  = CHTNB
C
C     Q = HEAT FLUX (BTU/SEC-FT2)
C     P = PRESSURE (PSIA)
C
      GOTO (10,20,30), IHTNB
   10 FHTNB=.23146*SQRT(ABS(Q))*EXP(P/1260.)
      RETURN
   20 FHTNB=(EXP(P/225.)/46656.)**.25*(ABS(Q))**.75
      RETURN
   30 FHTNB=CHTNB
      RETURN
      END
      FUNCTION XDO(Q,GO,P,D)
C     CORRELATION FOR QUALITY AT LOCATION OF DRYOUT
C     CORRELATION OBTAINED FROM WOLF  ET AL
C     Q = HEAT FLUX (BTU-SEC-FT2)
C     GO = MASS FLOW RATE (LBM/FT2-SEC)
```

```
C     P = PRESSURE (PSIA)
C     D = HYDRAULIC DIAMETER (FT)
C
      GOMETR=GO*4.8824
      XDO=.944*(1.-P/3208.2)**1.054/(GOMETR/1000.)**.625
      RETURN
      END
      FUNCTION HTDO(COND,D,RE,PR,X,ROGROF)
C     POST-DRYOUT HEAT TRANSFER COEFF (BTU/SEC-FT2-F)
C     BISHOP CORRELATION
C     COND = THERMAL CONDUCTIVITY OF VAPOR
C     D = HYDRAULIC DIAMETER
C     RE = VAPOR REYNOLDS NUMBER
C     PR = VAPOR PRANDTL NUMBER
C     X = QUALITY
C     ROGROF = VAPOR DENSITY/LIQUID DENSITY
C
      HTDO=.0193*COND/D*RE**.8*PR**1.23*(X+(1.-X)*ROGROF)**.68*ROGROF
     1     **.068
      RETURN
      END
      FUNCTION HTS(COND,D,RE,PR)
C     SUPERHEATED STEAM HEAT TRANSFER COEFF (BTU/SEC-FT2-F)
C     HEINEMANN CORRELATION USED
C
      HTS=COND /D*.0133*RE**.84*PR**.33
      RETURN
      END
      COMPLEX FUNCTION FDHNU(H,TWTS,DELT1,IHTNB)
C     HEAT TRANSFER COEFF PERTURBATIONS IN NUCLEATE BOILING REGION
C     PERTURBED VARIABLE - DELT1
C
C     CHANGE THE FOLLOWING STATEMENT IF HEAT TRANS. CORR. IS CHANGED ...
C     DHDT1 = PARTIAL DERIVATIVE OF H.T. COEFF W.R.T. WALL TEMP
C
      COMPLEX DELT1
      GOTO (10,20,30), IHTNB
   10 DHDT1=H/TWTS
      GOTO 40
   20  DHDT1=3.*H/TWTS
      GOTO 40
   30 DHDT1=0.
   40 FDHNU =DHDT1*DELT1
      RETURN
      END
      COMPLEX FUNCTION FDHDO (H,X,RHO,VEL,ROGROF,VFG,DELVEL,DELRHO)
C     HEAT TRANSFER COEFF PERTURBATIONS IN POST-DRYOUT REGION
C     PERTURBED VARIABLES - DELRHO, DELVEL
C     PERTURBED VARIABLES - DELRHO, DELVEL
C     BISHOP"S CORRELATION IS USED BELOW
C
C     IF CHANGES IN H.T. COEFF. CORR. IS NEEDED, CHANGE THE FOLLOWING
```

```
C     TWO STATEMENTS ACCORDINGLY......
C     1. DHSDRO = PARTIAL DERIVATIVE OF H.T. COEFF. W.R.T. STEAM DENSITY
C     2. DHSDV = P ARTIAL DERIVATIVE OF H.T. COEFF. W.R.T. VELOCITY
C
      COMPLEX DELVEL,DELRHO
      DHDX=H*(1.-ROGROF)/(X+(1.-X)*ROGROF)
      DHDV=.8*H/VEL
      DHDRO=.8*H/RHO
      DXDRHO=-1./RHO**2/VFG
      FDHDO=DHDV*DELVEL+(DHDX*DXDRHO+DHDRO)*DELRHO
      RETURN
      END
      COMPLEX FUNCTION FDHS(H,RHO,VEL,DELRHO,DELVEL)
C     HEAT TRANSFER COEFF. PERTURBATIONS IN SUPERHEATER
C     HEINEMANN"S CORRELATION IS USED BELOW
C
C     IF CHANGES IN H.T. COEFF. CORR. IS NEEDED, CHANGE THE FOLLOWING
C     TWO STATEMENTS ACCORDINGLY......
C     1. DHSDRO = PARTIAL DERIVATIVE OF H.T. COEFF. W.R.T. STEAM DENSITY
C     2. DHSDV = P ARTIAL DERIVATIVE OF H.T. COEFF. W.R.T. VELOCITY
      COMPLEX DELRHO,DELVEL
      DHSDRO=.84*H/RHO
      DHSDV=.84*H/VEL
      FDHS=DHSDRO*DELRHO+DHSDV*DELVEL
      RETURN
      END
      FUNCTION FVGJ(A,B,VGJN)
C
C     THIS FUNCTION CORRELATES VAPOR-LIQUID DRIFT VELOCITY FROM
C             A = CONSTANT DEFINED IN CALLING PROGRAM
C             B=VOID FRACTION
C
C       FOR HOMOGENEOUS MODEL
C      FVGJ=0.
C      RETURN
C
      FVGJ=A*(1.-B)**VGJN
      RETURN
      END
      FUNCTION FCO1(BETA,B1)
C     THIS FUNCTION CORRELATES CO1, THE VOID-FRACTION WEIGHTED VOLUMETRI
C     FLUX PROFILE.
C     REFERENCE - DIX
C          B1=(DENSITY OF STEAM/DENSITY OF LIQUID)**.1
C     ******DO NOT SET  FCO1 EQUAL TO VERY SMALL NUMBER AS THIS MAY LEAD
C     TO INACCURACY IN INITIAL CONDITIONS******************
C     SET FCO1 EQUAL TO AT LEAST .1
C          BETA = A FUNCTION OF QUALITY DEFINED IN CALLING PROGRAM
C
C       FOR HOMOGENEOUS MODEL
C      FCO1=1.
C      RETURN
```

```
      IF (BETA.LT.1.E-8) GOTO 10
      FC01=BETA*(1.+(1./BETA-1.)**B1)
      RETURN
   10 FC01=0.2
      RETURN
      END
      FUNCTION DVGJDA(VGJC,ALPHA,VGJN)
C
C       FOR HOMOGENEOUS MODEL
C       DVGJDA=0.
C       RETURN
      DVGJDA=-VGJC*VGJN*(1.-ALPHA)**(VGJN-1.)
      RETURN
      END
      FUNCTION DVGJDR(A,B,C,VGJN)
C     THIS FUNCTION CORRELATES THE DERIVATIVE OF THE VAPOR-LIQUID DRIFT
C     VELOCITY WITH RESPECT TO DENSITY.
C     THE CORRELATION HAS TO CORRESPOND TO THE DRIFT-FLUX FUNCTION FVGJ
C
C      FOR HOMOGENEOUS MODEL
C      DVGJDR=0.
C      RETURN
      DVGJDR=A*(B-C)**(VGJN-1.)
      RETURN
      END
      SUBROUTINE POLPLT(XREAL, YIMAG, NUM)
C
C     SUBROUTINE POLPLT PLOTS POLAR DIAGRAMS IN THE COMPLEX PLANE
C     XREAL = ARRAY OF ABSCISSAS
C     YIMAG = ARRAY OF ORDINATES
C     NUM = NUMBER OF POINTS TO BE PLOTTED  (MUST BE .GE. 2)
C
      INTEGER CHAR(10)
      INTEGER PWIDTH
      DIMENSION IP(100,60), XREAL(1), YIMAG(1)
      COMMON /PLOT/ IP, XORG, YORG, XSLOT, YSLOT, PWIDTH, LENGTH
      DATA IBLNK /1H /, CHAR /     1H1, 1H2, 1H3, 1H4, 1H5, 1H6, 1H7,
     1      1H8, 1H9, 1H0/
      PWIDTH = 100
      LENGTH = 60
C
C     DETERMINE  THE WIDTH OF THE AXES ON THE NYQUIST PLOT
C
      XMAX = 0.0
      YMAX = 0.0
      XMIN = 0.0
      YMIN = 0.0
C
      DO 10 IM = 1,NUM
      IF(XMAX - XREAL(IM)) 4,10,10
    4 XMAX = XREAL(IM)
   10 CONTINUE
```

```
C
      DO 20 IM = 1,NUM
      IF(YMAX - YIMAG(IM)) 14,20,20
   14 YMAX = YIMAG(IM)
   20 CONTINUE
C
      DO 30 IM = 1,NUM
      IF(XMIN - XREAL(IM)) 30,30,24
   24 XMIN = XREAL(IM)
   30 CONTINUE
C
      DO 40 IM = 1,NUM
      IF(YMIN - YIMAG(IM)) 40,40,34
   34 YMIN = YIMAG(IM)
   40 CONTINUE
C
C
      ABSXY = AMAX1(ABS(XMAX), ABS(YMAX), ABS(XMIN), ABS(YMIN))
      IF(ABSXY - 0.1) 51, 52, 52
   51 IEXP = INT(ALOG10(ABSXY))
      AMULT = 10.0**IEXP
      GO TO 53
   52 AMULT = 1.0
   53 CONTINUE
      IF(XMAX .LT. AMULT) XMAX = AMULT
      IF(YMAX .LT. AMULT) YMAX = AMULT
      IF(XMIN .GT. (-AMULT)) XMIN = -AMULT
      IF(YMIN .GT. (-AMULT)) YMIN = -AMULT
      XSLOT = FLOAT(PWIDTH - 1)/(XMAX - XMIN)
      YSLOT = FLOAT(LENGTH - 1)/(YMAX - YMIN)
      XORG = (XMAX - FLOAT(PWIDTH)*XMIN) / (XMAX - XMIN) + 0.5
      YORG = (YMAX - FLOAT(LENGTH)*YMIN) / (YMAX - YMIN) + 0.5
C
C     ERASE SURFACE OF PAPER
C
      DO 102 K = 1, PWIDTH
      DO 102 L = 1, LENGTH
  102 IP(K,L) = IBLNK
C
C     DRAW AXES
C
      CALL YLINE(-1.0*AMULT)
      CALL YLINE( 0.0)
      CALL YLINE(+1.0*AMULT)
      CALL XLINE(-1.0*AMULT)
      CALL XLINE( 0.0)
      CALL XLINE(+1.0*AMULT)
C
C     DRAW DIAGRAM
C
      DO 105 KJ = 2,NUM
  105 CALL LINE(XREAL(KJ-1), YIMAG(KJ-1),  XREAL(KJ), YIMAG(KJ))
```

```
C
C     LABEL POINTS TO BE PRINTED
C
      DO 106 KJ = 1, NUM
      IND = MOD(9+KJ, 10) + 1
  106 CALL PTTY(XREAL(KJ), YIMAG(KJ), CHAR(IND))
C
C     PLOT DIAGRAM ON PLOTTER
C
      WRITE(6,112)  (IP(KI,1), KI = 1,PWIDTH), AMULT
  112 FORMAT(1H , 9X, 100A1, 6HSCALE=, 1PE7.1)
      DO 110 KJ = 2, LENGTH
  110 WRITE(6,111) (IP(KI,KJ), KI = 1,PWIDTH)
  111 FORMAT(1HZ, 9X, 100A1)
      RETURN
      END
      SUBROUTINE LINE(X11, Y11, X22, Y22)
C
C     SUBROUTINE LINE DRAWS A LINE BETWEEN POINTS 1 AND 2
C
      INTEGER PWIDTH
      DIMENSION IP(100,60)
      COMMON /PLOT/ IP, XORG, YORG, XSLOT, YSLOT, PWIDTH, LENGTH
      DATA IDOT /1H*/
C
      ICX(Z) =  IFIX(XORG + Z*XSLOT)
      ICY(Z) =  IFIX(YORG + Z*YSLOT)
C
      X1 = X11
      X2 = X22
      Y1 = Y11
      Y2 = Y22
C
C     ENSURE LINE IS DRAWN FROM TOP TO BOTTOM
C
      IF(Y1 .GE. Y2) GO TO 6
      X3 = X1
      Y3 = Y1
      X1 = X2
      Y1 = Y2
      X2 = X3
      Y2 = Y3
C
    6 J1 = LENGTH + 1 - ICY(Y1)
      J2 = LENGTH + 1 - ICY(Y2)
      RXSLOT = 1.0/XSLOT
      IF(ABS(X1-X2) .LE. RXSLOT) GO TO 10
      IF(J1 .EQ. J2) GO TO 20
      GRADE = (X2-X1) / FLOAT(J2-J1)
      DO 1 J = J1, J2
      I = ICX(X1 + FLOAT(J-J1)*GRADE)
    1 IP(I,J) = IDOT
```

```
      RETURN
C
   10 I = ICX(0.5*(X1+X2))
      DO 11 J = J1,J2
   11 IP(I,J) = IDOT
      RETURN
C
   20 I11 = ICX(X1)
      I22 = ICX(X2)
      I1 = MINO(I11,I22)
      I2 = I11 + I22 - I1
      DO 21 I = I1, I2
   21 IP(I,J1) = IDOT
      RETURN
      END
      SUBROUTINE XLINE(Y)
C
C     PLOTS HORIZONTAL AXES
C
      INTEGER PWIDTH
      DIMENSION IP(100,60)
      COMMON /PLOT/ IP, XORG, YORG, XSLOT, YSLOT, PWIDTH, LENGTH
      DATA MINUS /1H-/
C
      J = LENGTH + 1 - IFIX(YORG + Y*YSLOT)
      DO 1 I = 1,PWIDTH
    1 IP(I,J) = MINUS
      RETURN
      END
      SUBROUTINE YLINE(X)
C
C     PLOTS VERTICAL LINES
C
      INTEGER PWIDTH
      DIMENSION IP(100,60)
      COMMON /PLOT/ IP, XORG, YORG, XSLOT, YSLOT, PWIDTH, LENGTH
      DATA IBAR /1HI/
C
      I = IFIX(XORG + X * XSLOT)
      DO 1 J = 1, LENGTH
    1 IP(I,J) = IBAR
      RETURN
      END
      SUBROUTINE PTTY(X, Y, IC)
C
C     PLOTS A POINT ON THE LINE PRINTER
C
      INTEGER PWIDTH
      DIMENSION IP(100,60)
      COMMON /PLOT/ IP, XORG, YORG, XSLOT, YSLOT, PWIDTH, LENGTH
C
      ICX(Z) =  IFIX(XORG + Z*XSLOT)
```

```
      ICY(Z) =  IFIX(YORG + Z*YSLOT)
      I  = ICX(X)
C
      J = LENGTH + 1 - ICY(Y)
      IP(I,J) = IC
      RETURN
      END
      SUBROUTINE PRTPL4(NO,  N,NL,KX,JX,MPLOT,YSC)
C
C     NO - TITLE OF GRAPH (A6,A4)
C     B - MATRIX B(N,M) CONTAINING DATA TO BE PLOTTED.
C           M=1 CONTAINS THE ABSCISSAS
C           M=2...12 CONTAINS THE ORDINATES
C           MAXIMUM DIMENSIONS OF B IN CALLING PROGRAM B(KX,JX)
C     N - NUMBER OF POINTS IN EACH CURVE
C     NL - NUMBER OF LINES IN PLOT
C     KX AND JX - DIMENSIONS OF B IN CALLING PROGRAM
C     MPLOT - ORDER OF VARIABLE TO BE PLOTTED
C     YSC - RANGE OF ORDINATE OF GRAPH (CORRECTED INTERNALLY IF NOT
C           ADEQUATE).
C
      COMMON/CBODE/B   (100,9),DPREAL(100),DPIMAG(100)
      DIMENSION OUT(101),YPR(12),          A(200)
      DATA ANG/1H*/, BLANK /1H /
C
    1 FORMAT(I1, 60X,9H PLOT OF , A6,A4,/)
    2 FORMAT(1HZ,F11.4  , 5X, 101A1, E12.4)
    3 FORMAT(1HZ,117X, I12)
    7 FORMAT(1HZ,16X,101H.         .         .         .         .
     1    .         .         .         .         .         .)
    8 FORMAT(1HZ,9X,11F10.4)
C
      DO 5 IZ= 1,101
    5 OUT(IZ) = BLANK
C
      IADV = 1
      MPLOT1 = MPLOT + 1
      WRITE(6,1) IADV, NO
C
C     CONVERT ABSCISSAS TO LOG COORDINATES AND STORE IN A . . . . . . .
      DO 10 I = 1,N
   10 A(I) =-ALOG(B(I,1))
C
C     DETERMINE EXTREMA  . . . . . . . . . . . . . . . . . . . . . . .
C
      YMIN=1.0E30
      YMAX=-1.0E30
      DO 40 K = 1,N
      IF(B(K,MPLOT1) .GT. YMAX) YMAX = B(K,MPLOT1)
      IF(B(K,MPLOT1) .LT. YMIN) YMIN = B(K,MPLOT1)
   40 CONTINUE
C
```

```
C     FIND SCALES FOR PLOTTING . . . . . . . . . . . . . . . . . . . . . .
      NLL=NL
      IF(NLL .LE. 0) NLL = 50
      YRANGE = YMAX - YMIN
      XSCAL=(A(N)-A(1))/(FLOAT(NLL-1))
      YSCAL = 0.01 * YRANGE
      IF(YSCAL .EQ. 0.0) YSCAL = 1.0
      IF((YSC .GT. YRANGE) .AND. (YRANGE .GT. YSC/10.0)) YSCAL=0.01*YSC
      XB=A(1)
      WRITE(6,7)
      L = 1
      DO 80 I=1,NLL
      IF(L .GT. N) GO TO 80
      F = FLOAT(I-1)
      XPR=XB+F*XSCAL
      IF(A(L)-XPR-XSCAL*0.5) 50,50,70
   50 JP = IFIX((B(L,MPLOT1)-YMIN)/YSCAL) + 1
      OUT(JP)=ANG
      WRITE(6,2) B(L,1),(OUT(IZ),IZ=1,101),B(L,MPLOT1)
      OUT(JP) = BLANK
      L = L + 1
      GO TO 80
   70 WRITE(6,3) I
   80 CONTINUE
      WRITE(6,7)
      YPR(1)=YMIN
      DO 90 KN=1,10
   90 YPR(KN+1)=YPR(KN)+YSCAL*10.1
      WRITE(6,8)(YPR(IP),IP=1,11)
      RETURN
      END
```

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