
The Development of NUFREQ-N, An Analytical Model for the Stability Analysis of Nuclear Coupled Density-Wave Oscillations in Boiling-Water Nuclear Reactors

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ABSTRACT

A state-of-the-art one-dimensional thermal-hydraulic model has been developed to be used for the linear analysis of nuclear-coupled density-wave oscillations in a boiling water nuclear reactor (BWR). The model accounts for phasic slip, distributed spacers, subcooled boiling, space/time-dependent power distributions and distributed heated wall dynamics. In addition to a parallel channel stability analysis, a detailed model was derived for the BWR loop analysis of both the natural and forced circulation modes of operation.

In its final form, this model constitutes a multi-input, multi-output(MIMO) linear system, which features a general nodal neutron kinetics model. Kinetics parameters for use in the kinetics model have been obtained by utilizing self-consistent nodal data and power distributions. The stability characteristics of a typical BWR/4 has been investigated with the Nyquist criterion.

The computer implementation of this model, NUFREQ-N, was used for the parametric study of a typical BWR/4 and comparisons were made with existing in-core and out-of-core data. Also, NUFREQ-N was used to analyze the expected stability characteristics of a typical BWR/4.

The parametric results revealed important factors influencing BWR stability margin.

It was found that NUFREQ-N generally agreed well with out-of-core data. This was especially true for the predicted power-to-flow transfer function, which is the most important transfer function in thermal-hydraulic stability analysis.

In the stability analysis of a typical BWR/4 it was found that it is very important to use accurate models of thermal-hydraulic and neutron kinetic phenomena. Moreover, the accuracy of the nuclear input data is extremely important.

PART 1

INTRODUCTION

1.1 HISTORICAL REVIEW

As the power density and number of fuel rods in boiling water nuclear reactors(BWR) has increased, nuclear coupled, thermal-hydraulic instabilities have gotten increased attention. This is because these phenomena may cause flow excursions or oscillations which can induce a premature boiling transition, disturb the plant control system, or cause mechanical damage.

Thermal-hydraulic instabilities in two-phase system can be categorized in many different ways^[1]. Phenomenologically one can distinguish between static instabilities, which are explainable in terms of steady-state laws, and dynamic instabilities, which require the use of the conservation equations. The dynamic instabilities of interest in BWR technology can, depending on the boundary conditions, be divided into two categories: parallel channel and loop oscillations.

The most common thermal-hydraulic instability mode in BWRs is known as density-wave oscillations. This type instability is the subject of this study. A good physical description of this instability mechanism has been given previously^[2], and will not be repeated herein. Briefly, this type of instability is caused by the lag introduced

due to the finite speed of propagation of perturbations in density. These so-called density waves propagate at the kinematic wave speed of the two-phase flow.

Many experimental and theoretical studies have been performed to understand density-wave oscillations. Due to the tremendous complexity of the thermal-hydraulic mechanisms in a BWR, it has been difficult to properly scale parametric experiments. Moreover most previous analyses have used simplified models employing various assumptions which could lead to unnecessary restrictions in BWR design and operating criteria. Numerous experimental studies have been reported by Bergles^[4], Veziroglu^[3], Christensen^[5] and Nylund, et al.^[6] for a system of electrical heated channels. Experimental studies^[7], ^[8] also have been performed in modern BWRs. In previous theoretical works^[9], ^[10], ^[11], various models have been developed. No attempt will be made to give a complete listing of assumptions in such models. However, some typical assumptions and simplifications are:

- (1) simplistic assumptions on slip (e.g., homogeneous flow),
- (2) uniform axial heat flux through the heated channel,
- (3) simplified heated wall dynamics models,
- (4) no subcooled boiling,
- (5) point kinetics modelling of the neutronics.

These, and other simplifying assumptions, can lead either to unnecessary restrictions in the design licensing criteria, if the assumptions prove to be conservative, or to operating difficulties if the assumptions prove to be non-conservative.

1.2 PROBLEM DISCRIPTION

The purpose of the study reported herein was to develop a state-of-the art one-dimensional thermal-hydraulic model which can be used for the linear analysis of density-wave oscillations in a BWR. The resultant model accounts for phasic slip, subcooled boiling, space-time dependent power distributions, and distributed heated wall dynamics modelling.

The heated channel is divided into three regions (ie: the single-phase region, the subcooled boiling region, and the bulk boiling region) in which the pressure drop and void fraction perturbations are calculated. In the subcooled boiling region a mechanistic thermal non-equilibrium model^[2] is used. In contrast, in the bulk boiling region, the thermal equilibrium model applies.

In order to allow for an arbitrary axial power distribution, the actual heat flux curve was replaced by a staircase (ie: piece-wise constant) function such that the linearized, Laplace transformed conservation equations could be integrated analytically over the length of each node. Analytical models were also developed for heated

wall dynamics for both parallel plate, cylindrical tube and BWR fuel rod geometries. In addition to parallel channel stability analysis capabilities, a detailed model was derived for BWR loop analysis for both natural and forced circulation modes of operation.

In its final form, this model constitutes a multi-input/multi-output(MIMO) linear system, which features 3-D nodal neutral kinetics^[12]. The stability characteristics of a BWR is investigated using the Nyquist criterion^[13].

The present work is presented in two sections. One deals with the derivation of the state-of-the-art thermal-hydraulic model, Parts 2 and 3. The second section, Part 4, is concerned with the application of the coupled neutron-kinetics thermal-hydraulics model to the analyses of BWR instability. The computer implementation of this model, NUFREQ-N, was used for the parametric study of a typical BWR/4. These results, and comparisons with several experiments is shown in Part 5. The results show that NUFREQ-N agreed with the existing data, and revealed several important factors influencing the BWR stability margin.

PART 2

PARALLEL CHANNEL ANALYSIS

2.1 GENERAL

In BWR's, the most common instability type is density-wave oscillations. This phenomenon is caused by the lag introduced due to finite speed of propagation of so-called kinematic density waves. As noted previously, many analytical and experimental investigations have been conducted to analyze this phenomenon. Because of the complicated mechanisms involved, various assumptions have been introduced to simplify the BWR stability analysis. As will be shown, many of these assumptions are conservative, and thereby lead to potentially unnecessary restrictions to the reactor design and operation.

The objective of this study is to calculate more realistic stability margins in BWRs by using a state-of-the-art thermal-hydraulic model, which accounts for phasic slip, subcooled boiling, space time-dependent power distribution, and distributed heated wall dynamics.

A BWR channel can be divided into three regions; the single-phase region, the subcooled boiling region, and the bulk boiling region. Each region can be analyzed by using a nodal approximation of the drift-flux conservation equations. Thus the arbitrary axial power distribution is

replaced by a step-wise uniform (ie: stair-case) function) such that the linearized, Laplace transformed conservation equations could be integrated analytically over the node. The subcooled boiling effects are represented by a mechanistic thermal non-equilibrium model^[2].

Analytical models are also developed for heated wall dynamics for various geometries: parallel plates, cylindrical tubes, and BWR fuel rods. In the following subsections, the detailed models governing the thermal-hydraulics for BWR stability analysis will be introduced.

2.2 THE DRIFT-FLUX MODEL FOR AN ARBITRARY POWER DISTRIBUTION

2.2.1 Assumptions

The principal assumptions for the governing equations are listed below:

- 1) The system pressure is constant. Moreover, the pressure gradient along the channel is assumed to be small enough for the pressure dependent functions of state (eg: saturation enthalpy, densities of water and steam, etc.) to be constant along the channel.
- 2) The flow in the channel is treated to be one-dimensional by using the cross-sectional averaged quantities.
- 3) Potential and kinetic energy terms are ignored in comparison with thermal energy term.

- 4) There is negligible internal heat generation (q''') and heat conduction in the fluid.
- 5) The mass transfer between channels is neglected.
- 6) The flow at the channel inlet is fully developed. That is, entrance effects are considered negligible.
- 7) The thermal properties of the heater (k , c_p , etc.) are assumed to be uniform.
- 8) In the subcooled boiling region, the wall voidage region^[2] is neglected because of the small void fraction involved, and subcooled boiling is assumed to start at the void departure point (Z_d).

2.2.2 Governing Equations

Under the above assumptions, the drift-flux conservation equations and constitutive relations governing the thermal-hydraulic model are^[2] [14] the:

- (1) Mixture continuity equation,

$$\frac{\partial \langle j \rangle}{\partial z} = \Omega, \quad (2.1)$$

- (2) Mixture energy equation,

$$\frac{\Delta \rho}{\rho_g} (1 - \langle \alpha \rangle) \frac{\partial h_2}{\partial t} + v_{fg} G (1 - \langle x \rangle) \frac{\partial h_2}{\partial z} = \frac{q'' P_H v_{fg}}{A_{x-s}} - \Omega (h_g - h_2) \quad (2.2)$$

- (3) Mixture momentum equation,

$$-\frac{\partial p}{\partial z} = \frac{1}{g_c} \left[\frac{\partial G}{\partial t} + \frac{\partial}{\partial z} \left(\frac{G^2}{\langle \bar{\rho} \rangle} \right) \right] + \frac{1}{g_c} \frac{\partial}{\partial z} \left[\left(\frac{\rho_f - \langle \bar{\rho} \rangle}{\langle \bar{\rho} \rangle \rho_g} \right) \frac{\rho_f \rho_g}{\langle \bar{\rho} \rangle} (v'_{gj})^2 \right] + \frac{g}{g_c} \langle \bar{\rho} \rangle$$

$$\begin{aligned}
& + \frac{fG^2}{2g_c \rho_f D_H} \phi_{\ell 0}^2 + \sum_{m=8}^M K_{\text{spacer}_m} \frac{G^2}{2g_c \rho_f} \phi(z) \delta(z - \xi_m) \\
& + K_{\text{exit}} \frac{1}{2g_c} \left(\frac{G^2}{\rho_f} \right) \phi(z) \delta(z - L_H)
\end{aligned} \tag{2.3}$$

(4) Heated wall conduction equation,

$$\rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T + q'''(t) \tag{2.4}$$

(5) Void propagation equation,

$$\frac{\partial \langle \alpha \rangle}{\partial t} + C_K \frac{\partial \langle \alpha \rangle}{\partial z} = \left(\frac{\rho_f}{\Delta \rho} - C_0 \langle \alpha \rangle \right) \Omega, \tag{2.5}$$

where the kinematic wave velocity is defined as,

$$C_K = C_0 \langle j \rangle + V_{gj}, \tag{2.6}$$

Equation (2.1) is the mass conservation equation of the two-phase mixture. Equation (2.2), the liquid phase energy equation, is derived in Appendix-I. Equation (2.3) is the mixture momentum equation, written in terms of the center-of-mass^[2]. The two-phase density, $\langle \bar{\rho} \rangle$, is defined as,

$$\langle \bar{\rho} \rangle = \rho_f - \Delta \rho \langle \alpha \rangle \tag{2.7}$$

where,

$$\Delta \rho = \frac{\Delta}{\rho_f - \rho_g} \tag{2.8}$$

The second term of the right hand side of Equation (2.3) is called the spatial drift-flux gradient, and is due to the relative slip between the phases. It is convenient to consider this term as an additional volumetric force. The two-phase friction loss multiplier, $\phi_{\ell 0}^2$, is defined as,

$$\phi_{20}^2 \triangleq -\left(\frac{dp}{dz}\right)_{2\phi} / -\left(\frac{dp}{dz}\right)_{20} \quad (2.9)$$

A general expression for this multiplier is,

$$\phi_{20}^2 = [C_2 + C_1 \frac{v_{fg}}{v_f} \langle x \rangle] \quad (2.10)$$

where C_1 and C_2 are empirical parameters, which are both unity for homogeneous flow. In this study, as an option, we calculated C_1 and C_2 from a fit^[2] to the Martinelli-Nelson model,

$$C_{1,k} = D \frac{v_f}{v_{fg}} \langle x_{0,k} \rangle^{-0.176}$$

$$C_{2,k} = 1.0 \quad (2.11)$$

where,

$$D \triangleq \Pi(G,p) \cdot 1.2 \cdot (\rho_f/\rho_g)^{-1}$$

$$\Pi(G,p) \triangleq \begin{cases} 1.36 + 0.0005p + 0.1(G/10^6)^{-0.000714p(G/10^6)}, & \text{for } (G/10^6) < 0.7 \\ \text{otherwise,} & \\ 1.26 - 0.0004p + 0.119 \left(\frac{10^6}{G}\right) + 0.00028p \left(\frac{10^6}{p}\right) & \end{cases}$$

In Equation (2.6), C_0 is the distribution parameter which is defined as^[2],

$$C_0 \triangleq \langle ja \rangle / (\langle j \rangle \langle \alpha \rangle) \quad (2.12)$$

This parameter quantifies the effect of the radial void and volumetric flux distribution. The so-called drift velocity, V_{gj} , is defined as,

$$V_{gj} \triangleq \langle (u_g - j) \alpha \rangle / \langle \alpha \rangle \quad (2.13)$$

and is a measure of the local slip between the liquid and vapor phase.

2.2.3 Discretization, Linearization and Laplace Transformation of the Governing Equations

Previous workers [9] [15] [16] have performed BWR stability analysis in terms of a lumped parameter system having a uniform power distribution. This was presumably done because of its relative simplicity. For an actual BWR, it is more realistic to allow an arbitrary axial power distribution. A nodal approximation is used herein, in which the axial power distribution is replaced by a staircase (ie: piece-wise constant) function.

Non-linearities in the two-phase conservation equations are removed through a first order perturbation expansion. The resultant equations are Laplace transformed to convert the analysis of system dynamics from the time domain to the frequency domain.

Figure 2.1 shows the nodal configuration of the channel and the node index. Each governing equations in Section 2.2.2 can be perturbed and Laplace transformed for each node in both of the single and the two-phase region. A node having a moving (ie: boiling) boundary is treated with respect to the corresponding fixed steady-state boundary. The effect of boundary movement can be accounted for by the application of Leibniz's rule when the governing equations

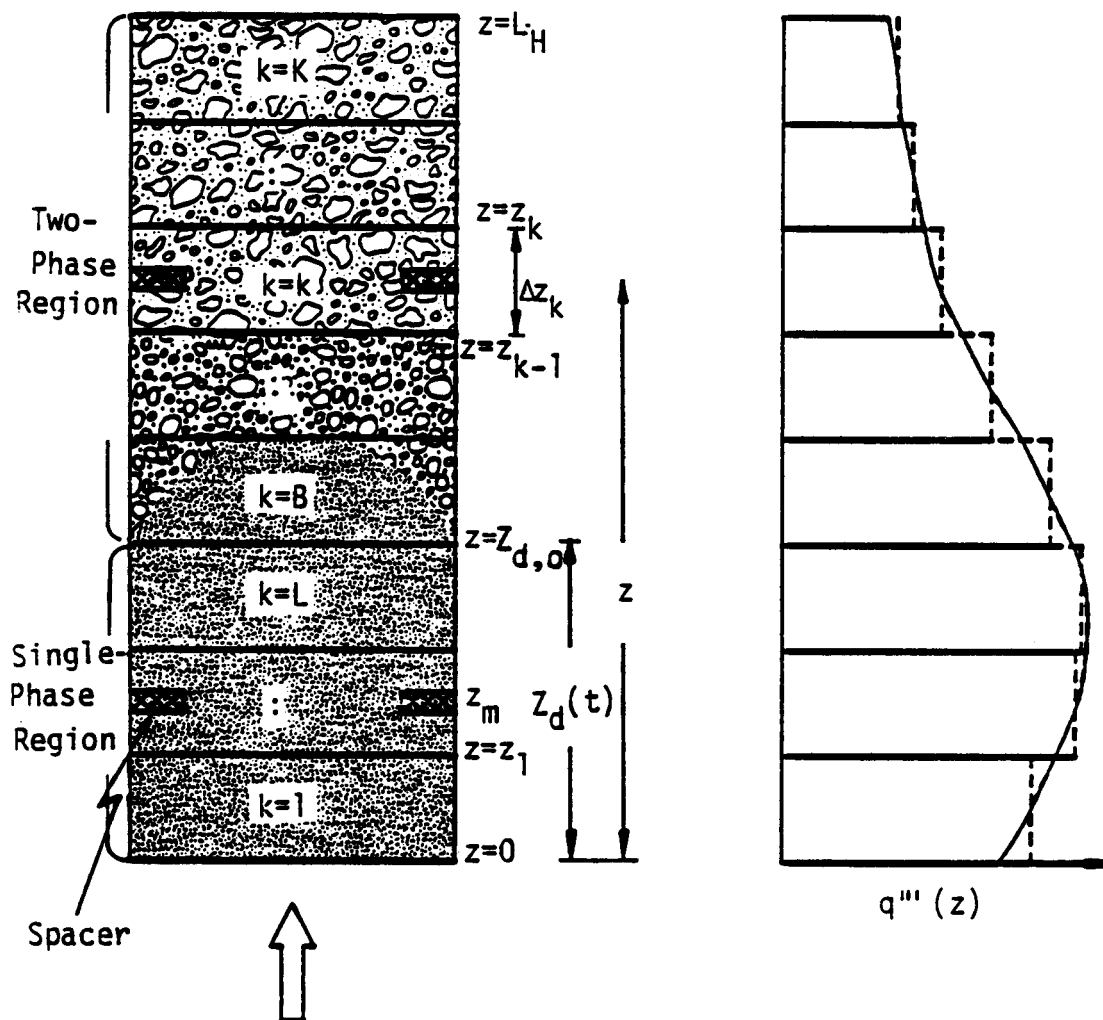


Figure 2.1 The Nodal Configuration of the Heated Channel

of the node are integrated.

The final forms of the nodal perturbed and transformed conservation equations are given for the k-th node(k B) as:

(1) Nodal mixture continuity equation,

$$\frac{\partial \delta \langle j \rangle_k}{\partial z} = \delta \hat{\Omega}_k, \quad (2.14)$$

(2) Nodal liquid phase energy equation,

$$\begin{aligned} G_o v_{fg} (1 - \langle \bar{x}_o \rangle_k) \frac{d \delta \hat{h}_l}{dz} + \left[\frac{\Delta \rho}{\rho_g} (1 - \langle \bar{\alpha}_o \rangle_k) s - \Omega_{o,k} \right] \delta \hat{h}_l \\ = v_{fg} G_o \frac{d(h_{l,o})}{dz} \delta \langle \bar{x} \rangle_k - v_{fg} (1 - \langle \bar{x}_o \rangle_k) \left(\frac{d(h_{l,o})}{dz} \right)_o \delta \hat{G}_k \\ + \frac{P_H v_{fg}}{Ax-s} \delta \hat{q}_k'' - \{h_g (h_{l,o})_k\} \delta \hat{\Omega}_k \end{aligned} \quad (2.15)$$

(3) Nodal momentum equation(including spacers),

$$\begin{aligned} \frac{d}{dz} \delta(\Delta \hat{p}_{2\phi})_k &= \frac{1}{g_c} (s \delta \hat{G} + \frac{\partial \delta \hat{G}'}{\partial z}) + \frac{f G_o \phi_{l,o}^2}{g_c \rho_f D_H} \delta \hat{G} + \frac{f G_o^2}{2 g_c D_H \rho_f} \delta \phi_{i,o}^2 \\ &+ \frac{g}{g_c} \delta \langle \bar{\rho} \rangle + \frac{d}{dz} \delta \left\{ \overline{\left(\frac{\rho_f - \langle \bar{\rho} \rangle}{\langle \bar{\rho} \rangle - \rho_g} \right) \frac{\rho_f \rho_g}{\langle \bar{\rho} \rangle} (v'_{gj})^2} \right\} + \sum_{m=1}^M K_{spacer_m} \left\{ \frac{G_o \phi_o}{g_c \rho_f} \right\}_{z=z_m} \\ &\delta \hat{G}(s, z_m) + \frac{G_o^2}{2 g_c \rho_f} \Big|_{z=z_m} \delta \hat{\phi}(s, z_m) \Big\} \delta(z - z_m) + K_{exit} \left\{ \frac{G_o \phi_o}{g_c \rho_f} \right\}_{z=L_H} \\ &\delta \hat{G}(s, L_H) + \frac{G_o^2}{2 g_c \rho_f} \Big|_{z=L_H} \delta \hat{\phi}(s, L_H) \Big\} \delta(z - L_H) \end{aligned} \quad (2.16)$$

(4) Nodal conduction equation,

$$\nabla^2 \hat{T}_k - \frac{s}{\alpha} \hat{T}_k + \frac{1}{k} \delta \hat{q}_k''' = 0 \quad (2.17)$$

where,

$$\alpha \triangleq \frac{k}{\rho c_p}$$

5) nodal void propagation equation,

$$s \hat{\alpha}_k + \frac{d\langle \alpha_o \rangle_k}{dz} \delta (C_K)_k + (C_{K,o})_k \frac{d\delta \langle \alpha \rangle_k}{dz} = \left[\frac{\rho_f}{\Delta \rho} - C_o \langle \alpha_o \rangle_k \right] \delta \Omega_k - C_o \Omega_{o,k} \delta \langle \alpha \rangle_k \quad (2.18)$$

2.3 HEATED WALL DYNAMICS

Heated wall dynamics is important in the stability analysis of a BWR. In the single-phase region, heated wall dynamics affects the boiling boundary dynamics and thus introduces a lag between the inlet flow perturbation and the void fraction perturbations in the two-phase region. In the two-phase region it also plays an important role because of the time lag between the local power perturbations($\delta \hat{q}_k'''$), the heat flux perturbations($\delta \hat{q}_k''$) and the void fraction perturbations($\delta \hat{\alpha}_k$), which directly affects the reactor reactivity perturbation.

Previous investigators [2], [15], [16] have considered heated wall dynamics for special cases, or with a simple lumped parameter model. In this study we have developed a distributed parameter model for three typical heater geometries(ie: a parallel plate, a cylindrical tube, and a BWR fuel rod).

2.3.1 Parallel Plate

For the parallel plate heater shown in Figure 2.2a, we assume an insulated outer surface and constant thermal conductivity and heat capacity. Solving Equation (2.17) for the j -th node,

$$\frac{d^2 \hat{\delta T}_j}{dx^2} - \frac{s}{\alpha} \hat{\delta T}_j + \frac{1}{k} \hat{\delta q}_j''' = 0 \quad (2.19)$$

with the perturbed boundary conditions,

$$-k \left. \frac{d\hat{\delta T}_j}{dx} \right|_{x=0} = 0 \quad (2.19a)$$

$$-k \left. \frac{d\hat{\delta T}_j}{dx} \right|_{x=b} = q_j'' \quad (2.19b)$$

we obtain,

$$\hat{\delta T}_j(x_j, s) = -\frac{\hat{\delta q}_j'''}{\epsilon k \sinh(\epsilon b)} \cosh(\epsilon x_j) + \frac{\hat{\delta q}_j'''}{\rho c_p s} \quad (2.20)$$

where,

$$\epsilon = \frac{\Delta}{\sqrt{s/\alpha}}$$

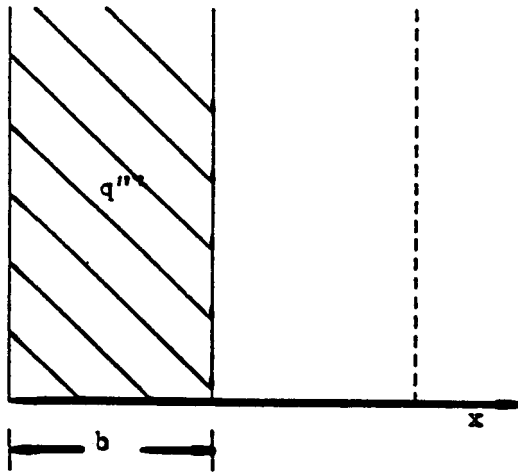
Thus the heated wall temperature perturbation of the j -th node at $x = b$ can be expressed as,

$$\hat{\delta T}_{w_j} = Z_{1p} \hat{\delta q}_j'' + Z_{2p} \hat{\delta q}_j''' \quad (2.21)$$

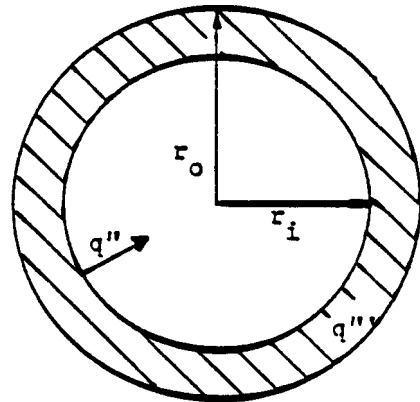
where,

$$Z_{1p} = \frac{\Delta}{\epsilon k} = \frac{\coth(\epsilon b)}{\epsilon k}$$

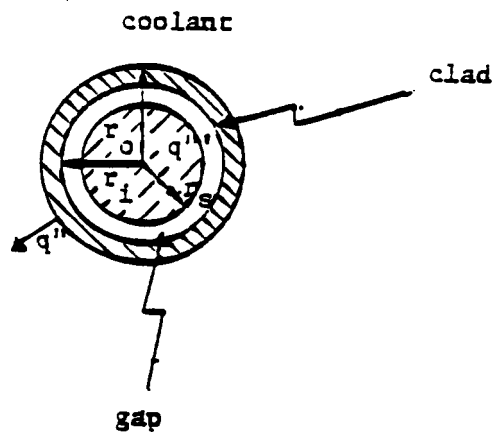
$$Z_{2p} = \frac{\Delta}{\rho c_p s} = \frac{1}{\rho c_p s}$$



a) Parallel Plate



b) Cylindrical Tube



c) BWR Fuel Rod

Figure 2.2 Heated Wall Geometries

2.3.2 Cylindrical tube

For a cylindrical tube, Equation (2.17) becomes an inhomogeneous modified Bessel equation,

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{d\hat{T}_j}{dr} \right) - \frac{s}{a} \hat{T}_j + \frac{1}{k} \hat{q}''' = 0 \quad (2.22)$$

Integrating Equation (2.22) with the perturbed boundary conditions,

$$-k \left. \frac{d\hat{T}_j}{dr} \right|_{r=r_i} = \hat{q}''$$

$$k \left. \frac{d\hat{T}_j}{dr} \right|_{r=r_o} = 0$$

the heater wall temperature perturbation at $r=r_i$ is,

$$\hat{T}_{w_j} = Z_{1c}(s) \hat{q}_j' + Z_{2c} \hat{q}_j'' \quad (2.23)$$

where,

$$Z_{1c} \triangleq - \frac{[K_1(\epsilon r_o) I_0(\epsilon r_i) + I_1(\epsilon r_o) K_c(\epsilon r_i)]}{[I_1(\epsilon r_i) K_1(\epsilon r_o) - K_1(\epsilon r_i) I_1(\epsilon r_o)]} \frac{1}{\epsilon k}$$

$$Z_{2c} \triangleq \frac{1}{\rho_k c_p s}$$

2.3.3 BWR Fuel Rod

Let us next consider a BWR fuel rod, in which the gap conductance is assumed to be constant. The perturbed heat conduction equation, Equation (2.17), for the fuel pin and

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{d\hat{\delta T}_f}{dr} \right) - \frac{s}{\alpha_f} \hat{\delta T}_f + \frac{1}{k_f} \hat{\delta q}''' = 0 \quad (2.24)$$

Clad

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{d\hat{T}_c}{dr} \right) - \frac{s}{\alpha_c} \hat{\delta T}_c = 0 \quad (2.25)$$

The perturbed boundary conditions for each region are^[2],

$$-k_f \left. \frac{d\hat{\delta T}_f}{dr} \right|_{r=r_s} = \left(\frac{r_i}{r_s} \right) \hat{\delta q}_s'' \quad (2.26)$$

$$-k_c \left. \frac{d\hat{\delta T}_c}{dr} \right|_{r=r_i} = \hat{\delta q}_s'' = H_g (\hat{\delta T}_s - \hat{\delta T}_i) \quad (2.27)$$

$$-k_c \left. \frac{d\hat{\delta T}_c}{dr} \right|_{r=r_o} = \hat{\delta q}''$$

$$k_f \left. \frac{d\hat{\delta T}_c}{dr} \right|_{r=0} = 0 \quad (2.29)$$

These equations give the outer cladding surface temperature perturbation for the j -th node as,

$$\hat{\delta T}_{w,j} = Z_{1f}(s) \hat{\delta q}_j'' + Z_{2f}(s) \hat{\delta q}_j''' \quad (2.30)$$

where,

$$Z_{1,f} = \frac{1}{A} \left[\frac{a_1 K_o (\epsilon_c r_o) - a_2 I_o (\epsilon_c r_o)}{\epsilon_c k_c} \right]$$

$$Z_{2,f} = \frac{1}{A} \left[\frac{I_1(\epsilon_c r_o) K_o(\epsilon_c r_o) + K_1(\epsilon_c r_o) I_o(\epsilon_c r_o)}{\rho_f c_p s} \right]$$

$$a_1 = I_o(\epsilon_c r_i) - W_s I_1(\epsilon_c r_i)$$

$$a_2 = K_o(\epsilon_c r_i) + W_s K_1(\epsilon_c r_i)$$

$$A = a_1 K_1(\epsilon_c r_o) + a_2 I_1(\epsilon_c r_o)$$

$$W_s = \epsilon_c k_c \left\{ \frac{I_o(\epsilon_f r_s)}{k_f \epsilon_f I_1(\epsilon_f r_s)} \left(\frac{r_i}{r_s} \right) + \frac{1}{H_g} \right\}$$

It is interesting to note that all of Eqs. (2.21), (2.23) and (2.30) have the same functional form. The parameters Z_1 and Z_2 reflect the different type heated wall geometries.

In order to express $\hat{\delta q}_j''$ in terms of the forcing functions, $\hat{\delta q}'''$, we can eliminate $\hat{\delta T}_{w,j}$ from Equations (2.21), (2.23) or (2.30) by using a Newton's law of convective cooling. In particular, for the single-phase region,

$$q'' = H_{\gamma\phi} (T_w - T_\infty) \quad (2.31)$$

By perturbing and Laplace transforming,

$$\left(\frac{\hat{\delta q}_j''}{q_0''} \right) = a \frac{\hat{\delta j}_1}{j_1} + \frac{H_{\gamma\phi 0}}{q_0''} (\hat{\delta T}_w - \hat{\delta T}_\infty) \quad (2.32)$$

where, for the Dittus-Boelter equation^[2], the Reynold's

number exponent is $a=0.8$. Using any of heated wall dynamics models, and noting that, $\hat{\delta T}_w = \frac{\delta h}{c_{pf}}$,

$$\frac{\hat{\delta q}_0'''}{q_0'''} = \frac{1}{(1-H_1\phi_0 Z_1)} \left[a \frac{\hat{\delta j}_1}{j_{1_0}} + \frac{H_1\phi_0 A_h Z_2}{V_h} \left(\frac{\hat{\delta q}_0'''}{q_0'''} \right) - \frac{H_1\phi_0 A_h}{c_{pf} V_h q_0'''} \delta h \right] \quad (2.33)$$

In the two-phase region, the convective heat transfer equation has the form^[2],

$$q'' = \kappa (T_w - T_{sat})^m \quad (2.34)$$

where, κ and m are empirical constants. By perturbing and Laplace transforming Equation (2.34) for the j -th node,

$$\hat{\delta q}_j'' = \chi_j \hat{\delta T}_{w,j} \quad (2.35)$$

where,

$$\chi_j = m\kappa (T_{wo,j} - T_{sat})^{m-1}$$

Using any of the heated wall dynamics models, Equations (2.21), (2.23) or (2.30), the final form of $\hat{\delta q}_j'''$ in the two-phase region is,

$$\hat{\delta q}_j''' = Z_{3,j} \hat{\delta q}_j'' \quad (2.36)$$

where,

$$Z_{3,j} = \frac{\chi_j Z_2}{1 - \chi_j Z_1}$$

2.4 SUBCOOLED BOILING DYNAMICS

In the analysis of subcooled boiling dynamics, there are three primary points of interest: the transient evaluation of the so-called void departure point, Z_d , the steady and transient liquid enthalpy profile, and the rate of vapor generation. In order to determine Z_d , the Saha-Zuber correlation^[17] was used. Two different approaches^[2] are possible to quantify the transient prediction of the liquid enthalpy profile. One is the mechanistic approach and the other is the so-called profile-fit approach. Even though a profile-fit model is simple to apply, it is questionable for transient application, thus a mechanistic model was used in this study.

In our model, we neglect the void fraction in region-I, the wall voidage region, of Figure 2.3 because the void fraction there is quite small. The void departure point was determined by^[17],

$$h_f - (h_l)_d = \begin{cases} 0.0022 \frac{q'' D_H C_{pl}}{k_l}, & \text{for } Pe \triangleq \frac{GD_H C_{pl}}{k_l} < 70,000 \\ 154 q''/G, & \text{for } Pe > 70,000 \end{cases} \quad (2.37)$$

To obtain the void profile in the subcooled boiling region, we can use the void propagation equation, Equation (2.5), where the characteristic frequency is defined as,

$$\Omega \triangleq v_{fg} \Gamma \quad (2.38)$$

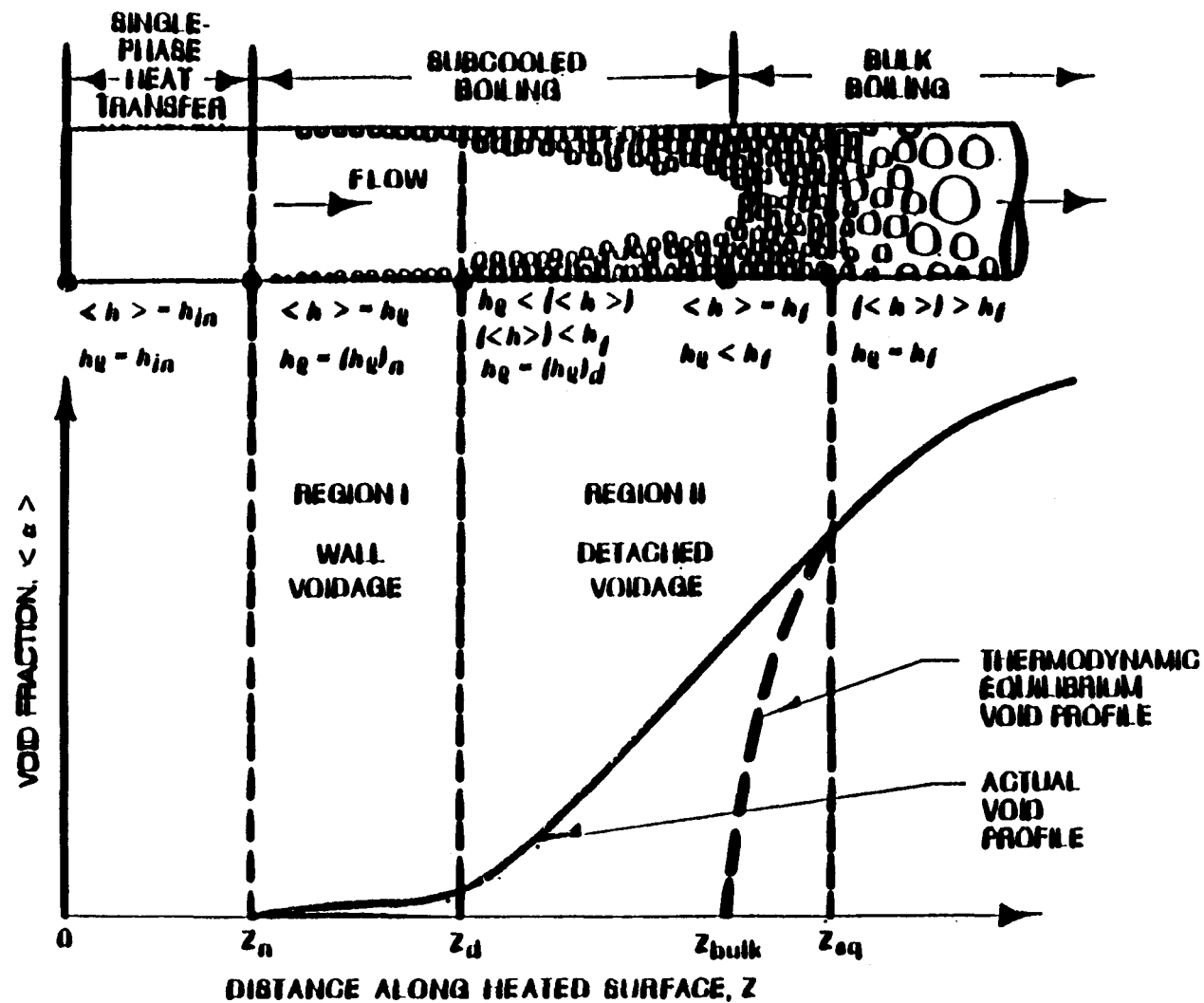


Figure 2.3 Void Fractions Profile for Forced Convection Subcooled Boiling

and the net amount of vapor formed per unit volume, Γ , is,

$$\Gamma = \frac{P_H q_b''(Z,t)}{A_{x-s} h_{fg} [1+\epsilon(Z,t)]} - \frac{P_H q_{\text{cond}}''(Z,t)}{A_{x-s} h_{fg}} + \frac{\langle \alpha \rangle}{h_{fg} A_{x-s}} \times$$

$$\left(\frac{1}{J} - \rho_g \frac{dh_g}{dp} \right) \frac{\partial p}{\partial t} \quad (2.39)$$

By combining Equations (2.38) and (2.39) for constant system pressure, we obtain,

$$\Omega(Z,t) = \frac{v_{fg} P_H q_b''(Z,t)}{A_{x-s} h_{fg} [1+\epsilon(Z,t)]} - \frac{v_{fg} P_H q_{\text{cond}}''(Z,t)}{A_{x-s} h_{fg}} \quad (2.40)$$

The second term of Equation (2.40) represents the condensation heat transfer process in the region away from the heated wall. For this term we used the empirical correlation derived previously by Lahey [2],

$$P_H q_{\text{cond}}'' = \frac{H_0 h_{fg} A_{x-s} \langle \alpha \rangle}{v_{fg}} \Delta T_{\text{sub}} \quad (2.41)$$

In the above equation, the condensation coefficient, H_0 , was taken as a function of mass flux. It was found that the correct functional form of this empirical relation was,

$$H_0 = \frac{1}{1+a\left(\frac{\langle j \rangle}{j_{10}}\right)^b} \quad (2.42)$$

The empirical parameters, a and b , which correspond to Lahey's original model [2] ($H_0 = 150. / \text{Hr-}^\circ\text{F}$) are, $a=23.0$ and $b=0$.

In order to optimize a and b , we compared Equation

(2.42) against the steady-state void fraction profile measurements of several experiments. Figures 2.4 and 2.5 indicate that when the Ohkawa/Lahey model [14] is used for The steady-state drift-flux parameters, an option in NUFREQ-N, the recommended values are $a=4.0$ and $b=2.0$. These values were confirmed by comparisons with the data of Christensen [5], Rouhani [18] and Lobachev [19], as shown in Figures 2.6, 2.7, and 2.8. The ratio of the heat flux due to microconvection (ie: pumping) to that causing vapor formation is given by Rouhani [18] as,

$$\epsilon(z,t) = \frac{\rho_l (h_f - h_l)}{\rho_g h_{fg}} \quad (2.43)$$

and the boiling heat flux was approximated by [2]

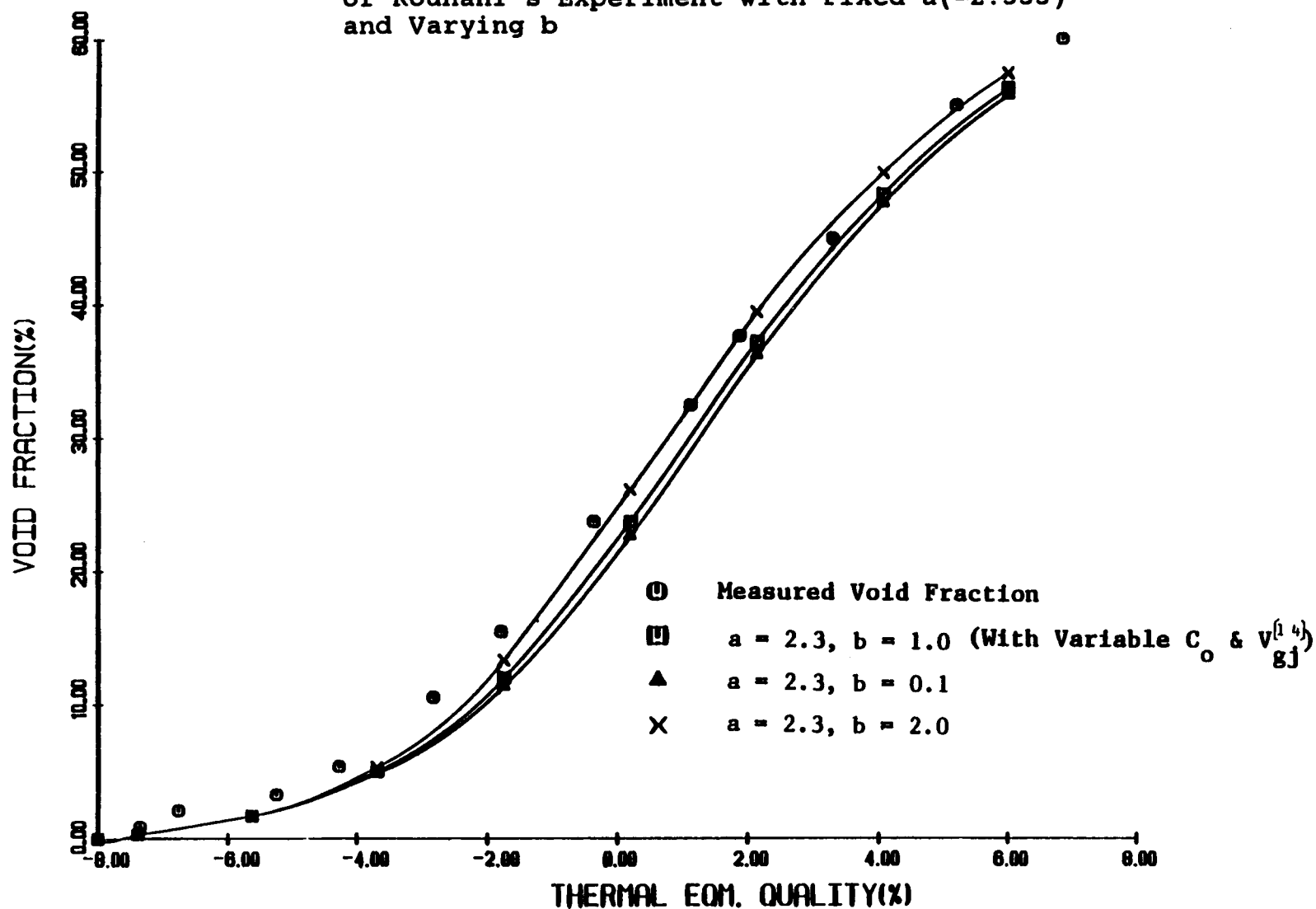
$$q_b''(z,t) = q''(z,t) \left\{ 1 - \frac{h_f - h_l(z,t)}{h_f - h_{l_d}(t)} \right\}. \quad (2.44)$$

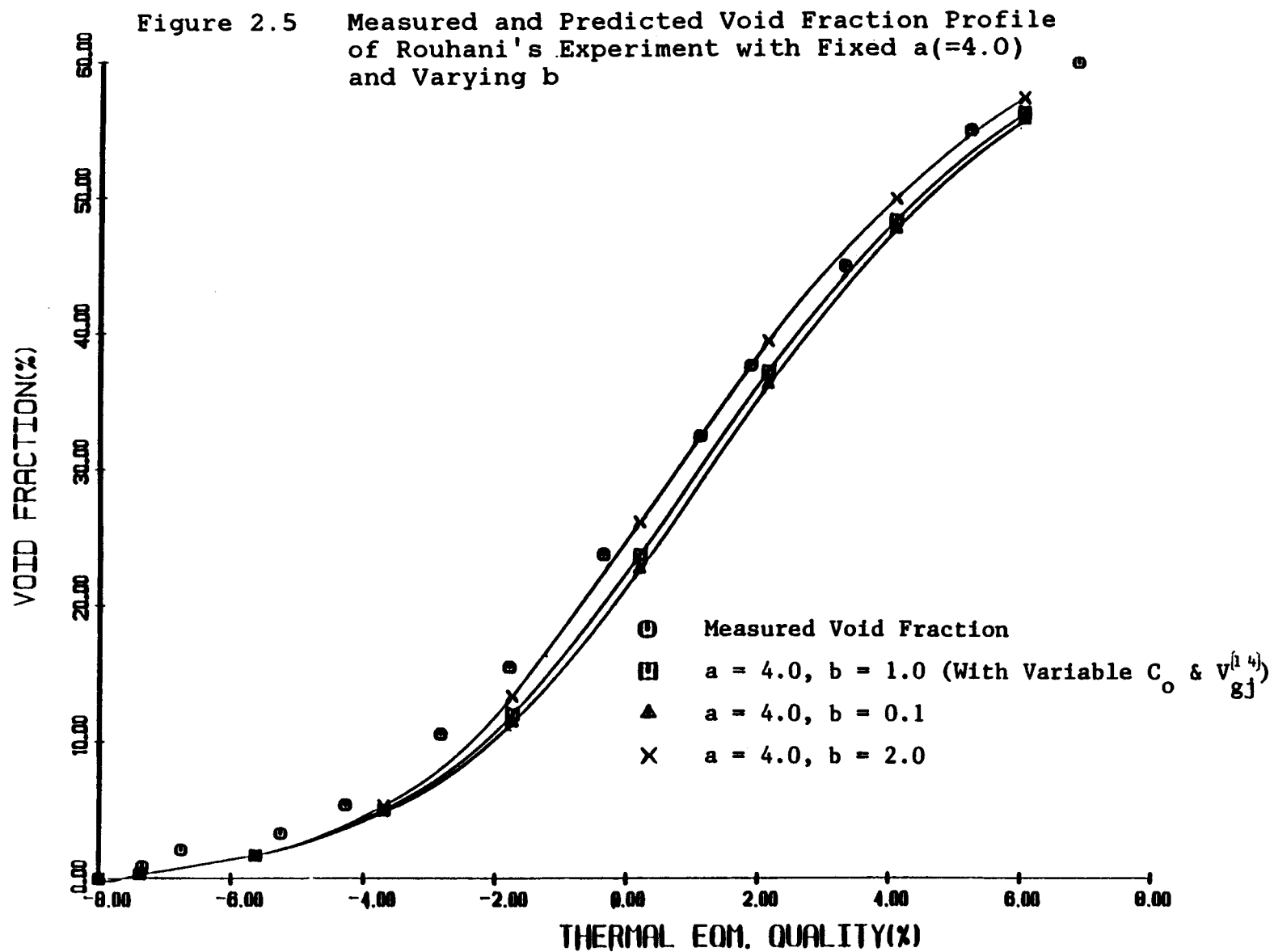
Thus inserting Equations (2.41), (2.43) and (2.44) into Equation (2.40),

$$\Omega(z,t) = \frac{\Delta p_H q''}{A_{x-s} \rho_f (h_f - h_{l_d})} \frac{h_l - h_{l_d}}{\{\rho_g h_{fg} + \rho_f (h_f - h_l)\}} - \frac{H_0 \langle \alpha \rangle}{c_{pf}} (h_f - h_l). \quad (2.45)$$

The other equations governing subcooled boiling dynamics are the void propagation equation, Equation (2.5) and the liquid-phase energy equation, Equation (2.2). In order to integrate these equations analytically, the node-average characteristic frequency of phase change, $\bar{\omega}_k(t)$,

Figure 2.4 Measured and Predicted Void Fraction Profile of Rouhani's Experiment with Fixed $a(=2.333)$ and Varying b





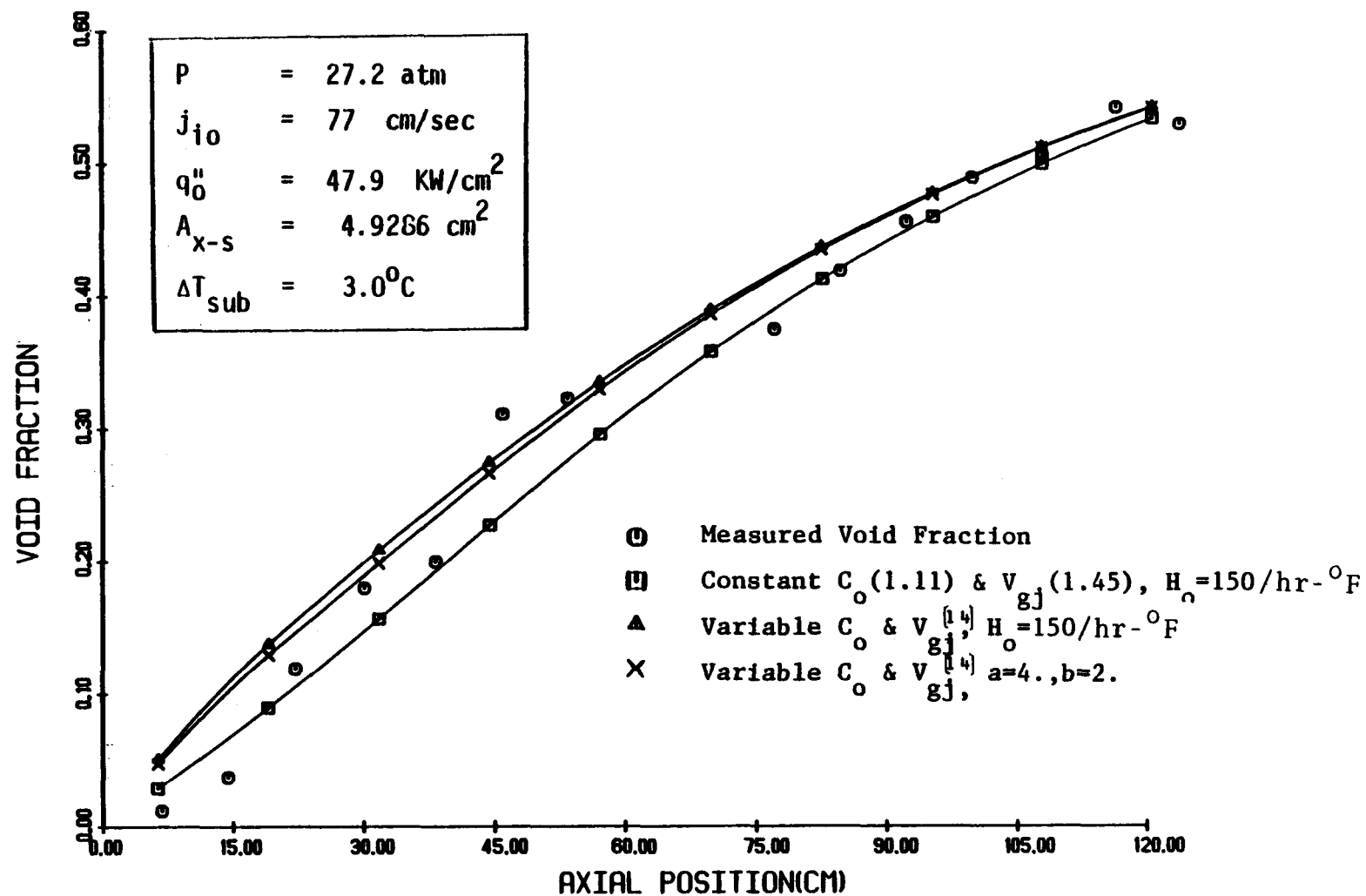


Figure 2.6 Measured and Predicted Void Fraction Profile of Christensen's Experiment

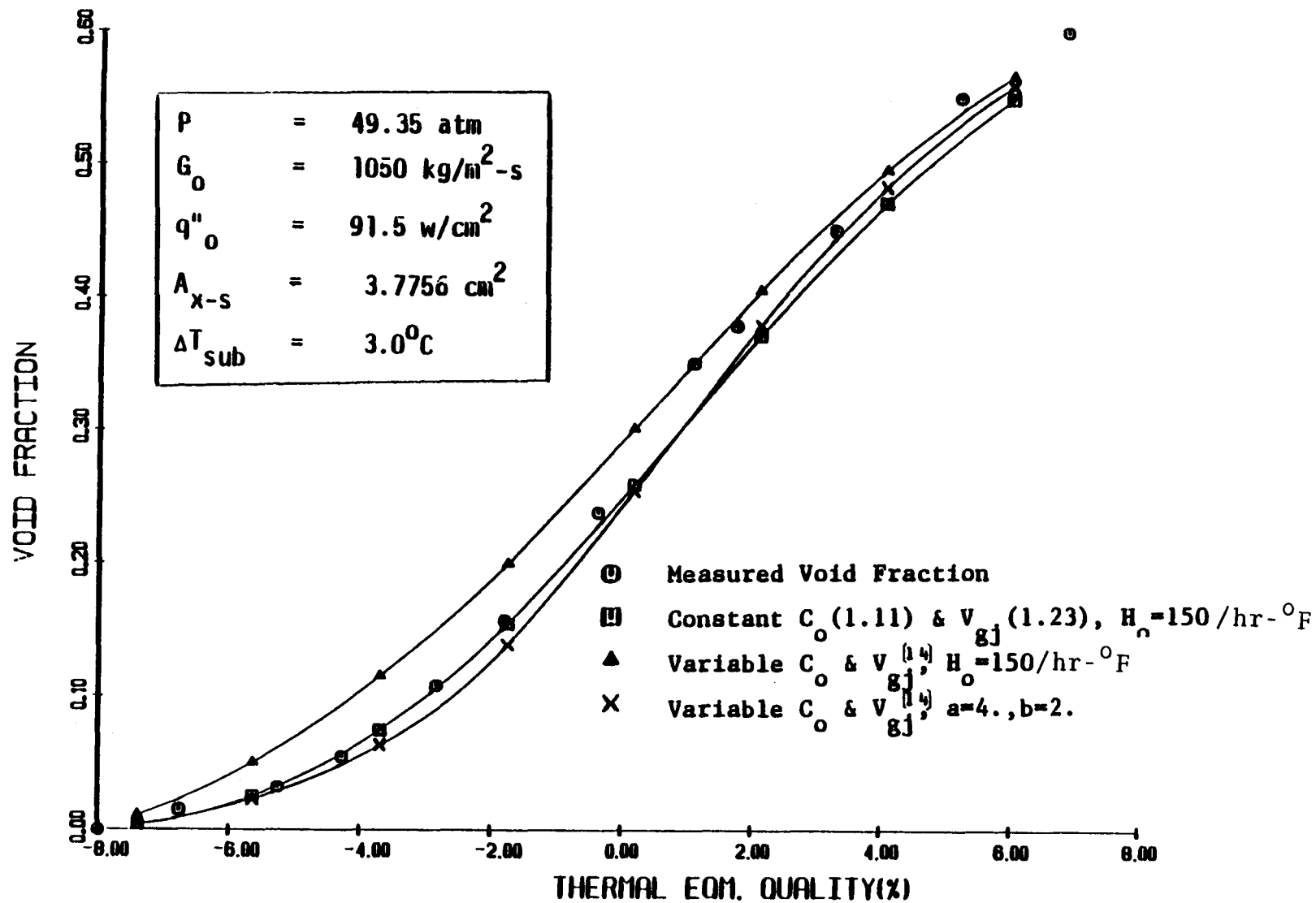
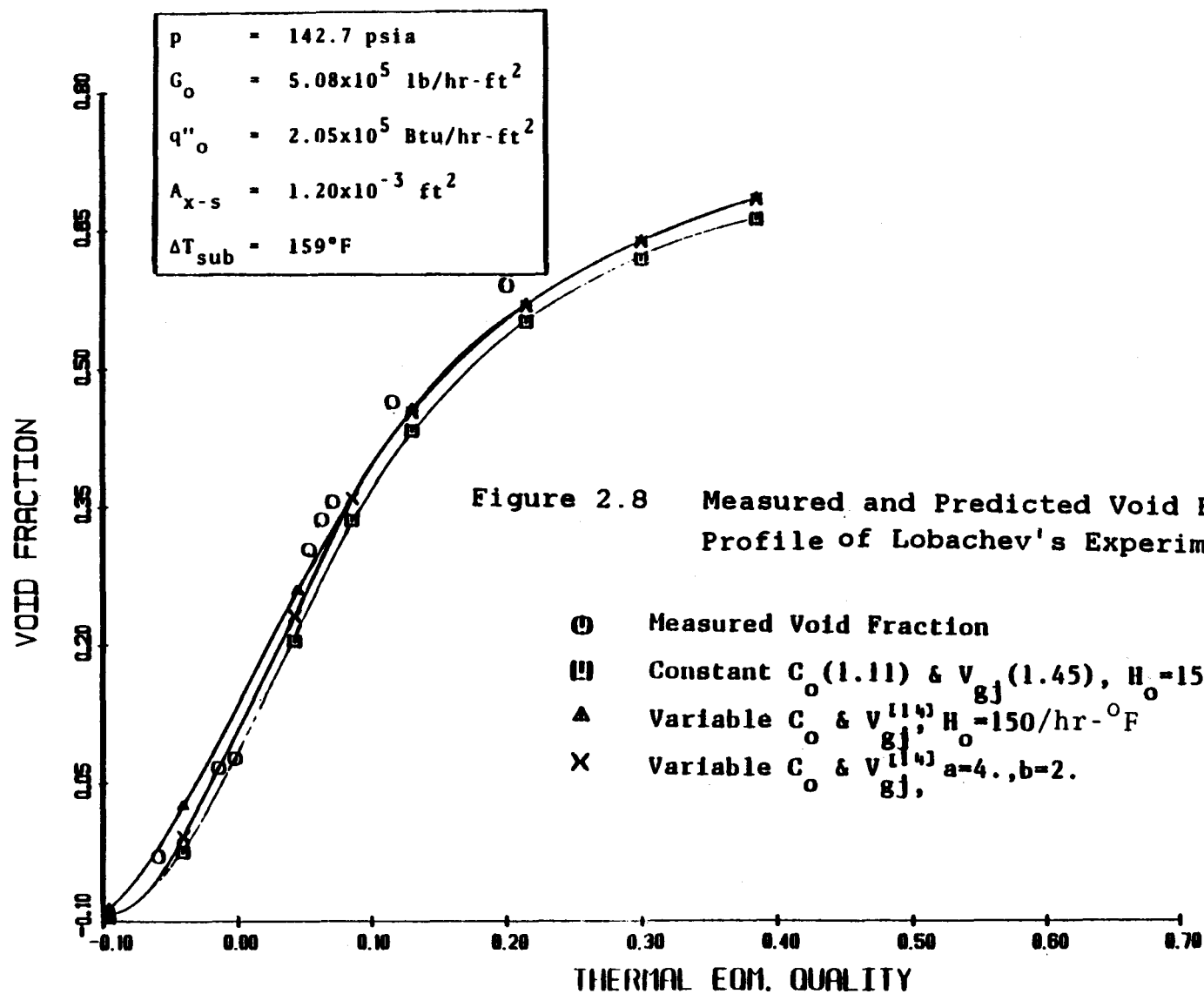


Figure 2.7 Measured and Predicted Void Fraction Profile of Rouhani's Experiment



was used, rather than $\Omega(z,t)$. This simplification does not introduce appreciable error, because for steady-state $\Omega(z)$ is strongly dependent on the heat flux and the liquid enthalpy, which are uniform and nearly linear in the node, respectively.

For steady-state, we can obtain the liquid enthalpy from Equation (2.2) if we use the node-averaged flow quality, $\langle \bar{x}_o \rangle_k$, and a coordinate transformation from z_k to ξ_k , defined by,

$$\xi_k(z_k) = \frac{\{C_{K,o}(z)\}_k}{(C_{K,o})_k^{\text{in}}} \quad (2.46)$$

such that the coordinate-transformed liquid enthalpy equation is expressed as,

$$\frac{d(h_{l,o})_k}{d\xi_k} - b_{2,k}(h_{l,o})_k = b_{3,k} \quad (2.47)$$

by solving Equation (2.47), the result for the k -th node is,

$$(h_{l,o})_k = b_{5,k} e^{b_{2,k}\xi_k} + b_{4,k} \quad (2.48)$$

where,

$$b_{2,k} = \frac{(C_{K,o})_k^{\text{in}}}{G_o v_{fg} C_o (1 - \langle \bar{x}_o \rangle_k)}$$

$$b_{4,k} = - \frac{(C_{K,o})_k^{\text{in}} \left(\frac{q_{o,k}'' H_{fg}^p}{A_{x-s}} - \bar{\Omega}_{o,k} h_g \right)}{b_{2,k} C_o \bar{\Omega}_{o,k} G_o v_{fg} (1 - \langle \bar{x}_o \rangle_k)} = - \frac{b_{3,k}}{b_{2,k}}$$

$$b_{5,k} = \left\{ (h_{l,o})_k^{\text{in}} - b_{3,k} \right\} e^{-b_{2,k}}$$

For constant system pressure, the continuity equation for a two-phase mixture is given by Equation (2.1). Since $\bar{\Omega}_{0,k}$ was assumed to be constant in each axial node, the cross-sectional averaged volumetric flux of the mixture can be calculated by integrating Equation (2.1). Then the kinematic wave velocity in the k-th node is given from Equation (2.6) as,

$$C_{K,0}(z_k) = (C_{K,0})_k^{\text{in}} + C_{0,\bar{\Omega}_{0,k}}(z - z_{k-1}) \quad (2.49)$$

The steady-state void fraction can be obtained from the coordinate- transformed void propagation equation as,

$$\xi_k \frac{d\langle \alpha_0 \rangle_k}{d\xi_k} + \langle \alpha_0 \rangle_k = \frac{\rho_f}{C_0 \Delta \rho} \quad (2.50)$$

where, from Eqs. (2.46) and (2.49),

$$dz_k = \frac{(C_{K,0})_k^{\text{in}}}{C_{0,\bar{\Omega}_{0,k}}} d\xi_k \quad (2.51)$$

Using the node inlet boundary condition, $\langle \alpha_0 \rangle_k^{\text{in}}$, Equation (2.50) integrates to,

$$\langle \alpha_0 \rangle_k = \frac{\rho_f}{C_0 \Delta \rho} (1 - \xi_k^{-1}) + \langle \alpha_0 \rangle_k^{\text{in}} \xi_k^{-1} \quad (2.52)$$

As mentioned previously, Equation (2.52) was derived based on a constant $\bar{\Omega}_{0,k}$ which is a function of $(h_{l,o})_k$. Thus in order to find $\bar{\Omega}_{0,k}$, we can insert $(\bar{h}_{l,o})_k$ and $\langle \bar{\alpha}_0 \rangle_k$ into Equation (2.45), which were obtained from node-

averaging Equations (2.47) and (2.52), respectively. The resultant transcendental equation was iterated using an initial guess for $\bar{\Omega}_{0,k}$, until convergence was achieved. This model was tested against several experimental data sets.

In order to obtain $\delta\hat{\Omega}_k$ in the subcooled boiling region, the liquid enthalpy perturbation can be calculated from Equation (2.15) based on the node-averaged values of $\langle\bar{\alpha}_0\rangle_k$ and $\langle\bar{x}_0\rangle_k$. Recall that,

$$\langle x \rangle = v_{fg} \frac{\langle j \rangle}{G} - \frac{p_g}{\Delta p} \quad (2.53)$$

Thus the flow quality perturbation, $\delta\langle\hat{x}\rangle_k$, can be expressed in terms of $\delta\langle\hat{j}\rangle_k$ and $\delta\hat{G}_k$, which are derived in Appendix-II, as,

$$\delta\langle\hat{x}\rangle = \frac{1}{v_{fg}G_{0,k}} \delta\langle\hat{j}\rangle_k - \frac{\langle j_0 \rangle_k}{v_{fg}G_{0,k}^2} \delta\hat{G}_k \quad (2.54)$$

By inserting Equations (II.4) and (II.8) into Equation (2.54) and averaging $\delta\langle\hat{x}\rangle_k$ over the k-th node,

$$\delta\langle\hat{x}\rangle_k = C_{1,k} \delta\langle\hat{j}\rangle_k^{\text{in}} + C_{2,k} \delta\hat{\Omega}_k + C_{3,k} \delta\langle\hat{\alpha}\rangle_k^{\text{in}} \quad (2.55)$$

where,

$$\begin{aligned} C_{1,k} = & \frac{1}{v_{fg}G_0} - \frac{(C_{K.0})_k^{\text{in}}}{v_{fg}G_0^2 C_0 \bar{\Omega}_{0,k} \Delta z_k} \left[\frac{(C_{K.0})_k^{\text{in}}}{C_0} g_{1,k} \left\{ \xi_k^{\text{out}} - 1 \right\} \right. \\ & - \frac{V_{gj}}{C_0} g_{1,k} \ln \xi_k^{\text{out}} - \frac{V_{gj} \bar{\Omega}_{0,k}}{C_0 \bar{\Omega}_{0,k-s}} g_{2,k} \left\{ (\xi_k^{\text{out}})^{1 - \frac{s}{C_0 \bar{\Omega}_{0,k}}} - 1 \right\} \\ & \left. + \frac{(C_{K.0})_k^{\text{in}} \bar{\Omega}_{0,k}}{2 C_0 \bar{\Omega}_{0,k-s}} g_{2,k} \left\{ (\xi_k^{\text{out}})^{2 - \frac{s}{C_0 \bar{\Omega}_{0,k}}} - 1 \right\} \right] \end{aligned}$$

$$\begin{aligned}
C_{2,k} = & - \frac{(C_{K.0})_k^{\text{in}}}{v_{fg} G_0^2 C_0 \bar{\Omega}_{0,k} \Delta z_k} [((C_{K.0})_k^{\text{in}} g_{4,k} - \frac{v_{gj}}{C_0} g_{3,k}) (\xi_k^{\text{out}} - 1) \\
& - \frac{v_{gj}}{C_0} g_{4,k} \ln \xi_k^{\text{out}} + \frac{(C_{K.0})_k^{\text{in}}}{2C_0} g_{3,k} \{ (\xi_k^{\text{out}})^2 - 1 \} \\
& - \frac{v_{gj} \bar{\Omega}_{0,k}}{C_0 \bar{\Omega}_{0,k} - s} g_{5,k} \{ (\xi_k^{\text{out}})^{1 - \frac{s}{C_0 \bar{\Omega}_{0,k}}} - 1 \} + \frac{(C_{K.0})_k^{\text{in}} \bar{\Omega}_{0,k}}{2C_0 \bar{\Omega}_{0,k} - s} g_{5,k} \times \\
& \{ (\xi_k^{\text{out}})^{2 - \frac{s}{C_0 \bar{\Omega}_{0,k}}} - 1 \}] + \frac{\Delta z_k}{2v_{fg} C_0}
\end{aligned}$$

$$\begin{aligned}
C_{3,k} = & - \frac{(C_{K.0})_k^{\text{in}}}{v_{fg} G_0^2 C_0 \bar{\Omega}_{0,k} \Delta z_k} [- \frac{v_{gj} \bar{\Omega}_{0,k}}{(C_0 \xi_k - s)} g_{6,k} \{ (\xi_k^{\text{out}})^{1 - \frac{s}{C_0 \bar{\Omega}_{0,k}}} - 1 \} \\
& + \frac{(C_{K.0})_k^{\text{in}} \bar{\Omega}_{0,k}}{2C_0 \bar{\Omega}_{0,k} - s} g_{6,k} \{ (\xi_k^{\text{out}})^{2 - \frac{s}{C_0 \bar{\Omega}_{0,k}}} - 1 \}]
\end{aligned}$$

After making a coordinate transformation in Equation (2.15), using Equation (2.55) and noting, from Equation (2.48), that

$$\frac{d(h_{2,0})_k}{d\xi_k} = b_{2,k} b_{5,k} e^{b_{2,k} \xi_k} \quad (2.56)$$

Equation (2.15) becomes,

$$\begin{aligned}
\frac{d\hat{h}_{2,k}}{d\xi_k} + C_{4,k} \hat{h}_{2,k} = & [C_{3,k} e^{b_{2,k} \xi_k} + C_{9,k} e^{b_{2,k} \xi_k} \xi_k^{-1} \\
& + C_{10,k} e^{b_{2,k} \xi_k} \xi_k^{-C_{5,k}}] \delta < j >_k^{\text{in}} + [C_{6,k} + C_{11,k} e^{b_{2,k} \xi_k}
\end{aligned}$$

$$\begin{aligned}
& + C_{12,k} e^{b_{3,k} \xi_k \xi_k^{-1}} + C_{13,k} e^{b_{2,k} \xi_k \xi_k^{-C_{5,k}}} \delta \hat{\Omega}_k \\
& + [C_{16,k} e^{b_{2,k} \xi_k} + C_{14,k} e^{b_{2,k} \xi_k \xi_k^{-C_{5,k}}} \delta \langle \hat{\alpha} \rangle_k^{in} + C_{15,k} \delta \hat{q}_k
\end{aligned}$$

(2.57)

where,

$$C_{4,k} \triangleq \frac{\frac{\Delta \rho}{\rho_g} (1 - \langle \bar{\alpha}_0 \rangle_k) s - \bar{\Omega}_{0,k}}{G_0 v_{fg} (1 - \langle \bar{\alpha}_0 \rangle_k) \frac{C_{0,\bar{\Omega}_{0,k}}}{(C_{K,0})_k^{in}}},$$

$$C_{5,k} \triangleq \frac{s}{C_{0,\bar{\Omega}_{0,k}}},$$

$$C_{6,k} \triangleq \frac{h_g - b_{3,k}}{G_0 v_{fg} (1 - \langle \bar{\alpha}_0 \rangle_k) \frac{C_{0,\bar{\Omega}_{0,k}}}{(C_{K,0})_k^{in}}},$$

$$C_{7,k} \triangleq \frac{b_{1,k}}{G_0 v_{fg} (1 - \langle \bar{\alpha}_0 \rangle_k) \frac{C_{0,\bar{\Omega}_{0,k}}}{(C_{K,0})_k^{in}}},$$

$$C_{3,k} \triangleq \frac{b_{2,k} b_{1,k}}{(1 - \langle \bar{\alpha}_0 \rangle_k)} C_{1,k},$$

$$C_{9,k} \triangleq \frac{b_{2,k} b_{5,k}}{G_0} g_{1,k},$$

$$C_{10,k} \triangleq \frac{b_{2,k} b_{5,k}}{G_0} g_{2,k},$$

$$C_{11,k} \triangleq b_{2,k} b_{5,k} \left(\frac{C_{2,k}}{(1 - \langle \bar{\alpha}_0 \rangle_k)} - \frac{g_{3,k}}{G_0} \right) + C_{7,k}$$

$$C_{12,k} \triangleq \frac{b_{2,k} b_{1,k}}{G_0} g_{4,k},$$

$$C_{13,k} \triangleq \frac{b_{2,k} b_{0,k}^1}{G_0} g_{5,k}$$

$$C_{14,k} \triangleq \frac{b_{2,k} b_{5,k}}{G_0} g_{6,k},$$

$$C_{15,k} \triangleq \frac{P_H (C_{K,0})_k^{in}}{G_0 C_{0,\bar{\Omega}_{0,k}} A_{x-s} (1 - \langle \bar{\alpha}_0 \rangle_k^{in})}$$

Equation (2.57) is a Bernoulli-type ordinary differential equation having an integrating factor, $e^{C_{4,k}\xi_k}$. Thus we can integrate Equation (2.57) as,

$$\begin{aligned}
 \delta \hat{h}_{2,k} e^{C_{4,k}\xi_k} - \delta \hat{h}_{2,k}^{\text{in}} e^{C_{4,k}} &= [C_{8,k} \int_1^{\xi_k} e^{a_k x} dx \\
 &+ C_{9,k} \int_1^{\xi_k} e^{a_k x} x^{-1} dx + C_{10,k} \int_1^{\xi_k} e^{a_k x} x^{-C_{5,k}} dx] \delta \langle j \rangle_k^{\text{in}} \\
 &+ [-C_{6,k} \int_1^{\xi_k} e^{C_{4,k} x} dx + C_{11,k} \int_1^{\xi_k} e^{a_k x} dx \\
 &+ C_{12,k} \int_1^{\xi_k} e^{a_k x} x^{-1} dx + C_{13,k} \int_1^{\xi_k} e^{a_k x} x^{-C_{5,k}} dx] \delta \hat{\Omega}_k \\
 &+ [C_{14,k} \int_1^{\xi_k} e^{a_k x} x^{-C_{5,k}} dx + C_{16,k} \int_1^{\xi_k} e^{a_k x} dx] \delta \langle \alpha \rangle_k^{\text{in}} \\
 &+ C_{15,k} \left[\int_1^{\xi_k} e^{C_{4,k} x} dx \right] \delta \hat{q}_k'''
 \end{aligned} \tag{2.58}$$

where,

$$a_k = \frac{\Delta \rho_F(C_{K,0})_k^{\text{in}} (1 - \langle \bar{\alpha}_0 \rangle_k)}{G_0 C_{0,0,k} (1 - \langle \bar{x}_0 \rangle_k)} s$$

Using standard integral tables [20] we find,

$$E_a^b(\theta) \stackrel{\Delta}{=} \int_1^{1+\theta} x^{a-1} e^{-bx} dx \tag{2.59}$$

$$= \frac{e^{-b}}{b} \sum_{k=0}^{\infty} \left[\frac{(a-1)(a-2)(a-k)}{b^k} \left\{ 1 - e^{-b\theta} e_k(b\theta) \right\} \right]$$

, for $b = \text{Complex}$

$$= \sum_{k=0}^{\infty} \left[\frac{(-b)^k}{k!(k+a)} \right] \left\{ (1+\theta)^{k+a} - 1 \right\}, \text{ for } b = \text{Real}$$

where,

$$e_k(x) \triangleq \sum_{m=0}^k \frac{x^m}{m!}$$

Hence the node-exit liquid enthalpy perturbation can be obtained from Equation (2.58) as,

$$\begin{aligned} \hat{\delta h}_{2,k}^{\text{out}} &= W_{1,k} \hat{\delta h}_{2,k}^{\text{in}} + W_{2,k} \hat{\delta q}_k^{\text{in}} + W_{3,k} \hat{\delta \langle j \rangle}_k^{\text{in}} + W_{4,k} \hat{\delta \hat{\Omega}}_k \\ &\quad + W_{5,k} \hat{\delta \langle \alpha \rangle}_k^{\text{in}} \end{aligned} \quad (2.60)$$

where,

$$\begin{aligned} W_{1,k} &\triangleq e^{C_{4,k}(1-\xi_k^{\text{out}})} & W_{2,k} &\triangleq \frac{C_{15,k}}{C_{4,k}} \{1 - e^{C_{4,k}(1-\xi_k^{\text{out}})}\} \\ W_{3,k} &\triangleq \left[\frac{C_{8,k}}{a_k} (e^{a_k \xi_k^{\text{out}}} - e^{a_k}) + C_{9,k} E_0^{-a_k} \{-a_k(\xi_k^{\text{out}} - 1)\} \right. \\ &\quad \left. + C_{10,k} E_{1-C_{5,k}}^{-a_k} \{-a_k(\xi_k^{\text{out}} - 1)\} \right] e^{-C_{4,k} \xi_k^{\text{out}}} \\ W_{4,k} &\triangleq e^{-C_{4,k} \xi_k^{\text{out}}} \left[-\frac{C_{6,k}}{C_{4,k}} (e^{C_{4,k} \xi_k^{\text{out}}} - e^{C_{4,k}}) \right. \\ &\quad \left. + \frac{C_{11,k}}{a_k} (e^{a_k \xi_k^{\text{out}}} - e^{a_k}) + C_{12,k} E_0^{-a_k} \{-a_k(\xi_k^{\text{out}} - 1)\} \right] \\ W_{5,k} &\triangleq e^{-C_{4,k} \xi_k^{\text{out}}} \left[C_{14,k} E_{1-C_{5,k}}^{-a_k} \{-a_k(\xi_k - 1)\} + \frac{C_{16,k}}{a_k} (e^{a_k \xi_k^{\text{out}}} - e^{a_k}) \right] \end{aligned}$$

We are also interested in the node-averaged liquid enthalpy perturbation, which can be obtained by node-averaging

Equation (2.57) and integrating with Equation (2.59) , as before, to obtain,

$$\begin{aligned}\hat{\delta h}_{\ell,k} &= \frac{(C_{K,o})_k^{\text{in}}}{\Delta z_k C_o \bar{\Omega}_{o,k}} \int_1^{\xi_k^{\text{out}}} \hat{\delta h}_{\ell,k} d\xi_k \\ &= U_{1,k} \hat{\delta h}_{\ell,k}^{\text{in}} + U_{2,k} \hat{\delta q}_k'' + U_{3,k} \delta \langle j \rangle_k^{\text{in}} + U_{4,k} \hat{\delta \Omega}_k \\ &\quad + U_{5,k} \delta \langle \alpha \rangle_k^{\text{in}}\end{aligned}\quad (2.61)$$

where,

$$\begin{aligned}U_{1,k} &= \frac{(C_{K,o})_k^{\text{in}}}{\Delta z_k C_o \bar{\Omega}_{o,k} C_{4,k}} [1 - W_{1,k}] \\ U_{2,k} &= - \frac{(C_{K,o})_k^{\text{in}}}{\Delta z_k C_o \bar{\Omega}_{o,k} C_{4,k}} W_{2,k} + \frac{C_{15,k}}{C_{4,k}} \\ U_{3,k} &= \frac{(C_{K,o})_k^{\text{in}}}{\Delta z_k C_o \bar{\Omega}_{o,k} C_{4,k}} [-W_{3,k} + \frac{C_{8,k}}{b_{2,k}} \{e^{b_{2,k} \xi_k^{\text{out}}} - e^{b_{2,k}}\} \\ &\quad + C_{9,k} E_o^{-b_{2,k}} \{-b_{2,k} (\xi_k - 1)\} + C_{10,k} E_{1-C_{5,k}}^{-b_{2,k}} \{-b_{2,k} (\xi_k - 1)\}] \\ U_{4,k} &= \frac{(C_{K,o})_k^{\text{in}}}{\Delta z_k C_o \bar{\Omega}_{o,k} C_{4,k}} [-W_{4,k} - C_{6,k} (1 - \xi_k^{\text{out}}) \\ &\quad + \frac{C_{11,k}}{b_{2,k}} (e^{b_{2,k} \xi_k^{\text{out}}} - e^{b_{2,k}}) + C_{12,k} E_o^{-b_{2,k}} \{-b_{2,k} (\xi_k^{\text{out}} - 1)\} \\ &\quad + C_{13} [E_{1-C_{5,k}}^{-b_{2,k}} \{-b_{2,k} (\xi_k - 1)\}]] \\ U_{5,k} &= \frac{(C_{K,o})_k^{\text{in}}}{\Delta z_k C_o \bar{\Omega}_{o,k} C_{4,k}} [-W_{5,k} + \frac{C_{16,k}}{b_{2,k}} (e^{b_{2,k} \xi_k^{\text{out}}} - e^{b_{2,k}})]\end{aligned}$$

$$+ C_{14,k} E_{1-C_{5,k}}^{-b_{2,k}} \{-b_{2,k}(\xi_k^{\text{out}} - 1)\}] \quad .$$

Finally, as shown in Appendix-IV, we can obtain $\delta \hat{\Omega}_k$ by inserting the node-averaged liquid enthalpy and void fraction perturbation into the equation obtained by perturbing, Laplace transforming and averaging Equation (2.45) as,

$$\begin{aligned} \delta \hat{\Omega}_k = & Y_{1,k} \delta \hat{j}_i + Y_{6,k} \delta \hat{q}_B'' + Y_{2,k} \delta \hat{q}_k'' + Y_{3,k} \delta \hat{h}_{l,k}^{\text{in}} + Y_{4,k} \delta \langle \hat{j} \rangle_k^{\text{in}} \\ & + Y_{5,k} \delta \langle \hat{\alpha} \rangle_k^{\text{in}} \end{aligned} \quad (2.62)$$

where the Y's are tabulated in Appendix-IV.

In the fully developed bulk boiling region, Equation (2.45) reduces to,

$$\delta \hat{\Omega}_k = \frac{P_H^v f_{fg}}{A_{x-s} h_{fg}} \delta \hat{q}_k'' \quad (2.63)$$

Thus the transfer functions, Y's, will be,

$$Y_{2,k} = \frac{P_H^v f_{fg}}{A_{x-s} h_{fg}} \quad , \quad (2.64)$$

$$Y_{i,k} = 0 \quad (i = 1, 3, 4, 5) \quad .$$

The boundary conditions at the void departure point, Z_d , are given in Appendix-VIII as,

$$\delta \langle \hat{j} \rangle_{Z_d} = \delta \hat{j}_i - \Omega_{0,B} \delta \hat{Z}_d \quad (2.65)$$

where $\delta \hat{Z}_d$ is derived in Appendix-V,

$$\delta \langle \hat{a} \rangle_{Z_{d,0}} = - \frac{\rho_f \bar{\Omega}_{0,B}}{\Delta \rho (C_{K,0})_B^{in}} \delta \hat{Z}_d \quad (2.66)$$

and,

$$\delta (\hat{h}_\ell)_{Z_{d,0}} = x_1 \delta \hat{q}_{Z_d} + x_2 \delta \hat{j}_i - \frac{1}{G_0} \frac{q_{d,0}^{''} P_H}{A_{x-s}} \delta \hat{Z}_d \quad (2.67)$$

where,

$$x_1 = \begin{cases} -0.0022 \frac{P_H C_{pf}}{k_f} & \text{for } Pe \leq 70,000 \\ -154/G_0 & \text{for } Pe > 70,000 \end{cases}$$

$$x_2 = \begin{cases} 0 & \text{for } Pe \leq 70,000 \\ 154 q_{0,d}^{''} \rho_f / G_0^2 & \text{for } Pe > 70,000 \end{cases}$$

If subcooled boiling is neglected, the two-phase flow begins at the boiling boundary, λ_0 , where the liquid enthalpy is equal to the saturated enthalpy. Thus δZ_d will be replaced with, $\delta \hat{\lambda}$, which is given by,

$$\delta \hat{\lambda} = \frac{-\delta \hat{h}(s, \lambda_0)}{\left[\frac{dh(\lambda_0)}{dz} \right]} \quad (2.68)$$

Since $\delta \hat{h}(s, \lambda_0)$ is derived in Equation (VI.9), the boiling boundary perturbation becomes,

$$\delta \hat{\lambda} = \Lambda_1(s) \delta \hat{j}_i + \Lambda_2(s) \sum_{k=1}^L H_k^i \delta \hat{q}_{t,k}^{'''} + \Lambda_3(s) \delta \hat{h}_i \quad (2.69)$$

where,

$$\Lambda_k(s) = - \frac{\rho_f A_{x-s} j_{i,0}}{q_{B_0}^{''' } P_H} H_k(s) \quad (\text{for } k=1,2,3)$$

The subcooled boiling model just discussed was combined with the other system thermal-hydraulic and neutronic transfer functions to investigate its effect on the stability margin. The results for several experiments are shown in Part 5, and indicate that the assumption of thermodynamic equilibrium overestimates stability margin, although the difference in the margin depends on the operating conditions. The following subsection shows the final form of system thermal-hydraulic transfer function governing the BWR stability analysis.

2.5 FINAL FORM OF THE THERMAL-HYDRAULIC TRANSFER FUNCTION

The stability analysis in this study can be investigated by externally oscillating the inlet velocity $\hat{\delta j}_i$, volumetric heat generation rate, $\hat{\delta q}_{ext}'''$, or reactivity, $\hat{\delta k}_{ext}$. For a point kinetics model this is illustrated [2] in Figure 2.9. Even though no stability analysis is possible by externally oscillating the inlet enthalpy in this study, for convenience it will be included in the system transfer function as an "external" forcing function. When the thermal-hydraulic loop is closed this perturbation will disappear.

Corresponding to these external perturbation quantities, the transfer functions of the total channel pressure drop perturbation (including spacers) can be obtained by summing the nodal pressure drop perturbations

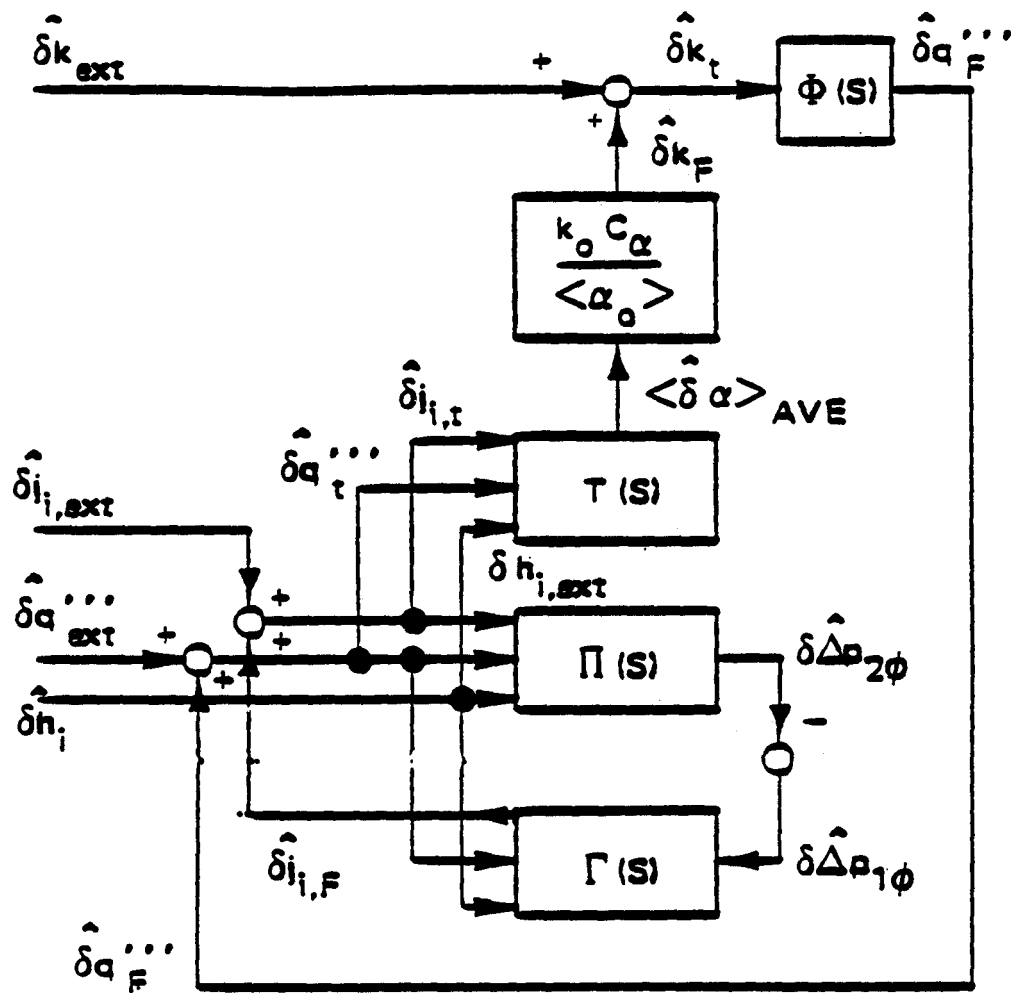


Figure 2.9 Simplified BWR Block Diagram

which are calculated from the analytical integration of the drift-flux momentum equation in both the single-phase and two-phase region.

For the single-phase region, the momentum equation reduces to,

$$\frac{\partial p}{\partial z} = \frac{\rho_f}{g_c} \frac{dj_i}{dt} + \frac{f \rho_f j_i^2}{2g_c D_H} + \frac{g}{g_c} \rho_f + \sum_{m=1}^{M_s} K_{spacer_m} \frac{\rho_f j_i^2}{g_c} \delta(z - \xi_m) \quad (2.70)$$

, where K_{spacer_m} represents the local loss coefficient of the spacer at $z = \xi_m$ (including the channel inlet restriction). Applying Leibniz's rule, we can calculate the total pressure drop perturbation in the single-phase region by integrating, perturbing and Laplace transforming Equation (2.70) as,

$$\begin{aligned} \delta(\hat{\Delta p}_{1\phi}) &= \int_0^{Z_{d,0}} \left[\frac{\rho_f}{g_c} s \delta \hat{j}_i + \frac{f \rho_f j_{i0}}{g_c D_H} \delta \hat{j}_i \right] dz + \left(\sum_{m=1}^{M_s} K_{spacer_m} \right) \frac{\rho_f j_{i0}}{g_c} \delta \hat{j}_i \\ &+ \left(\frac{f \rho_f j_{i0}^2}{2g_c D_H} + \frac{g}{g_c} \rho_f \right) \delta \hat{Z}_d \end{aligned} \quad (2.71)$$

Using the expression of $\delta \hat{Z}_d$ given in Equation (V.10),

$$\delta(\hat{\Delta p}_{1\phi}) = \Gamma_1(s) \delta \hat{j}_i + \sum_{k=1}^L \Gamma_{2,k} \delta \hat{q}_{t,k}^m + \Gamma_3(s) \delta \hat{h}_{in} \quad (2.72)$$

where,

$$\Gamma_1(s) = \left(\frac{\rho_f}{g_c} s + \frac{f \rho_f j_{i0}}{g_c D_H} \right) \lambda_0 + \left(\sum_{m=1}^{M_s} K_{spacer_m} \right) \frac{G_0}{g_c} + C_2 \Lambda_1(s)$$

$$\Gamma_{2,k} = \begin{cases} C_2 \Lambda_2^i & , \text{ for } k \leq L \\ 0 & , \text{ for } k > L \end{cases}$$

$$\Gamma_3(s) = C_2 \Lambda_3(s)$$

$$C_2 = \left[\frac{fG_0^2}{2g_c D_H \rho_f} + \frac{g}{g_c} \rho_f \right]$$

In order to obtain the two-phase pressure drop perturbation, $\delta(\hat{\Delta p}_{2\phi})$, the perturbed mixture momentum equation should be integrated node-by-node and summed up over all the nodes in the two-phase region. For the k-th node ($k > B$), $\delta(\hat{\Delta p}_{2\phi})_k$ comes from the integration of Eq. (2.16) as (exclusive of local loss),

$$\begin{aligned} \delta(\hat{\Delta p}_{2\phi})_k = & \int_{z_{k-1}}^{z_k} \left[\frac{1}{g_c} (s \delta \hat{G} + \frac{\partial \delta \hat{G}'}{\partial z}) + \frac{fG_0 \bar{\phi}_{lo}^2}{g_c \rho_f D_H} \delta \hat{G} + \frac{fG_0^2}{2g_c D_H \rho_f} \delta \hat{\phi}_{lo}^2 \right. \\ & \left. + \frac{g}{g_c} \delta \langle \bar{\rho} \rangle + \frac{1}{g} \frac{d}{dz} \delta \left\{ \left(\frac{\rho_f - \langle \bar{\rho} \rangle}{\langle \bar{\rho} \rangle - \rho_g} \right) \frac{\rho_f \rho_g}{\langle \bar{\rho} \rangle} (v'_{gj})^2 \right\} \right] dz \end{aligned} \quad (2.73)$$

shifting coordinates as in Eqs. (2.46) and (2.51), Equation (2.73) becomes,

$$\begin{aligned} \delta(\hat{\Delta p}_{2\phi})_k = & \frac{(C_{K,o})_k^{in}}{C_{o,\Omega_{o,k}}} \int_1^{\xi_k^{out}} \left[\frac{1}{g_c} (s \delta \hat{G} + \frac{C_{o,\bar{\Omega}_{o,k}}}{(C_{K,o})_k^{in}} \frac{\partial \delta \hat{G}'}{\partial \xi_k} \delta \hat{G} + \frac{fG_0 \bar{\phi}_{lo}^2}{g_c \rho_f D_H} \delta \hat{G} \right. \\ & \left. + \frac{fG_0^2}{2g_c D_H} + \frac{g}{g_c} \delta \langle \bar{\rho} \rangle + \frac{1}{g} \frac{C_{o,\bar{\Omega}_{o,k}}}{(C_{K,o})_k^{in}} \frac{d}{d\xi_k} \delta \left\{ \left(\frac{\rho_f - \langle \bar{\rho} \rangle}{\langle \bar{\rho} \rangle - \rho_g} \right) \frac{\rho_f \rho_g}{\langle \bar{\rho} \rangle} (v'_{gj})^2 \right\} \right] d\xi_k \end{aligned} \quad (2.74)$$

Now if we integrate Equation (2.74) term-by-term, and use

Equations (II.8), (VII.5), (VII.13) and (VII.17), we obtain the non-local loss part of the two-phase pressure drop perturbation in each interior node as,

$$\delta(\Delta p_{2\phi})_k = G_{1,k}(s) \delta \langle j \rangle_k^{\text{in}} + G_{2,k} \delta \bar{\Omega}_k + G_{3,k} \delta \langle \omega \rangle_k^{\text{in}} \quad (2.75)$$

where,

$$\begin{aligned} G_{1,k} \triangleq & \frac{(C_{K,o})_k^{\text{in}}}{g_c C_{o,o} \bar{\Omega}_{o,k}} \left[s g_{1,k} + \frac{r G_o}{\rho_f D_H} (\bar{\Phi}_{2o,o}^2 g_{1,k} + \frac{G_o}{2} f_{2,k}) \right] \ln(\epsilon_k^{\text{out}}) \\ & + \frac{(C_{K,o})_k^{\text{in}}}{g_c (C_{o,o} \bar{\Omega}_{o,k} - s)} \left[s g_{2,k} + \frac{r G_o}{\rho_f D_H} (\bar{\Phi}_{2o,o}^2 g_{2,k} + \frac{G_o}{2} f_{3,k}) \right] \\ & \times \left\{ (\epsilon_k^{\text{out}})^{\frac{C_{o,o} \bar{\Omega}_{o,k} - s}{C_{o,o} \bar{\Omega}_{o,k} - 1}} - 1 \right\} \\ & + \frac{(C_{K,o})_k^{\text{in}}}{g_c} \left[\frac{r G_o^2}{2 \rho_f D_H C_{o,o} \bar{\Omega}_{o,k}} + \frac{\Delta \rho_o P_{2,k}}{\epsilon_k^{\text{out}}} \right] \left\{ (\epsilon_k^{\text{out}}) - 1 \right\} \\ & + \frac{(C_{K,o})_k^{\text{in}} r G_o^2}{2 g_c \rho_f D_H (2 C_{o,o} \bar{\Omega}_{o,k} - s)} f_{4,k} \left\{ (\epsilon_k^{\text{out}})^{\frac{2 C_{o,o} \bar{\Omega}_{o,k} - s}{C_{o,o} \bar{\Omega}_{o,k} - 1}} - 1 \right\} \\ & + \frac{1}{g_c} \gamma_{2,k} \left\{ (\epsilon_k^{\text{out}})^{-2} - 1 \right\} \\ & + (C_{K,o})_k^{\text{in}} \Delta \rho_o P_{2,k} \frac{C_{o,o} \bar{\Omega}_{o,k}}{s} \left\{ (\epsilon_k^{\text{out}})^{\frac{s}{C_{o,o} \bar{\Omega}_{o,k} - 1}} - 1 \right\} \\ & + \frac{\gamma_{2,k}}{g_c} \left\{ (\epsilon_k^{\text{out}})^{-\frac{s + C_{o,o} \bar{\Omega}_{o,k}}{C_{o,o} \bar{\Omega}_{o,k} - 1}} - 1 \right\} \end{aligned}$$

$$+ \frac{\gamma_1}{g_c} + \frac{1}{g_c} \left\{ B_1(s, \epsilon_k^{\text{out}}) - B_1(s, 1) \right\}$$

$$G_{2,k} \triangleq \frac{(C_{K,o})_k^{\text{in}}}{g_c C_{o,o} \bar{\Omega}_{o,k}} \left[s g_{3,k} + \frac{f G_o}{\rho_f D_H} (\bar{\phi}_{2o,o}^2 g_{3,k} + \frac{G_o}{2} f_{5,k}) + \frac{C_{o,o} \bar{\Omega}_{o,k}}{(C_{K,o})_k^{\text{in}}} \gamma_{3,k} \right]$$

$$\times \left\{ \epsilon_k^{\text{out}} - 1 \right\} + \frac{(C_{K,o})_k^{\text{in}}}{g_c C_{o,o} \bar{\Omega}_{o,k}} \left[s g_{4,k} + \frac{f G_o}{\rho_f D_H} (\bar{\phi}_{2o,o}^2 g_{4,k} + \frac{G_o}{2} f_{6,k}) \right]$$

$$\times \ln(\epsilon_k^{\text{out}}) + \frac{[(C_{K,o})_k^{\text{in}}]^2 \Delta o}{g_c C_{o,o} \bar{\Omega}_{o,k}} p_{2,k} \left\{ (\epsilon_k^{\text{out}})^{-1} - 1 \right\}$$

$$+ \frac{(C_{K,o})_k^{\text{in}} f G_o^2}{C_{o,o} \bar{\Omega}_{o,k} 4 g_c \rho_f D_H} f_{7,k} \left\{ (\epsilon_k^{\text{out}})^2 - 1 \right\}$$

$$- \frac{[(C_{K,o})_k^{\text{in}}]^2 \Delta o}{g_c s} \left\{ (\epsilon_k^{\text{out}})^{-\frac{s}{C_{o,o} \bar{\Omega}_{o,k}}} - 1 \right\} + \frac{(C_{K,o})_k^{\text{in}} f G_o^2}{(2 C_{o,o} \bar{\Omega}_{o,k} - s) 2 g_c \rho_f D_H}$$

$$\times \left\{ (\epsilon_k^{\text{out}})^{\frac{2 C_{o,o} \bar{\Omega}_{o,k} - s}{C_{o,o} \bar{\Omega}_{o,k}}} - 1 \right\} + \frac{(C_{K,o})_k^{\text{in}}}{g_c (C_{o,o} \bar{\Omega}_{o,k} - s)} \left[s g_{5,k} + \frac{f G_o}{g_c \rho_f D_H} \right]$$

$$\times \left(\bar{\phi}_{2o,o}^2 g_{5,k} + \frac{G_o}{2} f_{8,k} \right) + \frac{(C_{o,o} \bar{\Omega}_{o,k} - s)}{(C_{K,o})_k^{\text{in}} (\epsilon_k^{\text{out}})^2} \gamma_{4,k}$$

$$\left\{ (\epsilon_k^{\text{out}})^{\frac{C_{o,o} \bar{\Omega}_{o,k} - s}{C_{o,o} \bar{\Omega}_{o,k}}} - 1 \right\} + \frac{1}{g_c} \left\{ B_2(s, \epsilon_k^{\text{out}}) - B_2(s, 1) \right\}$$

$$G_{3,k} \triangleq \frac{(C_{K,o})_k^{\text{in}}}{g_c (C_{o,o} \bar{\Omega}_{o,k} - s)} \left[s g_{6,k} + \frac{f G_o}{\rho_f D_H} (\bar{\phi}_{2o,o}^2 g_{6,k} + \frac{G_o}{2} f_{10,k}) \right]$$

$$\begin{aligned}
& \times \left\{ \left(\varepsilon_k^{\text{out}} \right) \frac{C_{0,0} \bar{\Omega}_{0,k}^{-s}}{C_{0,0} \bar{\Omega}_{0,k} - 1} + \frac{(C_{K,0})_k^{\text{in}} \frac{FG_0^2}{g_c (2C_{0,0} \bar{\Omega}_{0,k}^{-s}) 2\alpha_{FH}}}{g_c} \left\{ \left(\varepsilon_k^{\text{out}} \right) \frac{2C_{0,0} \bar{\Omega}_{0,k}^{-s}}{C_{0,k} \bar{\Omega}_{0,k}} \right. \right. \\
& \left. \left. - 1 \right\} + \frac{(C_{K,0})_k^{\text{in}} \Delta \rho}{g_c s} \left\{ \left(\varepsilon_k^{\text{out}} \right) \frac{s + C_{0,0} \bar{\Omega}_{0,k}}{C_{0,0} \bar{\Omega}_{0,k} - 1} \right\} \right. \\
& \left. + \frac{\gamma_{S,k}}{g_c} \left\{ \left(\varepsilon_k^{\text{out}} \right) \frac{s + C_{0,0} \bar{\Omega}_{0,k}}{C_{0,0} \bar{\Omega}_{0,k} - 1} \right\} + \frac{1}{g_c} \left\{ B_3(s, \varepsilon_k) - B_3(s, 1) \right\} \right\}
\end{aligned}$$

and, $p_{2,k}$ is defined in Appendix II.

Equation (2.75) is expressed in terms of the node inlet boundary conditions and $\hat{\delta \Omega}_k$, which are functions of each other. In order to convert these quantities to independent external forcing functions, we can link node-by-node the quantities at the inlet of the boiling boundary node to that of each subsequent node using the conservation of each parameter at the interface of the adjacent nodes (Appendix VIII). Therefore from Equations (VIII.18), (VIII.19), (VIII.20), Equation (2.75) will be,

$$\begin{aligned}
\delta(\hat{\Delta p}_{2\phi})_k &= (G_{1,k} V_{1,k} + G_{2,k} M_{1,k} + G_{3,k} K_{1,k}) \hat{\delta j}_i + \sum_{i=1}^{k-1} (G_{1,k} V_{2,k}^i \\
&+ G_{2,k} M_{2,k}^i + G_{3,k} K_{2,k}^i) \hat{\delta q}_{t,i} + (G_{1,k} V_{3,k} + G_{2,k} M_{3,k} \\
&+ G_{3,k} K_{3,k}) \hat{\delta h}_i
\end{aligned} \tag{2.76}$$

For the inlet node of the two-phase region, the effect of the movement of the boiling boundary is given by,

$$\begin{aligned}
\delta(\hat{\Delta p}_{2\phi})_B &= \int_{Z_d(t)}^{Z_B} \left(-\frac{d\delta p}{dz}\right) dz \\
&= \int_{Z_{d,0}}^{Z_B} \left(-\frac{d\delta p}{dz}\right) dz - \left(-\frac{dp}{dz}\right)_{Z_{d,0}} \delta Z_d
\end{aligned} \quad (2.77)$$

Thus from Equations (2.3) and (2.75),

$$\delta(\hat{\Delta p}_{2\phi})_B = G_{1,B} \delta\langle \hat{j} \rangle_{\lambda_0} + G_{2,B} \delta\bar{\Omega}_B + G_{3,B} \delta\langle \hat{\alpha} \rangle_{Z_{d,0}} - R \delta Z_d \quad (2.78)$$

where,

$$R = \frac{\Delta}{g_c} \left[\frac{G_0 j_{i_0} \bar{\Omega}_{0,B}}{C_0 j_{i_0} + v_{gj}} + \frac{f G_0^2}{2 D_H \rho_f} + g \rho_f + \frac{\rho_f \rho_g \bar{\Omega}_{0,B} \{v_{gj} + (C_0 - 1) j_{i_0}\}^2}{(\rho_f - \rho_g)(C_0 j_{i_0} + v_{gj})} \right]$$

Using Equations (2.65), (2.66), (2.67), (V.10), and (VIII.17),

$$\delta(\hat{\Delta p}_{2\phi})_B = C_{18}(s) \delta \hat{j}_i + \sum_{i=1}^B C_{19}^i(s) \delta \hat{q}_{t,i} + C_{17} \Lambda_3 \delta \hat{h}_i \quad (2.79)$$

where,

$$C_{18}(s) = G_{1,B} + G_{2,B} (Y_{1,B} + Y_{2,B} X_3 + Y_{4,B}) + \Delta C_{17} G_{19}^i(s)$$

$$C_{19}^i = \begin{cases} \Lambda_2^i C_{17} & , \text{ for } i \leq L \\ (Y_{2,B} + Y_{3,B} + Y_{6,B}) Z_{8,B} & , \text{ for } i=B \end{cases}$$

$$C_{17}(s) = -\Omega_{0,B} \left\{ G_{1,B} + G_{2,B} \left(\frac{\rho_f}{\Delta \rho (C_{K,0})_{B,0}} + Y_{3,B} X_2 + Y_{4,B} + Y_{1,B} \right) \right\}$$

Next the local pressure drop perturbation due to spacers, a loss at the channel exit, is given by,

$$\delta \Delta p_{\text{spacer}}(z'_m) = K_{\text{spacer}} \left\{ \frac{G_0 \phi_0}{g_c \rho_f} \right\}_{z=z'_m} \delta \hat{G}(s, z'_m) + \frac{G_0^2}{2g_0 \rho_f} \delta \phi(s, z'_m) \quad (2.80)$$

If the spacers is located within the m-th node (ie: if, $z_{m-1} \leq z'_m < z_m$), then from Equations (II.8) and (VII.13),

$$\delta \hat{p}_{\text{spacer}}(z'_m) = S_1(s, z'_m) \delta \langle j \rangle_m^{\text{in}} + S_2(s, z'_m) \delta \hat{\Omega}_m + S_3(s, z'_m) \delta \langle \alpha \rangle_k^{\text{in}} \quad (2.81)$$

where,

$$\begin{aligned} S_1(s, z'_m) &= a(g_{1,m} \xi_{z'_m}^{-1} + g_{2,m} \xi_{z'_m}^{-\frac{s}{C_{0\hat{\Omega}_0,m}}}) + b(f_{1,m} + f_{2,m} \xi_{z'_m}^{-1} \\ &\quad + f_{3,m} \xi_{z'_m}^{-\frac{s}{C_{0\hat{\Omega}_0,m}}} + f_{4,m} \xi_{z'_m}^{-\frac{s}{C_{0\hat{\Omega}_0,m}} + 1}) \\ S_2(s, z'_m) &= a(g_{3,k} + g_{4,k} \xi_{z'_m}^{-1} + g_{5,k} \xi_{z'_m}^{-\frac{s}{C_{0\hat{\Omega}_0,m}}}) + b(f_{5,m} + f_{6,m} \xi_{z'_m}^{-1} \\ &\quad + f_{7,m} \xi_{z'_m}^{-\frac{s}{C_{0\hat{\Omega}_0,m}}} + f_{8,m} \xi_{z'_m}^{-\frac{s}{C_{0\hat{\Omega}_0,m}} + 1} + f_{9,m} \xi_{z'_m}^{-\frac{s}{C_{0\hat{\Omega}_0,m}} + 1}) \\ S_3(s, z'_m) &= a(g_{6,k} \xi_{z'_m}^{-\frac{s}{C_{0\hat{\Omega}_0,m}}}) - b(f_{10,m} \xi_{z'_m}^{-\frac{s}{C_{0\hat{\Omega}_0,m}}} + f_{11,m} \xi_{z'_m}^{-\frac{s}{C_{0\hat{\Omega}_0,m}} + 1}) \\ a &= K_{\text{spacer}} \frac{G_0 \phi_0}{g_0 \rho_f} \Big|_{z=z'_m}, \quad b = K_{\text{spacer}} \frac{G_0^2}{2G_0 \rho_f} \Big|_{z=z'_m} \end{aligned}$$

Now from Equations (VIII.8), (VIII.19) and (VIII.20),

$$\begin{aligned} \delta \hat{\Delta p}_{\text{spacer}}(z_m') = & S_1 V_{1,m} + S_2 M_{1,m} + S_3 K_{1,m} \delta \hat{j}_i + \sum_{i=1}^{m-1} [S_1 V_{2,m}^i + S_1 M_{2,m}^i \\ & + S_2 M_{2,m}^i + S_3 K_{2,m}^i] \delta \hat{q}_{t,i}''' + (S_1 V_{3,m} + S_2 M_{3,m} + S_3 K_{3,m}) \delta \hat{h}_i \end{aligned} \quad (2.82)$$

Finally, we can obtain the total pressure drop perturbation in the two-phase region by summing all $\delta(\Delta p_{2\phi})_k$ including $\delta(\Delta p_{\text{spacer}}(z_m'))$, which are given in Equations (2.76), (2.78), and (2.82), as,

$$\delta(\Delta p_{2\phi}) = \pi_1 \delta \hat{j}_i + \sum_{k=1}^K \pi_2^k \delta \hat{q}_{t,k}''' + \pi_3 \delta \hat{h}_i \quad (2.83)$$

where,

$$\begin{aligned} \pi_1 = & C_{78} + \sum_{k=8+1}^N (G_{1,k} V_{1,k} + G_{2,k} M_{1,k} + G_{3,k} K_{1,k}) \\ & + \sum_{m=2_s+1}^M (S_1 V_{1,m} + S_2 M_{1,m} + S_3 K_{1,m}) \\ \pi_2^k = & C_{79}^k + \sum_{i=8+1}^K (G_{1,i} V_{2,i}^k + G_{2,i} M_{2,i}^k + G_{3,i} K_{2,i}^k) \\ & + \sum_{i=8}^K \delta n_{\text{sp}(i)}^{(0)} \left\{ \sum_{n=1}^{N_{\text{sp}}(i)} (S_1 V_{2,i}^k + S_2 M_{2,i}^k + S_3 K_{2,i}^k) \right\} \quad \text{for } k \leq 8 \end{aligned}$$

$$\left\{ = \sum_{i=k}^K G_{1,i} V_{2,i}^k + G_{2,i} M_{2,i}^k + G_{3,i} M_{2,i}^k \right.$$

$$+ \delta_{n_{sp}(i)}(0) \sum_{n=1}^{N_{sp}(i)} (S_1 V_{2,i}^k + S_2 M_{2,i}^k + S_{30} K_{2,i}^k)$$

for $k > B$

$$\pi_3 = C_{17} \Lambda_3 + \sum_{k=B+1}^K (G_{3,k} V_{3,k} + G_{2,k} M_{3,k} + G_{3,k} K_{3,k})$$

$$+ \sum_{m=\ell_s+1}^M (S_1 V_{3,m} + S_2 M_{3,m} + S_3 K_{3,m})$$

$n_{sp}(j)$: The total number of spacers in the j -th node

ℓ_s : The total number of spacers in the single-phase region

$$\delta_i(k) = \begin{cases} 0, & k=i \\ 1, & k \neq i \end{cases}$$

The node-averaged void fraction transfer function is derived in Appendix III. Using Equations (VIII.18), (VIII.19) and (VIII.21), Equation (III.3) can be written,

$$\delta \langle \hat{\alpha} \rangle_k = T_{1,k}(s) \hat{\delta j}_i + \sum_{i=B}^k (T_{2,i}^k(s) \hat{\delta q}_{t,i}') + T_{3,k}(s) \hat{\delta h}_i \quad (2.84)$$

where,

$$T_{1,k} = Y_{1,k}V_{1,k} + Y_{2,k}M_{1,k} + Y_{3,k}K_{1,k}$$

$$T_{2,i}^k = Y_{1,k}V_{2,k}^i + Y_{2,k}M_{2,k}^i + Y_{3,k}K_{2,k}^i$$

$$T_{3,k} = Y_{1,k}V_{3,k} + Y_{2,k}M_{3,k} + Y_{3,k}K_{3,k}$$

Now the Γ_i , π_i , T_i ($i=1,2,3$) in Equations. (2.72), (2.83) and (2.84) are the fundamental thermal-hydraulic nodal transfer functions for parallel channel stability analysis. These transfer functions can be combined with appropriate neutronic transfer functions to achieve a model capable of parallel channel analysis of BWRs. Before we consider the coupling with neutron kinetics models, let us next consider the extension of these thermal-hydraulics models to a closed loop, in particular, we are interested in the BWR recirculation loop.

PART 3

BWR LOOP ANALYSIS

3.1 General

Since a BWR consists of a recirculating loop which includes the various components shown in Figure 3.1, density-wave oscillations can occur in the recirculating loop as well as within a core channel. This part of the report presents the development of an analytical model for multichannel loop stability analysis.

The only fundamental difference between parallel channel oscillations and the loop oscillations is the boundary condition which induces the feedback to the core inlet flow rate. As discussed previously, core inlet enthalpy perturbations are inherent in the loop stability analysis, and are due to the enthalpy perturbation wave moving through the downcomer and the lower plenum.

The recirculating loop in a BWR, shown schematically in Figure 3.1, can be divided into four regions; the core, the upper plenum, the adiabatic/riser separator complex and the external single-phase loop, including the downcomer, recirculating pumps and the lower plenum. A detailed model for the core region was discussed in the previous part. The following sections present an analytical model for each component in the recirculating loop, and counts for the

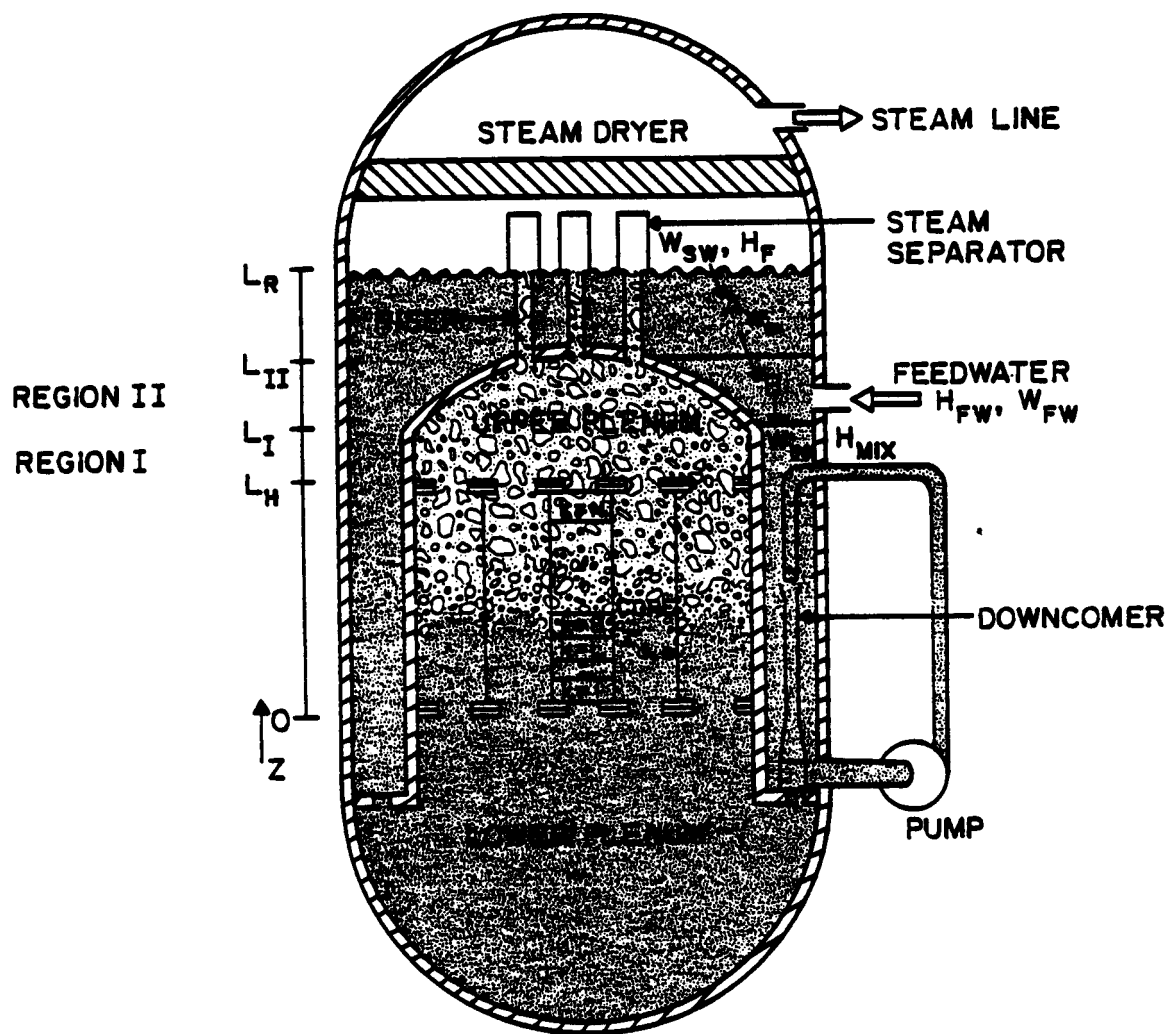


Figure 3.1 The Configuration of the Recirculating Loop

multichannel configuration of the core.

3.2 STEADY-STATE CHANNEL INLET FLOW REDISTRIBUTION

In a multichannel analysis of a BWR recirculation loop, the inlet flows to the individual heated channel are permitted to redistribute themselves in such a way as to satisfy the imposed pressure drop boundary condition. The flow split to the bypass region is assumed to be a constant fraction(eg: 10%) of the total flow in the loop(w_o), and is subtracted prior to input. Thus to find the individual channel's inlet velocity, we calculated the steady-state total pressure drop for a given core flow split as,

$$\Delta p_{total} = \Delta p_{inlet} + \Delta p_{1\phi} + \Delta p_{2\phi} + \Delta p_{exit} \quad . \quad (3.1)$$

The inlet flows were adjusted until channel pressure drops were the same, within a convergence criterion ϵ . That is, if,

$$\left| \frac{\Delta p_{guess}^{(m)} - \Delta p_i^{(m)}}{\Delta p_i^{(m)}} \right| > \epsilon_1, \quad (3.2)$$

then,

$$j_{io}^{(m+1)} = \sqrt{\frac{\Delta p_{guess}^{(m)}}{\Delta p_i^{(m)}}} j_{io}^{(m)} \quad (3.3)$$

If the boundary condition is satisfied, then we compare the total calculated flow rate with the core inlet flow rate, w_{in} , which was given as input (ie: $w_{in} = w_o - w_{bypass}$). That is, using,

$$w^{(n)} = \sum_{i=1}^N \rho j_{i0}^{(n)} A_{x-s} \quad (3.4)$$

$$\text{if, } \left| \frac{w^{(n)} - w_{in}}{w_{in}} \right| > \epsilon_2, \text{ then,}$$

$$\Delta p_{guess}^{(n+1)} = \Delta p_{guess}^{(n)} \left\{ 1 + \frac{\sqrt{w_{in}} - \sqrt{w^{(n)}}}{\sqrt{w_{in}}} \right\} \quad (3.5)$$

and we repeat the process until both the core pressure drop and flow rate convergence are satisfied. A flow chart for the calculation process is given in Figure 3.2.

3.3 PRESSURE DROP PERTURBATION THROUGH THE LOOP

In order to obtain the core inlet flow rate feedback which satisfies the boundary condition of constant pressure drop perturbation through the recirculating loop, we can calculate the pressure drop perturbation of each region.

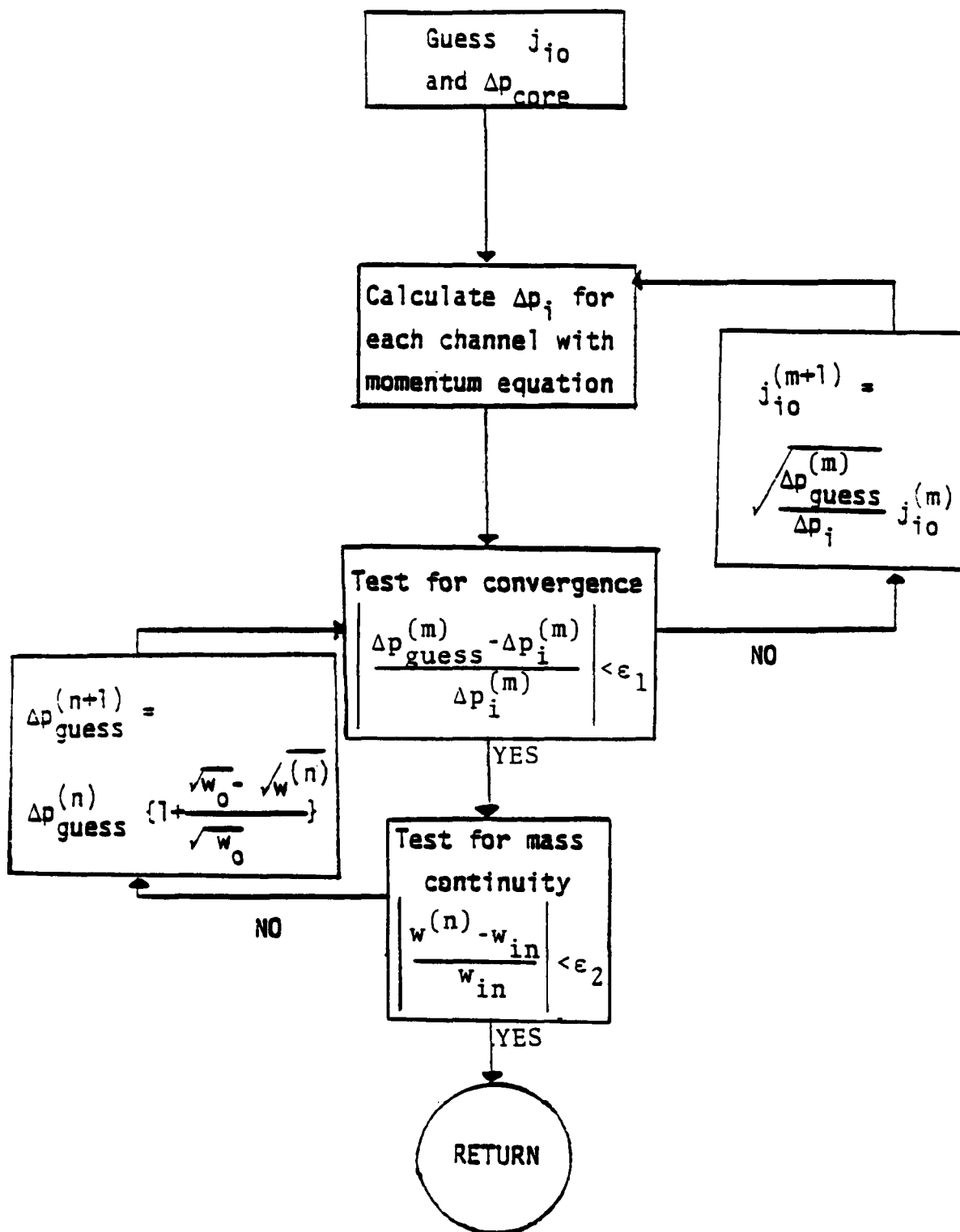


Figure 3.2 Flow Chart for Channel Inlet Flow Rate Redistribution

3.3.1 Upper Plenum

For convenience, the upper plenum can be divided into two regions. As shown in Figure 3.1, in Region-I, the flow area is assumed to be constant, while in Region-II it varies in the axial direction. Homogeneous flow is assumed in the upper plenum because the mixing is expected to be quite good.

Let the constant flow area in Region-I be denoted by "A". For the adiabatic system, equations (2.1) and (2.5) reduce to,

$$\frac{\partial \langle j \rangle}{\partial z} = 0 \quad (3.6)$$

$$\frac{\partial \langle \alpha \rangle}{\partial t} + C_K \frac{\partial \langle \alpha \rangle}{\partial z} = 0 \quad (3.7)$$

By perturbing, Laplace transforming and integrating Equations (3.6) and (3.7), the exit flow velocity and void fraction perturbation of Region-I can be obtained as,

$$\delta \langle \hat{j}_I \rangle^{\text{out}} = \delta \langle \hat{j}_p \rangle^{\text{in}} \quad (3.8)$$

$$\delta \langle \hat{\alpha}_I \rangle^{\text{out}} = \delta \langle \hat{\alpha}_p \rangle^{\text{in}} e^{-\frac{s}{\langle j_p \rangle_0} \Delta L_I} \quad (3.9)$$

where, $\Delta L_I = L_I - L_H$.

For steady-state,

$$\langle j_I \rangle_0^{\text{out}} = \langle j_p \rangle_0^{\text{in}} \quad (3.10)$$

$$\langle \alpha_I \rangle_0^{\text{out}} = \langle \alpha_p \rangle_0^{\text{in}} \quad . \quad (3.11)$$

Since there is a sudden expansion of the flow area at the inlet of the upper plenum, the inlet velocity and void fraction perturbation of the upper plenum will be, as shown in Appendix IX,

$$\delta \langle \hat{j}_p \rangle^{\text{in}} = \sum_i^N J_{1,k} \delta \langle j(L_H) \rangle_i + \sum_i^N J_{2,i} \delta \langle \hat{\alpha}(L_H) \rangle_i + \sum_i^N J_{3,i} \delta \hat{w}_i \quad (3.12)$$

$$\delta \langle \hat{\alpha}_p \rangle^{\text{in}} = \sum_i^N F_{1,i} \delta \langle \hat{j}(L_H) \rangle_i + \sum_i^N F_{2,i} \delta \langle \hat{\alpha}(L_H) \rangle_i + \sum_i^N F_{3,i} \delta \hat{w}_i \quad (3.13)$$

From Equations (VIII.20) and (VIII.21), Equations (3.12) and (3.13) become,

$$\delta \langle \hat{j}_p \rangle^{\text{in}} = \sum_i^N N_{1,i}(s) \delta \hat{j}_i + \sum_i^N \sum_j^K N_{2,i}^j(s) \delta \hat{q}_{i,j}''' + N_3(s) \delta \hat{h}_i \quad (3.14)$$

$$\delta \langle \hat{\alpha}_p \rangle^{in} = \sum_i^N P_{1,i}(s) \delta \hat{j}_i + \sum_i^N \sum_j^K P_{2,i}^j(s) \delta \hat{q}_{i,j}''' + P_3(s) \delta \hat{h}_i \quad (3.15)$$

where,

$$N_{1,i}(s) = \sum J_{1,i} V_{1,K+1}^i + J_{2,2} K_{1,K+1}^i + J_{3,i} A_{x-s}^i \rho_f$$

$$N_{2,i}^j(s) = J_{1,k} (V_{2,K+1}^j)^i + J_{2,i} (K_{2,K+1}^j)^i$$

$$N_{3,i}(s) = \sum_i \{ J_{1,i} V_{3,K+1}^i + J_{2,i} K_{3,K+1}^i \}$$

$$P_{1,i}(s) = \sum_i^N \{ F_{1,i} V_{1,K+1}^i + F_{2,i} K_{1,K+1}^i + F_{3,i} A_{x-s}^i \rho_f \}$$

$$P_{2,i}^j = F_{1,i} (V_{2,K+1}^j)^i + F_{2,i} (K_{2,K+1}^j)^i$$

$$P_{3,i} = \sum_i \{ F_{1,i} V_{3,K+1}^i + F_{2,i} K_{3,K+1}^i \}$$

In Region-II, the plenum flow area is no longer constant, but rather, $A(z)$. The appropriate mass continuity equation for varying flow area^[14] is,

$$\frac{\partial \langle j \rangle}{\partial z} = - \langle j \rangle \frac{d(\ln A)}{dz} \quad (3.16)$$

By perturbing, Laplace transforming and integrating

Equation (3.16),

$$\delta \langle \hat{j}_{II} \rangle = \frac{A_p}{A(z)} \delta \langle \hat{j}_{II} \rangle^{in} \quad (3.17)$$

where, for steady-state,

$$\langle j_{II} \rangle_0 = \frac{A_p}{A(z)} \langle j_{II} \rangle_0^{in} \quad (3.18)$$

For the void fraction profile in Region-II, Equation (3.9) must be replaced by,

$$\delta \langle \hat{\alpha}_{II} \rangle^{out} = e^{-\int_{L_I}^{L_{II}} \frac{s}{(C_{K,II})_0} dz} \delta \langle \hat{\alpha}_{II} \rangle^{in} \quad (3.19)$$

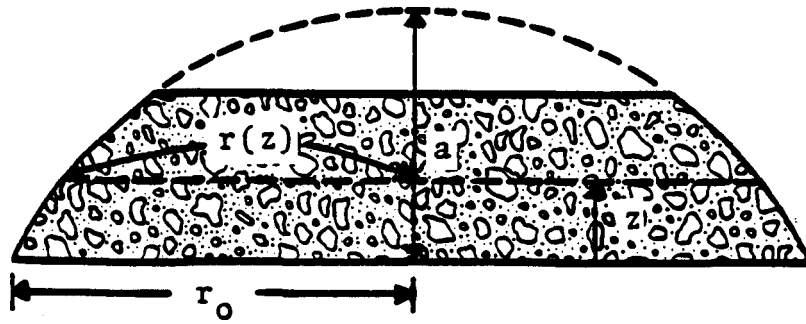
where, for steady-state,

$$\langle \alpha_{II}(z) \rangle_0 = \langle \alpha_{II} \rangle_0^{in} \quad (3.20)$$

Since, for homogeneous flow, $(C_{K,II})_0 = \langle j_{II}(z) \rangle_0$ in the upper plenum, Equations (3.18) and (3.19) yield,

$$\delta \langle \hat{\alpha}_{II} \rangle^{out} = \left[e^{-\frac{s}{A_p \langle j_p \rangle_0^{in}} \int_{L_I}^{L_{II}} A(z) dz} \right] \delta \langle \hat{\alpha}_{II} \rangle^{in} \quad (3.21)$$

Now in order to estimate $A(z)$, we have assumed that Region-II has the form of a chopped hemisphere,



thus,

$$A(z) = -\pi z^2 + \pi(a - \frac{r_0^2}{a})z + \pi r_0^2 \quad (3.22)$$

Inserting Equation (3.22) into Equation (3.21) and performing the integration, the exit void fraction perturbation of Region-II is given by,

$$\delta \hat{\alpha}_{II}^{out} = e^{-\frac{sA}{A_p \langle j_p \rangle_0^{in}}} \delta \hat{\alpha}_{II}^{in} \quad (3.23)$$

where,

$$A = A_p(L_{II} - L_I) + (\pi a - \frac{A_p}{a}) \frac{(L_{II}^2 - L_I^2)}{2} - \frac{\pi}{3} (L_{II}^3 - L_I^3) \quad .$$

Finally, the exit values from the upper plenum, which provide the inlet values for the riser, can be obtained from Equations (3.8) to (3.23) as,

$$\langle j_{II} \rangle_0^{out} = \frac{A_p}{A_R} \langle j_p \rangle_0^{in} \quad (3.24)$$

$$\langle \alpha_{II} \rangle_0^{out} = \langle \alpha_p \rangle_0^{in} \quad (3.25)$$

$$\delta \langle \hat{j}_{II} \rangle^{out} = \frac{A_p}{A_R} \delta \langle \hat{j}_p \rangle^{in} \quad (3.26)$$

$$\delta \langle \hat{\alpha}_{II} \rangle^{out} = \delta \langle \hat{\alpha}_p \rangle^{in} e^{-\frac{s}{\langle j_p \rangle_o^{in}} \{ \Delta L_I + \frac{A}{A_p} \}} \quad (3.27)$$

The pressure drop perturbation across the upper plenum can be calculated from the perturbed mixture momentum equation, Equation (2.16). Due to the large cross-sectional flow area and mixing, the hydrostatic head is the dominant contribution to the pressure drop. Thus Equation (2.16) for the upper plenum reduces to,

$$\delta(\hat{\Delta p})_{up} = \frac{g}{g_c} \int_{L_H}^{L_{II}} \delta \langle \hat{\rho} \rangle dz \quad (3.28)$$

From Equations (VIII.3) and (3.9),

$$\delta(\hat{\Delta p})_{up} = U \delta \langle \hat{\alpha} \rangle_p^{in} \quad (3.29)$$

where,

$$U = \frac{g \Delta \rho \langle j_p \rangle_o^{in}}{g_c s} \left[e^{-\frac{s}{\langle j_p \rangle_o^{in}} (L_{II} - L_H)} - 1 \right]$$

3.3.2 Riser/Steam Separator

In the junction between the exit of the upper plenum and the inlet of the riser, the homogeneous flow assumed in

the upper plenum will convert to slip flow in the riser. Therefore the flow velocity and the void fraction for the abruptly changing flow pattern are calculated based on the conservation of the flow quality and flow rate at the junction, in a similar fashion as at the interface between the core exit and the upper plenum inlet. From the conservation of quality at the junction and the Zuber-Findlay void-quality relation ^[2], we obtain the inlet void fraction of the riser as,

$$\langle \alpha_R \rangle_0^{\text{in}} = \frac{\frac{\rho_g}{\rho_f} \langle \alpha_{II} \rangle_0^{\text{out}}}{\left(C_{0,R} \frac{\rho_g}{\rho_f} + \frac{\rho_g V_{gj,R}}{\langle G_R \rangle_0^{\text{in}}} \right) \left(1 - \frac{\Delta \rho}{\rho_f} \langle \alpha_{II,0} \rangle_0^{\text{out}} \right) + C_{0,R} \frac{\Delta \rho \rho_g}{\rho_f^2} \langle \alpha_{II,0} \rangle_0^{\text{out}}} \quad (3.30)$$

where, $C_{0,II} = 1.0$ and $V_{gj,II} = 0.0$. From Equations (3.24), (3.25) and $G_{R,0}^{\text{in}} = A_{x-s} G_0 / A_R$, Equation (3.30) yields,

$$\langle \alpha_R \rangle_0^{\text{in}} = \frac{\frac{\rho_g}{\rho_f} \langle \alpha_p \rangle_0^{\text{in}}}{\left(C_{0,R} \frac{\rho_g}{\rho_f} + \frac{\rho_g V_{gj,R}}{\frac{A_{x-s}}{A_R} G_0} \right) \left(1 - \frac{\Delta \rho}{\rho_f} \langle \alpha_p \rangle_0^{\text{in}} \right) + C_{0,R} \frac{\Delta \rho \rho_g}{\rho_f^2} \langle \alpha_p \rangle_0^{\text{in}}} \quad (3.31)$$

Since, $G_R = [\rho_f - \Delta \rho C_{0,R} \langle \alpha_R \rangle] \langle j_R \rangle - \Delta \rho V_{gj,R} \langle \alpha_R \rangle$, we have,

$$\langle j_R \rangle_0^{in} = \frac{\frac{A_{x-s}}{A_R} G_0 + \Delta p V_{gj,R} \langle \alpha_R \rangle_0^{in}}{(\rho_f - \Delta p C_{0,R} \langle \alpha_R \rangle_0^{in})} \quad (3.32)$$

Now in order to find $\delta \langle \hat{j}_R \rangle^{in}$ and $\delta \langle \hat{\alpha}_R \rangle^{in}$, we can use,

$$\delta \langle \hat{x}_{II} \rangle^{out} = \delta \langle \hat{x}_R \rangle^{in} \quad (3.33)$$

$$\delta \langle \hat{G}_{II} \rangle^{out} = \delta \langle \hat{G}_R \rangle^{in} \quad (3.34)$$

Inserting Equations (IX.7) and (IX.8) into Equations (3.33) and (3.34),

$$F_{1,II} \delta \langle \hat{\alpha}_{II} \rangle^{out} = F_{1,R} \delta \langle \hat{\alpha}_R \rangle^{in} + F_{2,R} \delta \langle \hat{j}_R \rangle^{in} \quad (3.35a)$$

and,

$$[\rho_f - \Delta p \langle \alpha_{II} \rangle_0^{out}] \delta \langle \hat{j}_{II} \rangle^{out} - \Delta p \langle j_{II} \rangle_0^{out} \delta \langle \hat{\alpha}_{II} \rangle^{out} =$$

$$[\rho_f - \Delta p C_{0,R} \langle \alpha_R \rangle_0^{in}] \delta \langle \hat{j}_R \rangle^{in} - \Delta p (C_{0,R} \langle j_R \rangle_0^{in} + V_{gj,R}) \delta \langle \hat{\alpha}_R \rangle^{in}$$

(3.35b)

where,

$$F_{1,II} = \frac{\rho_g + \Delta p \langle x_{II} \rangle_0^{out}}{\rho_f - \Delta p \langle \alpha_{II} \rangle_0^{out}}$$

$$F_{1,R} =$$

$$\frac{C_{0,R} \frac{\rho_g}{\rho_f} + \frac{\rho_g V_{gj,R}}{(G_R)_0^{in}} + C_{0,R} \frac{\Delta \rho}{\rho_f} \langle \alpha_R \rangle_0^{in} + \frac{\Delta \rho_g V_{gj,R}}{\{(G_R)_0^{in}\}^2} \langle \alpha_R \rangle_0^{in} (C_{K,R})_0^{in}}{(1 - C_{0,R} \frac{\Delta \rho}{\rho_f} \langle \alpha_R \rangle_0^{in})}$$

$$F_{2,R} = - \frac{\rho_f \rho_g V_{gj,R}}{\{(G_R)_0^{in}\}^2} \langle \alpha_R \rangle_0^{in} .$$

Solving these simultaneous equations for $\delta \langle \hat{j}_R \rangle^{in}$ and $\delta \langle \hat{\alpha}_R \rangle^{in}$,

$$\delta \langle \hat{j}_R \rangle^{in} = 0_{1,1} \delta \langle \hat{j}_{II} \rangle^{out} + 0_{1,2} \delta \langle \hat{\alpha}_{II} \rangle^{out} \quad (3.36)$$

$$\delta \langle \hat{\alpha}_R \rangle^{in} = 0_{2,1} \delta \langle \hat{j}_{II} \rangle^{out} + 0_{2,2} \delta \langle \hat{\alpha}_{II} \rangle^{out} \quad (3.37)$$

where,

$$0_{1,1} \triangleq \frac{1}{0_D} [\rho_f - \Delta \rho \langle \alpha_{II} \rangle_0^{out}] F_{1,R}$$

$$0_{1,2} \triangleq \frac{1}{0_D} [\Delta \rho (C_{0,R} \langle j_R \rangle_0^{in} + V_{gj,R}) F_{1,II} - \Delta \rho \langle j_{II} \rangle_0^{out} F_{1,R}]$$

$$0_{2,1} \triangleq - \frac{1}{0_D} [\rho_f - \Delta \rho \langle \alpha_{II} \rangle_0^{out}] F_{2,R}$$

$$0_{2,2} \triangleq \frac{1}{0_D} [\Delta \rho \langle j_{II} \rangle_0^{out} F_{2,R} + (\rho_f - \Delta \rho C_{0,R} \langle \alpha_R \rangle_0^{in}) F_{1,II}]$$

$$0_D \triangleq \Delta \rho (C_{0,R} \langle j_R \rangle_0^{in} + V_{gj,R}) F_{2,R} + [\rho_f - \Delta \rho C_{0,R} \langle \alpha_R \rangle_0^{in}] F_{1,R} .$$

From Equations (3.26) and (3.27),

$$\delta \langle \hat{j}_R \rangle^{in} = 0_{1,1} \frac{A_D}{A_R} \delta \langle \hat{j}_p \rangle^{in} + 0_{1,2} e^{-\frac{s}{\langle j_p \rangle_o} [\Delta L_I + \frac{A}{A_p}]} \delta \langle \hat{\alpha}_p \rangle^{in} \quad (3.38)$$

$$\delta \langle \hat{\alpha}_R \rangle^{in} = 0_{2,1} \frac{A_D}{A_R} \delta \langle \hat{j}_p \rangle^{in} + 0_{2,2} e^{-\frac{s}{\langle j_p \rangle_o} \{\Delta L_I + \frac{A}{A_p}\}} \delta \langle \hat{\alpha}_p \rangle^{in} \quad (3.39)$$

The pressure drop perturbation along the adiabatic riser can be calculated from the two-phase momentum equation, Equation (2.16), as,

$$\begin{aligned} -\frac{\partial p_R}{\partial z} = & \frac{1}{g_c} \left[\frac{\partial G_R}{\partial t} + \frac{\partial G_R'}{\partial z} \right] + \frac{1}{g_c} \frac{\partial}{\partial z} \left[\left(\frac{\rho_f - \langle \bar{\rho}_R \rangle}{\langle \bar{\rho}_R \rangle - \rho_g} \right) \frac{\rho_f \rho_g}{\langle \bar{\rho}_R \rangle} (V'_{gj})^2_R \right] \\ & + \frac{g}{g_c} \langle \bar{\rho}_R \rangle + \frac{f G_R^2}{2 g_c \rho_f D_{H,R}} \phi_{2o,R}^2 + K_{inlet,R} \frac{G_R^2 \phi_R}{2 g_c \rho_f} \delta(z - L_{II}) \\ & + K_{exit,R} \frac{G_R^2 \phi_R}{2 g_c \rho_f} \delta(z - L_R) \quad (3.40) \end{aligned}$$

Integrating, perturbing, and Laplace transforming Equation (3.36),

$$\begin{aligned} \delta(\Delta \hat{p}_{2\phi})_{riser} = & \frac{1}{g_c} \int_{L_{II}}^{L_R} \left[s \delta \hat{G}_R + \frac{\partial}{\partial z} (\delta \hat{G}_R') + \frac{\partial}{\partial z} \delta \left\{ \left(\frac{\rho_f - \langle \hat{\rho}_R \rangle}{\langle \hat{\rho}_R \rangle - \rho_g} \right) \frac{\rho_f \rho_g}{\langle \hat{\rho}_R \rangle} \right. \right. \\ & \left. \left. \times (V'_{gj})^2_R \right\} + g \delta \langle \hat{\rho}_R \rangle + \frac{f G_{R,o}^2}{2 \rho_f D_{H,R}} \delta \phi_{2o}^2 + \frac{f G_{R,o} (\phi_{2o}^2)}{\rho_f D_{H,R}} \delta \hat{G}_R \right] dz \end{aligned}$$

$$\begin{aligned}
& + K_{\text{inlet},R} \left\{ \frac{G_{R,0} \phi_R}{g_c \rho_f} \right|_{z=L_{II}} \delta \hat{G}(s, L_{II}) + \frac{G_{R,0}^2}{2g_c \rho_f} \right|_{z=L_{II}} \delta \hat{\phi}_R(s, L_{II}) \Big\} \\
& + K_{\text{exit},R} \left\{ \frac{G_{R,0} \phi_R}{g_c \rho_f} \right|_{z=L_R} \delta \hat{G}(s, L_R) + \frac{G_{R,0}^2}{2g_c \rho_f} \right|_{z=L_R} \delta \hat{\phi}_R(s, L_R) \Big\} .
\end{aligned} \tag{3.41}$$

where $K_{\text{exit},R}$ incorporates the loss of the steam separator. As shown in Appendix X, integrating Equation (3.41) term-by-term, the pressure drop perturbation in the riser has the form,

$$\delta(\Delta p_{2\phi})_{\text{riser}} = R_1(s) \delta \langle j \rangle_p^{\text{in}} + R_2(s) \delta \langle \alpha \rangle_p^{\text{in}} \tag{3.42}$$

where $R_1(s)$ and $R_2(s)$ are given in Appendix-X.

3.3.2 Single-Phase Portion of Loop Including the Downcomer and Lower Plenum

The saturated water from the separator will be mixed with subcooled feedwater and enter the downcomer. The flow rate perturbation of the saturated water induces a downcomer water level perturbation, and causes a downcomer length perturbation, $\delta \hat{L}_D$.

In order to obtain $\delta \hat{L}_D$, we can perturb and Laplace transform the mass continuity equation in control volume A of Figure 3.1. By assuming perfect mixing and a constant flow rate, w_{fw} , and enthalpy, h_{fw} , of the feedwater into

control volume B, we obtain

$$\hat{\delta L}_D = \frac{1}{\rho_f A_D S} [\hat{\delta w}_{sw} - \rho_f A_{x-s} \hat{\delta j}_1] \quad (3.43)$$

Since $w_{sw} = (1 - \langle x_R \rangle^{\text{out}}) A_R G_R^{\text{out}}$, the perturbed flow rate of the saturated water can be calculated from Equation (2.54) as,

$$\hat{\delta w}_{sw} = - \frac{A_R}{v_{fg}} \delta \langle j \rangle_R^{\text{out}} + A_R (1 - \frac{\rho_f}{\Delta \rho}) \hat{\delta G}_R^{\text{out}} \quad (3.44)$$

Inserting Equations (X.2), (3.36) and (3.37) into Equation (3.44), the final form of $\hat{\delta w}_{sw}$ is,

$$\hat{\delta w}_{sw} = L_1(s) \delta \langle j_p \rangle^{\text{in}} + L_2(s) \delta \langle \alpha_p \rangle^{\text{in}} \quad (3.45)$$

where,

$$L_1(s) = (L_1' O_{1,1} - L_2' O_{1,1}) \frac{A_p}{A_R} - \frac{s}{\langle j_p \rangle_o^{\text{in}}} \left\{ \Delta L_1 + \frac{A}{A_p} \right\}$$

$$L_2(s) = (L_1' O_{1,2} - L_2' O_{2,2}) e$$

$$L_1' = - \frac{A_R}{v_{fg}} + \frac{A_R \rho_f}{\Delta \rho} (\rho_f - \Delta \rho C_{o,R} \langle \alpha_R \rangle_o^{\text{in}})$$

$$L_2' = A_R \rho_f (C_{k,R})_o e - \frac{s}{(C_{k,R})_o} \Delta L_R$$

The pressure drop perturbation in control volume A can be calculated from integrating the momentum equation,

subject to the moving boundary, $\delta \hat{L}_D$. Thus,

$$\delta(\Delta \hat{p}_{DC}) = \left(\frac{L_D s}{g_c A_D} + \frac{f_D L_D W_{sw,o}}{g_c D_{H,D} A_D^2 \rho_f} \right) \delta \hat{w}_{sw} + \left(\frac{f W_{sw,o}^2}{2 g_c D_{H,D} A_D^2 \rho_f} - \frac{g}{g_c} \rho_f \right) \delta \hat{L}_D \quad (3.46)$$

From Equations (3.45) and (3.46), Equation (3.46) becomes,

$$\delta(\Delta \hat{p}_{DC}) = D_1(s) \delta \langle \hat{j}_p \rangle^{in} + D_2(s) \delta \langle \hat{\alpha}_p \rangle^{in} + D_3(s) \delta \hat{w} \quad (3.47)$$

where,

$$D_1(s) = D_4(s) L_1(s) \quad D_2(s) = D_4(s) L_2(s),$$

$$D_3(s) = - \frac{f W_{sw,o}^2}{2 g_c D_{H,D} A_D^2 \rho_f s} + \frac{g}{g_c A_D s}$$

$$D_4(s) = \frac{L_D s}{g_c A_D} + \frac{f_D L_D W_{sw,o}}{g_c D_{h,D} A_D^2 \rho_f} = D_3(s)$$

The single-phase portion of the recirculation loop in a BWR may have various cross-sectional flow areas, A_i for each segments, L_i . In addition, during forced circulation, the pressure increase due to the recirculation pump has to be included. Thus, from the single-phase momentum equation,

$$\delta(\Delta \hat{p}_{1\phi,loop}) = D_5(s) \delta \hat{w} \quad (3.48)$$

where,

$$D_5(s) = \frac{1}{g_c} \left(\sum_i^L \frac{L_i}{A_i} \right) s + \frac{w_o}{g_c \rho_f} \left(\sum_i^L \frac{f_i L_i}{D_{H,i} A_i^2} \right) - \frac{\xi}{\rho_f}$$

and L is the total number of axial segments. The parameter, ξ , is defined as the slope of the recirculation pump's head-flow curves^[22], shown in Figure 3.3 for a typical BWR/4. Also, as shown in Figure 3.4, for jet pumps, if the ratio, M , of the jet pump flow to the drive flow is known, ξ can be obtained from equivalent jet pump head-flow curves^[23].

From Equations (3.29), (3.42), (3.47) and (3.48), the total pressure drop perturbation around that part of flow loop external to the core is given as,

$$\delta(\hat{\Delta p}_{loop}) = (R_1 + D_1) \delta \langle \hat{j}_p \rangle^{in} + (U + R_2 + D_2) \delta \langle \hat{\alpha}_p \rangle^{in} + (D_3 + D_5) \delta \hat{w} \quad (3.49)$$

From Equations (3.14), (3.15), and noting, $\delta \hat{w} = \sum_i^N \delta \hat{w}_i$, Equation (3.49) becomes,

$$\delta(\hat{\Delta p}_{loop}) = \sum_i^N Q_{1,i} \delta \hat{j}_i + \sum_i^N \sum_j^K Q_{2,i}^j \delta \hat{q}_{i,j}''' + Q_3 \delta \hat{h}_i \quad (3.50)$$

where,

$$Q_{1,i} = (R_1 + D_1) N_{1,i} + (U + R_2 + D_2) P_{1,i} + (D_3 + D_5) \rho_f A_{x-s,i}$$

$$Q_{2,i}^j = (R_1 + D_1) N_{2,i}^j + (U + R_2 + D_2) P_{2,i}^j$$

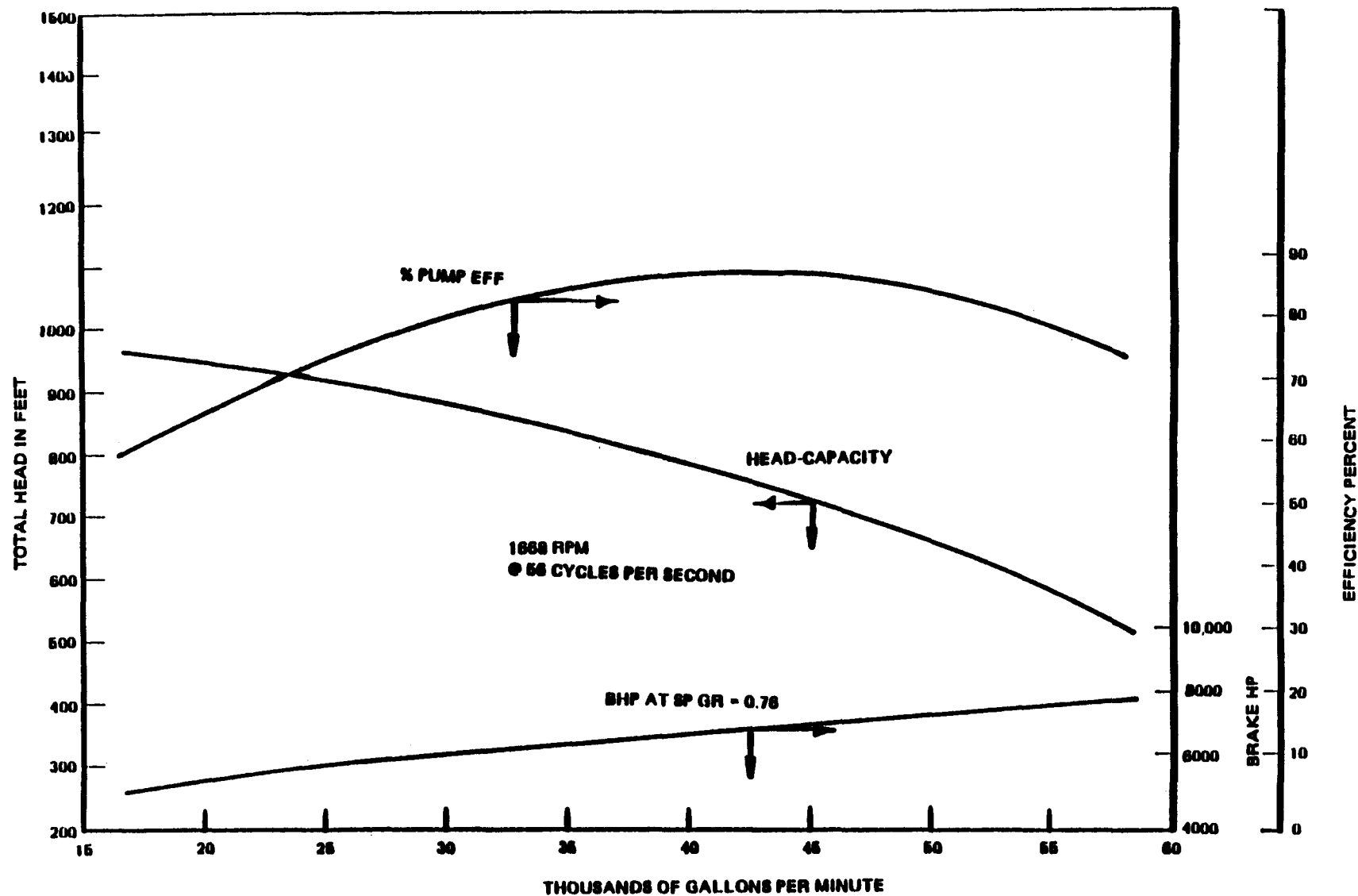


Figure 3.3 Recirculation Pump Characteristics at Rated Pump Speed

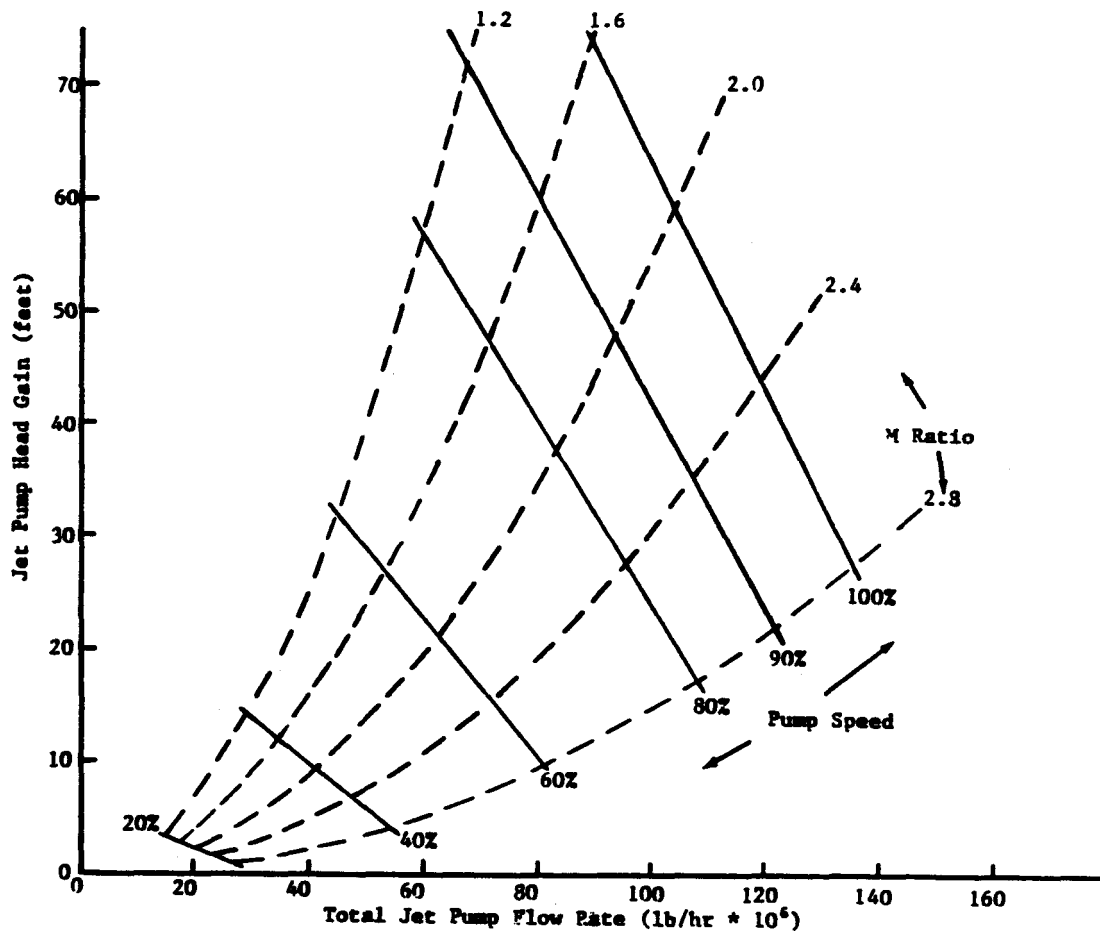


Figure 3.4 Typical Jet Pump System Head-Capacity Characteristics

$$Q_{3,i} = (R_1 + D_1)N_3 + (U + R_2 + D_2)P_3$$

3.4 ENTHALPY FEEDBACK

In the recirculating loop another feedback mechanism is the enthalpy perturbation which is caused by the flow rate perturbation in the downcomer and the wall dynamics of the reactor vessel. These enthalpy perturbations propagate as thermal waves to the core inlet and cause an inlet enthalpy perturbation, $\hat{\delta h}_i$, to the core. This perturbation must be eliminated in terms of the external forcing functions, $\hat{\delta j}_i$ and $\hat{\delta q}_{\text{core}}''''$. In order to accomplish this, we will use the time-dependent single-phase energy equation and a lumped parameter pressure vessel wall dynamics model for the downcomer and lower plenum. The energy equation of the fluid is,

$$\frac{\partial(wh)}{\partial z} + \rho A_v \frac{\partial h}{\partial t} = - q_v'' P_{H,v} \quad (3.51)$$

In order to solve this first order differential equation, we must obtain the proper boundary condition, the downcomer inlet enthalpy perturbation ($\hat{\delta h}_{\text{mix}}$). This can be obtained from the energy balance for control volume B in Figure 3.1,

$$wh_{\text{mix}} = w_e h_f + w_{fw} h_{fw} \quad (3.52)$$

Since we have assumed no storage, and that w_{fw} and h_{fw} are

constant, we can perturb and Laplace transform Equation(3.52) to obtain,

$$w_o \delta \hat{h}_{mix} + h_{mix,o} \delta \hat{w} = h_f \delta \hat{w}_e \quad (3.53)$$

The mass continuity equation for the region, assuming incompressibility, yields,

$$\delta \hat{w}_e = \delta \hat{w}_{in} \quad (3.54)$$

Therefore inserting Equation (3.54) into Equation (3.53),

$$\delta \hat{h}_{mix} = \frac{h_f - h_{mix,o}}{w_o} \delta \hat{w}_{in} \quad (3.55)$$

Since,

$$h_{mix,o} = \frac{w_{sw,o}}{w_o} h_f + \frac{w_{fw,o}}{w_o} h_{fw,o}$$

we have,

$$\delta \hat{h}_{mix} = \frac{w_{fw}}{2 w_o} (h_f - h_{fw}) \delta \hat{w} \quad (3.56)$$

Now perturbing and Laplace transforming Equation (3.51) and using the boundary condition in Equation (3.56), the exit enthalpy perturbation of the downcomer has the form (Appendix-XI),

$$\delta h_{DC}^{out} = D(s) \delta \hat{w} \quad (3.57)$$

In order to take into account the thermal inertia of

the lower plenum, one can assume "perfect mixing" and apply a lumped parameter vessel wall dynamics model. Thus the lower plenum energy equation will be,

$$M_{LP} c_{pf} \frac{dT_{LP}}{dt} = w_{LP}^{in} h_{LP}^{in} - w_{core} h_i - q_{LP}'' P_{H,LP} \quad (3.58)$$

Since, $w_{LP}^{in} = w_{core} = w$ and, $c_{pf} \delta \hat{T}_{LP} = \delta \hat{h}_i$, perturbing and Laplace transforming Equation (3.58) yields,

$$\delta \hat{h}_i = \frac{1}{M_{LP}s + w_0} \left[w_0 \delta \hat{h}_{DC}^{out} + (h_{DC,0} - h_{i0}) \delta \hat{w}_{core} - \delta \hat{q}_{LP}'' P_{H,LP} \right] \quad (3.59)$$

where,

$$h_{DC,0} = \frac{P_{H,V}}{w_0} \frac{b}{b_1} (e^{-b_1 L_{DC}} - 1) + h_{mix,0} \quad .$$

and b_1, b are defined in Appendix-XI. Using the results derived in Appendix-XI, $\delta \hat{q}_{LP}''$ can be obtained from Equation (XI.4) as,

$$\delta \hat{q}_{LP}'' = \frac{k_f \epsilon_v}{k_v \epsilon_v + H_{1\phi,0} \tanh(\epsilon_v d)} \left[\frac{a q_{LP,0}''}{w_0} \delta \hat{w} + \frac{H_{1\phi,0}}{c_{pf}} \delta \hat{h}_i \right] \quad (3.60)$$

where d is the effective thickness of the vessel wall in the lower plenum, and,

$$q_{LP,0}'' = \frac{H_{1\phi,0} (T_{in} - T_0)}{1 + H_{1\phi,0} \frac{d}{k_v}} \quad .$$

Inserting Equations (3.57) and (3.60) into Equation (3.59),

$$\hat{\delta h}_i = Y(s) \hat{\delta j}_i \quad (3.61)$$

Where,

$$Y(s) = \left[\frac{w_o D(s) + (h_{DC,o} - h_{1o}) - \tau(s) A_{H,LP} \frac{aq_{LP,o}'''}{w_o}}{M_{LP}s + w_o + \tau(s) \frac{H_{1\phi,o}}{c_{pf}} A_{H,LP}} \right] \rho_f A_{x-s}$$

$$\tau(s) = \frac{k_v \epsilon_v}{k_v \epsilon_v + H_{1\phi,o} \tanh(\epsilon_v d)}$$

Finally, the pressure drop perturbations for the core and the recirculating loop; Equations (2.72), (2.83) and (3.50), can be combined with Equation (3.61), such that the resulting expressions in terms of only the external forcing functions, $\hat{\delta j}_i$ and $\delta q_{core}'''$.

The final thermal-hydraulics transfer function for the core and recirculating loop can be combined with the appropriate neutronic transfer functions to perform BWR stability analysis in the frequency domain. Such analyses will be considered in the next part.

PART 4

STABILITY ANALYSIS

4.1 GENERAL

As discussed previously, self-excited oscillations may be caused by the lag introduced through finite speed of propagation of so-called kinematic density waves.

In a BWR, this thermal-hydraulic instability is further complicated due to inherent void-reactivity feedback. The interrelations of the important mechanisms that affect BWR stability characteristics are shown in the block diagram, given in Figure 4.1. Disturbances which enter the system can be due to reactivity perturbations from a control rod movement (δk_{ext}), or perturbation of such reactor parameters as flow rate, system pressure, power or inlet subcooling. In this study, our concern will be with flow rate, power, and reactivity perturbations.

In general, a BWR responds to a perturbation in a nonlinear manner. However, if the perturbation is sufficiently small, the nonlinear mathematical method for the system can be linearized and the resultant characteristic equation can be solved for the response of the variable of interest. The small perturbation stability procedures have been developed by Liapounov^[24]. This study uses these small perturbation procedures to evaluate the

stability of a BWR system, which is characterized by linear models of the thermal-hydraulics and neutron kinetics.

In the evaluation of the stability of a large linear system, the traditional approach has been to simplify the situation to that of considering only a single-input and single-output(SISO). The differential equations, with results from linearization of the nonlinear system about a given operating condition, can be simplified to algebraic equations by taking the Laplace transform with respect to time.

In order to easily represent the interrelation between the various transfer functions, block diagrams were utilized, which consisted of operational blocks that represent the transfer function of the variables of interest and the directions of operational flows. The simplified block diagram shown in Figure 4.1 shows the interrelations of the important mechanisms that affect the stability characteristics of a BWR.

The BWR stability analyses have normally^[25] been divided into two portions; reactor thermal-hydraulic analysis and coupled core neutron kinetics analysis. A state-of-the-art model for the reactor thermal-hydraulics has been developed herein. This model gives the void fraction perturbations required for neutronic coupling, and the channel inlet velocity feedback due to density-wave oscillation phenomena. The core neutron kinetics determines the time-

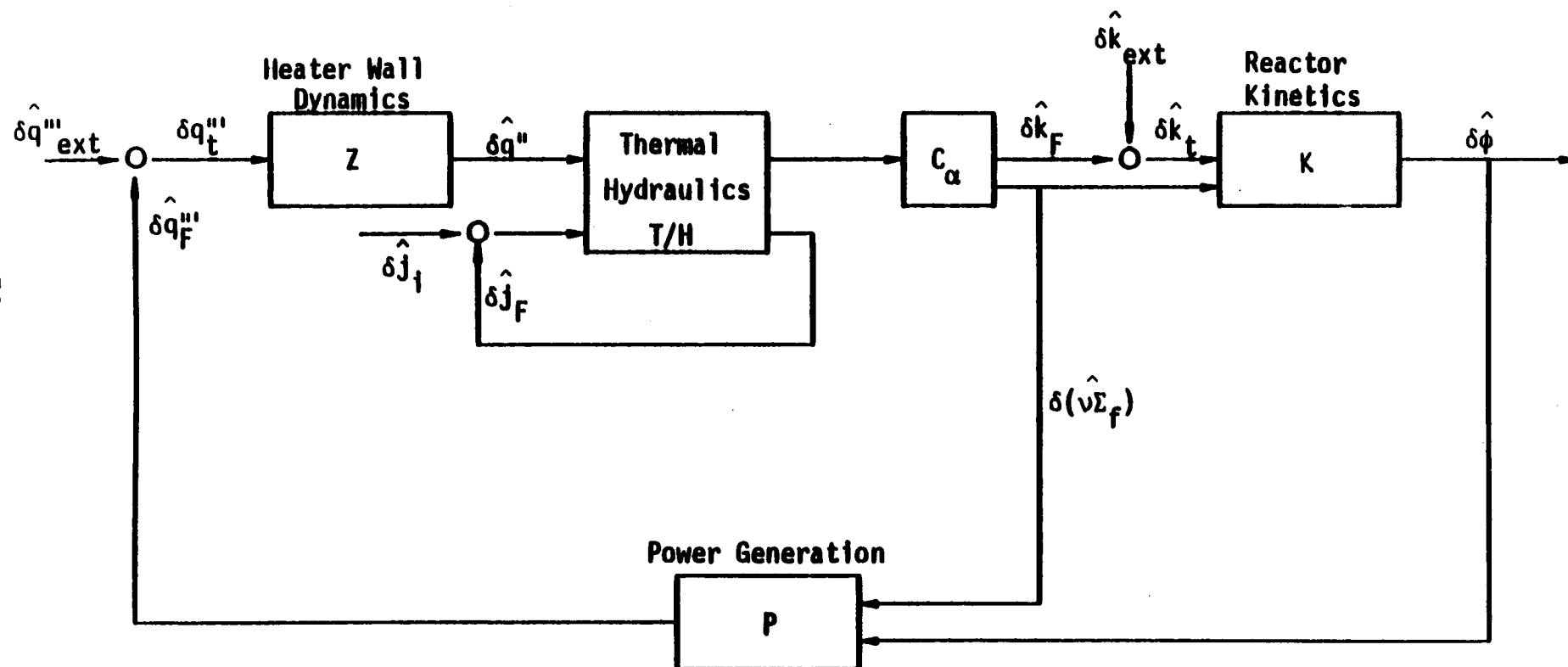


Figure 4.1 System Block Diagram for a BWR

dependent neutron flux balance which, in turn, causes a fuel rod surface heat flux perturbation, after a delay for a period of time related to the fuel element time constant. In this study, fuel temperature-reactivity feedback was neglected.

Previous works [9], [26] simplified the neutron kinetics model to point kinetics, perturbing only the reactivity among the various kinetics parameters. However it is widely recognized that the point kinetics model fails to account for the dynamic behaviour of a large core, or even a small core where a relatively small flux shape change may occur over short periods of time. In this study general space-time dependent kinetics^[27] will be utilized to analyze the neutron kinetics feedback in a BWR having non-uniform distributions of power, void, exposure, and control.

The final form of the state-of-the-art model for coupled thermal-hydraulics and neutron kinetics constitutes a multi-input, multi-output(MIMO) linear system. The stability of a typical BWR/4 has been investigated by servo-techniques. That is, by Nyquist or Bode plots.

4.2 DESCRIPTION OF NEUTRON KINETICS MODELS

A general space-time dependent kinetics model has been developed by utilizing 3D nodal analysis^[28]. A general flow scheme for nuclear kinetics is shown in Figure 4.2. As shown in this figure, the steady-state nodal parameters

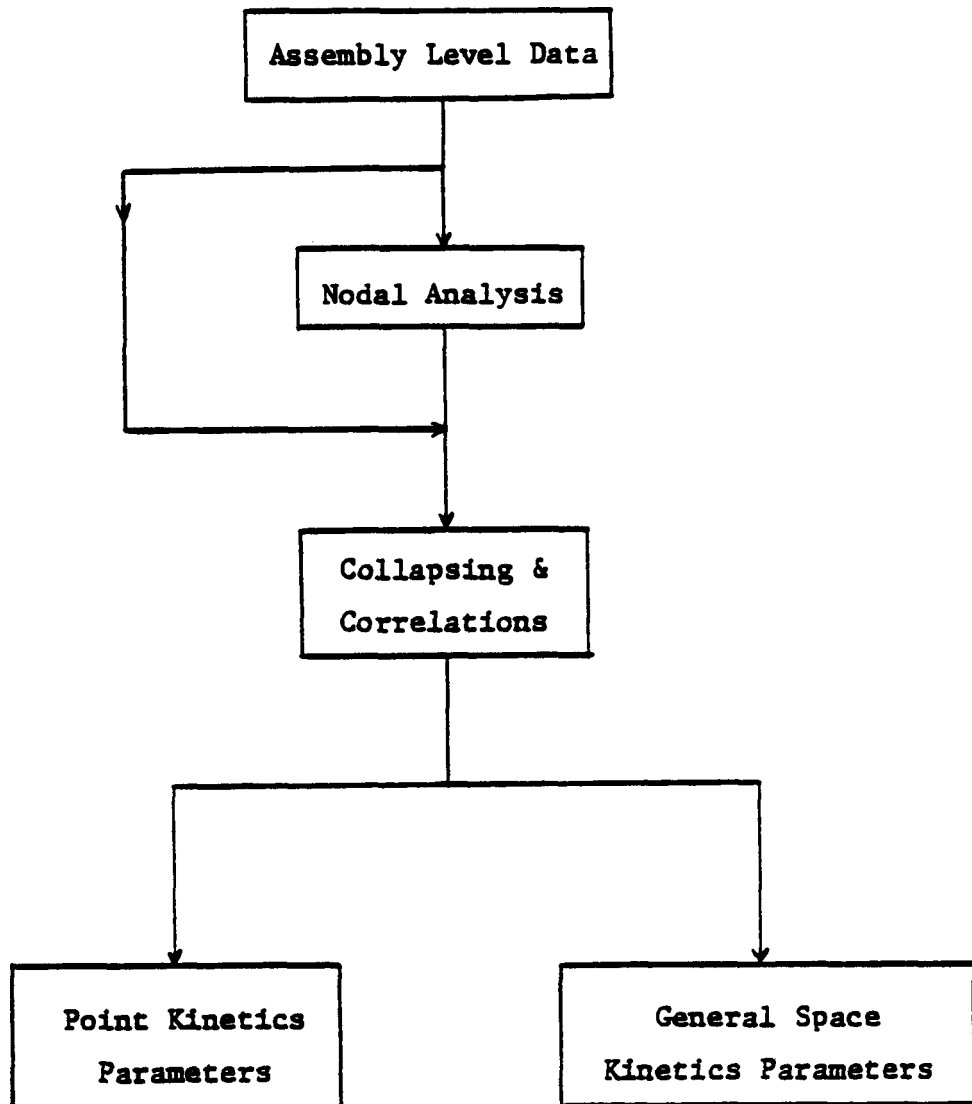


Figure 4.2 Data Flow Scheme for Nuclear Kinetics

and power distribution are obtained from a nodal code such as SIMULATE^[29] using assembly level data obtained from codes such as CASMO^[30], CPM^[31], or EPRICELL^[32]. Nuclear kinetics parameters are then calculated by using correlations as functions of void fraction and exposure^[33].

The present work for neutron kinetics can treat a general point kinetics model, where all nuclear parameters are perturbed. The spatially coupled nodal kinetics models include axially coupled(1-D), radially coupled(2-D), and 3-dimensionally coupled options.

4.2.1 Point Kinetics Model

The general form of the point kinetics equation^[27] obtained from the time-dependent diffusion equation is given as,

$$\frac{dn}{dt} = \frac{\rho - \bar{\beta}}{\Lambda} n + \sum_{l=1}^6 \lambda_l C_l, \quad (4.1)$$

$$\frac{dC_l}{dt} = \frac{\bar{\beta}_l}{\Lambda} n - \lambda_l C_l, \quad (4.2)$$

where the subscript l is the group index of the delayed neutrons, and the other notation is conventional.

Perturbing and Laplace transforming Equations (4.1) and (4.2) gives,

$$s\hat{\delta n} = -\frac{\beta_0}{\Lambda_0} \hat{\delta n} + \frac{n_0}{\Lambda_0} (\hat{\delta \rho} - \hat{\delta \beta}) + \frac{\beta_0}{\Lambda_0^2} n_0 \hat{\delta \Lambda} + \sum_{l=1}^6 \lambda_l \hat{\delta C}_l, \quad (4.3)$$

$$s\hat{C}_l = \frac{\beta_{l0}}{\Lambda_0} \delta\hat{n} + \frac{n_0}{\Lambda_0} \delta\hat{\beta}_l - \frac{\beta_{l0}n_0}{\Lambda_0^2} \delta\hat{\Lambda} - \lambda_l \delta\hat{C}_l, \quad (4.4)$$

Substituting Equation (4.4) into Equation (4.3), and rearranging, yields,

$$\left(s - \frac{s}{\Lambda_0} \sum_{l=1}^6 \frac{\beta_{l0}}{s+\lambda_l}\right) \delta\hat{n} = \frac{n_0}{\Lambda_0} (\delta\hat{\rho} - s \sum_{l=1}^6 \frac{\delta\hat{\beta}_l}{s+\lambda_l} + \frac{s}{\Lambda_0} \delta\hat{\Lambda} \sum_{l=1}^6 \frac{\beta_{l0}}{s+\lambda_l}) \quad (4.5)$$

The power(P) produced by the fissile material in the fuel has been expressed as,

$$P = V_f q''' = \kappa_f \sum_f \phi V \quad (4.6)$$

where V_f and κ_f are fuel volume and the average energy release associated with the fission process, respectively. However, some portion of the power generated is due to the fission product decay heat. Thus, a more realistic q''' can be given as,

$$q''' = \frac{P}{V_f} = \kappa_f \sum_f \phi (1-\epsilon) \frac{V}{V_f} + \frac{P_d}{V_f} \quad (4.7)$$

where ϵ is the fraction of κ_f attributable to fission product decay, which is assumed to be the same for each node.

For the power attributable to fission product decay, P_d we can write,

$$P_d = \sum_{l=1}^{N_G} \lambda_l I_l E_l V \quad (4.8)$$

where N_G , λ_l , I_l and E_l are the number of fission product

groups, and the decay constant, the number density, and the energy release per decay of the ℓ -th group, respectively.

The rate equation for the ℓ -th group is given as,

$$\frac{dI_{\ell}}{dt} = \gamma_{\ell} \sum_f \phi - \lambda_{\ell} I_{\ell} \quad (4.9)$$

where γ_{ℓ} is the yield fraction of the ℓ -th group.

Combining the perturbed and Laplace transformed equations for Equations (4.8) and (4.9), we obtain,

$$\hat{\delta P}_d = \frac{V}{v} \sum_{\ell=1}^{N_G} \frac{\lambda_{\ell} \epsilon_{\ell} \kappa_f}{s + \lambda_{\ell}} \{ (\nu \sum_f)_0 \hat{\delta \phi} + \phi_0 \delta(\hat{\nu} \sum_f) \} \quad (4.10)$$

where,

$$\epsilon_{\ell} = \frac{\gamma_{\ell}}{\kappa_f} E_{\ell}$$

Perturbing and Laplace transforming Equation (4.7) yields,

$$\hat{\delta q}''' = \frac{\kappa_f}{v} (1 - \epsilon) \frac{V}{V_f} \{ (\nu \sum_f)_0 \hat{\delta \phi} + \phi_0 \delta(\hat{\nu} \sum_f) \} + \frac{\hat{\delta P}_d}{V_f} \quad (4.11)$$

Inserting Equation (4.10) into Equation (4.11),

$$\hat{\delta q}''' = \frac{\kappa_f}{v} \frac{V}{V_f} \{ 1 - \epsilon + \sum_{\ell=1}^{N_G} \frac{\lambda_{\ell} \epsilon_{\ell}}{s + \lambda_{\ell}} \} \{ (\nu \sum_f)_0 \hat{\delta \phi} + \phi_0 \delta(\hat{\nu} \sum_f) \} \quad (4.12)$$

For steady-state, Equations (4.8) and (4.9) yield,

$$P_{d,0} = \frac{V \kappa}{v} \sum_{\ell=1}^{N_G} \epsilon_{\ell} (\nu \sum_f)_0 \phi_0 \quad (4.13)$$

Inserting Eq. (4.13) into Eq. (4.7) and using,

$$q_0''' = \frac{\kappa_f}{v} \frac{V}{V_f} (v \sum_f)_0 \phi_0 \quad (4.14)$$

Finally, from Equation (4.14), and noting, $\phi = nv$, Equation (4.12) becomes,

$$\frac{\delta \hat{q}_0'''}{q_0'''} = C \left\{ \frac{\delta \hat{n}}{n_0} + \frac{\delta \hat{v}}{v_0} + \frac{\delta (\hat{v} \sum_f)}{(v \sum_f)_0} \right\} \quad (4.15)$$

where,

$$C \triangleq 1 - \epsilon + \sum_{\ell=1}^{NG} \frac{\lambda_{\ell} \epsilon_{\ell}}{s + \lambda_{\ell}}$$

If we neglect the fission product decay heat effect, C in Equation (4.15) will be unity. Eleven fission product groups were used to predict C in this study. Table 4.1 shows ϵ_{ℓ} and λ_{ℓ} for each group.

Substituting Equation (4.5) into Equation (4.15) gives,

$$\delta \hat{q}_0''' = C \left\{ \frac{q_0'''}{v_0} \delta \tilde{v} + \frac{q_0'''}{v \Sigma_{f0}} \delta v \Sigma_f + \frac{q_0'''}{\Lambda_0 s + s \sum_{\ell=1}^6 \frac{\beta_{\ell 0}}{s + \lambda_{\ell}}} \right. \\ \left. \times \left[\delta \tilde{\rho} - s \sum_{\ell=1}^6 \frac{\delta \beta_{\ell}}{s + \lambda_{\ell}} + \frac{\delta \Lambda}{\Lambda_0} s \sum_{\ell=1}^6 \frac{\beta_{\ell 0}}{s + \lambda_{\ell}} \right] \right\} \quad (4.16)$$

Using the void coefficients, C_{ρ} , C_{Λ} , $C_{\beta_{\ell}}$, $C_{v \Sigma_f}$ and C_v , of the nuclear parameters, ρ , Λ , β_{ℓ} , $v \Sigma_f$ and v respectively, the final form of point kinetics transfer function, $\Phi(s)$, is,

Table 1

Fission Product Group Constants

<u>Group, (g)</u>	<u>ϵ_g</u>	<u>$\lambda^{(g)}(\text{sec}^{-1})$</u>
1	0.00299	1.772
2	0.00825	0.5774
3	0.01550	6.743×10^{-2}
4	0.01935	6.214×10^{-3}
5	0.01165	4.739×10^{-4}
6	0.00645	4.810×10^{-5}
7	0.00231	5.344×10^{-6}
8	0.00164	5.726×10^{-7}
9	0.00085	1.036×10^{-7}
10	0.00043	2.959×10^{-8}
11	0.0057	7.585×10^{-10}

Table 4.1 Fission Product Group Constant

$$\delta q''' = \phi(s) \delta \langle \hat{\alpha} \rangle \quad (4.17)$$

where,

$$\phi = c \left[\frac{C_v}{v_0} + \frac{C_{v\Sigma_f}}{v\Sigma_{f0}} + \frac{C_\rho - s \sum_{l=1}^6 \frac{C_{\beta_l}}{s+\lambda_l} + \frac{C_\Lambda}{\Lambda_0} s \sum_{l=1}^6 \frac{\beta_{l0}}{s+\lambda_l}}{\Lambda_0 s + s \sum_{l=1}^6 \frac{\beta_{l0}}{s+\lambda_l}} \right] q_0''$$

4.2.2 General Space Kinetics Model

The one-energy-group kinetics equation is given as,

$$\frac{\partial}{\partial \tau} \left(\frac{\phi}{v} \right) = \nabla \cdot D \nabla \phi + \frac{1}{k_{eff}} (1-\beta) v \Sigma_f \phi - \Sigma_a \phi + \sum_{l=1}^6 \lambda_l C_l, \quad (4.18a)$$

$$\frac{\partial C_l}{\partial \tau} = \frac{1}{k_{eff}} \beta_l v \Sigma_f \phi - \lambda_l C_l, \quad (4.18b)$$

where the notation is conventional.

Perturbing and Laplace transforming Equations (4,18a) and (4,18b), and integrating the resultant equations over the volume of node-m, V_m , yields,

$$\begin{aligned} & -\frac{1}{V_m} \int_{V_m} \nabla \cdot D_0 \nabla \delta \phi dV + \left\{ \Sigma'_{amo} - \frac{1}{k_{eff}} (1-\beta_{mo}) v \Sigma_{fmo} \right\} \delta \phi_m \\ & = \frac{1}{V_m} \int_{V_m} \nabla \cdot \delta D \nabla \phi_0 dV + \left\{ \frac{1}{k_{eff}} (1-\beta_{mo}) \delta v \Sigma_{fmo} - \delta \Sigma'_{amo} \right\} \end{aligned}$$

$$- \frac{v\Sigma_{fmo}}{k_{eff}} \delta \tilde{\beta}_m \} \phi_{mo} + \sum_{l=1}^6 \lambda_l \delta \tilde{C}_{lm} , \quad (4.19)$$

$$\begin{aligned} \delta \tilde{C}_{lm} = & \frac{1}{(s+\lambda_l)k_{eff}} (\beta_{lmo} \delta v \tilde{\Sigma}_{fm} + v\Sigma_{fmo} \delta \tilde{\beta}_{lm}) \phi_{mo} \\ & + \frac{\beta_{lmo} v\Sigma_{fmo}}{(s+\lambda_l)k_{eff}} \delta \tilde{\phi}_m , \end{aligned} \quad (4.20)$$

where,

$$\Sigma'_{amo} = \Sigma_{amo} + \frac{s}{v_{mo}} ,$$

$$\delta \tilde{\Sigma}'_{am} = \delta \tilde{\Sigma}_{am} - \frac{s}{v_{mo}^2} \delta \tilde{v}_m ,$$

Substituting Equation (4.20) into Equation (4.19) gives,

$$\begin{aligned} & - \frac{1}{v_m} \int_{V_m} \nabla \cdot D_0 \nabla \delta \tilde{\phi} dV + \{ \Sigma'_{amo} - \frac{1}{k_{eff}} (1-s \sum_{l=1}^6 \frac{\beta_{lmo}}{s+\lambda_l}) v\Sigma_{fmo} \} \delta \tilde{\phi}_m \\ & = \frac{1}{v_m} \int_{V_m} \nabla \cdot \delta D \nabla \phi_0 dV + \{ \frac{1}{k_{eff}} (1-s \sum_{l=1}^6 \frac{\beta_{lmo}}{s+\lambda_l}) \delta v \tilde{\Sigma}_{fm} - \delta \tilde{\Sigma}'_{am} \\ & \quad - \frac{s}{k_{eff}} (\sum_{l=1}^6 \frac{\delta \tilde{\beta}_{lm}}{s+\lambda_l}) v\Sigma_{fmo} \} \phi_{mo} . \end{aligned} \quad (4.21)$$

The neutron leakage term in Equation (4.21) can be calculated from the divergence and mean value theorem by applying the nodal method [34] as,

$$-\frac{1}{V_m} \int_{V_m} \nabla \cdot D_o \nabla \delta \tilde{\phi} dV = \sum_{n=1}^6 (a_m)_n v \Sigma_{fmo} \delta \tilde{\phi}_m - \sum_{n=1}^6 (a_n)_m (v \Sigma_{fno})_m \delta (\phi_n)_m, \quad (4.22)$$

$$\begin{aligned} \frac{1}{V_m} \int_{V_m} \nabla \cdot \delta \tilde{D} \nabla \phi_o dV &= \frac{\delta \tilde{D}_m}{D_{mo}} \left\{ - \sum_{n=1}^6 (a_{mo})_n v \Sigma_{fmo} \phi_{mo} \right. \\ &\quad \left. + \sum_{n=1}^6 (a_{no})_m (v \Sigma_{fno})_m (\phi_{no})_m \right\}, \end{aligned} \quad (4.23)$$

where,

$$(a_m)_n = \frac{(A_n)_m}{V_m} \frac{r_{mo}(1-\rho_{mo})}{(1-\rho_{mo}\rho_{mo})} \frac{t'_m}{t'_m-1} \frac{k_{mo}^{-1}}{k_{mo}},$$

$$(a_n)_m = \frac{(A_n)_m}{V_m} \frac{r_{mo}(1-\rho_{mo})}{(1-\rho_{mo}\rho_{mo})} \frac{t'_n}{t'_n-1} \frac{k_{no}^{-1}}{k_{no}},$$

$$(a_{mo})_n = \frac{(A_n)_m}{V_m} \frac{r_{mo}(1-\rho_{mo})}{(1-\rho_{mo}\rho_{mo})} \frac{t_{mo}}{t_{mo}-1} \frac{k_{mo}^{-1}}{k_{mo}},$$

$$(a_{no})_m = \frac{(A_n)_m}{V_m} \frac{r_{mo}(1-\rho_{mo})}{(1-\rho_{mo}\rho_{mo})} \frac{t_{no}}{t_{no}-1} \frac{k_{no}^{-1}}{k_{no}},$$

and, $(A_n)_m$ is the interface area between node m and surrounding node n. The nodal parameters, ρ , r , t , k are the node escape probability, the neutron direct reflection

factor, the total nodal multiplication, and the infinite multiplication factor of the node, respectively.

Combining Equations (4,21), (4,22) and (4,23) and inserting the result into Equation (4.15), we obtain,

$$B_m \delta \tilde{q}_m''' - \sum_{n=1}^6 (a_n)_m \delta (\tilde{q}_n''')_m = - \sum_{n=1}^6 (z_n)_m (q_{no}''')_m \delta \langle \tilde{\alpha} \rangle_n$$

$$+ \{ K_m q_{mo}''' + \frac{C_{Dm}}{D_{mo}} \sum_{n=1}^6 (a_{no})_m (q_{no}''')_m \} \delta \langle \tilde{\alpha} \rangle_m, \quad (4.24)$$

where,

$$B_m = \sum_{n=1}^6 (a_{mo})_n + \frac{1}{k_{eff}} (s \sum_{l=1}^6 \frac{\beta_{lmo}}{s + \lambda_l} - 1) + \frac{\Sigma'_{amo}}{v \Sigma_{fmo}},$$

$$K_m = - \frac{C_{Dm}}{D_{mo}} \sum_{n=1}^6 (a_{mo})_n - \frac{s}{k_{eff}} \sum_{l=1}^6 \frac{C_{\beta_{lm}}}{s + \lambda_l} - \frac{C_{\Sigma'_{am}}}{v \Sigma_{fmo}}$$

$$+ \frac{C_{v \Sigma_{fmo}}}{v \Sigma_{fmo}} \{ \sum_{n=1}^6 (a_m)_n + \frac{\Sigma'_{amo}}{v \Sigma_{fmo}} \},$$

$$(z_n)_m = \frac{C_{(v \Sigma_{fn})_m}}{(v \Sigma_{fno})_m} (a_n)_m,$$

Finally, Equation (4.24) can be written in matrix form as,

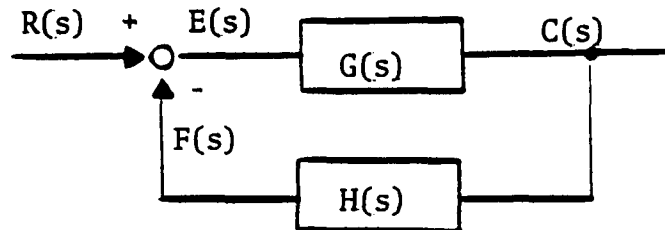
$$\underline{P} \underline{\delta \tilde{q}_f'''} = \underline{L} \underline{\delta \langle \tilde{\alpha} \rangle} \quad (4.25)$$

The general nodal kinetics equation, Equation (4,25),

can be applied to various geometries such as one-dimension(single channel, axial coupling), two-dimension(multi-channel, radial coupling), and three-dimensional arrays.

4.3 STABILITY CRITERION

As discussed previously, in the evaluation of the stability of a large linear system, the traditional approach has been to simplify the situation to that of considering only a SISO stability analysis. Thus the simple block diagram for a feedback control system, shown below, is used.



The closed-loop system transfer function becomes,

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1+G(s)H(s)} \quad (4.26)$$

where $G(s)$ is the so-called forward loop transfer function and $H(s)$ is the feedback loop transfer function.

The transfer functions, $G(s)$ and $H(s)$, determine the various forms of the closed loop transfer function(eg:

rational, polynomial or exponential) for the actual system. However, we can approximate Equation (4.26) by Taylor's expansion of the exponential delay terms to obtain a simple rational form of polynomials,

$$C(s) = \left[\frac{b_0 + b_1 s + \dots + b_m s^m}{a_0 + a_1 s + \dots + a_n s^n} \right] R(s) \quad (4.27)$$

The partition method and inverse Laplace transform for Equation (4.27) results in the transient response of the system as,

$$C(t) = \sum_{i=1}^M A_i e^{-\sigma_i t} + \sum_{k=1}^N B_k e^{-\alpha_k t} \sin \omega_k t \quad (4.28)$$

where $s = \sigma_i$, $-\alpha_k \pm j\omega_k$ are the real and complex roots of the denominator of Equation (4.27).

The transient response implied by Equation (4.28) is composed of exponential terms and damped oscillating terms. Obviously, in order for the response to be stable (ie: bounded for a bounded input), the real parts of the roots, σ_i and α_k are required to be in the left-hand portion of the s-plane.

In order to determine the locations of the poles of Equation (4.26) [ie: the roots of the denominator, the so-called characteristic equation], various methods have been developed^[35]. In this study, the Nyquist criterion was employed, relating the number of zeros of the open loop

transfer function, having non-negative real parts, to the number of poles with non-negative real parts, and as shown in Figure 4.3, the number of encirclements of the $(-1,0)$ point by the GH locus (or, equivalently, the number of encirclements of the origin of $1+GH$). In particular, if GH has no poles in the right half-plane ($\text{Re}(s) \geq 0$), the necessary sufficient and conditions for stability is that the Nyquist locus does not go through or encircle the $(-1,0)$ point.

The question of the number of poles of the transfer function for a boiling channel was discussed previously^[35]. It was shown there that in the case of a simple two-phase flow model (no slip, uniform heat flux, etc.) all the singularities of the transfer function, $\Gamma_1 + \pi_1$, are removable. Although a similar proof for a more complicated model, such as that used in this paper, would be extremely difficult, indirect evidence for the above property can be provided by examining the nature of the nodal system equations, complemented by a parametric analysis of numerical results and their experimental verification.

Since in the case considered here we use, $1+GH = 1 + \frac{\pi_1}{\Gamma_1} = \frac{\Gamma_1 + \pi_1}{\Gamma_1}$, where $\Gamma_1(s)$ has no zeros for $\text{Re}(s) \geq 0$, we conclude that the boiling system is stable (or unstable) if the Nyquist locus for its open loop transfer function does (or does not) go through or encircle the point $(-1,0)$.

A typical Nyquist plot is shown in Figur

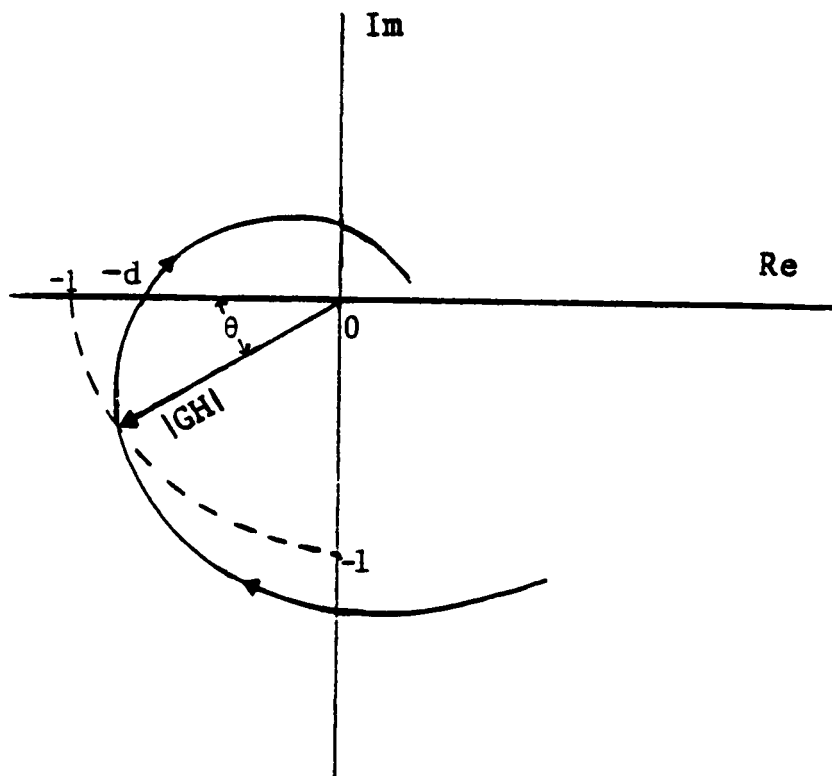


Figure 4.3 A Typical Nyquist Plot

From the plot shown in Fig. 4.3, we can determine two stability margins. First, the gain margin, M , is a measure of how much the system gain would have to be increased for the GH locus to pass through the -1 point on the complex plane. It is defined in terms of decibels as,

$$M = 20 \log(1/d)$$

where d is the distance shown in Figure 4.2. The next is the phase margin, θ , which is defined as the phase angle through which the GH locus must be rotated in order that the unity magnitude point, $|GH| = 1$ pass through the -1 point in the GH plane. These two factors are a measure of the system's relative stability, and can be read off the Nyquist plot.

Another approach which was used to determine BWR stability in this study, is the damping ratio, ζ , which is a global measure of the decay of all oscillatory response modes. The characteristic equation of Equation (4.27) may have a pair of complex conjugate poles, which have the form of $\{1 + (2\zeta/\omega_n)j\omega + (j\omega/\omega_n)^2\}$, where ω_n is called as the natural frequency. To demonstrate analytically that no divergent oscillation will occur in the system, the damping ratio must be positive (ie; $\zeta > 0$). Moreover, the desirable specification is a large ζ , which insures a rapid approach to the desired steady-state. In order to

determine ζ , a Bode diagram was used, which is a plot of the system's closed loop transfer function. The damping ratio can be determined by fitting a reduced order transfer function to the magnitude and phase in the system's Bode plot. The general empirical model^[37] is shown in Appendix-XII.

The next section shows the stability analysis procedure used for obtaining the open loop transfer function for the coupled thermal-hydraulics and neutron kinetics models of the parallel channels and the recirculating loop of a BWR.

4.4 FREQUENCY DOMAIN STABILITY ANALYSIS

Density-wave oscillation phenomena are based on a constant pressure drop boundary condition which, for the parallel channel case(ch), is^[2],

$$\delta(\hat{\Delta p}_{1\phi})_{ch} + \delta(\hat{\Delta p}_{2\phi})_{ch} = 0 \quad (4.29)$$

and, for the recirculating loop case(loop), is^[2],

$$\delta(\hat{\Delta p}_{1\phi})_{loop} + \delta(\hat{\Delta p}_{2\phi})_{loop} = 0 \quad (4.30)$$

By inserting the appropriate transfer functions, discussed in the previous parts of this report, into these boundary conditions, Equations (4.29) and(4.30), we can obtain the open loop transfer functions,

$$GH = - \frac{\delta \hat{q}_F'''}{\delta \hat{q}_t'''} , \quad - \frac{\delta \hat{j}_{i,F}}{\delta \hat{j}_{i,t}} , \text{ or } , - \frac{\delta \hat{k}_F}{\delta \hat{k}_{ext}} \quad (4.31)$$

which are measures of the stability in the Nyquist criterion. It has been shown previously [39] that all of these expressions yield the same instability threshold, but that stability margin is nonunique. Thus case must be used in the application of the Nyquist technique to a BWR.

For the core-average power perturbation, the appropriate block diagram is shown in Figure 4.4. For various types of spatial coupling, the matrix form of the neutron kinetics is given in Equation (4.25) as,

$$\underline{\underline{P}} \underline{\underline{\delta \hat{q}_F'''}} = \underline{\underline{L}} \underline{\underline{\delta \langle \hat{\alpha} \rangle}} \quad (4.32)$$

The power-to-node-average-void-fraction transfer function is derived in Appendix XIII for coupled parallel channels in the core and the recirculating loop, as,

$$\underline{\underline{\delta \langle \hat{\alpha} \rangle}} = \underline{\underline{F}} \underline{\underline{\delta \hat{q}_{core,t}'''}} \quad (4.33)$$

Combining Equations (4.32) and (4.33) yields,

$$\underline{\underline{P}} \underline{\underline{\delta \hat{q}_F'''}} = \underline{\underline{L}} \underline{\underline{F}} \underline{\underline{\delta \hat{q}_{core,t}'''}} \quad (4.34)$$

The technique used to solve this matrix equation was the Gauss-Reduction^[39] method since the matrices P and L are sparse. Thus the number of arithmetic operations and the amount of data storage required can be kept small by treating only the non-zero elements.

The core-average $\delta \hat{q}_{core,F}'''$ is obtained by volume

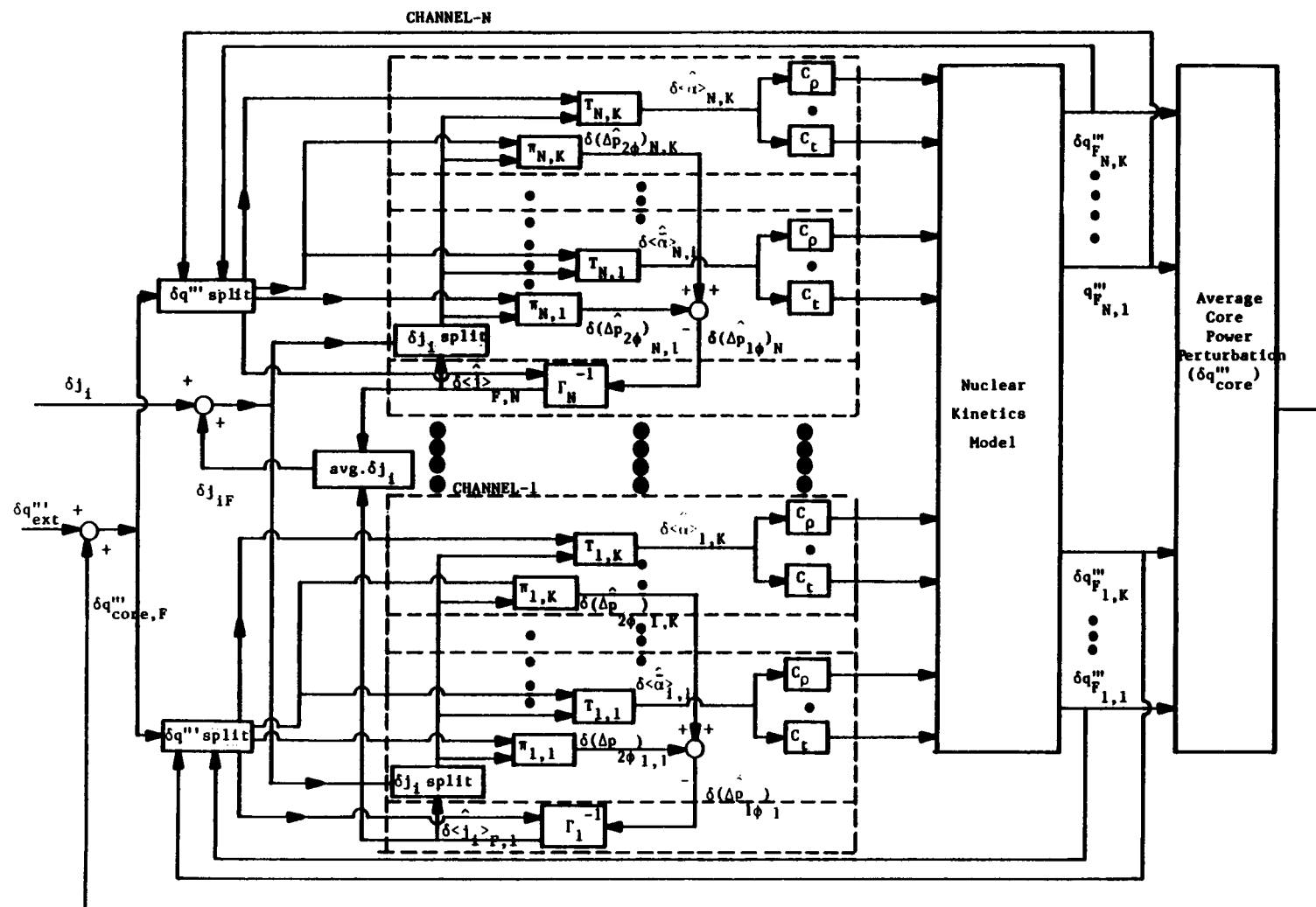


Figure 4.4 System Block Diagram for General Space Kinetics Model

weighting as,

$$\hat{\delta q}_{core,F}''' = \frac{\sum_{n=1}^N \hat{\delta q}_{n,F}''' V_n}{\sum_{n=1}^N V_n} \quad (4.35)$$

where N stands for the total number of nodes.

Finally the open loop transfer function may be written as,

$$- \frac{\hat{\delta q}_{core,F}'''}{\hat{\delta q}_{core,t}'''} = - \frac{\sum_{n=1}^N \hat{\delta q}_{n,F}''' V_n}{\hat{\delta q}_{core,t}''' \sum_{n=1}^N V_n} \quad (4.36)$$

The open loop transfer function of the channel inlet flow velocity, $-\hat{\delta j}_{i,F}/\hat{\delta j}_{i,t}$, has not been worked out for the multidimensional model shown in Figure 4.4, but can be determined from the block diagram shown in Figure 2.9, for the case of point kinetics,

$$- \frac{\hat{\delta j}_{i,F}}{\hat{\delta j}_{i,t}} = \frac{1}{\Gamma_1} \left\{ \pi_1 + \frac{\Phi C_\alpha T_1 (\Gamma_2 + \pi_2)}{1 - T_2 \Phi C_\alpha} \right\} \quad (4.37)$$

Similarly, for the case of reactivity perturbation, in the point kinetics model,

$$- \frac{\hat{\delta k}_F}{\hat{\delta k}_{ext}} = - \Phi C_\alpha \left\{ T_2^{-T_1} \frac{\pi_2 + \Gamma_2}{\pi_1 + \Gamma_1} \right\} \quad (4.38)$$

In order to perform BWR stability analysis with these open loop transfer functions (ie: Equations (4.36), (4.37),

and(4.38)), a digital computer code, NUFREQ-N, was developed. In the following part of this report, the NUFREQ-N code will be discussed and compared with various experiments. Finally a typical BWR/4 will be analyzed and the effect of several reactor parameters on the stability margin will be demonstrated.

PART 5
RESULTS FROM THE NUFREQ-N CODE

5.1 GENERAL DESCRIPTION OF THE NUFREQ-N CODE

A computer code called NUFREQ-N has been developed to analyze, in the frequency domain, nuclear coupled density-wave oscillations in BWRs. The NUFREQ-N code is a vastly improved version of the NUFREQ code^[9].

The NUFREQ-N code can produce a Nyquist plot corresponding to a perturbation in one of three reactor parameters; the channel inlet velocity, the core-average power density, or the core neutron multiplication factor. In addition, other important transfer functions (eg: power-to-void, and, power-to-flow) can be evaluated to analyze experimental data. The detailed mathematical models for the thermal-hydraulics of the reactor and the core neutron kinetics have been discussed in previous parts of this report.

The reactor core is represented in the NUFREQ-N code using nodalization. One node per assembly is used in the radial direction and a maximum 30 axial nodes can be used. This is compatible with replacing the actual power generation curve by a stair-case (ie: piece-wise constant) function. Based on the channel inlet conditions and channel geometry, the steady-state parameters of each node,

and the nodal pressure drop perturbation and void fraction perturbations can be calculated at any chosen angular frequency(ω). In this calculation, various correlations are optionally used to generate the steady-state parameters(eg: the heat transfer coefficient in the two-phase region, and the drift-flux parameters, etc.). Next, the nodal pressure drop perturbations are summed to obtain the channel pressure drop perturbation, and the nodal void fraction perturbations are averaged to obtain the void fraction perturbation in the channel. The channel's pressure drop perturbation is added to the pressure drop perturbation in the recirculating loop, to determine the pressure drop perturbation in the loop.

By applying the constant pressure drop boundary conditions and coupling the node-averaged, or channel-averaged, void fraction perturbation with the neutron kinetics model, one can obtain the open-loop transfer function discussed in Part 4. This procedure is summarized in the overall flow chart shown in Figure 5.1. A brief description of all subroutines used in the NUFREQ-N code are listed in Appendix XIV. Appendix XV gives the input/output instruction for the use of NUFREQ-N code, and Appendix XVI presents a sample problem. A FORTRAN listing of the NUFREQ-N code is given in Appendix XVII.

In order to confirm the nodal approach in the code we tested the sensitivity of the results to increasing the

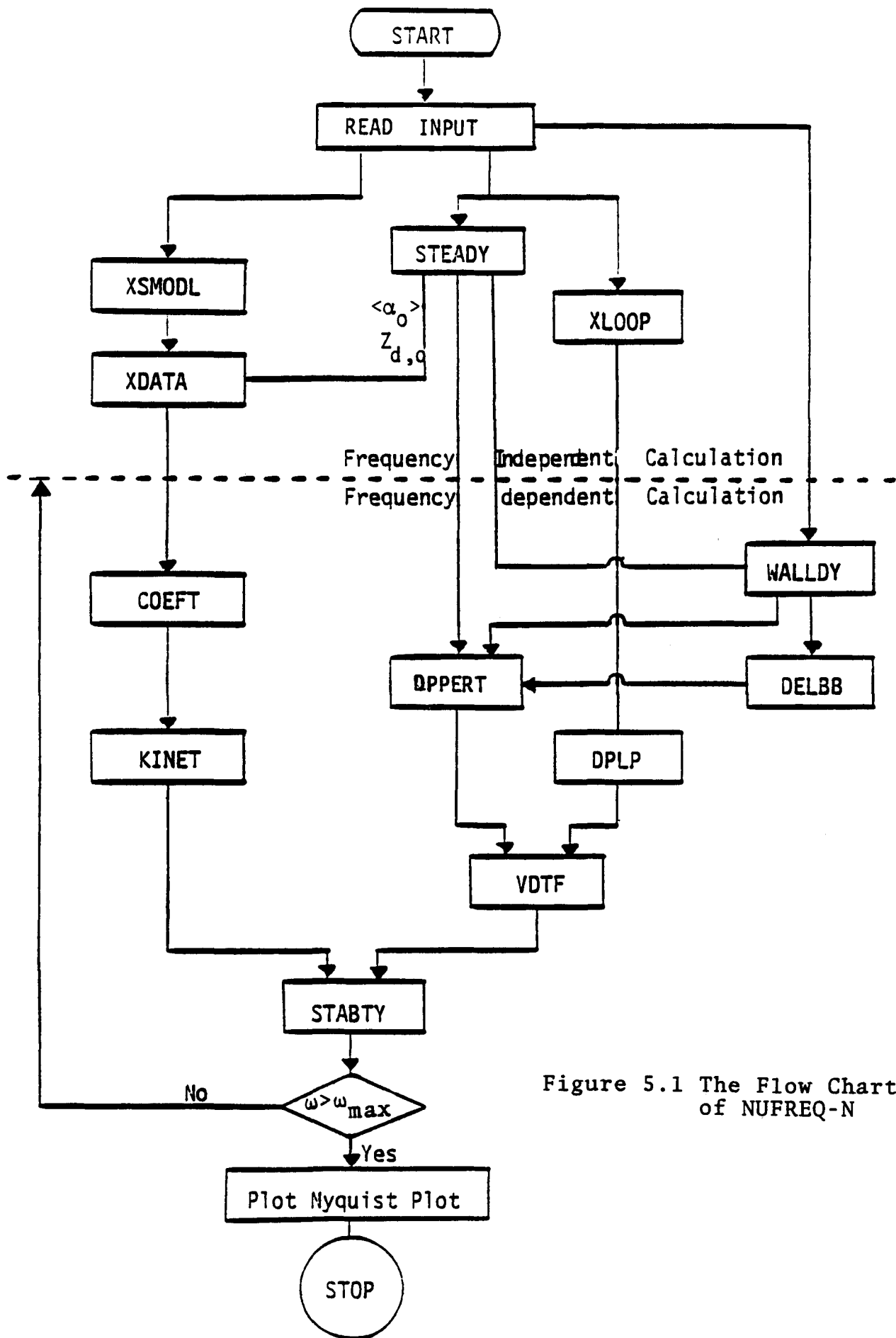


Figure 5.1 The Flow Chart of NUFREQ-N

number of nodes for both uniform and nonuniform power distribution. In these sensitivity studies typical BWR/4 conditions and point kinetics model was employed. As shown in Figures 5.2 and 5.3, it has been found that 8 axial nodes for the uniform power distribution and 12 axial nodes for the nonuniform power distribution converged quite well to benchmark solutions for 24 axial nodes.

5.2 PARAMETRIC STUDY

Using the NUFREQ-N code, we have investigated the effect of various thermal-hydraulic parameters on BWR instability. These parametric runs were performed for a typical BWR parallel channel case having subcooled boiling, but no nuclear coupling. The parameters investigated are listed as follows:

- (1) nonuniformity of axial power distribution
- (2) power level
- (3) phasic slip
- (4) gap conductance
- (5) inlet and exit restriction
- (6) spacers
- (7) inlet velocity and subcooling
- (8) system pressure

The operating conditions for the reference case are summarized in Table 5.1.

- (1) The Effect of Nonuniform Axial Power Distribution

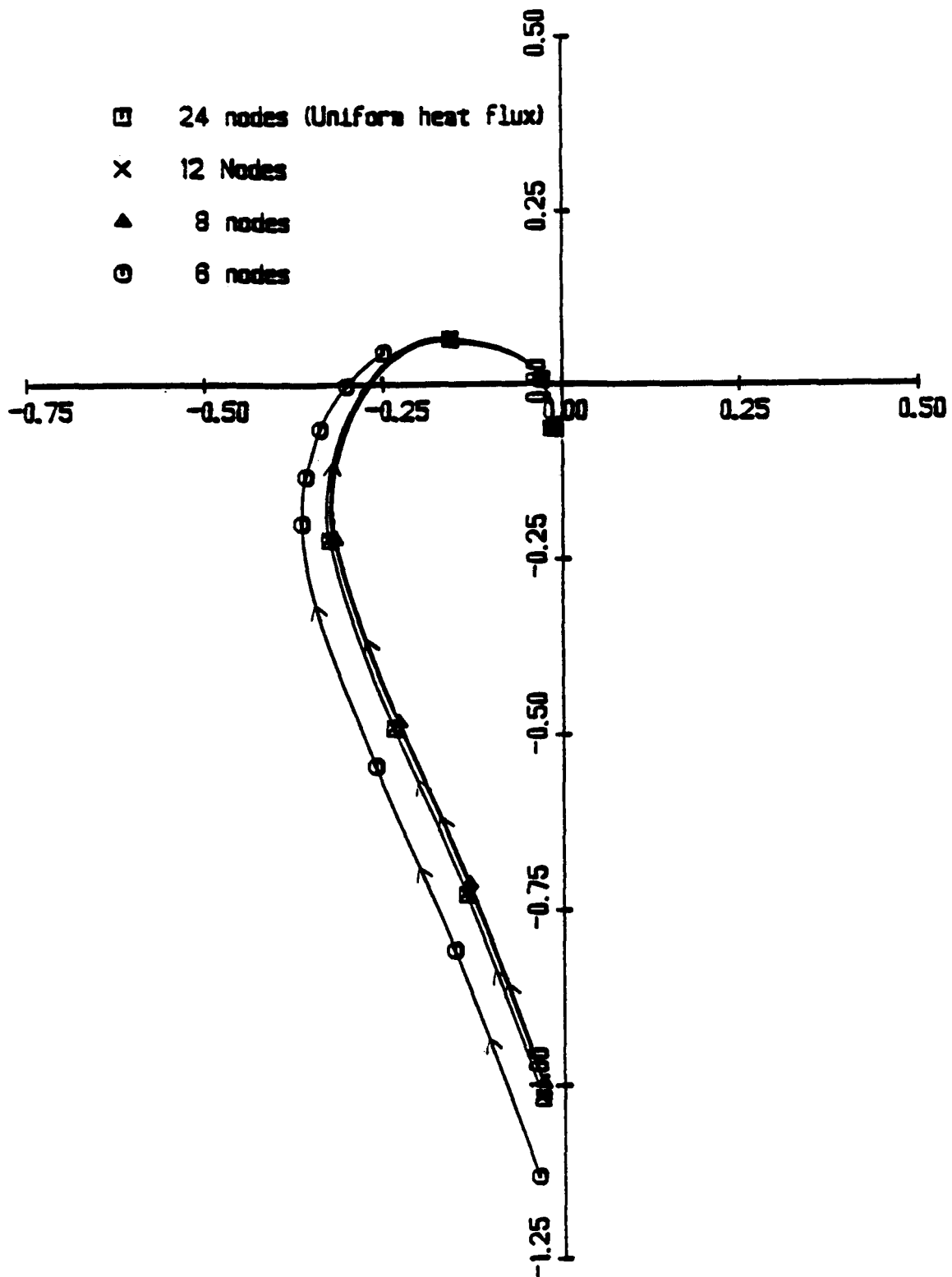


Figure 5.2 Test of NUFREQ-N Code for Uniform Axial Power Distribution(BWR/4 conditions)

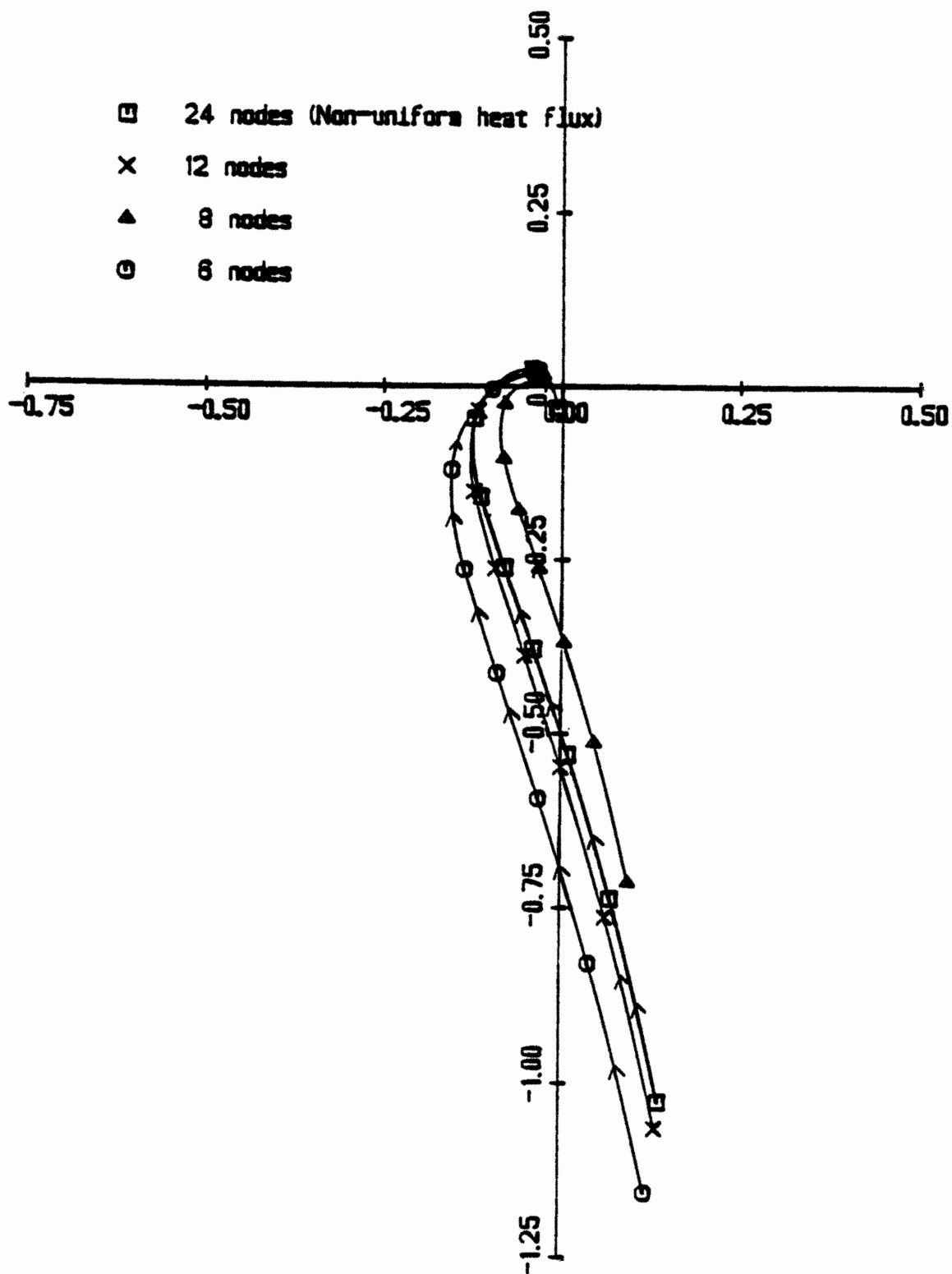


Figure 5.3 Test of NUFREQ-N Code for Nonuniform Axial Power Distribution(BWR/4conditions)

TABLE 5.1
Operating Conditions of Reference Test

<u>Variables</u>	
System pressure(psia)	987.0
Uniform heat flux(Btu/hr-ft ²)	2.0X10 ⁵
Channel flow area(ft ²)	0.1069
Heated length(ft)	12.0
Channel inlet flow velocity(ft/s)	4.906
Channel inlet flow temperature(°F)	513.3
Heated perimeter(ft)	7.222
Hydraulic diameter(in)	0.5716
Void departure point, $Z_{d,o}$ (ft)	0.0889
Channel average void fraction	0.561
Channel exit quality	0.233
Inlet loss coefficient	27.8
Exit loss coefficient	0.14
Total number of spacers	7
Spacer loss coefficient	1.04
Specific heat of fuel pin(Btu/lb-°F)	0.08
Thermal conductivity of fuel pin (Btu/hr-ft-°F)	6338.9
Density of fuel pin(lb/ft)	600.2
Specific heat of clad(Btu/lb-°F)	0.1081

Thermal conductivity of clad (Btu/hr-ft-°F)	262.8
Density of clad (Btu/ft-F-hr)	409.0
Radius of fuel pin(in)	0.2362
Inner radius of clad(in)	0.2398
Outer radius of clad(in)	0.2758
Gap conductance(Btu/hr-ft-°F)	1000.0

The four different axial power distributions, shown in Figure 5.4, were investigated. These shapes were for uniform, chopped cosine, bottom peaked, and top peaked power distributions. As can be seen in Figure 5.5, the bottom peaked axial power distribution is the least stable, and the top peaked the most stable for the conditions investigated here. However, no general conclusions (except that nonuniformity is important) are possible since the effect of the axial nonuniformity on stability margin can depend on the conditions being investigated.

(2) The Effect of Power Level

The influence of power level on the channel's stability is related to its effect on the single-phase length and the void fraction and the pressure drop in the two-phase region. The principal effect of the single-phase length is to introduce a transport time delay between the flow perturbation and the corresponding void change in the two-phase region. Thus, as shown in Figure 5.6, a decrease in power stabilizes the system.

(3) The Effect of Slip

Figure 5.7 shows the effect of introducing phasic slip via the drift-flux parameters C_0 and V_{gj} . Since phasic slip decreases the transport time of a density-wave through the channel, as well as the channel void fraction, and thus two-phase frictional and momentum pressure drop, slip flow

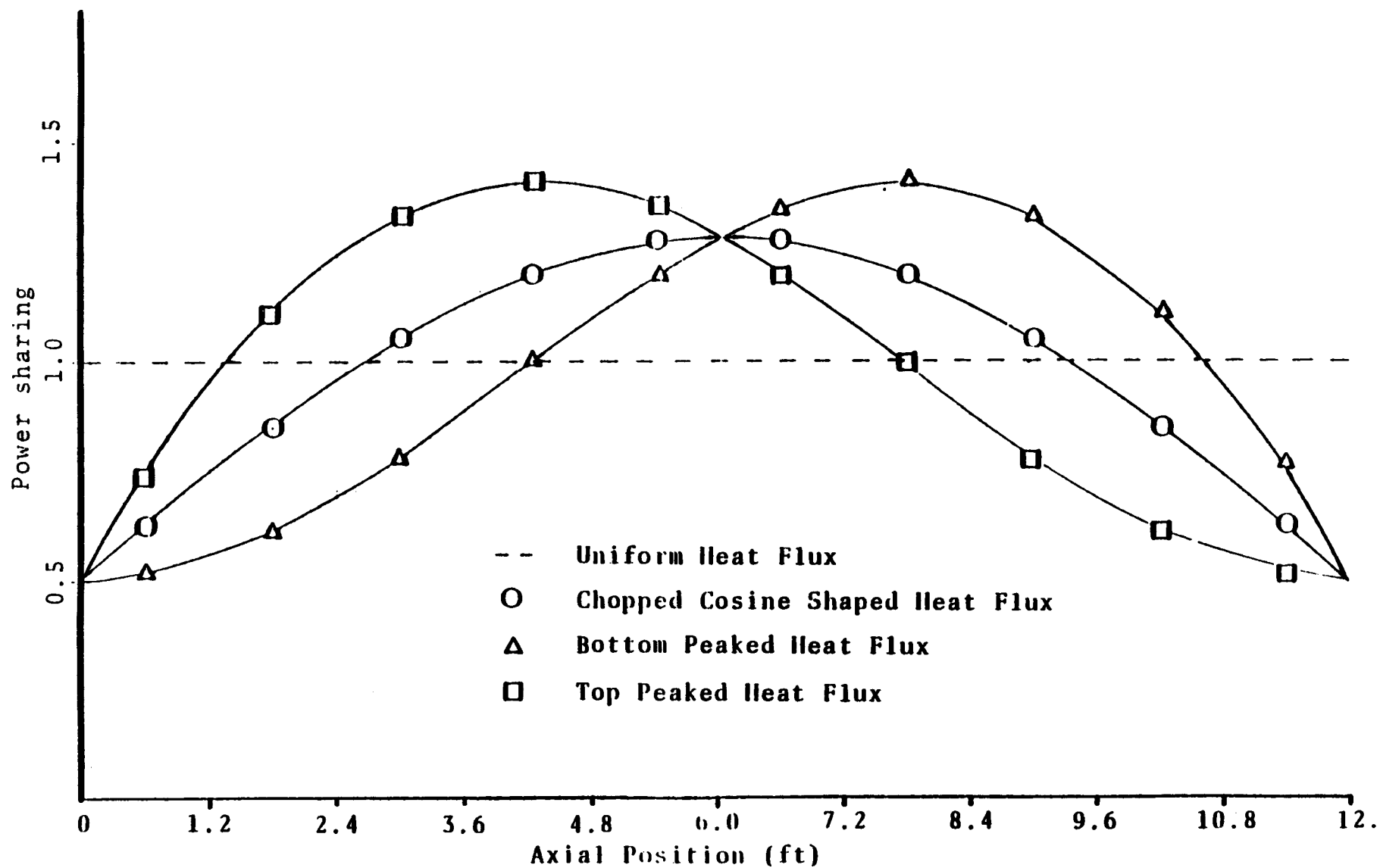
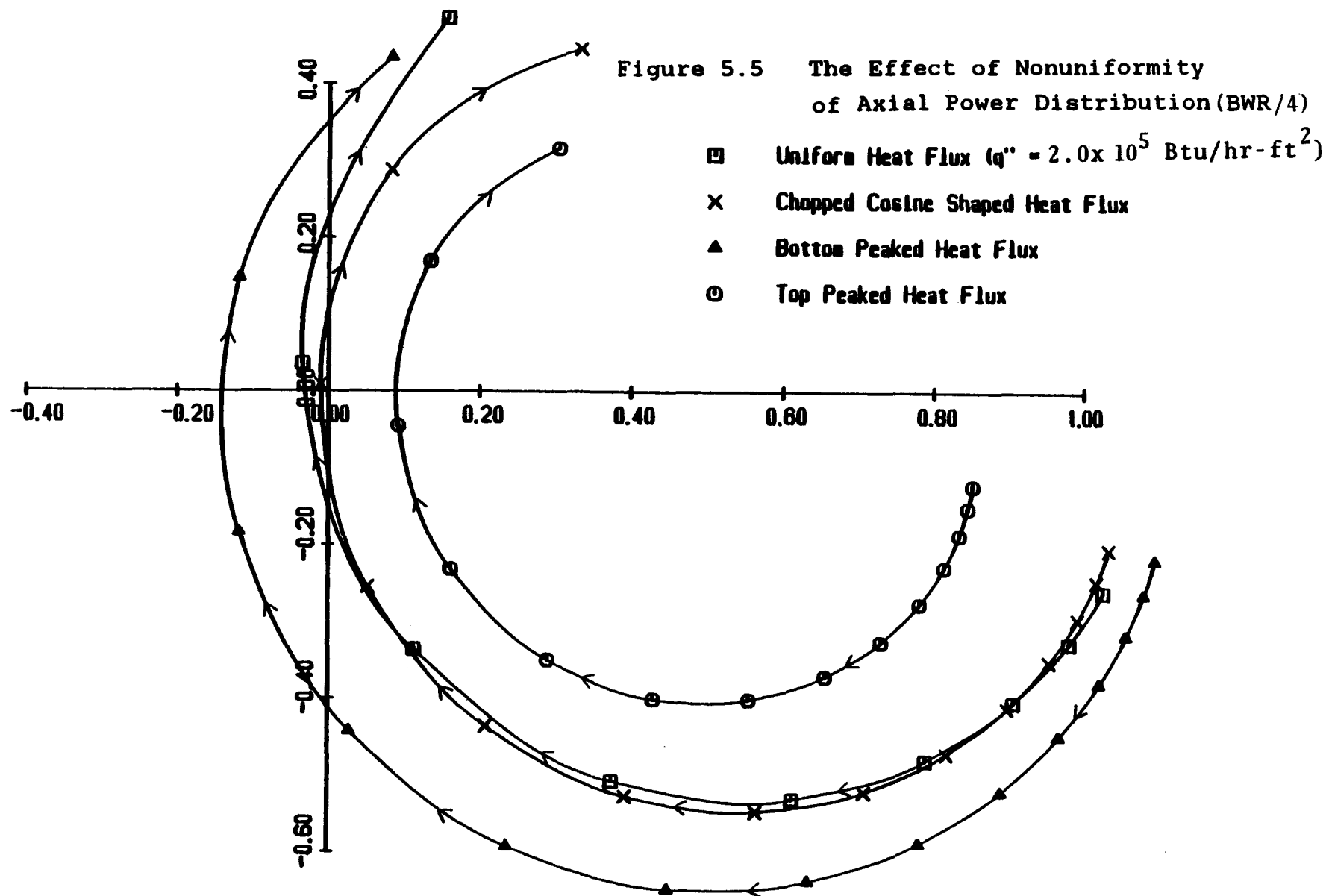
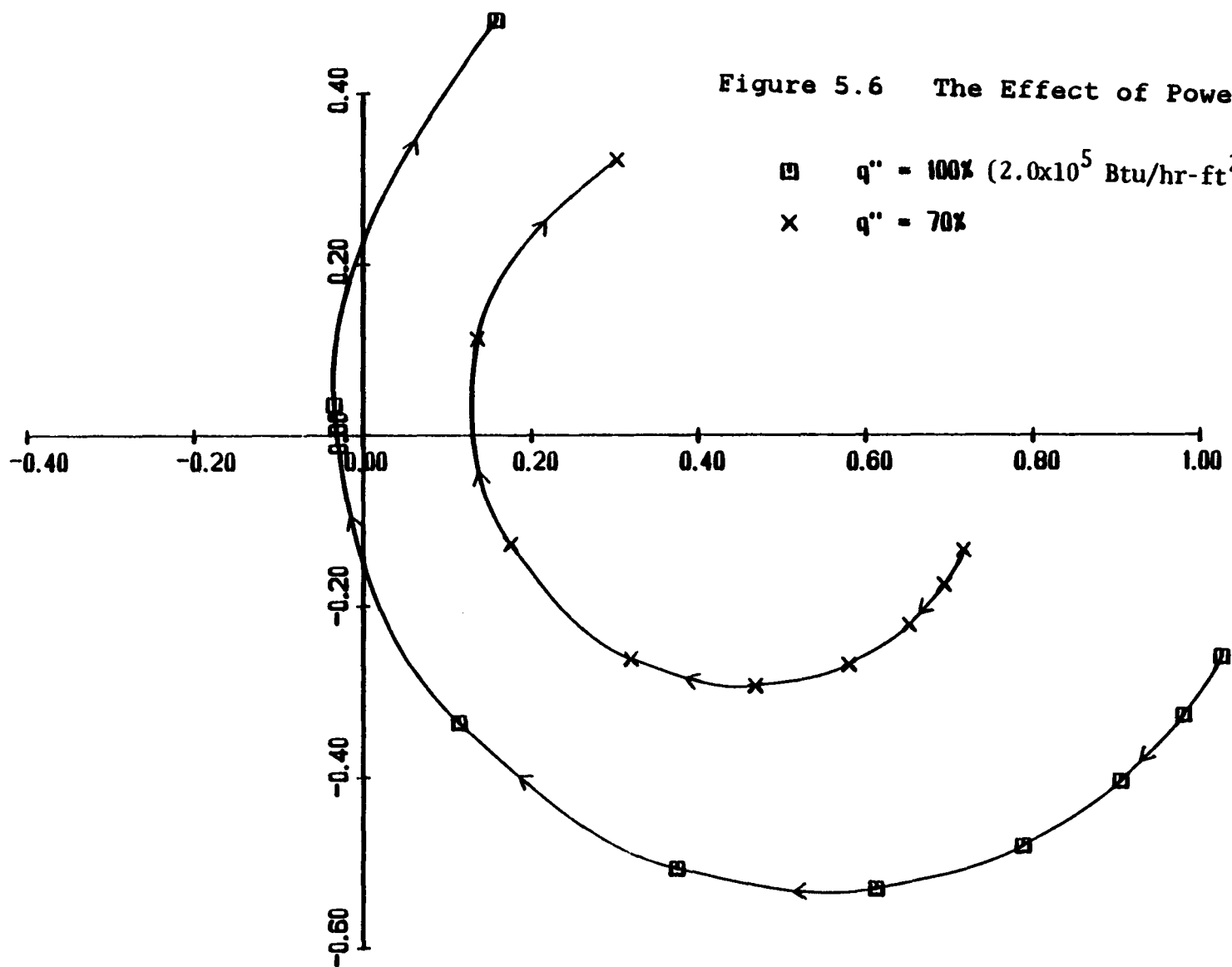
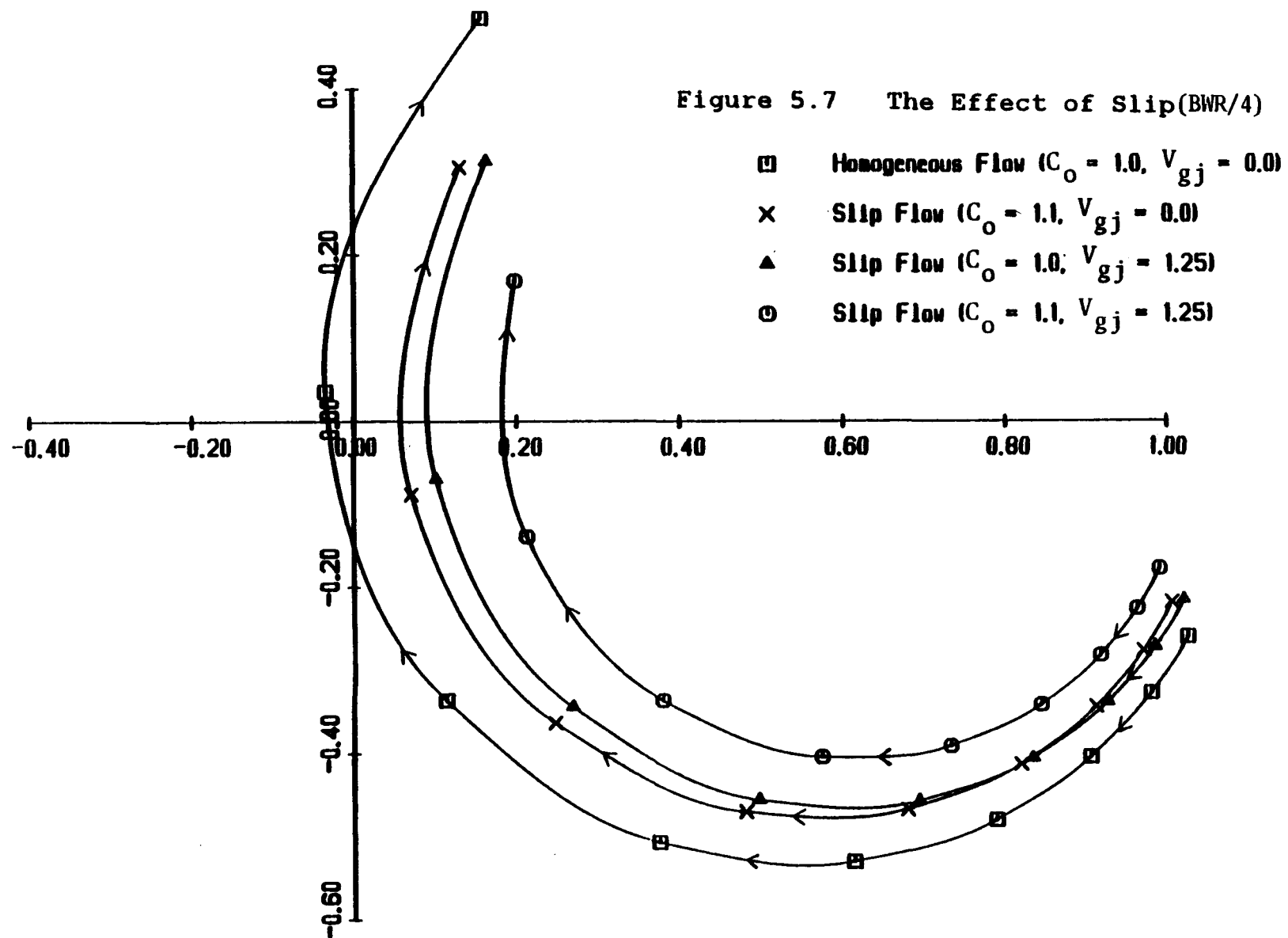


Fig. 5.4 Schematic Representation of Various Axial Power Distribution







is more stable than homogeneous flow.

(4) The Effect of Inlet and Exit Restrictions

An inlet restriction increases single phase loss, which is in-phase with the inlet flow perturbation. Hence an inlet restriction increases flow stability as shown in Figure 5.8. In contrast, a restriction at the channel exit increases the two-phase exit loss, which is out-of-phase with the inlet flow perturbation. Thus, as seen in Figure 5.8, an exit restriction reduces flow stability.

(5) The Effect of Spacers

Spacers located in the single-phase and the two-phase region have similar relative effects as do inlet and exit restrictions. Typically, a BWR has 7 spacers which are equally spaced along the heated length. Since more of these spacers are in the two-phase region, they tend to destabilize the system, as shown in Fig.5.9.

(6) The Effect of the Inlet Velocity and Subcooling

An increase in the inlet velocity decreases the void fraction and increases the single-phase length. Thus it increases the stability of the boiling channel, as shown in Figure 5.10. The effect of inlet subcooling on the stability is known not to be straight-forward⁴, but dependent on the initial operating conditions. At large subcooling, the effect of an increase is to stabilize the system. However, at smaller subcoolings, increase of inlet subcooling may destabilize the system. In this parametric

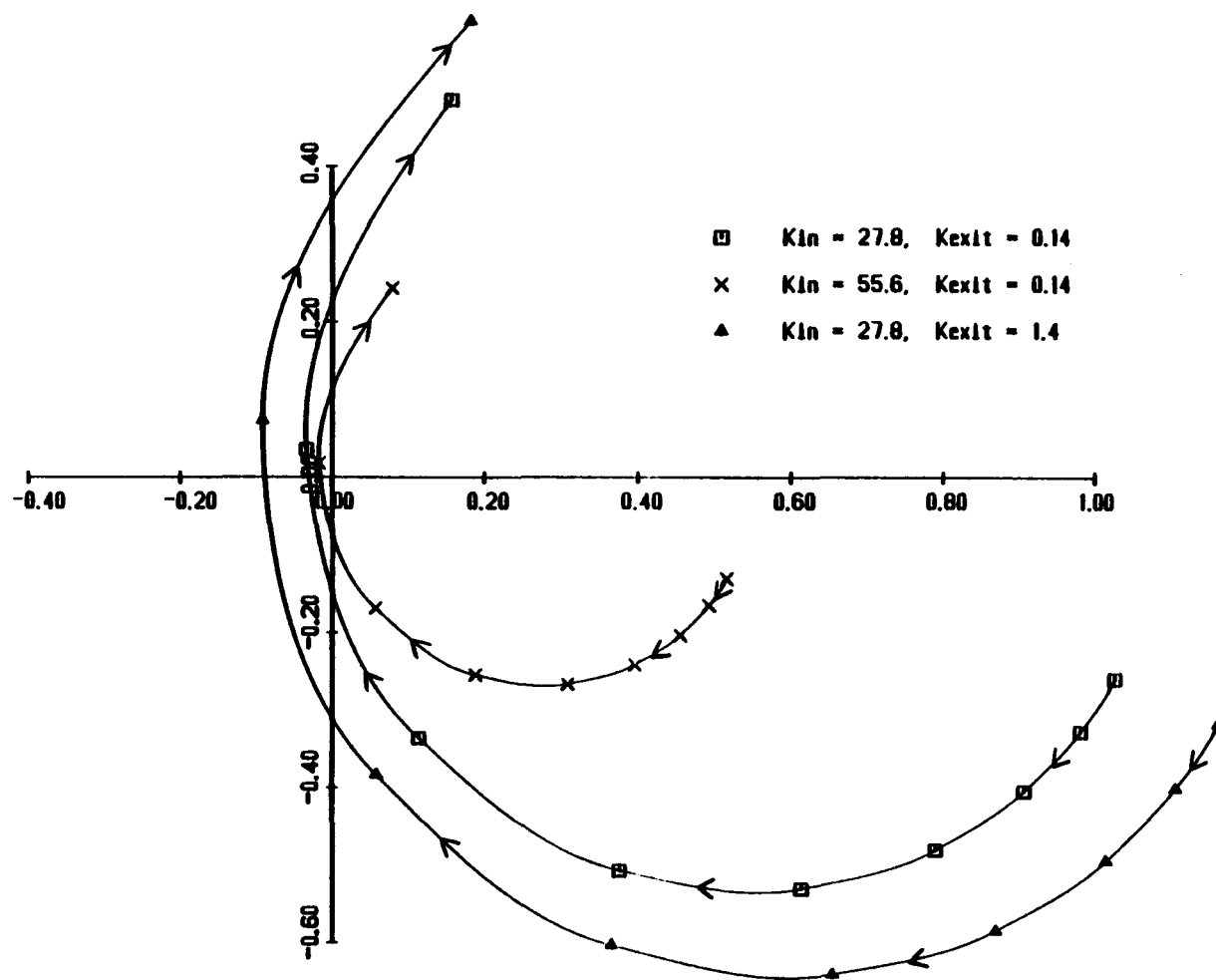


Figure 5.8 The Effect of Inlet and Exit Restriction (BWR/4)

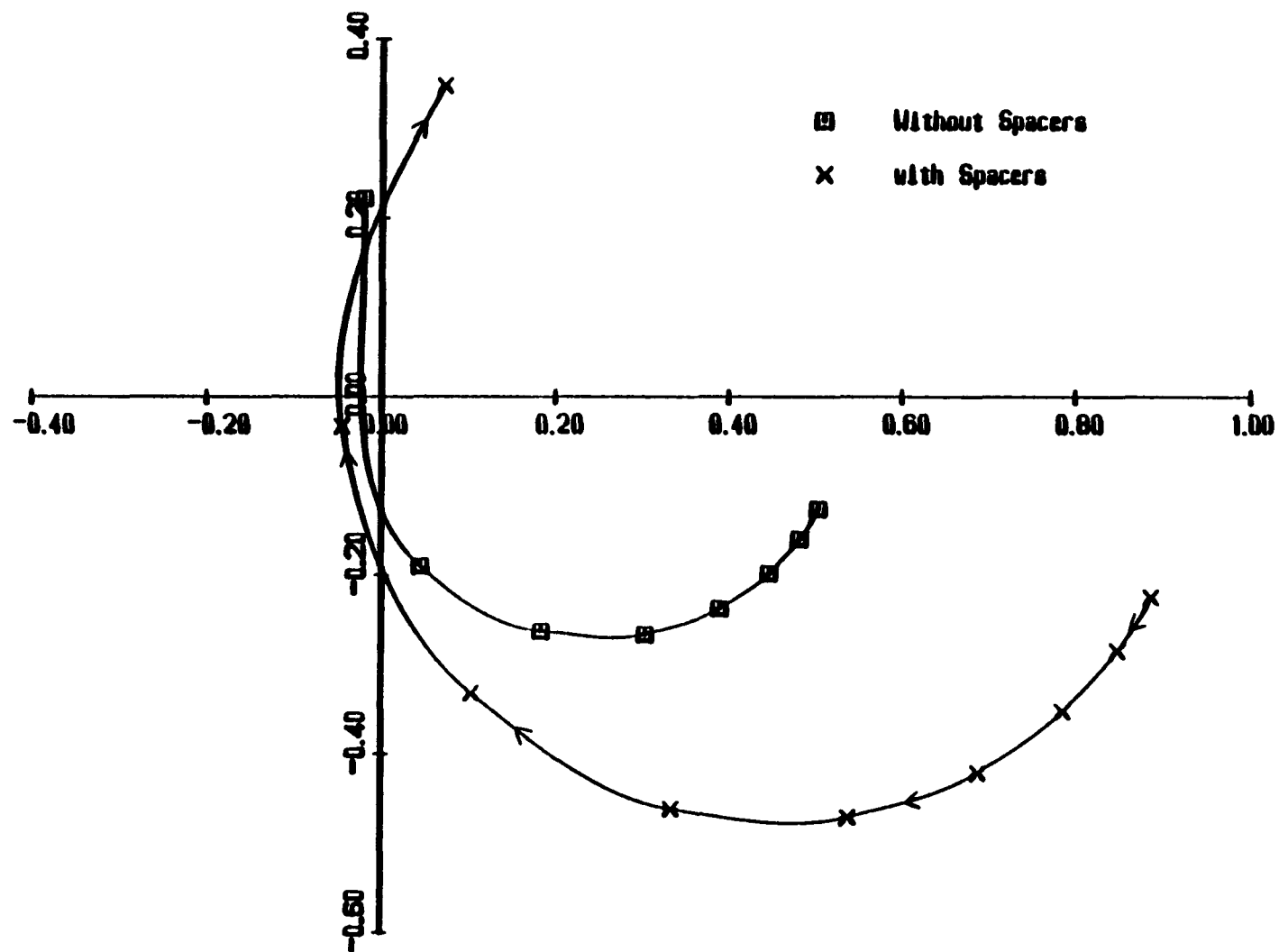


Figure 5.9 The Effect of Spacers (BWR/4)

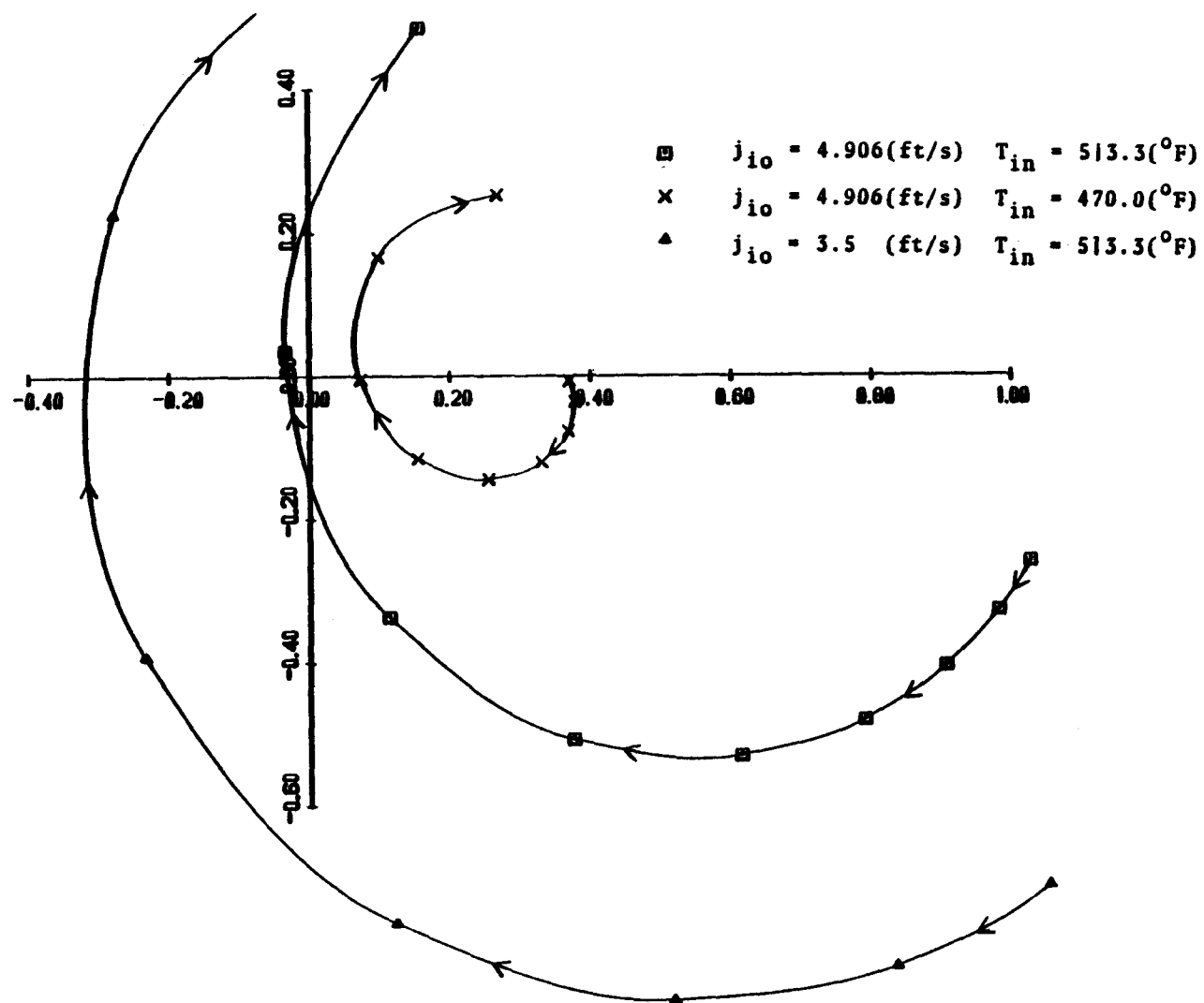


Figure 5.10 The Effect of Inlet velocity and Subcooling (BWR/4)

study, the inlet subcooling is relatively large, $\Delta T_{\text{sub}} = 29.7^\circ\text{F}$, and thus an increase in inlet subcooling stabilized the system as shown in Figure 5.10.

(8) The Effect of the System Pressure

The effect of an increase of system pressure is to reduce the void fraction, and thus the two-phase frictional and momentum pressure drop. Figure 5.11 shows that, for the operating conditions of interest here, an increase in system pressure stabilized the system.

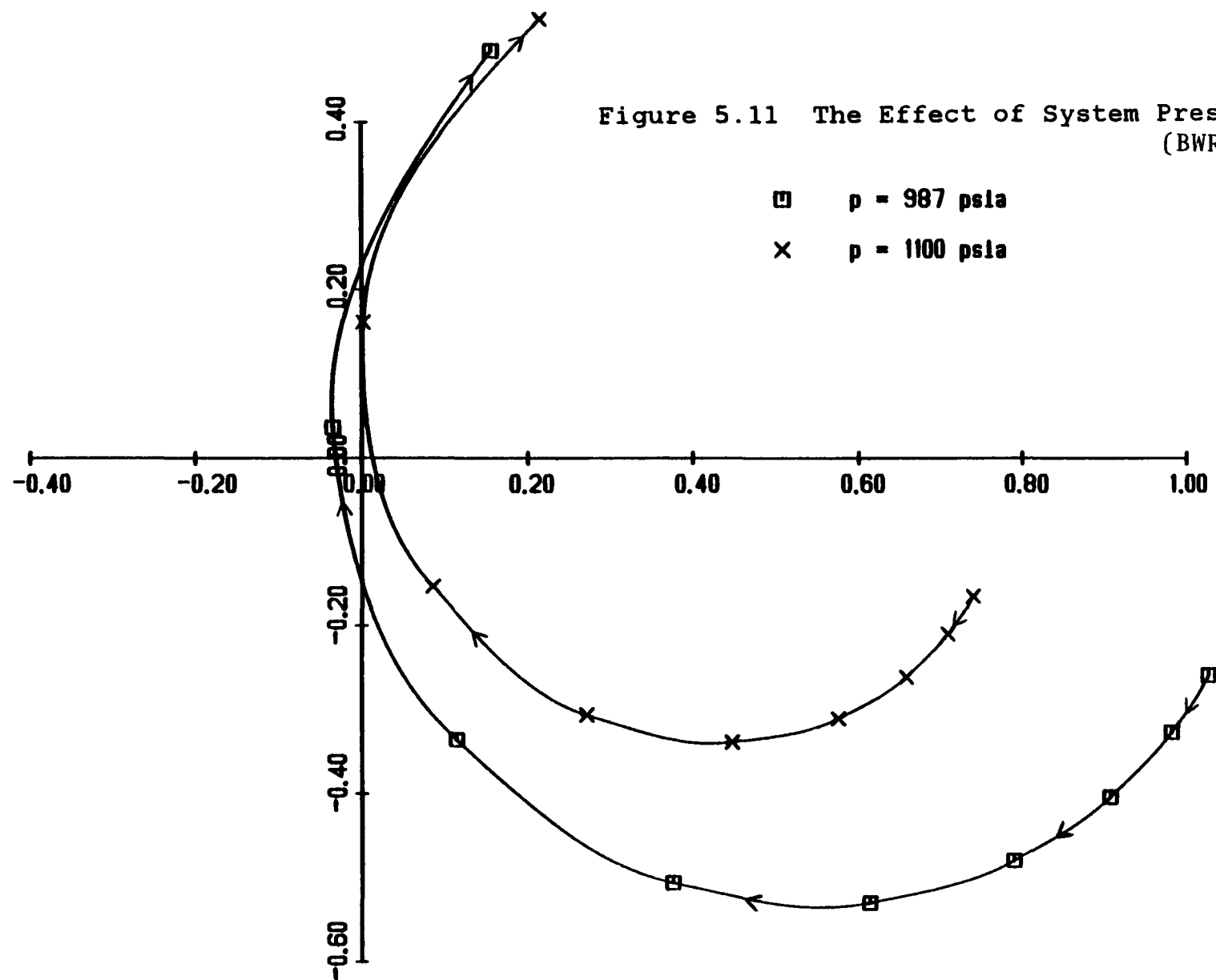
As seen in Figures 5.5 to 5.11, the parametric results from the NUFREQ-N code agree with well-known effects of these parameters. While this is good qualitative verification of NUFREQ-N, quantitative verification is also needed. In the next section, we will compare NUFREQ-N with several experiments to assess its predictive capabilities.

5.3 COMPARISONS WITH EXPERIMENTAL DATA

Five sets of experimental data were selected to assess the predictive capabilities of NUFREQ-N. As will be seen, there is considerable uncertainty associated with these data sets. Nevertheless, they represent the best steam/water stability data available.

5.3.1 FRIGG Loop Power-to-mass-flux Transfer Functions

The 8 MW FRIGG loop was used to test the stability



characteristics of a uniformly heated 36-rod bundle, which consisted of rods having 14.42 ft heated length and 0.543 inch outer diameter [6]. In addition, an unheated center rod of 0.787 in diameter was present, and 8 grid spacers were used to maintain clearances. Details of the FRIGG loop are shown in Figure 5.12.

The FRIGG loop can be operated in both forced and natural circulation modes. The experimental measurements taken included the two-phase flow pressure drop, axial and radial void fraction distribution, steady-state CHF, and the mass flux. In order to obtain channel stability information, the power-to-flow transfer function were measured by oscillating power. The authors compared their measurements with the HYDRO⁴ code and showed good agreement.

In this study, three tests are analyzed with the NUFREQ-N code. The detailed experimental conditions for these tests are shown in Table 5.2. Since the FRIGG loop experiments were conducted with a uniform axial power distribution, the transfer function of interest can be obtained from Equations (2.72) and (2.83) as,

$$\delta(\hat{\Delta p})_{1\phi} = \Gamma_1(s)\delta\hat{j}_i + \Gamma_2(s)\delta\hat{q}''' \quad (5.1)$$

$$\delta(\hat{\Delta p})_{2\phi} = \pi_1(s)\delta\hat{j}_i + \pi_2(s)\delta\hat{q}''' \quad (5.2)$$

Using the constant loop pressure drop boundary condition,

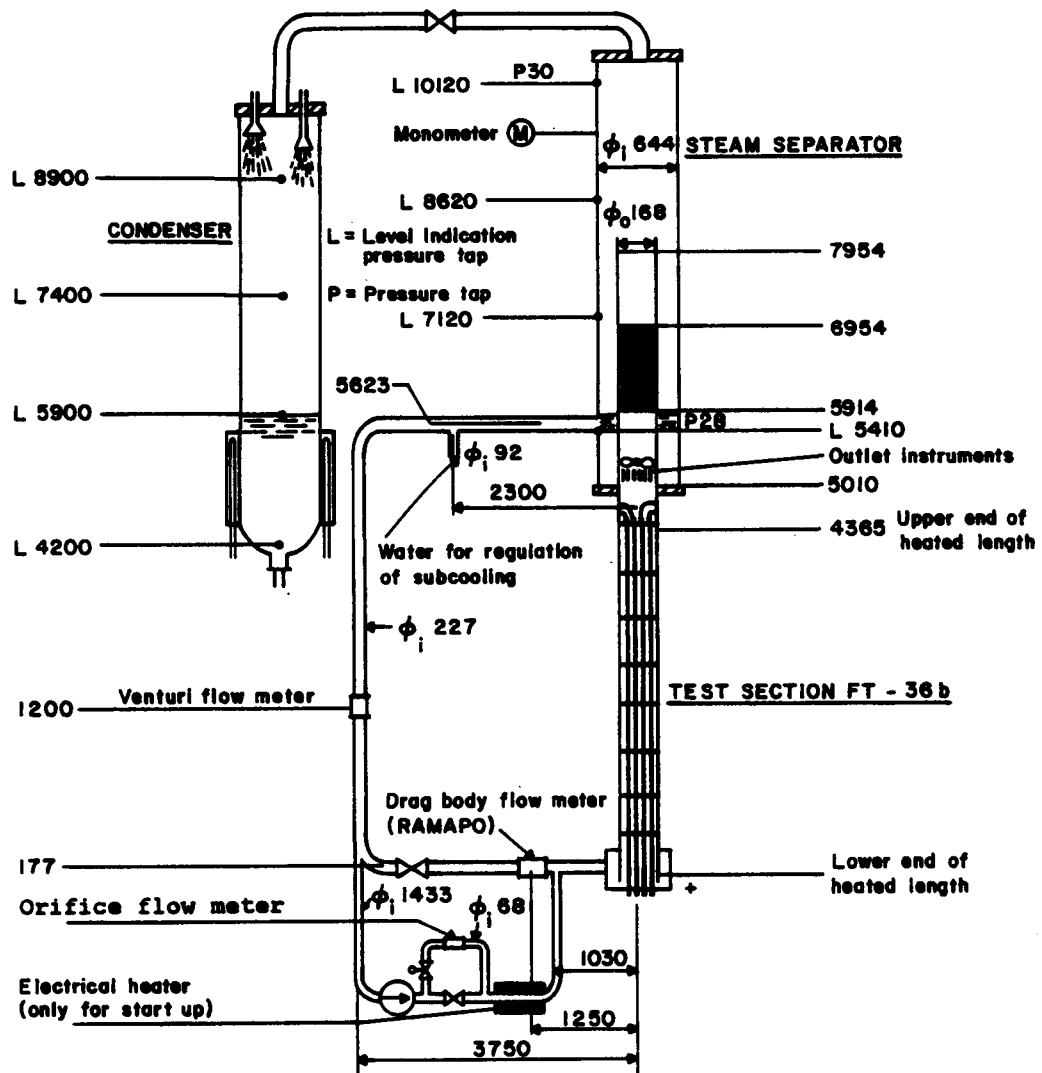


Figure 5.12 Schematic FRIGG Loop

Table 5.2
Experimental Conditions for FRIGG Loop Test

Parameters	No. 362008	No. 362016	No. 362022
p (psia)	721.		
L_H (ft)	14.42		
A_{x-s} (ft ²)	0.157		
P_H (ft)	5.099		
D_H (in)	1.082		
q_o'' (Btu/ft ² -hr)	6.786×10^4	6.297×10^5	1.662×10^5
G_o (lb/ft ² -hr)	6.116×10^5	6.322×10^5	6.142×10^5
ΔT_{sub} (°F)	7.38	8.28	7.02
T_{in} (°F)	498.6		
C_o	1.13		
V_{gj}	1.293		
C_{pH} (Btu/lb-°F)	0.11		
ρ_H (lb/ft ³)	488.		
K_{in}	5.1		
K_{spacer}	0.58		
K_{exit}	0.58		
L_p (length of upper plenum)	0.		
L_R (riser length, ft)	4.99		
A_R (ft ²)	0.226		
$K_{R,exit}$	0.99		
$\sum \frac{L_i}{A_i}$	97.47		

$\sum \frac{f_i L_i}{D_{H,i} A_i^2} (ft^{-4})$	6.014

$$\delta(\hat{\Delta p})_{1\phi} + \delta(\hat{\Delta p})_{2\phi} = 0 \quad (5.3)$$

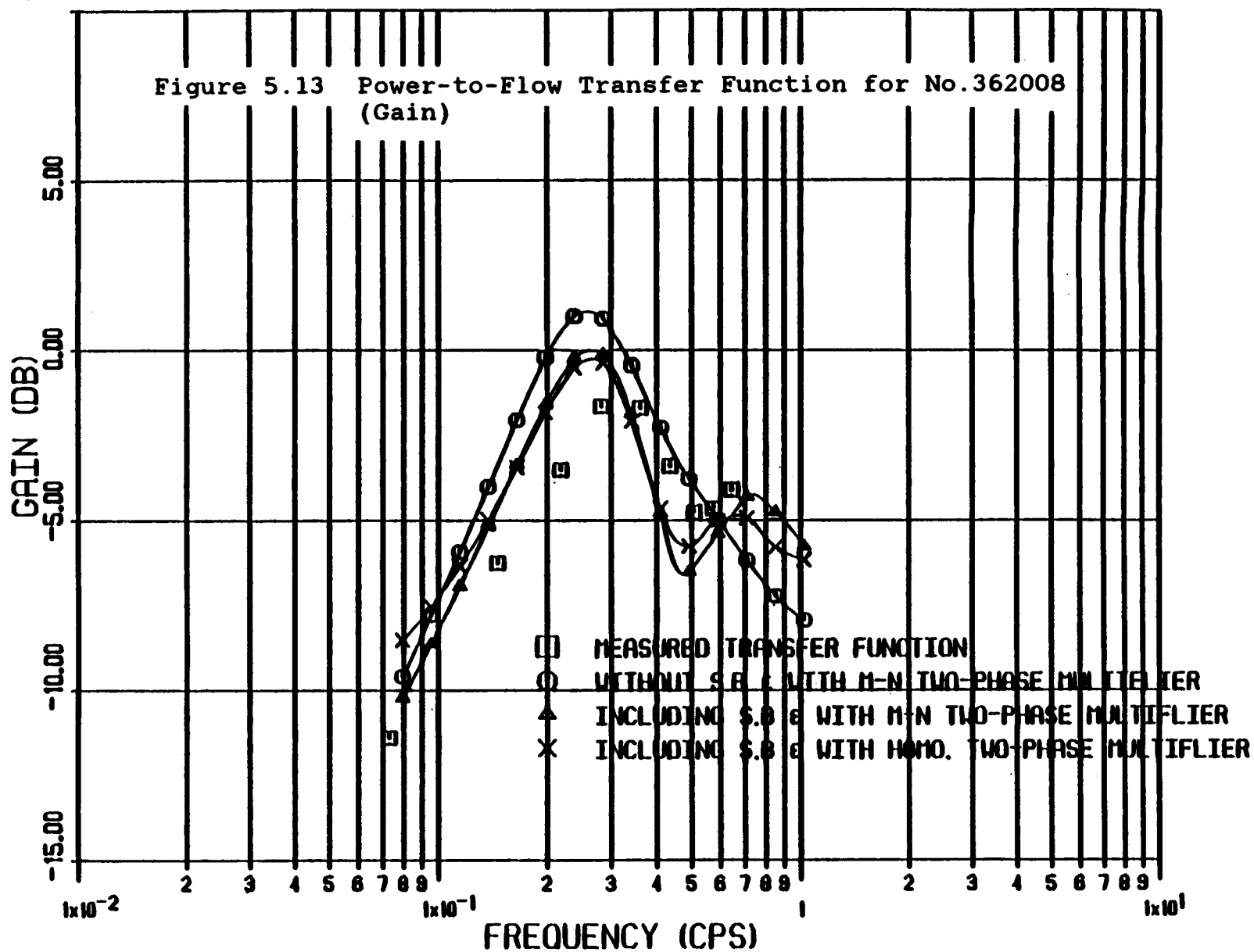
the power-to-flow transfer function is,

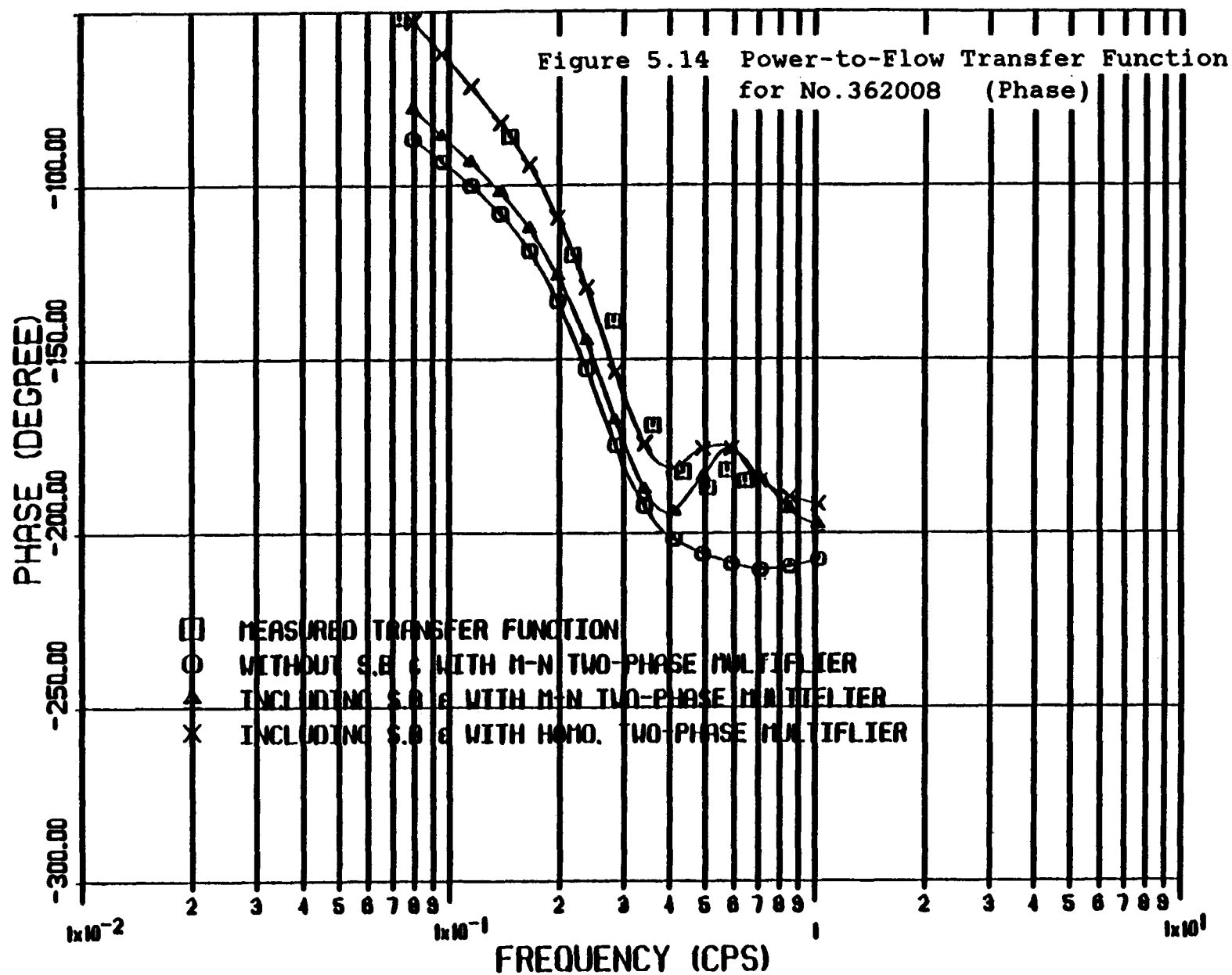
$$\frac{\delta \hat{j}_i}{\delta \hat{q}''' } \Delta G_{PF}(s) = - \frac{\Gamma_2(s) + \pi_2(s)}{\Gamma_1(s) + \pi_1(s)} \quad (5.4)$$

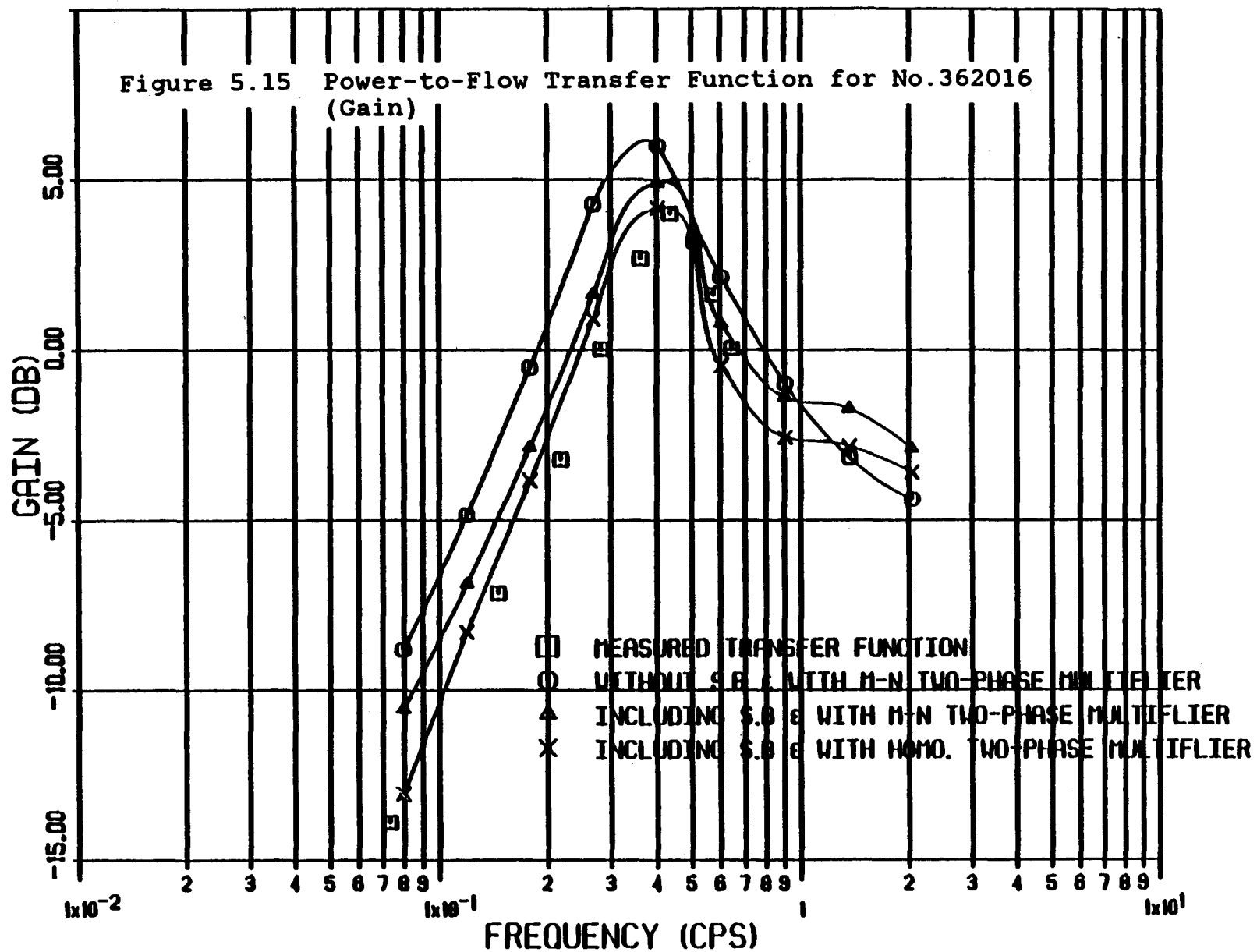
Figures 5.13 to 5.20 show the results for the three cases chosen. Included is a parametric investigation of the effect of, subcooled boiling, $\phi_{\ell 0}^2$ modeling, and various correlations for $H_{2\phi}$, on the power-to-flow transfer function. As can be seen in these figures, including subcooled boiling improves the results. The homogeneous $\phi_{\ell 0}^2$ gives better results than the Martinelli-Nelson two-phase multiplier, which overestimates the frictional pressure drop and thus yields conservative estimation. This is expected, since it is well-known that in rod bundles the spacers tend to homogenize the flow. Interestingly, the two correlations for heat convection($H_{2\phi}$) yield nearly similar results. It was found that results from the NUFREQ-N code having subcooled boiling and a homogeneous multiplier showed excellent agreement with measured data.

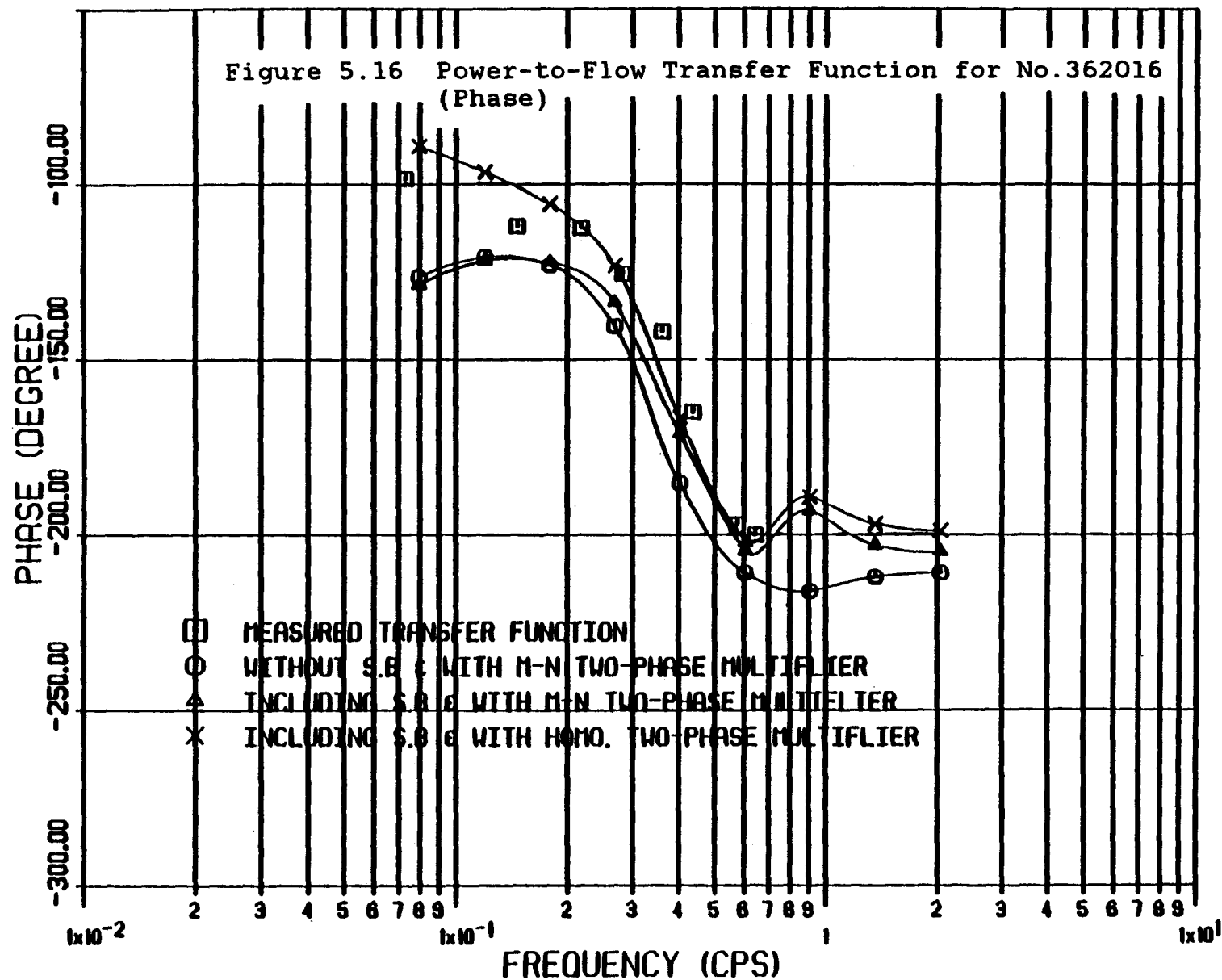
5.3.2 Christensen's Power-to-void Transfer Functions

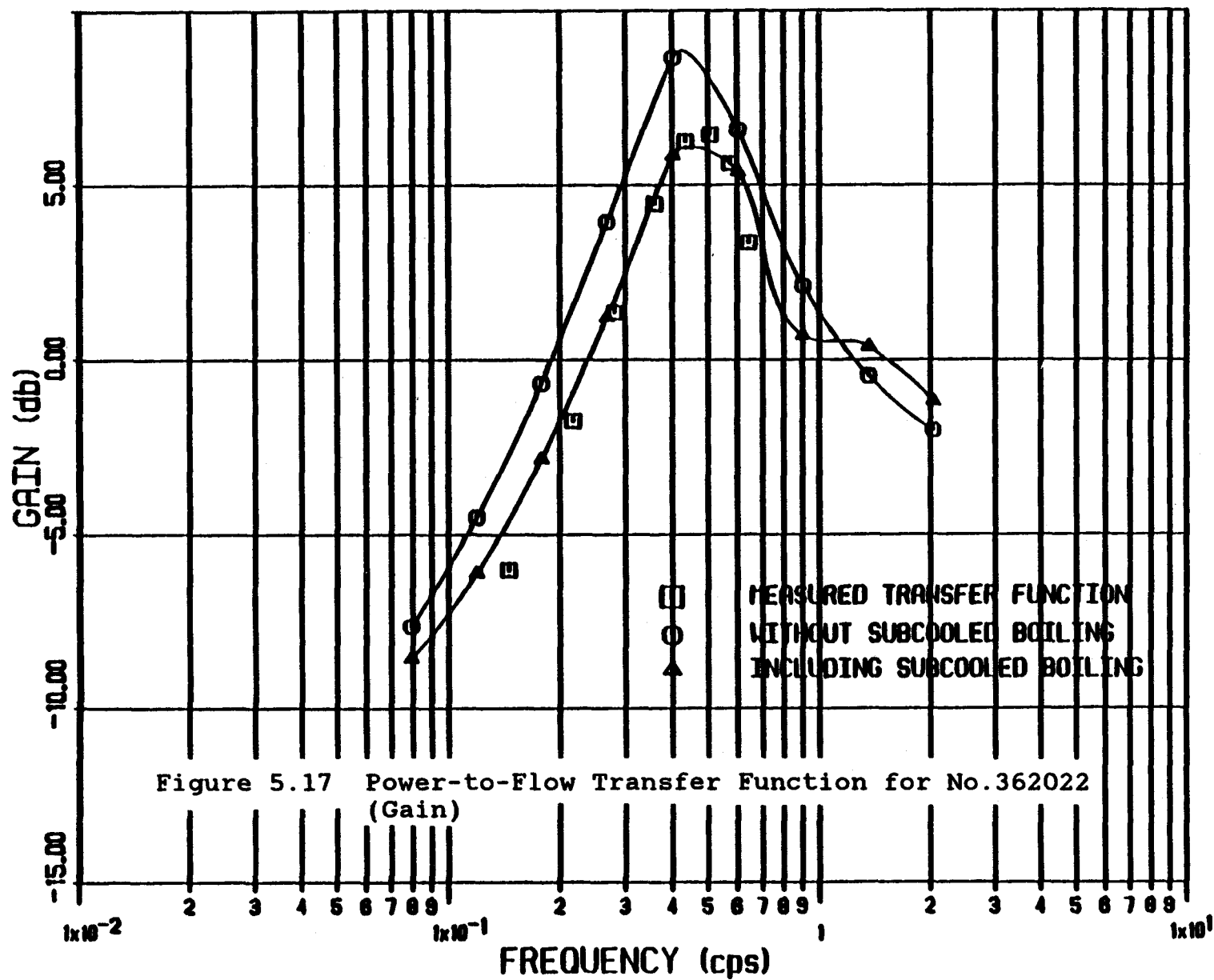
In this experiment⁵ the heating power was sinusoidally oscillated in a uniformly heated channel to observe the power-to-void transfer function. The test section was a

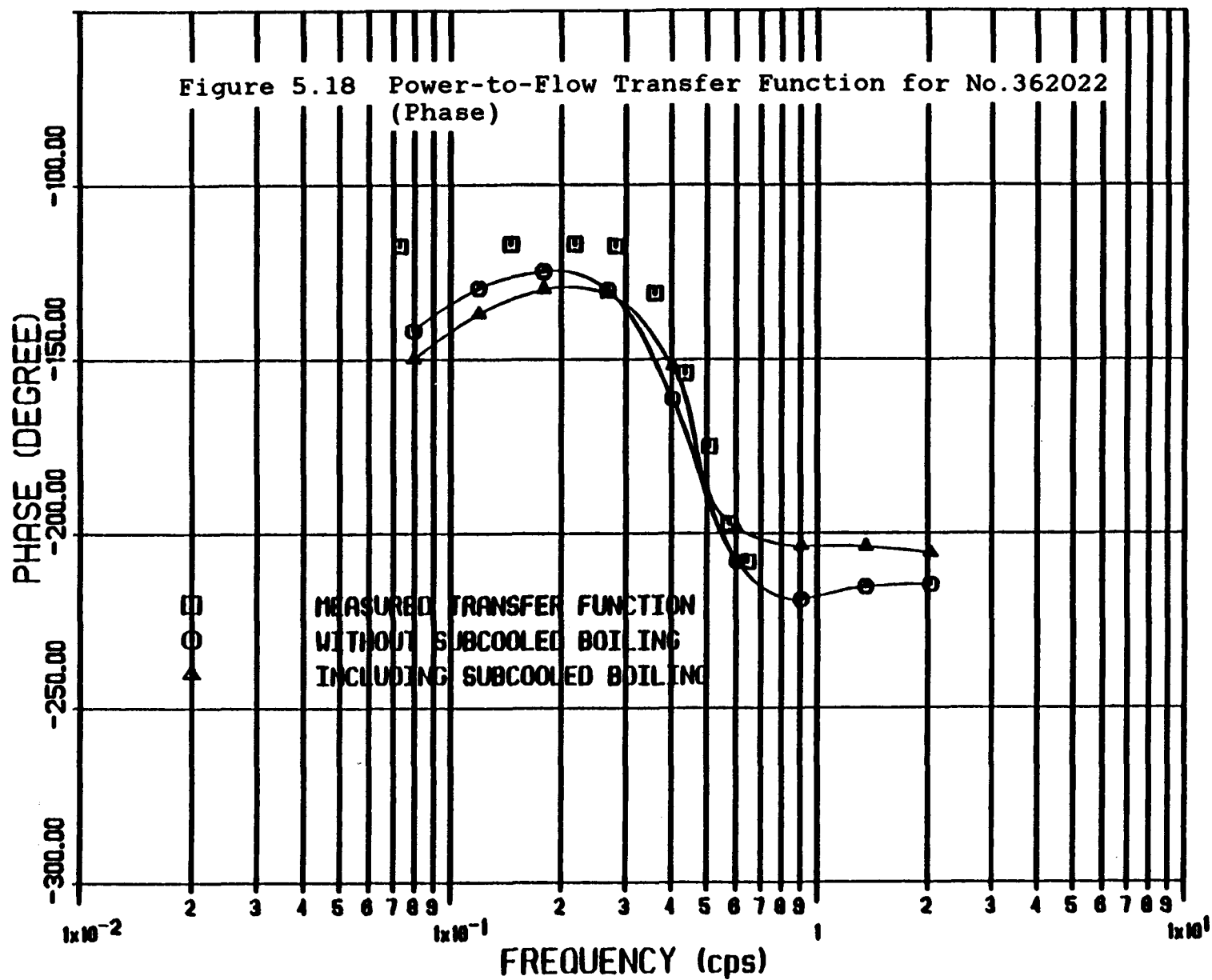












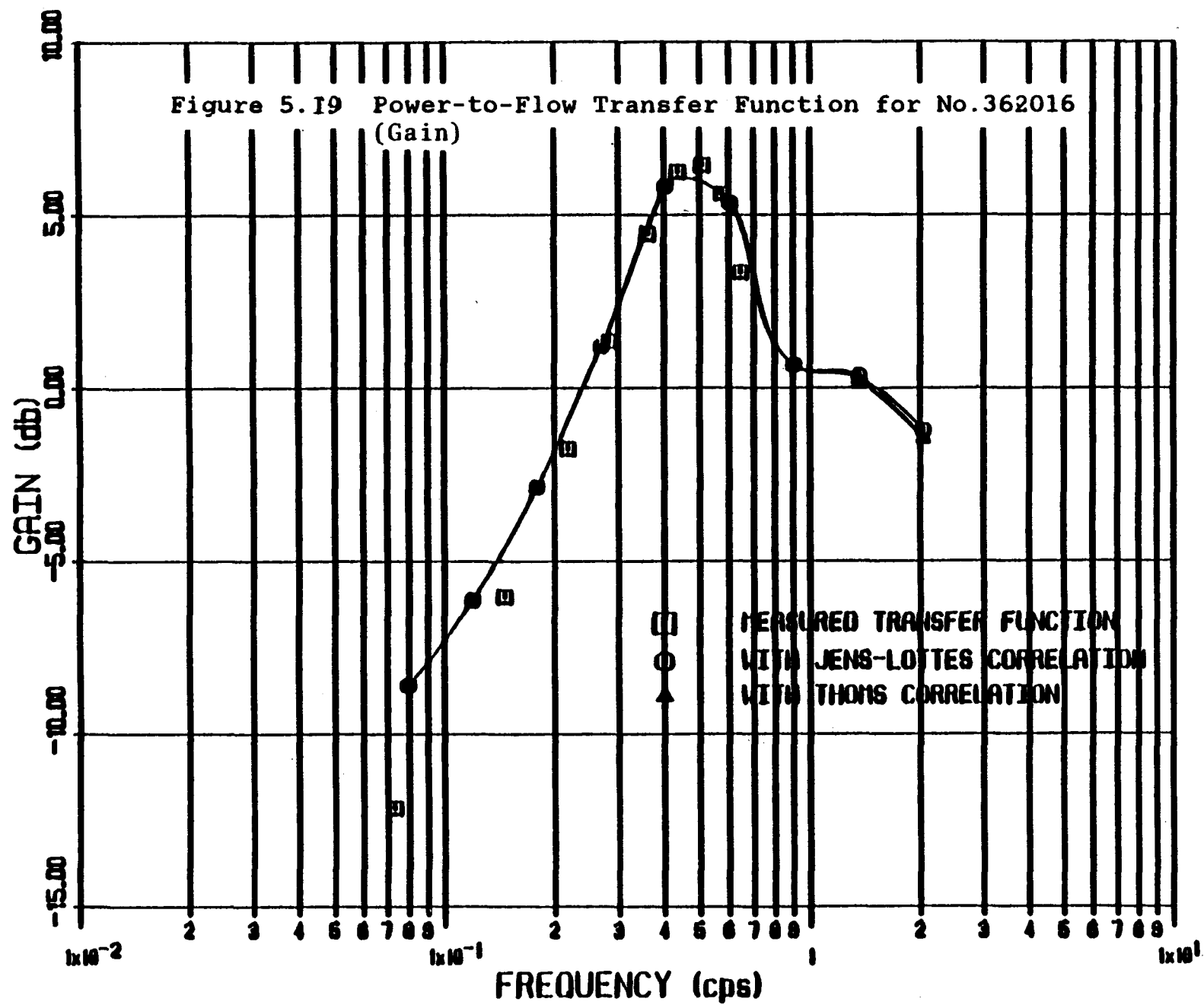
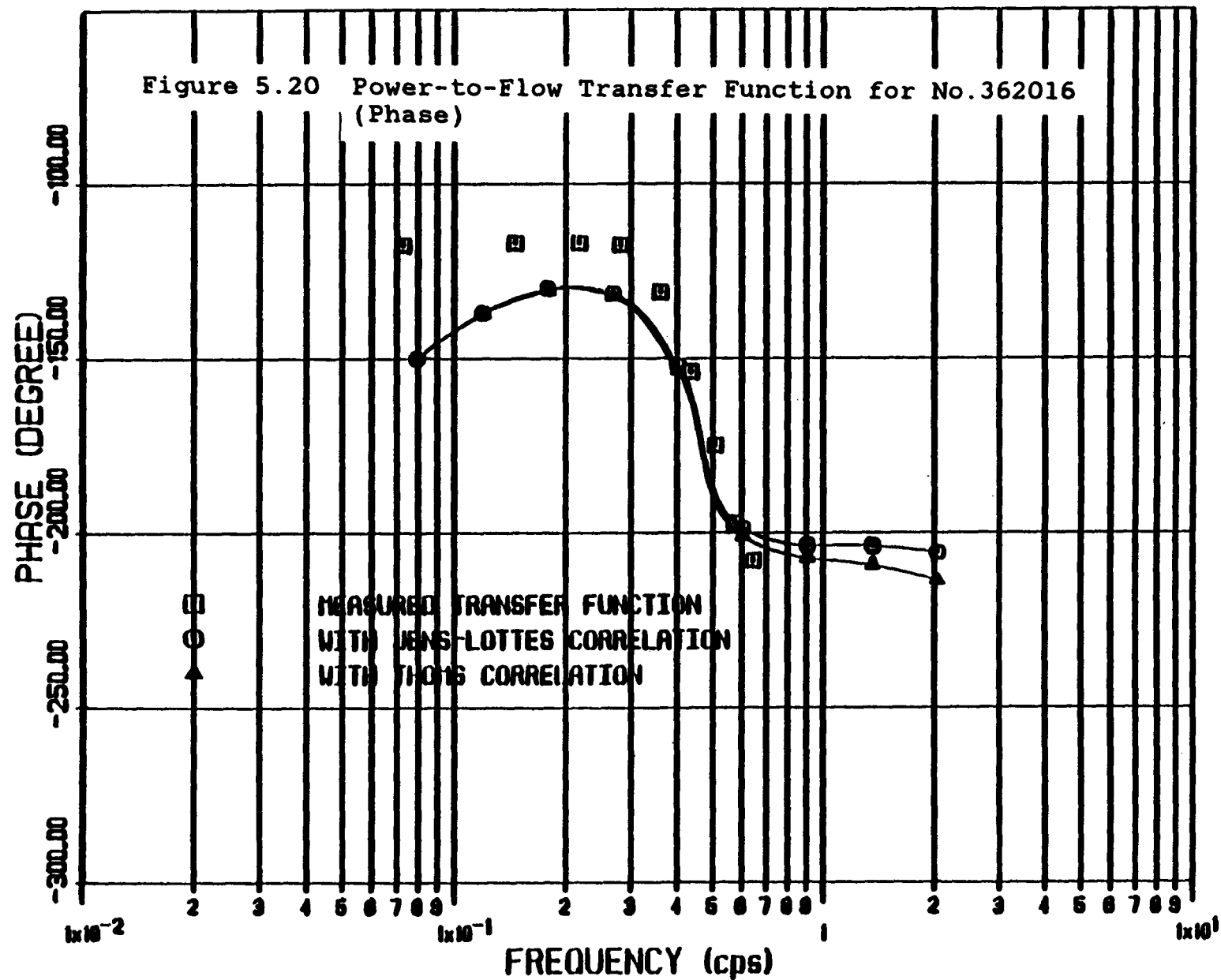


Figure 5.20 Power-to-Flow Transfer Function for No.362016
(Phase)



rectangular channel of stainless steel, having 4.167 ft length and 0.146x0.0364 ft inner dimension.

A thermal-hydraulic test loop at Argonne National Laboratory was used for this experiment. A schematic of this loop is shown in Figure 5.21. The test was performed for the forced circulation, and maintained the following parameters constant:

- 1) flow rate of inlet water to the test channel
- 2) temperature of the inlet water
- 3) pressure at the exit of the test section

Due to the constant pressure drop boundary condition around the loop, the inlet flow rate actually must oscillate corresponding to the power perturbation. Thus in this study we allowed for inlet flow rate feedback, as derived in Appendix-XIII. The NUFREQ-N code calculated the power-to-void transfer function at the channel exit for two cases, whose experimental conditions are shown in Table 5.3. The transfer function is obtained by using Equation (2.84) as,

$$\delta \langle \alpha \rangle_H^{out} = T_1(s) \delta j_i + T_2(s) \delta q''' \quad (5.5)$$

Using Equation (XIII.9), the inlet flow feedback to a single uniformly heated channel is,

$$\delta j_i = G_X(s) \delta q''' \quad (5.6)$$

where,

$$G_X(s) = \frac{1}{\rho_f A_{x-s}} \sum_{k=1}^K x^k$$

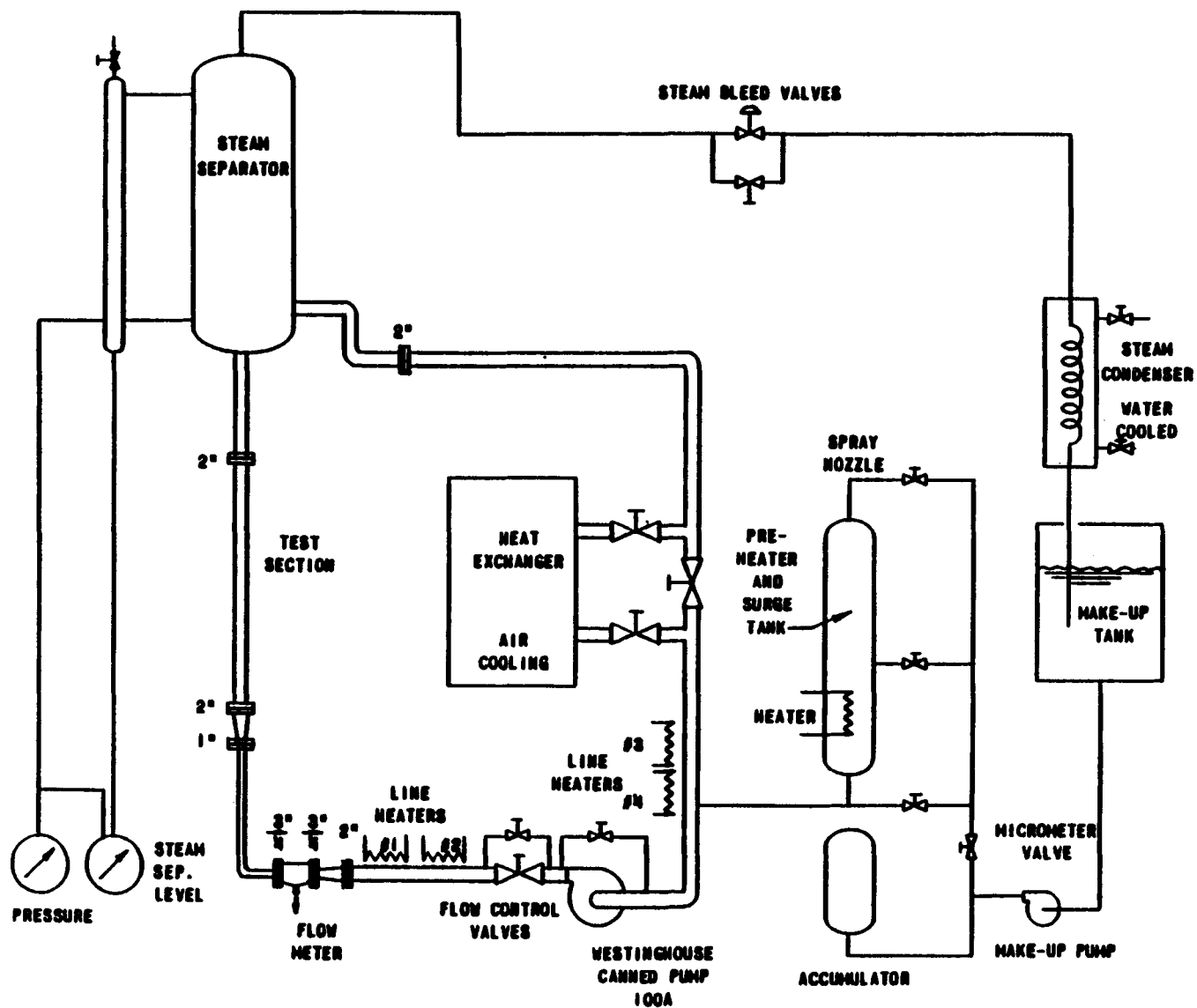


Figure 5.21 Sketch of the Test Loop in Christensen's Experiment

Table 5.3
Experimental Conditions for Christensen's Experiment

Parameters	Run #9	Run #13
p (psia)	400	600
L_H (ft)	4.167	
A_{x-s} (ft ²)	0.531×10^{-2}	
P_H (ft)	0.364	
D_H (in)	0.699	
q_o'' (Btu/ft ² -hr)	6.746×10^4	1.124×10^4
J_{io} (ft/s)	2.526	3.773
ΔT_{sub} (°F)	5.2	6.0
C_o and V_{gj}	1.16 , 1.35	
C_{pH} (Btu/lb-°F)	0.11	
k_H (Btu/ft-°F-s)	3.028×10^{-3}	
ρ_H (lb/ft ³)	488	
b (wall thickness, in)	3.544×10^{-2}	
K_{in}	20	
K_{exit}	0.57	
L_p (length of upper plenum)	0	
L_R (riser length, ft)	5	
A_R (ft ²)	2.182×10^{-2}	
$K_{R,exit}$	0.945	
$\sum \frac{L_i}{A_i}$	31.4	

$\sum \frac{f_i L_i}{D_{H,i} A_i^2} \text{ (ft}^{-4}\text{)}$	61.16

Now inserting Equation (5.6) into Equation (5.5), the power-to-void transfer function at the channel exit is given by,

$$\frac{\delta \langle \hat{\alpha} \rangle_H^{\text{out}}}{\delta \hat{q}'''} = H(s) = T_1(s)G_x(s) + T_2(s) \quad (5.7)$$

Figures (5.22) to (5.25) show comparisons between the measured and calculated transfer functions for Runs #9 and #13. It can be seen that the data scatter is excessive. Nevertheless, the results with subcooled boiling show an apparent resonance, similar to the experimental data, although the peak frequency is somewhat higher. This shift in the peak may be explained by Christensen's analysis [5] which included the effect of system pressure perturbation.

5.3.3 Niemi's Power-to-void Transfer Functions

This experiment [42] was run at the General Electric Company to improve the quality of the data taken by Christensen [5], which had excessive data scatter. In this experiment the power-to-void transfer function was measured in a rectangular uniformly-heated channel at 1000 psia. The test section had the dimension of 0.188x1.56 in and the height of 6.35 ft. Also six simulated spacers provide pressure losses up the channel representative of BWR grid spacers.

A schematic of the two-phase transient loop is shown in

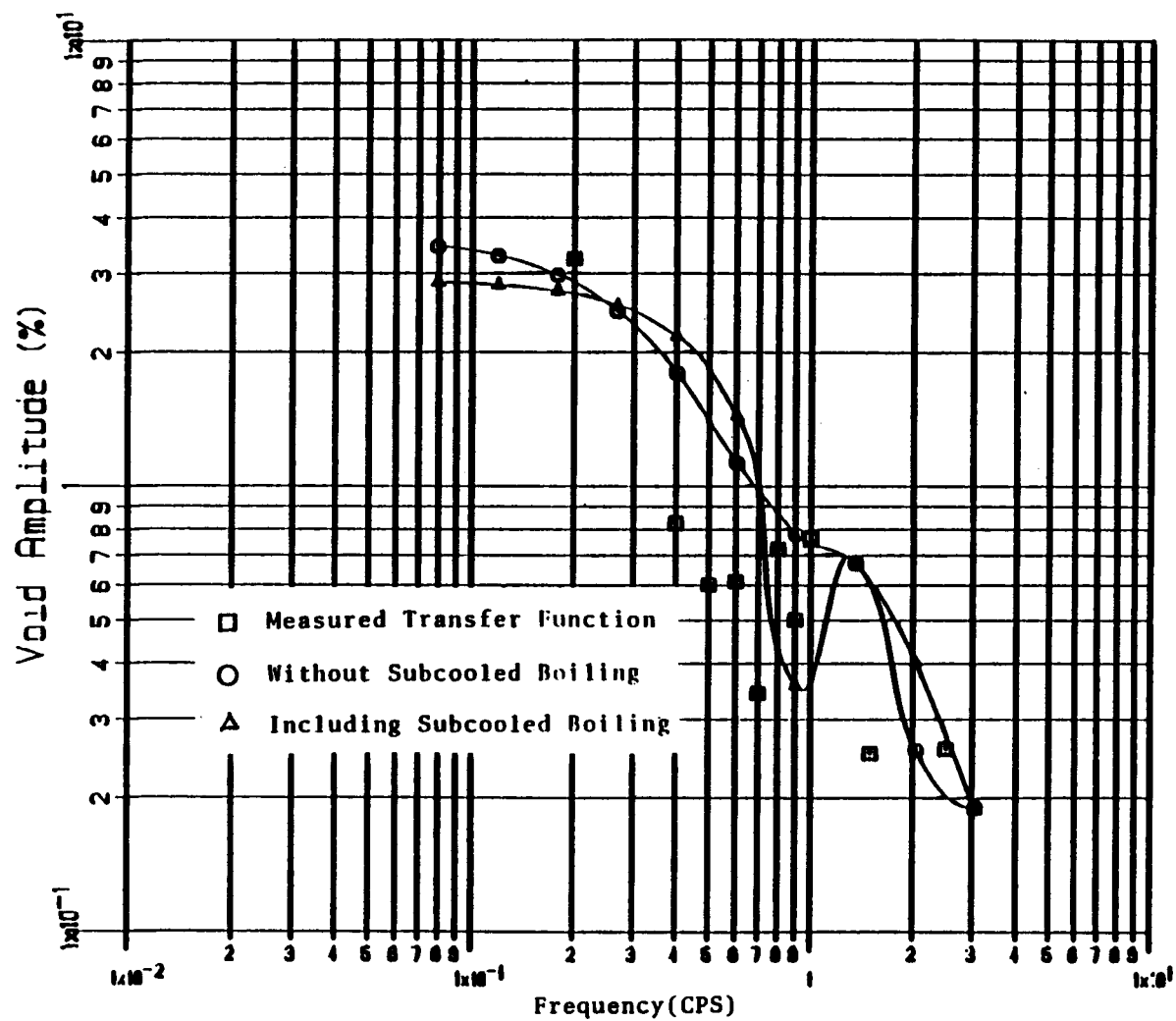


Figure 5.22 Power-to-Void Transfer Function for Run #9 (Gain)

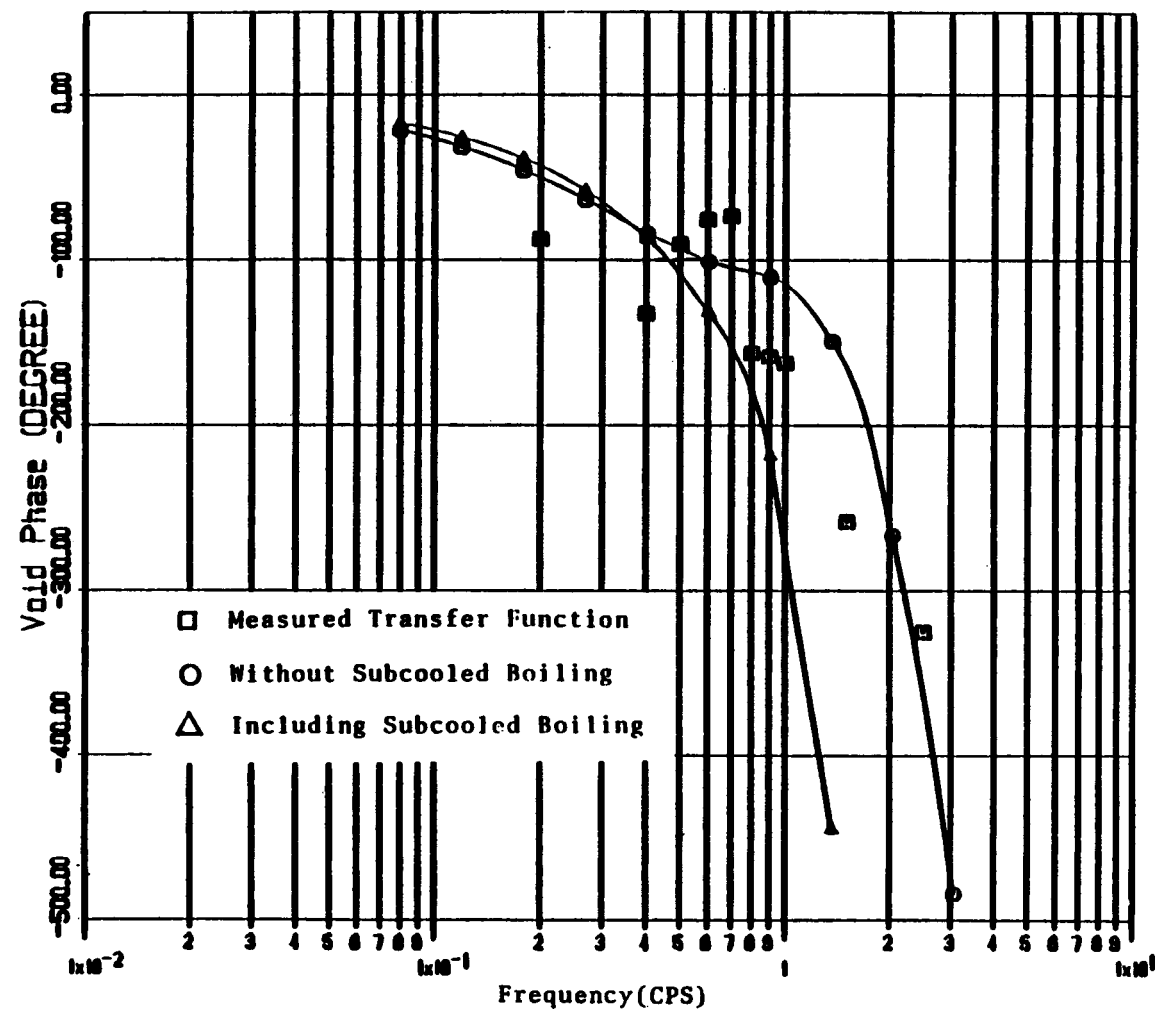


Figure 5.23 Power-to-Void Transfer Function for Run #9 (Phase)

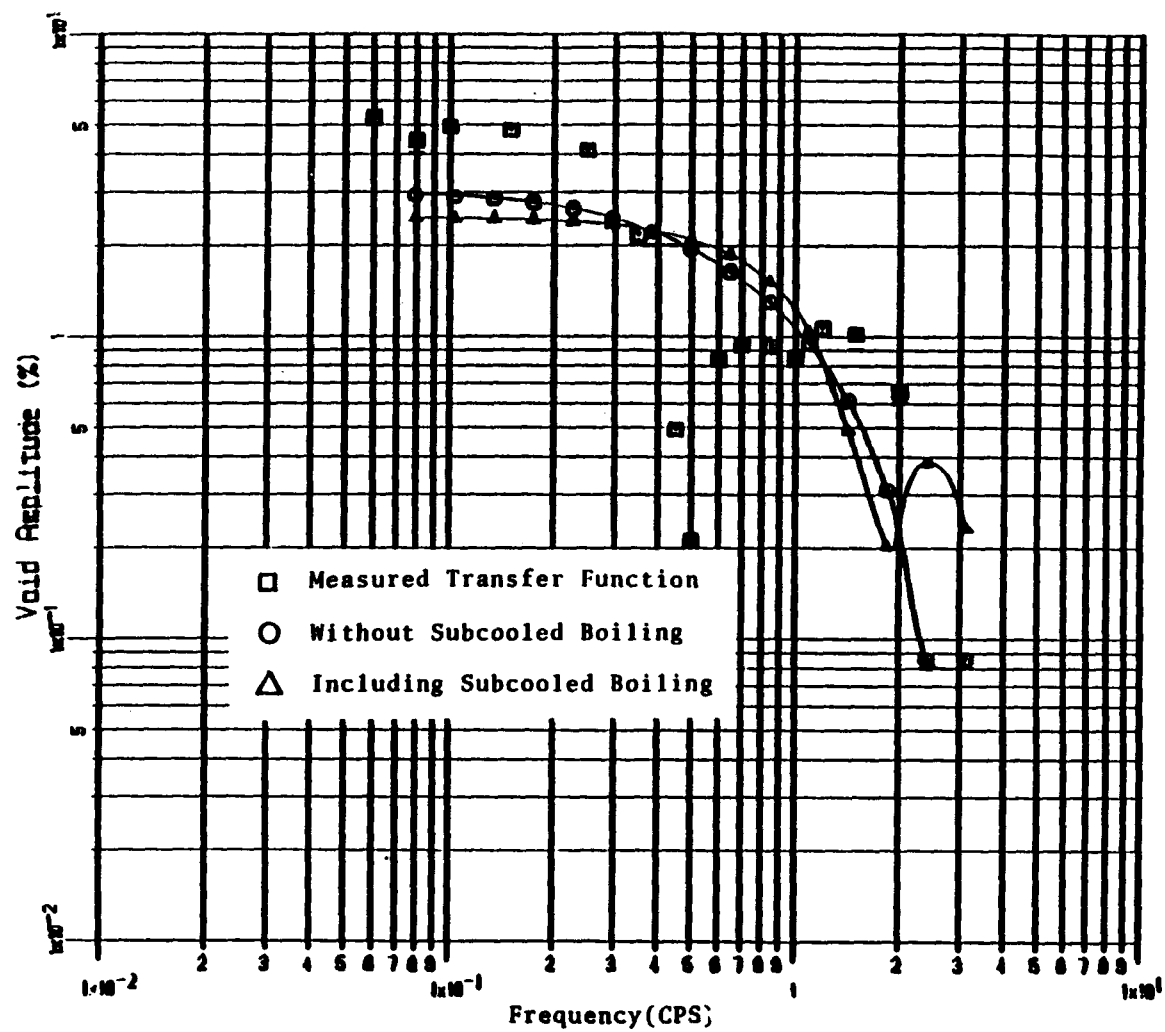


Figure 5.24 Power-to-Void Transfer Function for Run #13

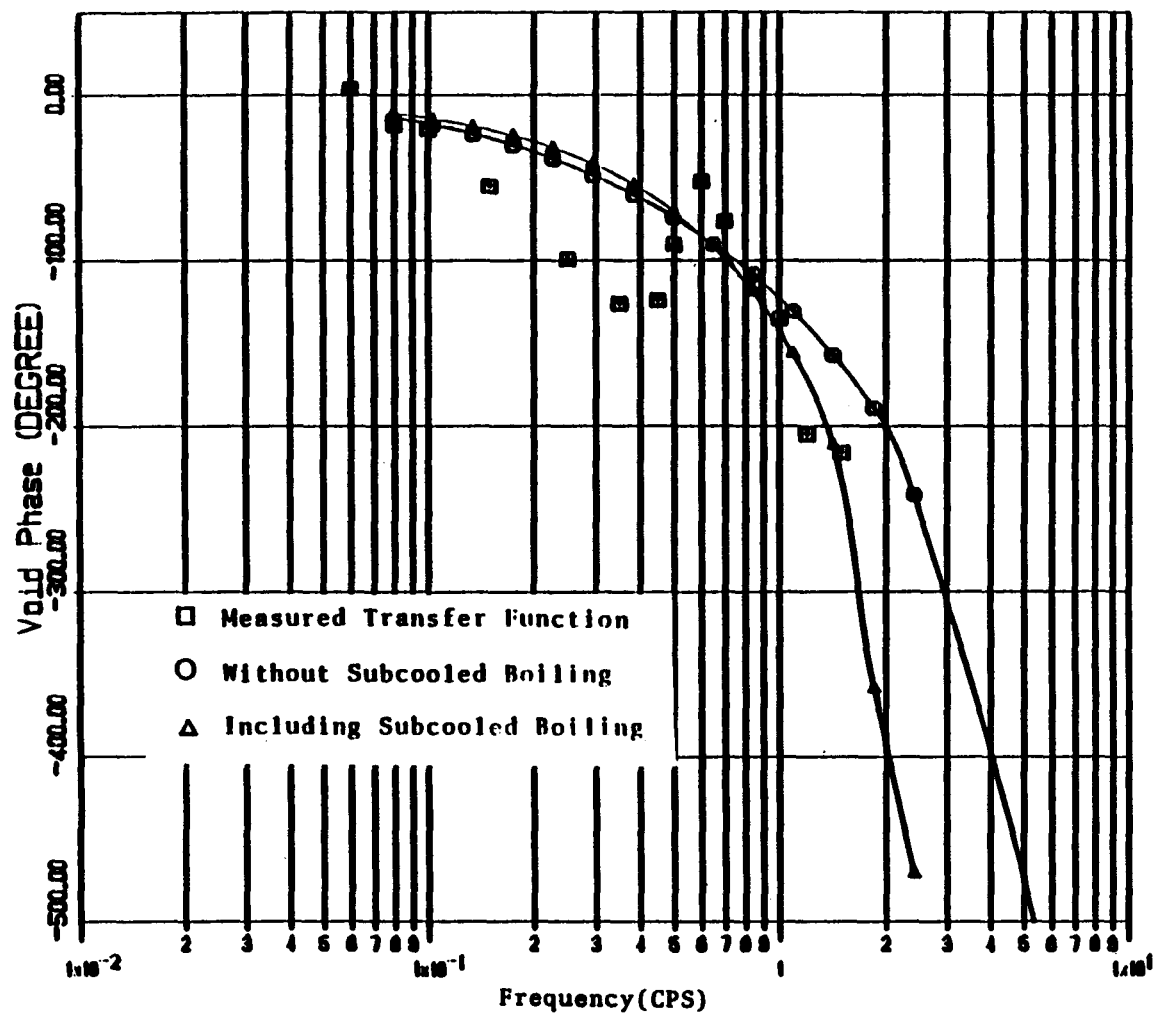


Figure 5.25 Power-to-Void Transfer Function for Run #13 (Phase)

Figure 5.26. It consists of a heated section, a steam drum for steam separation, a condenser, a variable speed centrifugal pump, three interchangeable spool pieces which allowed for variation of the effective downcomer length, an orifice meter, and a turbine flow meter.

Void measurements were made at several axial position, and also integrated to obtain the average void response. In this study we analyzed the power-to-average-void transfer function(including flow feedback) for Run PEP-03. The calculated transfer function can be obtained a procedure similar to that used to deduce Equation (5.7), except for replacing the exit void fraction transfer function in Equation (5.5) with the channel-averaged transfer function, which is obtained by channel- averaging Equation (2.84).

For the test conditions shown in Table 5.4, the analyses were performed using the NUFREQ-N code. The results are shown in Figure 5.27 to 5.36, in which the effect of the following thermal-hydraulic parameters and models were investigated:

- 1) subcooled boiling
- 2) phasic slip
- 3) two-phase multiplier, ϕ_{LO}^2
- 4) power level and flow rate
- 5) inlet subcooling and system pressure

It can be seen that the data scatter is much less than

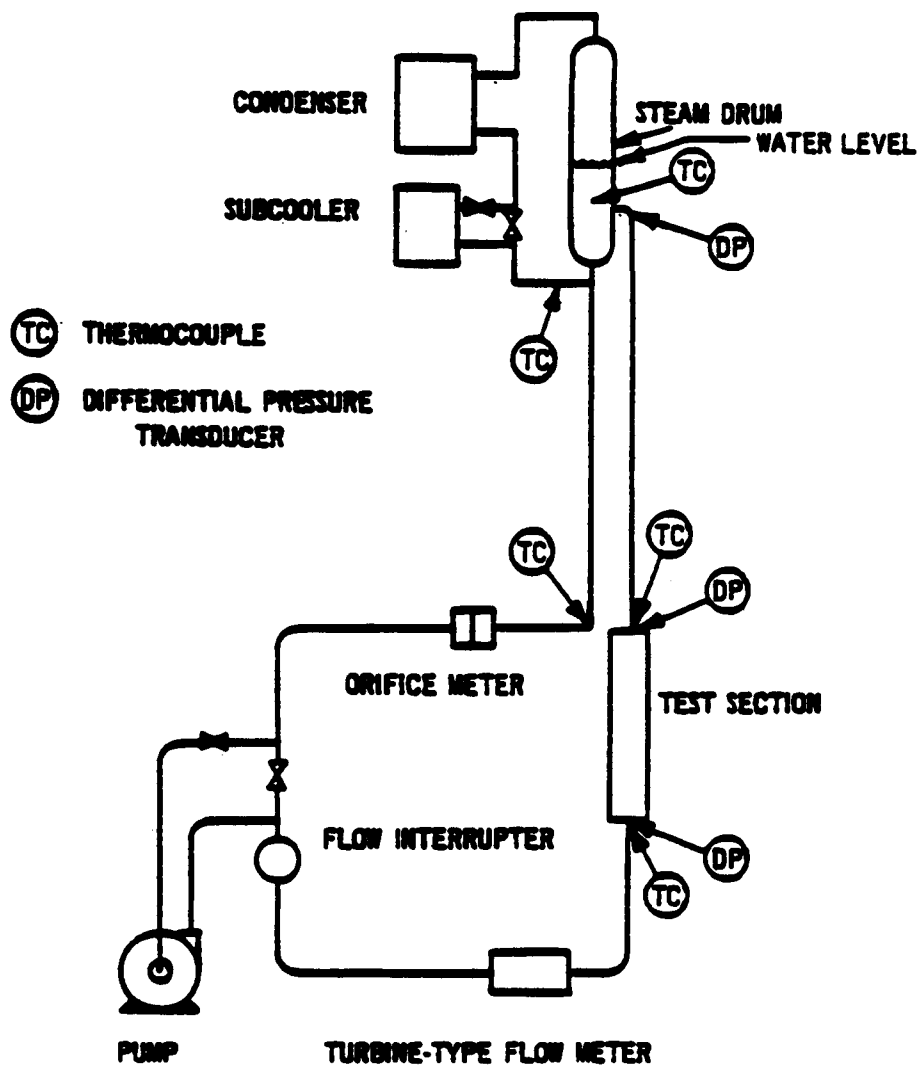


Figure 5.26 Sketch of Test Loop for Niemi's Experiment

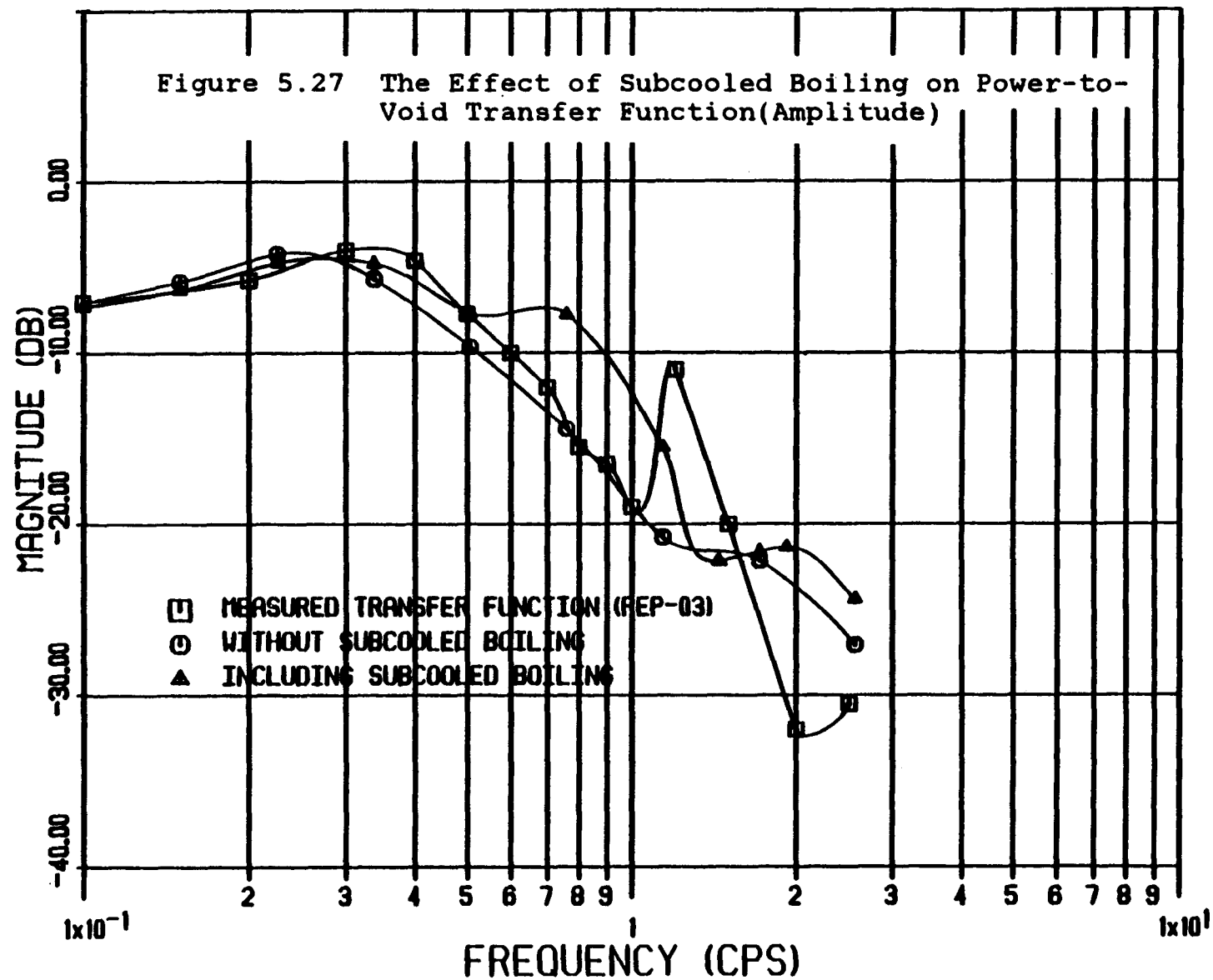
Table 5.4
The Test Conditions for Niemi Experiment

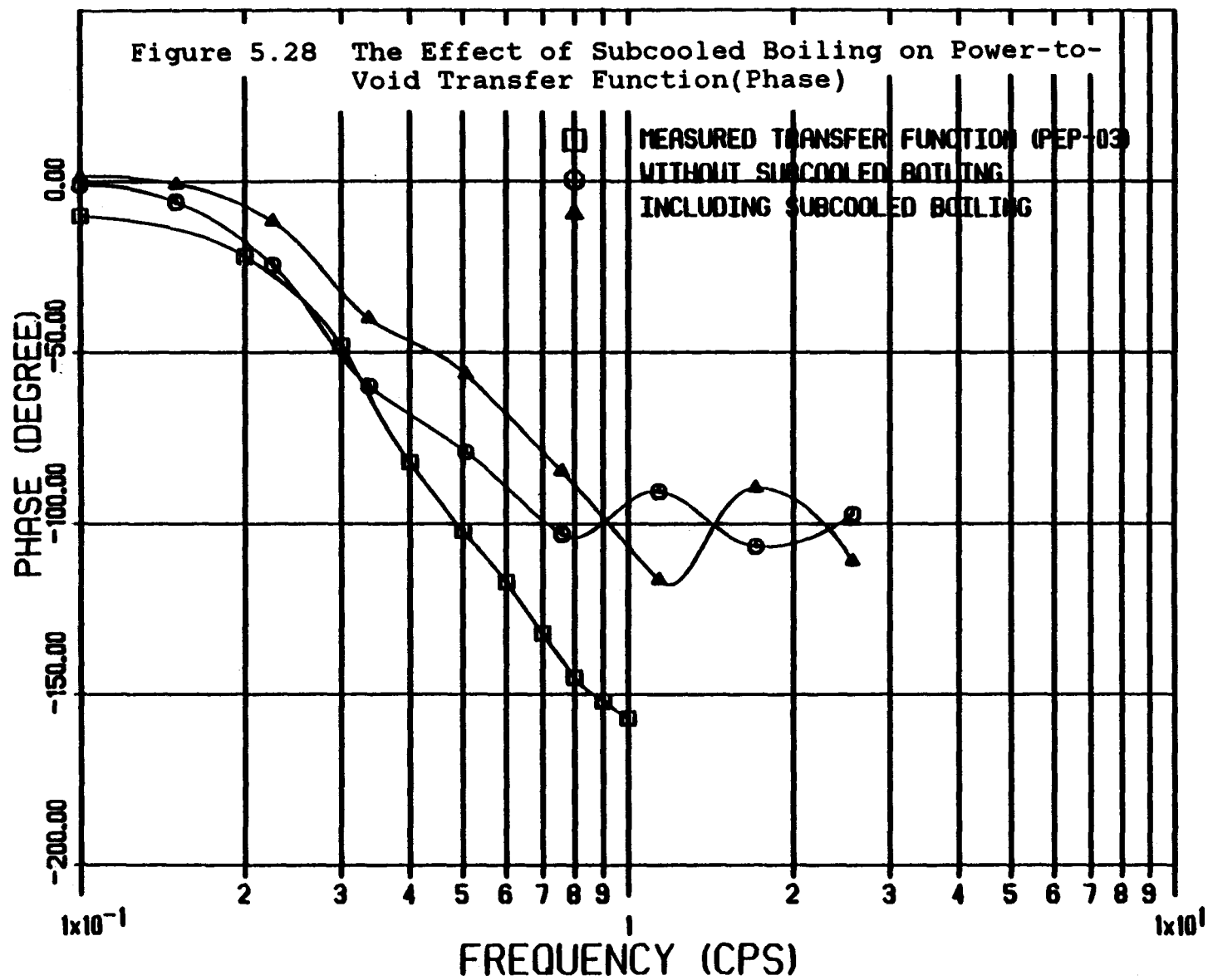
Variables

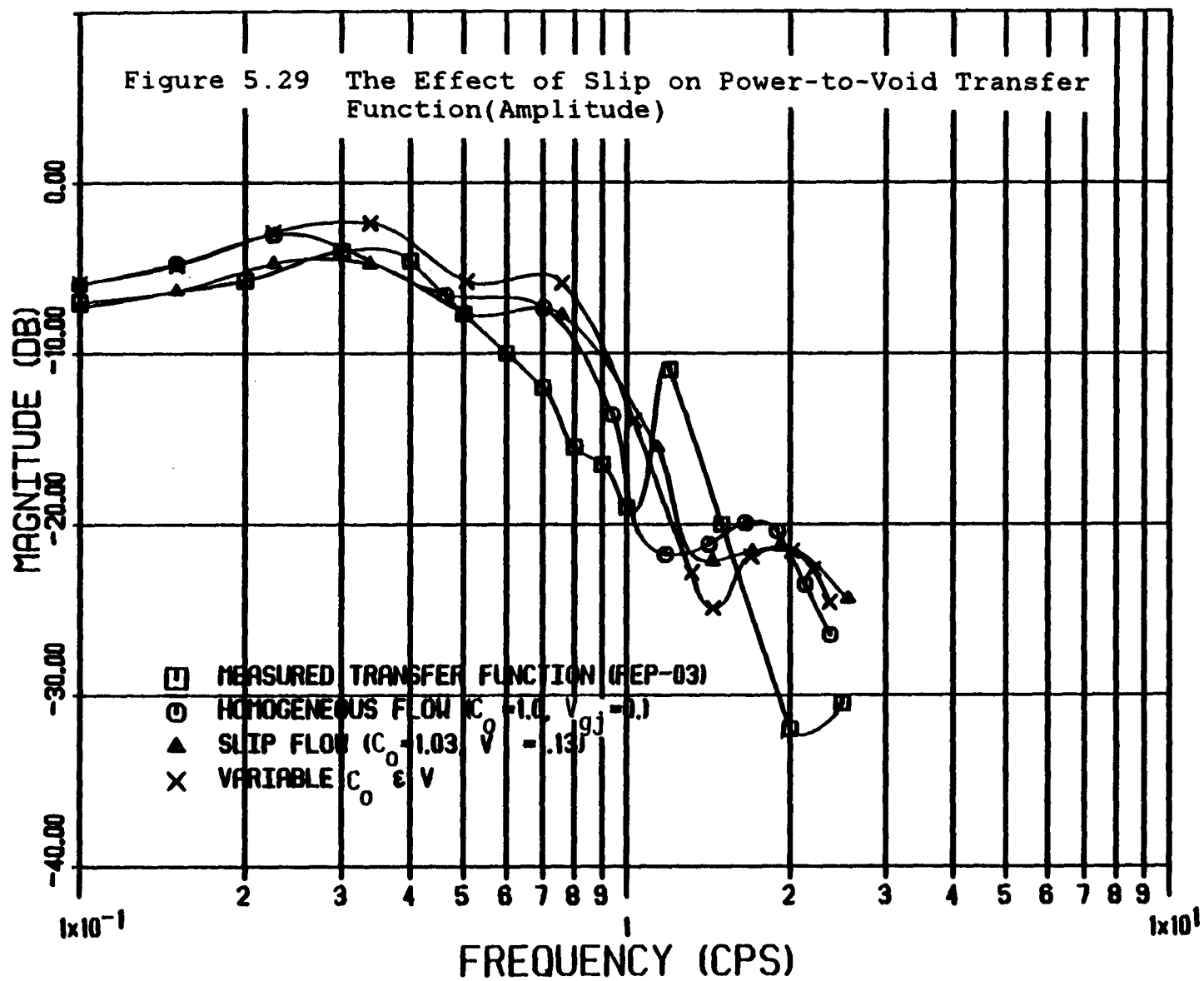
$p(\text{psia})$	1,000.
$L_H (\text{ft})$	6.35
$A_{x-s} (\text{ft}^2)$	2.035×10^{-3}
$P_H (\text{ft})$	0.25
$D_H (\text{in})$	0.346
$q_o'' (\text{Btu}/\text{ft}^2\text{-hr})$	6.962×10^4
$J_{io} (\text{ft}/\text{s})$	4.0
$\Delta T_{\text{sub}} (^\circ\text{F})$	15.2
C_o and V_{gj}	1.03 , 1.13
$C_{PH} (\text{Btu}/\text{lb-}^\circ\text{F})$	0.11
$k_H (\text{Btu}/\text{ft-}^\circ\text{F-s})$	3.028×10^{-3}
$\rho_H (\text{lb}/\text{ft}^3)$	488.
b (wall thickness, in)	1.333×10^{-3}
K_{in}	39.46
K_{spacer}	2.58
K_{exit}	0.62
L_p (length of upper plenum)	0.432
L_R (riser length, ft)	12.21
$A_R (\text{ft}^2)$	0.3×10^{-2}
$K_{R,\text{exit}}$	23.67
$\sum \frac{L_i}{A_i}$	172.51

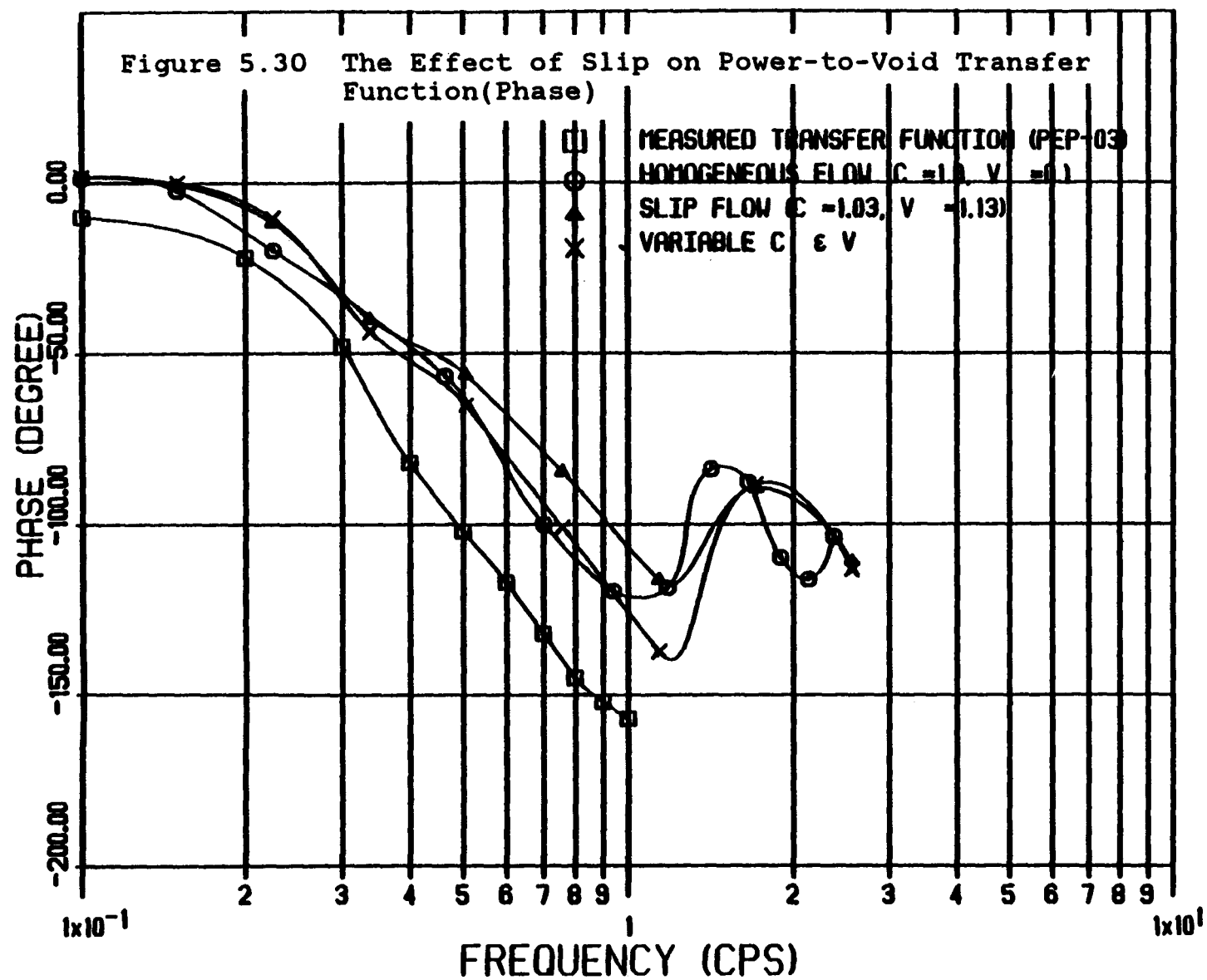
$$\sum \frac{f_i L_i}{D_{H,i} A_i^2} (ft^{-4})$$

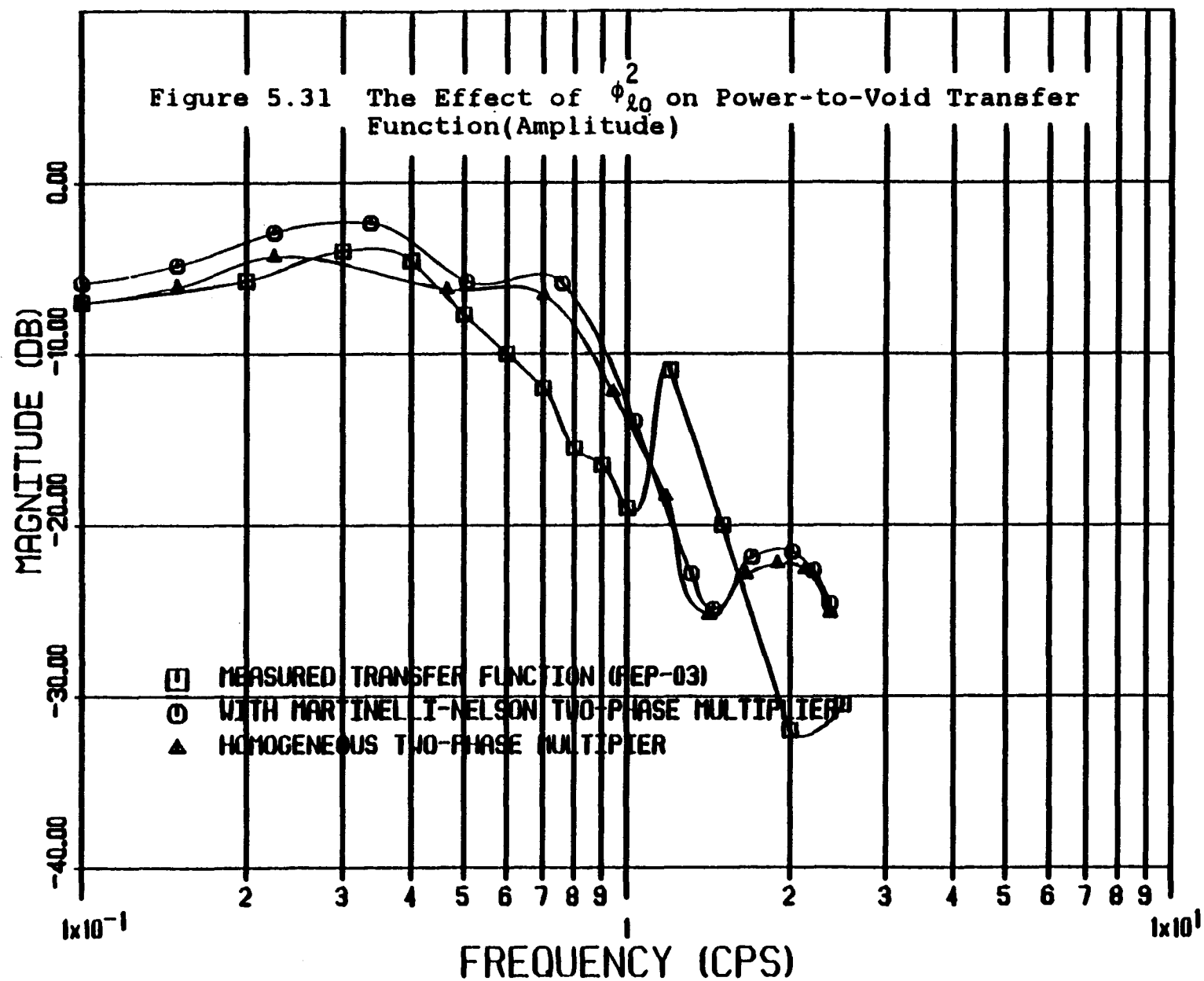
478.96

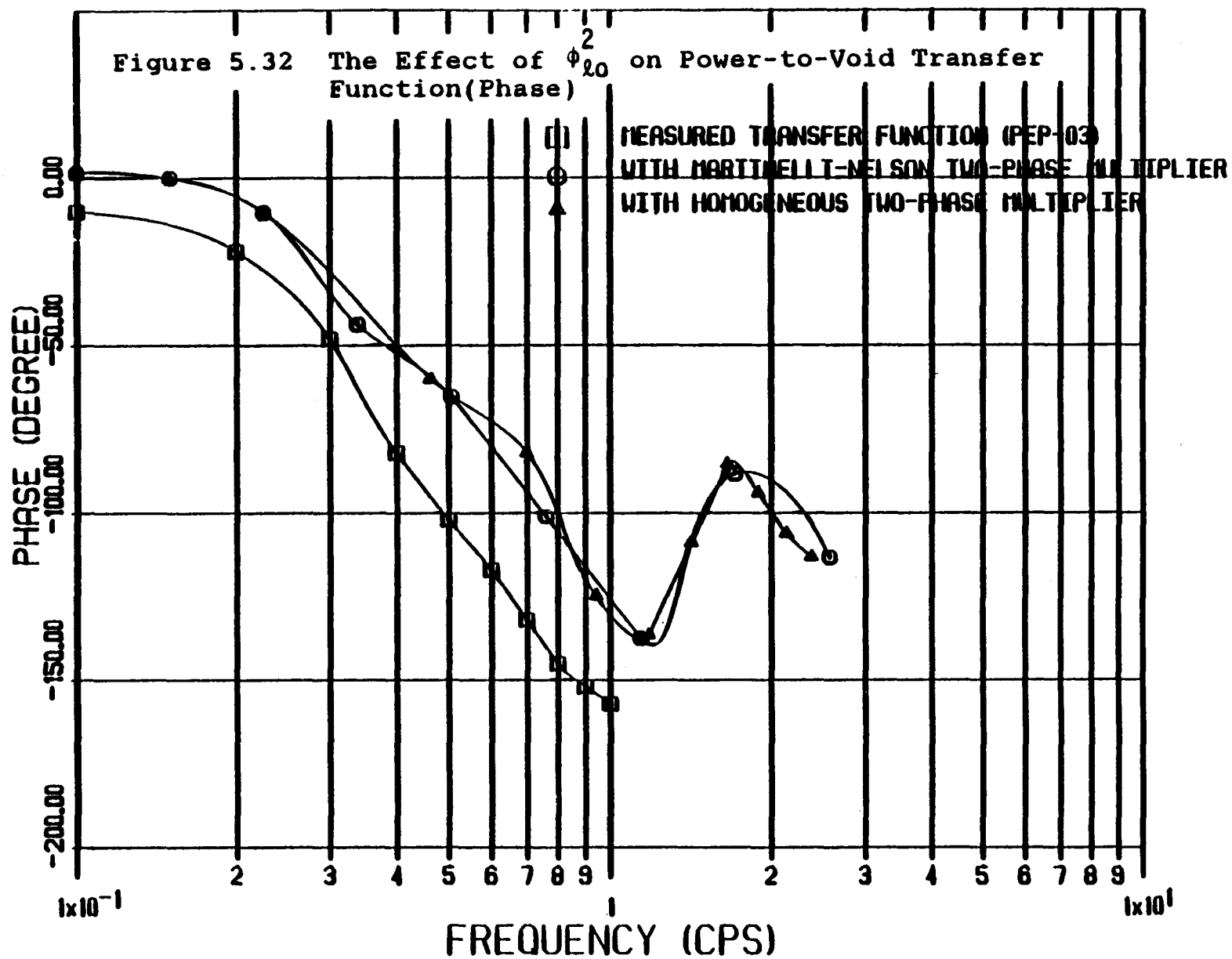


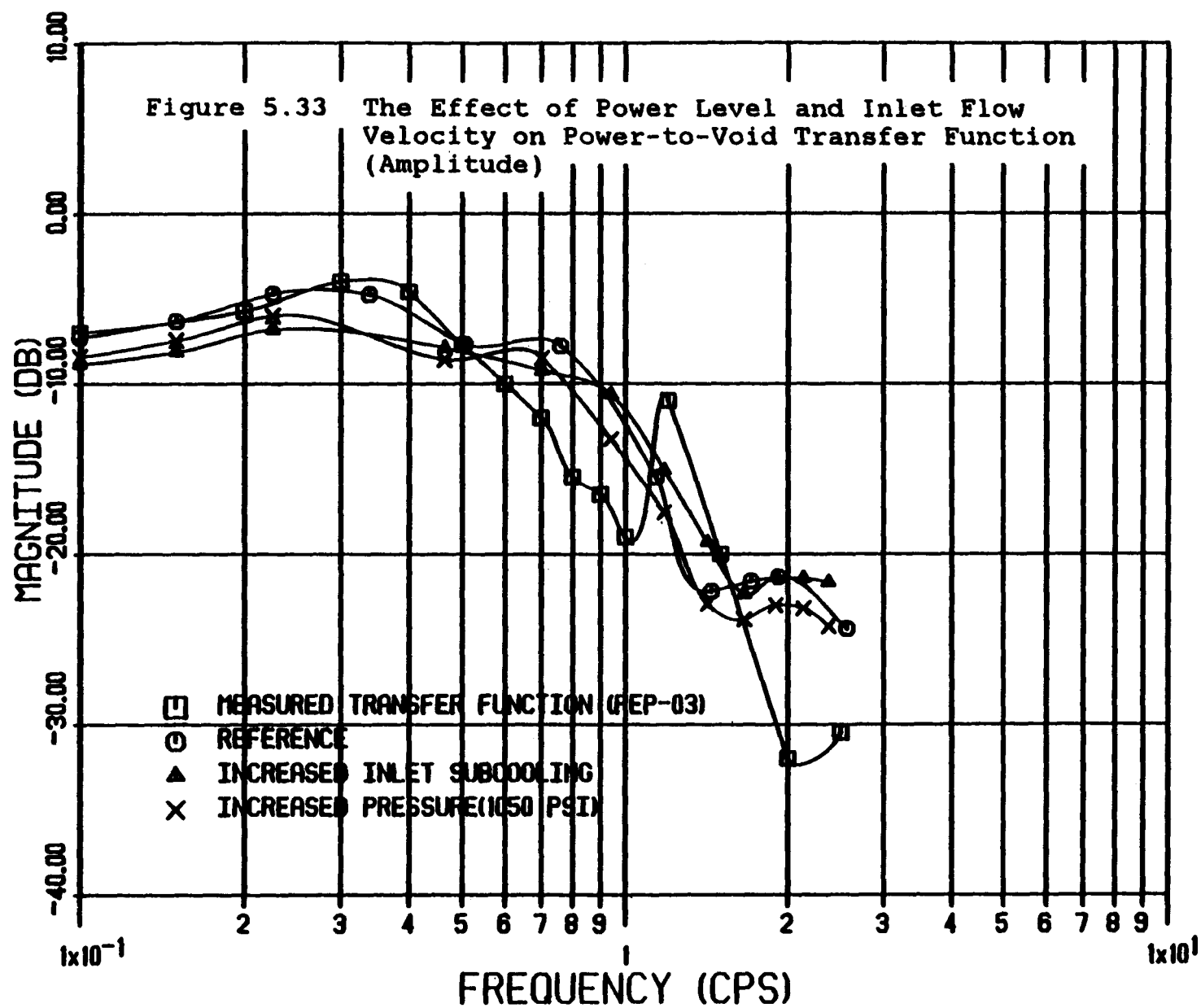


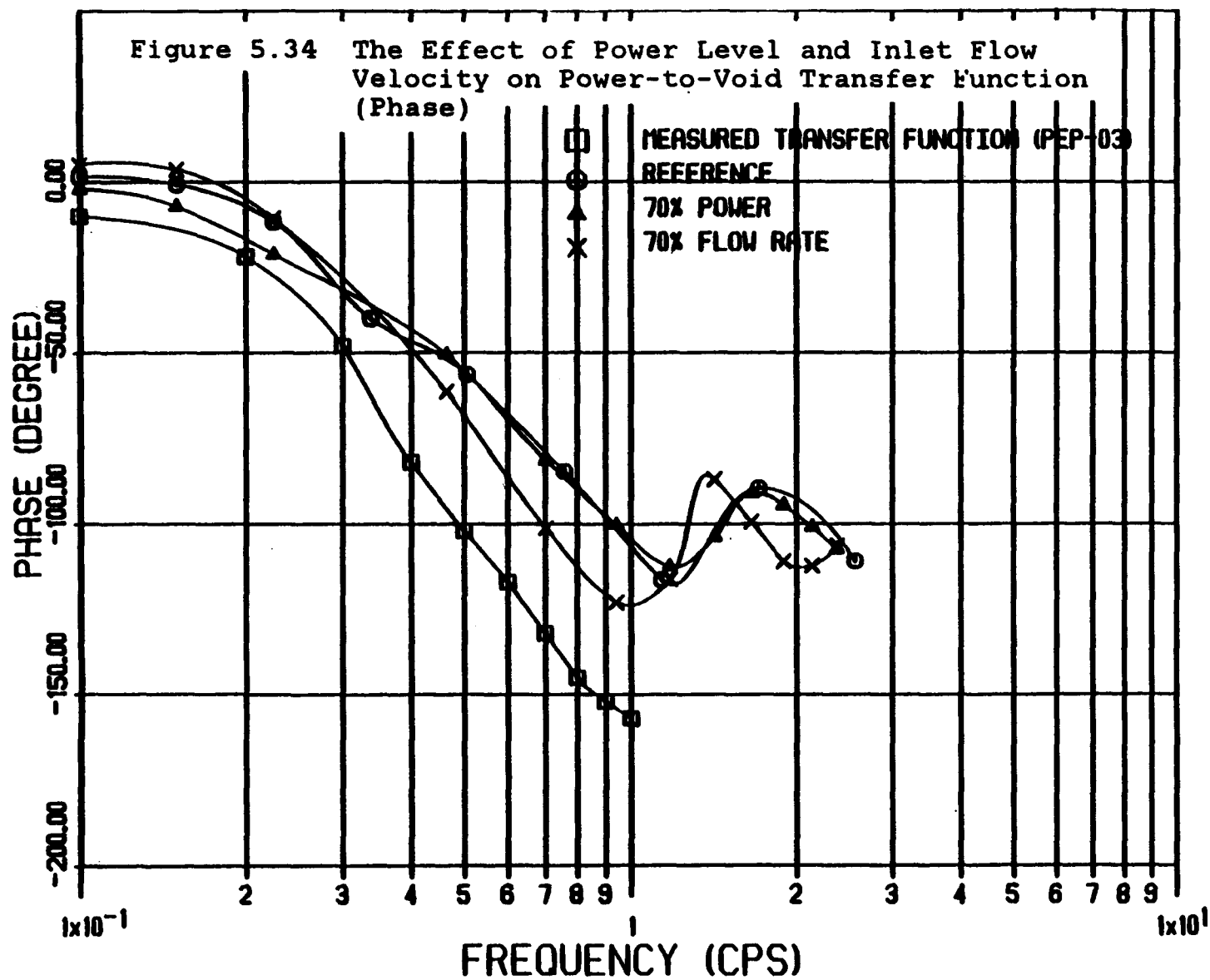


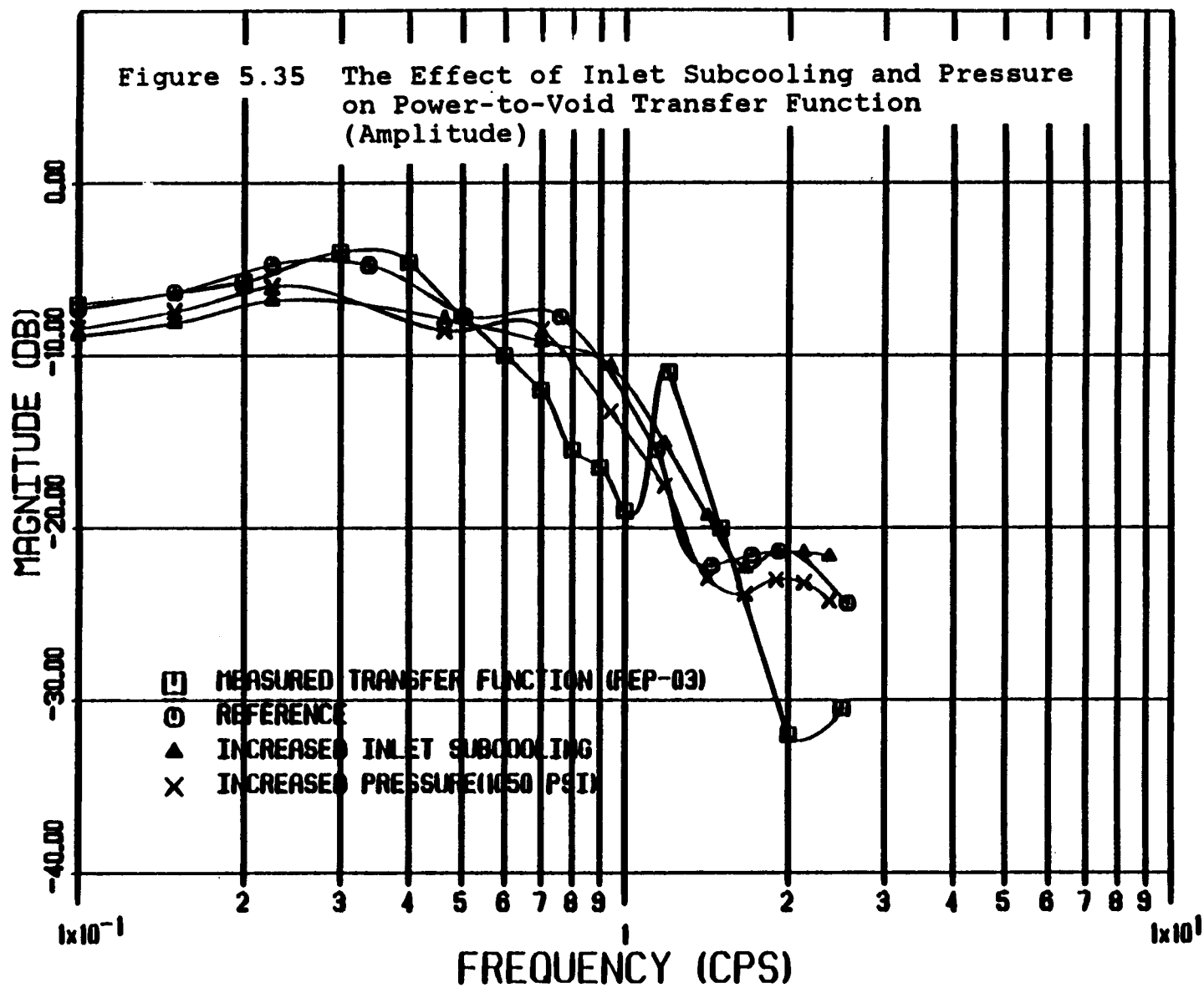


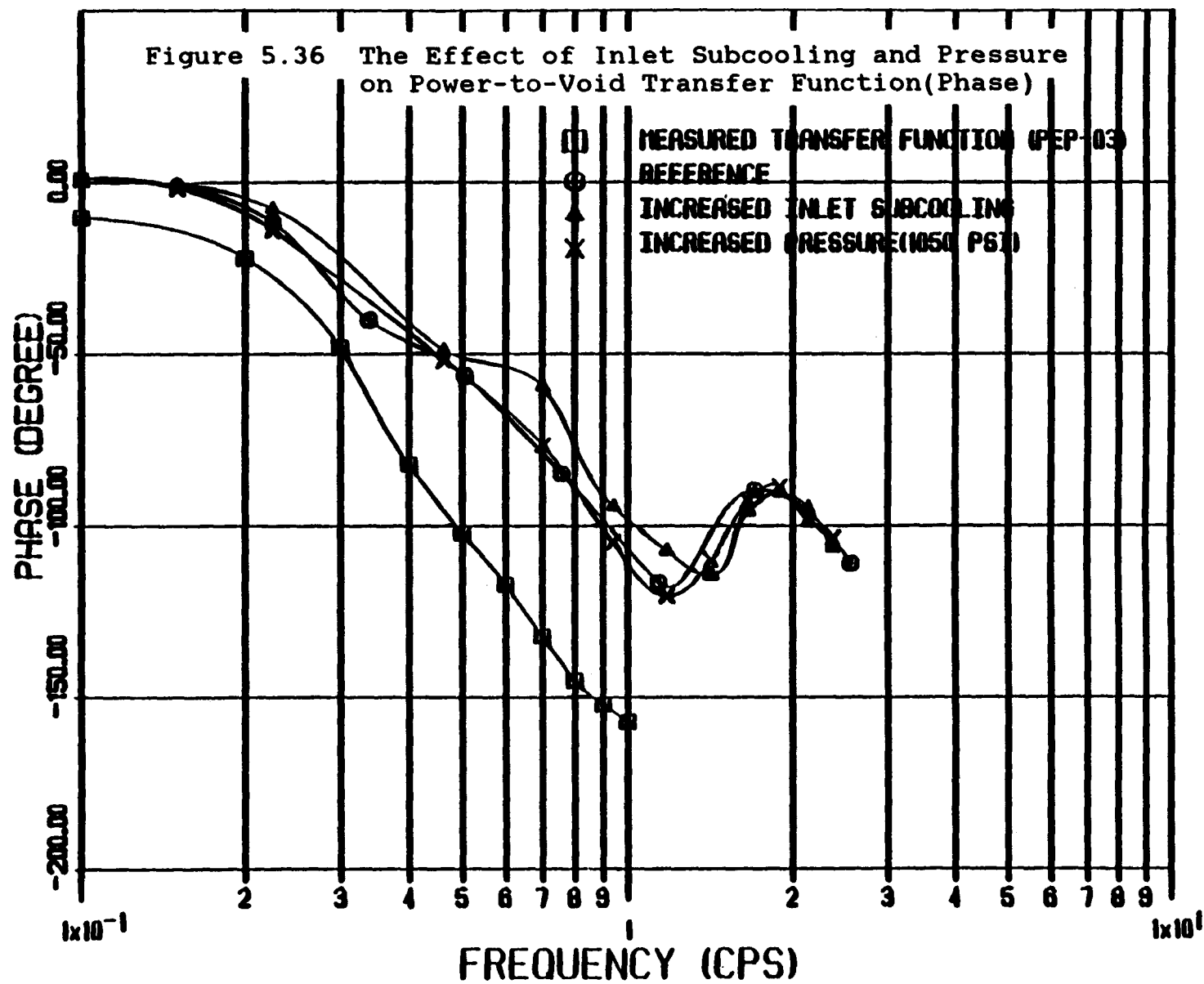












in Christensen's experiment. However, the calculated transfer function did not show the observed resonance at 1.2 cps, and had a consistently larger amplitude in range, 0.5 - 1 cps. Moreover, the measured phase angle shows a stronger roll-off than predicted. The differences between the data and the predictions of NUFREQ-N were found to be relatively insensitive to variations in the major thermal-hydraulic parameters (ie: slip, ϕ_{lo}^2 , power level, flow rate, pressure and subcooling). This indicates that there may be a systematic bias in the data. While it is difficult to determine for sure that a bias existed, since Niemi took data^[8] with a Boonshaft Ruchs analog analyzer, it is possible that an uncompensated RC circuit is in the data. Indeed, it was found that if the data were correct for a first order lag (typical of an RC circuit) of the form, $1.2/(0.2s+1)$, then the agreement between NUFREQ-N and the corrected data was improved considerably. This was particularly true, for the phase angle, which was found especially insensitive to changes in the thermal-hydraulic parameters investigated.

5.3.4 Dresden-3 Rod Oscillator Test

All experiments analyzed and discussed so far were out-of-core experiments which were performed in electrically heated channels. The control rod oscillator test at the Dresden Nuclear Power Station Unit 3 was run to determine

BWR dynamic characteristics, and was performed by General Electric Company and Commonwealth Edison Company^[6].

In this experiment one control rod was oscillated to determine the neutron flux response to the reactivity perturbation produced by an oscillating control rod. The power-flow map used in these tests is shown in Figure 5.37. In this study three tests were chosen; Runs 214, 220 and 230, whose experimental conditions are shown in Table 5.5, and core-average axial power distribution for each case is shown in Figure 5.38.

The calculated transfer function from the NUFREQ-N code is the closed-loop reactivity-to-neutron flux transfer function given as,

$$\frac{\delta \hat{\phi}}{\delta \hat{k}_{\text{ext}}} = \frac{\phi}{1 - C_{\alpha} F \phi} \quad (5.8)$$

where ϕ , k , C_{α} are the neutron flux, core multiplication factor and void-reactivity coefficient, respectively. Here, ϕ is the point kinetics transfer function defined in Equation (4.17) and $F(s)$ is the power-to-average void transfer function defined in Equation (XIII.10).

In order to compare with the experimental data, the closed-loop transfer function in Equation (5.8) was normalized in the same way as the Dresden-3 experiment^[6], by assuming that, at higher frequencies, the hydrodynamic effects disappear and the closed-loop transfer function merges with the reactor kinetics transfer function, ϕ . The

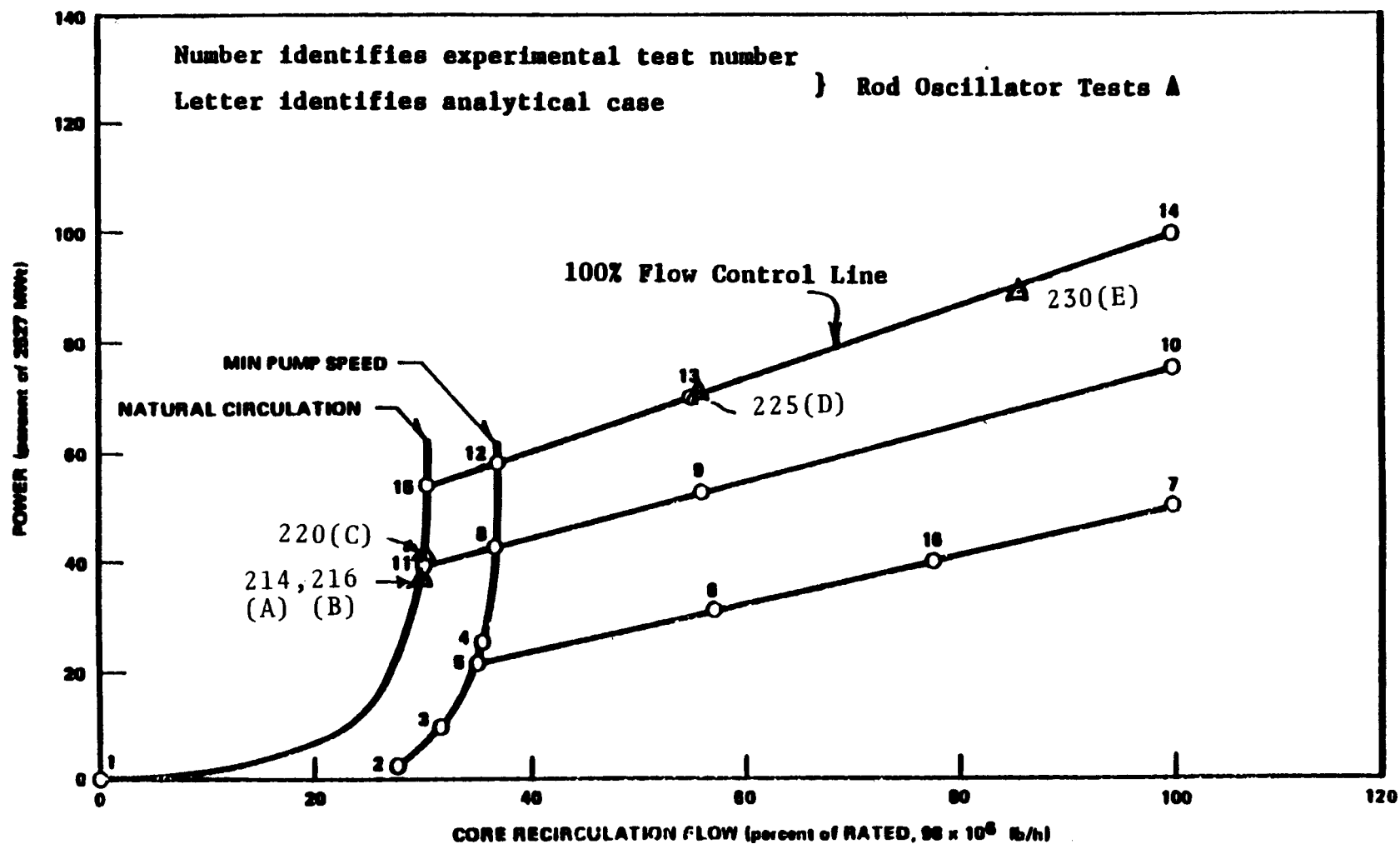


Figure 5.37 Flow Control Line for Dresden-3 Rod Oscillator Tests

Table 5.5
Operating Conditions for Dresden-3 Rod Oscillator Tests

Variables	RUN 214	RUN 220	RUN 230
p (psia)	946	946	1002
L_H (ft)	12		
A_{x-s} (ft ²)	0.121		
p_H (ft)	7.222		
D_H (in)	0.641		
$\bar{q}_o$ (Btu/ft ³ -hr)	5.162×10^6	6.394×10^6	1.383×10^7
J_{io} (ft/s)	1.826	1.826	4.204
ΔT_{sub} (°F)	30.6	39.6	18.4
C_o & V_{qj}		1.1 & 1.25	
K_{in}	7.8		
K_{exit}	0.14		
K_{spacer}	1.04		
c_{pH} (Btu/lb)	0.077		
k_H (Btu/lb- F-s)	0.564×10^{-3}		
ρ_H (lb/ft ³)	650.52		
c_{pc} (Btu/lb)	0.075		
k_c (Btu/lb- F-s)	0.252×10^{-2}		
ρ_c (lb/ft ³)	410.17		
γ_s (ft)	2.0333×10^{-2}		
γ_i (ft)	2.0792×10^{-2}		
γ_o (ft)	2.346×10^{-2}		
H_g (Btu/ft ² -s)	0.2778		
L_p (ft)	5.568		
$K_{R,exit}$	0.14		
L_R (ft)	8.948		
A_R (ft ²)	0.2006		
L_{DL} (for downcomer)	9.99		
(ft)			

Table 5.5 (Continued)
Operating Conditions for Dresden-3 Rod Oscillator Tests

Variables	RUN 214	RUN 220	RUN 230
A_{DL} (for downcomer)	293.108		
Circulation type			
N: Natural			
F: Forced	N($\xi=0.0$)	N($\xi=0.0$)	F($\xi=0.2$)
$\sum \frac{L_i}{A_i} \text{ (ft}^{-1}\text{)}$	2.67	2.67	16.67
$\sum \frac{f_i L_i}{D_{H,i} A_i^2} \text{ (ft}^{-4}\text{)}$	0.027	0.027	0.127

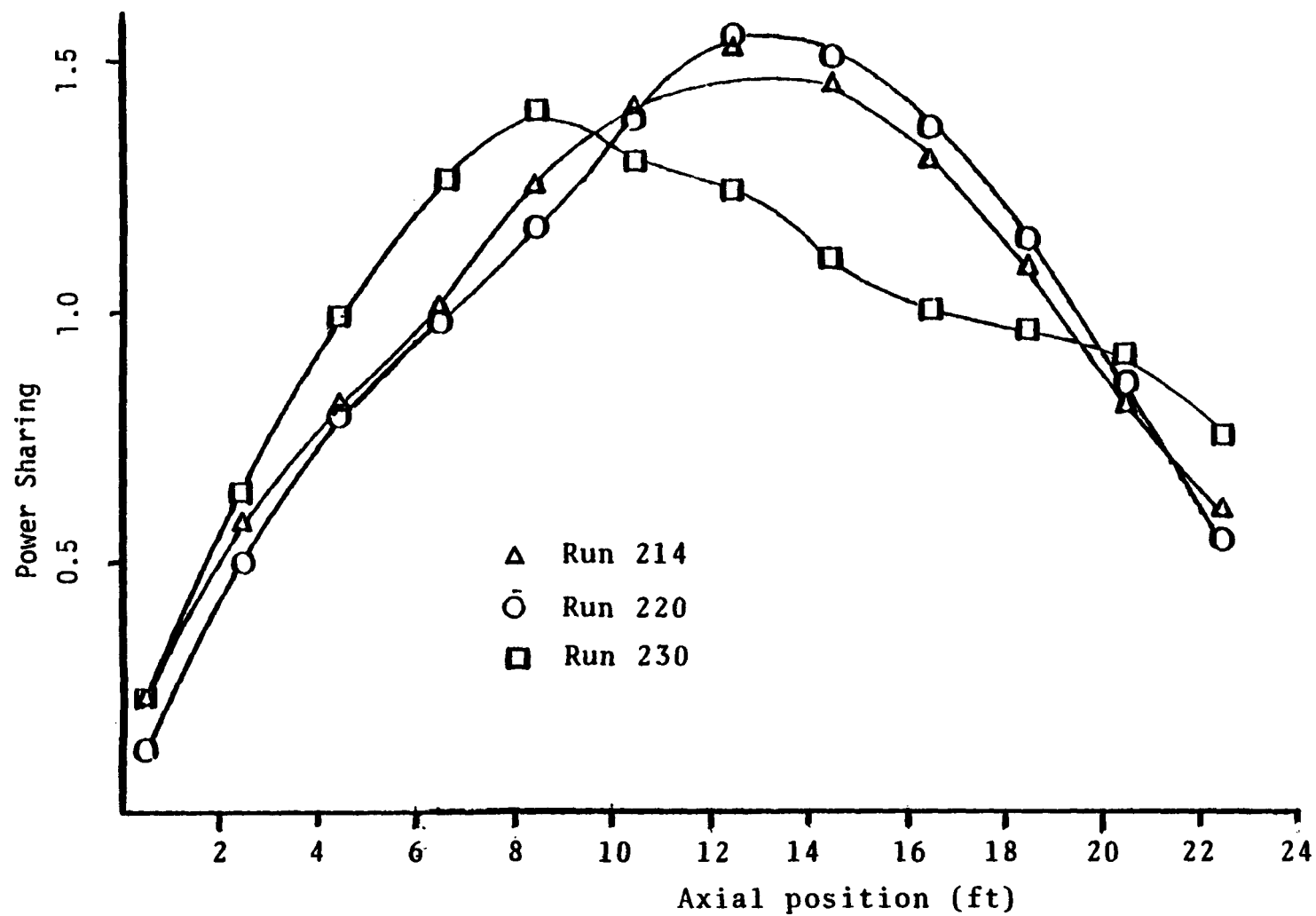


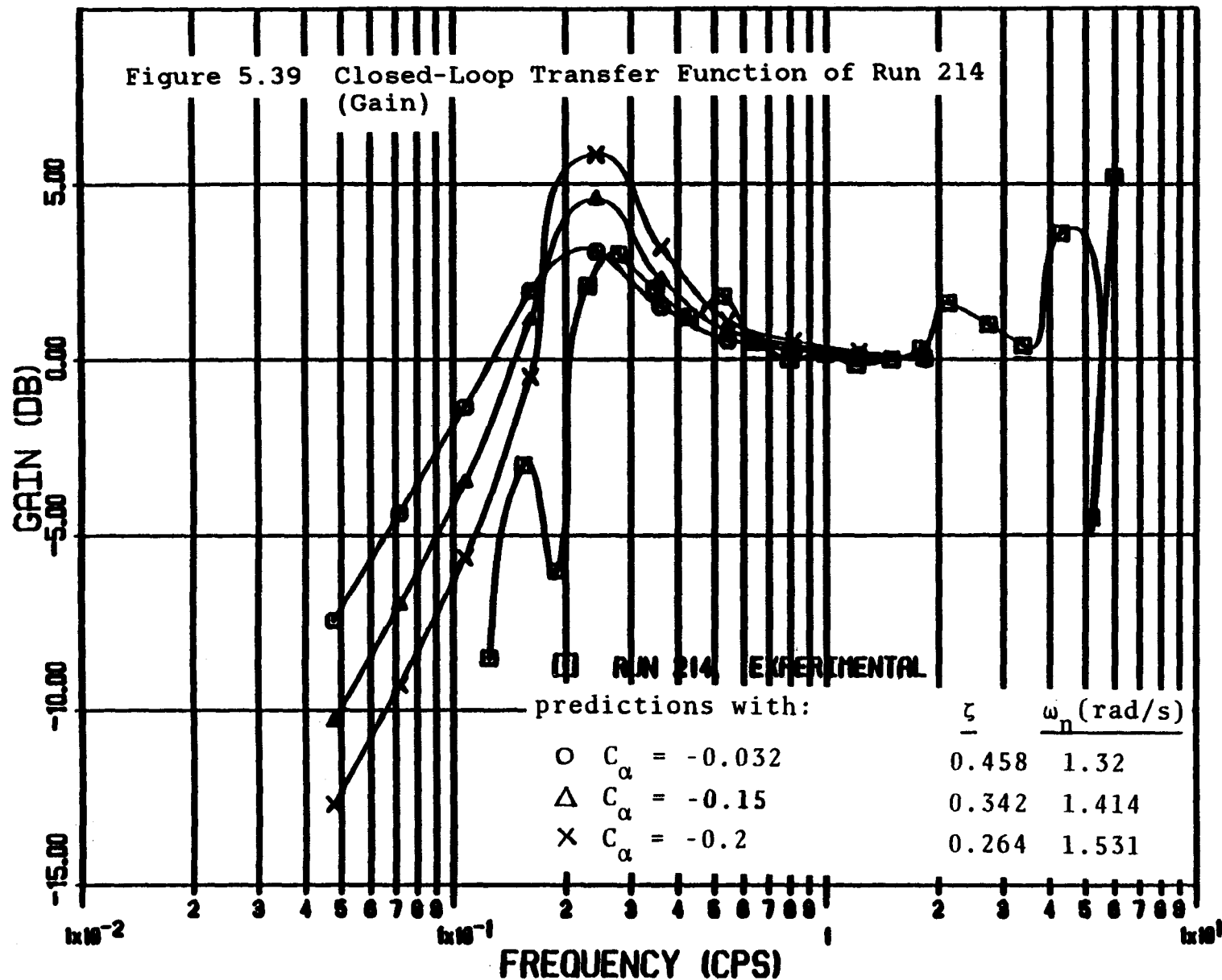
Figure 5.38 Core Average Axial Power Distribution for Dredsen-3 Rod Oscillator Test

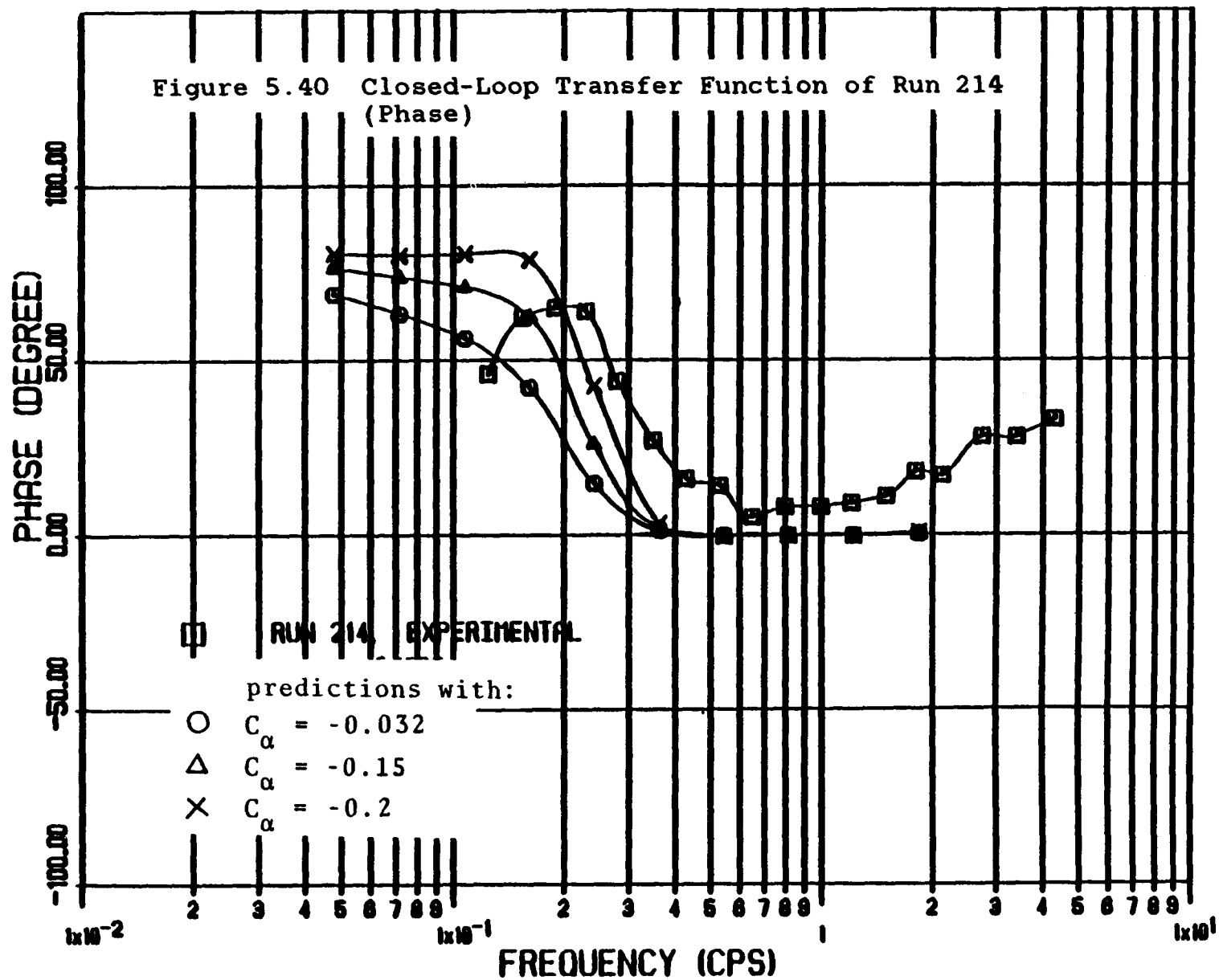
results are shown through Figure 5.39 to 5.44. Also shown are the calculated the damping ratio(ζ) and natural frequency(ω_n), using the procedure presented in Appendix-XII. It can be seen that the data trends are erratic, however the overall trends are predicted by NUFREQ-N.

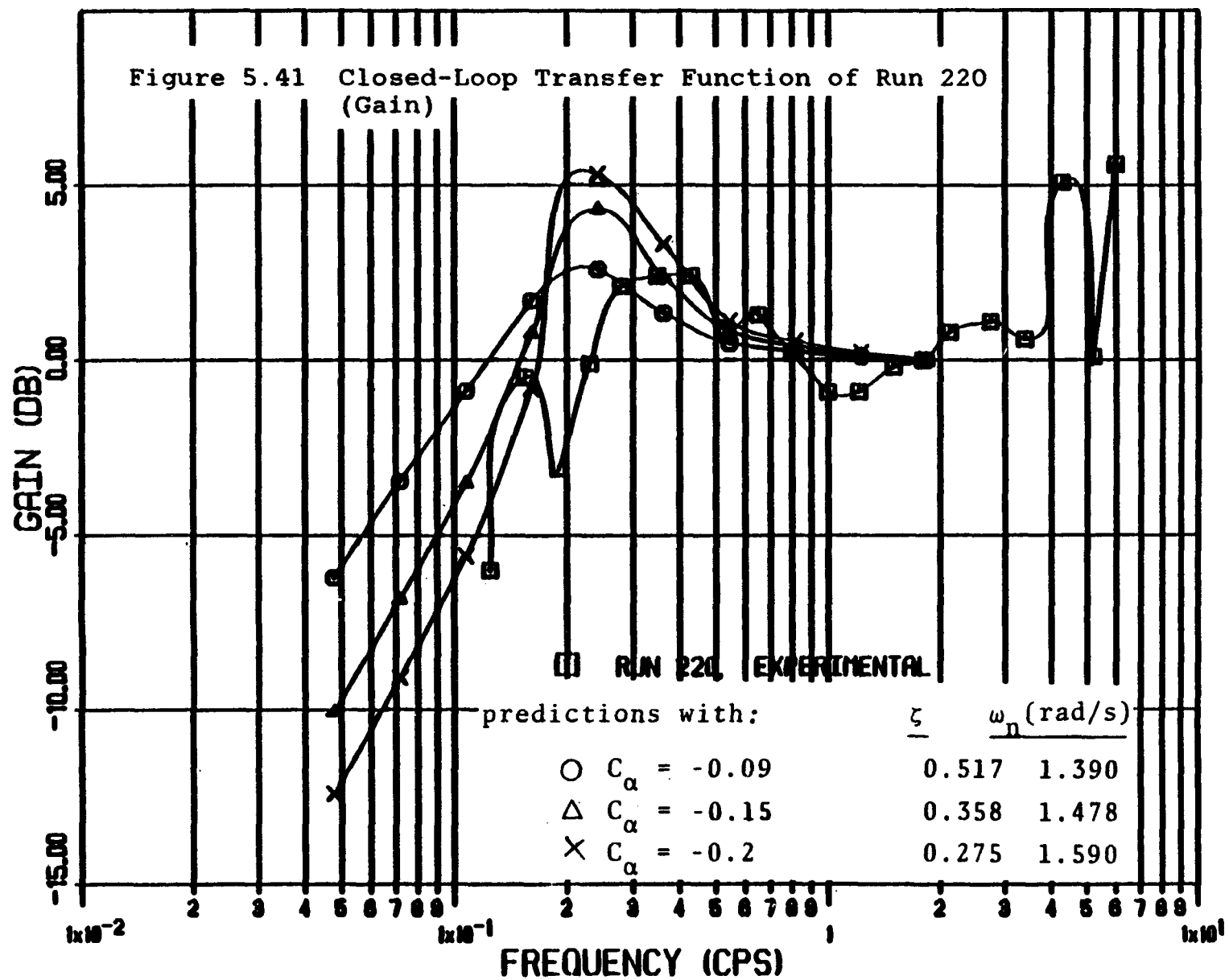
Due to the lack of exact nuclear data for the Dresden-3 operating conditions, it was difficult to determine the exact value of the void-reactivity coefficient, C_α , which is one of most important parameter in the neutron kinetics model. Thus, we tested the parametric effect of C_α by varying its magnitude. As can be seen, for negative C_α values, the reactor is destabilized as the magnitude of C_α increases due to negative feedback (ie: a dynamic instability). In contrast, for positive C_α , the reactor will be unstable due to well-known positive feedback effects (ie: a static instability). Thus it was found that in nuclear-coupled BWR stability analysis the value used for C_α plays an important role, and strongly affects the stability margin. That is, the predicted damping ratio shown in these figures is quite sensitive to the void-reactivity coefficient.

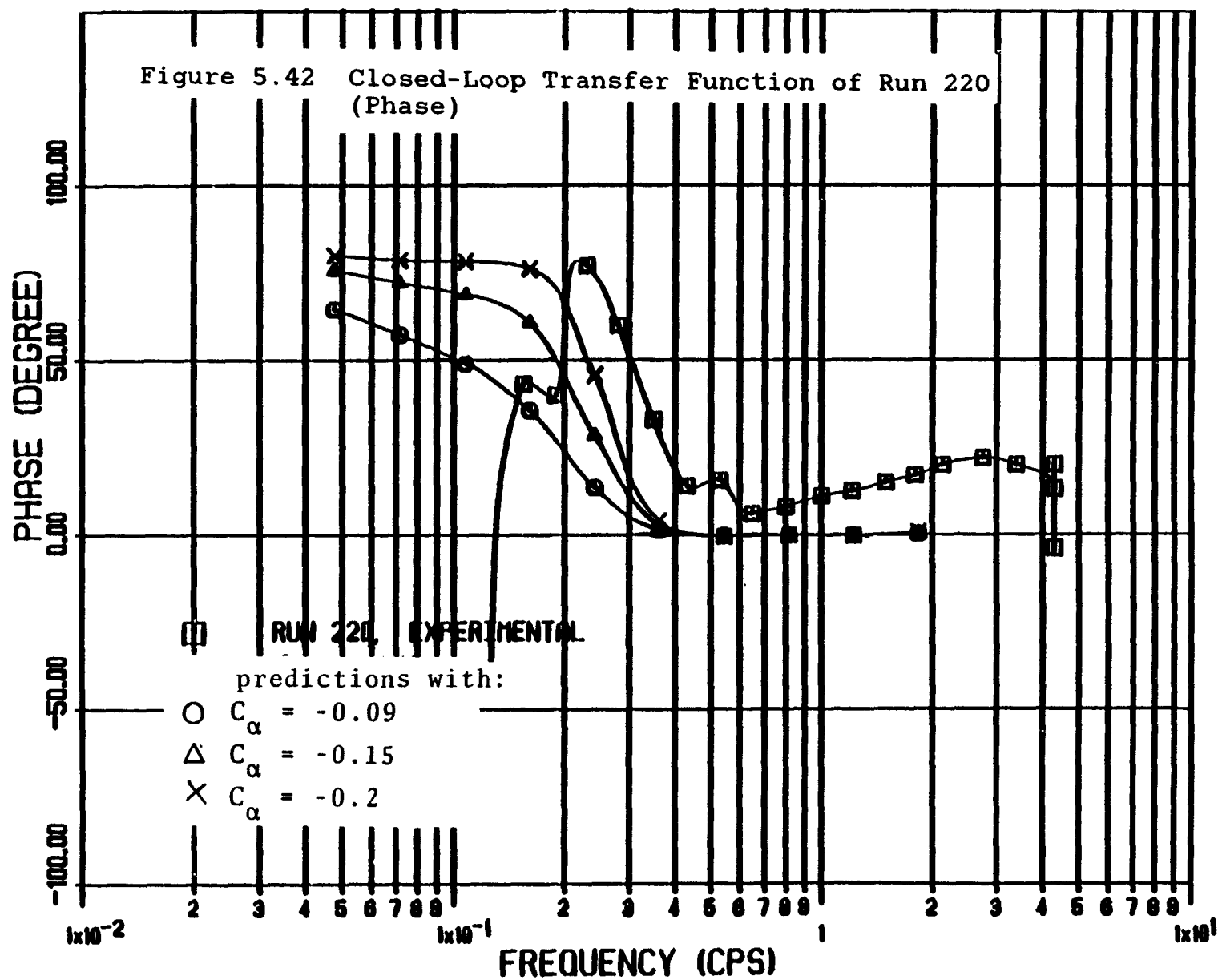
5.3.5 Peach Bottom Stability Tests

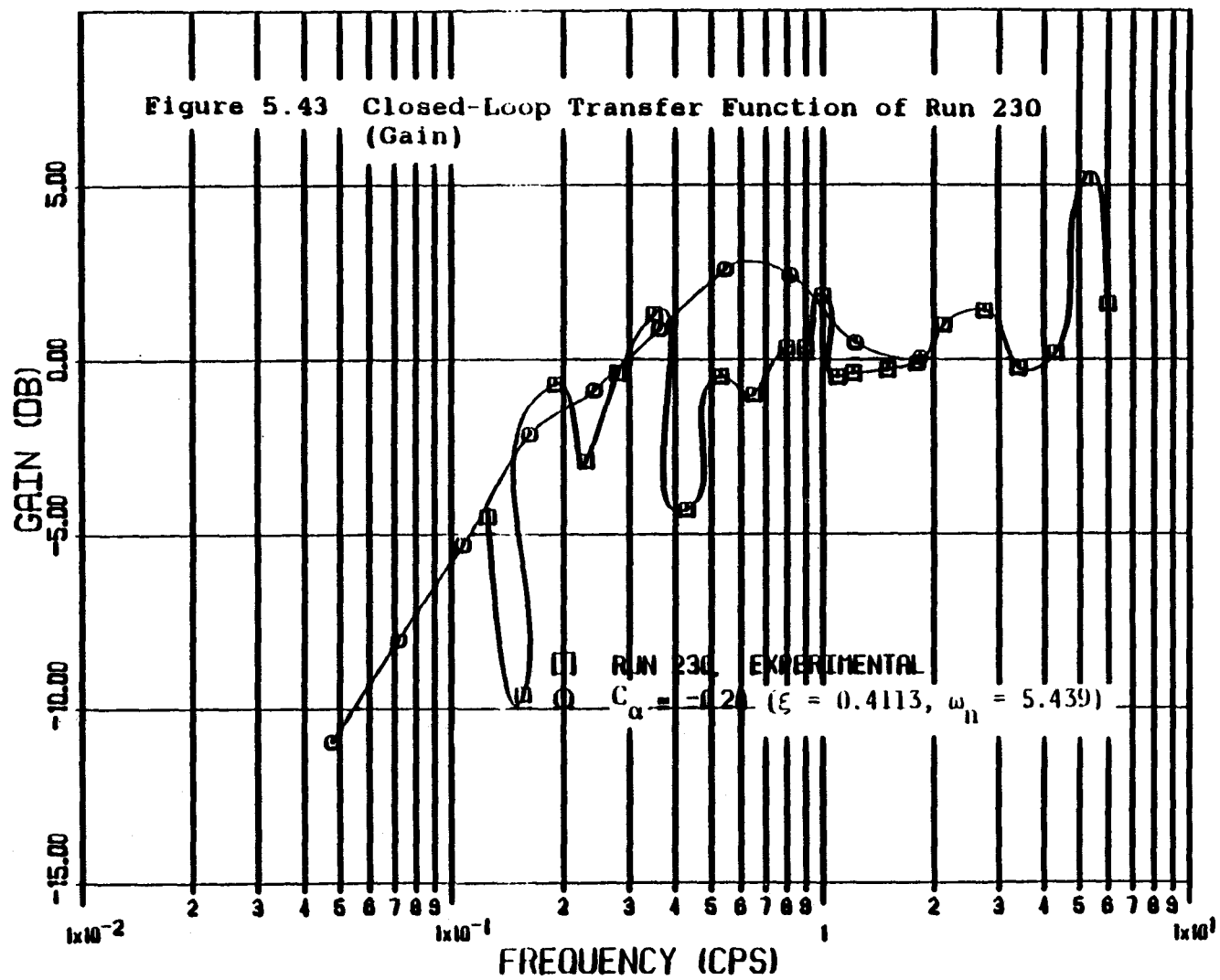
Core stability tests were performed at the Peach Bottom-2 BWR/4 nuclear power plant at the End of Cycle(EOC)^[7] Two. These tests were intended to determine

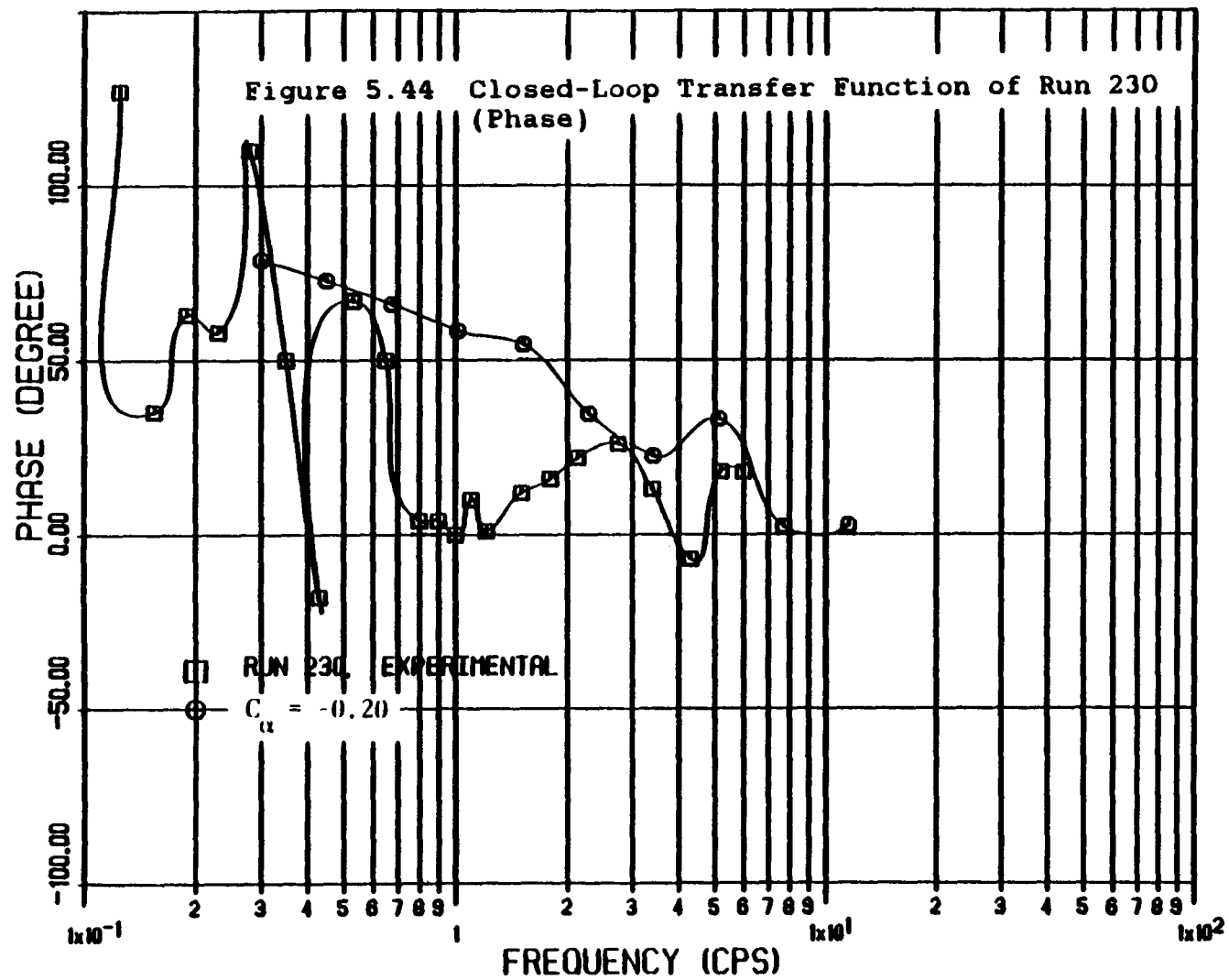












the stability margin of the boiling water reactor core by making small perturbations in system pressure.

Since there is no option for external pressure perturbation in the NUFREQ-N code, we simulated the test with external core-average power perturbations. The stability analysis was performed at 59.2% rated power and 38% rated core flow rate (Test PT3), and the nuclear data for full power and flow rate condition at EOC of cycle 2 (core average exposure of 12800 MWD T). The relative power and inlet flow rate distribution calculated by RPI's version of SIMULATE^[2,3] with the modified coarse mesh diffusion theory (MCMDT) are shown in Figure 5.45 and 5.46. The other operating and geometrical parameters have been given previously^[4,5], and are summarized in Table 5.6.

In this study two configurations were considered; one is a hot channel analysis in which the core is composed of only hot channels, another is a checker-board configuration in which the core is composed of an infinitely repeated array (ie: checker board) having four channels of different power level. Both configuration are expected to be somewhat conservative.

Since NUFREQ-N does not have the capability for system pressure perturbation, we were not able to compare directly with the measured data. Rather, comparison were made in terms of the damping ratio (ζ) and the natural frequency (ω_n). The results shown in Figure 5.47 to 5.50

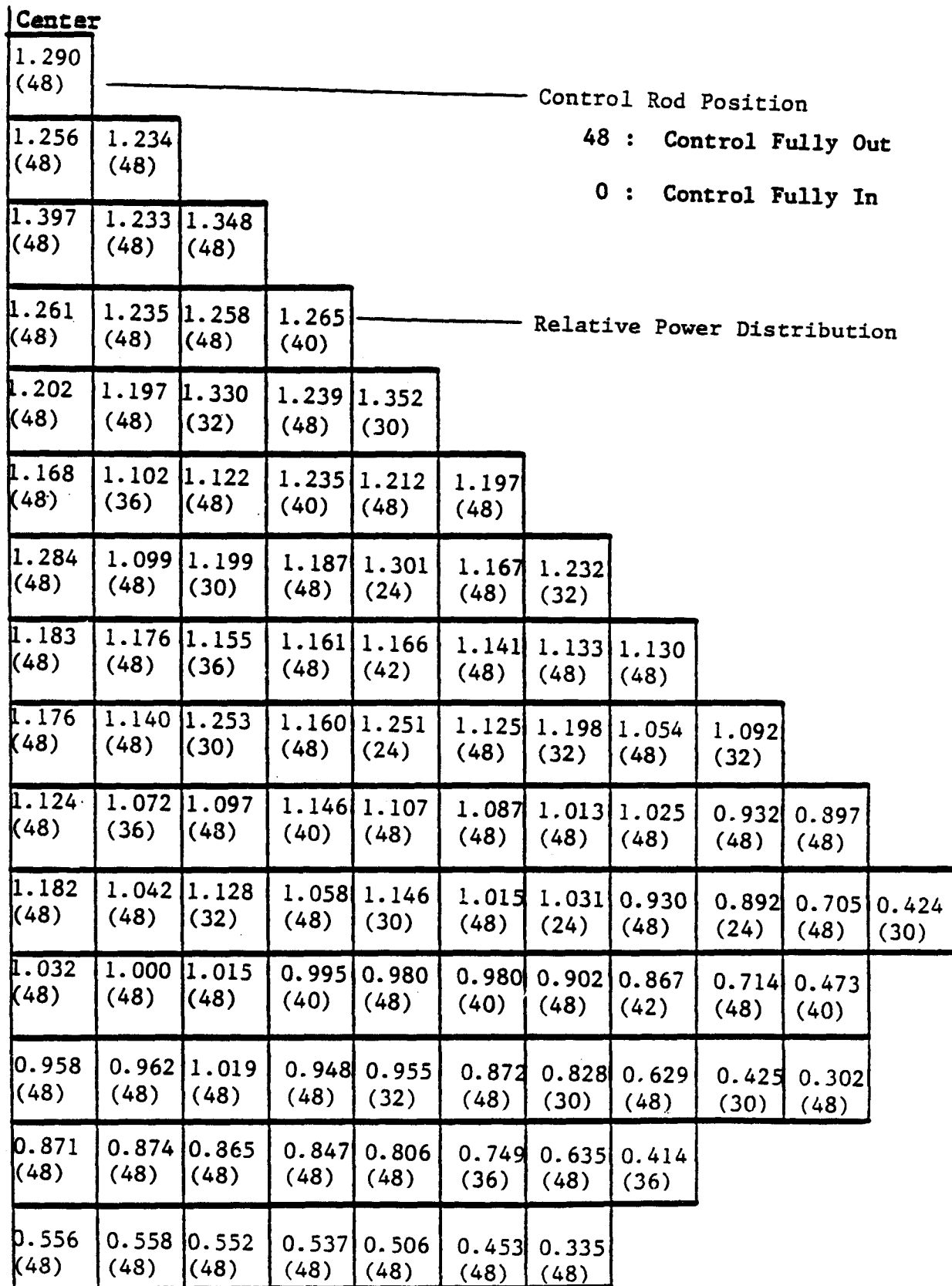


Figure 5.45 1/8 Core Relative Power Distribution and Control Configuration at EOC of Peach Bottom Cycle-2

Center										
0.091 (4)										
0.092 (2)	0.092 (2)	Channel Flow (MLb/hr)								
0.088 (4)	0.092 (2)	0.089 (4)	Fuel Type							
			2; Type 2 (Initially Loaded)							
			4; Type 4 (Reloaded)							
0.092 (2)	0.092 (2)	0.092 (2)	0.091 (2)							
0.093 (2)	0.093 (2)	0.090 (4)	0.092 (2)	0.089 (4)						
0.094 (2)	0.095 (2)	0.095 (2)	0.092 (2)	0.093 (2)	0.093 (2)					
0.091 (4)	0.095 (2)	0.093 (4)	0.093 (2)	0.090 (4)	0.094 (2)	0.092 (4)				
0.093 (2)	0.093 (2)	0.094 (2)	0.094 (2)	0.094 (2)	0.094 (2)	0.094 (2)	0.094 (2)			
0.093 (2)	0.094 (2)	0.091 (4)	0.094 (2)	0.091 (4)	0.094 (2)	0.093 (4)	0.096 (2)	0.095 (4)		
0.095 (2)	0.096 (2)	0.095 (2)	0.094 (2)	0.095 (2)	0.095 (2)	0.097 (2)	0.097 (2)	0.099 (2)	0.100 (4)	
0.093 (4)	0.096 (2)	0.094 (4)	0.096 (2)	0.094 (4)	0.097 (2)	0.097 (4)	0.099 (2)	0.100 (4)	0.104 (2)	0.056 (2)
0.097 (2)	0.097 (2)	0.097 (2)	0.097 (2)	0.098 (2)	0.098 (2)	0.100 (2)	0.100 (4)	0.104 (2)	0.056 (2)	
0.098 (2)	0.098 (2)	0.097 (4)	0.099 (2)	0.098 (4)	0.100 (2)	0.101 (4)	0.106 (2)	0.056 (2)	0.057 (2)	
0.100 (4)	0.100 (4)	0.101 (2)	0.101 (4)	0.102 (2)	0.103 (4)	0.106 (2)	0.056 (2)			
0.055 (2)	0.055 (2)	0.055 (2)	0.056 (2)	0.056 (2)	0.056 (2)	0.056 (2)				

Figure 5.46 Channel Flow Rate and Fuel Type of 1/8 core at EOC of Peach Bottom Cycle-2

Table 5.6
Operating and Geometrical Parameters for PT3

1) System parameters

p (psia)	1005.0
L_H (ft)	12.0
q_o''' (Btu/ft ³ -hr)	1.285×10^7
w_o (lb/hr)	37.26
ΔT_{sub} (Mlb/°F)	11.7
K_{in}	27.8
K_{exit}	0.14
K_{spacer}	1.04
L_p (ft)	5.56
L_R	4.948
A_R	0.2006
$K_{R,exit}$	0.12
$\sum \frac{L_i}{A_i}$	1.52
$\sum \frac{f_i L_i}{D_{H,i} A_i}$	0.016

2) Channel parameters

	<u>Type 2 (7x7)</u>	<u>Type 4 (8x8)</u>
Number of channels	572	192
A_{x-s} (ft ²)	0.1087	0.1086
P_H (ft)	7.222	8.260
D_H (in)	0.581	0.520
γ_s (in)	0.2385	0.2080
γ_i (in)	0.2445	0.2125
γ_o (in)	0.2815	0.2465

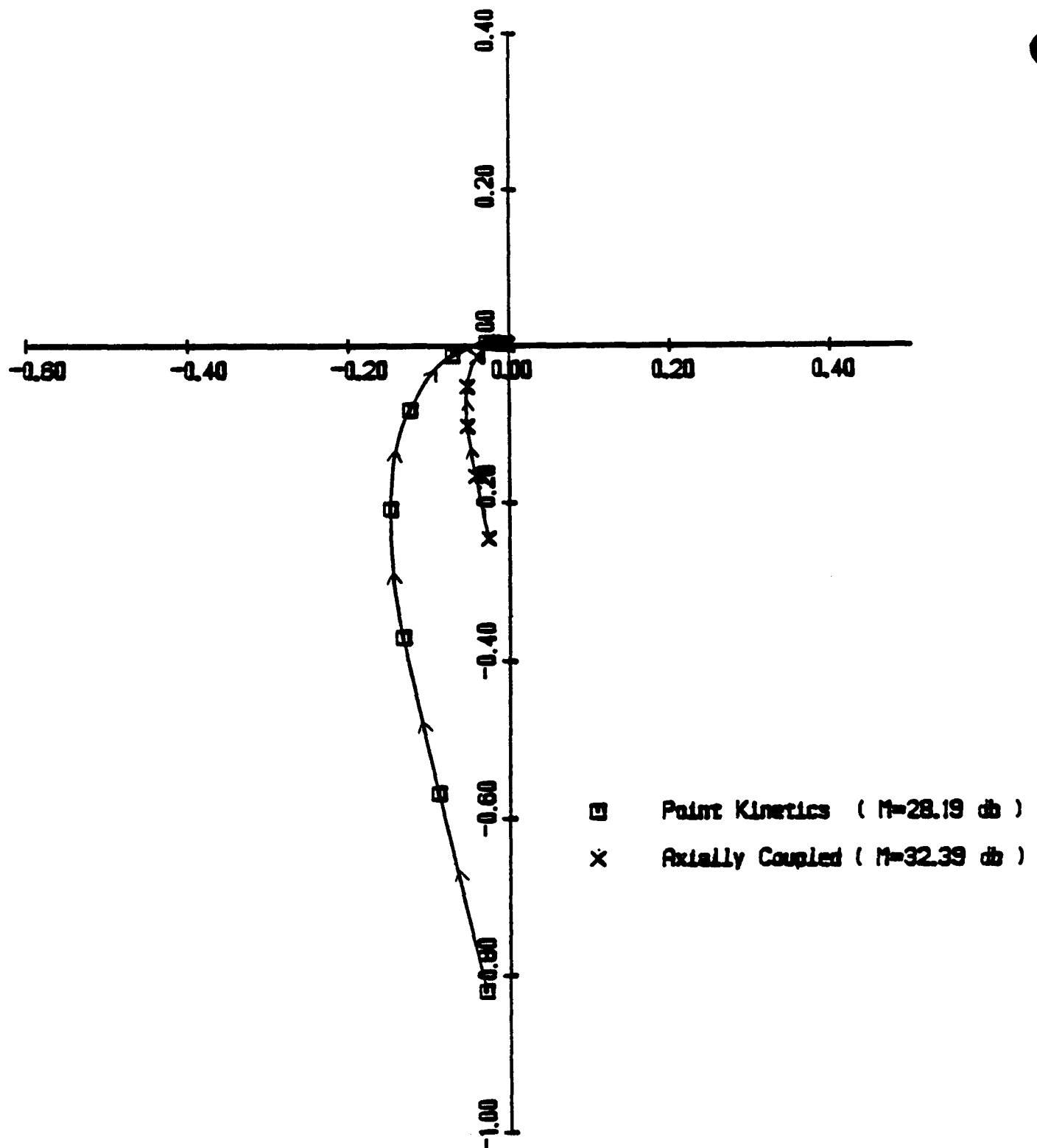


Figure 5.47 Nyquist Plot for PT3 Hot Channel Analysis

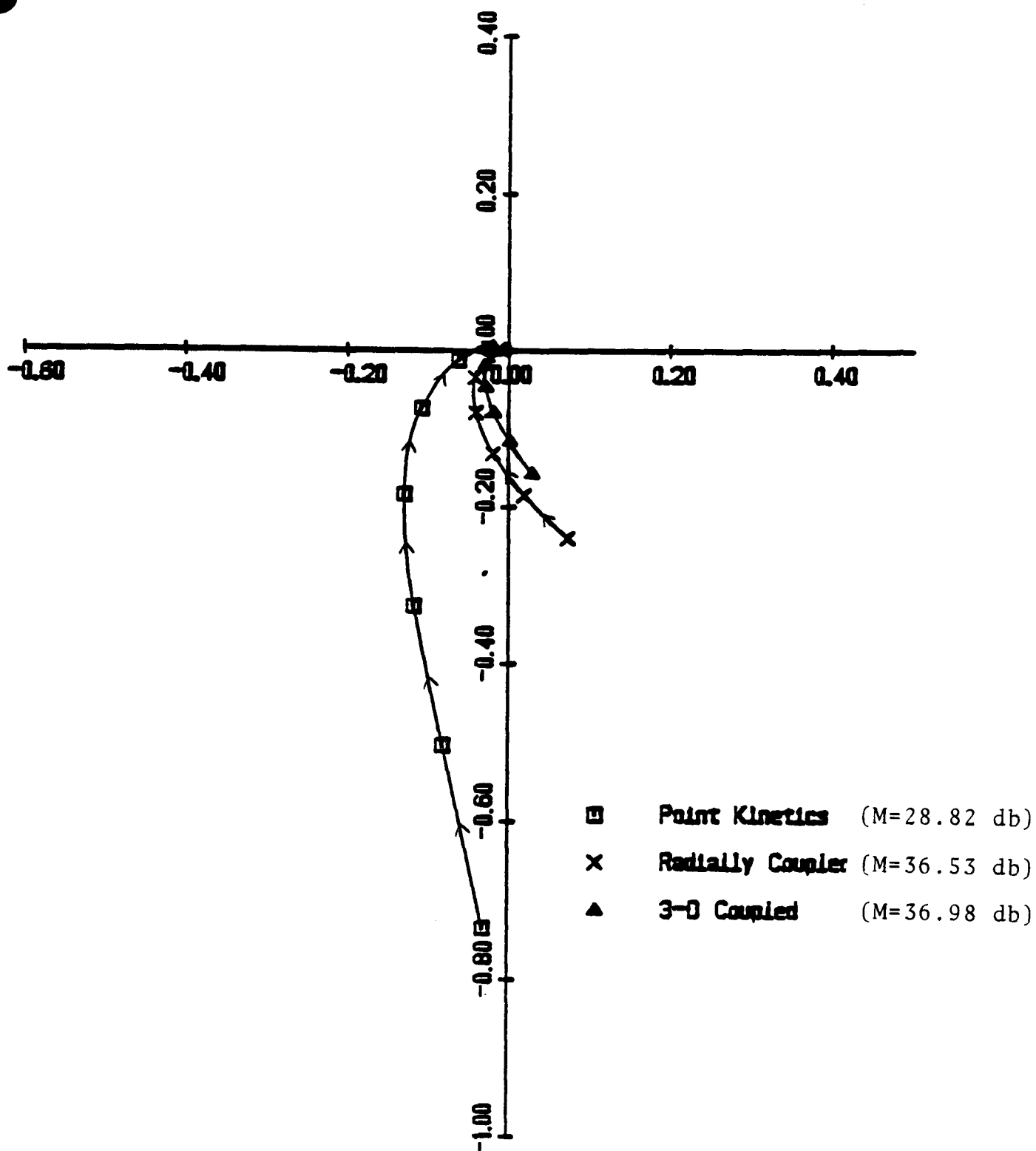


Figure 5.48 Nyquist Plot for PT3 Checker Board Analysis

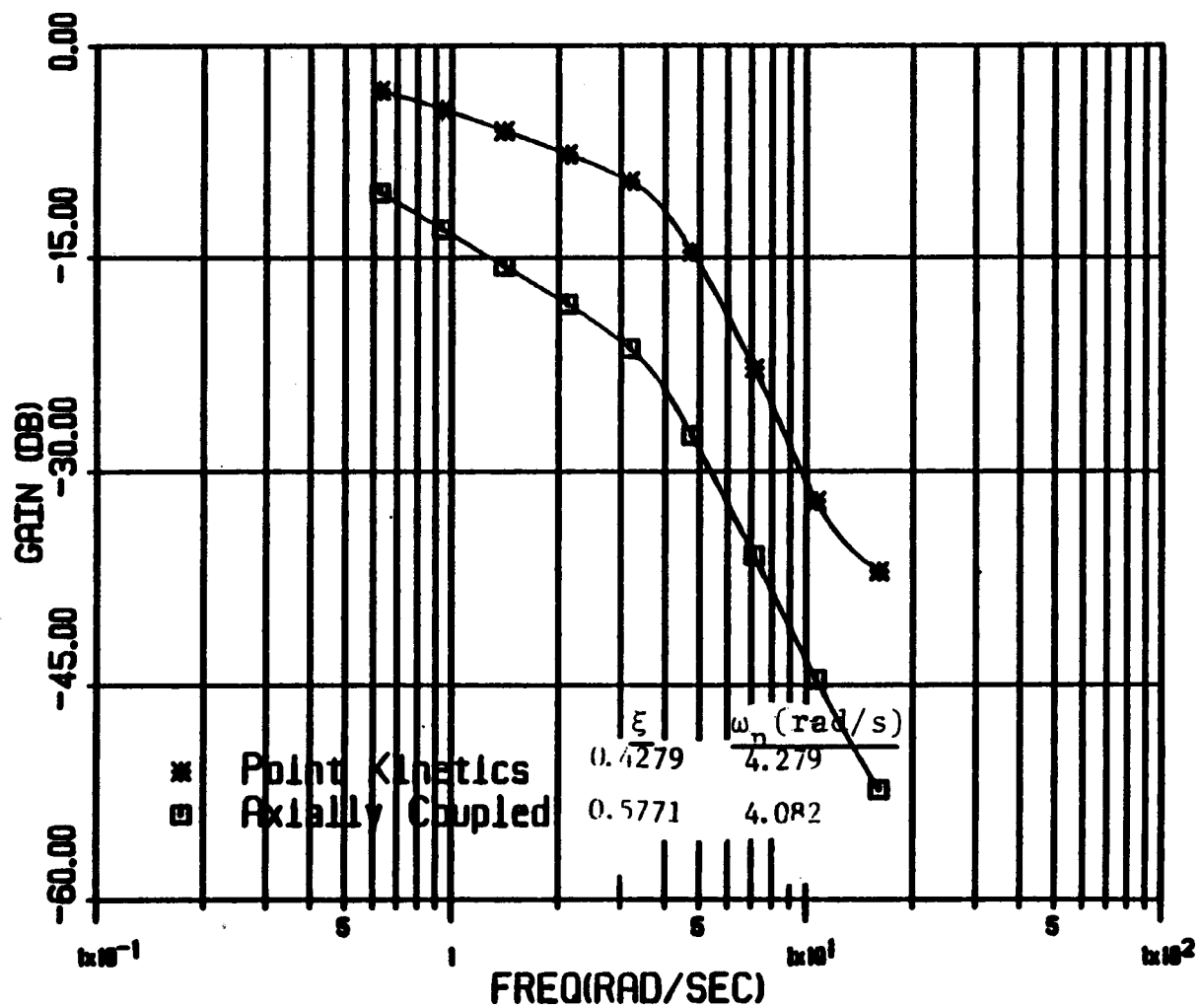


Figure 5.49 Bode Diagram for PT3 Hot Channel Analysis

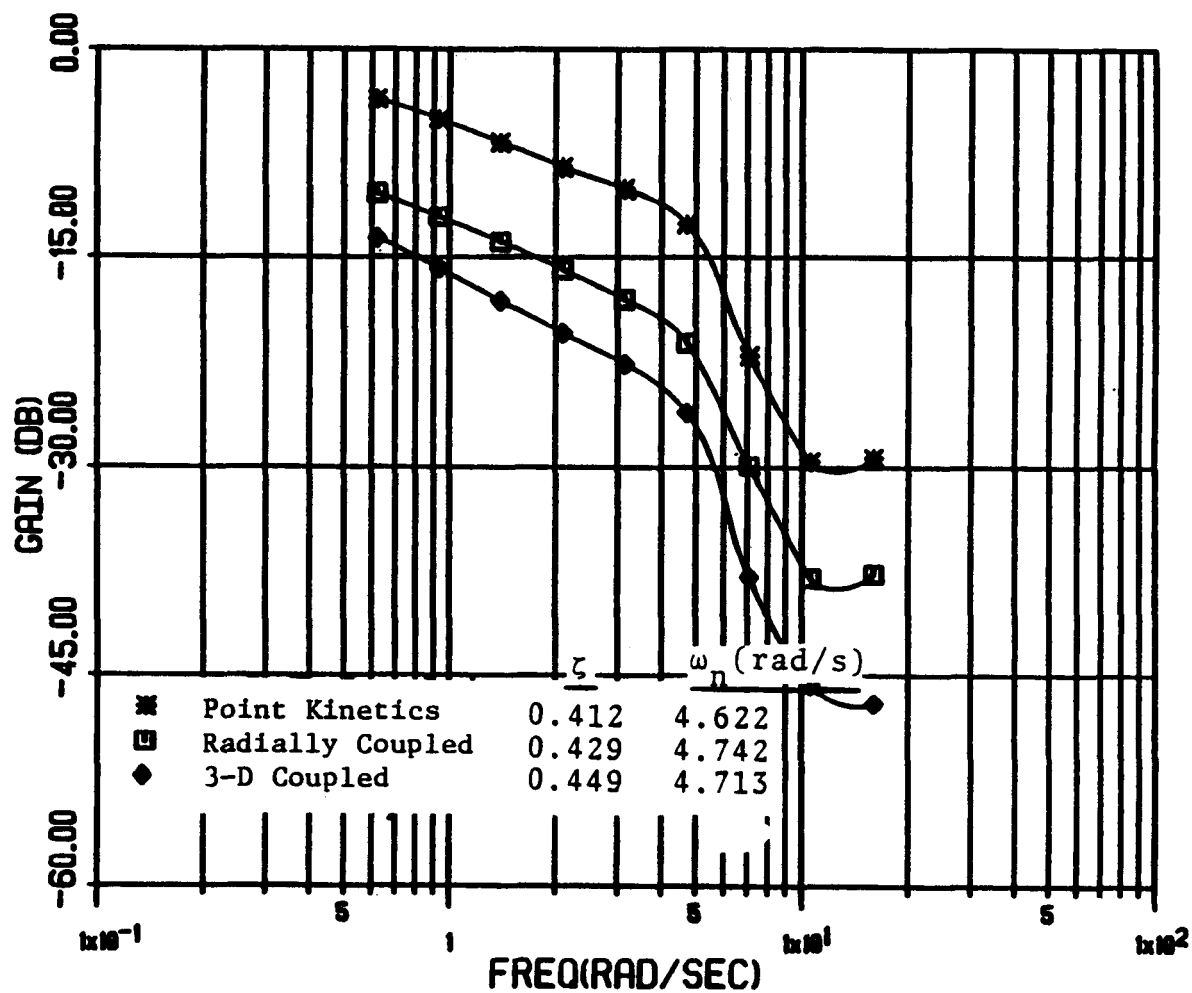


Figure 5.50 Bode Diagram for PT3 Checker Board Analysis

were generated for various neutron kinetics models. It is interesting to note that the calculated stability margin increases as the spatial detail in neutronic model increases.

The calculated damping ratios shown in figures 5.49 and 5.50 are large compared with the experimental data: $\zeta = 0.17$ (in which a 1 zero and 3 poles fit was made to the data). The reason for the larger damping ratio predicted by NUFREQ-N is not clear at this time, but may be due in part to the modeling assumptions made in NUFREQ-N (eg: the neutronic parameters corresponding to actual conditions were not available). However the trend of $\zeta\omega_n$, which is a measure of the system stability, agrees with the results from the Nyquist plot. Moreover, if the void-reactivity coefficient is arbitrarily increased, the predicted value of damping ratio can be brought closer to the experimental value.

5.4 STABILITY ANALYSIS FOR A TYPICAL BWR/4

Hopefully it is obvious to the reader that there is a great lack of reliable steam/water stability data against which to assess NUFREQ-N. We have used the best that could be found in an extensive literature search^[44]. It has been impossible, though, to thoroughly check all aspects of the code against these data. Nevertheless, the agreement with

the FRIGG loop data (the best out-of-core steam/water data we found) was quite good, and the problems with the Peach Bottom test could be attributed to uncertainties in available information.

Thus it appears that NUFREQ-N gives reasonable results, and is appropriate for BWR stability analysis. Hence NUFREQ-N was used to analyze the stability in more detail. Various neutron kinetics models were employed, using data representative of an actual BWR^[4 3] at full power conditions ($p_{th} = 3247$ MWth) at EOC of cycle 2 (core average exposure of 12800 MWD T).

Heterogeneous and complex geometries of fuel assembly types 2 and 4 were loaded. The operating and geometric parameters employed are shown in Table 5.6. Figures 5.51 and 5.52 show the fuel assembly loading pattern, control pattern, and channel inlet flow and core relative power distribution, which were calculated by SIMULATE^[2 9] with MCMDT.

These stability analyses were performed for parallel channels and for the recirculating loop, with various neutronic kinetics models for the hot channel and the checker-board configuration previously discussed. Figures 5.53 to 5.57 show the results obtained. As can be seen in Figure 5.53, including subcooled boiling in the parallel channel case is destabilizing, due to decreased single-phase length and increased the void fraction in the two-

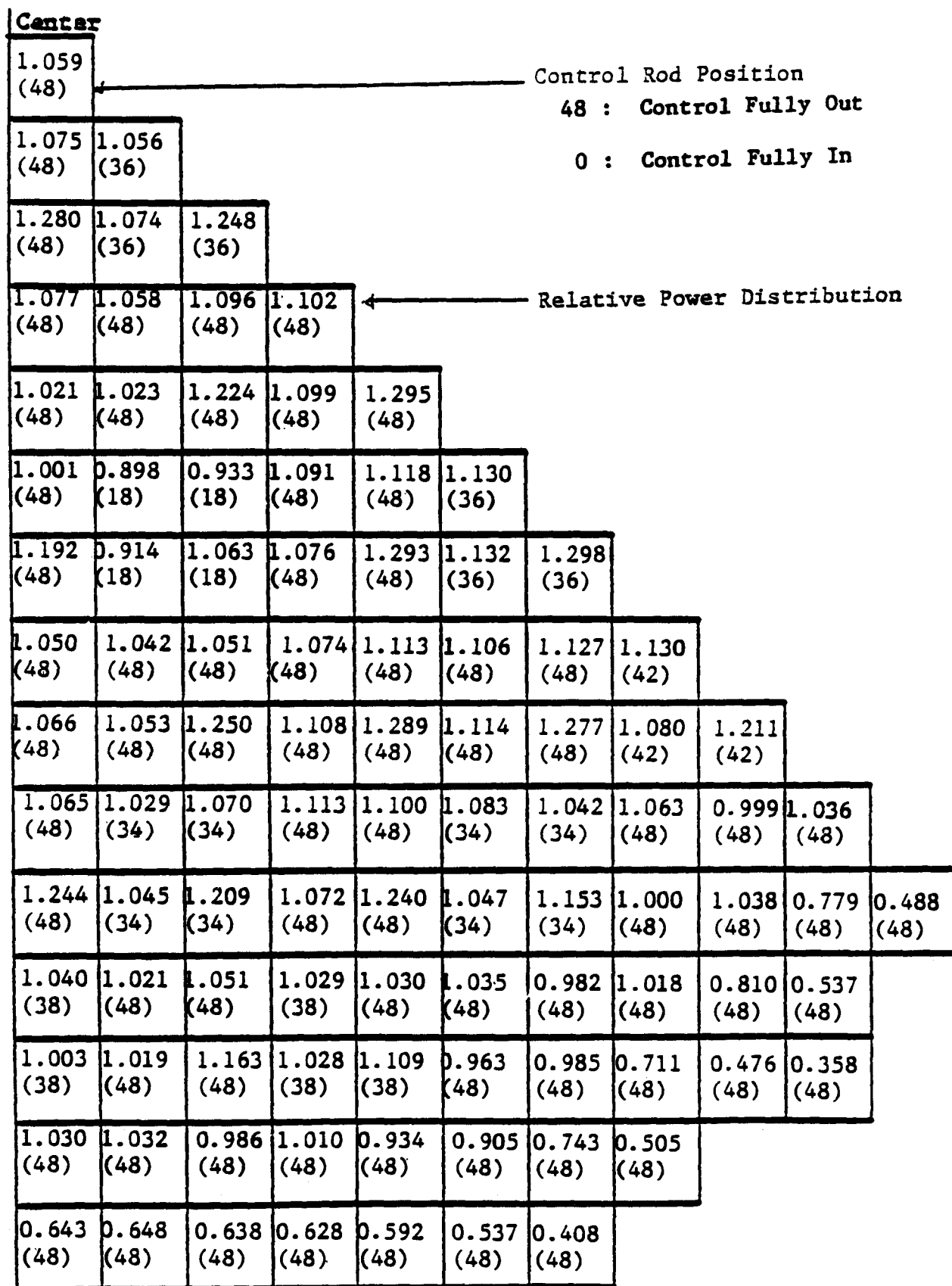


Figure 5.51 1/8 Core Relative Power Distribution and Control Configuration for a Typical BWR/4 at Rated Power

Center										
0.134 (4)		Channel Flow (MLb/hr)								
0.133 (2)	0.134 (2)									
0.126 (4)	0.133 (2)	0.127 (4)	Fuel Type							
			2: Type 2 (Initially Loaded)							
			4; Type 4 (Reloaded)							
0.133 (2)	0.134 (2)	0.133 (2)	0.132 (2)							
0.135 (2)	0.135 (2)	0.128 (4)	0.133 (2)	0.125 (4)						
0.136 (2)	0.140 (2)	0.139 (2)	0.133 (2)	0.132 (2)	0.131 (2)					
0.129 (4)	0.139 (2)	0.134 (4)	0.133 (2)	0.125 (4)	0.131 (2)	0.125 (4)				
0.134 (2)	0.134 (2)	0.134 (2)	0.133 (2)	0.131 (2)	0.131 (2)	0.131 (2)	0.130 (2)			
0.133 (2)	0.134 (2)	0.126 (4)	0.131 (2)	0.125 (4)	0.131 (2)	0.125 (4)	0.132 (2)	0.126 (4)		
0.133 (2)	0.134 (2)	0.133 (2)	0.131 (2)	0.131 (2)	0.132 (2)	0.133 (2)	0.132 (2)	0.134 (2)	0.132 (4)	
0.126 (4)	0.133 (2)	0.127 (4)	0.132 (2)	0.126 (4)	0.133 (2)	0.129 (4)	0.134 (2)	0.132 (4)	0.141 (2)	0.063 (2)
0.133 (2)	0.134 (2)	0.133 (2)	0.133 (2)	0.133 (2)	0.133 (2)	0.134 (2)	0.132 (4)	0.140 (2)	0.063 (2)	
0.134 (2)	0.133 (2)	0.127 (4)	0.133 (2)	0.129 (4)	0.135 (2)	0.133 (4)	0.143 (2)	0.063 (2)	0.063 (2)	
0.132 (4)	0.132 (4)	0.133 (2)	0.132 (4)	0.135 (2)	0.136 (4)	0.141 (2)	0.063 (2)			
0.062 (2)	0.062 (2)	0.062 (2)	0.062 (2)	0.062 (2)	0.063 (2)	0.063 (2)				

Figure 5.52 Channel Flow Rate and Fuel Type of 1/8 core for a Typical 3WR/4 at Rated Power

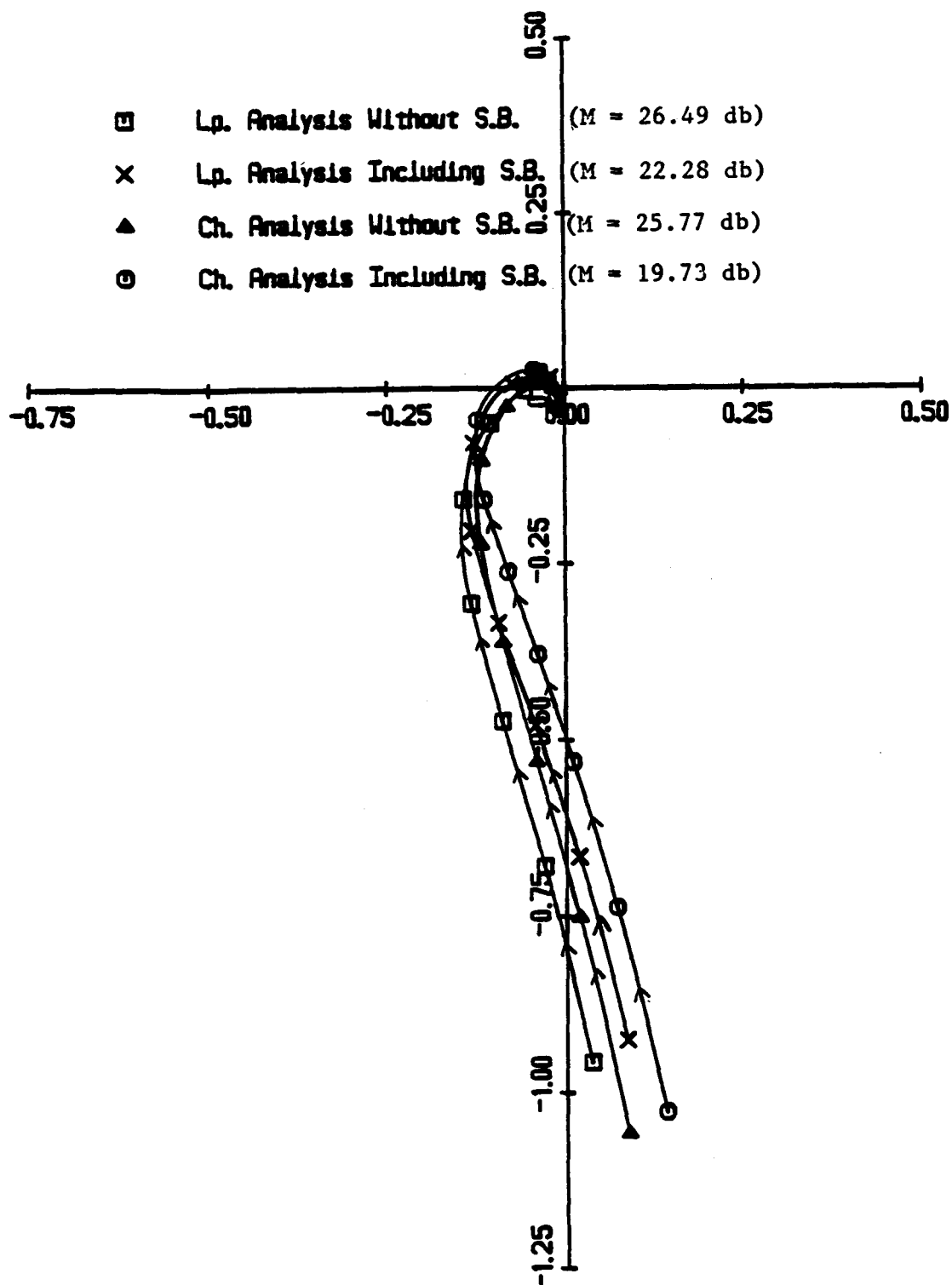


Figure 5.53 Nyquist Plots for a Parallel Channel(Ch.) and Loop(Lp.) Analysis with the Point Kinetics Model

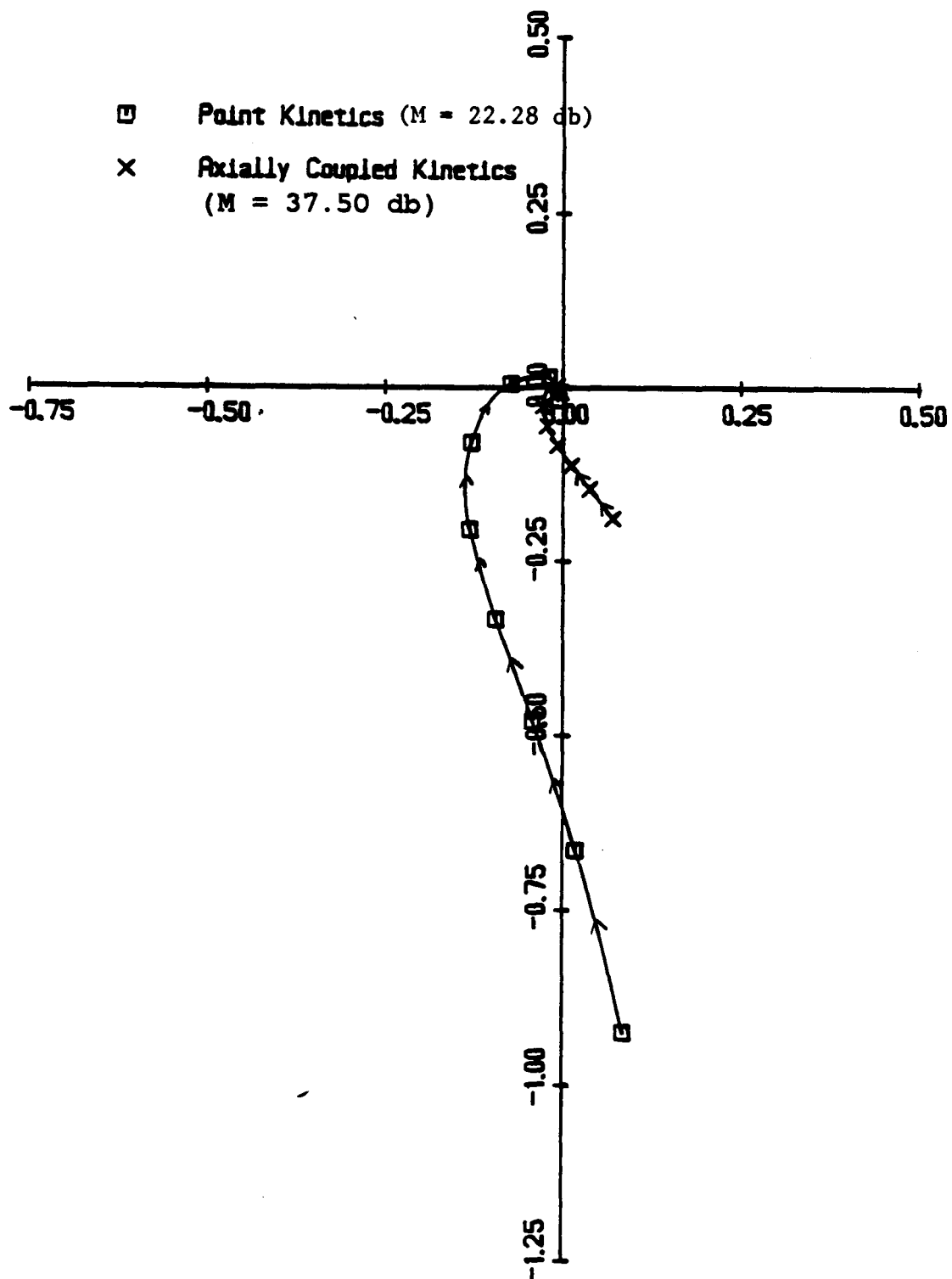


Figure 5.54 Nyquist Plots for the Hot Channel Loop Analysis with Various Kinetics Models

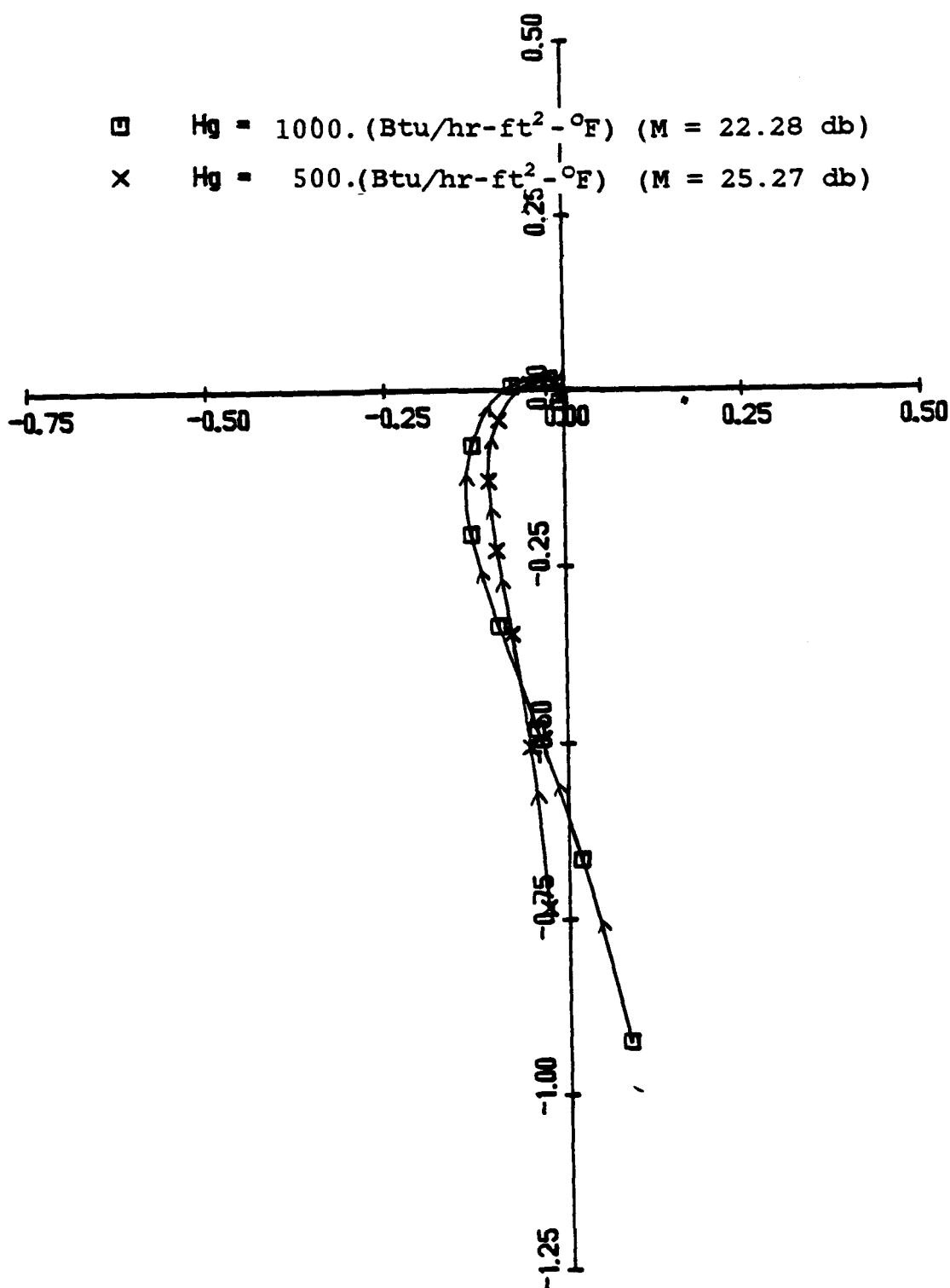


Figure 5.55 Nyquist Plots for Investigating the Effect of Gap Conductance with Point Kinetics Model

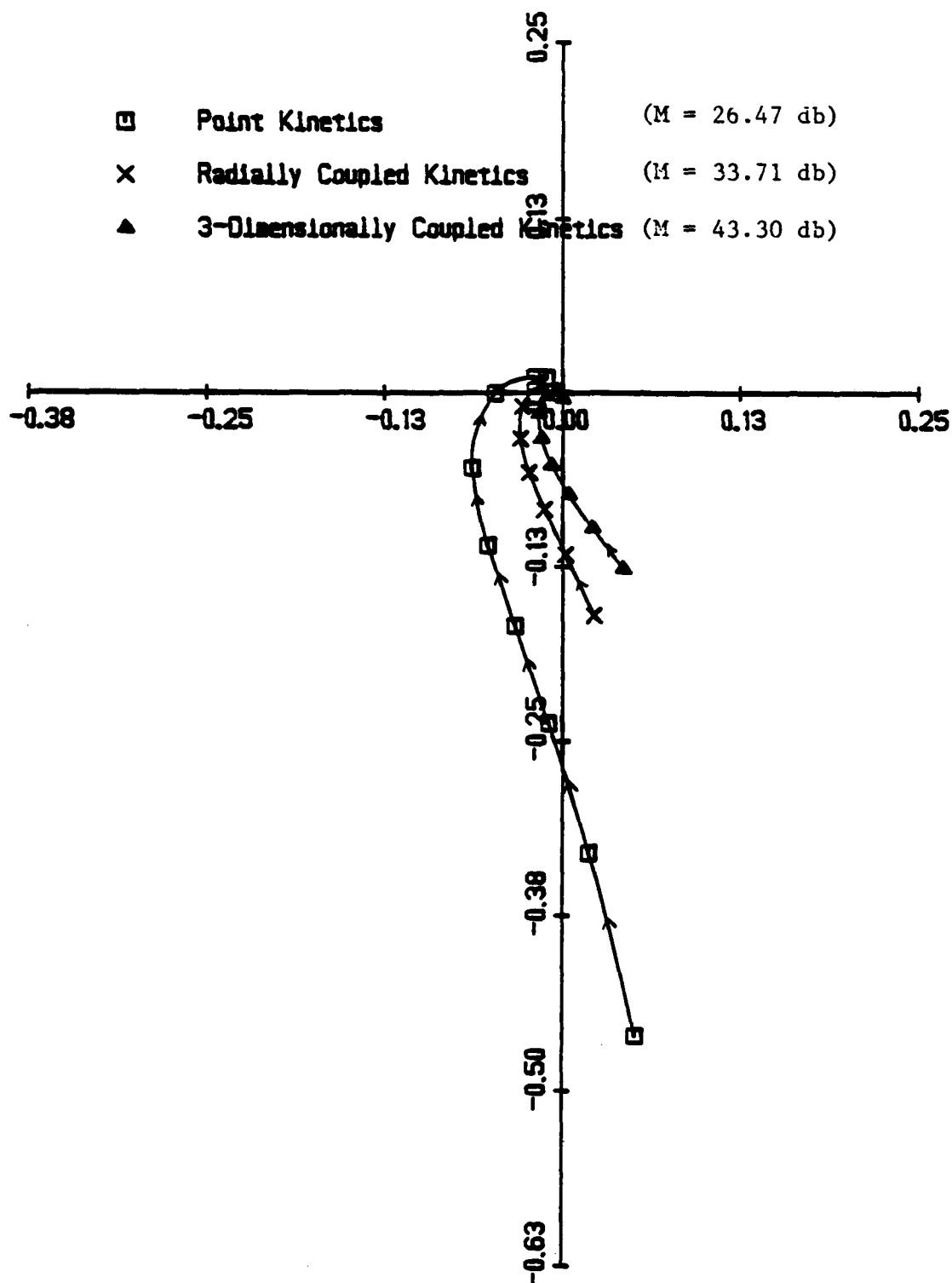


Figure 5.56 Nyquist Plots for Checker Board Loop Analysis with Various Kinetics Models

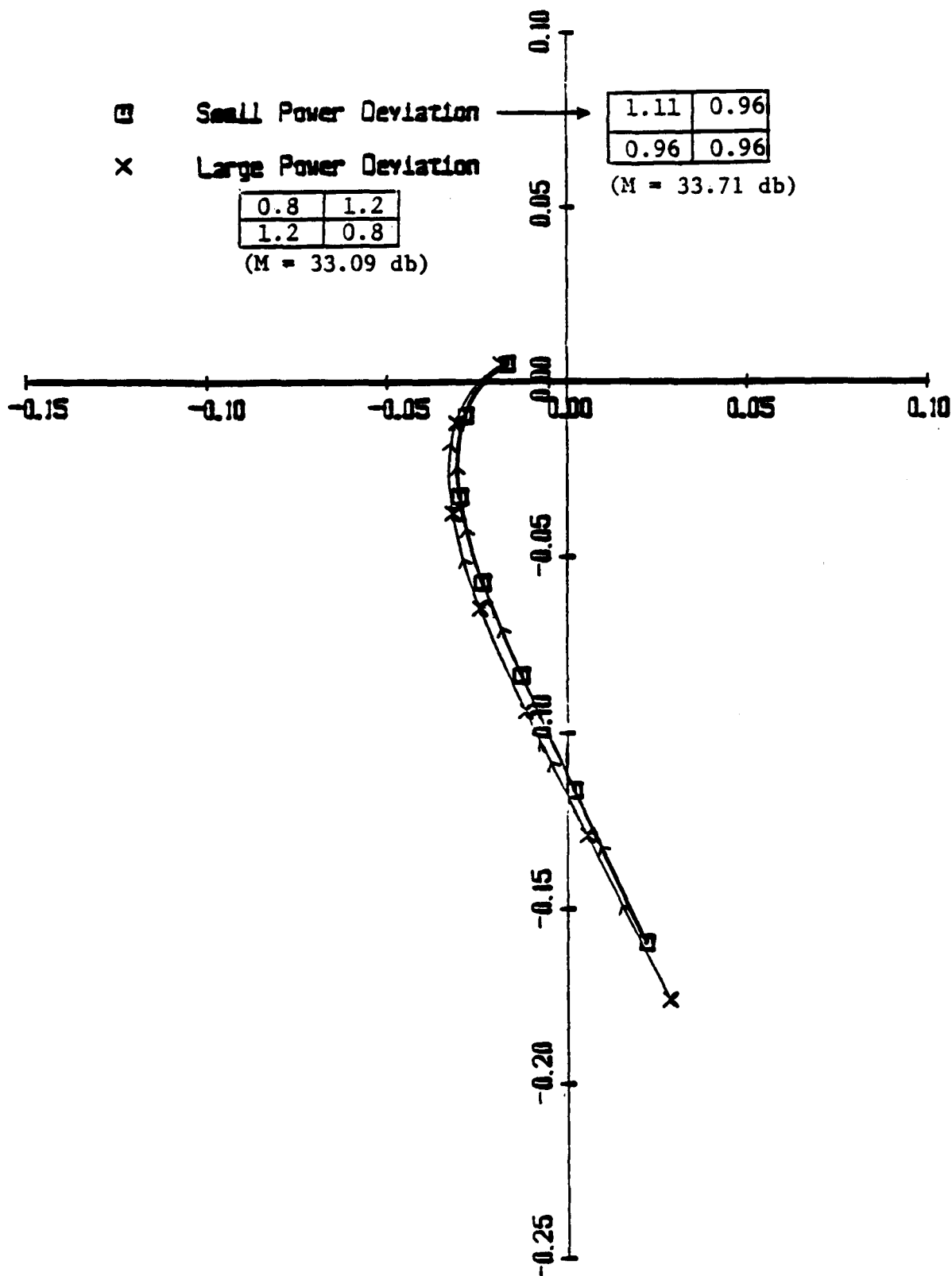


Figure 5.57 Nyquist Plots for Investigating the Effect of Radial Nonuniformity in Checker Board Arrays Using the Radially Coupled Kinetics Model

phase region. The loop analysis shows the same trends, although the results depend on the operating conditions as discussed previously^[45]. In Figure 5.54, the point kinetics model was compared with the axially coupled kinetics model for the hot channel. It can be seen that, as discussed previously, the point kinetics model is the more conservative. The effect on stability margin of gap conductance in the distributed parameter model was also tested. As the gap conductance is reduced, the thermal resistance in the gap increases. The effect of this on the fuel time constant is to increase the phase lag in the power-to-void transfer function. Thus a decrease of the gap conductance can reduce the phase margin, which is a destabilizing effect. However, it also reduces the amplitude of the power-to-void transfer function so that the gain margin is increased, which is a stabilizing effect. These opposing effects are shown in Figure 5.55.

Figure 5.57 shows comparisons with three different neutron kinetics models for a checker-board problem. As discussed previously, it is found that the spatial neutron coupling has a stabilizing effect for conditions with and without subcooled boiling^[34]. Also the effect of the radial nonuniformity on the stability margin was tested for the checker-board array using the radially coupled kinetics model. As shown in Figure 5.57, large nonuniformity has a smaller stability margin as expected.

It may be concluded that it is as important in BWR stability analysis to use accurate models for neutron kinetics as for thermal-hydraulics.

PART 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Due to the tremendous complexity inherent in the thermal-hydraulic mechanisms in two-phase systems, most previous stability analyses have made various simplifying assumptions which have lead to unnecessary restrictions in design and operating criteria, and/or to operational difficulties.

In this study, a state-of-the-art one-dimensional thermal-hydraulic model was developed to more accurately obtain the stability margin of both parallel channels and a BWR loop. This model, called NUFREQ-N, accounts for phasic slip, subcooled boiling, arbitrary space time-dependent power distribution, distributed heated wall dynamics and an analytical model for each component in the recirculating loop.

The thermal-hydraulic model in NUFREQ-N was coupled with the general nodal neutron kinetics model, which included the option for point kinetics, such that one can efficiently perform BWR linear stability analysis in the frequency domain. NUFREQ-N was compared with existing in-core and out-of-core data, and used to analyze the expected stability characteristics of a typical BWR/4.

The parametric results revealed important factors

influencing BWR stability margin. The parameters which improve BWR stability include increases in: inlet restriction, inlet velocity, inlet subcooling, phasic slip and system pressure. Also a decrease in: power level, exit restriction, the number of spacers in the two-phase part of the channel, is stabilizing. It was further verified that the shape of the axial power distribution, and the heat capacity of the heater plays a significant role in stability analyses.

Comparisons of transfer function predictions by the NUFREQ-N code, with several out-of-core experiments were made. Also, several important thermal-hydraulic parameters and models were tested; including, subcooled boiling, the two-phase friction multiplier(ϕ_{LO}) and heat transfer coefficient($H_{2\phi}$). Due to lack of reliable data, and/or of information on a number of important operating parameters, and also due to insufficient knowledge of some complicated two-phase mechanisms in the experiments, it was not always possible to obtain the exact agreement between the measured and predicted transfer functions. However the predicted trends on NUFREQ-N were in good agreement with the available data. This was especially true for the predicted power-to-flow transfer function, which is the most important transfer function for thermal-hydraulic stability analysis.

Once NUFREQ-N had been assessed against the existing

data, a study was conducted to analyze the stability of a typical BWR/4. In these parametric studies, it was found accurate nuclear data and operating conditions were essential. Also, it was found that a more accurate neutron kinetics model can reduce unnecessary design restrictions. Finally, a major modelling improvement was made for BWR loop analysis, in that the recirculating loop analysis in NUFREQ-N accounts for the interactions between the various channels in the core. This can be contrasted with previous models in which the core was treated as one equivalent channel during loop analyses.

In conclusion, state-of-the-art thermal-hydraulic and neutronic models have been developed to estimate BWR stability characteristics. It was found that it is very important in stability analyses to use the accurate models of thermal-hydraulic and neutron kinetic phenomena. Moreover, in BWR stability analysis, accuracy of the nuclear input data is also extremely important.

To aid the NUFREQ-N user, Appendix-XIV gives a summary of the subroutines in NUFREQ-N; Appendix-XV, an input/output description; Appendix-XVI gives the input and output of a sample problem; Appendix-XVII, a FORTRAN listing of NUFREQ-N; and Appendix-XVIII, an explanation of the error messages that may occur during use of NUFREQ-N. It felt that the code is well documented, debugged and is recommended for use in the stability analysis of BWRs.

RECOMMENDED FUTURE WORK

It is clear that more of analysis is needed to develop a version of NUFREQ-N which allows for system pressure perturbation as an external forcing function. This will allow direct comparisons with BWR stability data, such as that of Peach Bottom stability test. Also, for loop analysis, more accurate models for the jet pumps, including the capability to analyze single loop operation, is needed. The neutron kinetic models also need to be improved to include the fuel temperature-reactivity feedback due to the Doppler effect, and the numerics improved to reduce the computing cost and memory storage for full core 3-D stability analysis. Also, the question of what is the appropriate stability margin to be used for a BWR needs to be addressed, since the correct approach has many deficiencies.

Finally, this study was entirely analytical in nature, and relied on the data of other investigation. It is apparent that there is a real need for reliable out-of-core steam/water stability data. This is particularly true for the case of parallel channel data, since no reliable steam water data of this type could be found. In addition, it appears that freon properties should be developed for NUFREQ-N, since there are a number of freon out-of-core stability data available which could be used for further code assessment.

Nomenclature

A	=	flow area (ft^2)
C_o	=	void concentration parameter
C_k	=	kinematic wave velocity (ft/s)
D_H	=	hydraulic diameter (ft)
f	=	Darcy-Weisbach friction factor
G	=	flow mass flux (lb/hr-ft^2)
g	=	acceleration of gravity
g_c	=	conversion factor ($32.174 \text{ lb-ft/lb}_f\text{-s}^2$)
h	=	enthalpy (Btu/lb)
H_g	=	gap conductance in fuel rod
H_o	=	condensation parameter in the subcooled boiling
$H_{2\phi}$	=	two-phase heat transfer coefficient ($\text{Btu/hr-ft}^2\text{-}^\circ\text{F}$)
$H_{1\phi}$	=	single-phase heat transfer coefficient ($\text{Btu/hr-ft}^2\text{-}^\circ\text{F}$)
j_i	=	channel inlet velocity (ft/s)
K	=	local pressure loss coefficient
k	=	thermal conductivity ($\text{Btu/ft-}^\circ\text{F-s}$)
L	=	total number of single-phase nodes in the channel
L_H	=	heated channel length (ft)
M	=	gain margin (in db)
M_t	=	total number of spacers
N	=	total number of nodes in the channel
P	=	pressure (psia)
P_H	=	heater perimeter (ft)

- q'' = heat flux (Btu/hr-ft²)
 q''' = volumetric heat generation rate (Btu/hr-ft³)
 s = $j\omega$, where ω is frequency (rad/s)
 T = temperature (°F)
 V_{gj} = drift velocity (ft/s)
 $\langle x \rangle$ = cross-sectional average flow quality
 Z_d = void departure point (ft)
 z = axial position (ft) Δz = axial length of the node
 α = thermal diffusivity (ft²/s)
 $\langle \alpha \rangle$ = cross-sectional average void fraction in the two-phase region
 ξ = slope of pump head-flow curve
 ζ = damping ratio
 σ = surface tension (lb_f/ft)
 ϕ_{lo}^2 = two-phase friction loss multiplier
 ϕ = two-phase local loss multiplier
 θ = phase margin (in deg)
 ρ = density
 Ω = characteristic frequency of phase change
 $\langle \psi \rangle$ = cross-sectional average of parameter ψ
 $\hat{\delta\psi}$ = the perturbed and Laplace-transformed ψ

Subscript/Superscript

- 1ϕ = single-phase
 2ϕ = two-phase
 B = inlet boundary node index of the two-phase region
 d = void departure point

DC = downcomer
exit = channel exit
f = saturated liquid
g = saturated vapor
fw = feedwater
in = channel inlet
LP = lower plenum
P = upper plenum
R = riser
sw = saturated water
v = reactor vessel
w = heater wall

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APPENDIX I
TWO-PHASE ENERGY EQUATION

The two-phase energy equation is [2],

$$\rho_l (1-\langle\alpha\rangle) \frac{D_l h_l}{Dt} + \rho_g \langle\alpha\rangle \frac{D_g h_g}{Dt} = \frac{q'' P_H}{A_{x-s}} + \frac{1}{J} \frac{\partial p}{\partial t} - \left(\frac{\delta w'}{A_{x-s}} \right) (h_g - h_l) \quad (I.1)$$

Noting,

$$G(1-\langle x \rangle) = \rho_l \langle u_l \rangle_l (1-\langle\alpha\rangle)$$

$$G\langle x \rangle = \rho_g \langle u_g \rangle_g \langle\alpha\rangle,$$

Equation (I.1) becomes,

$$\begin{aligned} \rho_l (1-\langle\alpha\rangle) \frac{\partial h_l}{\partial t} + G(1-\langle x \rangle) \frac{\partial h_l}{\partial z} + \rho_g \langle\alpha\rangle \frac{\partial h_g}{\partial t} + G\langle x \rangle \frac{\partial h_g}{\partial z} \\ = \frac{q'' P_H}{A_{x-s}} + \frac{1}{J} \frac{\partial p}{\partial t} - \left(\frac{\delta w'}{A_{x-s}} \right) (h_g - h_l) \end{aligned} \quad (I.2)$$

Using Equation (2.38), Equation (I.2) becomes,

$$\frac{\Delta p}{\rho_g} (1-\langle\alpha\rangle) \frac{\partial h_l}{\partial t} + v_{fg} G(1-\langle x \rangle) \frac{\partial h_l}{\partial z} = \frac{q'' P_H v_{fg}}{A_{x-s}} - \Omega (h_g - h_l) \quad (I.3)$$

APPENDIX II

THE EVALUATION OF TWO-PHASE MASS FLUX PERTURBATION

The mass flux in the two-phase region can be written as,

$$\dot{G} = [\rho_f - \Delta\rho C_0 \langle \alpha \rangle] \langle j \rangle - \Delta\rho V_{gj} \langle \alpha \rangle \quad (\text{II.1})$$

Perturbing and Laplace transforming Equation (II.1),

$$\hat{\delta\dot{G}} = [\rho_f - \Delta\rho C_0 \langle \alpha_0 \rangle] \delta \langle \hat{j} \rangle - \Delta\rho (C_0 \langle j_0 \rangle + V_{gj}) \delta \langle \alpha \rangle \quad (\text{II.2})$$

Using the definition of the kinematic wave velocity, Equation (2.6), and Equation (2.46), the steady-state volumetric flux, $\langle j_0 \rangle_k$, for the k-th node is,

$$\langle j_0 \rangle_k = \frac{(C_{K,0})_k - V_{gj}}{C_0} = \frac{(C_{K,0})_k^{\text{in}} \epsilon_{0,k} - V_{gj}}{C_0} \quad (\text{II.3})$$

The volumetric flux perturbation, $\delta \langle \hat{j} \rangle_k$, can be easily determined by integrating the nodal continuity equation, Equation (2.14), under the assumption of constant $\delta \hat{\Omega}_k$ for each node. By coordinate-transforming with Equation (2.46) and using the node inlet boundary condition, $\delta \langle \hat{j} \rangle_k^{\text{in}}$,

$$\delta \langle \hat{j} \rangle_k = \delta \langle \hat{j} \rangle_k^{\text{in}} + \frac{(C_{K,0})_k^{\text{in}}}{C_0 \hat{\Omega}_{0,k}} (\epsilon_{0,k} - 1) \delta \hat{\Omega}_k \quad (\text{II.4})$$

The void fraction perturbation, $\delta \langle \hat{\alpha} \rangle_k$ for the k-th node can be also calculated from Equation (2.18). Using Equation (2.51) we can transform the coordinates in Equation (2.18) as,

$$\begin{aligned} \xi_k \frac{d\delta\langle\hat{\alpha}\rangle_k}{d\xi_k} + \left(\frac{s}{C_{0,\bar{\Omega}_{0,k}}}\right) \delta\langle\hat{\alpha}\rangle_k = \frac{1}{C_{0,\bar{\Omega}_{0,k}}} \left(\frac{\rho_f}{\Delta\rho} - C_{0,\langle\alpha\rangle_k}\right) \delta\hat{\Omega}_k \\ - \frac{C_{0,\bar{\Omega}_{0,k}}}{(C_{k,o})_k^{\text{in}}} \frac{d\langle\hat{\alpha}_0\rangle_k}{d\xi_k} \delta(\hat{C}_k)_k \end{aligned} \quad (\text{II.5})$$

From Equation (2.52) and $\delta(\hat{C}_k)_k = C_o \delta\langle\hat{j}\rangle_k$, Equation (II.5) becomes,

$$\begin{aligned} \frac{d\delta\langle\hat{\alpha}\rangle_k}{d\xi_k} + \left(1 + \frac{s}{C_{0,\bar{\Omega}_{0,k}}}\right) \xi_k^{-1} \delta\langle\hat{\alpha}\rangle_k = \frac{P_{1,k}}{C_{0^2 o,k} (C_{k,o})_k^{\text{in}}} \xi_k^{-2} \delta\hat{\Omega}_k \\ - \frac{P_{1,k}}{(C_{k,o})_k^{\text{in} 2}} \xi_k^{-3} \delta\langle\hat{j}\rangle_k \end{aligned} \quad (\text{II.6})$$

where,

$$P_{1,k} = \left(\frac{\rho_f}{\Delta\rho} - C_{0,\langle\alpha_0\rangle_k^{\text{in}}}\right) (C_{k,o})_k^{\text{in}}$$

Now inserting Equation (II.4) into Equation (II.6), we can integrate this Bernoulli-type differential equation, subject to the boundary condition, $\delta\langle\hat{\alpha}\rangle_k^{\text{in}}$,

$$\begin{aligned} \delta\langle\hat{\alpha}\rangle_k = -P_{2,k} C_{0,\bar{\Omega}_{0,k}} \left\{ \xi_k^{-2} - \xi_k^{-\frac{s+C_{0,\bar{\Omega}_{0,k}}}{C_{0,\bar{\Omega}_{0,k}}}} \right\} \delta\langle\hat{j}\rangle_k^{\text{in}} + P_{2,k} (C_{k,o})_k^{\text{in}} \left\{ \xi_k^{-2} \right. \\ \left. - \xi_k^{-\frac{s+C_{0,\bar{\Omega}_{0,k}}}{C_{0,\bar{\Omega}_{0,k}}}} \right\} \delta\hat{\Omega}_k + \xi_k^{-\frac{s+C_{0,\bar{\Omega}_{0,k}}}{C_{0,\bar{\Omega}_{0,k}}}} \delta\langle\hat{\alpha}\rangle_k^{\text{in}} \end{aligned} \quad (\text{II.7})$$

where,

$$P_{2,k} = \frac{P_{1,k} [(C_{k,o})_k^{\text{in}}]^{-2}}{(s - C_{0,\bar{\Omega}_{0,k}})}$$

Finally we can obtain $\hat{\delta G}_k$ by inserting Equations (2.52), (II.3), (II.4), and (II.7) into Equation (II.2) to yield,

$$\begin{aligned} \hat{\delta G}_k = & \left\{ g_{1,k} \xi_k^{-1} + g_{2,k} \xi_k - \frac{s}{C_{0\bar{\Omega}_{0,k}}} \right\} \delta \langle j \rangle_k^{\text{in}} + \left\{ g_{3,k} + g_{4,k} \xi_k^{-1} \right. \\ & \left. + g_{5,k} \xi_k - \frac{s}{C_{0\bar{\Omega}_{0,k}}} \right\} \hat{\delta \Omega}_k + g_{6,k} \xi_k - \frac{s}{C_{0\bar{\Omega}_{0,k}}} \delta \langle \alpha \rangle_k^{\text{in}} \end{aligned} \quad (\text{II.8})$$

where,

$$g_{1,k} \stackrel{\Delta}{=} (\rho_f - \Delta \rho C_{0\langle \alpha \rangle_k^{\text{in}}}) \frac{s}{(s - C_{0\bar{\Omega}_{0,k}})}$$

$$g_{2,k} \stackrel{\Delta}{=} -(\rho_f - \Delta \rho C_{0\langle \alpha \rangle_k^{\text{in}}}) \frac{C_{0\bar{\Omega}_{0,k}}}{(s - C_{0\bar{\Omega}_{0,k}})}$$

$$g_{3,k} \stackrel{\Delta}{=} (\rho_f - \Delta \rho C_{0\langle \alpha \rangle_k^{\text{in}}}) \frac{(C_{K,0})_k^{\text{in}}}{C_{0\bar{\Omega}_{0,k}}}$$

$$g_{4,k} \stackrel{\Delta}{=} (\rho_f - \Delta \rho C_{0\langle \alpha \rangle_k^{\text{in}}}) \left\{ \frac{-(C_{K,0})_k^{\text{in}}}{(s - C_{0\bar{\Omega}_{0,k}})} - \frac{(C_{K,0})_k^{\text{in}}}{C_{0\bar{\Omega}_{0,k}}} \right\}$$

$$g_{5,k} \stackrel{\Delta}{=} (\rho_f - \Delta \rho C_{0\langle \alpha \rangle_k^{\text{in}}}) \frac{(C_{K,0})_k^{\text{in}}}{(s + C_{0\bar{\Omega}_{0,k}})}$$

$$g_{6,k} \stackrel{\Delta}{=} -\Delta \rho (C_{K,0})_k^{\text{in}}$$

APPENDIX III

NODE-AVERAGED VOID FRACTION PERTURBATION

The node-averaged void fraction perturbation is given by,

$$\delta \langle \hat{\alpha} \rangle_k = \frac{1}{\Delta z_k} \int_{z_{k-1}}^{z_k} \delta \langle \hat{\alpha} \rangle_k dz \quad (\text{III.1})$$

or, using a coordinate-transformation,

$$\delta \langle \hat{\alpha} \rangle_k = \frac{(C_{k,o})_k^{\text{in}}}{\Delta z_k C_{o,\bar{n}o,k}} \int_1^{\xi_k^{\text{out}}} \delta \langle \hat{\alpha} \rangle_k d\xi_k \quad (\text{III.2})$$

Thus, from Equation (II.7),

$$\delta \langle \hat{\alpha} \rangle_k = \psi_{1,k} \delta \langle j \rangle_k^{\text{in}} + \psi_{2,k} \delta \hat{\bar{n}}_k + \psi_{3,k} \delta \langle \hat{\alpha} \rangle_k^{\text{in}} \quad (\text{III.3})$$

where,

$$\psi_{1,k} = \frac{\Delta P_{2,k} (C_{k,o})_k^{\text{in}}}{\Delta z_k} \left[\left(\frac{1}{\xi_k^{\text{out}}} - 1 \right) - \frac{C_{o,\bar{n}o,k}}{s} \left\{ (\xi_k^{\text{out}})^{-\frac{s}{C_{o,\bar{n}o,k}}} - 1 \right\} \right]$$

$$\psi_{2,k} = \frac{\Delta P_{2,k} (C_{k,o})_k^{\text{in}}}{\Delta z_k s} \left\{ (\xi_k^{\text{out}})^{-\frac{s}{C_{o,\bar{n}o,k}}} - 1 \right\} - \frac{P_{2,k} (C_{k,o})_k^{\text{in}}}{\Delta z_k C_{o,\bar{n}o,k}} \left(\frac{1}{\xi_k^{\text{out}}} - 1 \right)$$

$$\psi_{3,k} = - \frac{(C_{k,o})_k^{\text{in}}}{\Delta z_k s} \left\{ (\xi_k^{\text{out}})^{-\frac{s}{C_{o,\bar{n}o,k}}} - 1 \right\}$$

APPENDIX IV

NODE-AVERAGED CHARACTERISTIC FREQUENCY PERTURBATION

By using the steady-state parameters with node-averaged values, we can perturb and Laplace transform Equation (2.45) to obtain $\delta\hat{\Omega}_k$ as,

$$\delta\hat{\Omega}_k = Q_k D_k \delta\hat{q}_k'' + F_k \delta\hat{h}_{l,k} - G_k \delta\hat{\alpha}_k + E_k \delta\hat{h}_{ld} \quad (\text{IV.1})$$

where,

$$Q_k = \frac{\Delta\rho P_H q_{k,0}''}{A_{x-s} \rho_f (h_f - h_{l,d,0})}, \quad D_k = \frac{\bar{h}_{l,0} - h_{l,d,0}}{\rho_g h_{fg} + \rho_f (h_f - \bar{h}_{l,0})}$$

$$F_k = Q_k \frac{\rho_g h_{fg} + \rho_f (h_f - h_{l,d,0})}{\{\rho_g h_{fg} + \rho_f (h_f - \bar{h}_{l,0})\}^2} + \frac{H_2}{c_{pf}} \langle \bar{\alpha}_0 \rangle_k$$

$$G_k = \frac{H_2}{c_{pf}} (h_f - \bar{h}_{l,0}), \quad E_k = Q_k D_k \frac{\bar{h}_{l,0} - h_f}{(h_f - h_{l,d,0})(\bar{h}_{l,0} - h_{l,d,0})}$$

Inserting Equations (III.3), (2.61) and (2.67) into Eq.(IV.1), the final form of $\delta\hat{\Omega}_k$ can be expressed as,

$$\delta\hat{\Omega}_k = Y_{1,k} \delta j_i + Y_{6,k} \delta\hat{q}_B'' + Y_{2,k} \delta\hat{q}_k'' + Y_{3,k} \delta\hat{h}_{l,k}^{in} + Y_{4,k} \delta\hat{j}_k^{in} + Y_{5,k} \delta\hat{\alpha}_k^{in} \quad (\text{IV.2})$$

where,

$$Y_{0,k} = 1 - F_k U_{4,k} + G_k \psi_{2,k}, \quad Y_{1,k} = (E_k X_2) / Y_{0,k},$$

$$Y_{2,k} = (\frac{D_k Q_k}{q_{k,o}} + F_k U_{2,k}) / Y_{o,k}$$

$$Y_{3,k} = \frac{F_k U_{1,k}}{Y_{o,k}}$$

$$Y_{4,k} = \frac{1}{Y_{o,k}} (U_{3,k} F_k - G_k \psi_{1,k}) .$$

$$Y_{5,k} = \frac{1}{Y_{o,k}} (U_{5,k} F_k - G_k \psi_{3,k}) . \quad Y_{6,k} = (E_k X_1) / Y_{o,k}$$

APPENDIX V

THE PERTURBATION OF THE VOID DEPARTURE POINT

From the Saha-Zuber model, Equation (2.37), the liquid enthalpy at Z_d has the form,

$$h_{\ell_d} = h_{\ell}(q''_d, G_d) \quad (V.1)$$

Expanding Equation (V.1) into a Taylor series and ignoring higher order terms, we obtain,

$$\begin{aligned} h_{\ell}(Z_d) = h_{\ell,o}(Z_{d,o}) &+ \left. \frac{\partial h_{\ell}}{\partial q''} \right|_{(q''_{d,o}, G_o)} [q''(Z_d) - q''_o(Z_{d,o})] \\ &+ \left. \frac{\partial h_{\ell}}{\partial G} \right|_{(q''_{d,o}, G_o)} [G(Z_d) - G_o] \end{aligned} \quad (V.2)$$

Let us express $q''(Z_d, t)$ as,

$$\begin{aligned} q''(Z_d) = [q''(Z_d, t) - q''(Z_{d,o}, t)] &+ [q''(Z_{d,o}, t) - q''_o(Z_{d,o})] \\ &+ q''_o(Z_{d,o}) \end{aligned} \quad (V.3)$$

From a Taylor expansion for $q''(Z_d, t)$ with respect to Z , Equation (V.3) becomes,

$$q''(Z_d) - q''_o(Z_{d,o}) = \left. \frac{dq''_o}{dz} \right|_{Z_{d,o}} \delta Z_d + \delta q''(Z_{d,o}, t) \quad (V.4)$$

Since,

$$G(Z_d(t)) \stackrel{\Delta}{=} G_i(t) = G_o + \delta G_i(t), \quad (V.5)$$

Equation (V.4) and (V.5) can be substituted into Equation

(V.2) to yield,

$$h_{\ell}(Z_d, t) - h_{\ell,0}(Z_{d,0}) = \left. \frac{\partial h_d}{\partial q_d''} \right|_{(q_{d,0}'', G_0)} \frac{dq_0''}{dz} \Big|_{Z_{d,0}} \delta Z_d + \left. \frac{\partial h_d}{\partial q_d''} \right|_{(q_{d,0}'', G_0)} \delta q''(Z_{d,0}, t) + \left. \frac{\partial h_d}{\partial G_d} \right|_{(q_{d,0}'', G_0)} \delta G_i(t) \quad (V.6)$$

Using the single-phase energy equation for constant pressure, the left-hand side of Equation (V.6) can be written as,

$$h_{\ell}(Z_d, t) - h_{\ell,0}(Z_{d,0}) = \frac{1}{G_0} \frac{q_{d,0}'' P_H}{A_{x-s}} \delta Z_d + \delta h_{\ell}(Z_{d,0}) \quad (V.7)$$

Thus Equation (V.2) will be rearranged using the assumption of constant heat flux in each node as,

$$\delta Z_d = \frac{G_0 A_{x-s}}{q_{d,0}'' P_H} [-\delta h_{\ell}(Z_{d,0}) + \left. \frac{\partial h_{\ell}}{\partial q_d''} \right|_{(q_{d,0}'', G_0)} \delta q''(Z_{d,0}, t) + \left. \frac{\partial h_{\ell}}{\partial G_d} \right|_{(q_{d,0}'', G_0)} \delta G_i] \quad (V.8)$$

Since

$$\left. \frac{\partial h_{\ell}}{\partial q_d''} \right|_{(q_{d,0}'', G_0)} \triangleq X_1$$

$$\left. \frac{\partial h_{\ell}}{\partial G_d} \right|_{(q_{d,0}'', G_0)} \triangleq X_2$$

and,

$$\delta h(Z_{d,0}, t) = H_1(s) \delta j_i + H_2(s) \sum_{i=1}^L H_i'(s) \delta q_{t,i}'' + H_3(s) \delta h_i \quad (V.9)$$

where X_1 and X_2 are defined in Equation (2.67) and the H 's are the transfer functions defined in Appendix VI, equation (V.8) becomes,

$$\hat{\delta Z}_d = \Lambda_1(s) \hat{\delta j}_i + \sum_{i=1}^B \Lambda_2^i(s) \hat{\delta q}_{t,i}'' + \Lambda_3(s) \hat{\delta h}_i \quad (V.10)$$

where,

$$\Lambda_1(s) = \frac{G_0 A_{x-s}}{q_{d,o}'' p_H} \{X_2 - H_1(s)\}$$

$$\Lambda_2^i(s) = \begin{cases} \frac{G_0 A_{x-s}}{q_{d,o}'' p_H} H_2(s) H_i'(s), & \text{for } i \leq L \\ \frac{G_0 A_{x-s}}{q_{d,o}'' p_H} X_1 Z_{3,B}(s), & \text{for } i = B \end{cases}$$

$$\Lambda_3(s) = \frac{G_0 A_{x-s}}{q_{d,o}'' p_H} H_3(s)$$

APPENDIX VI

SINGLE-PHASE ENTHALPY PERTURBATION AT THE VOID DEPARTURE
POINT

The single-phase energy equation can be deduced from Equation (2.2) as,

$$\frac{\partial h}{\partial t} + j_i \frac{\partial h}{\partial z} = \frac{p_h q''''(z, t)}{A_{x-s}} \quad (\text{VI.1})$$

Perturbing and Laplace transforming,

$$\frac{\partial(\hat{\delta h})}{\partial z} + \frac{s}{j_{i0}} \hat{\delta h} = - \frac{p_h q''''(z)}{\rho_f j_{i0} A_{x-s}} \left(\frac{\hat{\delta j}_i}{j_{i0}} \right) + \frac{p_h q''''(z)}{\rho_f j_{i0} A_{x-s}} \quad (\text{VI.2})$$

Using the heated wall dynamics relation shown in Equation (2.33) for $\hat{\delta q}''$, the resultant form of Equation (VI.2) will be,

$$\frac{d(\hat{\delta h})}{dz} + \phi(s) \hat{\delta h}(s, z) = \theta(s) \frac{\hat{\delta j}_i}{j_{i0}} + \beta(s) \left(\frac{\hat{\delta q}''''}{q_0} \right) \quad (\text{VI.3})$$

where,

$$\phi(s) = \frac{s}{j_{i0}} + \frac{p_h}{\rho_f j_{i0} c_{pf} A_{x-s}} \left(\frac{H_1 \phi_0}{1 - H_1 \phi_0 Z_1(s)} \right)$$

$$\theta(s, z) = \frac{p_h V_h q''''(z)}{\rho_f A_{x-s} j_{i0} A_h} \left[\frac{a}{(1 - H_1 \phi_0 Z_1(s))} - 1 \right]$$

$$\beta(s, z) = \frac{h q''''(z)}{\rho_f j_{i0} A_{x-s}} \left(\frac{H_1 \phi_0}{1 - H_1 \phi_0 Z_1(s)} \right) Z_2(s)$$

Let,

$$\theta'(s) = \frac{\theta(s, z)}{q_0'''(z)}$$

$$\beta'(s) = \frac{\beta(s, z)}{q_0'''(z)}$$

Using these relation, Equation (VI.3) becomes,

$$\frac{d(\delta h)}{dz} + \phi(s) \delta h = \theta'(s) \frac{\delta j_i}{j_{i_0}} q_0'''(z) + \beta'(s) \delta q_0'''(z) \quad (\text{VI.4})$$

We can solve this differential equation with the boundary condition, , as,

$$\begin{aligned} \delta h(s, Z_{d,0}) = & [\theta' e^{-\phi Z_{d,0}} \int_0^{Z_{d,0}} e^{\phi z} q_0'''(z) dz] \frac{\delta j_i}{j_{i_0}} + \beta' e^{-\phi Z_{d,0}} \times \\ & \int_0^{Z_{d,0}} e^{\phi z} \delta q_0'''(z) dz + e^{-\phi Z_{d,0}} \delta h_i \end{aligned} \quad (\text{VI.5})$$

Since $q_0'''(z)$ is assumed to be step-wise uniform (ie: assumed axially uniform within each axial node),

$$\delta h(s, Z_{d,0}) = \left\{ \frac{\theta'}{\phi} e^{-\phi Z_{d,0}} \sum_{k=1}^L q_0'''(e^{\phi z_k} - e^{\phi z_{k-1}}) \right\} \frac{\delta j_i}{j_{i_0}} + \frac{\beta'}{\phi} e^{-\phi Z_{d,0}}$$

$$\sum_{k=1}^L \delta q_0'''(e^{\phi z_k} - e^{\phi z_{k-1}}) + e^{-\phi Z_{d,0}} \delta h_i \quad (\text{VI.6})$$

or,

$$\delta h(s, Z_{d,0}) = H_1(s) \delta j_i + H_2(s) \sum_{k=1}^L H'_k \delta q_0''' + H_3(s) \delta h_i \quad (\text{VI.7})$$

where,

$$H_1(s) = \frac{\theta'}{\phi} \frac{e^{-\phi Z_{d,0}}}{j_{i_0}} \sum_{k=1}^L (e^{\phi z_k} - e^{\phi z_{k-1}}) q_0'''_{0,k}$$

$$H_2(s) = \frac{\beta'}{\phi} e^{-\phi Z_{d,0}}$$

$$H_3(s) = e^{-\phi Z_{d,0}}$$

$$H'_k(s) = (e^{\phi Z_k} - e^{\phi Z_{k-1}})$$

APPENDIX VII

EVALUATION OF THE PERTURBED MIXTURE PARAMETERS IN THE TWO-PHASE PRESSURE DROP PERTURBATION CALCULATION

$$(1) \frac{\delta \hat{G}'}{\delta \hat{G}'}$$

Since,

$$G' = \frac{\Delta G^2}{\langle \bar{\rho} \rangle} \quad (VII.1)$$

then,

$$\delta \hat{G}' = \frac{2G_0}{\langle \bar{\rho}_0 \rangle} \delta \hat{G} - \frac{G_0^2}{\langle \bar{\rho}_0 \rangle^2} \delta \langle \hat{\rho} \rangle \quad (VII.2)$$

The mixture density perturbation can be obtained from its definition Equation (2.7) as,

$$\delta \langle \hat{\rho} \rangle_k = - \Delta \rho \delta \langle \hat{\alpha} \rangle_k \quad (VII.3)$$

From Equation (II.7),

$$\begin{aligned} \delta \langle \hat{\rho} \rangle_k &= \Delta \rho C_{0,\bar{\Omega}_{0,k}} P_{2,k} (\xi_k^{-2} - \xi_k - \frac{s+C_{0,\bar{\Omega}_{0,k}}}{C_{0,\bar{\Omega}_{0,k}}}) \delta \langle \hat{j} \rangle_k^{in} - \Delta \rho P_{2,k} (C_{K,0})_k^{in} \\ & \quad (\xi_k^{-2} - \xi_k - \frac{s+C_{0,\bar{\Omega}_{0,k}}}{C_{0,\bar{\Omega}_{0,k}}}) \delta \hat{\Omega}_k - \Delta \rho \xi_k - \frac{s+C_{0,\bar{\Omega}_{0,k}}}{C_{0,\bar{\Omega}_{0,k}}} \delta \langle \hat{\alpha} \rangle_k^{in} \end{aligned} \quad (VII.4)$$

Inserting Equations (II.8) and (VII.4) into Equation (VII.2),

$$\delta \hat{G}' = B_1(s, \xi_k) \delta \langle \hat{j} \rangle_k^{in} + B_2(s, \xi_k) \delta \hat{\Omega}_k + B_3(s, \xi_k) \delta \langle \hat{\alpha} \rangle_k^{in} \quad (VII.5)$$

where,

$$B_1(s, \xi_k) = \frac{\Delta 2G_0}{\langle \bar{\rho}_0 \rangle_k} (g_{1,k} \xi_k^{-1} + g_{2,k} \xi_k - \frac{s}{C_0 \bar{\Omega}_{0,k}}) - \frac{G_0^2}{\langle \bar{\rho}_0 \rangle_k^2} \Delta \rho C_0 \bar{\Omega}_{0,k} P_{2,k} (\xi_k^{-2} - \xi_k - \frac{s+C_0 \bar{\Omega}_{0,k}}{C_0 \bar{\Omega}_{0,k}})$$

$$B_2(s, \xi_k) = \frac{\Delta 2G_0}{\langle \bar{\rho}_0 \rangle_k} (g_{3,k} + g_{4,k} \xi_k^{-1} - g_{5,k} \xi_k - \frac{s}{C_0 \bar{\Omega}_{0,k}}) + \frac{G_0^2}{\langle \bar{\rho}_0 \rangle_k^2} \Delta \rho P_{2,k} (C_{k,0})_k \left\{ \xi_k^{-2} - \xi_k - \frac{s+C_0 \bar{\Omega}_{0,k}}{C_0 \bar{\Omega}_{0,k}} \right\}$$

$$B_3(s, \xi_k) = \frac{\Delta 2G_0}{\langle \bar{\rho}_0 \rangle_k} g_{0,k} \xi_k - \frac{s}{C_0 \bar{\Omega}_{0,k}} + \frac{G_0^2}{\langle \bar{\rho}_0 \rangle_k^2} \Delta \rho \xi_k - \frac{s+C_0 \bar{\Omega}_{0,k}}{C_0 \bar{\Omega}_{0,k}}$$

(2) $(\bar{\phi}_{l0}^2)_k$ and $\{\delta \hat{\phi}_{l0}^2\}$

The general two-phase friction loss coefficient, ϕ_{l0}^2 , used in this study was given in Equation (2.10) as,

$$\phi_{l0}^2 = [C_2 + C_1 \frac{v_{fg}}{v_f} \langle x \rangle] \quad (VII.6)$$

The Zuber-Findlay void-quality relation [18], for steady-state, yields,

$$\langle x \rangle_k = \frac{\langle \alpha_0 \rangle_k (C_0 \frac{\rho_g}{\rho_f} + \frac{\rho_g v_{fg}}{G_0})}{1 - \langle \alpha_0 \rangle_k C_0 \frac{\Delta \rho}{\rho_f}} \quad (VII.7)$$

From Equation (2.53),

$$\langle x \rangle_k = \frac{\rho_f}{C_0 \Delta \rho} (C_0 \frac{\rho_g}{\rho_f} + \frac{\rho_g v_{fg}}{G_0}) \left\{ \frac{\rho_f}{\rho_f - C_0 \Delta \rho \langle \alpha_0 \rangle_k} \xi_k^{-1} - 1 \right\} \quad (VII.8)$$

Therefore inserting Equation (VII.8) into Equation (VII.6),

$$\phi_{20k}^2 \triangleq a_k + b_k \xi_k \quad (\text{VII.9})$$

where,

$$a_k \triangleq (C_{2,k} - C_{1,k}) - \frac{C_{1,k} \rho_f V_{gj}}{C_0 G_0}$$

$$b_k \triangleq C_{1,k} \left(1 + \frac{\rho_f V_{gj}}{C_0 G_0} \right) \left[\frac{\rho_f}{\rho_f - C_0 \Delta \rho \langle \alpha_0 \rangle_k^{in}} \right]$$

If we perturb and Laplace transform Equation (VII.6),

$$\delta(\hat{\phi}_{20}^2) = C_1 \frac{v_{fg}}{v_f} \delta \hat{x}_k \quad (\text{VII.10})$$

From Equation (2.54),

$$\delta \hat{x} = \frac{\delta \langle j \rangle G_0 - \langle j_0 \rangle \delta G}{v_{fg} G_0^2} \quad (\text{VII.11})$$

Inserting Equation (VII.11) into Equation (VII.10),

$$\delta(\hat{\phi}_{20}^2)_k = \frac{C_1}{G_0 v_f} \delta \langle j \rangle - \frac{C_1}{G_0^2 v_f} \langle j_0 \rangle \delta G \quad (\text{VII.12})$$

Now from Equation (II.4) and (II.8), we obtain,

$$\begin{aligned} \delta(\hat{\phi}_{20}^2)_k = & (f_{1,k} + f_{2,k} \xi_k^{-1} + f_{3,k} \xi_k + f_{4,k} \xi_k) \delta \langle j \rangle_k^{in} \\ & + (f_{5,k} + f_{6,k} \xi_k^{-1} + f_{7,k} \xi_k + f_{8,k} \xi_k) \delta \langle \alpha \rangle_k^{in} \\ & + f_{9,k} \xi_k \left(-\frac{s - C_0 \bar{\Omega}_{0,k}}{C_0 \bar{\Omega}_{0,k}} \right) \delta \hat{\Omega}_k + (f_{10,k} \xi_k - \frac{s}{C_0 \bar{\Omega}_{0,k}}) \delta \langle \alpha \rangle_k^{in} \\ & + f_{11,k} \xi_k \left(-\frac{s - C_0 \bar{\Omega}_{0,k}}{C_0 \bar{\Omega}_{0,k}} \right) \delta \langle \alpha \rangle_k^{in} \end{aligned} \quad (\text{VII.13})$$

where,

$$f_{1,k} = \frac{C_1}{G_0 v_f} - \frac{C_1 (C_{K,o})_k^{in}}{C_0 v_f G_0^2} g_{1,k}$$

$$f_{2,k} = \frac{C_1 v_{gj}}{C_0 v_f G_0^2} g_{1,k}$$

$$f_{3,k} = \frac{C_1 v_{gj}}{C_0 v_f G_0^2} g_{2,k}$$

$$f_{4,k} = - \frac{C_1 (C_{K,o})_k^{in}}{C_0 v_f G_0} g_{2,k}$$

$$f_{5,k} = - \frac{C_1}{C_0 v_f G_0} \frac{(C_{K,o})_k^{in}}{\Omega_{o,k}} + \frac{C_1}{C_0 v_f G_0^2} \left\{ v_{gj} g_{3,k} - (C_{K,o})_k^{in} g_{4,k} \right\}$$

$$f_{6,k} = \frac{C_1 v_{gj}}{C_0 v_f G_0^2} g_{4,k}$$

$$f_{7,k} = \frac{C_1}{C_0 v_f G_0} \frac{(C_{K,o})_k^{in}}{\Omega_{o,k}} - \frac{C_1}{C_0 v_f G_0^2} (C_{K,o})_k^{in} g_{3,k}$$

$$f_{8,k} = \frac{C_1 v_{gj}}{C_0 v_f G_0^2} g_{5,k}$$

$$f_{9,k} = - \frac{C_1 (C_{K,o})_k^{in}}{C_0 v_f G_0^2} g_{5,k}$$

$$f_{10,k} = \frac{C_1 v_{gj}}{C_0 v_f G_0^2} g_{6,k}$$

$$f_{11,k} = - \frac{C_1 (C_{K,o})_k^{in}}{C_0 v_f G_0^2} g_{6,k}$$

(3) Spatial drift-flux gradient, $\hat{\delta S}_{DG}$

Let us define,

$$\hat{\delta S}_{DG} \triangleq \overline{\delta \left[\left(\frac{\rho_f - \langle \bar{\rho} \rangle}{\langle \bar{\rho} \rangle - \rho_g} \right) \left(\frac{\rho_f \rho_g}{\langle \bar{\rho} \rangle} \right) (v'_{gj})^2 \right]} \quad (\text{VII.14})$$

where,

$$v'_{gj} \triangleq (C_0 - 1) \langle j \rangle + v_{gj}$$

Thus,

$$\begin{aligned} \hat{\delta S}_{DG} = & \rho_f \rho_g (v'_{gj})_0^2 \left[\frac{-\delta \langle \hat{\bar{\rho}} \rangle (\langle \bar{\rho}_0 \rangle^2 - \rho_g \langle \bar{\rho}_0 \rangle) (2 \langle \bar{\rho}_0 \rangle \delta \langle \hat{\bar{\rho}} \rangle - \rho_g \delta \langle \hat{\bar{\rho}} \rangle)}{(\langle \bar{\rho}_0 \rangle^2 - \rho_f \langle \bar{\rho}_0 \rangle)^2} \right] \\ & + 2 \left(\frac{\rho_f - \langle \bar{\rho}_0 \rangle}{\langle \bar{\rho}_0 \rangle - \rho_g} \right) \left(\frac{\rho_f \rho_g}{\langle \bar{\rho}_0 \rangle} \right) (v'_{gj})_0 (C_0 - 1) \delta \langle \hat{j} \rangle \end{aligned} \quad (\text{VII.15})$$

since, $\delta \hat{v}'_{gj} = (C_0 - 1) \delta \langle \hat{j} \rangle$, this can be written more compactly as,

$$\hat{\delta S}_{DG} = -\bar{V}'_1 \delta \langle \hat{\bar{\rho}} \rangle + 2\bar{V}'_2 (C_0 - 1) \delta \langle \hat{j} \rangle \quad (\text{VII.16})$$

where,

$$\bar{V}'_1 \triangleq \frac{\rho_f \rho_g (v'_{gj})_0^2}{\langle \bar{\rho}_0 \rangle^2 - \rho_g \langle \bar{\rho}_0 \rangle} \left\{ 2\rho_f \langle \bar{\rho}_0 \rangle^2 - \langle \bar{\rho}_0 \rangle^2 - \rho_f \rho_g \right\}$$

$$\bar{V}'_2 \triangleq \left(\frac{\rho_f - \langle \bar{\rho}_0 \rangle}{\langle \bar{\rho}_0 \rangle - \rho_g} \right) \left(\frac{\rho_f \rho_g}{\langle \bar{\rho}_0 \rangle} \right) (v'_{gj})_0$$

from Eq. (II.4) and (VII.4),

$$\begin{aligned}
 \delta \hat{S}_{DG} = & (\gamma_{1,k} + \gamma_{2,k} \epsilon_k^{-2} - \gamma_{2,k} \frac{s+C_0 \bar{\Omega}_{0,k}}{C_0 \bar{\Omega}_{0,k}}) \delta \langle j \rangle_k^{in} + (\gamma_{2,k} - \gamma_{3,k} \epsilon_k \\
 & + \gamma_{4,k} \epsilon_k^{-2} + \gamma_{4,k} \epsilon_k - \frac{s+C_0 \bar{\Omega}_{0,k}}{C_0 \bar{\Omega}_{0,k}}) \delta \hat{\Omega}_k \\
 & + \gamma_{5,k} \epsilon_k - \frac{s+C_0 \bar{\Omega}_{0,k}}{C_0 \bar{\Omega}_{0,k}} \delta \langle \alpha \rangle_k^{in}
 \end{aligned} \tag{VII.17}$$

, where

$$\gamma_{1,k} = \frac{\Delta}{2V_2} (C_0 - 1) ,$$

$$\gamma_{2,k} = -\bar{V}_1^i \Delta \rho P_{2,k} C_0 \bar{\Omega}_{0,k} .$$

$$\gamma_{3,k} = -\gamma_{1,k} \frac{(C_{k,o})_k^{in}}{C_0 \bar{\Omega}_{0,k}} ,$$

$$\gamma_{4,k} = +\bar{V}_1^i \Delta \rho P_{2,k} (C_{k,o})_k^{in}$$

$$\gamma_{5,k} = \bar{V}_1^i \Delta \rho$$

APPENDIX VIII

EXPRESSIONS FOR $\delta\langle j \rangle_k^{\text{in}}$, $\delta\langle \alpha \rangle_k^{\text{in}}$, AND $\delta\hat{\Omega}_k$ IN TERMS OF EXTERNAL FORCING FUNCTIONS

(1) For $\delta\langle j \rangle_k^{\text{in}}$

From Equation (2.14),

$$\delta\langle j \rangle_k^{\text{in}} = \delta\langle j \rangle_B^{\text{in}} + \delta_k(B) \sum_{i=B}^{k-1} \delta\hat{\Omega}_i \Delta z_i \quad (\text{VIII.1})$$

where,

$$\delta_k(x) = \begin{cases} 0, & \text{if } k=E \\ 1, & \text{if } k \neq E \end{cases}$$

Since, $\langle j(Z_d(t)) \rangle = j_i(t)$,

$$\langle j_0(Z_d) \rangle + \delta\langle j(Z_d) \rangle = \langle j_0 \rangle + \delta j_i \quad (\text{VIII.2})$$

From Taylor expanding $\langle j_0(Z_d(t)) \rangle$ with respect to $\delta\hat{Z}_d$, and neglecting higher other terms,

$$\langle j_0(Z_d) \rangle = \langle j_0 \rangle + \left. \frac{\partial \langle j_0 \rangle}{\partial z} \right|_{Z_{d,0}} \delta\hat{Z}_d \quad (\text{VIII.3})$$

Inserting Equation (VIII.3) into Equation (VIII.2),

$$\delta\langle j \rangle_B^{\text{in}} = \delta\langle j(Z_{d,0}) \rangle = \delta j_i - \bar{\Omega}_{0,B} \delta\hat{Z}_d \quad (\text{VIII.4})$$

since, $\left. \frac{d\langle j_0 \rangle}{dz} \right|_{Z_{d,0}} = \bar{\Omega}_{0,B}$ from Equation (2.1) for steady-state. Now combining Equations (VIII.1) and (VIII.4),

$$\delta\langle j \rangle_k^{\text{in}} = \delta j_i - \bar{\Omega}_{0,B} \delta\hat{Z}_d + \delta_k(B) \sum_{j=B}^{k-1} \delta\hat{\Omega}_j \Delta z_j \quad (\text{VIII.5})$$

(2) For $\delta\langle\hat{\alpha}\rangle_k^{\text{in}}$ ($k > B+1$)

From Equation (II.7),

$$\delta\langle\hat{\alpha}\rangle_k^{\text{in}} = \theta_1^{k-1} \delta\langle\hat{j}\rangle_{k-1} + \theta_2^{k-1} \delta\hat{q}_{k-1} + \theta_3^{k-1} \delta\langle\hat{\alpha}\rangle_{k-1}^{\text{in}} \quad (\text{VIII.6})$$

where,

$$\begin{aligned} \theta_1^k &= -p_{2,k} c_0 \bar{\Omega}_{0,k} \left\{ (\xi_k^{\text{out}})^{-2} - (\xi_k^{\text{out}})^{-\frac{s+C_0\bar{\Omega}_{0,k}}{C_0\bar{\Omega}_{0,k}}} \right\} \\ \theta_2^k &= p_{2,k} \left\{ (\xi_k^{\text{out}})^{-2} - (\xi_k^{\text{out}})^{-\frac{s+C_0\bar{\Omega}_{0,k}}{C_0\bar{\Omega}_{0,k}}} \right\} \left(\frac{p_H v_{fg}}{A_{x-s} h_{fg}} \right) Z_{3,k} \\ \theta_3^k &= (\xi_k^{\text{out}})^{-\frac{s+C_0\bar{\Omega}_{0,k}}{C_0\bar{\Omega}_{0,k}}} \end{aligned}$$

Marching node-by-node for Equation (VIII.6), and noting continuity at the node interface, $\delta\langle\hat{\alpha}\rangle_k^{\text{in}} = \delta\langle\hat{\alpha}\rangle_{k-1}^{\text{out}}$,

$$\begin{aligned} \delta\langle\hat{\alpha}\rangle_k^{\text{in}} &= \left(\sum_{i=8}^{k-1} a_i \right) \delta\hat{j}_i - \bar{\Omega}_{0,B} \left(\sum_{i=8}^{k-1} a_i \right) \delta\hat{\lambda} + \sum_{i=8}^{k-1} \left[a_i \left\{ \sum_{j=8}^{i-1} \Delta z_j \delta\hat{\Omega}_j \right\} \right. \\ &\quad \left. + \sum_{i=8}^{k-1} b_i \delta\hat{\Omega}_i - \frac{\bar{\Omega}_{0,B} c_k}{\rho_g v_{fg} (C_{k,0})_k^{\text{in}}} \delta Z_d \right] \quad (\text{VIII.7}) \end{aligned}$$

where,

$$a_i (i < k-1) = \left(\prod_{j=1}^{k-1-i} \theta_3^{k-j} \right) \theta_1^i,$$

$$a_{k-1} = \theta_1^{k-1},$$

$$b_i (i < k-1) = \left(\prod_{j=1}^{k-1-i} \theta_3^{k-j} \right) \theta_2^i.$$

$$b_{k-1} = \theta_2^{k-1}.$$

$$c_k = \left(\prod_{i=8}^{k-1} \theta_3^i \right)$$

From Equation (V.12) and

$$\sum_{i=1}^{k-1} \left\{ a_i \delta_i(1) \sum_{j=1}^{i-1} x_j \right\} = \delta_k(2) \sum_{i=1}^{k-2} \left(\sum_{j=i+1}^{k-1} a_j \right) x_i, \quad (\text{VIII.8})$$

Equation (VIII.7) becomes,

$$\delta \langle \hat{\alpha} \rangle_k^{in} = x_{1,k} \hat{\delta j}_i + \sum_{i=8}^{k-1} x_{2,k}^i \hat{\delta \bar{\Omega}}_j + x_{3,k} \hat{\delta Z}_d \quad (\text{VIII.9})$$

where,

$$x_{1,k} = \sum_{i=8}^{k-1} a_i$$

$$x_{2,k}^i = \begin{cases} \left(\sum_{j=i+1}^{k-1} a_j \right) \Delta z_i & i < k-1 \\ b_i & i = k-1 \end{cases}$$

$$x_{3,k} = - \left\{ \sum_{i=8}^{k-1} a_i + \frac{c_k}{\rho_f v_{fg}(C_{K,o})_k^{in}} \right\} \bar{\Omega}_{o,B}$$

(3) For $\hat{\delta \bar{\Omega}}_k$

In order to express $\hat{\delta \bar{\Omega}}_k$ given in Equation (IV.2) in terms of the external forcing functions, let us first find $\delta \langle \hat{h}_\ell \rangle$. From the boundary condition, $\delta h(Z_d) = \delta \hat{h}_{Z_d}$ (Equation (2.67)), we can combine Equation (2.60) node-by-node, keeping conservation of $\delta \langle \hat{h}_\ell \rangle_k^{in}$ at the node interfaces, to obtain,

$$\begin{aligned} \delta \langle \hat{h} \rangle_k^{in} = & \theta_{1,k} \delta \hat{h}_{\ell_d} + \sum_{i=1}^{k-1} \theta_{2,k}^i \delta \hat{q}_i'' + \sum_{i=1}^{k-1} \theta_{3,k}^i \delta \langle \hat{j} \rangle_i^{in} + \sum_{i=1}^{k-1} \theta_{4,k}^i \delta \hat{\Omega}_i \\ & + \sum_{i=1}^{k-1} \theta_{5,k}^i \delta \langle \hat{\alpha} \rangle_i^{in} \end{aligned} \quad (\text{VIII.10})$$

where,

$$\theta_{1,k} = \begin{cases} \prod_{i=1}^{k-1} W_{1,i} & , \text{ for } k \geq B+1 \\ 1 & , \text{ for } k=B \end{cases}$$

$$\theta_{\ell,k}^i (\ell=2, 3, 4, 5) = \begin{cases} \left(\prod_{j=i+1}^{k-1} W_{\ell,j} \right) W_{\ell,i} & , \text{ for } k \geq B+1 \\ 0 & , \text{ for } k=1 \\ W_{\ell,k-1} & , \text{ for } i=k-1 \end{cases}$$

Inserting Equation (VIII.10) into Equation (IV.2),

$$\begin{aligned} \delta \hat{\Omega}_k = & X_{1,k} \delta \hat{j}_i + X_{7,k} \delta \hat{q}_1'' + X_{2,k} \delta \hat{h}_{\ell_d} + \sum_{i=1}^k X_{3,k}^i \delta \hat{q}_i'' + \sum_{i=1}^k X_{4,k}^i \delta \langle \hat{j} \rangle_i^{in} \\ & + \sum_{i=1}^{k-1} X_{5,k}^i \delta \hat{\Omega}_i + \sum_{i=1}^k X_{6,k}^i \delta \langle \hat{\alpha} \rangle_i^{in} \end{aligned} \quad (\text{VIII.11})$$

where,

$$X_{1,k} = Y_{1,k} \quad X_{2,k} = Y_{3,k} \theta_{1,k},$$

$$X_{j,k}^i (j=3,4,5,6) = Y_{3,k} \theta_{j-1,k}^i \quad \text{for } i \leq k-1.$$

$$X_{3,k}^k = Y_{2,k} \quad X_{4,k}^k = Y_{4,k}$$

$$X_{6,k}^k = Y_{5,k} \quad X_{7,k} = Y_{6,k}$$

Using the boundary conditions, Equation (2.65), (2.66), and (2.67),

$$\begin{aligned} \hat{\delta\Omega}_k = & Z_{1,k} \hat{\delta j}_i + \sum_{i=1}^k Z_{2,k}^i \hat{\delta q}_i'' + \sum_{i=2}^k Z_{3,k}^i \delta \langle j \rangle_i^{in} + \sum_{i=1}^{k-1} Z_{4,k}^i \hat{\delta\Omega}_i \\ & + \sum_{i=2}^k Z_{5,k}^i \delta \langle \alpha \rangle_i^{in} + Z_{6,k} \hat{\delta Z}_d \end{aligned} \quad (\text{VIII.12})$$

where,

$$Z_{1,k} = X_{1,k} + X_{4,k}^1 + X_{2,k} X_2$$

$$Z_{2,k}^i = \begin{cases} X_{3,k}^1 + X_{2,k} X_1 + X_{7,k} & , \text{ for } i=1 \\ X_{3,k}^i & , \text{ for } i > 1 \end{cases}$$

$$Z_{3,k}^i = X_{4,k}^i, \quad Z_{4,k}^i = X_{5,k}^i$$

$$Z_{5,k}^i = X_{6,k}^i$$

$$Z_{6,k} = - \left\{ \frac{\rho_f \bar{\Omega}_{0,b}}{\Delta \rho (C_{k,0})_B} - \bar{\Omega}_{0,B} (x_{2,k} X_2 + X_{4,k}^B + Y_{1,k}) \right\}$$

Then from Equations (VIII.5), (VIII.9) and the relationship,

$$\sum_{i=2}^k \Lambda_i \sum_{j=1}^{i-1} \beta_j X_j = \sum_{i=1}^{k-1} (\beta_i \sum_{j=i+1}^k \Lambda_j) X_i \quad (\text{VIII.13})$$

Equation (VIII.12) becomes,

$$\hat{\delta\Omega}_k = T_{1,k} \hat{\delta j}_i + \sum_{i=1}^k T_{2,k}^i \hat{\delta q}_i'' + \sum_{i=1}^{k-1} T_{3,k} \hat{\delta\Omega}_i + T_{4,k} \hat{\delta Z}_d \quad (\text{VIII.14})$$

where,

$$T_{1,k} = Z_{1,k} + \sum_{i=2}^k (Z_{3,k}^i + Z_{3,k}^i X_{1,i}) \quad T_{2,k}^i = Z_{2,k}^i$$

$$T_{3,k}^i = \sum_{j=i+1}^k (Z_{3,k}^j \Delta z_i + X_{2,j}^i Z_{5,k}^j) + Z_{4,k}^i$$

$$T_{4,k} = Z_{6,k} - \bar{\Omega}_{0,B} \sum_{i=B+1}^k Z_{3,k}^1 + \sum_{i=B+1}^k Z_{5,k}^i X_{3,i}$$

Now by forward substitution, we can rearrange Equation (VIII.14) as,

$$\begin{aligned} \delta \hat{\Omega}_k = & \sum_{i=2}^k \Lambda_{k,i} [T_{1,i} \delta \hat{j}_i + \sum_{j=1}^i T_{2,i}^j \delta \hat{q}_j'' + T_{3,i}^1 \delta \hat{\Omega}_1 \\ & + T_{4,i} \delta \hat{Z}_d] \end{aligned} \quad (\text{VIII.15})$$

where,

$$\Lambda_{k,i} = \begin{cases} 1 & \text{for } i=k \\ \sum_{j_1=i+1}^k T_{3,j_1}^i \sum_{j_2=j_1+1}^k T_{3,j_2}^{j_1} \sum_{j_3=j_2+1}^k T_{3,j_3}^{j_2} \dots \\ \dots \sum_{j_m=j_{m-1}+1}^k T_{3,j_m}^{j_{m-1}} & m=k-i \end{cases}$$

Since, from Equation (IV.2)

$$\begin{aligned} \delta \hat{\Omega}_B = & (Y_{1,B} + Y_{3,B} X_2 + Y_{4,B}) \delta \hat{j}_1 + (Y_{2,B} + Y_{3,1} X_1 + Y_{6,B}) \delta \hat{q}_1'' \\ & - \bar{\Omega}_{0,B} \left(\frac{\rho_f}{\Delta \rho (C_{k,o})_B} \ln + Y_{3,B} X_2 + Y_{4,B} + Y_{1,B} \right) \delta \hat{Z}_d \end{aligned} \quad (\text{VIII.16})$$

Equation (VIII.16) can be rearranged as,

$$\delta \hat{\Omega}_k = M'_{1,k} \delta j_1 + \sum_{i=1}^k M_{2,k}^{i'} \delta \hat{q}_{t,i}''' + M'_{3,k} \delta \hat{Z}_d \quad (\text{VIII.17})$$

where,

$$M'_{1,k} = \sum_{i=2}^k \Lambda_i \{T_{1,i} + T_{3,i}^B (Y_{1,1} + Y_{3,1}X_2 + Y_{4,1})\}$$

$$M_{2,k}^{i'} = \begin{cases} \sum_{j=2}^k \Lambda_i (T_{2,j}^1 + T_{3,i}^1 (Y_{2,1} + Y_{3,1}X_1 + Y_{6,1})) & , \text{ for } i=B \\ \sum_{j=i}^k \Lambda_j T_{2,j}^i & , \text{ for } i>B \end{cases}$$

$$M'_{3,k} = \sum_{i=B+1}^k \Lambda_1 \left\{ T_{4,i} - T_{3,i}^B \bar{\Omega}_{0,B} \left(\frac{\rho_f}{\Delta \rho (C_{K,O})_B} + Y_{3,B}X_2 + Y_{4,B} + Y_{1,B} \right) \right\}$$

From Equations (V.10) and (2.36), the final form of $\delta \hat{\Omega}_k$ will be,

$$\delta \hat{\Omega}_k = M_{1,k} \delta \hat{j}_1 + \sum_{i=1}^k M_{2,k}^i \delta \hat{q}_{t,i}''' + M_{3,k} \delta \hat{h}_i \quad (\text{VIII.18})$$

where,

$$M_{i,k} = M'_{1,k} + \Lambda_1 M'_{3,k}$$

$$M_{2,k}^i = \begin{cases} M'_{3,k} \Lambda_2 H_i & , \text{ for } i \leq L \\ (M_{2,k}^{i'}) Z_{3,i} & , \text{ for } i \geq B \end{cases}$$

$$M_{3,k} = M'_{3,k} \Lambda_3$$

Finally, inserting Equation (VIII.18) into Equations (VIII.5) and (VIII.9), we get the inlet velocity and void fraction perturbation to the k-th node as,

$$\delta \langle \hat{j} \rangle_k^{in} = V_{1,k} \delta \hat{j}_i + \sum_{i=1}^{k-1} V_{2,k}^i \delta \hat{q}_i''' + V_{3,k} \delta \hat{h}_i \quad (\text{VIII.19})$$

where,

$$V_{1,k} = 1 - \bar{\Omega}_{0,B} \Lambda_1 + \sum_{i=B}^{k-1} \Delta z_i M_{1,i}$$

$$V_{2,k}^i = \begin{cases} -\bar{\Omega}_{0,B} \Lambda_2 + \sum_{i=B}^{k-1} M_{2,k}^i \Delta z_i & , \text{ for } i \leq L \\ \sum_{j=i}^{k-1} \Delta z_j M_{2,j}^i & , \text{ for } i \geq B \end{cases}$$

$$V_{3,k} = -\bar{\Omega}_{0,B} \Lambda_3 + \sum_{i=B}^{k-1} M_{3,i} \Delta z_i$$

and,

$$\delta \langle \hat{\alpha} \rangle_k^{in} = K_{1,k} \delta \hat{j}_i + \sum_{i=1}^{k-1} K_{2,k}^i \delta \hat{q}_i''' + K_{3,k} \delta \hat{h}_i \quad (\text{VIII.20})$$

where,

$$K_{1,k} = \chi_{1,k} + \chi_{3,k} \Lambda_1 + \sum_{i=B}^{k-1} \chi_{2,k}^i M_{1,i}$$

$$K_{2,k}^i = \begin{cases} \chi_{3,k} \Lambda_2 + \sum_{i=B}^{k-1} M_{2,k}^i \chi_{2,k}^i & , \text{ for } i \leq L \\ \sum_{j=1}^{k-1} \chi_{2,k}^i M_{2,j}^i & \end{cases}$$

$$K_{3,k} = \chi_{3,k} \chi_3 + \sum_{i=B}^{k-1} M_{3,k} \chi_{2,k}^i$$

APPENDIX IX
DERIVATION OF $\delta \langle \hat{j}_p \rangle^{in}$ AND $\delta \langle \hat{\alpha}_p \rangle^{in}$

Since quality is conserved at an abrupt change flow area.

$$\langle x_p \rangle^{in} = \frac{\sum w_{g,i}}{\sum w_i} \quad (IX.1)$$

From $\langle x \rangle_i = w_{g,i}/w_i$, Equation (IX.1) becomes,

$$\langle x_p \rangle^{in} = \frac{\sum_i^N \langle x(L_H) \rangle_i w_i}{w_0} \quad (IX.2)$$

From the Zuber-Findlay void-quality relation for homogeneous flow, we can obtain,

$$\langle \alpha_p \rangle_0^{in} = \frac{\langle x_p \rangle_0^{in} \rho_f}{\rho_g + \Delta \rho \langle x_p \rangle_0^{in}} \quad (IX.3)$$

and,

$$\langle j_p \rangle_0^{in} = \frac{w_0}{A_p \langle \rho_p \rangle_0^{in}} = \frac{w_0}{A_p \{ \rho_f - \Delta \rho \langle \alpha_p \rangle_0^{in} \}} \quad (IX.4)$$

By perturbing and Laplace transforming Equation (IX.2),

$$\begin{aligned} \delta \langle \hat{x}_p \rangle^{in} &= \frac{1}{w_0} \sum_i w_{i0} \delta \langle \hat{x}(L_H) \rangle_i + \frac{1}{w_0} \sum_i \langle x_0(L_H) \rangle_i \delta \hat{w}_i \\ &\quad - \frac{\langle x_p \rangle_0^{in}}{w_0} \delta \hat{w}. \end{aligned} \quad (IX.5)$$

Since $\delta \hat{w} = \sum \delta \hat{w}_i$,

$$\delta \langle \hat{x}_p \rangle^{in} = \sum_i \frac{w_{i0}}{w_0} \delta \langle \hat{x}(L_H) \rangle_i + \sum_i \frac{\langle x_0(L_H) \rangle_i - \langle x_p \rangle_0^{in}}{w_0} \delta \hat{w}_i \quad (IX.6)$$

Now rearranging the Zuber-Findlay relation for slip flow, we obtain,

$$\begin{aligned} & \left[C_0 \frac{\rho_g}{\rho_f} + \frac{\rho_g V_{gj}}{G_0} + C_0 \frac{\Delta \rho}{\rho_f} \langle x \rangle + \frac{\Delta \rho \rho_g V_{gj}}{G_0^2} \langle \alpha \rangle (C_0 \langle j \rangle + V_{gj}) \right] \delta \hat{\alpha} \\ & = \left\{ 1 - C_0 \frac{\Delta \rho}{\rho_f} \langle \alpha \rangle \right\} \delta \langle x \rangle + \frac{\rho_g V_{gj}}{G_0^2} \left\{ \rho_f - \Delta \rho C_0 \langle \alpha \rangle \right\} \delta \langle j \rangle \quad . \quad (IX.7) \end{aligned}$$

where,

$$\delta \hat{G} = [\rho_f - \Delta \rho C_0 \langle \alpha \rangle] \delta \langle j \rangle - \Delta \rho (C_0 \langle j \rangle + V_{gj}) \delta \hat{\alpha} \quad (IX.8)$$

Thus,

$$\delta \langle x(L_H) \rangle_i + F_{1,i}' \delta \langle j(L_H) \rangle_i + F_{2,i}' \delta \langle \alpha(L_H) \rangle_i \quad (IX.9)$$

where,

$$F_{1,i}' = - \frac{\rho_g V_{gj,i}}{G_{0,i}^2} \frac{\rho_f}{\rho_f} \langle \alpha_0(L_H) \rangle_i$$

$$\begin{aligned} F_{2,i}' = & \left[\frac{\rho_g}{\rho_f} C_{0,i} + \frac{\rho_g V_{gj,i}}{G_{0,i}} + \frac{\Delta \rho}{\rho_f} C_{0,i} \langle x_0(L_H) \rangle_i + \frac{\Delta \rho \rho_g V_{gj,i}}{G_{0,i}^2} \times \right. \\ & \left. \langle \alpha_0(L_H) \rangle_i \{ C_{K,0}(L_H) \}_i \right] / \left[1 - \frac{\Delta \rho}{\rho_f} C_{0,i} \langle \alpha_0(L_H) \rangle_i \right] \end{aligned}$$

From perturbing and Laplace transforming Equation (IX.3), and combining Equations (IX.6) and (IX.9),

$$\delta \langle \hat{\alpha}_p \rangle^{in} = \sum_i^N F_{1,i}' \delta \langle j(L_H) \rangle_i + \sum_i^N F_{2,i}' \delta \langle \alpha(L_H) \rangle_i + \sum_i^N F_{3,i}' \delta \hat{w}_i \quad (IX.10)$$

where,

$$F_{1,i} = \frac{\rho_f \rho_g w_{i,0}}{(\rho_g + \Delta \rho \langle x_p \rangle_0^{in})^2 w_0} \quad F'_{1,i}$$

$$F_{2,i} = \frac{\rho_f \rho_g w_{i,0}}{(\rho_g + \Delta \rho \langle x_p \rangle_0^{in})^2 w_0} \quad F'_{2,i},$$

$$F_{3,i} = \frac{\rho_f \rho_g (\langle x_o(L_N) \rangle_2 - \langle x_p \rangle_0^{in})}{(\rho_g + \Delta \rho \langle x_p \rangle_0^{in})^2 w_0}.$$

Based on the assumption of homogeneous flow in the upper plenum, we can calculate $\delta \langle j_p \rangle^{in}$ from,

$$\delta \hat{G}_p = \sum \frac{A_{x-s,i}}{A_p} \delta \hat{G}_f(L_H) \quad (IX.11)$$

From Equation (IX.8), Equation (IX.11) becomes,

$$\begin{aligned} & [\rho_f - \Delta \rho \langle \alpha_p \rangle_0^{in}] \delta \langle j_p \rangle^{in} - \Delta \rho \langle j_p \rangle_0^{in} \delta \langle \alpha_p \rangle^{in} \\ &= \sum_i^N \left\{ \frac{A_i}{A_p} (\rho_f - \Delta \rho C_{o,i}(L_H)) \langle \alpha_o(L_H) \rangle_i \delta \langle j(L_H) \rangle_i \right\} \\ & \quad - \sum_i^N \left[\frac{A_i}{A_p} \Delta \rho \{C_{K,o}(L_H)\}_i \delta \langle \alpha(L_H) \rangle_i \right]. \end{aligned} \quad (IX.12)$$

Now inserting Equation (IX.10),

$$\delta \langle j_p \rangle^{in} = \sum_i^N J_{1,i} \delta \langle j(L_H) \rangle_i + \sum_i^N J_{2,i} \delta \langle \alpha(L_H) \rangle_i + \sum_i^N J_{3,i} \delta \hat{w}_i \quad (IX.13)$$

where,

$$J_{1,i} = \frac{\{\Delta \rho \langle j_p \rangle_0^{in} F_{1,i} + \frac{A_i}{A_p} (\rho_f - \Delta \rho C_{o,i}(L_H)) \langle \alpha_o(L_H) \rangle_i\}}{\{\rho_f - \Delta \rho \langle \alpha_p \rangle_0^{in}\}}$$

$$J_{2,i} = \frac{[\Delta\rho < j_p >_o^{in} F_{2,i} - \frac{A_i}{A_p} \Delta\rho \{C_{K,o}(L_H)\}_i]}{\{\rho_f - \Delta\rho < \alpha_p >_o^{in}\}}$$

$$J_{3,i} = \frac{\Delta\rho < j_p >_o^{in} F_{3,i}}{\{\rho_f - \Delta\rho < \alpha_p >_o^{in}\}} \quad .$$

APPENDIX X
CALCULATION OF $\delta(\Delta \hat{p}_{\text{riser}})$

Let us integrate Equation (3.41) term-by-term,

$$(i) \quad \frac{1}{g_c} \int_{L_{II}}^{L_R} \left[s + \frac{f G_{R,0} \phi_{L,0}^2}{\rho_f D_{H,R}} \right] \delta \hat{G}_R dz \triangleq I_{R,1} \quad (X.1)$$

From Equations (IX.8), (3.8) and (3.9), for the adiabatic riser,

$$\begin{aligned} \delta \hat{G}_R = & [\rho_f - \Delta \rho C_{O,R} \langle \alpha_R \rangle_0^{in}] \delta \langle \hat{j}_R \rangle^{in} - \Delta \rho (C_{K,R})_0 \\ & \times e^{-\frac{s}{(C_{K,R})_0} (z - L_{II})} \delta \langle \hat{\alpha}_R \rangle^{in} \end{aligned} \quad (X.2)$$

Thus,

$$\begin{aligned} I_{R,1} \triangleq & \left(\frac{s}{g_c} + \frac{f G_{R,0} \phi_{L,0}^2}{g_c \rho_f D_{H,R}} \right) \left[(\rho_f - \Delta \rho C_{O,R} \langle \alpha_R \rangle_0^{in}) \Delta L_R \delta \langle \hat{j}_R \rangle^{in} + \right. \\ & \left. \frac{\Delta \rho (C_{K,R})_0^2}{s} \left\{ e^{-\frac{s}{(C_{K,R})_0} \Delta L_R} - 1 \right\} \delta \langle \hat{\alpha}_R \rangle^{in} \right] \end{aligned} \quad (X.3)$$

where the riser length is given by, $\Delta L_R = L_R - L_{II}$

$$(ii) \quad I_{R,2} \triangleq \frac{1}{g_c} \int_{L_{II}}^{L_R} \frac{\partial}{\partial z} (\delta \hat{G}_R) dz = \frac{1}{g_c} \delta \hat{G}_R \Big|_{L_{II}}^{L_R} \quad (X.4)$$

Since,

$$\delta \hat{G}_R' = \frac{2G_{R,0}}{\langle \bar{\rho}_R \rangle_0} \delta \hat{G}_R - \frac{G_{R,0}^2}{\langle \bar{\rho}_R \rangle_0^2} \delta \langle \bar{\rho}_R \rangle$$

and the void fraction is constant along the riser,

$$\delta \hat{G}_R' = 2 \frac{G_{R,0}}{\langle \bar{\rho}_R \rangle_0^{in}} \delta \hat{G}_R + \Delta \rho \left(\frac{G_{R,0}}{\langle \bar{\rho}_R \rangle_0^{in}} \right)^2 \delta \langle \alpha_R \rangle \quad (X.5)$$

From Equations (3.9) and (X.2),

$$\begin{aligned} \delta \hat{G}_R' = 2 \frac{G_{R,0}}{\langle \bar{\rho}_R \rangle_0^{in}} (\rho_f - \Delta \rho C_{0,R} \langle \alpha_R \rangle_0^{in}) \delta \langle j_R \rangle^{in} \\ + C_{R,1} e^{-\frac{s}{(C_{K,R})_0} (z-L_{II})} \delta \langle \alpha_R \rangle^{in} \end{aligned} \quad (X.6)$$

where,

$$C_{R,1} \triangleq -2 \frac{G_{R,0}}{\langle \bar{\rho}_R \rangle_0^{in}} \Delta \rho (C_{K,R})_0 + \Delta \rho \left(\frac{G_{R,0}}{\langle \bar{\rho}_R \rangle_0^{in}} \right)^2$$

Thus,

$$I_{R,2} = \frac{C_{R,1}}{g_c} \left[e^{-\frac{s}{(C_{K,R})_0} \Delta L_R} - 1 \right] \delta \langle \alpha_R \rangle^{in} \quad (X.7)$$

$$\begin{aligned} (iii) \quad I_{R,3} &\triangleq \frac{1}{g_c} \int_{L_{II}}^{L_R} \frac{\partial}{\partial z} \hat{\delta} \left\{ \left(\frac{\rho_f - \langle \bar{\rho}_R \rangle}{\langle \bar{\rho}_R \rangle - \rho_g} \right) \frac{\rho_f \rho_g}{\langle \bar{\rho}_R \rangle} (v'_{gj}) \right\} dz \\ &= \frac{1}{g_c} \hat{\delta} \left\{ \left(\frac{\rho_f - \langle \bar{\rho}_R \rangle}{\langle \bar{\rho}_R \rangle - \rho_g} \right) \frac{\rho_f \rho_g}{\langle \bar{\rho}_R \rangle} (v'_{gj})^2 \right\} \Big|_{L_{II}}^{L_R} \end{aligned} \quad (X.8)$$

Since,

$$\hat{\delta} \left\{ \left(\frac{\rho_f - \langle \bar{\rho}_R \rangle}{\langle \bar{\rho}_R \rangle - \rho_g} \right) \frac{\rho_f \rho_g}{\langle \bar{\rho}_R \rangle} (V'_{gj})_R^2 \right\} = V_{R,1} \delta \langle \hat{j}_R \rangle^{in} + V_{R,2} \delta \langle \hat{\alpha}_R \rangle \quad (X.9)$$

where,

$$V_{R,1} \triangleq 2 \left(\frac{\rho_f - \langle \bar{\rho}_R \rangle_0^{in}}{\langle \bar{\rho}_R \rangle_0^{in} - \rho_f} \right) \left(\frac{\rho_f \rho_g}{\langle \bar{\rho}_R \rangle_0^{in}} \right) (V'_{gj,R}) (C_{O,R} - 1)$$

$$V_{R,2} \triangleq \frac{\Delta \rho \rho_f \rho_g \langle V'_{gj,R} \rangle_0^2}{|\langle \bar{\rho}_R \rangle_0^{in}|^2 - \rho_f \langle \bar{\rho}_R \rangle_0^{in}|^2} \left\{ 2 \rho_f \langle \bar{\rho}_R \rangle_0^{in} - (\langle \bar{\rho}_R \rangle_0^{in})^2 - \rho_f \rho_g \right\} .$$

Then,

$$I_{R,3} = \frac{V_{R,2}}{g_c} \left[e^{-\frac{s}{(C_{K,R})_0} \Delta L_R} - 1 \right] \delta \langle \hat{\alpha}_R \rangle^{in} \quad (X.10)$$

$$(iv) \quad \frac{g}{g_c} \int_{L_{II}}^{L_R} \delta \langle \bar{\rho}_R \rangle dz = - \frac{g}{g_c} \Delta \rho \left\{ \int_{L_{II}}^{L_R} e^{-\frac{s}{(C_{K,R})_0} (z-L_{II})} dz \right\} \delta \langle \hat{\alpha}_R \rangle^{in}$$

$$= \frac{g \Delta \rho (C_{K,R})_0}{g_c s} \left[e^{-\frac{s}{(C_{K,R})_0} \Delta L_R} - 1 \right] \delta \langle \hat{\alpha}_R \rangle^{in}$$

(X.11)

$$(v) \quad \frac{f G_{R,0}^2}{2 g_c \rho_f D_{H,R}} \int_{L_{II}}^{L_R} \delta \phi_{20,R}^2 dz$$

$$\begin{aligned}
&= \frac{f G_{R,0}^2 C_{1,R} V_{fg}}{2 g_c D_{H,R}} \int_{L_{II}}^{L_R} \delta \langle \hat{x}_R \rangle dz \\
&= \frac{f G_{R,0}^2 C_{1,R} V_{fg}}{2 g_c D_{H,R}} \int_{L_{II}}^{L_R} \left\{ \frac{\delta \langle \hat{j}_R \rangle}{V_{fg} G_{R,0}} - \frac{\langle j_R \rangle_0}{V_{fg} G_{R,0}^2} \delta \hat{G}_R \right\} dz \\
&= C_{R,3} \Delta L_R \delta \langle \hat{j}_R \rangle^{in} + C_{R,4} \left\{ e^{-\frac{s}{(C_{K,R})_0} \Delta L_R} - 1 \right\} \delta \langle \hat{\alpha}_R \rangle^{in}
\end{aligned} \tag{X.12}$$

where,

$$\begin{aligned}
C_{R,3} &\triangleq \frac{f G_{R,0} C_{1,R}}{2 g_c D_{H,R}} \left\{ 1 - \frac{\langle j_R \rangle_0^{in}}{G_{R,0}} (\rho_f - \Delta \rho C_{O,R} \langle \alpha_R \rangle_0^{in}) \right\} \\
C_{R,4} &\triangleq \frac{f C_{1,R} \langle j_R \rangle_0^{in} \Delta \rho (C_{K,R})_0^2}{2 g_c D_{H,R} s}
\end{aligned}$$

$$\begin{aligned}
(vi) \quad I_{R,4} &= K_{inlet,R} \left\{ \frac{G_{R,0} \phi_R}{g_c \rho_f} \Big|_{z=L_{II}} \delta \hat{G}(s, L_{II}) \right. \\
&\quad \left. + \frac{G_{R,0}^2}{2 g_c \rho_f} \Big|_{z=L_{II}} \delta \hat{\phi}_R(s, L_{II}) \right\} \\
&= K_{inlet,R} \left(\frac{G_{R,0} \phi_R}{g_c \rho_f} - \frac{C_{1,R} \langle j_R \rangle_0^{in}}{2 g_c} \right) \delta \hat{G}_R(s, L_{II}) \\
&\quad + K_{inlet,R} \frac{G_{R,0} C_{1,R}}{2 g_c} \delta \langle j_R \rangle^{in}
\end{aligned} \tag{X.13}$$

$$\begin{aligned}
&= K_{\text{inlet},R} \left(\frac{G_{R,0} \phi_R}{g_c \rho_f} - \frac{C_{1,R} \langle j_R \rangle_0^{\text{in}}}{2g_c} \right) [(\rho_f - \Delta \rho_{O,R} \langle \hat{j}_R \rangle_0^{\text{in}} - \\
&\quad \Delta \rho (C_{K,R})_0 \delta \langle \hat{\alpha}_R \rangle^{\text{in}}] + K_{\text{inlet},R} \frac{G_{R,0} C_{1,R}}{2g_c} \delta \langle \hat{j}_R \rangle^{\text{in}} \\
&= K_{\text{inlet},R} C_{R,5} \delta \langle \hat{j}_R \rangle^{\text{in}} + K_{\text{inlet},R} C_{R,6} \delta \langle \hat{\alpha}_R \rangle^{\text{in}} \quad (\text{X.14})
\end{aligned}$$

where,

$$C_{R,5} = \left\{ \left(\frac{G_{R,0} \phi_R}{g_c \rho_f} - \frac{C_{1,R} \langle j_R \rangle_0^{\text{in}}}{2g_c} \right) (\rho_f - \Delta \rho_{O,R} \langle \hat{\alpha}_R \rangle_0^{\text{in}}) + \frac{G_{R,0} C_{1,R}}{2g_c} \right\}$$

$$C_{R,6} = - \Delta \rho (C_{K,R})_0 \left(\frac{G_{R,0} \phi_R}{g_c \rho_f} - \frac{C_{1,R} \langle j_R \rangle_0^{\text{in}}}{2g_c} \right)$$

$$\begin{aligned}
(\text{vii}) \quad I_{R,5} &\triangleq K_{\text{exit},R} \left\{ \frac{G_{R,0} \phi_R}{g_c \rho_f} \right|_{z=L_R} \delta \hat{G}(s, L_R) \\
&\quad + \frac{G_{R,0}^2}{2g_c \rho_f} \Big|_{z=L_R} \delta \Phi_R(s, L_R) \Big\}
\end{aligned}$$

$$\begin{aligned}
&= K_{\text{exit},R} \left(\frac{G_{R,0} \phi_R}{g_c \rho_f} - \frac{C_{1,R} \langle j_R \rangle_0^{\text{in}}}{2g_c} \right) \delta \hat{G}_R(s, L_R) \\
&\quad + K_{\text{exit},R} \frac{G_{R,0} C_{1,R}}{2g_c} \delta \langle \hat{j}_R \rangle^{\text{in}}
\end{aligned}$$

$$= K_{\text{exit},R} C_{R,5} \delta \langle \hat{j}_R \rangle^{\text{in}} +$$

$$K_{\text{exit},R} C_{R,6} e^{-\frac{s}{(C_{K,R})_0} \Delta L_R} \delta \hat{\alpha}_R^{\text{in}}. \quad (\text{X.15})$$

Inserting Equations (X.3) to (X.15) into Equation (3.41),

$$\delta(\hat{\Delta p})_{\text{riser}} = R_1' \delta \hat{j}_R^{\text{in}} + R_2' \delta \hat{\alpha}_R^{\text{in}} \quad (\text{X.16})$$

where,

$$\begin{aligned} R_1' \triangleq & \left(\frac{s}{g_c} + \frac{f G_{R,0} (\phi_{LOR}^2)_0}{g_c \rho_f D_{H,R}} \right) (\rho_f - \Delta \rho C_{0,R} \hat{\alpha}_R^{\text{in}}) \Delta L_R \\ & + C_{R,3} \Delta L_R + (K_{\text{inlet},R} + K_{\text{exit},R}) C_{R,5} \\ R_2' \triangleq & \left(\frac{s}{g_c} + \frac{f G_{R,0} (\phi_{LOR}^2)_0}{g_c \rho_f D_{H,R}} \right) \cdot \frac{\Delta \rho (C_{K,R})_0^2}{s} \left\{ e^{-\frac{s}{(C_{K,R})_0} \Delta L_R} \right. \\ & - 1 \left. \right\} \left\{ e^{-\frac{s}{(C_{K,R})_0} \Delta L_R} - 1 \right\} + \frac{1}{g_c} \left\{ C_{R,1} + V_{R,2} \right. \\ & + \frac{g \Delta \rho (C_{K,R})_0}{s} + g_c C_{R,4} \left. \right\} + C_{R,6} \left\{ K_{\text{inlet},R} + \right. \\ & \left. K_{\text{exit},R} e^{-\frac{s}{(C_{K,R})_0} \Delta L_R} \right\}. \end{aligned}$$

From Equations (3.38) and (3.39), Equation (X.16) becomes,

$$\delta(\Delta p)_{\text{riser}} = R_1(s) \delta \hat{j}_p^{\text{in}} + R_2(s) \delta \hat{\alpha}_p^{\text{in}} \quad (\text{X.17})$$

where,

$$R_1(s) = \frac{A_p}{A_R} (0_{1,1}R'_1 + 0_{2,1}R'_2)$$

$$R_2(s) = (0_{1,2}R'_1 + 0_{2,2}R'_2) e^{-\frac{s}{\langle j_p \rangle_{in}} \left\{ \Delta L_I + \frac{A}{A_p} \right\}}$$

APPENDIX XI

THE EXIT ENTHALPY PERTURBATION OF THE DOWNCOMER

If we neglect curvature of the pressure vessel, the vessel wall dynamics can be calculated using the heat conduction equation for parallel plates, presented in Sec.2.3.1 with the following boundary conditions,

$$\hat{\delta T}|_{z=a} = 0 \quad (XI.1)$$

$$-k \frac{\partial \hat{\delta T}}{\partial z}|_{z=0} = \hat{\delta q}_v'' \quad (XI.2)$$

where the vessel's outer wall temperature is assumed to be constant.

Thus the vessel inner wall temperature perturbation is given by,

$$\hat{\delta T}_v(0) = \frac{\hat{\delta q}_v''}{k \epsilon_v} \tanh(\epsilon_v d) \quad (XI.3)$$

where $\epsilon_v = \sqrt{s/\alpha_v}$, α_v is the thermal diffusivity of the vessel and d is the vessel wall thickness.

Using a similar procedure to that shown to Equations (2.31) to (2.33), to express $\hat{\delta q}''$ in terms of $\hat{\delta w}$ and $\hat{\delta h}$, $\hat{\delta q}''$ can be converted to,

$$\hat{\delta q}_v'' = \frac{k_v \epsilon_v}{(k_v \epsilon_v + H_{1\phi,0} \tanh(\epsilon_v d))} \left[\frac{a q_{v,0}''}{w_0} \hat{\delta w} + \frac{H_{1\phi,0}}{c_{pf}} \hat{\delta h} \right] \quad (XI.4)$$

Perturbing and Laplace transforming Equation (3.51),

$$\frac{d(\hat{\delta h})}{dz} + \frac{\rho A}{w_0} s \hat{\delta h} = - \frac{q_{v,o}'' P_{H,v}}{w_0} \left(\frac{\hat{\delta q}_v''}{q_{v,o}''} - \frac{\hat{\delta w}}{w_0} \right) . \quad (XI.5)$$

Inserting Equation (XI.4), Equation (XI.5) becomes,

$$\frac{d(\hat{\delta h})}{dz} + \phi(s) \hat{\delta h} = \theta'(s) \frac{\hat{\delta w}}{w_0} \quad (XI.6)$$

where,

$$\phi(s) = \frac{\rho A}{w_0} s + \frac{P_{H,v} H_{1\phi,o} k_v \epsilon_v}{w_0 c_{pf} (k_v \epsilon_v + H_{1\phi,o} \tanh \epsilon_v d_1)}$$

$$\theta'(s) = - \frac{q_{v,o}'' P_{H,v}}{w_0} \left[\frac{a k_v \epsilon_v}{k_v \epsilon_v + H_{1\phi,o} \tanh \epsilon_v d_1} - 1 \right] .$$

Now for steady-state, the conduction equation in the vessel wall is,

$$k_v \frac{d^2 T_v}{dz^2} = 0 \quad (XI.7)$$

with boundary conditions given by:

$$T_v = T_0 \text{ at } z=a$$

$$-k_v \left. \frac{dT_v}{dz} \right|_{z=0} = q_{v,o}'' .$$

Thus,

$$T_v(0) = T_0 + \frac{q_{v,o}''}{k_v} d_1 . \quad (XI.8)$$

Since,

$$q_{v,o}'' = H_{1\phi,o} [T_{bulk} - T_v(o)] ,$$

we obtain,

$$q_{v,o}'' = \frac{H_{1\phi,o}}{(1 + \frac{d_1 H_{1\phi,o}}{k_v})} (T_{bulk} - T_o) . \quad (XI.9)$$

From the steady-state energy equation in the downcomer,

$$w_o c_{pf} \frac{dT_{bulk}}{dz} = - q_{v,o}'' P_{H,v} . \quad (XI.10)$$

and Equation (XI.6),

$$\frac{dT_{bulk}}{dz} + b_1 T_{bulk} = b_2 \quad (XI.11)$$

where,

$$b_1 = \frac{P_{H,v} H_{1\phi,o}}{w_o c_{pf} (1 + \frac{d_1 H_{1\phi,o}}{k_v})}$$

$$b_2 = \frac{P_{H,v} H_{1\phi,o} T_o}{w_o c_{pf} (1 + \frac{d_1 H_{1\phi,o}}{k_v})} .$$

Hence,

$$T_{bulk}(z) = T_o + (T_{bulk}^{in} - T_o) e^{-b_1 z} . \quad (XI.12)$$

By inserting Equation (XI.12) into Equation (XI.9),

$$q_{v,o}'' = b e^{-b_1 z} \quad (XI.13)$$

where,

$$b = \frac{H_{1\phi,0}}{\left(1 + \frac{d_1 H_{1\phi,0}}{k_v}\right)} (\tau_{bulk}^{in} - \tau_0) \quad .$$

Combining Equations (XI.6) and (XI.13),

$$\frac{d(\hat{\delta h})}{dz} + \phi(s)\hat{\delta h} = \theta(s) e^{-b_1 z} \frac{\hat{\delta w}}{w_0} \quad (XI.14)$$

where,

$$\theta(s) = - \frac{b^p_{H,v}}{w_0} \left[\frac{ak_v \epsilon_v}{k_v \epsilon_v + H_{1\phi,0} \tanh(\epsilon_v d_1)} - 1 \right] \quad .$$

Solving this Bernoulli-type differential equation with the boundary condition, $\hat{\delta h}_{DC}^{in} = \hat{\delta h}_{mix}$

$$\hat{\delta h}_{DC}(z) = \frac{\theta(s)}{[\phi(s) - b_1]} \left\{ e^{-b_1 z} - e^{-\phi z} \right\} \frac{\hat{\delta w}}{w_0} + e^{-\phi z} \hat{\delta h}_{mix} \quad (XI.15)$$

Finally, from Equation (3.56), the exit enthalpy perturbation of the downcomer becomes,

$$\hat{\delta h}_{DC}^{out} = D(s) \hat{\delta w} \quad (XI.16)$$

where,

$$D(s) = \frac{\theta(s) \{ e^{-b L_{DC}} - e^{-\phi L_{DC}} \}}{w_0 \{ \phi(s) - b_1 \}} + \frac{\langle x_o \rangle_R^{out}}{w_0} (h_f - h_{fw,0}) e^{-\phi L_{DC}}$$

and L_{DC} is the length of the downcomer.

APPENDIX XII

EVALUATION OF DAMPING RATIO BY CURVE FITTING

The general form of the expanded system transfer function is given as,

$$T(j\omega) = \frac{K_b \prod (1+j\omega/\omega_z)}{\prod (1+j\omega/\omega_p) \prod \{1+j2\xi_k\omega/\omega_{n,k} + (j\omega/\omega_{n,k})^2\}} \quad (\text{XII.1})$$

Equation (XII.1) can be written in the form of polynomials by expansion as,

$$T(j\omega) = \frac{\sum_{m=0}^M \beta_m (j\omega)^m}{1 + \sum_{\ell=1}^L \alpha_\ell (j\omega)^\ell} \quad (\text{XII.2})$$

Then, let us express transfer function to be fitted, $T'(s)$, as,

$$T'(s) = \frac{N(s)}{D(s)} = T_R'(\omega) + j T_I'(\omega) \quad (\text{XII.3})$$

, where $s = j\omega$

Matching Equations (XII.2) and (XII.3), we can define the error as,

$$E(\omega) = \{1 + \sum_{\ell=1}^L \alpha_\ell (j\omega)^\ell\} \{T_R'(\omega) + j T_I'(\omega)\} - \sum_{m=0}^M \beta_m (j\omega)^m \quad (\text{XII.4})$$

Considering even and odd cases for the number of zeros and poles, we can sort Equation (XII.4) into real and imaginary parts (ie: $E(\omega) = E_R(\omega) + j E_I(\omega)$). Then the weighted total error, ET, becomes,

$$ET = \sum_{i=1}^N f(\omega_i) [E_R^2(\omega_i) + E_I^2(\omega_i)] \quad (XII.5)$$

where the weighting factor, $f(\omega_i)$, was taken as unity in this study.

The coefficients, α_ℓ and β_ℓ in Equation (XII.2) can be obtained to make ET a minimum. Once we get these coefficients, the roots of the numerator and denominator can be calculated. For complex conjugate roots, ζ and ω can be determined from the quadratic form of the denominator in Equation (XII.1). The detailed computing process is shown in the flow chart in Figure XII.1.

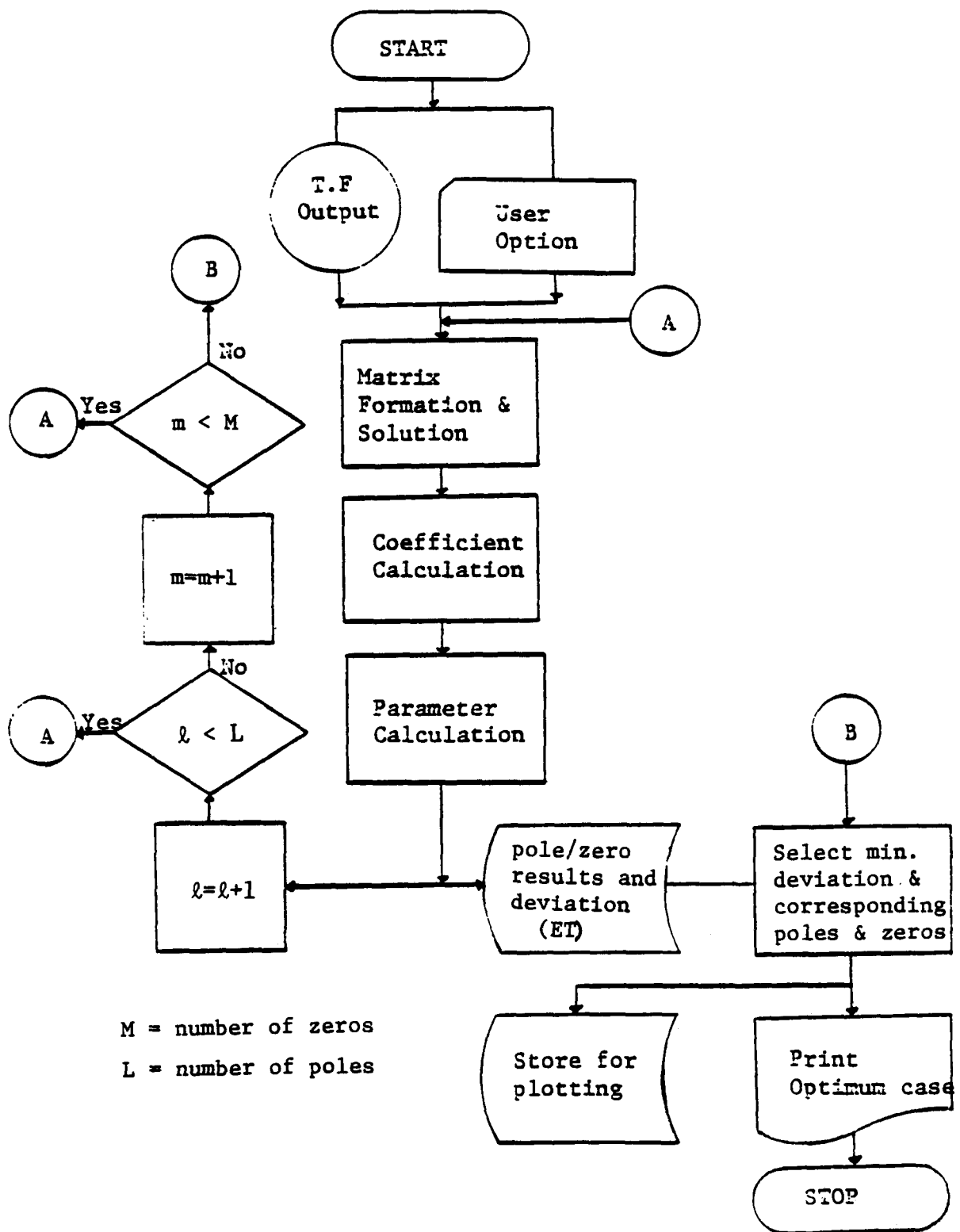


Figure XII.1 Flow Chart for the Evaluation of Damping Ratio and Natural Frequency by Curve Fitting

APPENDIX XIII

THE POWER-TO-NODE-AVERAGE-VOID-FRACTION TRANSFER FUNCTION

The boundary conditions for multiple-interacting-channel loop analysis are,

$$\delta \hat{\Delta p}_i = \delta \hat{\Delta p}_j \neq 0, \text{ for all } i, j \text{ (} i \neq j \text{)} \quad (\text{XIII.1})$$

$$\delta \hat{\Delta p}_i + \delta \hat{\Delta p}_{\text{loop}} = 0, \text{ for all } i \quad (\text{XIII.2})$$

$$\delta \hat{\Delta p}_i = \delta (\hat{\Delta p}_{1\phi})_i + \delta (\hat{\Delta p}_{2\phi})_i \quad (\text{XIII.3})$$

$$\delta \hat{w} = \sum_i^N \delta \hat{w}_i \quad (\text{XIII.4})$$

where i is the channel index and N is the total number of channels.

From Equations (2.72), (2.83), (3.61) and (XIII.3), we can define,

$$\delta (\hat{\Delta p}_i) = H_{1,i} \delta \hat{w}_i + \sum_{k=1}^K H_{2,i}^k \delta \hat{q}_{i,k}''' \quad (\text{XIII.5})$$

where,

$$H_{1,i} = \{\Gamma_{1,i} + \pi_{1,i} + \Gamma_{3,i} + \pi_{3,i}\} Y(s) \} A_{x-s,i} \rho_f$$

$$H_{2,i}^k = \Gamma_{2,i}^k + \pi_{2,i}^k$$

From boundary conditions (1) and (2), and Equation (3.50),

$$H_{1,i} \delta \hat{w}_i + \sum_{k=1}^K H_{2,i}^k \delta \hat{q}_{i,k}''' = H_{1,j} \delta \hat{w}_j + \sum_{k=1}^K H_{2,j}^k \delta \hat{q}_{j,k}''' \quad (\text{XIII.6})$$

$$H_{1,i} \delta \hat{w}_i + \sum_{k=1}^K H_{2,i}^k \delta \hat{q}_{i,k}''' + \sum_{j=1}^N R_j \delta \hat{w}_j + \sum_{j=1}^N \sum_{k=1}^K Q_{2,k}^j \delta \hat{q}_{j,k}''' = 0 \quad (XIII.7)$$

where,

$$R_j = (Q_{1,j} + Q_3 + Q_3 Y) A_{x-s,j} \rho_f$$

and R_j and $Q_{2,k}^j$ will be zero in the parallel channel analysis.

Combining Equations (XIII.6) and (XIII.7), we obtain,

$$\{H_{1,i}(1 + \sum_{j \neq i}^N \frac{R_j}{H_{1,j}}) + R_i\} \delta \hat{w}_i = - \sum_{j=1}^N \sum_{k=1}^K \theta_{j,k} \delta \hat{q}_{j,k}''' \quad (XIII.8)$$

where,

$$H_{j,k} = \begin{cases} Q_2^j - R_j \frac{\theta_{i,k}}{H_{1,j}} & \text{for } j \neq i \\ H_{2,i}^k + Q_{2,k}^i + \sum_{\ell \neq i}^N R_\ell \frac{H_{1,i}^k}{H_{1,\ell}} & \text{for } j = i \end{cases}$$

Thus the inlet flow rate feedback of the i -th channel can be calculated from Equation (XIII.8) as,

$$\delta \hat{w}_i = \sum_{j=1}^N \sum_{k=1}^K X_{i,j}^k \delta \hat{q}_{j,k}''' \quad (XIII.9)$$

where,

$$X_{i,j}^k = - \frac{\theta_{j,k}}{\{H_{1,i}(1 + \sum_{\ell \neq i}^N \frac{R_\ell}{H_{1,\ell}}) + R_i\}}$$

Finally from Equations (2.84) and (XIII.9), the power-to-node-average-void-fraction transfer function is expressed

as,

$$\delta \langle \hat{\alpha} \rangle_k = \sum_{j=1}^N \sum_{k=1}^K F_{i,j}^k \delta \hat{q}_{j,k}''' \quad (\text{XIII.10})$$

where,

$$F_{2,j}^k = \begin{cases} X_{i,i}^k (T_{1,i} + T_3 Y) + T_{2,k}^k & , \text{ for } j=i \\ X_{i,j}^k (T_{1,k} + T_3 Y) & , \text{ for } j \neq i \end{cases}$$

APPENDIX XIV
SUBROUTINES IN NUFREQ-N

The purpose of each NUFREQ-N subroutines is briefly explained below,

(1) SUBROUTINES

CONSS	Calculates the steady-state system and channel parameters which are independent of axial node.
STEADY	Computes the steady-state nodal thermal-hydraulic parameters in the core channels.
ASSIGN	Node index and node size will be reassigned by the void departure point or the bulk boiling boundary.
XLOOP	Calculates the steady-state thermal-hydraulic parameters in the recirculating loop and prepares frequency-independent values for loop stability analysis.
CON2DP	Prepares the frequency-dependent constants for

the two-phase pressure drop perturbation calculation.

DELBB Calculates the transfer functions for boiling boundary perturbation.

WALLDY Calculate the transfer functions of heated wall dynamics for various wall geometries.

DPPERT Calculates the transfer functions of pressure Drop perturbation and void fraction perturbation for the parallel channels analysis

DPLP Calculates the transfer functions of the pressure drop perturbation in the recirculating loop.

VDTE Calculation of the thermal-hydraulic transfer functions.

STABTY Calculates the open-loop or the closed-loop transfer functions and the stability margins corresponding to various external forcing functions.

POLPLT
LINE]

XLINE	Plotting subroutines for Nyquist plot
YLINE	
PTTY	
PRTPL4	
NUCLER	Reads 3-dimensional power and exposure distribution.
XSMODL	Reads nuclear data for reference void fraction and exposure, and calculates fitting coefficients of data at certain exposure and void fraction.
XDATA	Fits the nuclear data for certain exposure and void fraction.
COEFT	Calculate nodal nuclear parameters for the steady-state and for the transient case.
KINET	Generates kinetics parameters for given geometries.
OPENTF	Calculates open-loop transfer function by the Gauss reduction method.
MATXIN	Matrix inversion by matrix partition method

MATMUL Matrix multiplication

(2) FUNCTIONS

HL Liquid enthalpy (Btu/lb)

DENS Liquid density (lb/ft³)

VF Specific volume of saturated liquid (ft /lb)

VFG $v_{fg} = v_g - v_f$ (ft³/lb)

HF Saturated liquid enthalpy (Btu/lb)

HFG h_{fg}

MULT Viscosity of saturated liquid (lb/ft-hr)

COND Thermal conductivity of saturated liquid
(Btu/ft- F-hr)

MARNEL Calculation of $\bar{I}(p,G)$ in the Martinelli-Nelson
correlation, Eq.(2.11), for the two-phase fric-
tion loss multiplier

SGMA surface tension of water (lb_f/ft)

ANGL(Z)	Argument of complex value z
CCOTH(Z)	Coth(z) for complex z
EPOW(X,Z)	x^z for real x and complex z
BSIO(Z)	Modified Bessel Function of the 1st kind of order 0 for complex z
BSI1(Z)	Modified Bessel Function of the 1st kind of order 1 for complex z
BSK0(Z)	Modified Bessel Function of the 2nd kind of order 0 for complex z
BSK1(Z)	Modified Bessel Function of the 2nd kind of order 1 for complex z
BER	Ber function
BEI	Bei function
BEIS	Bei' function
BERS	Ber' function

RKER	Ker function
RKEI	Kei function
RKEIS	Kei' function
RKERS	Ker' function
GIFN1	$E_a^b(\theta)$ in Eq.(2.58) for complex b
GIFN2	$E_a^b(\theta)$ in Eq.(2.58) for real b

APPENDIX XV INPUT/OUTPUT DESCRIPTION

I. NUFREQ-N INPUT

1. Input for system geometry and thermal properties
(FILE = 5)

	<u>Variables</u>	<u>Description</u>
CARD1	COMM1	TITLE
CARD2	COMM2	COMMENTS
CARD3	(814)	NEUTRONIC OPTIONS AND SPECIFICA- TIONS OF CHANNEL
	ICASE=1	Point kinetics(uniform), core average
	=2	Point kinetics accounting the radially non-uniform nuclear properties
	=3	Point kinetics accounting the axially non-uniform nuclear properties
	=4	Radially coupled kinetics
	=5	Axially coupled kinetics, identical channel
	=6	Axially coupled kinetics, averaged channel
	=7	Point kinetics accounting the radially non-uniform nuclear properties in the specific

	channel
=8	General space kinetics(3-D), checker board
=9	Point kinetics(uniform), specific channel
=10	Radially coupled kinetics, checker board
=11	Point kinetics accounting the radially non-uniform nuclear properties in the checker- board
	checker board
=12	Point kinetics(uniform), checker-board
=13	Two group axially coupled kinetics, specific channel(coarse mesh diffusion theory, CMDT)
ISPEC	Number of row of specific channel
JSPEC	Number of column of specific channel
IRUN =0	Stop computing
=1	Continue computing with different data set
ICAL =0	Only steady-state calculation
=1	Parallel channel analysis
=2	Recirculating loop analysis without inlet enthalpy feedback
=3	same as ICAL=2, but with inlet enthalpy feedback
=4	Calculation of power-to-void fraction transfer function
=5	Calculation of power-to-void fraction transfer function

		including the inlet enthalpy feedback
	=6	Calculation of power-to-flow transfer function
CARD4	(8I4)	NODAL CONFIGURATION
	NCH	Total number of channels
	NODES	Total number of axial nodes in a channel
	NSP	Total number of spacers
CARD5	COMM3 (8I4)	OPTIONS
	IOSUB =0	Bulk boiling only
	=1	Subcooled boiling
	IOHW =0	No heated wall dynamics
	=1	Lumped parameter model
	=2	Distributed parameter model for parallel plates
	=3	Distributed parameter model for cylindrical tube
	=4	Distributed parameter model for BWR fuel rods
	IO2Q =0	No heat flux perturbation in the two-phase region
	=1	Include heat flux perturbation in the two-phase region
	IK =0	No nuclear coupling
	=1	Nuclear coupling included
	ISI	Number of significant figure in rounding values of oscillation period

IREG	=0	Next frequency is automatically adjusted by a factor of WMULT
	=1	WMULT is simply multiplied
	=2	WMULT is simply added
IBODE	=0	Calculate the open-loop transfer function
	=1	Calculate the closed-loop transfer function
IPRINT	=0	All steady-state values are not printed
	=1	Only the pressure drop of each node are printed
	=2	Only void fraction and flow velocity are printed
	=3	Only channel geometry is printed
	=4	Void fraction and pressure drop will be printed
	=5	Void fraction, pressure drop, axial power and heat flux distribution are printed
	=6	All of steady-state values are printed

CARD6

(814)

OPTIONS(CONTINUED)

IPILO	=0	C_1 and C_2 in Eq.(2.10) will be specified by the user
	=1	C_1 and C_2 will be calculated by Martinelli-Nelson empirical correlation
ISLIP	=0	Use constant drift-flux parameters
	=1	use variable drift-flux parameters(Ohkawa/Lahey)
IRW	=0	Channel inlet flow velocities are fixed by input

	=1	Channel inlet flow velocities will be redistributed (Channel inlet flow velocities given by input will be initially guessed values)
CARD7	COMM4 (6E10.4)	CORE THERMAL PARAMETERS
	p	System pressure (psia)
	TIN	Inlet coolant temperature ($^{\circ}$ F)
	ALHEAT	Heated channel length, i.e active fuel length (ft)
	TSATP	Saturation temperature corresponding to p (F)
	AVEQ	Core averaged volumetric heat generation rate (Btu/hr-ft ³)
CARD8	COMM5 (6E10.4)	CORE PARAMETERS(SKIPPED, IF IRW=0)
	DPGS	Constant core pressure drop initially guessed (psia)
	WIN	Core inlet flow rate, $w_o - w_{bypass}$ (Mlb/hr)
CARD9	COMM6 (6E10.4)	CHANNEL PARAMETERS
	CZERO	Void concentration parameter
	VGJ	Drift velocity(ft/s)
	DELX	Channel radial size (cm)
	DELZ	Channel axial size (ft)
	CHOMO1	C_1 in Eq.(2.10)
	CHOMO2	C_2 in Eq.(2.10)
CARD10	COMM7 (6E10.4)	EMPIRICAL CONSTANTS FOR TWO-PHASE HEAT TRANSFER COEFFICIENT
	CKI	in Eq.(2.34)

	CMP	m in Eq.(2.34) (e.g m=4 for Jens-Lottes correlation)
CARD11	COMM8 (2E12.6)	SPACERS
	ZSP(N)	Locations of spacers (ft)
	KLOSS(N)	Local loss coefficients of spacers
CARD12	COMM9 (6E10.4)	THERMAL PARAMETERS FOR LOOP ANALYSIS (SKIP TO CARD17, IF ICAL IS LESS THAN UNITY)
	AXSCH	Total core flow area (ft ²)
	AP	Flow area of the upper plenum (ft ²)
	RAR	Total flow area of the riser (ft ²)
	RPO	Chopped length of the upper plenum, a in Eq.(3.17) (ft)
	RP1	Upper location of Region I in Fig.3.1 (ft)
	RP2	Upper location of Region II in Fig.3.1 (ft)
CARD13	COMM10 (6E10.4)	RISER PARAMETERS
	COR	Void concentration parameter for the riser
	VGJR	Drift velocity for the riser (ft/s)
	RL	Upper location of the riser (ft)
	AR	Flow area of a riser (ft ²)
	DRIN	Hydraulic diameter of a riser (in)
	RKIN	Local loss coefficient at the inlet of the riser
	RKEXIT	Local loss coefficient at the exit of the riser

CARD14	COMM11	PARAMETERS IN THE SINGLE-PHASE PORTION OF THE LOOP
	SLOOP	$\sum \frac{L_i}{A_i}$ in Eq.(3.34) (ft^{-1})
	SFLOOP	$\sum \frac{r_i L_i}{Q_{H,i} A_i^2}$ in Eq.(3.34) (ft)
	AA	Slope of pump curve (psi-s/lb)
	AD	Flow area of Region A in Fig.3.1 (ft^2)
	DL	Hydraulic diameter of Region A in Fig.3.1 (ft)
	WO	Total recirculating flow rate (Mlb/hr)
	RATW	Total number of channel groups of interest in the core
CARD15	COMM12 (6E10.4)	THERMAL PARAMETERS OF INLET ENTHALPY FEEDBACK(SKIP TO CARD 17, IF ICAL IS NOT 3)
	HFV	Enthalpy of feedwater (Btu/lb)
	ADC	Flow area of the downcomer (ft^2)
	PHV	Heated perimeter of the vessel (ft)
	DKV	Thermal conductivity of the vessel wall ($\text{Btu/lb-}^\circ\text{F-s}$)
	CPV	Specific heat of the vessel wall (Btu/lb- F)
	DENSV	Density of the vessel wall (lb/ft^3)
	TEMV	Temperature of the vessel wall ($^\circ\text{F}$)
	TEMINV	Inlet coolant temperature of the downcomer ($^\circ\text{F}$)
	THV	Thickness of the vessel wall (ft)
	HOD	Heat transfer coefficient in the downcomer ($\text{Btu/ft}^2\text{-}^\circ\text{F-hr}$)

	DLENG	Length of the downcomer (ft)
CARD16	COMM13 (6E10.4)	LOWER PLENUM PARAMETERS
	PLM	Mass of coolant in the lower plenum (lb)
	AHLP	Heated area in the lower plenum (ft)
	THLP	Thickness of the vessel wall in the lower plenum (ft)
	HOLP	Heat transfer coefficient in the lower plenum ($\text{Btu}/\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{hr}$)
CARD17	COMM14 (6E10.4) VEL3D(J)	CHANNEL THERMAL PARAMETERS
		Channel inlet velocity (ft/s)
	PH(J)	Heated perimeter (ft)
	AXS(J)	Channel flow area (ft^2)
	DHIN(J)	Hydraulic diameter (in)
	CXF(J)	Cross-sectional area of the heater (ft^2)
	XKIN(J)	Local loss coefficient at the channel inlet
	XKEXIT(J)	Local loss coefficient at the channel exit
CARD18	COMM15 (6E10.4)	CORE POWER DENSITY PROFILE (SKIPPED, IF IK IS NOT ZERO)
	Q3D(I,J)	Power density parameter
CARD19	COMM16 (6E10.4)	PERTURBATION PARAMETER
	DELVI	If not zero, channel inlet flow velocity is externally oscillating
	DELQ0	If not zero, core-average power density is externally oscillated with the magnitude of DELQ0

	DELK	If not zero, reactivity is externally oscillated
CARD20	COMM17 (6E10.4)	FREQUENCY RANGE
	WFIN	Final frequency (rad/s)
	WINT	Initial frequency (rad/s)
	WMULT	Multiplication factor of frequency (rad/s)
CARD21	COMM18 (6E10.4)	HEATED WALL DYNAMICS PARAMETERS
	1) IOHW=1	LUMPED PARAMETER HEATER
	CPH	Specific heat (Btu/lb-°F)
	DENSH	Density (Btu/ft)
	2) IOHW=2	FOR PARALLEL PLATE HEATER
	CPH	Specific heat (Btu/lb-°F)
	TKH	Thermal conductivity (Btu/ft-°F-s)
	DENSH	Density (Btu/ft ³)
	THICKH	Heater wall thickness (ft)
	3) IOHW=3	FOR CYLINDRICAL TUBE HEATER
	CPH	Same as above
	TKH	
	DENSH	
	CRI	Heater inner radius (ft)
	CRO	Heater outer radius (ft)
	4) IOHW=4	FOR BWR FUEL ROD
	CPH	Same as above, but for fuel pin
	TKH	
	DENSH	

CPC	]	
TKC		
DENSC		
		Same as above, but for clad
CRS		Fuel pin radius (ft)
CRI		Inner radius of clad (ft)
CRO		Outer radius of clad (ft)
GAPC		Gap conductance (Btu/ft-°F-hr)

2. INPUT FOR NUCLEAR DATA (FILE = 4)

CARD1	NFTMX (10I3,50X)	Total number of fuel type
CARD2	(3F10.4,50X)	Reference data (3 reference point)
	REFE(I)	3 reference exposures
	REFU(I)	3 reference void fractions
CARD3	TITLE (20X,3E15.6)	NUCLEAR CROSS SECTION DATA ARRAY FOR 3 REFERENCE VOID FRACTIONS AND 3 REFERENCE EXPOSURES (IG : GROUP INDEX, IE : EXPOSURE INDEX, IU : VOID FRACTION INDEX). READ FOR EVERY FUEL TYPE.
	FLUX	Neutron flux, ϕ (neutrons/cm ² -s)
	SIGA	Absorption cross section, $\bar{\Sigma}_a$ (cm ⁻¹)
	SIGF (cm ⁻¹)	$\nu\bar{\Sigma}_f$
	VN2	Thermal neutron velocity, v (cm/s)
	DIFF	Diffusion coefficient, D (cm)
	SIG12	Removal cross section, (cm ⁻¹)
CARD4	(20X,6E10.4)	CONTINUED

BT Delayed neutron yield fraction
 (IGR : delayed neutron group index,
 IGR = 1,2,3,4,5,6)

3. INPUT FOR 3-D CORE COMPOSITION AND POWER AND EXPOSURE DISTRIBUTION (FILE = 7)

CARD1	TITLE (8I5)	CORE COMPOSITION
	IMAX	Maximum number of rows in 1/4 core
	JMAX	Maximum number of column in 1/4 core
	KMAX	Total number of axial nodes
	INUCLR	Nodal method option
	=0	CMDT is used
	=1	MCMDT is used
	NFTYPE	Total number of fuel type
	ICHEK	Checker-board option (if ICHEK is not 0, it is checker-board problem)
CARD2	PLAMDA(J) (8F10.4)	DECAY CONSTANT OF 6-GROUP DELAYED NEUTRONS
	FPDF(J)	ϵ_2 in Table 4.1
	FPLAM(J)	$\lambda^{(2)}$ in Table 4.1
CARD3(15I5)		
	JMX(I)	Total number channels in the i-th row for 1/4 core
	JJMX(I)	Total number channels in the i-th row for 1/8 core
CARD4	NFUEL(I,J) (15I5)	Fuel type indexing for 1/8 core

CARD5	NCONTL(I,J) (15I5)	Total number of uncontrolled nodes in (i,j) channel for 1/8 core
CARD6	(8F10.4)	ALBEDO ASSIGNMENT
	AL(I,J)	node albedo (has value only for core boundary nodes)
	TAL(I,J)	Upper plane albedo of channel top nodes
	BAL(I,J)	Lower plane albedo of channel bottom nodes
CARD7	(I2,1X,11F7.4)	POWER DISTRIBUTION FOR 1/8 CORE
	ASRC(I,J)	Normalized radial peaking factor
	SRC(I,J,K)	3-D power distribution
CARD8	(I2,1X,11F7.4)	EXPOSURE DISTRIBUTION FOR 1/8 CORE
	AEXP(I,J)	Channel-average exposure
	REXP(I,J,K)	3-D exposure distribution
CARD9	AXSRC(K) (10F8.4)	Normalized peaking factor of core- averaged power

II. NUFREQ-N OUTPUT

LIST1	SYSTEM THERMAL PROPERTIES (P, TIN, TSATP, ALHEAT, AVEQ, NCH, NODES)
LIST2	FREQUENCY DESCRIPTION; WINT, WFIN, WMULT (rad/s)
LIST3	OPTION DESCRIPTION; IOSUB, IOHW, IO2Q, IK, ISI, IREQ, IBODE
LIST4	EXTERNAL FORCING FUNCTION; DELVI, DELQO, DELK

LIST5

COOLANT PROPERTIES WHICH ARE
CALCULATED IN SUBROUTINE CONSS
ENTHT(h_{in}), ENTHP(h_f), DENSE(ρ_f), VEG1(v_{fg}),
RHOG(ρ_g), TSATP(T_{sat}), TAVE(T_{ave}), VISC(ν),
CPF(c_{pf}), KF(k_f), SIGM(σ)

LIST6

CHANNEL THERMAL-HYDRAULIC
PARAMETERS

AXS(I) Channel flow area (ft²)
PH(I) Channel heated perimeter (ft)
DHIN(I) Hydraulic diameter (in)
BBLAMB(I) Void departure point for IOSUB=1
or, bulk boiling boundary for
IOSUB=0 (ft)
FRICMO(I) Darcy-Weisbach friction factor

LIST7

PARAMETERS OF HEATED WALL
DYNAMICS WHICH ARE GIVEN IN
INPUT CARD 20 CORRESPONDING TO
HEATER GEOMETRY OPTION, IOHW

LIST8

TEMPERATURE DISTRIBUTION

TBULK(K) Coolant bulk temperature(°F)
TWALL(K) Heater wall temperature(°F)

LIST9

POWER AND HEAT FLUX DISTRIBUTION

Z(I,K) Location of node (ft)
QO(I,K) Heat flux distribution(Btu/hr-ft²)
QDIS(I,K) Volumetric heat generation rate
(Btu/hr-ft³)

LIST10

CHANNEL THERMAL-HYDRAULIC
PARAMETERS(CONTINUED)

CHALF Channel average void fraction
ALPOUT Channel exit void fraction
CZERO Void concentration parameter

	VGJ	Drift velocity (ft/s)
	XEXIT	Channel exit quality
	GOHR	Channel mass flux (lb/hr-ft ²)
	VIN	Channel average velocity in the single phase region (ft/s)
	VEX	Channel exit velocity (ft/s)
LIST11		NODE THERMAL PROPERTIES
	I	Node index
	DZ(I,K)	Axial node size (ft)
	K1(I,K)	Node characteristic frequency in phase change (s ⁻¹)
	COH(I,K)	Node void concentration parameter
	VGJH(I,K)	Node drift velocity (ft/s)
	ALFNOD(I,K)	Node average void fraction
	XEXIT(I,K)	Node exit quality
	AVGH(K)	Node average enthalpy (Btu/lb)
	JOIN(K)	Node inlet velocity (ft/s)
LIST12		LOCAL PRESSURE DROP TERMS
	ZSP(I)	Spacer location (ft)
	KLOSS(I)	Local loss coefficient
	DPSP(I)	Local pressure drop (psid)
LIST13		NODAL STEADY-STATE PRESSURE DROP EXPRESSED BY THE GRAVITATIONAL, FRICTIONAL AND ACCELERATION TERMS
LIST14		UPPER PLENUM DESCRIPTION INCLUDING FOLLOWING QUANTITIES
	UPALP	Void fraction in the upper plenum

	UPJIN	Velocity in the upper plenum (ft/s)
LIST15		RISER DESCRIPTION INCLUDING THE FOLLOWING QUANTITIES
	GOR	Mass flux in the riser (lb/hr-ft ²)
	VRO	Steady-state velocity (ft/s)
	ALPRO	Steady-state Void fraction
	CORPR	Two-phase friction loss multiplier of the riser
LIST16		PARAMETERS FOR SINGLE-PHASE LOOP ; SLOOP, SFLOOP, AA
LIST17		PARAMETERS FOR INLET ENTHALPY PERTURBATION FEEDBACK WHICH ARE GIVEN IN CARD 15
LIST18		STEADY-STATE PRESSURE DROP IN THE RECIRCULATING LOOP
	DPUL	Pressure drop in the upper plenum (psid)
	DPR	Pressure drop in the riser (psid)
	DPLOOP	Pressure drop in the single-phase portion of the loop including the downcomer and the lower plenum (psid)
	DPLPT	Total pressure drop in the core (psid)
	DPTOT	Total pressure drop in the recirculating loop (psid)
LIST19		CLOSED-LOOP TRANSFER FUNCTIONS FOR EACH FREQUENCY (WILL BE SKIPPED IF ICAL IS LESS THAN 3)
	CPS(I)	Frequency (cps)
	GHPV(I)	Closed-loop transfer function

	VMAG(I)	Magnitude (db)
	PHASE(I)	Phase angle (Degree)
LIST20		OPEN-LOOP TRANSFER FUNCTIONS(GH) FOR EACH FREQUENCY (WILL BE SKIPPED IF ICAL IS GREATER THAN 3)
	PER(I)	Period (s)
	XREA(I)	Real part of GH
	YIMA(I)	Imaginary part of GH
	AMOD(I)	Magnitude of GH
	ARGU(I)	Phase of GH (Degrees)
LIST21		NYQUIST PLOT INFORMATION
	STM(I)	Gain margin (db)
	STA(I)	Phase margin (Degrees)

APPENDIX XVI SAMPLE TEST

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(1) thermal-hydraulic data (file 5)	268
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(3) core power and exposure distribution (file 7) .	273
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(1) THERMAL-HYDRAULIC DATA (FILE 5)

SAMPLE TEST FOR PEACH BOTTOM UNIT 2 AT EOC

* HOT CHANNEL LOOP ANALYSIS WITH POINT KINETICS

* OPTIONS FOR CORE CONFIGURATION & OPERATION

9 9 7 1 3
121 24 7
* CARD 1 ; OPTIONS(ISUB, HW, 2Q, IK, ISI, IREG, IPRINT, IBODE)
1 4 1 1 2 1 0 6
1 0 0

* CARD 2 ; SYSTEM(CORE) PARAMETERS
1023.0 530.5 12.0 547.3 1.8581+07 0.0015
* CARD 3 ; CHANNEL PARAMETERS(CZERO, VGJ, DELX, DELZ, C1, C2)
1.11 1.45 15.24 0.5 1.0 1.0
2.0216-03 4.

* CARD 4 ; LOCAL LOSS COEFFICIENT

1.6 1.04
3.2 1.04
4.8 1.04
6.4 1.04
8. 1.04
9.6 1.04
11.2 1.04

* CARD 5 ; FOR THE UPPER PLENUM
82.3446 243.97 42.3323 2.582 16.276 17.568

* CARD 6 ; FOR THE RISER
1.03 0.85 26.516 0.0559 6.065 0.14
0.14

* CARD 7 ; FOR THE SINGLE-PHASE LOOP
41.68 0.3174 0.0 293.108 9.9896 2.716
15.25 764.

* CARD 8 ; FOR THE DOWNCOMMER
502.6 109.63 65.7116 9.5000+00 0.12 498.
500. 517. 0.5365 1.3597+03 26.427

* CARD 9 ; FOR THE LOWER PLENUM
3.7471+03 1.1845+03 0.625 0.9997+03

* CARD 7 ; CHANNEL PARAMETERS
6.059 8.2604 1.0858-01 0.5202 0.8484-01 27.8
0.14

* CARD 8 ; PERTURBATION PARAMETERS & FREQUENCY

0. 1. 0. 0. 0.
20. 0.623 1.5 1.1

* CARD 9 ; FUEL PARAMETERS
7.7354-02 5.6369-04 650.52 7.5318-02 2.5230-03 410.17
1.7330-02 1.7710-02 2.0540-02 1000.

DATA FOR TEST CASE IN NUFREQ-N

* ORIGINAL NUFREQ DATA

* OPTIONS FOR CORE CONFIGURATION & OPERATION

7 1 1 0 1

(2) NUCLEAR CROSS SECTION (FILE 4)

4
0.0 10.0 20.0 TOTAL NUMBER OF FUEL TYPES: NFTMX
.0 .4 .7 REFERENCE EXPOSURES : REFE(3) GWD/T
REFERENCE VOID FRACTIONS : REFU(3)
**** FUEL TYPE PBT2A, UNCONTROLLED, NFT=1 ****
IU=1 : 0 % VOID 0. MWD/KG 10. MWD/KG 20. MWD/KG
FAST FLUXES .130720E-00 .134060E-00 .150080E-00
FAST ABS XS .732620E-02 .767510E-02 .809260E-02
FAST NFIS XS .491100E-02 .429720E-02 .374230E-02
FAST NEUT VEL .158909E+08 .163244E+08 .162813E+08
FAST DIFF COEF .137950E+01 .138450E+01 .140710E+01
REMOV. XS .198910E-01 .192470E-01 .192830E-01
THRM FLUXES .471060E-01 .476720E-01 .570190E-01
THRM ABS XS .548070E-01 .534450E-01 .507930E-01
THRM NFIS XS .664370E-01 .708340E-01 .614450E-01
THRM NEUT VEL .380793E+06 .377117E+06 .374000E+06
THRM DIFF COEF .352090E-00 .350720E-00 .348710E-00
REMOV. XS .198910E-01 .192470E-01 .192830E-01
6 GP BETA(E=0.) .2130E-03 .1464E-02 .1350E-02 .2783E-02 .9240E-03 .3300E-03
6 GP BETA(E=10.) .1670E-03 .1227E-02 .1096E-02 .2211E-02 .7630E-03 .2710E-03
6 GP BETA(E=20.) .1300E-03 .1047E-02 .9130E-03 .1835E-02 .6750E-03 .2240E-03
IU=2 : 40 % VOID
FAST FLUXES .172110E-00 .176110E-00 .194610E-00
FAST ABS XS .689960E-02 .724950E-02 .762940E-02
FAST NFIS XS .467130E-02 .417380E-02 .372660E-02
FAST NEUT VEL .165577E+08 .171771E+08 .172411E+08
FAST DIFF COEF .160800E+01 .161640E+01 .163840E+01
REMOV. XS .141510E-01 .135370E-01 .134690E-01
THRM FLUXES .467650E-01 .447710E-01 .506540E-01
THRM ABS XS .518580E-01 .527480E-01 .517530E-01
THRM NFIS XS .636290E-01 .723880E-01 .663140E-01
THRM NEUT VEL .390122E+06 .386100E+06 .383127E+06
THRM DIFF COEF .441400E-00 .438680E-00 .435660E-00
REMOV. XS .141510E-01 .135370E-01 .134690E-01
6 GP BETA(E=0.) .2090E-03 .1447E-02 .1343E-02 .2781E-02 .9450E-03 .3360E-03
6 GP BETA(E=10.) .1600E-03 .1201E-02 .1078E-02 .2183E-02 .7780E-03 .2750E-03
6 GP BETA(E=20.) .1260E-03 .1038E-02 .9120E-03 .1843E-02 .7000E-03 .2320E-03
IU=3 : 70 % VOID 0. MWD/KG 10. MWD/KG 20. MWD/KG
FAST FLUXES .227430E-00 .232550E-00 .254080E-00
FAST ABS XS .636810E-02 .670140E-02 .703410E-02
FAST NFIS XS .439380E-02 .401160E-02 .363790E-02
FAST NEUT VEL .175396E+08 .184193E+08 .186501E+08
FAST DIFF COEF .183830E+01 .185090E+01 .187240E+01
REMOV. XS .996710E-02 .943110E-02 .931710E-02
THRM FLUXES .460320E-01 .415190E-01 .445220E-01
THRM ABS XS .491790E-01 .525110E-01 .532170E-01
THRM NFIS XS .606050E-01 .738480E-01 .711890E-01
THRM NEUT VEL .401703E+06 .397983E+06 .394166E+06
THRM DIFF COEF .540040E-00 .513640E-00 .525770E-00
REMOV. XS .996710E-02 .943110E-02 .931710E-02
6 GP BETA(E=0.) .2040E-03 .1425E-02 .1332E-02 .2772E-02 .9670E-03 .3430E-03


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6 GP BETA(E=10.) .1540E-03 .1171E-02 .1058E-02 .2155E-02 .7960E-03 .2790E-03
6 GP BETA(E=20.) .1230E-03 .1024E-02 .9070E-03 .1846E-02 .7250E-03 .2400E-03
**** FUEL TYPE PBT4, UNCONTROLLED, NFT=2 ****
IU=1 : 0 % VOID      0. MWD/KG      10. MWD/KG      20. MWD/KG
FAST FLUXES          .131910E-00      .132170E-00      .147440E-00
FAST ABS XS          .745550E-02      .772820E-02      .813380E-02
FAST NFIS XS          .507130E-02      .441490E-02      .383420E-02
FAST NEUT VEL          .159347E+08      .164047E+08      .163468E+08
FAST DIFF COEF          .137110E+01      .137270E+01      .139380E+01
REMOV. XS            .195240E-01      .188440E-01      .188850E-01
THRM FLUXES          .431890E-01      .440330E-01      .525740E-01
THRM ABS XS          .592480E-01      .557140E-01      .528310E-01
THRM NFIS XS          .717830E-01      .760620E-01      .660860E-01
THRM NEUT VEL          .383774E+06      .379018E+06      .375643E+06
THRM DIFF COEF          .356860E-00      .355020E-00      .352780E-00
REMOV. XS            .195240E-01      .188440E-01      .188850E-01
6 GP BETA(E=0.)      .2130E-03 .1463E-02 .1348E-02 .2778E-02 .9190E-03 .3290E-03
6 GP BETA(E=10.)      .1730E-03 .1264E-02 .1131E-02 .2283E-02 .7790E-03 .2780E-03
6 GP BETA(E=20.)      .1370E-03 .1084E-02 .9490E-03 .1908E-02 .6890E-03 .2320E-02
IU=2 : 40 % VOID      0. MWD/KG      10. MWD/KG      20. MWD/KG
FAST FLUXES          .175480E-00      .175230E-00      .193410E-00
FAST ABS XS          .700370E-02      .728630E-02      .765520E-02
FAST NFIS XS          .482150E-02      .428930E-02      .381900E-02
FAST NEUT VEL          .166154E+08      .172831E+08      .173274E+08
FAST DIFF COEF          .160210E+01      .160660E+01      .162740E+01
REMOV. XS            .137640E-01      .131260E-01      .130660E-01
THRM FLUXES          .429380E-01      .414670E-01      .469530E-01
THRM ABS XS          .560680E-01      .548460E-01      .537220E-01
THRM NFIS XS          .682690E-01      .772850E-01      .707710E-01
THRM NEUT VEL          .394166E+06      .388682E+06      .385416E+06
THRM DIFF COEF          .449760E-00      .446300E-00      .442870E-00
REMOV. XS            .137640E-01      .131260E-01      .130660E-01
6 GP BETA(E=0.)      .2080E-03 .1442E-02 .1337E-02 .2767E-02 .9380E-03 .3340E-03
6 GP BETA(E=10.)      .1660E-03 .1234E-02 .1109E-02 .2248E-02 .7920E-03 .2810E-03
6 GP BETA(E=20.)      .1330E-03 .1069E-02 .9410E-03 .1902E-02 .7110E-03 .2380E-03
IU=3 : 70 % VOID      0. MWD/KG      10. MWD/KG      20. MWD/KG
FAST FLUXES          .234310E-00      .233940E-00      .255870E-00
FAST ABS XS          .644380E-02      .671810E-02      .703970E-02
FAST NFIS XS          .452870E-02      .411660E-02      .376050E-02
FAST NEUT VEL          .176404E+08      .185808E+08      .187864E+08
FAST DIFF COEF          .183410E+01      .184320E+01      .186370E+01
REMOV. XS            .956630E-02      .901890E-02      .891580E-02
THRM FLUXES          .422840E-01      .385400E-01      .414230E-01
THRM ABS XS          .529900E-01      .543590E-01      .550600E-01
THRM NFIS XS          .644660E-01      .782910E-01      .753300E-01
THRM NEUT VEL          .406918E+06      .400320E+06      .397172E+06
THRM DIFF COEF          .552390E-00      .543320E-00      .536700E-00
REMOV. XS            .956630E-02      .901890E-02      .891580E-02
6 GP BETA(E=0.)      .2030E-03 .1416E-02 .1323E-02 .2753E-02 .9590E-03 .3400E-03
6 GP BETA(E=10.)      .1590E-03 .1199E-02 .1085E-02 .2211E-02 .8080E-03 .2850E-03

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6 GP BETA(E=20.) .1280E-03 .1048E-02 .9310E-03 .1892E-02 .7330E-03 .2450E-03
 **** FUEL TYPE PBT2A, CONTROLLED, NFT=3 ****

IU=1 : 0 % VOID	0. MWD/KG	10. MWD/KG	20. MWD/KG
FAST FLUXES	.159460E-00	.159890E-00	.180350E-00
FAST ABS XS	.996030E-02	.102210E-01	.106450E-01
FAST NFIS XS	.495930E-02	.432500E-02	.375700E-02
FAST NEUT VEL	.165120E+08	.169955E+08	.169952E+08
FAST DIFF COEF	.140850E+01	.141030E+01	.143430E+01
REMOV. XS	.179040E-01	.172740E-01	.172390E-01
THRM FLUXES	.385760E-01	.389610E-01	.464260E-01
THRM ABS XS	.752280E-01	.716640E-01	.683800E-01
THRM NFIS XS	.774600E-01	.836510E-01	.728640E-01
THRM NEUT VEL	.392680E+06	.387222E+06	.383362E+06
THRM DIFF COEF	.371730E-00	.369320E-00	.366800E-00
REMOV. XS	.179040E-01	.172740E-01	.172390E-01
6 GP BETA(E=0.)	.1840E-03	.1277E-02	.1184E-02
6 GP BETA(E=10.)	.1490E-03	.1100E-02	.9900E-03
6 GP BETA(E=20.)	.1160E-03	.9310E-03	.8220E-03
IU=2 : 40 % VOID	0. MWD/KG	10. MWD/KG	20. MWD/KG
FAST FLUXES	.222330E-00	.222690E-00	.247600E-00
FAST ABS XS	.956270E-02	.981470E-02	.101860E-01
FAST NFIS XS	.466720E-02	.416090E-02	.370580E-02
FAST NEUT VEL	.174356E+08	.181032E+08	.182226E+08
FAST DIFF COEF	.164230E+01	.164800E+01	.167060E+01
REMOV. XS	.120420E-01	.114820E-01	.113640E-01
THRM FLUXES	.378300E-01	.360230E-01	.403790E-01
THRM ABS XS	.722690E-01	.720970E-01	.712280E-01
THRM NFIS XS	.727710E-01	.846450E-01	.783510E-01
THRM NEUT VEL	.406322E+06	.400497E+06	.396697E+06
THRM DIFF COEF	.482150E-00	.478290E-00	.474700E-00
REMOV. XS	.120420E-01	.114820E-01	.113640E-01
6 GP BETA(E=0.)	.1730E-03	.1214E-02	.1135E-02
6 GP BETA(E=10.)	.1380E-03	.1037E-02	.9410E-03
6 GP BETA(E=20.)	.1080E-03	.8910E-03	.7950E-03
IU=3 : 70 % VOID	0. MWD/KG	10. MWD/KG	20. MWD/KG
FAST FLUXES	.313770E-00	.315410E-00	.346090E-00
FAST ABS XS	.897020E-02	.919440E-02	.949950E-02
FAST NFIS XS	.431560E-02	.393730E-02	.359730E-02
FAST NEUT VEL	.189491E+08	.198708E+08	.201767E+08
FAST DIFF COEF	.187160E+01	.188270E+01	.190370E+01
REMOV. XS	.781630E-02	.736850E-02	.722770E-02
THRM FLUXES	.362900E-01	.324790E-01	.343210E-01
THRM ABS XS	.692960E-01	.729810E-01	.745890E-01
THRM NFIS XS	.675290E-01	.849450E-01	.832270E-01
THRM NEUT VEL	.423083E+06	.416858E+06	.413736E+06
THRM DIFF COEF	.606320E-00	.596600E-00	.589770E-00
REMOV. XS	.781630E-02	.736850E-02	.722770E-02
6 GP BETA(E=0.)	.1610E-03	.1142E-02	.1079E-02
6 GP BETA(E=10.)	.1260E-03	.9670E-03	.8880E-03
6 GP BETA(E=20.)	.1010E-03	.8420E-03	.7620E-03

.2451E-02 .8310E-03 .2960E-03
 .2008E-02 .7060E-03 .2510E-03
 .1663E-02 .6230E-03 .2080E-03
 .2364E-02 .8280E-03 .2930E-03
 .1923E-02 .7040E-03 .2480E-03
 .1622E-02 .6320E-03 .2110E-03
 .2264E-02 .8220E-03 .2900E-03
 .1830E-02 .7010E-03 .2460E-03
 .1571E-02 .6390E-03 .2130E-03

**** FUEL TYPE PBT4, CONTROLLED, NFT=4 ****

IU=1 : 0 % VOID	0. MWD/KG	10. MWD/KG	20. MWD/KG
FAST FLUXES	.158190E-00	.157330E-00	.176770E-00
FAST ABS XS	.100490E-01	.102620E-01	.106730E-01
FAST NFIS XS	.511320E-02	.444160E-02	.384920E-02
FAST NEUT VEL	.166279E+08	.170964E+08	.170765E+08
FAST DIFF COEF	.139650E+01	.139740E+01	.141970E+01
REMOV. XS	.174840E-01	.168830E-01	.168580E-01
THRM FLUXES	.352390E-01	.361460E-01	.429230E-01
THRM ABS XS	.796000E-01	.741150E-01	.706930E-01
THRM NFIS XS	.841910E-01	.894550E-01	.781960E-01
THRM NEUT VEL	.396102E+06	.389423E+06	.385342E+06
THRM DIFF COEF	.376570E-00	.373410E-00	.370690E-00
REMOV. XS	.174840E-01	.168830E-01	.168580E-01
6 GP BETA(E=0.)	.1870E-03	.1294E-02	.1198E-02 .2478E-02 .8350E-03 .2980E-03
6 GP BETA(E=10.)	.1550E-03	.1135E-02	.1022E-02 .2074E-02 .7210E-03 .2570E-03
6 GP BETA(E=20.)	.1220E-03	.9660E-03	.8540E-03 .1728E-02 .6360E-03 .2150E-03
IU=2 : 40 % VOID	0. MWD/KG	10. MWD/KG	20. MWD/KG
FAST FLUXES	.222830E-00	.221280E-00	.245720E-00
FAST ABS XS	.961970E-02	.983050E-02	.101910E-01
FAST NFIS XS	.480910E-02	.427480E-02	.379850E-02
FAST NEUT VEL	.175982E+08	.182511E+08	.183463E+08
FAST DIFF COEF	.163260E+01	.163690E+01	.165820E+01
REMOV. XS	.116120E-01	.110830E-01	.109760E-01
THRM FLUXES	.345380E-01	.334360E-01	.374260E-01
THRM ABS XS	.763610E-01	.743660E-01	.735230E-01
THRM NFIS XS	.786310E-01	.900760E-01	.835410E-01
THRM NEUT VEL	.411235E+06	.403714E+06	.399952E+06
THRM DIFF COEF	.492150E-00	.486720E-00	.482790E-00
REMOV. XS	.116120E-01	.110830E-01	.109760E-01
6 GP BETA(E=0.)	.1760E-03	.1227E-02	.1146E-02 .2385E-02 .8310E-03 .2950E-03
6 GP BETA(E=10.)	.1430E-03	.1067E-02	.9690E-03 .1979E-02 .7170E-03 .2540E-03
6 GP BETA(E=20.)	.1140E-03	.9190E-03	.8210E-03 .1673E-02 .6420E-03 .2160E-03
IU=3 : 70 % VOID	0. MWD/KG	10. MWD/KG	20. MWD/KG
FAST FLUXES	.318430E-00	.317460E-00	.348770E-00
FAST ABS XS	.899150E-02	.918020E-02	.947480E-02
FAST NFIS XS	.443970E-02	.403840E-02	.368210E-02
FAST NEUT VEL	.192038E+08	.201199E+08	.203953E+08
FAST DIFF COEF	.186330E+01	.187310E+01	.189300E+01
REMOV. XS	.738890E-02	.696950E-02	.684130E-02
THRM FLUXES	.330290E-01	.300740E-01	.317730E-01
THRM ABS XS	.729450E-01	.749540E-01	.767760E-01
THRM NFIS XS	.722960E-01	.898130E-01	.880510E-01
THRM NEUT VEL	.429997E+06	.421336E+06	.418008E+06
THRM DIFF COEF	.623090E-00	.611170E-00	.603570E-00
REMOV. XS	.738890E-02	.696950E-02	.684130E-02
6 GP BETA(E=0.)	.1620E-03	.1151E-02	.1086E-02 .2277E-02 .8230E-03 .2900E-03
6 GP BETA(E=10.)	.1300E-03	.9920E-03	.9110E-03 .1877E-02 .7110E-03 .2500E-03
6 GP BETA(E=20.)	.1050E-03	.8620E-03	.7810E-03 .1610E-02 .6460E-03 .2170E-03/a/

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[illegible][illegible][illegible]

[illegible][illegible]

1	.643	.648	.638	.628	.592	.537	.408			
2	1.030	1.032	.986	1.010	.934	.905	.743	.505		
3	1.003	1.019	1.163	1.028	1.109	.963	.985	.711	.476	.358
4	1.040	1.021	1.051	1.029	1.030	1.035	.982	1.018	.810	.537
5	1.244	1.045	1.209	1.072	1.240	1.047	1.153	1.000	1.038	.779
6	1.065	1.029	1.070	1.113	1.100	1.083	1.042	1.063	.999	1.036
7	1.066	1.053	1.250	1.108	1.289	1.114	1.277	1.080	1.211	
8	1.050	1.042	1.051	1.074	1.113	1.106	1.127	1.130		
9	1.192	.914	1.063	1.076	1.293	1.132	1.298			
10	1.001	.898	.933	1.091	1.118	1.130				

11 1.021 1.023 1.224 1.099 1.295
 12 1.077 1.058 1.096 1.102
 13 1.280 1.074 1.248
 14 1.075 1.056
 15 1.059

RELATIVE POWER DISTRIBUTION BY NODE, SRC(I,J,K)

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***** I=1 *****
24 .141 .139 .137 .131 .124 .111 .100
23 .257 .253 .249 .240 .228 .205 .186
22 .364 .359 .355 .342 .325 .293 .260
21 .458 .453 .449 .434 .413 .371 .320
20 .538 .534 .530 .513 .489 .439 .369
19 .603 .600 .596 .580 .552 .497 .410
18 .655 .655 .650 .635 .604 .545 .444
17 .701 .702 .696 .682 .649 .587 .474
16 .742 .743 .737 .725 .690 .625 .501
15 .780 .783 .777 .765 .729 .661 .526
14 .817 .822 .816 .805 .768 .697 .551
13 .854 .860 .853 .845 .805 .733 .574
12 .890 .897 .890 .884 .841 .768 .595
11 .923 .931 .923 .919 .874 .798 .610
10 .949 .958 .947 .945 .898 .820 .615
09 .961 .969 .957 .957 .906 .826 .603
08 .949 .956 .942 .942 .888 .805 .567
07 .900 .907 .889 .887 .829 .746 .508
06 .805 .814 .791 .784 .723 .650 .435
05 .671 .685 .660 .646 .589 .536 .357
04 .536 .554 .531 .515 .469 .430 .285
03 .421 .440 .421 .406 .365 .338 .225
02 .318 .333 .320 .307 .276 .255 .172
01 .205 .208 .204 .191 .177 .159 .115
***** I=2 *****
24 .217 .215 .217 .204 .200 .179 .160 .117
23 .397 .393 .397 .375 .368 .331 .297 .215
22 .559 .555 .560 .533 .522 .471 .422 .305
21 .698 .694 .703 .671 .657 .594 .532 .383
20 .815 .812 .823 .790 .774 .700 .626 .447
19 .914 .912 .922 .891 .871 .791 .704 .500
18 .999 .998 1.004 .979 .952 .870 .770 .542
17 1.075 1.074 1.074 1.057 1.022 .942 .827 .579
16 1.146 1.146 1.140 1.130 1.088 1.009 .882 .612
15 1.215 1.216 1.204 1.203 1.153 1.077 .934 .644
14 1.284 1.286 1.269 1.277 1.220 1.148 .987 .674
13 1.357 1.359 1.334 1.354 1.289 1.222 1.041 .703
12 1.433 1.434 1.397 1.433 1.354 1.293 1.091 .730
11 1.506 1.507 1.458 1.511 1.416 1.364 1.132 .750
10 1.576 1.575 1.506 1.582 1.466 1.423 1.156 .761
09 1.621 1.618 1.526 1.628 1.484 1.455 1.145 .752
08 1.619 1.612 1.491 1.618 1.443 1.433 1.086 .715
07 1.537 1.527 1.380 1.520 1.322 1.333 .977 .646
```

06	1.361	1.354	1.194	1.318	1.121	1.159	.839	.554		
05	1.104	1.117	.967	1.042	.871	.947	.693	.457		
04	.865	.889	.764	.808	.672	.750	.554	.369		
03	.662	.688	.596	.617	.516	.578	.438	.292		
02	.479	.503	.448	.449	.386	.416	.330	.223		
01	.279	.295	.280	.264	.239	.242	.203	.143		
*****	I=3	*****								
24	.305	.301	.276	.283	.257	.253	.214	.195	.130	.098
23	.555	.546	.503	.516	.471	.465	.394	.354	.239	.183
22	.755	.741	.701	.717	.662	.648	.555	.479	.326	.236
21	.902	.885	.867	.872	.823	.788	.691	.578	.393	.313
20	1.011	.993	1.003	.990	.958	.896	.805	.658	.446	.356
19	1.096	1.080	1.115	1.083	1.070	.982	.901	.725	.488	.390
18	1.165	1.149	1.208	1.160	1.166	1.054	.983	.781	.524	.417
17	1.225	1.210	1.289	1.227	1.249	1.118	1.058	.832	.555	.440
16	1.279	1.266	1.364	1.289	1.328	1.177	1.129	.877	.583	.461
15	1.333	1.319	1.438	1.351	1.406	1.236	1.200	.922	.610	.479
14	1.387	1.373	1.513	1.413	1.488	1.297	1.271	.966	.636	.496
13	1.439	1.427	1.592	1.479	1.576	1.356	1.345	1.009	.661	.511
12	1.491	1.477	1.671	1.541	1.667	1.415	1.419	1.048	.683	.523
11	1.535	1.519	1.747	1.599	1.752	1.465	1.490	1.075	.700	.527
10	1.556	1.541	1.805	1.639	1.828	1.495	1.547	1.079	.705	.519
09	1.532	1.519	1.829	1.635	1.866	1.479	1.566	1.046	.689	.496
08	1.437	1.428	1.787	1.552	1.828	1.392	1.513	.969	.646	.456
24	.367	.369	.358	.351	.335	.311	.284	.233	.196	.127
23	.656	.643	.636	.627	.602	.566	.519	.427	.361	.234
22	.866	.839	.840	.830	.804	.777	.707	.597	.508	.330
21	1.017	.983	.990	.979	.954	.932	.847	.740	.632	.411
20	1.128	1.090	1.102	1.091	1.067	1.045	.954	.858	.730	.478
19	1.212	1.173	1.189	1.178	1.156	1.134	1.040	.955	.807	.531
18	1.280	1.238	1.259	1.248	1.230	1.206	1.111	1.039	.873	.574
24	.367	.369	.358	.351	.335	.311	.284	.233	.196	.127
23	.656	.643	.636	.627	.602	.566	.519	.427	.361	.234
22	.866	.839	.840	.830	.804	.777	.707	.597	.508	.330
21	1.017	.983	.990	.979	.954	.932	.847	.740	.632	.411
20	1.128	1.090	1.102	1.091	1.067	1.045	.954	.858	.730	.478
19	1.212	1.173	1.189	1.178	1.156	1.134	1.040	.955	.807	.531
18	1.280	1.238	1.259	1.248	1.230	1.206	1.111	1.039	.873	.574
17	1.336	1.294	1.318	1.308	1.293	1.268	1.175	1.114	.929	.611
16	1.385	1.343	1.371	1.363	1.351	1.326	1.234	1.184	.981	.644
15	1.432	1.391	1.421	1.415	1.407	1.383	1.292	1.253	1.033	.675
14	1.479	1.438	1.472	1.469	1.465	1.441	1.350	1.323	1.082	.705
13	1.526	1.483	1.523	1.522	1.522	1.501	1.408	1.396	1.133	.735
12	1.571	1.527	1.573	1.574	1.580	1.554	1.464	1.469	1.181	.763
11	1.605	1.559	1.613	1.616	1.627	1.598	1.510	1.538	1.219	.785
10	1.610	1.560	1.624	1.627	1.646	1.615	1.530	1.589	1.235	.796
09	1.553	1.497	1.573	1.575	1.603	1.572	1.492	1.596	1.212	.788
08	1.408	1.343	1.422	1.429	1.464	1.430	1.362	1.527	1.136	.752
07	1.176	1.095	1.160	1.187	1.224	1.178	1.131	1.366	1.009	.686

06	.888	.842	.891	.881	.915	.922	.904	1.165	.859	.597
05	.546	.612	.645	.523	.544	.687	.712	.962	.712	.501
04	.356	.441	.466	.341	.357	.512	.554	.777	.574	.413
03	.255	.327	.345	.247	.259	.389	.430	.606	.455	.331
02	.189	.245	.258	.183	.192	.295	.328	.444	.348	.253
01	.128	.169	.175	.125	.130	.201	.221	.265	.227	.159
*****	l=5	*****								
24	.384	.414	.381	.397	.356	.363	.316	.299	.240	.203
23	.686	.723	.682	.691	.640	.652	.574	.543	.439	.374
22	.935	.941	.932	.902	.879	.869	.795	.734	.614	.524
21	1.130	1.097	1.129	1.056	1.070	1.027	.974	.876	.760	.640
20	1.278	1.213	1.279	1.171	1.219	1.144	1.119	.983	.879	.730
19	1.390	1.298	1.396	1.258	1.334	1.235	1.234	1.068	.977	.799
18	1.478	1.364	1.489	1.326	1.428	1.309	1.330	1.139	1.060	.858
17	1.549	1.417	1.566	1.382	1.507	1.372	1.415	1.201	1.134	.909
16	1.607	1.462	1.631	1.431	1.577	1.431	1.494	1.258	1.203	.955
15	1.659	1.505	1.693	1.477	1.643	1.487	1.574	1.314	1.269	.998
14	1.712	1.549	1.757	1.524	1.711	1.546	1.656	1.370	1.337	1.042
13	1.769	1.592	1.827	1.570	1.780	1.605	1.742	1.425	1.407	1.084
12	1.829	1.637	1.902	1.615	1.852	1.664	1.830	1.478	1.478	1.123
11	1.882	1.669	1.977	1.651	1.917	1.712	1.917	1.520	1.542	1.151
10	1.915	1.662	2.029	1.652	1.960	1.724	1.983	1.537	1.591	1.157
09	1.891	1.569	2.003	1.583	1.946	1.651	1.977	1.497	1.598	1.127
08	1.752	1.317	1.754	1.402	1.810	1.404	1.760	1.367	1.541	1.053
07	1.460	.851	1.146	1.111	1.509	.918	1.177	1.139	1.401	.940
06	1.141	.587	.799	.830	1.173	.642	.852	.920	1.215	.811
05	.841	.418	.573	.589	.856	.465	.650	.737	1.014	.678
04	.608	.302	.413	.420	.619	.343	.494	.579	.823	.550
03	.443	.223	.302	.307	.450	.257	.373	.448	.638	.436
02	.319	.166	.217	.225	.320	.191	.273	.339	.463	.333
01	.194	.113	.133	.151	.194	.129	.168	.227	.275	.220
*****	l=6	*****								
24	.453	.458	.444	.429	.419	.401	.382	.343	.307	.243
23	.786	.784	.777	.761	.730	.716	.668	.618	.549	.444
22	1.013	1.007	1.012	1.003	.951	.952	.876	.832	.731	.619
21	1.169	1.163	1.176	1.169	1.110	1.116	1.030	.986	.868	.764
20	1.279	1.275	1.295	1.286	1.227	1.235	1.145	1.098	.974	.881
19	1.357	1.354	1.380	1.370	1.313	1.324	1.234	1.184	1.057	.978
18	1.411	1.412	1.443	1.432	1.378	1.393	1.306	1.253	1.125	1.060
17	1.448	1.453	1.489	1.479	1.430	1.451	1.367	1.312	1.185	1.132
16	1.473	1.482	1.522	1.514	1.474	1.501	1.423	1.365	1.239	1.199
15	1.491	1.505	1.550	1.544	1.513	1.549	1.478	1.417	1.291	1.264
14	1.510	1.526	1.579	1.575	1.553	1.599	1.533	1.468	1.343	1.329
13	1.528	1.552	1.611	1.606	1.592	1.649	1.588	1.520	1.393	1.397
12	1.547	1.577	1.646	1.638	1.631	1.698	1.642	1.565	1.442	1.465
11	1.553	1.587	1.669	1.658	1.659	1.736	1.685	1.600	1.480	1.524
10	1.523	1.552	1.650	1.643	1.654	1.733	1.692	1.608	1.494	1.570
09	1.426	1.436	1.548	1.560	1.581	1.647	1.616	1.557	1.462	1.579
08	1.238	1.184	1.289	1.370	1.401	1.388	1.377	1.414	1.363	1.530
07	.973	.756	.826	1.083	1.117	.904	.905	1.174	1.196	1.409

06	.737	.517	.568	.820	.850	.632	.643	.942	1.000	1.234
05	.546	.374	.411	.610	.632	.462	.478	.744	.809	1.036
04	.405	.276	.302	.448	.464	.342	.357	.571	.632	.840
03	.305	.208	.224	.329	.337	.252	.263	.419	.467	.644
02	.231	.156	.164	.233	.236	.183	.192	.307	.341	.463
01	.159	.107	.109	.153	.153	.121	.128	.206	.226	.273
*****	=7	*****								
24	.484	.486	.444	.462	.419	.432	.383	.385	.325	
23	.845	.832	.790	.802	.746	.751	.685	.670	.585	
22	1.091	1.067	1.069	1.038	1.013	.974	.935	.876	.805	
21	1.254	1.230	1.281	1.204	1.220	1.135	1.132	1.027	.983	
20	1.364	1.342	1.436	1.322	1.372	1.252	1.282	1.141	1.124	
19	1.438	1.419	1.548	1.405	1.487	1.338	1.397	1.227	1.235	
18	1.485	1.468	1.625	1.462	1.571	1.402	1.489	1.295	1.326	
17	1.507	1.494	1.673	1.499	1.633	1.451	1.563	1.352	1.404	
16	1.508	1.498	1.694	1.519	1.679	1.492	1.626	1.403	1.476	
15	1.495	1.485	1.697	1.529	1.716	1.528	1.684	1.452	1.545	
14	1.481	1.474	1.705	1.541	1.753	1.564	1.742	1.500	1.612	
13	1.476	1.473	1.727	1.557	1.796	1.601	1.802	1.548	1.681	
12	1.472	1.475	1.758	1.576	1.842	1.633	1.863	1.589	1.749	
11	1.454	1.465	1.783	1.586	1.882	1.657	1.917	1.622	1.809	
10	1.407	1.421	1.787	1.565	1.903	1.650	1.951	1.628	1.851	
09	1.304	1.316	1.735	1.484	1.874	1.579	1.933	1.577	1.855	
08	1.135	1.138	1.578	1.320	1.750	1.408	1.808	1.444	1.788	
07	.922	.900	1.303	1.087	1.512	1.138	1.537	1.227	1.624	
06	.722	.692	1.029	.849	1.221	.873	1.229	.986	1.388	
05	.553	.523	.796	.647	.942	.658	.946	.764	1.121	
04	.423	.396	.601	.481	.706	.485	.706	.548	.829	
03	.327	.302	.443	.339	.488	.349	.494	.320	.478	
02	.252	.228	.307	.195	.264	.241	.337	.206	.300	
01	.176	.157	.182	.115	.139	.155	.199	.133	.176	
*****	=8	*****								
24	.511	.511	.506	.494	.475	.462	.438	.410		
23	.886	.893	.866	.844	.814	.789	.759	.729		
22	1.139	1.156	1.114	1.082	1.048	1.015	.985	.965		
21	1.310	1.332	1.289	1.249	1.215	1.175	1.148	1.128		
20	1.427	1.451	1.411	1.364	1.333	1.290	1.266	1.246		
19	1.503	1.530	1.495	1.445	1.416	1.372	1.352	1.332		
18	1.546	1.576	1.546	1.496	1.472	1.430	1.415	1.398		
17	1.556	1.587	1.565	1.521	1.507	1.472	1.464	1.450		
16	1.530	1.553	1.541	1.519	1.525	1.502	1.504	1.494		
15	1.474	1.468	1.467	1.495	1.533	1.525	1.539	1.535		
14	1.423	1.404	1.416	1.476	1.541	1.548	1.574	1.575		
13	1.392	1.371	1.394	1.471	1.553	1.571	1.610	1.616		
12	1.371	1.349	1.384	1.471	1.567	1.594	1.641	1.649		
11	1.342	1.318	1.367	1.464	1.575	1.607	1.665	1.677		
10	1.286	1.260	1.320	1.427	1.554	1.590	1.661	1.674		
09	1.186	1.158	1.225	1.337	1.479	1.514	1.600	1.618		
08	1.041	1.009	1.077	1.187	1.329	1.355	1.448	1.476		
07	.867	.831	.890	.988	1.111	1.114	1.200	1.247		

06	.696	.660	.706	.782	.869	.838	.906	.985
05	.544	.511	.542	.598	.658	.619	.670	.751
04	.422	.394	.412	.449	.487	.452	.484	.532
03	.329	.305	.310	.319	.341	.326	.338	.308
02	.255	.233	.223	.186	.195	.226	.236	.196
01	.178	.161	.148	.111	.115	.147	.155	.126

***** I=9 *****

24	.498	.554	.514	.513	.463	.478	.432
23	.885	.948	.917	.885	.823	.835	.770
22	1.196	1.221	1.244	1.141	1.115	1.087	1.049
21	1.428	1.415	1.494	1.320	1.335	1.262	1.264
20	1.596	1.553	1.682	1.445	1.496	1.385	1.424
19	1.711	1.652	1.820	1.529	1.610	1.471	1.543
18	1.778	1.715	1.913	1.580	1.685	1.529	1.629
17	1.794	1.729	1.954	1.596	1.728	1.567	1.693
16	1.746	1.616	1.849	1.570	1.742	1.589	1.741
15	1.628	1.215	1.386	1.494	1.737	1.602	1.782
14	1.542	1.042	1.207	1.440	1.735	1.616	1.824
13	1.497	.984	1.168	1.416	1.748	1.633	1.872
12	1.477	.947	1.159	1.404	1.771	1.655	1.927
11	1.463	.906	1.148	1.387	1.791	1.670	1.979
10	1.434	.852	1.113	1.344	1.797	1.655	2.018
09	1.369	.777	1.042	1.257	1.761	1.581	2.010
08	1.253	.680	.936	1.117	1.648	1.416	1.889
07	1.091	.566	.799	.936	1.429	1.123	1.554
06	.911	.452	.645	.743	1.125	.693	.960
05	.737	.353	.502	.570	.859	.462	.645
04	.579	.275	.385	.431	.645	.332	.457
03	.451	.214	.291	.324	.473	.242	.323
02	.339	.164	.211	.233	.327	.174	.224
01	.210	.113	.130	.155	.193	.115	.135

***** I=10 *****

24	.549	.569	.558	.522	.511	.495
23	.927	.971	.962	.918	.873	.870
22	1.180	1.241	1.239	1.193	1.123	1.134
21	1.354	1.429	1.435	1.377	1.299	1.313
20	1.472	1.561	1.574	1.501	1.420	1.435
19	1.549	1.653	1.672	1.582	1.501	1.518
18	1.589	1.707	1.734	1.628	1.551	1.572
17	1.589	1.717	1.748	1.637	1.573	1.601
16	1.533	1.599	1.638	1.602	1.568	1.611
15	1.412	1.197	1.237	1.515	1.545	1.609
14	1.319	1.019	1.066	1.451	1.525	1.608
13	1.260	.952	1.011	1.417	1.513	1.611
12	1.216	.907	.975	1.395	1.509	1.620
11	1.170	.861	.936	1.369	1.501	1.622
10	1.104	.804	.881	1.319	1.469	1.597
09	1.008	.728	.806	1.230	1.391	1.515
08	.887	.635	.709	1.094	1.250	1.350
07	.750	.527	.593	.920	1.046	1.070

06	.608	.420	.471	.736	.805	.665
05	.478	.329	.366	.571	.608	.446
04	.375	.256	.283	.439	.458	.325
03	.296	.201	.219	.339	.347	.242
02	.232	.156	.168	.258	.260	.180
01	.163	.110	.116	.177	.176	.121

***** I=11 *****

24	.549	.549	.507	.530	.487
23	.921	.928	.898	.906	.864
22	1.165	1.180	1.208	1.163	1.168
21	1.329	1.351	1.437	1.341	1.393
20	1.438	1.466	1.600	1.461	1.555
19	1.506	1.540	1.710	1.539	1.665
18	1.541	1.579	1.774	1.582	1.732
17	1.544	1.582	1.793	1.593	1.761
16	1.510	1.540	1.759	1.570	1.758
15	1.442	1.442	1.667	1.520	1.733
14	1.382	1.368	1.601	1.474	1.711
13	1.337	1.320	1.569	1.445	1.703
12	1.298	1.283	1.552	1.425	1.707
11	1.254	1.240	1.541	1.402	1.710
10	1.188	1.177	1.516	1.357	1.702
09	1.088	1.079	1.455	1.273	1.659
08	.956	.948	1.338	1.140	1.554
07	.803	.795	1.160	.965	1.368
06	.645	.633	.949	.776	1.123
05	.501	.489	.754	.605	.887
04	.390	.379	.585	.466	.689
03	.308	.297	.453	.362	.526
02	.243	.232	.340	.279	.390
01	.173	.164	.212	.193	.242

***** I=12 *****

24	.536	.542	.535	.532
23	.914	.913	.918	.920
22	1.161	1.157	1.175	1.181
21	1.326	1.322	1.349	1.355
20	1.435	1.432	1.467	1.471
19	1.504	1.501	1.542	1.545
18	1.540	1.538	1.582	1.584
17	1.550	1.549	1.593	1.593
16	1.536	1.532	1.575	1.573
15	1.505	1.496	1.536	1.533
14	1.472	1.457	1.498	1.492
13	1.446	1.429	1.471	1.464
12	1.424	1.405	1.452	1.442
11	1.394	1.373	1.426	1.415
10	1.340	1.316	1.378	1.365
09	1.246	1.218	1.288	1.276
08	1.105	1.073	1.144	1.137
07	.922	.884	.948	.955

06	.726	.675	.725	.757
05	.556	.505	.546	.586
04	.427	.385	.416	.451
03	.334	.300	.324	.353
02	.261	.235	.252	.276
01	.183	.166	.176	.194

***** l=13 *****

24	.494	.535	.502
23	.868	.898	.884
22	1.163	1.143	1.187
21	1.378	1.311	1.408
20	1.530	1.423	1.565
19	1.631	1.496	1.671
18	1.693	1.540	1.735
17	1.726	1.560	1.767
16	1.737	1.561	1.772
15	1.735	1.550	1.761
14	1.731	1.535	1.751
13	1.732	1.525	1.750
12	1.738	1.515	1.757
11	1.740	1.497	1.768
10	1.731	1.451	1.764
09	1.683	1.353	1.712
08	1.565	1.191	1.568
07	1.346	.938	1.271
06	1.051	.578	.788
05	.802	.387	.530
04	.609	.285	.390
03	.466	.219	.297
02	.347	.168	.222
01	.214	.117	.140

***** l=14 *****

24	.531	.536
23	.885	.896
22	1.118	1.132
21	1.276	1.292
20	1.380	1.398
19	1.446	1.466
18	1.487	1.508
17	1.508	1.529
16	1.515	1.535
15	1.512	1.531
14	1.504	1.522
13	1.496	1.514
12	1.484	1.504
11	1.462	1.481
10	1.412	1.428
09	1.315	1.322
08	1.161	1.157
07	.953	.905

283

24 .532

22 1.113

21 1.264

20 1.362

19	1.425
10	1.468

18	1.463
17	1.423

17	1.483
16	1.482

16	1.490
15	1.480

15	1.489
14	1.481

14	1.481
13	1.472

13	1.472
12	1.458

11 1.431

10 1.374

09 1.271

08 1.118

07 .922

06 .714

05 .535

04	.404
03	.313

03	.313
02	244

02	.244
01	173

01 .173
AVERAGE

1 9.042 8.121 8.582 7.953 8.631 7.842 13.835

2 4.857 4.859 8.509 4.793 8.321 4.282 8.239 8.552

3 13.753 14.506 5.534 12.566 5.388 13.448 4.668 16.314 14.521 12.336

4 15.611 17.656 16.475 16.346 16.379 13.087 15.020 4.822 9.807 7.696

5	6.053	17.250	6.040	17.746	6.002	15.789	5.725	15.141	4.887	11.884	15.043

6 17.096 17.774 16.689 14.608 17.537 14.353 17.664 13.759 16.599 4.861

7	15.585	17.683	6.232	17.208	6.263	17.460	6.134	17.711	5.764
8	16.025	15.713	17.820	17.810	18.060	18.025	17.540	18.620	

8	16.925	15.713	17.889	17.810	18.060	18.025	17.540	14.629
9	6.316	18.055	6.313	17.108	6.105	16.173	6.383	

9	6.316	18.055	6.343	17.498	6.405	16.473	6.392
10	18.134	17.867	17.832	14.000	18.100	15.303	

10	18.134	17.887	17.832	14.990	18.100	15.302
11	18.079	18.014	6.317	18.035	6.436	

11	18.079	18.014	8.317	18.039	8.438
12	17.042	17.834	17.154	16.423	

12	17.042	17.034	17.134	10.423
13	6.254	18.316	6.285	

13	0.254	10.310	0.205
14	18.282	17.912	

15 17.879

EXPOSURE

EXPOSURE BY NODE, REXP(I,J,K)MWD/KGU

***** I=1 *****

24 1.786 1.627 1.731 1.558 1.656 1.481 3.716

23	3.250	2.971	3.156	2.852	3.027	2.715	6.660
22	4.589	4.187	4.464	4.032	4.291	3.853	8.991
21	5.746	5.230	5.591	5.050	5.393	4.847	10.717
20	6.694	6.085	6.512	5.893	6.307	5.677	11.971
19	7.442	6.764	7.234	6.567	7.036	6.348	12.897
18	8.036	7.295	7.792	7.100	7.615	6.883	13.588
17	8.517	7.718	8.238	7.524	8.085	7.319	14.119
16	8.919	8.071	8.608	7.878	8.481	7.686	14.542
15	9.266	8.379	8.929	8.188	8.828	8.011	14.895
14	9.581	8.663	9.217	8.476	9.147	8.314	15.204
13	9.882	8.936	9.489	8.752	9.451	8.608	15.485
12	10.182	9.207	9.755	9.031	9.754	8.904	15.745
11	10.492	9.485	10.026	9.316	10.066	9.210	16.004
10	10.819	9.779	10.311	9.613	10.395	9.532	16.252
09	11.163	10.084	10.602	9.925	10.744	9.866	16.476
08	11.521	10.417	10.915	10.262	11.096	10.223	16.691
07	11.900	10.760	11.236	10.608	11.475	10.593	16.878
06	12.289	11.081	11.540	10.929	11.844	10.923	16.982
05	12.594	11.301	11.756	11.141	12.117	11.132	16.958
04	12.651	11.250	11.734	11.076	12.131	11.062	16.686
03	12.127	10.639	11.174	10.452	11.580	10.442	15.918
02	10.524	9.033	9.583	8.845	9.982	8.830	14.190
01	7.046	5.951	6.373	5.800	6.633	5.747	10.479

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24	.877	.871	1.658	.830	1.611	.733	1.651	1.756
23	1.603	1.593	3.039	1.525	2.953	1.355	3.035	3.198
22	2.253	2.242	4.293	2.160	4.180	1.924	4.288	4.506
21	2.803	2.795	5.373	2.709	5.240	2.417	5.362	5.622
20	3.257	3.254	6.267	3.170	6.120	2.830	6.246	6.526
19	3.627	3.630	6.984	3.548	6.824	3.171	6.952	7.236
18	3.933	3.939	7.552	3.860	7.383	3.454	7.508	7.792
17	4.192	4.200	8.014	4.124	7.835	3.695	7.956	8.238
16	4.422	4.432	8.407	4.358	8.222	3.911	8.333	8.605
15	4.631	4.642	8.756	4.573	8.568	4.114	8.667	8.923
14	4.831	4.845	9.080	4.780	8.893	4.314	8.973	9.211
13	5.035	5.049	9.388	4.989	9.208	4.518	9.261	9.481
12	5.251	5.266	9.691	5.208	9.514	4.728	9.548	9.745
11	5.488	5.502	10.011	5.446	9.833	4.952	9.840	10.015
10	5.755	5.766	10.345	5.710	10.160	5.188	10.134	10.289
09	6.041	6.046	10.696	5.992	10.508	5.456	10.438	10.571
08	6.355	6.355	11.064	6.302	10.866	5.751	10.739	10.860
07	6.692	6.688	11.426	6.635	11.210	6.058	11.011	11.164
06	7.047	7.036	11.740	6.980	11.498	6.340	11.209	11.449
05	7.363	7.349	11.912	7.285	11.638	6.541	11.252	11.637
04	7.506	7.493	11.774	7.421	11.479	6.557	11.001	11.586
03	7.261	7.255	11.070	7.177	10.775	6.215	10.223	11.017
02	6.274	6.282	9.417	6.213	9.143	5.215	8.558	9.506
01	4.066	4.082	6.245	4.040	6.034	3.334	5.564	6.307

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24	3.162	3.387	1.110	2.695	1.035	2.902	.875	4.889	4.104	3.010

23	5.770	6.180	2.017	4.950	1.892	5.335	1.608	8.595	7.303	5.483
22	7.987	8.541	2.806	6.932	2.649	7.470	2.258	11.305	9.749	7.582
21	9.752	10.391	3.455	8.549	3.280	9.208	2.800	13.217	11.518	9.188
20	11.099	11.784	3.976	9.828	3.790	10.554	3.242	14.581	12.789	10.386
19	12.115	12.842	4.389	10.822	4.199	11.582	3.600	15.560	13.712	11.268
18	12.908	13.652	4.717	11.599	4.529	12.387	3.894	16.279	14.394	11.934
17	13.545	14.289	4.989	12.215	4.801	13.040	4.143	16.826	14.911	12.454
16	14.068	14.819	5.226	12.734	5.039	13.588	4.365	17.262	15.320	12.876
15	14.522	15.280	5.442	13.191	5.259	14.067	4.570	17.621	15.659	13.236
14	14.934	15.704	5.649	13.607	5.471	14.510	4.766	17.933	15.954	13.557
13	15.326	16.107	5.855	14.001	5.684	14.936	4.965	18.217	16.221	13.853
12	15.704	16.501	6.060	14.396	5.905	15.353	5.173	18.483	16.472	14.140
11	16.068	16.888	6.273	14.791	6.130	15.759	5.398	18.733	16.716	14.418
10	16.438	17.257	6.501	15.186	6.371	16.176	5.641	18.976	16.950	14.672
09	16.811	17.647	6.747	15.566	6.630	16.601	5.897	19.193	17.167	14.923
08	17.163	18.024	7.011	15.938	6.906	17.011	6.172	19.369	17.356	15.158
07	17.467	18.357	7.309	16.275	7.216	17.376	6.451	19.515	17.527	15.346
06	17.707	18.610	7.627	16.547	7.542	17.665	6.708	19.575	17.618	15.450
05	17.786	18.707	7.926	16.653	7.835	17.775	6.893	19.489	17.575	15.435
04	17.559	18.479	8.095	16.435	7.985	17.552	6.899	19.157	17.290	15.166
03	16.748	17.654	7.906	15.609	7.767	16.713	6.554	18.282	16.505	14.430
02	14.800	15.661	6.989	13.617	6.820	14.703	5.552	16.325	14.745	12.783
01	10.622	11.374	4.739	9.456	4.581	10.477	3.607	12.148	10.954	9.313

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24	4.039	5.474	4.419	4.339	4.206	2.955	3.605	.950	2.057	1.579
23	7.273	9.548	7.900	7.774	7.571	5.414	6.566	1.740	3.756	2.893
22	9.874	12.487	10.634	10.491	10.278	7.531	9.093	2.429	5.273	4.075
21	11.819	14.541	12.653	12.501	12.299	9.223	10.933	2.996	6.548	5.077
20	13.256	15.990	14.123	13.969	13.786	10.525	12.357	3.451	7.558	5.887
19	14.311	17.019	15.210	15.056	14.892	11.518	13.426	3.814	8.345	6.524
18	15.110	17.769	16.030	15.878	15.731	12.277	14.243	4.111	8.969	7.021
17	15.734	18.331	16.664	16.516	16.388	12.883	14.891	4.360	9.468	7.416
16	16.239	18.774	17.177	17.031	16.923	13.391	15.427	4.577	9.882	7.742
15	16.669	19.137	17.609	17.467	17.380	13.841	15.892	4.775	10.245	8.028
14	17.050	19.448	17.991	17.853	17.789	14.252	16.312	4.966	10.577	8.293
13	17.407	19.722	18.342	18.208	18.169	14.627	16.714	5.160	10.891	8.547
12	17.751	19.971	18.681	18.553	18.541	14.997	17.106	5.363	11.207	8.800
11	18.082	20.206	19.012	18.889	18.909	15.366	17.492	5.581	11.529	9.061
10	18.388	20.420	19.324	19.206	19.263	15.730	17.853	5.816	11.857	9.330
09	18.698	20.614	19.616	19.500	19.602	16.088	18.228	6.055	12.186	9.598
08	19.000	20.768	19.910	19.795	19.944	16.419	18.592	6.310	12.510	9.888
07	19.253	20.900	20.164	20.047	20.254	16.715	18.906	6.568	12.823	10.178
06	19.409	20.940	20.323	20.200	20.468	16.927	19.117	6.807	13.088	10.426
05	19.435	20.833	20.340	20.209	20.531	16.972	19.173	6.977	13.234	10.555
04	19.155	20.478	20.063	19.924	20.289	16.705	18.896	6.974	13.106	10.410
03	18.309	19.580	19.206	19.069	19.446	15.880	18.022	6.628	12.422	9.760
02	16.347	17.580	17.209	17.093	17.437	13.950	15.999	5.637	10.693	8.223
01	12.059	13.204	12.810	12.747	13.003	9.897	11.682	3.687	7.157	5.382

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24	1.498	4.954	1.481	5.397	1.410	4.035	1.256	3.716	.981	2.575	4.574

23	2.671	8.757	2.644	9.442	2.531	7.278	2.273	6.746	1.794	4.746	8.042
22	3.630	11.631	3.597	12.400	3.463	9.902	3.134	9.252	2.502	6.669	10.597
21	4.370	13.708	4.334	14.486	4.195	11.873	3.822	11.164	3.082	8.243	12.385
20	4.917	15.194	4.883	15.968	4.748	13.333	4.357	12.596	3.544	9.472	13.649
19	5.329	16.274	5.297	17.026	5.167	14.408	4.766	13.663	3.911	10.407	14.544
18	5.645	17.072	5.617	17.797	5.494	15.224	5.089	14.475	4.207	11.126	15.191
17	5.895	17.681	5.870	18.378	5.757	15.862	5.355	15.115	4.454	11.703	15.672
16	6.098	18.163	6.076	18.834	5.974	16.378	5.583	15.640	4.667	12.190	16.045
15	6.273	18.565	6.254	19.208	6.163	16.823	5.789	16.091	4.861	12.621	16.348
14	6.430	18.914	6.414	19.529	6.336	17.215	5.978	16.498	5.049	13.011	16.607
13	6.577	19.229	6.564	19.814	6.498	17.582	6.160	16.884	5.239	13.377	16.833
12	6.721	19.524	6.712	20.072	6.658	17.937	6.343	17.260	5.438	13.725	17.037
11	6.867	19.812	6.861	20.319	6.821	18.282	6.529	17.627	5.652	14.084	17.229
10	7.019	20.081	7.016	20.547	6.991	18.607	6.726	17.967	5.883	14.438	17.411
09	7.184	20.331	7.182	20.753	7.173	18.927	6.936	18.318	6.111	14.775	17.574
08	7.359	20.559	7.358	20.927	7.368	19.245	7.157	18.658	6.359	15.076	17.699
07	7.544	20.760	7.542	21.080	7.570	19.519	7.401	18.944	6.610	15.327	17.816
06	7.753	20.872	7.748	21.145	7.796	19.699	7.655	19.132	6.845	15.482	17.861
05	7.952	20.837	7.944	21.066	8.013	19.747	7.884	19.169	7.015	15.473	17.777
04	8.045	20.533	8.034	20.730	8.122	19.484	7.985	18.878	7.013	15.175	17.469
03	7.822	19.663	7.813	19.834	7.912	18.638	7.747	17.995	6.669	14.343	16.671
02	6.927	17.657	6.934	17.806	7.034	16.648	6.825	15.964	5.679	12.489	14.901
01	4.738	13.231	4.775	13.351	4.854	12.286	4.645	11.641	3.718	8.681	11.098

i=6 *****

24	4.917	5.663	4.706	3.709	5.208	3.597	5.350	3.304	4.579	.994
23	8.697	9.837	8.354	6.684	9.157	6.500	9.371	6.008	8.158	1.813
22	11.564	12.830	11.164	9.101	12.090	8.875	12.317	8.265	10.913	2.522
21	13.638	14.904	13.211	10.958	14.187	10.705	14.396	10.035	12.928	3.099
20	15.116	16.356	14.679	12.335	15.681	12.067	15.876	11.371	14.385	3.558
19	16.188	17.379	15.747	13.356	16.755	13.079	16.932	12.368	15.457	3.921
18	16.980	18.112	16.537	14.136	17.540	13.853	17.703	13.133	16.257	4.214
17	17.582	18.657	17.139	14.743	18.133	14.461	18.283	13.743	16.873	4.458
16	18.057	19.076	17.615	15.228	18.599	14.948	18.740	14.248	17.369	4.667
15	18.453	19.413	18.009	15.642	18.981	15.365	19.116	14.677	17.786	4.858
14	18.795	19.696	18.352	16.011	19.308	15.739	19.440	15.064	18.153	5.042
13	19.102	19.940	18.661	16.357	19.600	16.085	19.727	15.427	18.493	5.227
12	19.388	20.155	18.954	16.684	19.866	16.415	19.989	15.765	18.819	5.422
11	19.666	20.352	19.234	16.988	20.125	16.722	20.239	16.103	19.139	5.631
10	19.919	20.523	19.494	17.294	20.361	17.033	20.469	16.433	19.442	5.854
09	20.148	20.663	19.718	17.586	20.565	17.326	20.678	16.762	19.724	6.075
08	20.361	20.764	19.946	17.858	20.753	17.600	20.854	17.063	19.998	6.314
07	20.537	20.835	20.131	18.081	20.914	17.823	21.009	17.313	20.234	6.556
06	20.616	20.810	20.222	18.232	20.983	17.977	21.074	17.485	20.371	6.778
05	20.551	20.647	20.183	18.238	20.913	17.980	20.995	17.489	20.354	6.934
04	20.226	20.248	19.860	17.958	20.580	17.697	20.655	17.191	20.041	6.920
03	19.358	19.332	18.984	17.134	19.689	16.865	19.752	16.328	19.138	6.570
02	17.393	17.354	16.996	15.216	17.672	14.947	17.716	14.374	17.089	5.582
01	13.053	13.032	12.637	11.068	13.235	10.819	13.262	10.267	12.680	3.655

i=7 *****

24	4.299	5.540	1.685	4.996	1.628	5.163	1.515	5.405	1.308

23	7.672	9.657	2.984	8.819	2.891	9.082	2.702	9.453	2.355
22	10.316	12.640	4.022	11.712	3.913	12.002	3.675	12.409	3.226
21	12.262	14.729	4.795	13.806	4.689	14.099	4.430	14.491	3.923
20	13.675	16.194	5.355	15.298	5.258	15.593	4.991	15.970	4.460
19	14.700	17.229	5.762	16.379	5.678	16.669	5.412	17.023	4.868
18	15.455	17.974	6.056	17.172	5.988	17.457	5.735	17.789	5.189
17	16.032	18.526	6.278	17.769	6.225	18.051	5.987	18.365	5.451
16	16.494	18.952	6.453	18.239	6.415	18.518	6.192	18.818	5.675
15	16.876	19.295	6.598	18.625	6.574	18.901	6.369	19.189	5.875
14	17.209	19.583	6.726	18.957	6.715	19.229	6.526	19.507	6.055
13	17.515	19.833	6.842	19.252	6.846	19.521	6.674	19.788	6.229
12	17.801	20.055	6.953	19.524	6.971	19.789	6.819	20.043	6.404
11	18.069	20.262	7.062	19.788	7.096	20.048	6.965	20.287	6.582
10	18.300	20.441	7.174	20.030	7.225	20.288	7.115	20.509	6.768
09	18.533	20.593	7.292	20.238	7.359	20.489	7.277	20.710	6.967
08	18.742	20.706	7.416	20.438	7.506	20.679	7.448	20.877	7.174
07	18.892	20.789	7.550	20.603	7.658	20.840	7.625	21.023	7.402
06	18.945	20.778	7.705	20.675	7.839	20.908	7.830	21.080	7.639
05	18.864	20.630	7.852	20.611	8.015	20.837	8.027	20.993	7.848
04	18.503	20.243	7.902	20.279	8.096	20.502	8.122	20.647	7.930
03	17.630	19.338	7.660	19.391	7.875	19.610	7.906	19.740	7.678
02	15.706	17.364	6.785	17.392	7.003	17.597	7.028	17.703	6.749
01	11.562	13.035	4.666	12.995	4.839	13.173	4.854	13.250	4.581

***** I=8 *****

24	4.918	4.281	5.655	5.614	5.568	5.775	5.219	3.689
23	8.692	7.637	9.833	9.766	9.710	10.010	9.170	6.666
22	11.560	10.280	12.853	12.769	12.734	13.041	12.106	9.093
21	13.627	12.243	14.961	14.870	14.864	15.144	14.209	10.960
20	15.092	13.676	16.440	16.345	16.367	16.614	15.706	12.346
19	16.146	14.724	17.479	17.385	17.433	17.646	16.782	13.379
18	16.918	15.498	18.223	18.131	18.204	18.384	17.567	14.167
17	17.498	16.090	18.772	18.684	18.779	18.930	18.158	14.777
16	17.953	16.567	19.192	19.107	19.224	19.348	18.621	15.269
15	18.327	16.963	19.527	19.447	19.586	19.683	19.000	15.690
14	18.650	17.308	19.808	19.731	19.893	19.962	19.324	16.067
13	18.937	17.627	20.050	19.977	20.163	20.201	19.611	16.420
12	19.205	17.927	20.263	20.194	20.407	20.410	19.874	16.755
11	19.461	18.211	20.462	20.395	20.638	20.604	20.128	17.065
10	19.692	18.464	20.636	20.572	20.854	20.773	20.361	17.376
09	19.896	18.714	20.784	20.718	21.044	20.914	20.558	17.670
08	20.093	18.946	20.898	20.828	21.199	21.017	20.741	17.941
07	20.248	19.120	20.986	20.910	21.341	21.096	20.898	18.154
06	20.308	19.194	20.986	20.899	21.400	21.085	20.963	18.286
05	20.235	19.136	20.851	20.751	21.311	20.934	20.890	18.259
04	19.897	18.793	20.470	20.360	20.979	20.545	20.555	17.937
03	19.022	17.925	19.553	19.445	20.091	19.628	19.663	17.067
02	17.066	15.991	17.535	17.452	18.064	17.623	17.649	15.112
01	12.757	11.797	13.128	13.099	13.594	13.241	13.216	10.961

***** I=9 *****

24	1.788	5.827	1.783	5.259	1.747	4.568	1.664

23	3.150	10.090	3.144	9.229	3.090	8.127	2.959
22	4.231	13.145	4.225	12.184	4.168	10.912	4.014
21	5.021	15.258	5.018	14.299	4.969	12.955	4.812
20	5.585	16.729	5.587	15.792	5.549	14.439	5.397
19	5.981	17.754	5.987	16.863	5.963	15.513	5.826
18	6.259	18.482	6.270	17.636	6.259	16.307	6.137
17	6.461	19.015	6.477	18.212	6.479	16.911	6.373
16	6.616	19.419	6.637	18.659	6.650	17.388	6.559
15	6.743	19.740	6.767	19.021	6.791	17.782	6.716
14	6.850	20.006	6.878	19.327	6.913	18.124	6.854
13	6.947	20.232	6.978	19.595	7.023	18.434	6.981
12	7.038	20.429	7.072	19.837	7.128	18.730	7.104
11	7.128	20.611	7.164	20.072	7.231	19.012	7.225
10	7.220	20.770	7.257	20.285	7.333	19.275	7.346
09	7.319	20.904	7.357	20.460	7.443	19.502	7.476
08	7.427	20.999	7.467	20.624	7.567	19.736	7.619
07	7.547	21.074	7.585	20.759	7.699	19.925	7.771
06	7.692	21.062	7.729	20.802	7.861	20.023	7.956
05	7.831	20.913	7.867	20.711	8.024	19.994	8.146
04	7.871	20.524	7.909	20.360	8.098	19.673	8.248
03	7.613	19.601	7.659	19.460	7.876	18.795	8.049
02	6.704	17.576	6.771	17.452	7.005	16.799	7.189
01	4.552	13.163	4.641	13.048	4.842	12.436	4.994

***** I=10 *****

24	5.959	5.704	5.516	4.019	5.767	4.055
23	10.282	9.900	9.630	7.194	10.012	7.269
22	13.345	12.921	12.642	9.715	13.073	9.838
21	15.450	15.022	14.766	11.621	15.202	11.779
20	16.903	16.487	16.255	13.008	16.690	13.197
19	17.911	17.512	17.306	14.027	17.731	14.242
18	18.624	18.244	18.059	14.787	18.474	15.016
17	19.144	18.782	18.618	15.360	19.018	15.602
16	19.537	19.192	19.048	15.815	19.431	16.074
15	19.848	19.519	19.393	16.199	19.760	16.470
14	20.104	19.792	19.683	16.537	20.033	16.820
13	20.320	20.027	19.937	16.848	20.267	17.144
12	20.507	20.234	20.165	17.139	20.471	17.451
11	20.676	20.425	20.382	17.405	20.662	17.743
10	20.821	20.590	20.578	17.665	20.835	18.012
09	20.942	20.731	20.755	17.912	20.972	18.277
08	21.021	20.830	20.895	18.135	21.081	18.528
07	21.076	20.904	21.021	18.304	21.173	18.729
06	21.046	20.887	21.059	18.391	21.181	18.845
05	20.874	20.729	20.957	18.329	21.055	18.819
04	20.479	20.341	20.608	17.985	20.685	18.502
03	19.564	19.436	19.712	17.117	19.772	17.645
02	17.569	17.460	17.698	15.180	17.745	15.695
01	13.214	13.139	13.278	11.062	13.301	11.492

***** I=11 *****

24	5.990	5.818	1.831	5.610	1.805

23	10.324	10.074	3.221	9.782	3.187
22	13.380	13.120	4.314	12.827	4.290
21	15.473	15.225	5.105	14.965	5.099
20	16.914	16.688	5.667	16.463	5.679
19	17.910	17.708	6.054	17.518	6.083
18	18.615	18.433	6.324	18.274	6.368
17	19.127	18.965	6.518	18.832	6.575
16	19.514	19.368	6.666	19.260	6.734
15	19.819	19.689	6.784	19.604	6.862
14	20.068	19.955	6.883	19.893	6.971
13	20.278	20.184	6.970	20.146	7.069
12	20.459	20.383	7.051	20.372	7.161
11	20.616	20.566	7.131	20.587	7.250
10	20.753	20.724	7.212	20.786	7.340
09	20.860	20.859	7.298	20.959	7.437
08	20.924	20.952	7.387	21.099	7.549
07	20.958	21.020	7.496	21.228	7.669
06	20.905	21.000	7.623	21.273	7.821
05	20.712	20.838	7.738	21.176	7.973
04	20.307	20.451	7.755	20.836	8.035
03	19.398	19.546	7.487	19.945	7.803
02	17.436	17.561	6.593	17.922	6.927
01	13.148	13.221	4.499	13.471	4.775

***** l=12 *****

24	5.201	5.843	5.186	4.770
23	9.113	10.101	9.104	8.436
22	12.009	13.130	12.022	11.244
21	14.072	15.217	14.105	13.269
20	15.518	16.663	15.568	14.719
19	16.548	17.665	16.610	15.754
18	17.289	18.375	17.360	16.508
17	17.838	18.890	17.914	17.072
16	18.261	19.278	18.342	17.511
15	18.602	19.583	18.687	17.868
14	18.888	19.832	18.977	18.171
13	19.136	20.042	19.230	18.442
12	19.364	20.222	19.463	18.697
11	19.578	20.385	19.682	18.934
10	19.761	20.519	19.876	19.143
09	19.915	20.622	20.041	19.326
08	20.056	20.687	20.200	19.504
07	20.150	20.719	20.319	19.631
06	20.146	20.658	20.346	19.662
05	20.012	20.464	20.243	19.571
04	19.620	20.039	19.874	19.201
03	18.707	19.107	18.965	18.304
02	16.745	17.129	16.965	16.338
01	12.485	12.844	12.621	12.090

***** l=13 *****

24	1.835	6.071	1.840

23	3.217	10.451	3.228
22	4.300	13.540	4.316
21	5.080	15.661	5.101
20	5.633	17.117	5.658
19	6.012	18.122	6.040
18	6.275	18.831	6.305
17	6.462	19.343	6.494
16	6.603	19.729	6.637
15	6.715	20.033	6.750
14	6.808	20.280	6.845
13	6.891	20.490	6.929
12	6.969	20.671	7.008
11	7.046	20.835	7.085
10	7.127	20.980	7.165
09	7.216	21.104	7.252
08	7.309	21.190	7.343
07	7.426	21.258	7.456
06	7.559	21.244	7.585
05	7.679	21.086	7.701
04	7.693	20.699	7.716
03	7.406	19.777	7.437
02	6.477	17.747	6.529
01	4.354	13.316	4.430

***** l=14 *****

24	6.141	5.994
23	10.539	10.313
22	13.618	13.353
21	15.722	15.432
20	17.162	16.862
19	18.152	17.846
18	18.850	18.539
17	19.354	19.038
16	19.734	19.412
15	20.031	19.703
14	20.273	19.938
13	20.476	20.133
12	20.651	20.299
11	20.804	20.444
10	20.938	20.563
09	21.047	20.650
08	21.115	20.698
07	21.155	20.715
06	21.112	20.638
05	20.924	20.427
04	20.521	19.990
03	19.600	19.049
02	17.601	17.065
01	13.253	12.789

***** l=15 *****

24	6.049

23 10.387
 22 13.419
 21 15.485
 20 16.899
 19 17.870
 18 18.552
 17 19.044
 16 19.411
 15 19.696
 14 19.925
 13 20.113
 12 20.271
 11 20.401
 10 20.514
 09 20.590
 08 20.618
 07 20.612
 06 20.511
 05 20.279
 04 19.835
 03 18.905
 02 16.957
 01 12.740

.1728	.2691	.3684	.4909	.6488	.8495	1.0689	1.2736	1.3916	1.4364
1.4355	1.4129	1.3839	1.3578	1.3420	1.3389	1.3127	1.2675	1.2041	1.1184
1.0033	.8484	.6403	.3645						

(4) OUTPUT

1

SAMPLE TEST FOR PEACH BOTTOM UNIT 2 AT EOC

OSYSTEM PARAMETERS

P = SYSTEM PRESSURE (PSIA) = 1023.00
TIN = INLET TEMPERATURE (DEG-F) = 530.50
SATURATION TEMPERATURE CORRESPONDING TO P (F) = 547.30
ACTIVE FUEL (HEATER) LENGTH (FT/S) = 12.0000
CORE AVERAGE VOLUMETRIC HEAT(BTU/HR-FT**3) = 0.185810E+08
TOTAL NUMBER OF CHANNELS = 121
TOTAL NUMBER OF NODES IN CHANNEL = 24

FREQUENCY

INITIAL FREQ. = 0.623000
FINAL FREQ. = 20.000000
FREQ. INTERVAL = 1.500000

OPTION

IOSUB = 1
IOHW = 4
IO2Q = 1
IK = 1
ISI = 2
IREG = 1
IBODE = 0

EXTERNAL PERTURBATION

** DELQ0 = 1.000**

***** SYSTEM PROPERTIES *****

&CALPRO
ENTHT=523.91309, ENTHP=546.0896, DENSF=46.762482, DENS1=47.313065, VFG1=.41157424, RHOG=2.3082075,
&END
&PROPTY
TSATP=547.30005, TAVE=538.8999, HFG1=645.91748, VISC=.64212276E-04, CPF=1.2597322, KF=.91794762E-04, SIGM=.12051275E-02,
&END

CHANNEL GEOMETRY & BOILING BOUNDARY

FLOW AREA (FT2)	HEAT PERI. (FT)	HYDR.DIAM. (IN)	BOIL.BOUND. (FT)	FRICTION F.
0.1086	8.2604	0.5202	5.5000	0.0180

HEATED WALL DYNAMICS PARAMETER

*** BWR FUEL ROD ***

* FUEL REGION
 SPECIFIC HEAT OF FUEL =0.773540E-01(BTU/LB-F)
 THERMAL CONDUCTIVITY =0.563690E-03(BTU/S-FT-F)
 DENSITY OF FUEL = 650.5200(LB/FT3)
 FUEL RADIUS = 0.0173(IN)

* CLAD REGION
 SPECIFIC HEAT OF CLAD =0.753180E-01(BTU/LB-F)
 THERMAL CONDUCTIVITY =0.252300E-02(BTU/S-FT-F)
 DENSITY OF CLAD = 410.1699(LB/FT3)
 INNER RADIUS OF CLAD = 0.0177(IN)
 OUTER RADIUS OF CLAD = 0.0205(IN)

GAP CONDUCTANCE =0.100008E+04(BTU/HR-FT2-F)

BULK & WALL TEMPERATURE FOR STEADY-STATE

NODE	TBULK	TWALL
1	530.79	537.81
2	531.27	542.93
3	531.97	548.77
4	532.95	556.73
5	533.69	567.25
6	536.72	557.98
7	539.44	559.10
8	545.42	560.61
9	554.97	561.28
10	567.57	561.50
11	581.92	561.51
12	596.25	561.44
13	547.30	561.35
14	547.30	561.25
15	547.30	561.16
16	547.30	561.08
17	547.30	561.00
18	547.30	560.90

19	547.30	560.77	
20	547.30	560.59	
21	547.30	560.32	
22	547.30	559.94	
23	547.30	559.37	
24	547.30	558.47	
25	547.30	556.97	
NODE	Z	HEAT FLUX	POWER DENSITY
1	0.5000	5.5149	0.536956E+03
2	1.0000	9.1507	0.890949E+03
3	1.5000	13.1949	0.128472E+04
4	2.0000	18.6690	0.181770E+04
5	2.2663	26.3490	0.256546E+04
***** TWO-PHASE REGION *****			
6	2.5000	26.3490	0.256546E+04
7	3.0000	39.2171	0.381835E+04
8	3.5000	63.4827	0.618096E+04
9	4.0000	77.1678	0.751340E+04
10	4.5000	82.1108	0.799468E+04
11	5.0000	82.4376	0.802649E+04
12	5.5000	80.8444	0.787137E+04
13	6.0000	78.7201	0.766454E+04
14	6.5000	76.4733	0.744578E+04
15	7.0000	74.5125	0.725487E+04
16	7.5000	72.7967	0.708781E+04
17	8.0000	71.1218	0.692474E+04
18	8.5000	69.1610	0.673382E+04
19	9.0000	66.5465	0.647926E+04
20	9.5000	63.0333	0.613720E+04

21	10.0000	58.1720	0.566389E+04
22	10.5000	51.6358	0.502750E+04
23	11.0000	42.8528	0.417234E+04
24	11.5000	31.4554	0.306264E+04
25	12.0000	17.6477	0.171826E+04

AVERAGE VOID FRACTION IN TEST SECTION = 0.4179
 EXIT VOID FRACTION = 0.7418 CO = 1.110 VGJ = 1.450
 EXIT QUALITY = 0.22692
 MASS FLUX = 1.032E+06 LBM/HR FT2
 AVE. VELOCITY IN 1-PHASE REGION = 6.130 FT/S
 VELOCITY AT HEATED SECTION EXIT = 32.921 FT/S

INLET ENTHALPY = 523.9131 (BTU/LBM)
 VOID DEPARTURE ENTHALPY = 531.9490 (BTU/LBM)

1

NODE THERMAL-HYDRAULIC PROPERTIES

NODE	DELZ	K1	CO(Z)	VGJ(Z)	AVG. VOID	XEXIT(Z)	AVG. ENTH.	JOIN
6	0.2337	0.4957E-01	1.1100	1.4500	0.0007	0.98115E-04	0.53273E+03	0.6130E+01
7	0.5000	0.3655E+00	1.1100	1.4500	0.0129	0.16458E-02	0.53561E+03	0.6142E+01
8	0.5000	0.1442E+01	1.1100	1.4500	0.0652	0.77480E-02	0.53994E+03	0.6325E+01
9	0.5000	0.2798E+01	1.1100	1.4500	0.1675	0.19597E-01	0.54346E+03	0.7045E+01
10	0.5000	0.3635E+01	1.1100	1.4500	0.2849	0.34991E-01	0.54524E+03	0.8444E+01
11	0.5000	0.3899E+01	1.1100	1.4500	0.3847	0.51502E-01	0.54585E+03	0.1026E+02
12	0.5000	0.3894E+01	1.1100	1.4500	0.4606	0.67997E-01	0.54602E+03	0.1221E+02
13	0.5000	0.3816E+01	1.1100	1.4500	0.5180	0.84158E-01	0.54609E+03	0.1416E+02
14	0.5000	0.3707E+01	1.1100	1.4500	0.5622	0.99857E-01	0.54609E+03	0.1607E+02
15	0.5000	0.3612E+01	1.1100	1.4500	0.5973	0.11515E+00	0.54609E+03	0.1792E+02
16	0.5000	0.3529E+01	1.1100	1.4500	0.6259	0.13010E+00	0.54609E+03	0.1973E+02

17	0.5000	0.3448E+01	1.1100	1.4500	0.6497	0.14470E+00	0.54609E+03	0.2149E+02
18	0.5000	0.3353E+01	1.1100	1.4500	0.6697	0.15890E+00	0.54609E+03	0.2321E+02
19	0.5000	0.3226E+01	1.1100	1.4500	0.6866	0.17256E+00	0.54609E+03	0.2489E+02
20	0.5000	0.3056E+01	1.1100	1.4500	0.7010	0.18550E+00	0.54609E+03	0.2650E+02
21	0.5000	0.2820E+01	1.1100	1.4500	0.7130	0.19744E+00	0.54609E+03	0.2803E+02
22	0.5000	0.2503E+01	1.1100	1.4500	0.7230	0.20804E+00	0.54609E+03	0.2944E+02
23	0.5000	0.2077E+01	1.1100	1.4500	0.7309	0.21684E+00	0.54609E+03	0.3069E+02
24	0.5000	0.1525E+01	1.1100	1.4500	0.7368	0.22329E+00	0.54609E+03	0.3173E+02
25	0.5000	0.8555E+00	1.1100	1.4500	0.7404	0.22692E+00	0.54609E+03	0.3249E+02

LOCAL PRESSURE DROP BY SPACER

Z	LOCAL COEFF.	LOCAL DP
0.0	0.278000E+02	0.527310E+01
1.6000	0.104000E+01	0.197267E+00
3.2000	0.104000E+01	0.252887E+00
4.8000	0.104000E+01	0.543454E+00
6.4000	0.104000E+01	0.841745E+00
8.0000	0.104000E+01	0.109398E+01
9.6000	0.104000E+01	0.137590E+01
11.2000	0.104000E+01	0.151909E+01
12.0000	0.140000E+00	0.207852E+00

1

STEADY-STATE PRESSURE DROP

1) SINGLE-PHASE REGION
 LOCAL LOSS = 5.4704(Psi)
 GRAVITY = 0.7360(Psi)
 TOTAL DP = 0.9145(Psi)

FRICTION = 0.1785(Psi)

2) TWO-PHASE REGION

NODE	Z	GRAVITY (PSI)	FRICION(COR2PH) (PSI)	ACCELERATION (PSI)	TOTAL (PSI)
6	2.5000	0.0758	0.0185 (1.0066)	0.0005	0.0949
7	3.0000	0.1604	0.0422 (1.0703)	0.0084	0.2110
8	3.5000	0.1522	0.0505 (1.2820)	0.0329	0.2356
9	4.0000	0.1365	0.0662 (1.6802)	0.0623	0.2650
10	4.5000	0.1184	0.0867 (2.2017)	0.0783	0.2834
11	5.0000	0.1030	0.1085 (2.7549)	0.0809	0.2924
12	5.5000	0.0913	0.1296 (3.2898)	0.0781	0.2990
13	6.0000	0.0824	0.1494 (3.7936)	0.0743	0.3062
14	6.5000	0.0756	0.1680 (4.2670)	0.0705	0.3141
15	7.0000	0.0702	0.1856 (4.7139)	0.0674	0.3232
16	7.5000	0.0658	0.2024 (5.1391)	0.0648	0.3330
17	8.0000	0.0621	0.2184 (5.5457)	0.0627	0.3432
18	8.5000	0.0590	0.2337 (5.9346)	0.0605	0.3532
19	9.0000	0.0564	0.2483 (6.3048)	0.0580	0.3627
20	9.5000	0.0542	0.2620 (6.6531)	0.0550	0.3711
21	10.0000	0.0523	0.2747 (6.9748)	0.0508	0.3778
22	10.5000	0.0508	0.2860 (7.2631)	0.0453	0.3821
23	11.0000	0.0495	0.2957 (7.5088)	0.0378	0.3830
24	11.5000	0.0486	0.3033 (7.7007)	0.0279	0.3798
25	12.0000	0.0481	0.3082 (7.8272)	0.0157	0.3720
TOTAL		1.6125	3.6378	1.0322	6.2825

LOCAL LOSS = 5.8349(Psi)
TOTAL CHANNEL PRESSURE DROP = 18.5022(Psi)

WO = 0.4236E+04
0.16191E-01 0.15636E-01 0.26516E+02
DPUPL=0.3367E+00 DPR=0.8650E+00 DPLOOP=0.1315E+02

PARAMETERS FOR THE UPPER PLENUM

AREA	LENGTH I	LENGTH II	CURVATURE
243.9700	16.2760	17.5680	2.5820

VOID FRACTION =0.8560E+00VO,UP =0.1994E+01

PARAMETERS FOR THE RISER

LENGTH (FT)	FLOW AREA (FT2)	HYDR.DIAM. (IN)	CO	VGJ (FT/S)
26.5160	0.0559	6.0650	1.0300	0.8500

GO,R =0.1001E+03 VO,R =0.1149E+02 VOID FRACTION =0.7754E+00
CORPR =0.7867E+01

PARAMETERS FOR THE LOOP

SLOOP	SFLOOP	AA
0.4168E+02	0.3174E+00	0.0

PARAMETERS FOR DOWNCOMER

F.W. ENTH	FLOW AREA	LENGTH	VESSEL TEMP	TEMINV	PH	HO
0.5026E+03	0.1096E+03	0.2643E+02	0.5000E+03	0.5170E+03	0.6571E+02	0.1360E+04

VESSL WALL
THICKNESS(FT) = 0.5365E+00
THERMAL CONDUCTIVITY = 0.9500E+01
SPECIFIC HEAT = 0.1200E+00
DENSITY(LB/FT3) = 0.4980E+03

WO(LB/S) = 0.4236E+04 ENTH. MIX. = 0.5362E+03 ENTH. DC(EXIT) = 0.5362E+03

PARAMETERS FOR LOWER PLENUM

FLOW MASS(LB)	H/T AREA	HO	THICK	HEAT FLUX
0.3747E+04	0.1185E+04	0.9997E+03	0.6250E+00	0.8254E-01

3) PRESSURE DROP ACROSS THE CORE = 18.5022

4) PRESSURE DROP IN THE LOOP = 14.3479

TOTAL PRESSURE DROP IN THE WHOLE LOOP (PUMP HEAD) = 32.8501

FREQUENCY= 0.623E+00RAD/S PERIOD= 0.101E+02SEC (MULT.= 1.5000) 1
 REACT PCAPLA DRDU CALPHA ASGF AVEL CSGF CVL CLAMD ASGA CSA

0.7919E-01 0.2884E-04-0.8935E-01-0.2978E-01 0.1633E-01 0.2123E+07-0.1290E-01 0.1995E+07-0.4334E-05 0.1503E-01-0.1
 ZPKP = -0.8822E+05 0.3110E+05 F1 = 0.3324E-05 -0.7483E-05

OPEN LOOP T.F. FOR NYQUIST PLOT 0.6051E-01 -0.7635E+00 0.7659E+00 -85.47
 **RATIO = ** 0.605104E-01 -.763526E+00

FREQUENCY= 0.935E+00RAD/S PERIOD= 0.672E+01SEC (MULT.= 1.5000) 2
 ZPKP = -0.8453E+05 0.2357E+05 F1 = 0.1739E-05 -0.5958E-05

OPEN LOOP T.F. FOR NYQUIST PLOT 0.6552E-02 -0.5446E+00 0.5447E+00 -89.31
 **RATIO = ** 0.655160E-02 -.544623E+00

FREQUENCY= 0.140E+01RAD/S PERIOD= 0.448E+01SEC (MULT.= 1.5000) 3
 ZPKP = -0.8157E+05 0.1800E+05 F1 = 0.5227E-06 -0.4589E-05

OPEN LOOP T.F. FOR NYQUIST PLOT -0.3997E-01 -0.3837E+00 0.3858E+00 -95.95
 **RATIO = ** -.399690E-01 -.383739E+00

FREQUENCY= 0.210E+01RAD/S PERIOD= 0.299E+01SEC (MULT.= 1.5000) 4

ZPKP = -0.7930E+05 0.1379E+05 F1 = -0.3663E-06 -0.3314E-05
 OPEN LOOP T.F. FOR NYQUIST PLOT -0.7475E-01 -0.2578E+00 0.2684E+00 -106.17
 **RATIO = ** -.747494E-01 -.257768E+00

FREQUENCY= 0.315E+01RAD/S PERIOD= 0.199E+01SEC (MULT.= 1.5000)
 ZPKP = -0.7767E+05 0.1068E+05 F1 = -0.9293E-06 -0.2114E-05
 OPEN LOOP T.F. FOR NYQUIST PLOT -0.9476E-01 -0.1543E+00 0.1810E+00 -121.56
 **RATIO = ** -.947610E-01 -.154255E+00

FREQUENCY= 0.473E+01RAD/S PERIOD= 0.133E+01SEC (MULT.= 1.5000)
 ZPKP = -0.7657E+05 0.8567E+04 F1 = -0.1087E-05 -0.9996E-06
 OPEN LOOP T.F. FOR NYQUIST PLOT -0.9177E-01 -0.6723E-01 0.1138E+00 -143.77
 **RATIO = ** -.917681E-01 -.672321E-01

FREQUENCY= 0.710E+01RAD/S PERIOD= 0.885E+00SEC (MULT.= 1.5000)
 ZPKP = -0.7589E+05 0.7419E+04 F1 = -0.7850E-06 -0.1494E-06
 OPEN LOOP T.F. FOR NYQUIST PLOT -0.6068E-01 -0.5512E-02 0.6093E-01 -174.81
 **RATIO = ** -.606779E-01 -.551155E-02

FREQUENCY= 0.106E+02RAD/S PERIOD= 0.590E+00SEC (MULT.= 1.5000)
 ZPKP = -0.7544E+05 0.7294E+04 F1 = -0.2729E-06 0.1214E-06
 OPEN LOOP T.F. FOR NYQUIST PLOT -0.1970E-01 0.1115E-01 0.2264E-01 150.49
 **RATIO = ** -.197010E-01 0.111496E-01

FREQUENCY= 0.160E+02RAD/S PERIOD= 0.394E+00SEC (MULT.= 1.5000)
 ZPKP = -0.7500E+05 0.8287E+04 F1 = -0.3266E-07 -0.2317E-06
 OPEN LOOP T.F. FOR NYQUIST PLOT -0.4370E-02 -0.1711E-01 0.1766E-01 -104.33
 **RATIO = ** -.436996E-02 -.171093E-01
 1 PERIOD NYQUIST PLOT

1

-SCALE=1.0

7
6
*
*
5
*
*

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APPENDIX XVII
NUFREQ-N LISTING

The FORTRAN llisting of the NUFREQ-N code is shown in this appendix. Also the error messages in NUFREQ-N are explained in Appendix XVIII.

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C *****
C *
C *
C *      N  N  U  U  FFFFF  RRRR  EEEEE  QQQ      N  N
C *      NN N  U  U  F      R  R  E      Q  Q      NN N
C *      N N N  U  U  FFFFF  RRRR  EEEEE  Q  Q      N N N
C *      N  NN  U  U  F      R  R  E      Q  Q  Q      N  NN
C *      N  N   UUU  F      R  R  EEEEE  QQQ Q      N  N
C *
C *****
C
C      NUFREQ-N, A BWR LINEAR STABILITY ANALYSIS CODE IN THE FREQUENCY
C      DOMAIN. THE CODE WAS WRITTEN IN RPI BY GOON-CHERL PARK UNDER
C      DIRECTION OF PROFESSORS: R. T. LAHEY, JR, M. BECKER AND M.
C      PODOWSKI. NUFREQ-N FEATURES: DRIFT-FLUX THERMAL-HYDRAULICS,
C      ARBITRARY NONUNIFORM AXIAL POWER DISTRIBUTION, SUBCOOLED BOILING,
C      DISTRIBUTED AXIAL SPACERS, HEATED WALL DYNAMICS, AND NODAL
C      NUCLEAR KINETICS.
C
C ***** INPUT DESCRIPTION FOR NUFREQ-N *****
C
C * NODES - TOTAL NUMBER OF NODES IN THE AXIAL DIRECTION
C           (MUST BE EVEN AND LESS THAN 28)
C   (1) NODES = 1 ; A SINGLE NODE
C * NCH - TOTAL NUMBER OF CHANNELS IN THE CORE (LESS THAN 200)
C * NSP - TOTAL NUMBER OF SPACER IN A CHANNEL
C * ISPEC - ROW NUMBER OF CONCERNED CANNEL
C * JSPEC - COLUMN NUMBER OF CONCERNED CHANNEL
C * NBB - THE FINAL NODE INDEX IN THE SINGLE-PHASE REGION
C * NBB1 - THE FIRST NODE INDEX IN THE TWO-PHASE REGION
C * NP1 - THE TOTAL NUMBER OF INTERNALLY CALCULATED NODES
C
C * OPTIONS
C   (1) IOSUB ; TREATMENT OF SUBCOOLED BOILING
C       = 0 ; NO SUBCOOLED BOILING
C       = 1 ; SUBCOOLED BOILING MODEL USED
C   (2) IOHW ; HEATED WALL DYNAMICS
C       = 0 ; LUMPED PARAMETER MODEL
C       = 1 ; PARALLEL PLATE HEATER
C       = 2 ; CYLINDRICAL HEATER
C       = 3 ; BWR FUEL ROD
C   (3) IO2Q ; PERTURBATION OF Q'' IN TWO-PHASE REGION
C       = 0 ; NOT INCLUDED
C       = 1 ; INCLUDED
C   (4) IK ; OPTION OF NUCLEAR COUPLING
C       = 0 ; NO COUPLING
C       = 1 ; COUPLING INCLUDED
C   (5) ISI ; NUMBER OF SIGNIFICANT FIGURES IN ROUNDED VALUE OF

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C           THE PERIOD ( DEFAULT = 2)
C
C (6) IREQ ;
C   = 0 ; WMULT IS MODIFIED INTERNALLY (IE: W2 = W1*WMULT(NUFREQ-N))
C   = 1 ; WMULT IS MULTIPLIED (IE: W2 = W1*WMULT)
C   = 2 ; WMULT IS TO ADDED (IE: W2 = W1+WMULT)
C
C (7) IPRINT ; PRINT MODE FOR THE STEADY-STATE PARAMETERS
C   = 0 ; NO STEADY-STATE VALUES
C   = 1 ; ONLY PRESSURE DROP OF EACH NODE & CHANNEL PRINTED
C   = 2 ; AN THERMAL-HYDRAULIC PARAMETERS PRINTED
C   = 3 ; ONLY CHANNEL GEOMETRY PRINTED
C   = 4 ; VOID FRACTION & PRESSURE DROP PRINTED
C   = 5 ; VOID FRACTION, PRESSURE DROP, AXIAL POWER & HEAT
C         FLUX DISTRIBUTION PRINTED
C   = 6 ; ALL STEADY-STATE PARAMETERS PRINTED
C
C (8) IBODE
C   = 0 ; OPEN-LOOP TRANSFER FUNCTION(GH) FOR NYQUIST PLOT
C   = 1 ; CLOSED-LOOP TRANSFER FUNCTION OF REACTIVITY-TO-CORE
C         CORE FEEDBACK POWER PERTURBATION OR EXTERNAL CORE
C         POWER TO CORE FEED POWER PERTURBATION
C
C (9) IPILO; C1 & C2 OF TWO-PHASE MULTIPLIER
C   = 0 ; CONSTANT VALUES SPECIFIED BY USER
C   = 1 ; OBTAINED FROM MARTINELLI NELSON MODEL
C
C (10) ISLIP
C   = 0 ; DRIFT-FLUX PARAMETERS ARE USER SPECIFIED AND UNIFORM
C         FOR EVERY NODE
C   = 1 ; OBTAINED FROM Okawa/Lahey model
C
C (11) ICAL
C   = 0 ; ONLY STEADY-STATE ANALYSIS IS PERFORMED
C   = 1 ; PARALLEL-CHANNEL STABILITY ANALYSIS
C   = 2 ; LOOP STABILITY ANALYSIS WITHOUT DELHI
C   = 3 ; SAME AS ICAL=2, BUT WITH DELHI
C   = 4 ; POWER-TO-VOID FRACTION TRANSFER FUNCTION
C   = 5 ; POWER-TO-VOID FRACTION TRANSFER FUNCTION WITH
C         INLET ENTHALPY FEEDBACK
C   = 6 ; POWER-TO-FLOW TRANSFER FUNCTION
C
C (12) IRW
C   = 0 ; NO REDISTRIBUTION OF CHANNEL INLET FLOW RATE
C         VEL3D(I) = J10(I)
C   = 1 ; REDISTRIBUTION OF CHANNEL INLET FLOW RATE CALCULATED
C         BY NUFREQ-N
C         VEL3D(I) ; INITIAL GUESSED VALUE FOR J10(I)
C
C * SYSTEM(CORE) PARAMETER
C   1) P(PSIA) ; SYSTEM PRESSURE
C   2) TIN(F) ; INLET COOLANT TEMPRATURE
C   3) WIN(MLB/HR); TOTAL CORE INLET FLOW RATE
C   4) ALHEAT(FT) ; HEATED CHANNEL LENGTH (ACTIVE FUEL LENGTH)
C   5) TSATP(F) ; SATURATION TEMP. CORRESPONDING TO PRESSURE,P
C   6) KEFF ; EFFECTIVE CORE NEUTRON MULTIPLICATION FACTOR
C   7) AVEQ ; CORE-AVERAGED POWER DENSITY (BTU/HR-FT3)

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8) FOR THE RISER
 A) COR ; CO FOR THE RISER
 B) VGJR ; THE DRIFT VELOCITY, VGJ, FOR THE RISER (FT/S)
 C) LR(FT) ; THE TOTAL CHANNEL LENGTH INCLUDING THE RISER
 D) AR(FT**2) ; THE FLOW AREA OF THE RISER
 E) DRIN(IN) ; THE HYDRAULIC DIAMETER OF THE RISER
 9) FOR THE UPPER PLENUM
 A) RPO(FT) ; CURVATURE OF THE UPPER PLENUM
 B) RP1(FT) ; THE LENGTH OF REGION I
 C) RP2(FT) ; THE LENGTH OF REGION II
 D) AP(FT2) ; FLOW AREA OF THE UPPER PLENUM
 10) FOR THE LOOP
 A) SLOOP ; SUM OF (LI/AI) FOR I = 1,N; THE HYDRAULIC INERTIA
 OF THE LOOP (FT**-1)
 B) SFLOOP ; SUM OF FI*LI/(DHI*AI**2) FOR I = 1,N; EQUIVALENT
 FRICTIONAL RESISTANCE OF THE LOOP (FT**-4)
 LI(FT) - SEGMENT LENGTH, AI(FT**2) - SEGMENT FLOW AREA
 FI = SEGMENT FRICTION FACTOR
 DHI(FT) - SEGMENT HYDRAULIC DIAMETER
 C) AA ; SLOPE OF PUMP CURVE (LBF/FT2 / LBM/S)
 D) HFW(BTU/LB) ; ENTHALPY OF THE FEED WATER
 E) RFW ; THE RATIO OF FEEDWATER FLOW RATE TO CORE INLET FLOW RATE
 F) WO(MLB/HR) ; TOTAL CORE FLOW RATE (TOTAL RECIRCULATING
 LOOP FLOW MINUS LEAKAGE TO BYPASS REGION)
 * CHANNEL PARAMETERS
 (1) VCH(FT/S) ; STEADY-STATE CHANNEL INLET FLOW VELOCITY
 (2) PH(FT) ; HEATED PERIMETER OF CHANNEL
 (3) AXS(FT**2) ; CHANNEL FLOW AREA
 (4) DHIN(IN) ; CHANNEL HYDRAULIC DIAMETER
 (5) EXLOSS ; LOSS COEFFICIENT AT EXIT OF HEATED CHANNEL(IN
 VELOCITY HEAD)
 (6) INLOSS ; LOSS COEFFICIENT AT INLET OF HEATED CHANNEL(IN
 VELOCITY HEAD)
 (7) CPF(BTU/LB-F) ; SPECIFIC HEAT OF SATURATED WATER
 (8) CXF(FT**2) ; CROSS-SECTIONAL AREA OF HEATER
 (9) AXIAL NODE PARAMETERS
 A) DZ(I) ; NODE LENGTH (FT)
 B) QDIS(I) ; CONSTANT STEADY-STATE NODAL VOLUMETRIC HEAT
 GENERATION RATE (BTU/HR-FT**3)
 C) QO(I) ; CONSTANT STEADY-STATE NODAL HEAT FLUX
 (BTU/HR-FT**2)
 D) CZERO ; CO IN VOID-QUALITY EQUATION
 E) VGJ ; DRIFT VELOCITY (FT/S)
 F) CHOMO1,2 ; CORRECTION FACTOR FOR HOMO. TWO-PHASE
 MULTIPLIER
 G) CHALF ; STEADY-STATE CHANNEL AVERAGE VOID FRACTION
 CKIN(I) ; KINEMATIC WAVE VELOCITY AT INLET OF NODE-I (FT/S)
 CKOUT(I) ; KINEMATIC WAVE VELOCITY AT EXIT OF NODE-I (FT/S)
 ZETA(I) ; INLET WAVE VEL./EXIT WAVE VEL.

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C      JOIN(I) ; INLET FLOW VELOCITY TO NODE-I
C      DOIN(I) ; INLET DENSITY TO NODE-I
C      DOOUT(I) ; EXIT DENSITY FROM NODE-I
C      ALPIN(I) ; INLET VOID FRACTION TO NODE-I
C      ALPOUT(I) ; EXIT VOID FRACTION FROM NODE-I
C      ALFAVE(I) ; AVERAGE VOID FRACTION IN NODE-I
C
C      * PARAMETER FOR HEATED WALL DYNAMICS MODELS
C      (1) IOHW = 0 ; FOR LUMPED PARAMETER MODEL
C          A) CPF ; SPECIFIC HEAT OF HEATER (BTU/LB-F)
C          B) DENSH ; HEATER DENSITY (LB/FT**3)
C      (2) IOHW = 1 ; FOR PARALLEL PLATE
C          A) CPF ; SPECIFIC HEAT OF HEATER (BTU/LB-F)
C          B) TKH ; THERMAL CONDUCTIVITY OF HEATER (BTU/FT-F-S)
C          C) DENSH ; HEATER DENSITY (BTU/FT**3)
C          D) THICKH ; PLATE THICKNESS (FT)
C      (3) IOHW = 2 ; FOR CYLINDRICAL TUBE
C          A) CPF ; SPECIFIC HEAT OF HEATER (BTU/LB-F)
C          B) TKH ; THERMAL CONDUCTIVITY OF HEATER (BTU/FT-F-S)
C          C) DENSH ; HEATER DENSITY (LB/FT**3)
C          C) CRI ; INNER RADIUS OF CYLINDRICAL HEATER (FT)
C          D) CRO ; OUTER RADIUS OF CYLINDRICAL HEATER (FT)
C      (4) IOHW = 3 ; FOR FUEL ROD
C          A) CPF ; SPECIFIC HEAT OF FUEL PELLET (BTU/LB-F)
C          B) TKH ; THERMAL CONDUCTIVITY OF FUEL PELLET (BTU/FT-F-S)
C          B) DENSH ; FUEL PELLET DENSITY (BTU/FT**3)
C          C) CPC ; SPECIFIC HEAT OF CLAD (BTU/LB-F)
C          D) TKC ; THERMAL CONDUCTIVITY OF CLAD (BTU/S-FT-F)
C          D) DENSC ; CLAD DENSITY (LB/FT**3)
C          E) CRS ; RADIUS OF FUEL PELLET (FT)
C          F) CRI ; INNER RADIUS OF CLAD (FT)
C          G) CRO ; OUTER RADIUS OF CLAD (FT)
C          H) GAPC ; GAP CONDUCTANCE (BTU/S-FT**2)
C
C      FUNCTIONS CALLED.....
C
C      HL(P,T) - LIQUID ENTHALPY (BTU/LBM)
C      DENS(P,T,HL) - LIQUID DENSITY (LBM/FT**3)
C      HF(P) - SATURATED LIQUID ENTHALPY (BTU/LBM)
C      HFG(P) - LATENT HEAT (BTU/LBM)
C      MUTL(T) - LIQUID VISCOSITY (LBM/HR-FT)
C      COND(T) - THERMAL CONDUCTIVITY OF SATURATED LIQUID (BTU/HR-FT-F)
C      VFG(P) - SPECIFIC VOLUME OF THE GAS - SPECIFIC VOLUME OF LIQUID
C              (FT**3/LBM)
C      VF(P) - SPECIFIC VOLUME OF THE SATURATED LIQUID (FT**3/LBM)
C      MARNEL(P,G) - PARAMETER IN MARTINELLI-NELSON TWO-PHASE MULTIPLIER
C      SGMA(P,T) - SURFACE TENSION OF WATER(LBF/FT)
C      ANGL(Z) - ARGUMENT OF COMPLEX Z
C      BSIO(Z) - MODIFIED BESSEL FUNCTION OF THE 1ST KIND OF ORDER ZERO
C      BSII(Z) - MODIFIED BESSEL FUNCTION OF THE 1ST KIND OF ORDER ONE

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C BSKO(Z) - MODIFIED BESSEL FUNCTION OF THE 2ND KIND OF ORDER ZERO
 C BSK1(Z) - MODIFIED BESSEL FUNCTION OF THE 2ND KIND OF ORDER ONE
 C BER(Z) - BER FUNCTION
 C BEI(Z) - BEI FUNCTION
 C BERS(Z) - BER' FUNCTION
 C RKER(Z) - KER FUNCTION
 C RKEI(Z) - KEI FUNCTION
 C RKEIS(Z) - KEI' FUNCTION

C REAL KF, LAMBDA(200), K1, LR, KLOSS, MUTL, L1, L2, JOIN
 COMPLEX TAU1, TAU2, RATIO, S, Z1, Z2, Z3, M1, M2, M3, OLDRAT, TSUM2,
 1 OH, P11, P12, P13, GAM1, GAM2, GAM3, ZPKP, STC2, CSTB1, CSTB2,
 2 TG, TB1, TB2, TF, TR1, TR2, HS, STC1, TEE, AAA, U1, FALF, ZPK1
 COMPLEX F11, GHPV(100), ZPK, CXJ1, CXJ2, CXJ3, CXA1, CXA2, CXA3
 COMPLEX T, SANI, SAIN, AMN, ANM, RAIR, RAIN, SAKN, SANK, GAMN, TALP1
 COMPLEX RANI, GANM, ZNI, BI, RKI, XZNI, XBM, XRKM, CXK, CXKN, TALP3
 COMPLEX WW1, WW2, TZ1, TZ2, TWO, THREE, T1, DPH1, TGAM1, TP11
 COMPLEX RR1, RR2, RR3, DPUP1, DPUP2, DPUP3, DWSW1, DWSW2, DWSW3
 COMPLEX TH1, TH2, TH3

C DIMENSION VEL3D(200), Q3D(200, 30)
 DIMENSION XREA(100), YIMA(100), PER(100), AMOD(100), ARGU(100)
 DIMENSION COMM1(20), COMM2(20), COMM3(20), COMM4(20), COMM5(20),
 1 COMM6(20), COMM7(20), COMM8(20), COMM9(20), COMM10(20),
 2 COMM13(20), COMMEN(20)
 DIMENSION CPS(100), PHASE(100), VMAG(100)

C COMMON/OPTION/ IOSUB, IOHW, IO2Q, IPILO, ISLIP, IRW
 COMMON/CONST1/ C1(200), C2(200), C3(200), C4, C5(200), C8(200, 30),
 1 C9(200, 30), C18(200), C21(200), C22(200), C25(200),
 2 C26(200), T6, V7(200), DD1, CKI, CMP
 COMMON /CONSUB/ CSB2(200, 30), CSB3(200, 30), CSB4(200, 30),
 1 CSB5(200, 30), CSB6(200, 30), CSB7(200, 30), CSB8(200, 30),
 2 CSB9(200, 30), CSB10(200, 30), CSBQ(200, 30), CSBD(200, 30),
 3 CSBE(200, 30), CSBF(200, 30), CSBG(200, 30), CSBX1(200),
 4 CSBX2(200)
 COMMON/CONST2/ P, VCH, VIN(200), AXS(200), DH(200), DHIN(200),
 1 PH(200), TIN, TSATP, ENTH, DENSI, SIGM, ENTHP, VISC, CPF, KF,
 2 DENSF, VFG1, RHOG, GO(200), GO2(200), HO(200), GC, G1, KLOSS(30),
 3 FRICMO(200), VGJH(200, 30), COH(200, 30), CZERO, VGJ, DPTS,
 4 GO2RF(200), HFG1, ZSP(30), NUMBSP(200, 30), ALHEAT, CXF(200),
 5 AVEQ, CHOM01, CHOM02, XKIN(200), XKEXIT(200)

C COMMON/CONSS1/ QDIS(200, 30), QO(200, 30), DZ(200, 30), Z(200, 30),
 1 K1(200, 30), CKIN(200, 30), ZETA(200, 30), DOIN(200, 30),
 2 DOOUT(200, 30), ALPIN(200, 30), BEE(200, 30), CPI1(200, 30),
 3 COR2PH(200, 30), ZETSP(200, 30), WIN
 COMMON/PCHOUT/XCHOUT(200), ACHOUT(200), CCHOUT(200)
 COMMON /DIM1/ DELX, DELZ, CHLAMB(200), ALFNOD(200, 30),
 1 BBLAMB(200)

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COMMON/CONSS2/ NTOT(200),NBB(200),NBB1(200),NSP,N1PSP(200),
1 K2PSP(200), NDP(200), NDP1(200), ISUB(200)
COMMON /DPCON1/GAM1(200),GAM2(200,30),GAM3(200), P11(200),
1 P12(200,30),P13(200), TALP1(200,30),
2 TSUM2(200,30),TAU1(200),TAU2(200),TALP3(200,30)
COMMON /PERT/ DELVI, DELQO, DELK
COMMON /CONWD1/ CPH,TKH,DENSH,CPC,TKC,DENSC,CRS,CRI,CRO,
1 GAPC, V22(200,30), THICKH
COMMON /WD2/Z1, Z2, Z3(30)
COMMON /CPBOIL/ M1, M2, M3, TH1,TH2,TH3, HS(30)
COMMON /PBOIL/ CONBB
COMMON /DPCON3/ ST2(30)
COMMON /DPCON2/ STC1(30), STC(200,30), CSTB1(30), CSTB2(30),
1 STC2(30)
COMMON /CMP2/TG(6,30),TB1(3,30),TB2(3,30),TF(11,30),TR1(5,30),
1 TR2(5,30)

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COMMON /RISER/ COR,VGJR,CKRO,RL,AR,DRIN,DR,P1,CL1,CL2,CL3,CL4,
1 CL5, CL6, CR5, CR6, UPJ1, UPJ2, R011, R012,
2 R021, R022, XROUT, UPJIN
COMMON /CLOOP/ SLOOP, SFLOOP, RLOOP,AA, VL1, VL2, VL3, DPLPT
1 ,RATW
COMMON /CUPPER/ RKIN, RKEXIT, AP, RPO, RP1, RP2, CL10,CL11,
1 CLT,AXSCH,RAR,AD,DL,DHDL,FDL, F1(200),F2(200),
2 RJ1(200),RJ2(200),RJ3(200),F3(200)
COMMON /CDELH1/ HFW, ADC, PHV, DKV, CPV, DENV, TEMV, TEMINV,
1 THV, HOD, PLM, AHLF, THLP, HOLP, WO, DLENG
COMMON /CDELH2/ CH1, CH2, CH3, CH4, CH5, CH7, CH8, CH9, CH10
COMMON /CXCH/ CXJ1(200),CXJ2(200,30),CXJ3(200),CXA1(200),
1 CXA2(200,30),CXA3(200)
COMMON /CXLP/ RR1(200), RR2, RR3, DPUP1(200), DPUP2, DPUP3,
1 DWSW1(200), DWSW2, DWSW3, T1, DPH1
COMMON /CGHT/ F11
COMMON /RESULT/XZ, SS1, SS2

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COMMON/SIM1/IMAX,JMAX,KMAX, ICASE, ISPEC, JSPEC, INUCLR,XKEFF
COMMON/SIM2/JMX(20),NFT(15,15,30),AL(15,15),TAL(15,15),
1 BAL(15,15),ASRC(15,15),SRC(15,15,30),AEXP(15,15),
2 REXP(15,15,30),AXSRC(30),XXSRC(30)
COMMON/SIM3/JJD(15,15),DZ1(200),DZ2(200),NF(200,30),NB(200),
1 SCCC(200,30,6),XEXP(200,30),SIG1(200,30,11),
2 CSIG1(200,30,11)
COMMON/SIM4/TEE(15,15,30)
COMMON/SIM5/RXA(15,15),RXF(15,15),RV(15,15),RCXF(15,15),
1 RCXA(15,15),RCV(15,15)
COMMON/SIM6/RHOX(15,15,30),RHOZ(15,15,30),RX(15,15,30),
1 RZ(15,15,30),TEEO(15,15,30),PLAMDA(6), FPDF(15),
2 FPLAM(15)
COMMON/KIN1/XKINF(15,15,30),SIGF(15,15,30)
COMMON/KIN2/RRDF(15,15),RRCDF(15,15),RANO1(200,4),ADF(30),

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1      ACDF(30), GANOM(200,30,6), CFP
COMMON/KIN3/RANI(200,4), GANM(200,30,6), ZNI(200,4), BI(200)
COMMON/KIN5/RKI(200), XZNI(200,30,6), XBM(200,30), XRKM(200,30)
COMMON/PTK0/ZPK, ZPK1, ZPKP
COMMON/PTK1/AAA(200)
COMMON/COEF1/WA(10,2,11), WB(10,2,11), WC(10,2,11), WD(10,2,11),
1      WE(10,2,11), WF(10,2,11), WG(10,2,11), WH(10,2,11),
2      WI(10,2,11), WJ(10,2,11), WK(10,2,11)
COMMON/COEF2/D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D11,D12,SUMSRC
COMMON/COEF3/NFTMX
COMMON/XX/T(200,30,6), SANI(6), SAIN(6), AMN(6), ANM(6), RAIR(200),
1      RAIN(200,4), SAKN(2), SANK(2), GAMN(200,30,6)
COMMON/VOIDPT/FALF(200,30), U1(200), TGAM1(200), TPI1(200)
COMMON/TWOG1/SIG2(200,30,11), CSIG2(200,30,11), TFLX(2,4,30)
COMMON/TWOG2/WW1(100,100), WW2(100,100), TZ1(100,100),
1      TZ2(100,100), TWO(100,100), THREE(100,100)
COMMON/TEST/CXK(15,15,30), CXKN(200,30,6)

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*****      FORMAT      *****

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1  FORMAT(20A4)
2  FORMAT(8I4)
3  FORMAT(8F10.4)
4  FORMAT(6E10.4)
5  FORMAT(2E12.6)
6  FORMAT(2E15.5)
7  FORMAT(///10X, '*****  POWER-TO-VOID TRANSFER FUNCTION  *****')
8  FORMAT(///10X, '000  OPEN-LOOP TRANSFER FUNCTION AT  Z = ',
1      2X, F8.2, 2X, '000')
9  FORMAT(/12X, 'CPS', 17X, 'GH', 22X, 'MAG', 18X, 'PHASE')
10 FORMAT(1H0, '***** ERROR : E1 , XEXIT = ', F6.2)
12 FORMAT(/// '***** ERROR : E2 *****')
13 FORMAT(8X, F9.5, 3X, 2(2X, E10.4), 5X, E10.4, 5X, E10.4)
15 FORMAT(1H1, 10X, 6HPERIOD, 15X, 'NYQUIST PLOT' //
1      36X, 4HREAL, 10X, 4HIMAG, 9X, 'MODULE', 8X, 'ARG' //
2      (16, F11.4, 12X, 3E14.3, F11.4))
16 FORMAT(1H1, 50X, 16HNYQUIST DIAGRAM)
17 FORMAT(///15X, 'STABILITY MARGIN', /15X, 'MAGNITUDE =', F9.4,
1      (DB)', /15X, 'PHASE =', 4X, F9.4, ' (DEGREE)')
18 FORMAT(1X, 'STABILITY MARGIN', /, F10.4, ' (DB)')
19 FORMAT(2X, 'ICASE = ', I3)
20 FORMAT(///15X, '*** SYSTEM IS UNSTABLE ***')
21 FORMAT(10X, '**RATIO = **', 2(5X, E12.6))
31 FORMAT(1H1, 25X, 20A4 //)
33 FORMAT(1H1, /15X, '***** SINGLE NODE ANALYSIS *****')
34 FORMAT(//1H0, 18HSYSTEM PARAMETERS //
1      5X, 30H P = SYSTEM PRESSURE (PSIA) = , F9.2 /
2      5X, 35H TIN = INLET TEMPERATURE (DEG-F) = , F9.2 /
3      5X, 'SATURATION TEMPERATURE CORRESPONDING TO P (F) = '
4      F9.2 /

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5      5X,'ACTIVE FUEL (HEATER) LENGTH (FT/S) = ', F9.4/
6      5X,'CORE AVERAGE VOLUMETRIC HEAT(BTU/HR-FT**3) = ',E12.6/
7      5X,'TOTAL NUMBER OF CHANNELS = ',15/
8      5X,'TOTAL NUMBER OF NODES IN CHANNEL = ', 14)
35  FORMAT(//,'FREQUENCY',/5X,'INITIAL FREQ. = ',F9.6/
1    5X,'FINAL FREQ. = ',F9.6/5X,'FREQ. INTERVAL = ',F9.6)
36  FORMAT(//,'OPTION', /5X,'IOSUB = ',14/5X,'IOHW = ',14/
1    5X,'IO2Q = ', 14/5X,'IK = ',14/5X,'ISI = ',14/
2    5X,'IREG = ', 14/5X,'IBODE = ',14)
37  FORMAT(///,'EXTERNAL PERTURBATION' )
38  FORMAT(/5X,'** DELVI = ',F9.3, '**' )
39  FORMAT(/5X,'** DELQO = ',F9.3, '**' )
42  FORMAT(/5X,'** DELK = ',F9.3, '**' )
54  FORMAT(//13X, '** THE B.B. OF CORE-AVERAGED CHANNEL = ',
1    2X,F12.6,2X, '(FT) **' )
60  FORMAT(/// 46H **** NO FORCING FUNCTION WAS SPECIFIED **** )
61  FORMAT(/10X, '***** NODE-AVERAGED VOID FRACTION',
1    2X, '*****' )
62  FORMAT(/15X, 6(5X,E10.4) )
63  FORMAT(/10X, 'NODE = ',3X,13)
64  FORMAT(///11H FREQUENCY=,E10.3,5HRAD/S,10X,7HPERIOD=,E10.3,3HSEC,
1    5X, 8H(MULT.= , F7.4, 1H), 140)
65  FORMAT(/5X,'FREQUENCY',5X,'MAGNITUDE' )
66  FORMAT(/5X,'FREQUENCY',9X,'PHASE' )
70  FORMAT(/10X, '**** ERROR : E3 ****',
1    /15X,'PRESS. DROP ITERATION = ',14,
2    /15X,'FLOW RATE ITERATION = ',14)
71  FORMAT(/3X, '3) PRESSURE DROP ACROSS THE CORE = ', 2X,F10.4,
1    /3X, '4) PRESSURE DROP IN THE LOOP = ', 2X,F10.4,
2    /3X, 'TOTAL PRESSURE DROP IN THE WHOLE LOOP',
3    '(PUMP HEAD) = ', 2X,F10.4 )
C.....
C      ***** INPUT *****
C.....
1000 READ(5,1) COMMEN
C
      READ(5,1) COMM1
      READ(5,1) COMM2
      READ(5,2) ICASE, ISPEC, JSPEC, IRUN, ICAL
      IF(IRUN.EQ. 0) GO TO 2000
C
      READ(5,2) NCH, NODES, NSP
C * OPTION
      READ(5,1) COMM3
      READ(5,2) IOSUB, IOHW, IO2Q, IK, ISI, IREG, IBODE, IPRINT
      READ(5,2) IPILO, ISLIP, IRW
C * SYSTEM(CORE) PARAMETER
      READ(5,1) COMM4
      READ(5,4) P, TIN, ALHEAT, TSATP, AVEQ
C * PARAMETERS FOR FLOW REDISTRIBUTION

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      IF(IRW .EQ. 0) GO TO 100
      READ(5,4) DPGS, WIN
C    * CHANNEL COMMON PARAMETERS
100  READ(5,1) COMM5
      READ(5,4) CZERO, VGJ, DELX, DELZ, CHOM01, CHOM02
      READ(5,4) CK1, CMP
C    * LOCAL LOSS COEFFICIENT
      IF(NSP .EQ. 0) GO TO 3333
      READ(5,1) COMM6
      DO 101 N=1, NSP
      READ(5,5) ZSP(N), KLOSS(N)
101  CONTINUE
C
3333 IF(ICAL .LE. 1) GO TO 110
      IF(ICAL .EQ. 4) GO TO 110
C.....
C    * FOR THE LOOP ANALYSIS
C.....
C    (1) FOR THE UPPER PENUM
      READ(5,1) COMM7
      READ(5,4) AXSCH, AP, RAR, RPO, RP1, RP2
C    (2) FOR THE RISER
      READ(5,1) COMM8
      READ(5,4) COR, VGJR, RL, AR, DRIN, RKIN, RKEXIT
C    (3) FOR THE LOOP
      READ(5,1) COMM9
      READ(5,4) SLOOP, SFLOOP, AA, AD, DL, DHD, W0, RATW
C
      IF(ICAL .EQ. 3 .OR. ICAL .EQ. 5) GO TO 102
      GO TO 110
C
C    (4) FOR THE DOWNCOMER
102  READ(5,1) COMM10
      READ(5,4) HFW, ADC, PHV, DKV, CPV, DENV, TEMV, TEMINV, THV,
1      HOD, DLENG
      HOD = HOD/3600.
      THV = THV/3600.
C    (5) FOR THE LOWER PLENUM
      READ(5,1) COMM11
      READ(5,4) PLM, AHL, THLP, HOLP
      HOLP = HOLP/3600.
C
110  AVEQ = AVEQ/3600.
      W0 = W0*1.0E+06/3600.
      WIN = WIN*1.0E+06/3600.
      IF(ICASE.EQ.3 .OR. ICASE.EQ.5) IRW = 0
      IF(ICASE.EQ.6 .OR. ICASE.EQ.7 .OR. ICASE.EQ.9) IRW = 0
      IF(ICASE.EQ.13) IRW = 0
      IF(NCH .EQ. 1) IRW = 0
      IF(1K .EQ. 0) GO TO 111

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      NCH1 = NCH + 1
      IF(ICASE.EQ. 4.OR.ICASE.EQ.10) NCH1 = NCH
      IF(ICASE.EQ. 8.OR.ICASE.EQ.13) NCH1 = NCH
      IF(ICASE.EQ.14.OR.ICASE.EQ.15) NCH1=NCH
C.....
C      * READ 3D NUCLEAR INPUT DATA .....
C.....
      CALL NUCLER
C
C      * CHANNEL PARAMETRS
      READ(5,1) COMM12
      IF(ICASE.EQ.5.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 112
      JLL=1
      JRR=NCH
      JRR=NCH1
      GO TO 113
C
111 JJD(ISPEC,JSPEC) = 1
      KMAX = NODES
112 MSPEC=JJD(ISPEC,JSPEC)
      JLL=MSPEC
      JRR=MSPEC
      JRR=MSPEC
      NCH1=MSPEC
113 CONTINUE
C
      IF(ICASE.EQ.13) JRR=NCH
      DO 121 J=JLL,JRR
      READ(5,4) VEL3D(J),PH(J),AXS(J),DHIN(J),CXF(J),XKIN(J),
1      XKEXIT(J)
      IF(IK.NE. 0) GO TO 121
      READ(5,1) COMM4
      KNOD = 0
122 KNOD1 = KNOD + 1
      KNOD5 = KNOD + 5
      READ(5,4) (Q3D(J,i), i=KNOD1,KNOD5)
      KNOD = KNOD + 5
      IF(KNOD.LT. NODES) GO TO 122
121 CONTINUE
C      * PERTURBATION PARAMETER & FREQUENCY
      READ(5,1) COMM6
      READ(5,4) DELVI,DELQO,DELK
      READ(5,4) WFIN, WINT, WMULT, XKEFF
C      * PARAMETERS FOR HEATED WALL DYNAMICS
      READ(5,1) COMM7
      IF(10HW.EQ. 1) GO TO 130
      IF(10HW.EQ. 2) GO TO 131
      IF(10HW.EQ. 3) GO TO 132
      IF(10HW.EQ. 4) GO TO 133
130 READ(5,4) GPH, DENS

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GO TO 134
131 READ(5,4) CPH, TKH, DENSH, THICKH
GO TO 134
132 READ(5,4) CPH, TKH, DENSH, CRI, CRO
GO TO 134
133 READ(5,4) CPH,TKH,DENSH, CPC,TKC,DENSC, CRS,CRI,CRO, GAPC
GAPC = GAPC/3600.
134 CONTINUE
C
IF(1K .EQ. 0) GO TO 3000
C
IF( ICASE.EQ.13.OR. ICASE.EQ.14.OR. ICASE.EQ.15) GO TO 140
GO TO 150
140 CONTINUE
DO 160 N=1,NCH
READ(5,3) (TFLX(1,N,K9),K9=1,KMAX)
160 READ(5,3) (TFLX(2,N,K10),K10=1,KMAX)
150 CONTINUE
C
IF( ICASE.EQ.5.OR. ICASE.EQ.7.OR. ICASE.EQ.9) GO TO 200
C
DO 210 I=1,IMAX
JRL= JMX(I)
DO 210 J=1,JRL
M = JJD(I,J)
DO 210 K=1,KMAX
Q3D(M,K) = SRC(I,J,K) * AVEQ
210 CONTINUE
GO TO 220
200 CONTINUE
SUMSRC=0.
MSPEC=JJD(1SPEC,JSPEC)
DO 230 K=1,KMAX
230 SUMSRC=SUMSRC+SRC(1SPEC,JSPEC,K)/FLOAT(KMAX)
DO 240 K=1,KMAX
SRC(1SPEC,JSPEC,K)=SRC(1SPEC,JSPEC,K)/SUMSRC
240 Q3D(MSPEC,K)=SRC(1SPEC,JSPEC,K)*AVEQ
220 CONTINUE
C.....
C * NUCLEAR CROSS-SECTION MODELING
C.....
CALL XSMODL
C.....
C ***** PRINT INPUT PARAMETER *****
C.....
3000 WRITE(6,31) COMMEN
C
IF(NODES .EQ. 1) WRITE(6,33)
QQQ = AVEQ/3600.
WRITE(6,34) P, TIN, TSATP, ALHEAT, QQQ, NCH, NODES

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WRITE(6,35) WINT, WFIN, WMULT
WRITE(6,36) IOSUB, IOHW, IOZQ, IK, ISI, IREG, IBODE
C
WRITE(6,37)
IF((DELVI+DELQO+DELK) .LE. 0.0) GO TO 6000
IF(DELVI .NE. 0.) WRITE(6,38) DELVI
IF(DELQO .NE. 0.) WRITE(6,39) DELQO
IF(DELK .NE. 0.) WRITE(6,42) DELK
C
G1 = 32.17
GC = 32.17
PI = 3.141592654
C
IWIT = 0
KIP1 = 0
KIP2 = 0
MSPEC = 0
EPS1 = 1.0E-02
EPS2 = WIN*1.0E-02
IF(ICASE.EQ.5.OR.ICASE.EQ.7.OR.ICASE.EQ.9) MSPEC=JJD(ISPEC,JSPEC)
301 DO 340 I=JLL,JRR
300 VCH = VEL3D(I)
DO 315 J=1,NODES
DZ(I,J) = DELZ
IF(IK.EQ.0) GO TO 305
IF(I.EQ.NCH1 .AND. NCH1.NE.NCH) GO TO 310
QDIS(I,J) = Q3D(I,J)
GO TO 315
305 QDIS(I,J) = Q3D(I,J) * AVEQ
GO TO 315
310 CONTINUE
QDIS(I,J) = AXSRC(J) * AVEQ
IF(MSPEC.EQ.0) GO TO 315
QDIS(I,J)=Q3D(MSPEC,J)
315 CONTINUE
ICH = 0
IF(IRW.EQ.0) GO TO 316
IF(IRW.EQ.1 .AND. IWIT .LE. 1) GO TO 325
316 ICH = IPRINT
C.....
C * CALCULATE NODE-INDEPENDENT CONSTANTS
C.....
325 CALL CONSS(I,ICH,ICAL,IWIT)
C.....
C * CALCULATE STEADY-STATE NODAL QUANTITIES & PRESSURE DROPS
C.....
C
CALL STEADY(NODES, I, ICH, ICAL, IWIT)
C
C * FLOW REDISTRIBUTION WITH CONSTANT PRESSURE DROP BOUNDARY

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C      IF(IRW.EQ. 0) GO TO 335
      IF(IWIT.EQ. 2) GO TO 335
      RDPCH = (DPTS-DPGS) / DPGS
      IF(ABS(RDPCH).LE. EPS1) GO TO 330
      VEE = DPGS/DPTS
      VEL3D(1) = SQRT(VEE)*VEL3D(1)
      KIP1 = KIP1 + 1
      IF(KIP1.GT. 30) GO TO 4000
      IWIT = 1
      GO TO 300

C
330  IWIT = 0
      KIP1 = 0
      GO TO 340
335  IF((XCHOUT(1).GT.1.0) .OR. (XCHOUT(1).LE.0.0)) GO TO 5000
340  CONTINUE

C
C      * APPLY ANOTHER B.C ; WIN = SUM OF WI
C      WIN ; CORE TOTAL INLET FLOW RATE
C      WI ; CHANNEL INLET FLOW RATE
      IF(IRW.EQ. 0) GO TO 355
      IF(IWIT.EQ. 2) GO TO 355
      WSUM = 0.
      DO 345 J=JLL,JR
      WSUM = WSUM + VIN(J)*AXS(J)*DENSF
345  CONTINUE
      IF(ABS(WIN-WSUM).LE. EPS2) GO TO 350
      DPGS = DPGS*(1.+(SQRT(WIN)-SQRT(WSUM))/SQRT(WIN))
      KIP2 = KIP2 + 1
      IF(KIP2.GT. 30) GO TO 4000
      GO TO 301
350  IWIT = 2
      GO TO 301

C
355  DO 370 J=JLL,JRR
      IF(ISUB(J).GT. 0) GO TO 360
      LAMBDA(J) = CHLAMB(J)
      GO TO 370
360  LAMBDA(J) = 0.
370  CONTINUE

C
      WRITE(6,72) W0
72  FORMAT(/5X,'W0 =' ,E12.4)

C
      IF(1K.EQ. 0) GO TO 390
      DO 380 I=JLL,JR
      CHLAMB(I) = CHLAMB(I) * 30.48
380  CONTINUE

C

```

```

390 JL1=JLL
    JR1=JR
    IF(ICASE.EQ.5.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 440
    IF(ICASE.EQ.4.OR.ICASE.EQ.8.OR.ICASE.EQ.10) GO TO 440
    IF(ICASE.EQ.2.OR.ICASE.EQ.11.OR.ICASE.EQ.13) GO TO 440
    IF(ICASE.EQ.14.OR.ICASE.EQ.15) GO TO 440
    JL1=NCH1
    JR1=NCH1
440 CONTINUE
C.....
C * CALCULATE THE STEADY-STATE PARAMETERS OF THE LOOP
C.....
    DPLPT = 0.
    IF(IRW.EQ. 1) GO TO 393
    WOSUM = 0.
    DO 392 I=JLL,JR
    WOSUM = WOSUM + AXS(I)*GO(I)
392 CONTINUE
    WIN = WOSUM
    DPGS = DPTS
393 IF(ICAL.LE. 1) GO TO 391
    CALL XLOOP(ICAL, JLL, JRR)
391 DPTOT = DPGS + DPLPT
    WRITE(6,71) DPGS, DPLPT, DPTOT
    IF(IK.EQ. 0) GO TO 400
C.....
C * GENERATE 3D CROSS-SECTION AS FUNCTIONS OF VOID & EXPOSURE
C.....
    CALL XDATA
C
C
C
C $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C * CALCULATE EACH PERTURBATION CORRESPONDING TO THE ANGULAR
C FREQUENCY
C $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C
400 IF(ICAL.EQ.0) GO TO 2000
    WMUL=WMULT
    ISIG=ISI-1
    SIG = 10.0**(-ISI)
    SIGP1 = 1.0 + SIG
    OLDW=0.0
    RATIO = CMPLX(0.,0.)
C
    W1=WINT
    OLDW = 100000.0
    ICOUNT = 1

```

```

      IF(IREG .GE. 1) ICOUNT = 0
      GO TO 415
410  CONTINUE
      IF(IREG.EQ.2) W1=W1+WMUL
      IF(IREG.NE.2) W1=W1*WMUL
415  IF(W1.GT.WFIN)GO TO 600
      PERIOD = 2.0*PI/W1
      IF(IREG .GE. 1) GO TO 420
      OLDRAT = RATIO
      NPER=INT(ALOG10(PERIOD))
      IF(PERIOD.LE.1.0)ISIG=ISI
      PERIOD=AIN(10.**ISIG*PERIOD/(10.**NPER))*10.**(NPER-ISIG)
      W1 = 2.0*PI/PERIOD
      IF(ABS(OLDW-W1)/OLDW.LE.10.0**(-ISI)) GO TO 410
420  S=CMPLX(0.,W1)
C
      IF(IREG .GE. 1) GO TO 425
      IF(OLDW .GT. W1) GO TO 430
425  ICOUNT = ICOUNT + 1
      IF(ICOUNT .GT. 100) GO TO 600
430  WRITE(6,64)W1,PERIOD, WMUL, ICOUNT
C
      DO 460 K=JL1,JR1
C.....
C    ***  CALCULATE THE WALL DYNAMICS  ***
C.....
      IF(10HW .EQ. 0) GO TO 445
      CALL WALLDY(S, K)
445  CONTINUE
C.....
C    ***  CALCULATE THE PERTURBATION OF THE VOID DEPARTURE POINT
C          FOR IOSUB = 1, OR THE BOILING BOUNDARY FOR IOSUB = 0
C.....
      IF(ISUB(K) .GT. 0) GO TO 450
      XSBJ = 0.
      IF(IOSUB .EQ. 1) XSBJ = CSBX2(K)
      CALL DELBB(S, LAMBDA(K), K, XSBJ)
      GO TO 455
450  M1 = CMPLX(0.,0.)
      M2 = CMPLX(0.,0.)
      M3 = CMPLX(0.,0.)
C.....
C    ***  CALCULATE THE TOTAL PRESSURE DROP IN THE SINGLE- & THE TWO
C          PHASE REGION  ***
C.....
C    * CALCULATION OF CONSTANTS FOR PRESSURE DROP PERTURBATION
455  CALL CON2DP(S, K)
      CALL DPPERT(S, LAMBDA(K), K, ICAL)
460  CONTINUE
C.....

```



```

C      * CALCULATE PRESSURE DROP PERTURBATION FOR THE LOOP.
C.....
      DO 462 K=JLL,JRR
      RR1(K) = CMPLX(0.,0.)
      DWSW1(K) = CMPLX(0.,0.)
      DPUP1(K) = CMPLX(0.,0.)
462  CONTINUE
      RR2 = CMPLX(0.,0.)
      RR3 = CMPLX(0.,0.)
      DPUP2 = CMPLX(0.,0.)
      DPUP3 = CMPLX(0.,0.)
      DWSW2 = CMPLX(0.,0.)
      DWSW3 = CMPLX(0.,0.)
      T1 = CMPLX(0.,0.)
      DPH1 = CMPLX(0.,0.)
      IF(ICAL .LE. 1) GO TO 461
      CALL DPLP(ICAL,JL1,JR1,S)
C.....
C      * CALCULATE THE THERMAL-HYDRAULIC TRANSFER FUNCTION
C.....
461  CALL VDTF(ICAL,JL1,JR1,NCH)
      IF(ICAL .GE. 4) GO TO 590
C.....
C      *** CALCULATE NEUTRON KINETICS TRANSFER FUNCTION ***
C.....
      IF(IK) 470,470,471
470  ZPK = CMPLX(0.0,0.0)
      ZPKP= CMPLX(0.0,0.0)
      GO TO 480
C.....
471  CONTINUE
      IF(ICASE.EQ.13.OR.ICASE.EQ.14.OR.ICASE.EQ.15) GO TO 475
      CALL COEFT(S, IRUN, ICOUNT)
475  CALL KINET(S,ICOUNT,DELK)
C.....
C      * CALCULATE THE OPEN-LOOP TRANSFER FUNCTION, GH(S)
C.....
480  CALL STABTY(S,IK,RATIO,AMRAT,ARRAT,NCH1,ICOUNT,IBODE)
      WRITE(6,21) RATIO
C.....
C      $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C
C      DETERMINATION OF THE STEP SIZE TO GET POINTS EQUALLY SPACED IN THE
C      NYQUIST PLOT AND STORAGE OF DATA FOR PLOTTING
C.....
C      $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      PER(ICOUNT) = PERIOD
      XREA (ICOUNT) = REAL(RATIO)
      YIMA (ICOUNT) = AIMAG(RATIO)
      AMOD(ICOUNT) = AMRAT

```

```

    ARGU(ICOUNT) = ARRAT
    IF(IBODE .EQ. 1) GO TO 481
    IF(AMRAT.LE.1.E-40) GO TO 600
C
481 OLDW=W1
    IF(IREG .EQ. 1.OR. IREG.EQ.2) GO TO 410
    DRAT=CABS(OLDRAT-RATIO)
    IF(IBODE .EQ. 1) GO TO 482
    IF(AMRAT.LE.1.E-15) GO TO 410
482 DRAREL=DRAT/AMRAT
    IF(DRAREL.GT.0.4)GO TO 500
    IF(DRAREL.LE.0.1) GO TO 510
    GO TO 410
500 W1=W1/WMUL
    WMUL=SQRT(WMUL)
    IF(WMUL .LT. SIGP1) WMUL = 1.0 + SIG/2.0
    GO TO 410
510 WMUL=WMUL**2
    GO TO 410
C
590 CPS(ICOUNT) = W1/(2.*PI)
C
    GHPV(ICOUNT) = F11
    PHASE(ICOUNT) = SS2
    IF(ICAL .EQ. 6) GO TO 591
    VMAG(ICOUNT) = SS1 * DELQ0 * 100.
    GO TO 410
591 VMAG(ICOUNT) = ALOG10(SS1)*20.
    GO TO 410
C
600 IF(ICAL .LT. 4) GO TO 620
    WRITE(6,7)
    WRITE(6,8) XZ
    WRITE(6,9)
    WRITE(7,65)
    WRITE(8,66)
    DO 610 I=1,ICOUNT
        WRITE(6,13) CPS(I), GHPV(I), VMAG(I), PHASE(I)
        WRITE(7,6) CPS(I), VMAG(I)
        WRITE(8,6) CPS(I), PHASE(I)
610 CONTINUE
    GO TO 2000
C
620 ITCT = ICOUNT
    ICOUNT = ICOUNT - 1
C
    WRITE(6,15) (I, PER(I), XREA(I), YIMA(I), AMOD(I), ARGU(I),
1             I= 1, ITCT)
    WRITE(1,2) ITCT
    WRITE(1,6) (XREA(I),YIMA(I),I=1,ITCT)

```

```

C      * PLOT NYQUIST DIAGRAM
C      WRITE(6,16)
C      CALL POLPLT(XREA , YIMA , ICOUNT)
C      $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C      ***** STABILITY MARGIN CALCULATION *****
C      * STM ; MAGNITUDE MARGIN
C      * STA ; PHASE MARGIN
C      $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C      KV = 0
C      DO 630 I=2,ITCT
C      II = I - 1
C      KV = KV+1
C      YDIF = YIMA(I)*YIMA(II)
C      IF(YDIF .GT. 0.) GO TO 630
C      XMAG = XREA(II) + (XREA(I)-XREA(II))/(ABS(YIMA(I))+ABS(YIMA(II)))
C      1 *ABS(YIMA(II))
C      GO TO 640
C 630 CONTINUE
C 640 K2 = 0
C      XANG = -180.
C      IF(1.-AMOD(I) .GT. 0.) GO TO 660
C      DO 650 I=2,ICOUNT
C      IF(1.-AMOD(I) .LT. 0.) GO TO 650
C      II = I-1
C      K2 = K2+1
C      XANG=ARGU(II)+(ARGU(I)-ARGU(II))/(AMOD(I)-AMOD(II))*
C      1 (1.-AMOD(II))
C      GO TO 660
C 650 CONTINUE
C 660 IF(KV .EQ. ICOUNT-1 .OR. K2 .EQ. ICOUNT-1) GO TO 2000
C 660 STM = 20.*ALOG10(-1./XMAG)
C      STA = 180.+XANG
C      IF(STM .LE. 0 .OR. XANG .GE. 0.) WRITE(6,20)
C      WRITE(6,17) STM, STA
C      WRITE(1,18) STM
C      WRITE(1,19) ICASE
C      GO TO 2000
C      $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C 5000 WRITE (6,10) XCHOUT(1)
C      STOP

```

```

C
  4000 WRITE(6,70) KIP1,KIP2
      STOP
C
  6000 WRITE(6,12)
      STOP
C
  2000 IF( IRUN .GT. 0) GO TO 1000
      STOP
      END
C
C#####
C#####
C#####
C
C
C
C
C*****
C  VARIOUS FUNCTIONS (KAPL-M-6734, 1967)
C*****
C
C.....
  FUNCTION HL(P,T)
C.....
C  *      HL ; 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
C
C.....
  FUNCTION DENS(P,T,HPT)
C.....
C  *      DENS ; 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
C
C.....
  FUNCTION VF(P)
C.....
C
  VF = 1.7087E-02 + 0.6925E-05*P - 0.4254E-08*P**2 + 0.2180E-11*P**3

```

C - 0.0357E-14*P**4
 RETURN
 END

C
 C.....
 FUNCTION VFG(P)

C.....
 C
 VFG = 2.6454 - 5.9326E-03*P + 6.5891E-06*P**2 - 3.9249E-09*P**3
 C + 1.1897E-12*P**4 - 0.1441E-15*P**5
 RETURN
 END

C
 C.....
 FUNCTION HF(P)

C.....
 C
 HF = 323.9128 + 0.2964306*P - 0.944149E-04*P**2
 C + 0.165674E-07*P**3
 RETURN
 END

C
 C.....
 FUNCTION HFG(P)

C.....
 C
 HFG = 883.6608 - 0.2911105*P + 0.743325E-04*P**2
 C - 0.165592E-07*P**3
 RETURN
 END

C
 C.....
 REAL FUNCTION MUTL(T)

C.....
 C * VISCOSITY OF SATURATED LIQUID WATER IN RANGE
 C 32 TO 572 DEG. F(LBM/HR-FT)
 C * REF - ASME STEAM TABLES, PAGE 74
 C MUTL = 0.0584*10.0**(446.04/(207.6+T))
 RETURN
 END

C
 C.....
 FUNCTION COND(T)

C.....
 C * THERMAL CONDUCTIVITY OF SATURATED WATER IN RANGE
 C 32 TO 622 DEG. F(BTU/HR-FT-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
C
C
C.....
      FUNCTION MARNEL(P,G)
C.....
C *      CALCULATION OF PI(P,G) IN THE MARTINELLI-NELSON CORRELATION
C      FOR THE TWO-PHASE MULTIPLIER
      GHR = G*3600.
      G6 = GHR/1.E+06
      IF(G6 .GT. 0.7) GO TO 10
      MARNEL = 1.36 + 0.0005*P + 0.1*G6 - 0.000714*P*G6
      RETURN
C
10 MARNEL = 1.26 - 0.0004*P + 0.119/G6 + 0.00028*P/G6
      RETURN
      END
C
C
C
C
C      FUNCTION SGMA(P,TF)
C      ... SURFACE TENSION OF WATER(LBF/FT) AS FUNCTION OF PRESSURE
C      & SATURATED WATER TEMPERATURE
C      DIMENSION A(5)
C      DATA A/1.1609368E-01, 1.1214046E-03, -5.7528051E-06,
1      1.2862746E-08, -1.1497192E-11/
C
      SGMA = -1.0
      TR = (TF-32.0)*0.555555
      IF(TR .LT. 0. .OR. TR .GT. 374.15) GO TO 20
      TKMT = 374.15 - TR
      TKMTS = TKMT**2
      SGMA = (A(1)*TKMTS) / (1.0+0.83*TKMT)
      DO 10 N=2,5
      SGMA = SGMA + A(N)*TKMTS
      TKMTS = TKMTS*TKMT
10 CONTINUE
      SGMA = SGMA*0.68524E-04
20 CONTINUE
C
      RETURN
      END
C
C.....
      FUNCTION ANGL(COMP)
C.....
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 931
ANGL=57.296*ATAN2(FIMAG,DREAL)
RETURN
931 ANGL=90.0
IF(FIMAG.LE.0.0)ANGL=-90.0
IF(SQMOD.LE.1.0E-30)ANGL=0.0
RETURN
END

C
C.....
C      COMPLEX FUNCTION CCOTH(Z)
C.....
C      *      CALCULATE COTH(Z)      ,WHERE Z IS A COMPLEX VARIABLE
C
C      COMPLEX Z
C      IF(CABS(Z).GE. 99.) GO TO 1
C      CCOTH = (CEXP(Z)+CEXP(-Z)) / (CEXP(Z)-CEXP(-Z))
C      GO TO 2
C
C      1 CCOTH = CMPLX(1.,0.)
C      2 RETURN
C      END

C
C
C.....
C      COMPLEX FUNCTION EPOW(X,Z)
C.....
C      * CALCULATE X**Z      ( Z ; COMPLEX VARIABLE )
C
C      COMPLEX Z,Z1
C      IF(X.EQ. 1.) GO TO 10
C      Z1 = Z*ALOG(X)
C      EPOW = CEXP(Z1)
C      GO TO 20
C      10 EPOW = CMPLX(1.,0.)
C      20 RETURN
C      END

C
C
C.....
C      COMPLEX FUNCTION BS10(Z)
C.....
C      * MODIFIED BESSEL FUNCTION OF THE FIRST KIND OF ORDER ZERO
C      10(Z*SQRT(1)) = BER(Z) + I*BEI(Z)
C
C      Z1 = BER(Z)
C      Z2 = BEI(Z)

```

```

BS10 = CMPLX(Z1,Z2)
RETURN
END

```

```

C
C.....
COMPLEX FUNCTION BS11(Z)

```

```

C.....
C * MODIFIED BESSEL FUNCTION OF THE FIRST KIND OF ORDER ONE
C      I1(Z*SQRT(1)) = BE11(Z) - I*BER1(Z)
C      WHERE BE11(Z) = (SQRT(2)/2) * (BER'(Z)+BEI'(Z))
C      BER1(Z) = (SQRT(2)/2) * (BER'(Z)-BEI'(Z))
C

```

```

      BE11 = 0.707107 * (BERS(Z) + BEIS(Z))
      BER1 = 0.707107 * (BERS(Z) - BEIS(Z))

```

```

C
      BS11 = CMPLX(BE11, -BER1)
      RETURN
      END

```

```

C
C.....
COMPLEX FUNCTION BSK0(Z)

```

```

C.....
C * MODIFIED BESSEL FUNCTION OF THE SECOND KIND OF ORDER ZERO
C      K0(Z*SQRT(1)) = RKER(Z) + I*RKEI(Z)
C

```

```

      Z1 = RKER(Z)
      Z2 = RKEI(Z)
      BSK0 = CMPLX(Z1,Z2)
      RETURN
      END

```

```

C
C.....
COMPLEX FUNCTION BSK1(Z)

```

```

C.....
C * MODIFIED BESSEL FUNCTION OF THE SECOND KIND OF ORDER ONE
C      K1(Z*SQRT(1)) = -RKEI1(Z) + I*RKER1(Z)
C      WHERE RKEI1(Z) = (SQRT(2)/2) * (RKER'(Z)+RKEI'(Z))
C      RKER1(Z) = (SQRT(2)/2) * (RKER'(Z)-RKEI'(Z))
C

```

```

      REAL RKEI1, RKER1
      RKEI1 = 0.707107 * (RKERS(Z) + RKEIS(Z))
      RKER1 = 0.707107 * (RKERS(Z) - RKEIS(Z))

```

```

C
      BSK1 = CMPLX(-RKEI1, RKER1)
C
      RETURN
      END

```

```

C
C.....
FUNCTION BER(Z)

```



```

C.....
C      *** BER FUNCTION ***
C
C      DIMENSION P(7)
C      DATA P/ -64.0, 113.777778, -32.363457, 2.641914,
1      -0.083496, 0.001226, -0.000009/
C      DATA PI/3.141593/
C
C      IF(Z .GT. 10) GO TO 10
C      Y = Z/8.
C      BER = 1.
C      DO 1 I=1,7
C      I4 = 4 * I
C      BER = BER + P(I)*Y**I4
1 CONTINUE
C      RETURN
C
C* ASYMPTOTIC SOLUTION FOR Z>10
10 Z1 = (PI/180.) * (40.514*Z + 67.5)
C      Z2 = (PI/180.) * (40.514*Z + 22.5)
C      BER = (0.3989*EXP(Z/1.414214)/SQRT(Z)) * (SIN(Z1)+SIN(Z2)/(8.*Z))
C      RETURN
C      END
C
C.....
C      FUNCTION BEI(Z)
C.....
C      *** BEI FUNCTION ***
C
C      DIMENSION P(7)
C      DATA P/ 16.0, -113.777778, 72.817777, -10.567658,
1      0.521856, -0.011037, -0.000113/
C      DATA PI/3.141593/
C
C      IF(Z .GT. 10) GO TO 10
C      Y = Z/8.
C      BEI = 0.
C      DO 1 I=1,7
C      I1 = 2 * (2*I - 1)
C      BEI = BEI + P(I)*Y**I1
1 CONTINUE
C      RETURN
C
C* ASYMPTOTIC SOLUTION FOR Z>10
10 Z1 = (PI/180.) * (40.514*Z - 22.5)
C      Z2 = (PI/180.) * (40.514*Z - 67.5)
C      BEI = (0.3989*EXP(Z/1.414214)/SQRT(Z)) * (SIN(Z1)+SIN(Z2)/(8.*Z))
C      RETURN
C      END
C

```

```

C.....
C      FUNCTION BEIS(Z)
C.....
C      *** BEI' FUNCTION ***
C
C      DIMENSION P(6)
C      DATA P/ -10.666667, 11.377778, -2.311675, 0.146772,
1      -0.003794, 0.000046/
C      DATA PI/3.141593/
C
C      IF(Z .GT. 10) GO TO 10
C      Y = Z/8.
C      BEIS = 0.5
C      DO 1 I=1,6
C      I4 = 4 * I
C      BEIS = BEIS + P(I)*Y**I4
1 CONTINUE
C      BEIS = Z*BEIS
C      RETURN
C
C* ASYMPTOTIC SOLUTION FOR Z>10
10 Z1 = (PI/180.) * (40.514*Z + 22.5)
C      Z2 = (PI/180.) * (40.514*Z - 22.5)
C      BEIS = (0.3989*EXP(Z/1.414214)/SQRT(Z))
1      * (SIN(Z1) - SIN(Z2)*(3./(8.*Z)))
C      RETURN
C      END
C.....
C      FUNCTION BERS(Z)
C.....
C      *** BER' FUNCTION ***
C
C      DIMENSION P(7)
C      DATA P/ -4.0, 14.222222, -6.068148, 0.660478,
1      -0.026093, 0.000460, -0.000004/
C      DATA PI/3.141593/
C
C      IF(Z .GT. 10) GO TO 10
C      Y = Z/8.
C      BERS = 0.
C      DO 1 I=1,7
C      I1 = 2 * (2*I - 1)
C      BERS = BERS + P(I)*Y**I1
1 CONTINUE
C      BERS = Z*BERS
C      RETURN
C
C* ASYMPTOTIC SOLUTION FOR Z>10
10 Z1 = (PI/180.) * (40.514*Z + 112.5)

```

```

Z2 = (PI/180.) * (40.514*Z + 67.5)
BERS = (0.3989*EXP(Z/1.414214)/SQRT(Z)) * (SIN(Z1)-SIN(Z2)
1      *(3./(8.*Z)))
RETURN
END

```

```

C
C.....REAL FUNCTION RKER(Z)

```

```

C.....*** KER FUNCTION ***
C

```

```

DIMENSION P(7)
DATA P/-59.058197, 171.362721, -60.609775, 5.655391,
1      -0.196363, 0.003097, -0.000025/
DATA PI/3.141593/

```

```

C      IF(Z .GT. 10) GO TO 10
C      IF(Z .LT. 1) GO TO 20

```

```

C      X1 = Z/2.
C      X = -ALOG(X1)*BER(Z) + (PI/4.)*BEI(Z)
C      Y = Z/8.
C      RKER = -0.577216
C      DO 1 I=1,7
C      I4 = 4 * I
C      RKER = RKER + P(I)*Y**I4
1 CONTINUE
C      RKER = X + RKER
C      RETURN

```

```

C
C      * ASYMPTOTIC SOLUTION FOR Z>10
10 Z1 = (PI/180.) * (40.514*Z + 112.5)
C      Z2 = (PI/180.) * (40.514*Z - 22.5)
C      RKER = (1.2533*EXP(-Z/1.414214)/SQRT(Z)) * (SIN(Z1)+SIN(Z2)
1      /(8.*Z))
C      RETURN

```

```

C
C      20 A0 = 0.115932 - ALOG(Z)
C      X = Z/2.
C      RKER = A0 + (PI/4.)*X**2 - ((A0+3./2.)/4.)*X**4
1      - (PI/144.)*X**6 + ((A0+25./12.)/576.)*X**8
C      RETURN
C      END

```

```

C
C.....REAL FUNCTION RKEI(Z)

```

```

C.....*** KEI FUNCTION ***
C

```

```

C      DIMENSION P(7)

```

```

DATA P/ 6.764549, -142.918277, 124.235697, -21.300609,
1      1.175091, -0.026959, 0.000295/
DATA PI/3.141593/

C
IF(Z .GT. 10) GO TO 10
IF(Z .LT. 1) GO TO 20

C
X1 = Z/2.
X = -ALOG(X1)*BEI(Z) - (PI/4.)*BER(Z)
Y = Z/8.
RKEI = 0.
DO 1 I=1,7
  II = 2 * (2*I - 1)
  RKEI = RKEI + P(II)*Y**II
1 CONTINUE
RKEI = X + RKEI
RETURN

C
* ASYMPTOTIC SOLUTION FOR Z>10
10 Z1 = (PI/180.) * (40.514*Z + 22.5)
Z2 = (PI/180.) * (40.514*Z + 67.5)
RKEI = (1.2533*EXP(-Z/1.414214)/SQRT(Z)) * (-SIN(Z1)+SIN(Z2))
1      /(8.*Z))
RETURN

C
* FOR Z<1
20 A0 = 0.115932 - ALOG(Z)
X = Z/2.
RKEI = -PI/4. + (A0+1.)*X**2 - (PI/16.)*X**4
1      - ((A0+11./6.)/36.)*X**6 + (PI/2304.)*X**8
RETURN
END

C
C.....REAL FUNCTION RKEIS(Z)
C.....
C.....*** KEI' FUNCTION ***
C.....
C
DIMENSION P(6)
DATA P/-13.398589, 19.411828, -4.659508, 0.330494,
1      -0.009267, 0.000120/
DATA PI/3.141593/

C
IF(Z .GT. 10) GO TO 10
IF(Z .LT. 1) GO TO 20

C
X1 = Z/2.
X = -ALOG(X1)*BEIS(Z) - BEI(Z)/Z - (PI/4.)*BERS(Z)
Y = Z/8.
RKEIS = 0.211392
DO 1 I=1,6

```

```

      I4 = 4 * I
      RKEIS = RKEIS + P(I)*Y**I4
1 CONTINUE
      RKEIS = X + Z*RKEIS
      RETURN
C
C * ASYMPTOTIC SOLUTION FOR Z>10
10 Z1 = (PI/180.) * (40.514*Z - 22.5)
   Z2 = (PI/180.) * (40.514*Z + 22.5)
   RKEIS = (1.2533*EXP(-Z/1.414214)/SQRT(Z)) * (SIN(Z1)+SIN(Z2)
1       *(3./(8.*Z)))
      RETURN
C * FOR Z<1
20 A0 = 0.115932 - ALOG(Z)
   X = Z/2.
   RKEIS = (A0+0.5)*X + PI*X**3/8. - (A0+5./3.)*X**5/12.
1       - (PI*X**7)/576.
      RETURN
END
C
C.....
C..... REAL FUNCTION RKERS(Z)
C.....
C..... *** KER' FUNCTION ***
C.....
C      DIMENSION P(7)
      DATA P/ -3.691137, 21.420340, -11.364333, 1.413848,
1      -0.061364, 0.001161, -0.000011/
      DATA PI/3.141593/
C
      IF(Z .GT. 10) GO TO 10
      IF(Z .LT. 1) GO TO 20
C
      X1 = Z/2.
      X = -ALOG(X1)*BERS(Z) -BER(Z)/Z + (PI/4.)*BEIS(Z)
      Y = Z/8.
      RKERS = 0.
      DO 1 I=1,7
        II = 2 * (2*I - 1)
        RKERS = RKERS + P(I)*Y**II
1 CONTINUE
      RKERS = X + Z*RKERS
      RETURN
C
C * ASYMPTOTIC SOLUTION FOR Z>10
10 Z1 = (PI/180.) * (40.514*Z + 67.5)
   Z2 = (PI/180.) * (40.514*Z + 112.5)
   RKERS = -(1.2533*EXP(-Z/1.414214)/SQRT(Z)) * (SIN(Z1)+SIN(Z2)
1       *(3./(8.*Z)))
      RETURN

```



```

        DIFF1 = DABS(DIFF1)
        GO TO 403
402 DIFF1 = DREAL(C(N)) - DREAL(C(N1))
        DIFF1 = DABS(DIFF1)
403 IF(DIMAG(C(N)) .LE. 1.0E-06) GO TO 400
        DIFF2 = (DIMAG(C(N))-DIMAG(C(N1))) / DIMAG(C(N))
        DIFF2 = DABS(DIFF2)
        GO TO 401
400 DIFF2 = DIMAG(C(N)) - DIMAG(C(N1))
        DIFF2 = DABS(DIFF2)
401 IF(DIFF1 .LE. 1.0E-04 .AND. DIFF2 .LE. 1.0E-04) GO TO 200
        GO TO 300
C
200 GIFN2 = P1*C(N)
        GO TO 201
100 WRITE(6,10)
10 FORMAT(/5X,'*** EXP & POW INTEGRAL IS DIVERGE ***')
        STOP
201 RETURN
        END
C
C
C
C
C*****
        SUBROUTINE CONSS(I, ICH, ICAL, IWIT)
C*****
C      ..... CALCULATE THE STEADY-STATE CONSTANTS & SYSTEM PARAMETERS
        REAL KF, KLOSS, MUTL
        NAMELIST/CALPRO/ ENTH, ENTHP, DENSF, DENS1, VFG1, RHOG
        NAMELIST/PROPTY/ TSATP, TAVE, HFG1, VISC, CPF, KF, SIGM
        COMMON/CONST1/ C1(200), C2(200), C3(200), C4, C5(200), C8(200, 30),
1          C9(200, 30), C18(200), C21(200), C22(200), C25(200),
2          C26(200), T6, V7(200), DD1, CK1, CMP
        COMMON/CONST2/ P, VCH, VIN(200), AXS(200), DH(200), DHIN(200),
1          PH(200), TIN, TSATP, ENTH, DENS1, SIGM, ENTHP, VISC, CPF, KF,
2          DENSF, VFG1, RHOG, G0(200), G02(200), H0(200), GC, G1, KLOSS( 30),
3          FRICM0(200), VGJH(200, 30), COH(200, 30), CZERO, VGJ, DPTS,
4          G02RF(200), HFG1, ZSP( 30), NUMBSP(200, 30), ALHEAT, CXF(200),
5          AVEQ, CHOM01, CHOM02, XKIN(200), XKEXIT(200)
        COMMON /CUPPER/ RKIN, RKEXIT, AP, RPO, RP1, RP2, CL10, CL11,
1          CLT, AXSCH, RAR, AD, DL, DHD, FDL, F1(200), F2(200),
2          RJ1(200), RJ2(200), RJ3(200), F3(200)
        COMMON /CDELH1/ HFW, ADC, PHV, DKV, CPV, DENV, TEMV, TEMINV,
1          THV, HOD, PLM, AHL, THLP, HOLP, WO, DLENG
C
10 FORMAT(////10X,'***** SYSTEM PROPERTIES *****')
C
        IF(IWIT .GE. 1) GO TO 20
        TSAT=TSATP

```



```

TAVE=(TIN+TSAT)/2.
ENTHT=HL(P,TIN)
ENTHP=HF(P)
HFG1=HFG(P)
VISC=MUTL(TAVE)/3600.0
VISDL=MUTL(TSAT)/3600.0
SIGM = SGMA(P,TSATP)

C
CPF= (HL(P,TSAT)-ENTHT)/(TSAT-TIN)
KF=COND(TAVE)/3600.
DENS1 = DENS(P,TIN,DUMB)
DENSF=DENS(P,TAVE,DUMB)
VFG1 = VFG(P)
VGAS = VFG1 + VF(P)
RHOG = 1.0/VGAS
DH(1) = DHIN(1)/12.0

C
20 VIN(1) = VCH*DENS1/DENSF
GO(1)=DENSF*VIN(1)
GO2(1) = GO(1)**2
GO2RF(1) = GO2(1)/(2.0*DENSF*GC)
HO(1)=KF/DH(1) * .023 * (DENSF*VIN(1)*DH(1)/VISC)**(0.8)
1 * (CPF*VISC/KF)**(0.4)

C
C * CALCULATION OF THE SINGLE-PHASE DARCY-WEISBACH FRICTION FACTOR
C BY FITTING THE MOODY CURVES
C @ RPD ; SURFACE ROUGHNESS / DH(1) IN COMMERCIAL STEEL PIPE
C @ RE ; RENOLD'S NUMBER
RPD = -1.41E-05*DHIN(1) + 3.36E-04
RE = GO(1)*DH(1)/VISC
FRICMO(1) = 0.0055*(1.0 + (20000.*RPD + 1.0E+06/RE)**(1./3.))

C
IF(ICAL .GE. 2 ) GO TO 200
GO TO 201
200 RDL = -1.41E-05*(DHDL/12.0) + 3.36E-04
REDL = (WO/AD)*DHDL/VISDL
FDL = 0.0055*(1.0+(20000.*RDL + 1.0E+06/REDL)**(1./3.))

C
201 IF(IWIT .GE. 1) GO TO 30
202 T6 = G1/GC*DENSF
C4 = DENSF - RHOG
C5(1) = PH(1)*VFG1/(AXS(1)*HFG1)
C25(1) = C4*PH(1)/AXS(1)/DENSF
C26(1) = 1.14677E-06 * (3.*CCON(P)/CPF)

C
C
30 V7(1) = FRICMO(1)*GO(1)*VIN(1)/(2.*GC*DH(1))
C1(1) = PH(1)/(DENSF*VIN(1)*CPF*AXS(1))
C2(1) = V7(1) + T6
C3(1) = FRICMO(1)*GO(1)/(GC*DH(1))
C18(1) = CXF(1)/(GO(1)*AXS(1))

```

```

      DD1 = MARNEL(P,GO(1)) * (1.2*(DENSF/RHOG) - 1.)
C
      IF(IWIT .GE. 1) GO TO 100
      IF(ICH .EQ. 0) GO TO 100
      WRITE(6,10)
      WRITE(6,CALPRO)
      WRITE(6,PROPTY)
100 RETURN
      END
C
C
C
C
C*****
      SUBROUTINE STEADY(NODES,INODE,ICH,ICAL,IWIT)
C*****
C      * CALCULATE STEADY-STATE VALUES
C      * LAMBDA ; BOILING BOUNDARY
C      * JOIN(1) ; NODE INLET FLOW VELOCITY
C      * DOIN(1); NODE INLET DENSITY
C      * XEXIT ; STEADY-STATE CHANNEL EXIT QUALITY
C      * ALFNOD(INODE,1) ; NODE AVERAGE VOID FRACTION
C
      REAL K1,JOIN,KF,KLOSS
      DIMENSION DPH2PG(30), H(30),CZ(30),VGZ(30),TWALL(30),DPSP(30),
1      DPH2PF(30),DPH2PA(30),DPH2P(30),TBULK(30),CKSP(30),
2      XEXIT(30), JOIN(30)
      DOUBLE PRECISION XAVG,OMG,DELOMG,CTEM0,CTEM1,CTEM2,CTEM3,OMIN,
1      OMAX, SBHOUT(30),SBHIN(30),V1(30),ALPOUT(30),AVGH(30),
2      VOOOUT(30),CKOUT(30),OLDOMG(100),DIFF(100),C15(30),
3      C101(30),C103(30),C104(30),C105(30),C16(30),
4      C107(30),C108(30),C109(30),C110(30)
C
      COMMON/OPTION/ IOSUB, IOHW, IO2Q, IPILO, ISLIP, IRW
      COMMON/CONST1/ C1(200),C2(200),C3(200),C4,C5(200),C8(200,30),
1      C9(200,30),C18(200), C21(200), C22(200),C25(200),
2      C26(200), T6, V7(200), DD1, CK1, CMP
      COMMON /CONSUB/ CSB2(200,30),CSB3(200,30),CSB4(200,30),
1      CSB5(200,30),CSB6(200,30),CSB7(200,30),CSB8(200,30),
2      CSB9(200,30),CSB10(200,30),CSBQ(200,30),CSBD(200,30),
3      CSBE(200,30),CSBF(200,30), CSBG(200,30),CSBX1(200),
4      CSBX2(200)
      COMMON/CONST2/ P,VCH,VIN(200),AXS(200),DH(200),DHIN(200),
1      PH(200),TIN,TSATP,ENTHT,DENSI,SIGM,ENTHP,VISC,CPF,KF,
2      DENSF,VFG1,RHOG,GO(200),GO2(200),HO(200),GC,G1,KLOSS(30),
3      FRICMO(200),VGJH(200,30),COH(200,30),CZERO,VGJ,DPTS,
4      GO2RF(200),HFG1,ZSP(30),NUMBSP(200,30),ALHEAT,CXF(200),
5      AVEQ,CHOMO1,CHOMO2,XKIN(200),XKEXIT(200)
      COMMON /CONWD1/ CPH,TKH,DENSH,CPC,TKC,DENSC,CRS,CRI,CRO,
1      GAPC,V22(200,30), THICKH

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C      COMMON /RISER/ COR,VGJR,CKRO,RL,AR,DRIN,DR,PI,CL1,CL2,CL3,CL4,
1      CL5,CL6,CR5,CR6,UPJ1,UPJ2,RO11,RO12,
2      RO21,RO22,XROUT,UPJIN
      COMMON /CLOOP/ SLOOP,SFLOOP,RLOOP,AA,VL1,VL2,VL3,DPLPT
      COMMON /CUPPER/ RKIN,RKEXIT,AP,RPO,RP1,RP2,CL10,CL11,
1      CLT,AXSCH,RAR,AD,DL,DHDL,FDL,F1(200),F2(200),
2      RJ1(200),RJ2(200),RJ3(200),F3(200)
      COMMON /CDELH1/ HFW,ADC,PHV,DKV,CPV,DENV,TEMV,TEMINV,
1      THV,HOD,PLM,AHLP,THLP,HOLP,WO,DLENG
      COMMON /CDELH2/ CH1,CH2,CH3,CH4,CH5,CH7,CH8,CH9,CH10

C      COMMON/CONSS1/ QDIS(200,30),QO(200,30),DZ(200,30),Z(200,30),
1      K1(200,30),CKIN(200,30),ZETA(200,30),DOIN(200,30),
2      DOOUT(200,30),ALPIN(200,30),BEE(200,30),CPI1(200,30),
3      COR2PH(200,30),ZETSP(200,30),WIN
      COMMON /DIM1/ DELX,DELZ,CHLAMB(200),ALFNOD(200,30),
1      BBLAMB(200)
      COMMON/CONSS2/ NTOT(200),NBB(200),NBB1(200),NSP,N1PSP(200),
1      K2PSP(200),NDP(200),NDP1(200),ISUB(200)
      COMMON/PCHOUT/XCHOUT(200),ACHOUT(200),CCHOUT(200)

C *****
C * VIN IS THE AVERAGE VELOCITY IN THE SINGLE-PHASE
C REGION, ALL CALCULATIONS ARE BASED ON THIS VELOCITY.
C
C .....
C * FORMAT STATEMENTS
C .....
3  FORMAT(/10X,'*** NO BULK BOILING ALONG THE CHANNEL ; HEXIT =',
1  E12.4,' (BTU/LBM) ***')
5  FORMAT(/3X,'STEADY STATE VOID FRACTION WITH CONSTANT CO &VGJ')
7  FORMAT(/3X,'STEADY STATE VOID FRACTION WITH VARIABLE CO &VGJ')
9  FORMAT(2E15.5)
11 FORMAT(/5X,'CHANNEL GEOMETRY & BOILING BOUNDARY',/10X,
1  'FLOW AREA',6X,'HEAT PERI.',5X,'HYDR.DIAM.',5X,
2  'BOIL.BOUND.',5X,'FRICTION F.',/12X,'(FT2)',11X,
3  '(FT)',11X,'(IN)',11X,'(FT)' //9X,F9.4,4(6X,F9.4))
41 FORMAT(///'HEATED WALL DYNAMICS PARAMETER')
43 FORMAT(/5X,'***** NO HEATER WALL DYNAMICS *****')
45 FORMAT(/5X,'*** LUMPED PARAMETER MODEL ***',
1  //10X,'SPECIFIC HEAT OF HEATER =',E12.6,'(BTU/LB-F)',
2  /10X,'DENSITY OF HEATER =',E12.6,'(LB/FT3)')
47 FORMAT(/5X,'*** PARALLEL PLATE HEATER ***',/10X,
1  'SPECIFIC HEAT OF HEATER =',E12.6,'(BTU/LB-F)',/10X,
2  'DENSITY OF HEATER =',F9.4,'(LB/FT3)',/10X,
3  'THICKNESS OF HEATER =',F9.4,'(FT)')
49 FORMAT(/5X,'*** CYLINDRICAL INTERNALLY HEAT TUBE ***',
1  /10X,'SPECIFIC HEAT OF HEATER =',E12.6,'(BTU/LB-F)',/10X,
2  'DENSITY OF HEATER =',F9.4,'(LB/FT3)',/10X,

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3      'INNER RADIUS OF TUBE      =', F9.4, '(FT)'      ,/10X,
4      'OUTER RADIUS OF TUBE      =', F9.4, '(FT)'      }
51 FORMAT(/5X, '*** BWR FUEL ROD ***', //7X,
*      '* FUEL REGION'/10X,
1      'SPECIFIC HEAT OF FUEL      =', E12.6, '(BTU/LB-F)' ,/10X,
2      'THERMAL CONDUCTIVITY      =', E12.6, '(BTU/S-FT-F)' ,/10X,
3      'DENSITY OF FUEL           =', F9.4, '(LB/FT3)' ,/10X,
4      'FUEL RADIUS               =', F9.4, '(IN)' ,//7X,
5      '* CLAD REGION'/10X,
6      'SPECIFIC HEAT OF CLAD      =', E12.6, '(BTU/LB-F)' ,/10X,
7      'THERMAL CONDUCTIVITY      =', E12.6, '(BTU/S-FT-F)' ,/10X,
8      'DENSITY OF CLAD           =', F9.4, '(LB/FT3)' ,/10X,
9      'INNER RADIUS OF CLAD       =', F9.4, '(IN)' ,/10X,
*      'OUTER RADIUS OF CLAD       =', F9.4, '(IN)' ,//7X,
1     'GAP CONDUCTANCE            =', E12.6, '(BTU/FT2-F)' )
53 FORMAT(/5X, 'BULK & WALL TEMPERATURE FOR STEADY-STATE',
1     //10X, 'NODE', 12X, 'TBULK', 14X, 'TWALL')
55 FORMAT(10X, 13, 2(10X, F9.2))
57 FORMAT(10X, 'NODE', 8X, 'Z', 12X, 'HEAT FLUX', 5X, 'POWER DENSITY')
59 FORMAT(/10X, '***** TWO-PHASE REGION *****')
61 FORMAT(/10X, 13, 5X, F10.4, 3X, F10.4, 8X, E12.6)
63 FORMAT(/43H AVERAGE VOID FRACTION IN TEST SECTION = , F6.4/
1     'EXIT VOID FRACTION = ', F6.4 , 5X, 'CO = ', F7.3, 5X,
2     'VGJ = ', F7.3 /15H EXIT QUALITY = , F8.5 /
3     '13H MASS FLUX = , 1PE12.3, 12H LBM/HR FT2 /
4     '34H AVE. VELOCITY IN 1-PHASE REGION = , 0PF7.3, 5H FT/S /
5     '36H VELOCITY AT HEATED SECTION EXIT = , F8.3, 5H FT/S )
65 FORMAT(/5X, 'INLET ENTHALPY =', 2X, F10.4, 2X, '(BTU/LBM)',
1     /5X, 'VOID DEPARTURE ENTHALPY =', 2X, F10.4, 2X, '(BTU/LBM)')
67 FORMAT(1H1, ///, 'NODE THERMAL-HYDRAULIC PROPERTIES', //5X, 'NODE',
1     5X, 'DELZ',
2     8X, 'K1', 13X, 'CO(Z)', 5X, 'VGJ(Z)', 6X, 'AVG. VOID', 4X, 'XEXIT(Z)',
3     4X, 'AVG. ENTH.', 5X, 'JOIN')
69 FORMAT(/5X, 14, 2X, F9.4, 3X, E10.4, 3(3X, F9.4), 2(3X, E12.5), 3X, E12.4)
71 FORMAT(///, 'LOCAL PRESSURE DROP BY SPACER',
1     //11X, 'Z', 13X, 'LOCAL COEFF.', 7X, 'LOCAL DP')
73 FORMAT(/6X, F9.4, 10X, E12.6, 5X, E12.6)
75 FORMAT(1H1, ///, 'STEADY-STATE PRESSURE DROP', //3X,
1     '1) SINGLE-PHASE REGION', /6X, 'LOCAL LOSS =', F10.4, '(PSI)',
2     /6X, 'GRAVITY =', F10.4, '(PSI)', 16X, 'FRICTION =', F10.4,
3     '(PSI)', /6X, 'TOTAL DP =', F10.4, '(PSI)')
77 FORMAT(///, 3X, 2) TWO-PHASE REGION', //27X, 'GRAVITY', 9X,
1     'FRICTION(COR2PH)', 7X, 'ACCELERATION', 7X, 'TOTAL',
2     /6X, 'NODE', 5X, 'Z', 12X, '(PSI)', 15X, '(PSI)',
3     15X, '(PSI)', 12X, '(PSI)')
79 FORMAT(/5X, 14, F10.4, 2(5X, F10.4), ' ', F9.4, ')', 2(5X, F10.4))
81 FORMAT(/6X, 'TOTAL', 13X, F10.4, 3(5X, F10.4), //6X, 'LOCAL LOSS =',
1     F10.4, '(PSI)', /3X, 'TOTAL CHANNEL PRESSURE DROP =',
2     F10.4, '(PSI)')

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85 FORMAT(/10X,'*** ERROR : E4 ***')
87 FORMAT(/10X,'*** ERROR : E5 ***', F9.4)
C ..... COMMENTS .....
C ISUB = 0 ; THERE IS A SINGLE-PHASE REGION
C      = 1 ; NO SINGLE-PHASE REGION
C IWIT = 0 ; SINGLE CHANNEL CALCULATION OR INITIAL CALCULATION
C          FOR MULTI-CHANNEL CALCULATION
C      = 1 ; MULTI-CHANNEL CALCULATION
C      = 2 ; FINAL CALCULATION FOR MULTI-CHANNEL CALCULATION
C NDP1 ; FIRST NODE INDEX IN THE SUBCOOLED BOILING REGION
C NBB1 ; FIRST NODE INDEX IN THE BULK BOILING REGION
C .....
C IF(IWIT .GE. 1) GO TO 100
C H(1) = ENTH
C CRIT = ENTHP
C IF(ISLIP .EQ. 1) GO TO 101
C AA1 = 23.
C AA2 = 0.
C GO TO 100
101 AA1 = 4.
C AA2 = 2.
100 GOHR = GO(INODE)*3600.0
C PE = GO(INODE)*DH(INODE)*CPF/KF
C .....
C * DETERMINATION THE VOID DEPARTURE POINT WITH SAHA-ZUBER MODEL
C .....
C ISUB(INODE) = 0
C ITER = 0
C IBB = 0
C NP1 = NODES
C DO 120 J=1,NP1
C   JNOD = J
C   JA = J + 1
C   JN = J - 1
C   QFLUX = QDIS(INODE,J)*CXF(INODE)/PH(INODE)
C   BEE(INODE,J) = QDIS(INODE,J) /AVEQ
C   QO(INODE,J) = QFLUX
C   H(JA) = H(J) + QFLUX*PH(INODE)*DZ(INODE,J)/AXS(INODE)/
C   GO(INODE)
C 1 IF(IOSUB .EQ. 0) GO TO 1000
C   IF(PE .LE. 7.0E+04) GO TO 122
C   CRIT = ENTHP - 1.53846E+02*QFLUX/GO(INODE)
C   IF(H(JA) .GE. CRIT) GO TO 123
C   GO TO 120
122 CRIT = ENTHP - 2.1978E-03*QFLUX*DH(INODE)*CPF/KF
C   IF(H(JA) .GE. CRIT) GO TO 123
C   GO TO 120
1000 IF(H(JA) .GE. ENTHP) GO TO 124
120 CONTINUE
C

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123 IF(H(1) .GE. CRIT) GO TO 150
C
124 NDP(INODE) = JNOD
   INN = NDP(INODE)
   NDP1(INODE) = JNOD + 1
   NDM2 = JNOD - 1
   IF(10SUB .EQ. 0) GO TO 1001
   DZVD = (CRIT-H(JNOD))*AXS(INODE)*GO(INODE)/QFLUX/PH(INODE)
   IF(DZVD .LT. 0.) GO TO 131
   GO TO 140
1001 DZVD = (ENTHP-H(INN))*GO(INODE)*AXS(INODE)/(QDIS(INODE, INN)
1    *CXF(INODE))
   GO TO 140
131 QFLUX=(QO(INODE, JNOD)+QO(INODE, NDM2))/2.
   CRIT = ENTHP - 1.53846E+02*QFLUX/GO(INODE)
   IF(PE .LE. 7.0E+04) CRIT = ENTHP - 2.1978E-03*QFLUX*DH(INODE)
1    *CPF/KF
   DZVD = (CRIT-H(NDM2))*AXS(INODE)*GO(INODE)/QFLUX/PH(INODE)
   IF(DZVD .GE. DZ(INODE, NDM2)) GO TO 132
   NDP(INODE) = NDM2
   NDM2 = NDM2 - 1
   INN = NDP(INODE)
   NDP1(INODE) = INN + 1
   GO TO 140
132 DZVD = DZVD - DZ(INODE, NDM2)
140 IF(NDM2 .EQ. 0) GO TO 141
   ZSUM = 0.
   DO 142 I=1, NDM2
     ZSUM = ZSUM + DZ(INODE, I)
     Z(INODE, I) = ZSUM
142 CONTINUE
   CHLAMB(INODE) = ZSUM + DZVD
   GO TO 143
141 CHLAMB(INODE) = DZVD
C
C   * NODE REDISTRIBUTION IN THE SUBCOOLED BOILING REGION
C
143 CALL ASSIGN(NDP(INODE), NP1, CHLAMB(INODE), 0, INODE, 0)
   GO TO 160
C
150 1SUB(INODE) = 1
   NDP1(INODE) = 1
   GO TO 170
160 NP1 = NP1 + 1
170 INN1 = NDP1(INODE)
C
C   * CALCULATE THE THERMAL PARAMETERS IN THE SUBCOOLED BOILING
C     REGION
C   . . . . .
C

```

```

C      C101(J) = ALPIN(INODE,J)
C      C103(J) = JOIN(J)
C      C104(J) = CKIN(INODE,J)
C      C105(J) = ZETA(INODE,J)
C      C106(J) = DOOUT(INODE,J)
C      C107(J) = XEXIT(J)
C      C108(J) = ALFNOD(INODE,J)
C      C109(J) = CSB2(INODE,J)
C      C110(J) = CSB3(INODE,J)
C
190 DO 200 I=1,INN1
      C103(I) = VIN(INODE)
      C104(I) = C103(I)
      C101(I) = 0.
      DOIN(INODE,I) = DENSF
200 CONTINUE
      IST = 0
      DO 201 I=INN1,NP1
        COH(INODE,I) = CZERO
        VGJH(INODE,I) = VGJ
201 CONTINUE
      GO TO 202
9000 DO 203 I=INN1,NP1
      COH(INODE,I) = CZ(I)
      VGJH(INODE,I) = VGZ(I)
203 CONTINUE
202 C104(INN1) = COH(INODE,INN1)*C103(INN1)+VGJH(INODE,INN1)
      DO 204 I=INN1,NP1
        C15(I) = DENSF/(C4*COH(INODE,I))
        C16(I) = COH(INODE,I)*RHOG/DENSF + RHOG*VGJH(INODE,I)/GO(INODE)
204 CONTINUE
      IF(IOSUB.EQ. 0) GO TO 1002
      SBHIN(INN1) = CRIT
      V0OUT(J) = C103(J) + DZ(INODE,J)*OLDOMG(IBUN)
      AVGJ = (C103(J)+V0OUT(J))/2.
      A1 = 1./(1.+AA1*(AVGJ/VIN(INODE))**AA2)
      CKOUT(J) = COH(INODE,J)*V0OUT(J) + VGJH(INODE,J)
      C105(J) = CKOUT(J)/C104(J)
      ALPOUT(J) = C15(J)*(1.-(1./C105(J))) + C101(J)
1      * (1./C105(J))
      DOOUT(INODE,J) = DENSF - C4*ALPOUT(J)
      C107(J) = ALPOUT(J)*C16(J)/(1.-ALPOUT(J)/C15(J))
      V1(J) = C104(J)/(COH(INODE,J)*OLDOMG(IBUN)*DZ(INODE,J))
      C108(J) = V1(J) * (C15(J)*(C105(J)-1.) +
      V0OUT(J) = C103(J) + DZ(INODE,J)*OLDOMG(IBUN)
      AVGJ = (C103(J)+V0OUT(J))/2.
      A1 = 1./(1.+AA1*(AVGJ/VIN(INODE))**AA2)
      CKOUT(J) = COH(INODE,J)*V0OUT(J) + VGJH(INODE,J)
      C105(J) = CKOUT(J)/C104(J)
1      ALPOUT(J) = C15(J)*(1.-(1./C105(J))) + C101(J)
      * (1./C105(J))

```

```

DOOUT(INODE,J)= DENSF - C4*ALPOUT(J)
C107(J) = ALPOUT(J)*C16(J)/(1.-ALPOUT(J)/C15(J))
V1(J) = C104(J)/(COH(INODE,J)*OLDOMG(IBUN)*DZ(INODE,J))
C108(J) = V1(J) * (C15(J)*(C105(J)-1.) +
1 (C101(J) - C15(J))*DLOG(C105(J)))
XAVG = C108(J)*C16(J)/(1.-C108(J)/C15(J))
CTEMO = GO(INODE)*VFG1*(1.-XAVG)*COH(INODE,J)

```

```

C109(J) = C104(J)/CTEMO
C110(J) = (QFLUX*PH(INODE)*VFG1/AXS(INODE)-OLDOMG(IBUN)
1 *(ENTHP+HFG1)) / (CTEMO*OLDOMG(IBUN)/C104(J))
CTEM1 = -C110(J)/C109(J)
CTEM2 = (SBHIN(J)-CTEM1) * DEXP(-C109(J))
CTEM3 = C109(J)*C105(J)
SBHOUT(J) = CTEM2*DEXP(CTEM3) + CTEM1
AVGH(J) = (SBHOUT(J)+SBHIN(J))/2.

```

```

C
OMG = C25(INODE)*QFLUX*(AVGH(J)-CRIT)/(ENTHP-CRIT)/(RHOG*
1 HFG1+DENSF*(ENTHP-AVGH(J))) - A1*C108(J)*
2 (ENTHP-AVGH(J))

```

```

C
DIFF(IBUN) = (OLDOMG(IBUN) - OMG)
DELOMG = DIFF(IBUN) / OMG

```

```

C
IF(DABS(DELOMG) .LE. 1.0E-03) GO TO 212
IBUN2 = IBUN - 1
IBUN1 = IBUN
IBUN = IBUN + 1
IF(IBUN .LE. 2) GO TO 220
CHSIG = DIFF(IBUN1)*DIFF(IBUN2)
IF(CHSIG .LT. 0.) GO TO 221
GO TO 222

```

```

221 OMAX = DMAX1(OLDOMG(IBUN1),OLDOMG(IBUN2))
OMIN = DMIN1(OLDOMG(IBUN1),OLDOMG(IBUN2))

```

```

222 OLDOMG(IBUN) = (DIFF(IBUN1)*OLDOMG(IBUN2) - DIFF(IBUN2)*
1 OLDOMG(IBUN1)) / (DIFF(IBUN1) - DIFF(IBUN2))
IF(OLDOMG(IBUN).LT.OMIN) OLDOMG(IBUN)=(OLDOMG(IBUN1)+OMIN)/2.
IF(OLDOMG(IBUN).GT.OMAX) OLDOMG(IBUN)=(OLDOMG(IBUN1)+OMAX)/2.
GO TO 211
220 OLDOMG(IBUN)=OLDOMG(IBUN1)/2.
GO TO 211

```

```

C
212 IF(C105(J)-1. .LE. 1.0E-05) GO TO 224

```



```

      K1(INODE,J) = OMG
      QO(INODE,J) = QDIS(INODE,J)*CXF(INODE)/PH(INODE)
      BEE(INODE,J) = QDIS(INODE,J) / AVEQ
      ALPIN(INODE,J) = C101(J)
      JOIN(J) = C103(J)
      CKIN(INODE,J) = C104(J)
      ZETA(INODE,J) = C105(J)
      XEXIT(J) = C107(J)
      ALFNOD(INODE,J) = C108(J)
      CSB2(INODE,J) = C109(J)
      CSB3(INODE,J) = C110(J)
      GO TO 228
224 NP1 = NP1 - 1
      Z(INODE,INN) = Z(INODE,INN1)
      DZ(INODE,INN) = DZ(INODE,INN) + DZ(INODE,INN1)
      DO 225 I=INN1,NP1
        II = I + 1
        Z(INODE,I) = Z(INODE,II)
        DZ(INODE,I) = DZ(INODE,II)
        QDIS(INODE,I) = QDIS(INODE,II)
225 CONTINUE
      GO TO 190
C.....
C * PARAMETERS IN THE SUBCOOLED BOILING REGION CALCULATION
C.....
228 CSB4(INODE,J) = CKIN(INODE,J)*AVGJ / (COH(INODE,J)*K1(INODE,J)*
1      DZ(INODE,J)*VFG1*GO(INODE)**2)
      CTEM4 = CTEM0*K1(INODE,J)/CKIN(INODE,J)
      CSB5(INODE,J) = VFG1*DENSF*(1.-ALFNOD(INODE,J)) / CTEM4
      CSB6(INODE,J) = (ENTHP+HFG1-CTEM1) / CTEM4
      CSB7(INODE,J) = CTEM2 / CTEM4
      CSB8(INODE,J) = CSB2(INODE,J)*CTEM2/(1.-XAVG)
      CSB9(INODE,J) = -CSB2(INODE,J)*CTEM2/GO(INODE)
      CSB10(INODE,J) = (PH(INODE)*VFG1/AXS(INODE))/CTEM4
      CSBQ(INODE,J) = (C4*PH(INODE)*QO(INODE,J)/AXS(INODE)/DENSF) /
1      (ENTHP-CRIT)
      CSBD(INODE,J) = (AVGH(J)-CRIT)/(RHOG*HFG1+DENSF*(ENTHP-AVGH(J)))
      CSBF(INODE,J) = CSBQ(INODE,J)*(RHOG*HFG1+DENSF*(ENTHP-CRIT))
1      /((RHOG*HFG1+DENSF*(ENTHP-AVGH(J)))**2 + A1*
2      ALFNOD(INODE,J))
      CSBG(INODE,J) = A1*(ENTHP-AVGH(J))
      CSBE(INODE,J) = CSBQ(INODE,J)*CSBD(INODE,J)*(AVGH(J)-ENTHP)/
1      (ENTHP-CRIT)/(AVGH(J)-CRIT)
      CSBX1(INODE) = -2.1978E-03*DH(INODE)*CPF/KF
      IF(PE .GT. 7.0E+04) CSBX1(INODE) = -1.53846E+02/GO(INODE)
      CSBX2(INODE) = 0.
      IF(PE .GT. 7.0E+04) CSBX2(INODE)=1.53846E+02*QO(INODE,INN1)
1      *DENSF/GO(INODE)**2
      IF(IST .NE. 1) GO TO 234
      IF(J .EQ. NBB(INODE)) GO TO 301

```

```

234 IF(ITER .EQ. 1) GO TO 300
    IF(J .EQ. 1) GO TO 230
    Z(INODE,J) = Z(INODE,JN) + DZ(INODE,J)
    GO TO 231
230 Z(INODE,J) = DZ(INODE,J)
231 DIFFH = SBHOUT(J) - ENTHP
    IF(ABS(DIFFH) .LE. 0.1) GO TO 250
    IF(SBHOUT(J) .GE. ENTHP) GO TO 240
    GO TO 299

```

```

C.....* DETERMINE THE BULK BOILING POINT & NODE REDISTRIBUTION IN THE
C      TWO-PHASE REGION
C.....

```

```

240 IF(IST .EQ. 1) GO TO 301
    DZBB = DZ(INODE,J)*(ENTHP-SBHIN(J))/(SBHOUT(J)-SBHIN(J))
    IF(J .EQ. 1) GO TO 241
    BBLAMB(INODE) = Z(INODE,JN) + DZBB
    GO TO 242
241 BBLAMB(INODE) = DZBB
242 NBB(INODE) = J
    NBB1(INODE) = J + 1
    ISU = 1
    IF(H(1) .GT. CRIT) ISU = 0
    CALL ASSIGN(NBB(INODE), NP1, BBLAMB(INODE), ISU, INODE, 1)
    IBUN = 1
    OLDOMG(IBUN) = OLDOMG(1)
    ITER = 1
    GO TO 211

```

```

C
250 BBLAMB(INODE) = Z(INODE,J)
    NBB(INODE) = J
    NBB1(INODE) = J + 1
    IMM1 = NBB1(INODE)
    IF(IMM1 .GT. NP1) GO TO 310
    GO TO 301
299 CONTINUE
    NBB(INODE) = NP1
    NBB1(INODE) = NP1 + 1
    WRITE(6,3) SBHOUT(NP1)
    GO TO 310

```

```

C.....* CALCULATE CHARACTERISTIC PARAMETERS IN THE TWO-PHASE REGION
C.....

```

```

300 NP1 = NP1 + 1
    IMM1 = NBB1(INODE)
    GO TO 301
1002 IMM1 = NDP1(INODE)
    BBLAMB(INODE) = CHLAMB(INODE)
301 IF(NBB(INODE) .EQ. NP1) GO TO 311
    DO 302 I=IMM1,NP1

```

```

      INM1 = I - 1
      Z(INODE, I) = Z(INODE, INM1) + DZ(INODE, I)
302 CONTINUE
      DO 303 I=INM1, NP1
        IN = I - 1
        AVGH(I) = ENTHP
        C15(I) = DENSF/(C4*COH(INODE, I))
        C16(I) = COH(INODE, I)*RHOG/DENSF+RHOG*VGJH(INODE, I)/GO(INODE)
        Q0(INODE, I) = QDIS(INODE, I)*CXF(INODE)/PH(INODE)
        BEE(INODE, I) = QDIS(INODE, I) / AVEQ
        K1(INODE, I) = PH(INODE)*Q0(INODE, I)*VFG1/(AXS(INODE)*HFG1)
        IF(IOSUB.EQ. 0 .AND. I.EQ. IMM1) GO TO 304
        JOIN(I) = VOOOUT(IN)
        CKIN(INODE, I) = COH(INODE, I)*JOIN(I) + VGJH(INODE, I)
        ALPIN(INODE, I) = ALPOUT(IN)
        DOIN(INODE, I) = DENSF - C4*ALPIN(INODE, I)
        GO TO 305
304 JOIN(I) = VIN(INODE)
        CKIN(INODE, I) = COH(INODE, I)*JOIN(I) + VGJH(INODE, I)
        ALPIN(INODE, I) = 0.
305 VOOOUT(I) = JOIN(I) + DZ(INODE, I)*K1(INODE, I)
        CKOUT(I) = COH(INODE, I)*VOOOUT(I) + VGJH(INODE, I)
        ZETA(INODE, I) = CKOUT(I) / CKIN(INODE, I)
        ALPOUT(I) = C15(I)*(1.-1./ZETA(INODE, I)) + ALPIN(INODE, I)/
1      ZETA(INODE, I)
        DOOUT(INODE, I) = DENSF - C4*ALPOUT(I)
        V1(I) = CKIN(INODE, I) / (COH(INODE, I)*K1(INODE, I)*DZ(INODE, I))
        ALFNOD(INODE, I) = V1(I) * (C15(I)*(ZETA(INODE, I)-1.) +
1      (ALPIN(INODE, I) - C15(I))*ALOG(ZETA(INODE, I)))
        XEXIT(I) = ALPOUT(I)*C16(I)/(1.-COH(INODE, I)*C4*ALPOUT(I)/DENSF)
303 CONTINUE
310 CONTINUE
311 IF(ICAL.GT. 0 .AND. ICAL.LT. 4) GO TO 390
      IF(IRW.EQ. 0) GO TO 312
      IF(IWIT.LE. 1) GO TO 390
312 IF(IST.EQ. 0) WRITE(IFILE, 5)
      IF(IST.EQ. 1) WRITE(IFILE, 7)
      DO 320 I=INN1, NP1
C      ZAXIS = (Z(INODE, I)-DZ(INODE, I)/2.)*30.48
        ZAXIS = Z(INODE, I)-DZ(INODE, I)/2.
        XEQM = (ENTHT-ENTHP+QFLUX*PH(INODE)*ZAXIS/AXS(INODE)
1      /GO(INODE)) / HFG1
C      WRITE(IFILE, 9) ZAXIS, ALFNOD(INODE, I)
        WRITE(IFILE, 9) XEQM, ALFNOD(INODE, I)
320 CONTINUE
390 IF(ISLIP.EQ. 0) GO TO 500
      IF(IST.EQ. 1) GO TO 500
C.....
C      * Determine C0 & VgJ for each node with Okawa & Lahey model

```

```

C.....
  PC0 = RHOG / DENSF
  PC1 = SQRT(PC0)
  XC1 = 0.588116 - 1.81701*PC1 + 2.00025*PC1**2 - 3.34398*PC1**3
  YC0 = 4.72085 - 17.26736*PC1 + 56.14883*PC1**2 + 113.216*PC1**3
  1 - 1250.603*PC1**4 + 3039.767*PC1**5 - 2431.823*PC1**6
  YC1 = AMAX1(YC0,3.136)
  VGJ0 = (GC*G1*SIGM*C4)**0.25 / SQRT(DENSF)
  VGJ1 = 2.9*VGJ0
  DO 400 I=INN1,NP1
  VGJ2 = YC1*VGJ0*(1.-((ALFNOD(INODE,I)-XC1)/(1.-XC1))**2)
  C00 = -18.*ALFNOD(INODE,I)
  C01 = (1.2-0.2*PC1) * (1.-EXP(C00))
  C02 = 1.+0.2*(1.-PC1)*(1.-((ALFNOD(INODE,I)-XC1)/(1.-XC1))**2)
  IF(ALFNOD(INODE,I) .GE. XC1) GO TO 401
  VGZ(I) = VGJ1
  CZ(I) = C01
  GO TO 400
401 VGZ(I) = AMIN1(VGJ1,VGJ2)
  CZ(I) = AMIN1(C01,C02)
400 CONTINUE
  ITER = 0
  IST = 1
  GO TO 9000

C
  500 NTOT(INODE) = NP1
C.....
C * CHANNEL EXIT PARAMETERS
C.....
  XCHOUT(INODE) = XEXIT(NP1)
  CCHOUT(INODE) = CKOUT(NP1)
  ACHOUT(INODE) = ALPOUT(NP1)
  DO 501 I=INN1,NP1
  AVQT = C16(I)*ALFNOD(INODE,I)/(1.-ALFNOD(INODE,I)/C15(I))
  IF(IPILO .LT. 1) GO TO 502
  CPI1(INODE,I) = DD1*AVQT**(-0.176)/(VFG1*DENSF)
  CPI2 = 1.
  GO TO 503
502 CPI1(INODE,I) = CHOM01
  CPI2 = CHOM02
503 C8(INODE,I) = (CPI2-CPI1(INODE,I)) - CPI1(INODE,I)*DENSF*
  1 VGJH(INODE,I)/(COH(INODE,I)*GO(INODE,I))
  C9(INODE,I) = (CPI1(INODE,I)*DENSF) * (1.+DENSF*VGJH(INODE,I)/
  1 (COH(INODE,I)*GO(INODE,I))) / (DENSF - COH(INODE,I)*C4*
  2 ALPIN(INODE,I))
  COR2PH(INODE,I) = C8(INODE,I) + C9(INODE,I)*(ZETA(INODE,I)+1)
  1 /2.
501 CONTINUE
  IF(IRW .EQ. 0) GO TO 505
  IF(IWIT .LE. 1) GO TO 504

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```

505 C21(INODE) = K1(INODE, INN1)/(RHOG*VFG1*CKIN(INODE, INN1))
   IF(ISUB(INODE) .GT. 0) C21(INODE) = 0.
   C6 = (GO(INODE)*VIN(INODE)/CKIN(INODE, INN1)) * (1./GC)
   C7 = DENSF*RHOG*(VGJH(INODE, INN1)+(COH(INODE, INN1)-1.)*VIN(INODE)
1     )**2 / (C4*CKIN(INODE, INN1)) * (1./GC)
   C22(INODE) = (C6+C7)*K1(INODE, INN1) + C2(INODE)
C.....
C * CALCULATE WALL & BULK TEMPERATURE ASSUMING THAT THE BULK
C   TEMPERATURE IN THE TWO-PHASE REGION IS TSAT
C.....
   T1 = TIN
   IF(H(1) .GT. CRIT) GO TO 510
   INN = NDP(INODE)
   DO 511 I=1, INN
   TBULK(I) = T1 + QO(INODE, I)*PH(INODE)*(DZ(INODE, I)/2.)
1     / (CPF*GO(INODE)*AXS(INODE))
   TWALL(I) = TBULK(I) + QO(INODE, I)/HO(INODE)
   T1 = TBULK(I)
511 CONTINUE
C
510 DO 520 I=INN1, NP1
   TBULK(I) = TSATP
   IF(IOSUB .EQ. 0) GO TO 1003
   IF(IOSUB .EQ. 1 .AND. I .LT. NBB1(INODE)) GO TO 521
   GO TO 1003
521 TD = TSATP - (ENTHP-CRIT)/CPF
   TL = TSATP - (ENTHP-AVGH(I))/CPF
   TLN = (TSATP-TL) / (TSATP-TD)
   TBULK(I) = TD - (TSATP-TD)*ALOG(TLN)
1003 TWALL(I) = TSATP + (QO(INODE, I)/CKI)**(1./CMP)
   V22(INODE, I) = CKI*CMP*(TWALL(I)-TSATP)**(CMP-1.)
520 CONTINUE
C
   VEX = JOIN(NP1) + DZ(INODE, NP1)*K1(INODE, NP1)
   ALFSUM = 0.
   DO 530 I=INN1, NP1
530 ALFSUM = ALFSUM + ALFNOD(INODE, I)*DZ(INODE, I)
   CHALF = ALFSUM/ALHEAT
C.....
C * CHECK NODES WHICH INCLUDE SPACER
C   NUMBSP(I, J) ; THE NUMBER OF SPACERS IN NODE (I, J)
C.....
504 DO 550 I=1, NP1
   NUMBSP(INODE, I) = 0
550 CONTINUE
C
   IF(NSP .EQ. 0) GO TO 600
   KSP = 1
   I = 0
551 I = I + 1

```

```

      IF(I .GT. NP1) GO TO 552
      IF(ZSP(KSP) - Z(INODE,I) .GT. 1.0E-03) GO TO 551
553  NUMBSP(INODE,I) = NUMBSP(INODE,I) + 1
      KSP = KSP + 1
      IF(KSP .GT. NSP) GO TO 552
      IF(ZSP(KSP) .GT. Z(INODE,I)) GO TO 551
      GO TO 553
552  CONTINUE
C.....
C..... * PARAMETERS TO CALCULATE THE LOCAL PRESSURE DROP IN THE SINGLE-
C.....      & THE TWO-PHASE REGIONS
C.....      N1PSP(I) ; THE TOTAL NUMBER OF SPACERS IN THE SINGLE-PHASE REGION
C.....
      N1PSP(INODE) = 0
      IF(ISUB(INODE) .GT. 0) GO TO 560
      DO 561 I=1, INN
561  N1PSP(INODE) = N1PSP(INODE) + NUMBSP(INODE,I)
560  K2PSP(INODE) = N1PSP(INODE) + 1
C
      K2HSP = N1PSP(INODE) + 1
      DO 570 K=INN1, NP1
      KK = K - 1
      NNSP = NUMBSP(INODE,K)
      IF(NNSP .EQ. 0) GO TO 570
      IF(ISUB(INODE) .GT. 0 .AND. K .EQ. INN1) GO TO 571
      DO 572 N=1, NNSP
      DELSZ = ZSP(K2HSP) - Z(INODE, KK)
      CKSP(K2HSP) = CKIN(INODE,K) + DELSZ*COH(INODE,K)*K1(INODE,K)
      ZETSP(INODE,K2HSP) = CKSP(K2HSP) / CKIN(INODE,K)
572  K2HSP = K2HSP + 1
      GO TO 570
C
571  DO 573 N=1, NNSP
      CKSP(K2HSP) = CKIN(INODE,K) + ZSP(K2HSP)*COH(INODE,K)*K1(INODE,K)
      ZETSP(INODE,K2HSP) = CKSP(K2HSP) / CKIN(INODE,K)
573  K2HSP = K2HSP + 1
570  CONTINUE
C.....
C..... * CALCULATE STEADY-STATE PRESSURE DROPS . . . LOCAL . SPACER . TOTAL
C.....      ACCL      FRIC      GRAV      DPIN  DP1HSP  DP1HP
C.....      1) SINGLE-PHASE;      DPH1PF  DPH1PG      DPIN  DP1HSP  DP1HP
C.....      2) TWO-PH.(NODE);DPH2PA  DPH2PF  DPH2PG  DPEXIT  DPSP
C.....      TWO-PH.(TOTAL); DP2A      DP2F      DP2G      DP2HSP  DP2T
C.....      * 1) SINGLE-PHASE REGION
C.....
600  DPIN = XKIN(INODE)*G02RF(INODE)/144.0
      DP1HSP = DPIN
      DPH1P = 0.
      DPH1PG = 0.
      DPH1PF = 0.

```

```

      IF (ISUB(INODE) .GT. 0) GO TO 701
      INNSP = N1PSP(INODE)
      IF (INNSP .EQ. 0) GO TO 605
      DO 700 I=1, INNSP
      DPSP(I) = KLOSS(I)*G02RF(INODE)/144.0
      DP1HSP = DP1HSP + DPSP(I)
700 CONTINUE
C
605 DPH1PG = DENSF*CHLAMB(INODE)/144.0
      DPH1PF = FRICMO(INODE)*CHLAMB(INODE)*G02RF(INODE)/DH(INODE)/144.0
      DPH1P = DPH1PG + DPH1PF
C
      * 2) TWO-PHASE REGION
701 DP2G = 0.
      DP2F = 0.
      DP2A = 0.
      DP2T = 0.
      DO 710 I=INN1, NP1
      IF (ZETA(INODE, I) - 1. .LE. 1.0E-04) GO TO 702
      C19 = (G1/GC)*DZ(INODE, I)*DENSF*(1.-1./COH(INODE, I))
      C20 = (G1/GC)*(CKIN(INODE, I)/COH(INODE, I)/K1(INODE, I))*(DENSF/
1      COH(INODE, I) - C4*ALPIN(INODE, I))
      DPH2PG(I) = (C19 + C20*ALOG(ZETA(INODE, I)))/144.0
      GO TO 703
702 DINO = DENSF - C4*ALPIN(INODE, I)
      DPH2PG(I) = DINO*DZ(INODE, I)/144.0
703 DP2G = DP2G + DPH2PG(I)
      DPH2PF(I) = V7(INODE)*DZ(INODE, I)*COR2PH(INODE, I)/144.0
      DP2F = DP2F + DPH2PF(I)
      IF (I .EQ. INN1) GO TO 711
      II = I - 1
      RHOIN = (1.-XEXIT(II))*2/((1.-ALPIN(INODE, I))*DENSF) +
1      XEXIT(II)*2/(RHOG*ALPIN(INODE, I))
      GO TO 712
711 RHOIN = 1./DENSF
712 RHOOUT = (1.-XEXIT(I))*2/((1.-ALPOUT(I))*DENSF) + XEXIT(I)*2
1      /(RHOG*ALPOUT(I))
      DPH2PA(I) = (G02(INODE)/GC)*(RHOOUT - RHOIN) / 144.0
      DP2A = DP2A + DPH2PA(I)
      DPH2P(I) = DPH2PG(I) + DPH2PF(I) + DPH2PA(I)
      DP2T = DP2T + DPH2P(I)
710 CONTINUE
C
      DP2HSP = 0.
      KNSP = N1PSP(INODE)
      DO 720 I=INN1, NP1
      II = NUMBSP(INODE, I)
      IF (II .EQ. 0) GO TO 720
      DO 721 K=1, II
      KNSP = KNSP + 1
      DPSP(KNSP) = (KLOSS(KNSP)*G02(INODE)/(2.*GC*DENSF)) *

```

```

1          COR2PH(INODE,1) / 144.0
721 DP2HSP = DP2HSP + DPSP(KNSP)
720 CONTINUE
DPEXIT = XKEXIT(INODE)*G02(INODE)/(2.*GC*DENSF)*COR2PH(INODE,NP1)
1          /144.0
DP2HSP = DP2HSP+DPEXIT
C
DPHT = DPH1P + DP2T
DPTS = DP1HSP+ DPHT + DP2HSP
IF(IRW.EQ. 0) GO TO 800
IF(IWIT.LE. 1) GO TO 4000
C.....
C ***** PRINT OUT FOR CHANNEL CHARECTERISTICS IN STEADY-STATE *****
C.....
800 IF(ICH.NE.3 .AND. ICH.NE.6) GO TO 802
WRITE(6,11) AXS(INODE),PH(INODE),DHIN(INODE),BBLAMB(INODE),
1          FRICMO(INODE)
IF(ICAL.LE. 1) GO TO 801
IF(ICAL.EQ. 4) GO TO 801
C
801 WRITE(6,41)
IF(IOHW.EQ. 0) WRITE(6,43)
IF(IOHW.EQ. 1) WRITE(6,45) CPH, DENS
IF(IOHW.EQ. 2) WRITE(6,47) CPH, TKH, DENS
IF(IOHW.EQ. 3) WRITE(6,49) CPH, TKH, DENS, CRI, CRO
IF(IOHW.EQ. 4) WRITE(6,51) CPH,TKH,DENS,CRS, CPC,TKC,
1          DENS,CRI,CRO, GAPC
802 IF(ICH.NE.4 .AND. ICH.NE.6) GO TO 821
WRITE(6,53)
DO 810 K=1,NP1
WRITE(6,55) K, TBULK(K), TWALL(K)
810 CONTINUE
C
WRITE(6,57)
DO 820 I=1,NP1
IF(I.EQ. INN1) WRITE(6,59)
820 WRITE(6,61) I, Z(INODE,I),QO(INODE,I),QDIS(INODE,I)
821 IF(ICH.LE.1 .OR. ICH.EQ.3) GO TO 831
WRITE(6,63) CHALF, ALPOUT(NP1), CZERO, VGJ, XEXIT(NP1), GOHR,
1          VIN(INODE), VEX
C
WRITE(6,65) ENTHT, CRIT
IF(NODES.EQ. 1) GO TO 831
WRITE(6,67)
DO 830 I=INN1,NP1
WRITE(6,69) I,DZ(INODE,I),K1(INODE,I),COH(INODE,I),VGJH(INODE,I),
1          ALFNOD(INODE,I),XEXIT(I),AVGH(I), JOIN(I)
830 CONTINUE
831 IF(ICH.EQ.0 .OR. ICH.EQ.2 .OR. ICH.EQ.3) GO TO 4000
WRITE(6,71)

```



```

      ZIN = 0.0000
      WRITE(6,73) ZIN, XKIN(INODE), DPIN
      DO 840 I=1,NSP
      WRITE(6,73) ZSP(I), KLOSS(I), DPSP(I)
840  CONTINUE
      WRITE(6,73) ALHEAT, XKEXIT(INODE), DPEXIT
C
      IF(H(1) .GT. CRIT) GO TO 850
      WRITE(6,75) DP1HSP,DPH1PG,DPH1PF,DPH1P
850  WRITE(6,77)
      DO 860 I=INN1,NP1
      WRITE(6,79) I, Z(INODE,I), DPH2PG(I),DPH2PF(I),COR2PH(INODE,I),
1      DPH2PA(I), DPH2P(I)
860  CONTINUE
      WRITE(6,81) DP2G, DP2F, DP2A, DP2T, DP2HSP, DPTS
      GO TO 4000
C
2000 WRITE(6,85)
      STOP
C
4000 RETURN
      END

```

```

C
C
C
C
C*****
      SUBROUTINE XLOOP(ICAL,JLL,JRR)
C*****
C
C      * CALCULATE THE STEADY-STATE PARAMETERS OF THE LOOP ANALYSIS
C

```

```

      REAL MUTL, KF, KLOSS
      COMMON/OPTION/ IOSUB, IOHW, IO2Q, IPILO, ISLIP, IRW
      COMMON/CONST1/ C1(200),C2(200),C3(200),C4,C5(200),C8(200,30),
1      C9(200,30),C18(200), C21(200), C22(200),C25(200),
2      C26(200), T6, V7(200), DD1, CK1, CMP
      COMMON/CONST2/ P,VCH,VIN(200),AXS(200),DH(200),DHIN(200),
1      PH(200),TIN,TSATP,ENTHT,DENSI,SIGM,ENTHP,VISC,CPF,KF,
2      DENSE,VFG1,RHOG,G0(200),G02(200),H0(200),GC,G1,KLOSS(30),
3      FRICMO(200),VGJH(200,30),COH(200,30),CZERO,VGJ,DPTS,
4      G02RF(200),HFG1,ZSP(30),NUMBSP(200,30),ALHEAT,CXF(200),
5      AVEQ,CHOM01,CHOM02,XKIN(200),XKEXIT(200)
      COMMON/CONSS1/ QDIS(200,30), Q0(200,30), DZ(200,30),Z(200,30),
1      K1(200,30), CKIN(200,30), ZETA(200,30), DOIN(200,30),
2      DOOUT(200,30), ALPIN(200,30),BEE(200,30), CP11(200,30),
3      COR2PH(200,30), ZETSP(200,30), WIN
      COMMON/PCHOUT/XCHOUT(200), ACHOUT(200), CCHOUT(200)
      COMMON/CONSS2/ NTOT(200),NBB(200),NBB1(200),NSP,N1PSP(200),
1      K2PSP(200), NDP(200), NDP1(200), ISUB(200)

```

```

COMMON /RISER/ COR,VGJR,CKRO,RL,AR,DRIN,DR,PI,CL1,CL2,CL3,CL4,
1 CL5, CL6, CR5, CR6, UPJ1, UPJ2, RO11, RO12,
2 RO21, RO22, XROUT, UPJIN
COMMON /CLOOP/ SLOOP, SFLOOP, RLOOP,AA, VL1, VL2, VL3, DPLPT
1 ,RATW
COMMON /CUPPER/ RKIN, RKEXIT, AP, RPO, RP1, RP2, CL10,CL11,
1 CLT,AXSCH,RAR,AD,DL,DHDL,FDL, F1(200),F2(200),
2 RJ1(200),RJ2(200),RJ3(200),F3(200)
COMMON /CDELH1/ HFW, ADC, PHV, DKV, CPV, DENV, TEMV, TEMINV,
1 THV, HOD, PLM, AHLF, THLP, HOLP, WO, DLENG
COMMON /CDELH2/ CH1, CH2, CH3, CH4, CH5, CH7, CH8, CH9, CH10

```

C

```

15 FORMAT(/5X,'PARAMETERS FOR THE UPPER PLENUM', //10X,' AREA ',
1 6X,'LENGTH I', 6X,'LENGTH II', 6X,'CURVATURE')
17 FORMAT(/9X, F9.4, 3(6X, F9.4) )
19 FORMAT(/10X,'VOID FRACTION =' ,E10.4, 'VO,UP =' ,E10.4 )
21 FORMAT(/5X,'PARAMETERS FOR THE RISER', //10X,' LENGTH '
1 6X,'FLOW AREA', 5X,'HYDR.DIAM.', 9X,'CO', 12X,'VGJ',
2 /12X,'(FT)', 11X,'(FT2)', 11X,'(IN)', 25X,'(FT/S)' )
23 FORMAT(/9X, F9.4, 4(6X, F9.4) )
25 FORMAT(/10X,'GO,R =' ,E10.4, 5X,'VO,R =' ,E10.4, 5X,
1 'VOID FRACTION =' ,E10.4, /10X,'CORPR =' ,E10.4 )
27 FORMAT(/5X,'PARAMETERS FOR THE LOOP', //10X,' SLOOP ',
1 8X,'SFLOOP', 11X,'AA')
29 FORMAT(/4X, 2(5X,E10.4), 9X, F9.4)
31 FORMAT(/5X,'PARAMETERS FOR DOWNCOMER', //12X,'F.W. ENTH',
1 6X,'FLOW AREA', 8X,'LENGTH', 6X,'VESSEL TEMP',
2 9X,'PH', 13X,'HO' )
33 FORMAT(/7X, 7(5X,E10.4) )
35 FORMAT(/20X,'VESSL WALL', /20X,'THICKNESS(FT) =' ,3X,E10.4,
1 /20X,'THERMAL CONDUCTIVITY =' ,3X,E10.4,
2 /20X,'SPECIFIC HEAT =' ,3X,E10.4,
3 /20X,'DENSITY(LB/FT3) =' ,3X,E10.4)
37 FORMAT(/15X,'WO(LB/S) =' ,3X,E10.4, 10X,'ENTH. MIX. =' ,3X,E10.4,
1 10X,'ENTH. DC(EXIT) =' ,3X,E10.4)
39 FORMAT(/5X,'PARAMETERS FOR LOWER PLENUM', //10X,'FLOW MASS(LB)',
1 6X,'H/T AREA', 10X,'HO', 8X,'THICK', 10X,'HEAT FLUX')

```

C

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```

* CALCULATE THE INLET PARAMETERS OF THE UPPER PLENUM
XUPI ; INLET FLOW QUALITY
UPALP ; INLET VOID FRACTION
UPJIN ; INLET FLOW VELOCITY

```

```

B10 = 0.
DO 10 I=JLL,JRR
B10 = B10 + XCHOUT(I)*GO(I)*AXS(I)
10 CONTINUE
XUPI = B10/WIN
UPALP = XUPI*DENSF/(RHOG+C4*XUPI)
P2 = DENSF - C4*UPALP

```

```

UPJIN = W0/AP/P2
UPJOUT = (AP/RAR)*UPJIN
F = DENSF*RHOG/(RHOG+C4*XUPI)**2
GOP = UPJIN*P2
DO 11 I=JLL,JRR
NP1 = NTOT(I)
E1 = -RHOG*VGJH(I,NP1)*DENSF*ACHOUT(I)/GO(I)**2
E2 = (RHOG*COH(I,NP1)/DENSF + RHOG*VGJH(I,NP1)/GO(I) +
1   C4*COH(I,NP1)*XCHOUT(I)/DENSF + C4*RHOG*VGJH(I,NP1)*
2   ACHOUT(I)*CCHOUT(I)/GO(I)**2) / (1.-C4*COH(I,NP1)*
3   ACHOUT(I)/DENSF)
F1(I) = F*AXS(I)*GO(I)*E1/WIN
F2(I) = F*AXS(I)*GO(I)*E2/WIN
F3(I) = F*(XCHOUT(I)-XUPI) /WIN
RJ1(I) = (C4*UPJIN*F1(I)+AXS(I)*(DENSF-C4*COH(I,NP1)*ACHOUT(I))
1   /AP) / P2
RJ2(I) = (C4*UPJIN*F2(I)-AXS(I)*C4*CCHOUT(I)/AP) / P2
RJ3(I) = C4*UPJIN*F3(I) / P2
11 CONTINUE
C
DRP = RP2 - RP1
CLTX = 0.
IF(RP0.EQ. 0.) GO TO 12
CLTX = AP*DRP + (P1*RP0-AP/RP0)*(RP2**2-RP1**2)/2.
1   - P1*(RP2**3-RP1**3)/3.
12 CLT = (RP1 - ALHEAT + CLTX/AP) /UPJIN
C.....
C   INLET PARAMETERS IN THE RISER
C.....
GOR = (AP/RAR)*GOP
ALPRO = RHOG*UPALP / ((COR*RHOG/DENSF+RHOG*VGJR/GOR)*P2
1   + COR*C4*RHOG*UPALP/DENSF)
CL2 = DENSF - C4*COR*ALPRO
VRO = (GOR + C4*VGJR*ALPRO) / CL2
XROUT = XUPI
CKRO = COR*VRO + VGJR
IF(IPILO.EQ. 0) GO TO 13
RP11 = DD1*XROUT**(-0.176)/(VFG1*DENSF)
RP12 = 1.
GO TO 14
13 RP11 = CHOM01
RP12 = CHOM02
14 CORPR = RP12 + RP11*VFG1*DENSF*XROUT
RHOR = DENSF - C4*ALPRO
DR = DRIN/12.0
C1R = -1.41E-05*DRIN + 3.36E-04
VISR = MUTL(TSATP)/3600.0
RER = GOR*DR/VISR
FRICR = 0.0055*(1. + (20000.*C1R+1.0E+06/RER)**(1./3.))
RC1 = (RHOG + C4*XUPI) / P2

```

```

RC2 = COR*RHOG/DENSF + RHOG*VGJR/GOR + COR*C4*XROUT/DENSF
1  + C4*RHOG*VGJR*ALPRO*CKRO/GOR**2
RC3 = RC2 / (CL2/DENSF)
RC4 = -RHOG*DENSF*VGJR*ALPRO/GOR**2
ROD = C4*CKRO*RC4 + CL2*RC3
RO11 = (P2*RC3/ROD) * (AP/RAR)
RO12 = (C4*CKRO*RC1 - C4*UPJOUT*RC3) / ROD
RO21 = -(P2*RC4/ROD) * (AP/RAR)
RO22 = (C4*UPJOUT*RC4 + CL2*RC1) / ROD

```

C

```

CL1 = (FRICR*GOR*CORPR) / (GC*DENSF*DR)
CL3 = (FRICR*GOR/(2.*GC*DR)) * (1.-VRO*CL2/GOR) * RP11
CL4 = - (FRICR*VRO*C4*CKRO**2) / (2.*GC*DR) * RP11
CL5 = -2.*(GOR/RHOR)*C4*CKRO + C4*(GOR/RHOR)**2
CXX = DENSF*RHOG * ((COR-1.)*VRO+VGJR)**2
1  / (RHOR**2 - RHOG*RHOR)**2
CL6 = CXX * (2.*DENSF*RHOR - RHOR**2 - RHOG*DENSF) * C4
CRCON = (GOR*CORPR/DENSF - RP11*VRO/2.) / GC
CR5 = CRCON*CL2 + GOR*RP11/(2.*GC)
CR6 = -C4*CKRO*CRCON
CH1 = -RAR/VFG1 + (RAR*(1.-RHOG/C4))*CL2
CH2 = RAR*CKRO*(C4-RHOG)
WSWO = WO*(1.-XROUT)
CH9 = FDL*WSWO**2/(2.*GC*DHDL*AD**2*DENSF) - (G1/GC)*DENSF
CH10 = DL*FDL*WSWO/(GC*DHDL*AD**2*DENSF)

```

C.....

C 3) FOR THE SINLE-PHASE LOOP

C.....

```

VL1 = SLOOP/GC * RATW
VL2 = (WO/DENSF)*SFLOOP / GC * RATW
VL3 = AA * RATW

```

C.....

C * CALCULATE THE S.S PRESSURE DROP IN THE LOOP

C.....

C (1) FOR THE UPPER PLENUM

```

DPUPL = (G1/GC)*P2*(RP2-ALHEAT) / 144.0

```

C (2) FOR THE RISER

```

DPR = ( (RHOR + CL1*GOR/2.)*(RL-RP2) + (RKIN+RKEXIT)*
1  GOR**2*CORPR/(2.*GC*DENSF) ) / 144.0

```

C (3) FOR THE LOOP

```

DPLOOP = SFLOOP*(WO**2/2./GC/DENSF) / 144.0

```

C * TOTAL P.D. IN THE LOOP

```

DPLPT = DPUPL + DPR + DPLOOP

```

C

```

WRITE(6,1347) DPUPL, DPR, DPLOOP

```

```

1347 FORMAT(/3X,'DPUPL=',E10.4,3X,'DPR=',E10.4,3X,'DPLOOP=',E10.4)

```

C.....

C * CALCULATE THE PARAMETERS FOR THE DELHI

C.....

```

IF(ICAL.EQ. 3 .OR. ICAL.EQ. 5) GO TO 102

```

```

GO TO 100
102 CH3 = (PHV*HOD/WO/CPF) / (1.+THV*HOD/DKV)
CH4 = (ENTHP-HFW) * (XROUT/WO)
CH5 = HOD/(1.+THV*HOD/DKV) * (TEMINV - TEMV)
CH6 = (1.-XROUT)*ENTHP + XROUT*HFW
CHH = -CH3*DLENG
CH7 = (PHV*CH5/WO/CH3) * (EXP(CHH)-1.) + CH6
CH8 = HOLP*(TIN-TEMV) / (1.+HOLP*THLP/DKV)

```

C

```

100 WRITE(6,15)
WRITE(6,17) AP, RP1, RP2, RPO
WRITE(6,19) UPALP, UPJIN
WRITE(6,21)
WRITE(6,23) RL, AR, DRIN, COR, VGJR
WRITE(6,25) GOR, VRO, ALPRO, CORPR
WRITE(6,27)
WRITE(6,29) SLOOP, SFLOOP, AA
IF(ICAL.EQ. 3 .OR. ICAL.EQ. 5) GO TO 200
GO TO 101
200 WRITE(6,31)
WRITE(6,33) HFW, ADC, DLENG, TEMV, TEMINV, PHV, HOD
WRITE(6,35) THV, DKV, CPV, DENV
WRITE(6,37) WO, CH6, CH7
WRITE(6,39)
WRITE(6,33) PLM, AHLP, HOLP, THLP, CH5
101 RETURN
END

```

C

C

C

C

C*****

SUBROUTINE CON2DP(S, INODE)

C*****

C

C

C

C

CALCULATE THE CONSTANTS FOR TWO-PHASE PRESSURE DROP
PERTURBATION CALCULATION

```

REAL K1
COMPLEX S, TG, STC1, STC2, TB1, TB2, CSTB1, CSTB2, TF, TR1, TR2,
1 XX1, XX2
COMMON /CMP2/ TG(6,30), TB1(3,30), TB2(3,30), TF(11,30), TR1(5,30),
1 TR2(5,30)
COMMON/CONST1/ C1(200), C2(200), C3(200), C4, C5(200), C8(200,30),
1 C9(200,30), C18(200), C21(200), C22(200), C25(200),
2 C26(200), T6, V7(200), DD1, CK1, CMP
COMMON/CONST2/ P, VCH, VIN(200), AXS(200), DH(200), DHIN(200),
1 PH(200), TIN, TSATP, ENTH, DENS1, SIGM, ENTHP, VISC, CPF, KF,
2 DENSF, VFG1, RHOG, G0(200), G02(200), H0(200), GC, G1, KLOSS(30),
3 FRICM0(200), VGJH(200,30), COH(200,30), CZERO, VGJ, DPTS,

```

```

4      G02RF(200),HFG1,ZSP(30),NUMBSP(200,30),ALHEAT,CXF(200),
5      AVEQ,CHOM01,CHOM02,XKIN(200),XKEXIT(200)
COMMON/CONSS1/ QDIS(200,30),QO(200,30),DZ(200,30),Z(200,30),
1      KT(200,30),CKIN(200,30),ZETA(200,30),DOIN(200,30),
2      DOOUT(200,30),ALPIN(200,30),BEE(200,30),CPI1(200,30),
3      COR2PH(200,30),ZETSP(200,30),WIN
COMMON /DIM1/ DELX,DELZ,CHLAMB(200),ALFNOD(200,30),
1      BBLAMB(200)
COMMON/CONSS2/ NTOT(200),NBB(200),NBB1(200),NSP,N1PSP(200),
1      K2PSP(200),NDP(200),NDP1(200),ISUB(200)
COMMON /DPCON3/ ST2(30)
COMMON /DPCON2/ STC1(30),STC(200,30),CSTB1(30),CSTB2(30),
1      STC2(30)

```

C

```

NP1 = NTOT(INODE)
NST = NDP1(INODE)
DO 100 I=NST,NP1
ST1 = DENSF - C4*ALPIN(INODE,I)*COH(INODE,I)
ST2(I) = ST1*CKIN(INODE,I)/C4
STC2(I) = ST2(I)/(S-COH(INODE,I)*K1(INODE,I))/CKIN(INODE,I)**2
STC1(I) = S / (COH(INODE,I)*K1(INODE,I))
TG(1,I) = ST1 / (1.-1./STC1(I))
TG(2,I) = -ST1 / (STC1(I)-1.)
TG(3,I) = ST1*CKIN(INODE,I)/COH(INODE,I)/K1(INODE,I)
TG(4,I) = -TG(3,I) - C4*STC2(I)*CKIN(INODE,I)**2
TG(5,I) = ST1/(S-COH(INODE,I)*K1(INODE,I)) * CKIN(INODE,I)
TG(6,I) = -C4*CKIN(INODE,I)

```

C

```

XX1 = STC1(I) * ALOG(ZETA(INODE,I))
CSTB1(I) = CEXP(XX1)
XX2 = (1. + STC1(I)) * ALOG(ZETA(INODE,I))
CSTB2(I) = CEXP(XX2)
TB1(1,I) = 2.*(GO(INODE)/DOIN(INODE,I))*(TG(1,I) + TG(2,I))
TB2(1,I) = 2.*(GO(INODE)/DOOUT(INODE,I))*(TG(1,I)/ZETA(INODE,I)
1      + TG(2,I)/CSTB1(I)) - (GO(INODE)/DOOUT(INODE,I))**2 *
2      C4*COH(INODE,I)*K1(INODE,I)*STC2(I)*(1./ZETA(INODE,I))**2
3      - 1./CSTB2(I))
TB1(2,I) = 2.*(GO(INODE)/DOIN(INODE,I))*(TG(3,I) + TG(4,I) +
1      TG(5,I))
TB2(2,I) = 2.*(GO(INODE)/DOOUT(INODE,I))*(TG(3,I) +
1      TG(4,I)/ZETA(INODE,I) + TG(5,I)/CSTB1(I))
2      + (GO(INODE)/DOOUT(INODE,I))**2*C4*STC2(I)*
3      CKIN(INODE,I)*(1./ZETA(INODE,I))**2 - 1./CSTB2(I))
TB1(3,I) = 2.*(GO(INODE)/DOIN(INODE,I))*TG(6,I) +
1      (GO(INODE)/DOIN(INODE,I))**2*C4
TB2(3,I) = 2.*(GO(INODE)/DOOUT(INODE,I))*TG(6,I)/CSTB1(I) +
1      (GO(INODE)/DOOUT(INODE,I))**2*C4/CSTB2(I)

```

C

```

C14 = CPI1(INODE,I) * (VFG1*DENSF)
C11 = VGJH(INODE,I)/(COH(INODE,I)*VFG1*G02(INODE))

```

```

C12 = COH(INODE,1)*VFG1*G02(INODE)
TF(1,1) = (CPI1(INODE,1)*DENSF/G0(INODE)) * (1. - CKIN(INODE,1)
1      *TG(1,1)/COH(INODE,1)/G0(INODE))
TF(2,1) = C14*C11*TG(1,1)
TF(3,1) = C14*C11*TG(2,1)
TF(4,1) = -C14*(CKIN(INODE,1)/C12)*TG(2,1)
TF(5,1) = (CPI1(INODE,1)*DENSF/(G0(INODE)*COH(INODE,1))) *
1      (-CKIN(INODE,1)/K1(INODE,1) + (VGJH(INODE,1)/G0(INODE))*
1      TG(3,1) - (CKIN(INODE,1)/G0(INODE))*TG(4,1) )
TF(6,1) = CPI1(INODE,1)*VGJH(INODE,1)*DENSF/(G02(INODE)*
1      COH(INODE,1)) * TG(4,1)
TF(7,1) = CPI1(INODE,1)*DENSF/(COH(INODE,1)*G0(INODE)) * (
1      CKIN(INODE,1)/K1(INODE,1)-CKIN(INODE,1)/G0(INODE)*TG(3,1) )
TF(8,1) = C14*C11*TG(5,1)
TF(9,1) = -C14*(CKIN(INODE,1)/C12)*TG(5,1)
TF(10,1) = C14*C11*TG(6,1)
TF(11,1) = -C14*(CKIN(INODE,1)/C12)*TG(6,1)

```

C

```

VGJIN = ((COH(INODE,1)-1.)*CKIN(INODE,1) + VGJH(INODE,1))/
1      COH(INODE,1)
VGJOUT = ((COH(INODE,1)-1.)*CKIN(INODE,1)*ZETA(INODE,1) +
1      VGJH(INODE,1))/COH(INODE,1)
V1IN = (DENSF*RHOG*VGJIN**2/(DOIN(INODE,1)**2 - RHOG*
1      DOIN(INODE,1)**2) * (2.*DENSF*DOIN(INODE,1) -
2      DOIN(INODE,1)**2 - DENSF*RHOG)
V1OUT = (DENSF*RHOG*VGJOUT**2/(DOOUT(INODE,1)**2 -
1      RHOG*DOOUT(INODE,1)**2) * (2.*DENSF*DOOUT(INODE,1) -
2      DOOUT(INODE,1)**2 - DENSF*RHOG)
V2IN = ((DENSF - DOIN(INODE,1))/(DOIN(INODE,1) - RHOG))
1      * (DENSF*RHOG/DOIN(INODE,1)) * VGJIN
V2OUT = ((DENSF - DOOUT(INODE,1))/(DOOUT(INODE,1) - RHOG))
1      * (DENSF*RHOG/DOOUT(INODE,1)) * VGJOUT
TR1(1,1) = 2.*V2IN*(COH(INODE,1) - 1.)
TR2(1,1) = 2.*V2OUT*(COH(INODE,1) - 1.)
TR1(2,1) = - V1IN*C4*STC2(1)*COH(INODE,1)*K1(INODE,1)
TR2(2,1) = - V1OUT*C4*STC2(1)*COH(INODE,1)*K1(INODE,1)
TR1(3,1) = -TR1(1,1)*CKIN(INODE,1)/COH(INODE,1)/K1(INODE,1)
TR2(3,1) = -TR2(1,1)*CKIN(INODE,1)/COH(INODE,1)/K1(INODE,1)
TR1(4,1) = V1IN*C4*STC2(1)*CKIN(INODE,1)
TR2(4,1) = V1OUT*C4*STC2(1)*CKIN(INODE,1)
TR1(5,1) = V1IN*C4
TR2(5,1) = V1OUT*C4

```

C

```

100 CONTINUE
RETURN
END

```

C
C
C
C

```

C*****
SUBROUTINE DELBB(S, XLAMB, INODE, X2)
C*****
C      CALCULATE THE PERTURBATION OF VOID DEPARTURE POINT FOR IOSUB=1,
C      OR THE BOILING BOUNDARY FOR IOSUB=0.
C
      COMPLEX PHI, THETA, BETA, HS, HSUM1, HSUM2, Z1, Z2, Z3, TH1, TH2, TH3
      COMPLEX M1, M2, M3, S
      COMMON/OPTION/ IOSUB, IOPT, IO2Q, IPILO, ISLIP, IRW
      COMMON /CPBOIL/ M1, M2, M3, TH1, TH2, TH3, HS(30)
      COMMON /PBOIL/ CONBB
      COMMON/CONST1/ C1(200), C2(200), C3(200), C4, C5(200), C8(200, 30),
1      C9(200, 30), C18(200), C21(200), C22(200), C25(200),
2      C26(200), T6, V7(200), DD1, CK1, CMP
      COMMON/CONST2/ P, VCH, VIN(200), AXS(200), DH(200), DHIN(200),
1      PH(200), TIN, TSATP, ENTHT, DENS1, SIGM, ENTHP, VISC, CPF, KF,
2      DENSF, VFG1, RHOG, GO(200), G02(200), H0(200), GC, G1, KLOSS(30),
3      FRICM0(200), VGJH(200, 30), COH(200, 30), CZERO, VGJ, DPTS,
4      G02RF(200), HFG1, ZSP(30), NUMBSP(200, 30), ALHEAT, CXF(200),
5      AVEQ, CHOMO1, CHOMO2, XKIN(200), XKEXIT(200)
      COMMON/CONSS1/ QDIS(200, 30), Q0(200, 30), DZ(200, 30), Z(200, 30),
1      K1(200, 30), CKIN(200, 30), ZETA(200, 30), DOIN(200, 30),
2      DOOUT(200, 30), ALPIN(200, 30), BEE(200, 30), CPI1(200, 30),
3      COR2PH(200, 30), ZETSP(200, 30), WIN
      COMMON /DIM1/ DELX, DELZ, CHLAMB(200), ALFNOD(200, 30),
1      BBLAMB(200)
      COMMON/CONSS2/ NTOT(200), NBB(200), NBB1(200), NSP, N1PSP(200),
1      K2PSP(200), NDP(200), NDP1(200), ISUB(200)
      COMMON /WD2/ Z1, Z2, Z3(30)
C
      IF(IOPT .EQ. 0) GO TO 10
      AA = 0.8
      GO TO 12
10      H0(INODE) = 0.
      AA = 0.
C
12      PHI = S/VIN(INODE) + C1(INODE)*H0(INODE)/(1.-H0(INODE)*Z1)
      THETA = C18(INODE)*(AA/(1.-H0(INODE)*Z1) - 1.)
      BETA = C1(INODE)*CPF*Z2*H0(INODE)/(1. - H0(INODE)*Z1)
      HSUM1 = CMPLX(0., 0.)
      NEND = NDP(INODE)
      DO 1 I=1, NEND
      HS(I) = CEXP(PHI*Z(INODE, I)) * (1.-CEXP(-PHI*DZ(INODE, I)))
      HSUM1 = HSUM1 + HS(I)*QDIS(INODE, I)
1      CONTINUE
      HSUM2 = CEXP(-PHI*XLAMB)
      CONBB = GO(INODE)*AXS(INODE)/(Q0(INODE, NDP(INODE))*PH(INODE))
C
      TH1 = (THETA/PHI) * (HSUM2/VIN(INODE)) * HSUM1
      TH2 = (BETA/PHI) * HSUM2

```



```

      TH3 = HSUM2
C
      M1 = (-TH1+X2/DENSF) * CONBB
      M2 = -TH2 * CONBB
      M3 = -TH3 * CONBB
C
      RETURN
      END
C
C
C
C
C*****
      SUBROUTINE DPPERT(S, XLAMB, IND, ICAL)
C*****
C
C      *   CALCULATE PRESSURE DROP PERTURBATION IN THE CHANNEL
C
      INTEGER IOSUB
      REAL K1, KLOSS
      COMPLEX S, M1, M2, M3, M4, TH1, TH2, TH3, GAM1, GAM2, GAM3, P11, P12, P13
      COMPLEX STC1, STC2, CSTB1, CSTB2, Z3, HS, TG, TB1, TB2, TF, TR1, TR2, Z1,
1      Z2, TALP1, TALP2(30,30), TALP3, TSUM2, TAU1, TAU2
      COMPLEX CX1(30), CX2(30), CX3(30), CA(30), CB(30), CC(30),
1      CXS2(30), CBS(30), MM4, SPA1, SPA2, SPA3, SPB1, SPB2, SPB3
      COMPLEX DP1, DP2, DP3, DP4, DP5, DP6, DP7, SO3
      COMPLEX DP1V, DP2V, DP3V, DP4V, DP5V, DP6V, DP1Q, DP2Q, DP3Q, DP4Q,
1      DP5Q, DP6Q, DP1H, DP2H, DP3H, DP4H, DP5H, DP6H
      COMPLEX VAR1, VAR3, VAR4, VAR5, VAR6, Y3, Y4, B1, B2, B3, PAR1(30),
1      PAR2(30), PAR3(30), CX, VV1, VV2, GT2V, GT2Q, GT2H
      COMPLEX PINOD1(30), PINOD2(30,30), PINOD3(30), CK11(30), CK121(30)
1      , CK122(30,30), CK13(30), SPK1(30), SPK2(30,30), SPK3(30)
      COMPLEX SUMP1, SUMP2(30), SUMP3, SPT1, SPT2(30), SPT3
      COMPLEX PP1V, PP1H, PP2V, PP2H, PP3V, PP3H, PP4V, PP4H, PP5V, PP5H
C
      COMPLEX RX1, CR1, CR2, RX2, RR1, RR2(30), RR3, T1, SUPT
      COMPLEX CC7, SUP1, SUP2, SUP3, SH1, SH2, SH3, SH4, SH5, DPH1
      COMPLEX ALSUM, FVP(30), F11, SUM2(30)
      COMPLEX EPV, WC1, WC2, CC1, CC2, CC4, DPI, DTHET, DPIZ, DPIE,
1      DDD, TLP1, TLP2, CCOTH, DWSW1, DWSW21, DWSW2(30),
2      DWSW3, UPC1, UPC2, DPUP1, DPUP2(30), DPUP3
      COMPLEX SC1, SC2, SC3, SC4, SC5, SC7, SC8, SC9, SC10, SC11, SC12, SC13,
1      SC14, SC15, SC16, SIN1, SIN2, SIN3, SIN4, SIN5, SIN6, SIN7,
2      SIN9, SIN10, SIN11, SC01, SC02, SC03, EPOW, G1FN1, G1FN2,
3      AO1, AO4, AO5, U1K, U2K, U3K, U4K, U5K
      COMPLEX WK(5,30), YOK, YK(6,30), SUMS, SUMS1, SUMS2, SUMS3, SUMS4,
1      ZLK(5,30,30), SB1X, SB2X(30), SB7X, SBX(6,30), SK11(30),
2      SK12(30,30), SK13(30), SBZK(6,30,30), SBTk(5,30,30),
3      SGAM(30,30), SBM1(30), SBM2(30,30), SBM3(30), SBJ1(30),
4      SBJ3(30), SBJ2(30,30), SBJ21(30), CSM1, CSM2, CSM3,

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5      SBM21(30), CXJ1,CXJ2,CXJ3,CXA1,CXA2,CXA3

C      COMMON/OPTION/ IOSUB, IOHW, IO2Q, IPIL0, ISLIP, IRW
COMMON/CONST1/ C1(200),C2(200),C3(200),C4,C5(200),C8(200,30),
1      C9(200,30),C18(200), C21(200), C22(200),C25(200),
2      C26(200), T6, V7(200), DD1, CK1, CMP
COMMON /CONSUB/ CSB2(200,30),CSB3(200,30),CSB4(200,30),
1      CSB5(200,30),CSB6(200,30),CSB7(200,30),CSB8(200,30),
2      CSB9(200,30),CSB10(200,30),CSBQ(200,30),CSBD(200,30),
3      CSBE(200,30),CSBF(200,30), CSBG(200,30),CSBX1(200),
4      CSBX2(200)
COMMON/CONST2/ P,VCH,VIN(200),AXS(200),DH(200),DHIN(200),
1      PH(200),TIN,TSATP,ENTHT,DENSI,SIGM,ENTHP,VISC,CPF,KF,
2      DENSF,VFG1,RHOG,G0(200),G02(200),H0(200),GC,G1,KLOSS(30),
3      FRICM0(200),VGJH(200,30),COH(200,30),CZERO,VGJ,DPTS,
4      G02RF(200),HFG1,ZSP(30),NUMBSP(200,30),ALHEAT,CXF(200),
5      AVEQ,CHOM01,CHOM02,XKIN(200),XKEXIT(200)

C      COMMON/CONSS1/ QDIS(200,30),Q0(200,30),DZ(200,30),Z(200,30),
1      K1(200,30), CKIN(200,30), ZETA(200,30), DOIN(200,30),
2      DOOUT(200,30),ALPIN(200,30), BEE(200,30),CPI1(200,30),
3      COR2PH(200,30), ZETSP(200,30), WIN
COMMON /DIM1/ DELX, DELZ, CHLAMB(200), ALFNOD(200,30),
1      BBLAMB(200)
COMMON /DPCON1/GAM1(200),GAM2(200,30),GAM3(200), PI1(200),
1      PI2(200,30),PI3(200), TALP1(200,30),
2      TSUM2(200,30),TAU1(200),TAU2(200),TALP3(200,30)
COMMON /WD2/Z1, Z2, Z3(30)
COMMON/CONSS2/ NTOT(200),NBB(200),NBB1(200),NSP,N1PSP(200),
1      K2PSP(200), NDP(200), NDP1(200), ISUB(200)
COMMON /CPBOIL/ M1, M2, M3, TH1,TH2,TH3, HS(30)
COMMON /PBOIL/ CONBB
COMMON /DPCON3/ ST2(30)
COMMON /DPCON2/ STC1(30), STC(200,30), CSTB1(30), CSTB2(30),
1      STC2(30)
COMMON /CMP2/TG(6,30),TB1(3,30),TB2(3,30),TF(11,30),TR1(5,30),
1      TR2(5,30)
COMMON /CXCH/ CXJ1(200),CXJ2(200,30),CXJ3(200), CXA1(200),
1      CXA2(200,30),CXA3(200)
COMMON /CGHT/ F11
COMMON /RESULT/XZ, SS1, SS2

C      CHD1 = CSBX1(IND)
      CHD2 = CSBX2(IND)
      NP1 = NTOT(IND)
      NOSB = ISUB(IND)
      IF(NOSB.EQ. 0) NSF = NDP(IND)
      NTS = NDP1(IND)
      IF(IOSUB.EQ. 0) GO TO 6678
      IF(NOSB.GT. 0) GO TO 10

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      M4 = CONBB*CHD1*Z3(NTS)
      GO TO 9
10    M1 = CMPLX(0.,0.)
      M2 = CMPLX(0.,0.)
      M3 = CMPLX(0.,0.)
      M4 = CMPLX(0.,0.)
      9    NFB1 = NBB(IND)
          NFB2 = NBB1(IND)
6678  NSP1 = NTS + 1
C
      GAM1(IND) = CMPLX(0.,0.)
      GAM3(IND) = CMPLX(0.,0.)
      DO 7 I=1,NP1
          SBM3(I) = CMPLX(0.,0.)
      GAM2(IND,I) = CMPLX(0.,0.)
      7    CONTINUE
          DO 3806 I=1,NP1
              DO 3806 J=1,NP1
                  PINOD2(I,J) = CMPLX(0.,0.)
                  SPK2(I,J) = CMPLX(0.,0.)
                  TALP2(I,J) = CMPLX(0.,0.)
3806  CONTINUE
C.....
C    * CALCULATE THE SINGLE-PHASE PRESSURE DROP PERTURBATIONS
C.....
      IF(NOSB .GT. 0) GO TO 617
      OH = 0.
      NSPAC = N1PSP(IND)
      IF(NSPAC .EQ. 0) GO TO 641
      DO 6 I=1,NSPAC
          OH = OH + KLOSS(I)*GO(IND)/GC
      6    CONTINUE
641  OH = OH + XKIN(IND)*GO(IND)/GC
      GAM1(IND) = (DENSF*S/GC + C3(IND))*XLAMB + OH + C2(IND)*M1
      DO 8 I=1,NSF
          GAM2(IND,I) = C2(IND)*M2*HS(I)
      8    CONTINUE
          GAM2(IND,NTS) = C2(IND)*M4
          GAM3(IND) = C2(IND)*M3
          GO TO 200
617  GAM1(IND) = XKIN(IND)*GO(IND)/GC
C.....
C    * CALCULATE THE PRESSURE DROP PERTURBATIONS IN THE TWO-PHASE
C      REGION
C.....
200  DO 20 I=NTS,NP1
      CX = 1./ZETA(IND,I)**2 - 1./CSTB2(I)
      CX1(I) = -STC2(I)*COH(IND,I)*K1(IND,I)*CX
      CX2(I) = STC2(I)*CKIN(IND,I) * CX * C5(IND) * Z3(I)
      CXS2(I) = STC2(I)*CKIN(IND,I)*CX

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CX3(I) = 1./CSTB2(I)
PAR1(I) = (STC2(I)*CKIN(IND,I)/DZ(IND,I)) * ((1./ZETA(IND,I)
1 -1.) - (COH(IND,I)*K1(IND,I)/S)*(1./CSTB1(I)-1.))
PAR2(I) = (STC2(I)*CKIN(IND,I)**2/DZ(IND,I)) * ((1./CSTB1(I)
1 -1.)/S - (1./ZETA(IND,I)-1.)/(COH(IND,I)*K1(IND,I)))
PAR3(I) = -(CKIN(IND,I)/DZ(IND,I)/S) * (1./CSTB1(I)-1.)
20 CONTINUE

```

```

C.....
C * TRANSFER FUNCTIONS FOR SUBCOOLED BOILING NODE EXIT ENTHALPY
C PERTURBATION
C.....

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```

IF(IOSUB.EQ. 0) GO TO 401
NSP1 = NTS + 1
DO 201 K=NTS,NFB1
SC1 = 1. - STC1(K)
SC2 = (EPOW(ZETA(IND,K),SC1)-1.)/SC1
CO1 = CKIN(IND,K) / (COH(IND,K)*K1(IND,K)*DZ(IND,K))
CO2 = CKIN(IND,K)/COH(IND,K)
CO3 = VGJH(IND,K)/COH(IND,K)
SC01 = 2.-STC1(K)
SC02 = CO2*(EPOW(ZETA(IND,K),SC01)-1.)/SC01
SC03 = -CO3*SC2 + SC02
SC3=CO1 * (TG(1,K)*(CO2*(ZETA(IND,K)-1.)-CO3*ALOG(ZETA(IND,K)))
1 + TG(2,K)*SC03)
SC3 = (1.-SC3/GO(IND)) / (VFG1*GO(IND))
SC4=CO1 * ((-CO3*TG(3,K)+CO2*TG(4,K))*(ZETA(IND,K)-1.) - CO3*
1 TG(4,K)*ALOG(ZETA(IND,K)) + (CO2/2.)*TG(3,K)*
2 (ZETA(IND,K)**2-1.) + TG(5,K)*SC03)
SC4 = (DZ(IND,K)/2.-SC4/GO(IND)) / (VFG1*GO(IND))
SC5 = CO1 * SC03 * TG(6,K)
SC5 = -SC5/(VFG1*GO(IND)**2)
SC7 = CSB5(IND,K)*S - CSB2(IND,K)
SC8 = CSB8(IND,K)*SC3
SC9 = CSB9(IND,K)*TG(1,K)
SC10 = CSB9(IND,K)*TG(2,K)
SC11 = CSB8(IND,K)*SC4 + CSB9(IND,K)*TG(3,K) + CSB7(IND,K)
SC12 = CSB9(IND,K)*TG(4,K)
SC13 = CSB9(IND,K)*TG(5,K)
SC14 = CSB9(IND,K)*TG(6,K)
SC15 = CSB5(IND,K)*S
SC16 = CSB8(IND,K)*SC5

```

```

C
SIN1 = SC7*(1.-ZETA(IND,K))
SIN2 = SC15*ZETA(IND,K)
SIN3 = SC15*(1.-ZETA(IND,K))
SIN4 = SC7*ZETA(IND,K)
SIN5 = CEXP(SIN2) - CEXP(SC15)
SIN6 = CEXP(SIN4) - CEXP(SC7)
SIN7 = CMPLX(0.,0.)
SIN9 = G1FN1(SIN7,-SC15,SIN3)

```

SIN10 = GIFN1(SC1,-SC15,SIN3)
 SIN11 = CEXP(SIN4)

C

WK(1,K) = CEXP(SIN1)
 WK(2,K) = (CSB10(IND,K)/SC7) * (1.-CEXP(SIN1))
 WK(3,K) = ((SC8/SC15)*SIN5+SC9*SIN9+SC10*SIN10) / SIN11
 WK(4,K) = ((-CSB6(IND,K)/SC7)*SIN6+(SC11/SC15)*SIN5+SC12*SIN9+
 1 SC13*SIN10) / SIN11

WK(5,K) = (SC14*SIN10+(SC16/SC15)*SIN5)/SIN11

KM1 = K - 1

DO 451 J=1,5

DO 451 L=NTS,NFB1

ZLK(J,K,L) = CMPLX(0.,0.)

451 CONTINUE

DO 203 JJ=1,5

IF(JJ .EQ. 1) GO TO 204

IF(K .EQ. NTS) GO TO 205

DO 207 JS=NTS,KM1

IF(JS .EQ. KM1) GO TO 206

SUMS = CMPLX(1.,0.)

JSP1 = JS+1

DO 208 J=JSP1,KM1

SUMS = SUMS * WK(1,J)

208 CONTINUE

ZLK(JJ,K,JS) = SUMS * WK(JJ,JS)

GO TO 207

206 ZLK(JJ,K,JS) = WK(JJ,JS)

207 CONTINUE

GO TO 203

C

205 DO 210 JS=NTS,NFB1

ZLK(JJ,K,JS) = CMPLX(0.,0.)

210 CONTINUE

GO TO 203

C

204 IF(NOSB .GT. 0) GO TO 619

IF(K .EQ. NTS) GO TO 211

SUMS = CMPLX(1.,0.)

DO 212 JS=NTS,KM1

SUMS = SUMS * WK(1,JS)

212 CONTINUE

ZLK(1,K,1) = SUMS

GO TO 203

211 ZLK(1,K,1) = CMPLX(1.,0.)

GO TO 203

619 ZLK(1,K,1) = CMPLX(0.,0.)

203 CONTINUE

C.....
 C * TRANSFER FUNCTIONS FOR THE NODE-AVERAGED LIQUID ENTHALPY
 C PERTURBATION IN THE SUBCOOLED BOILING REGION

```

215 CONTINUE
   IF(K .EQ. NTS) GO TO 847
   DO 217 J=NSP1,K
     SBZK(3,K,J) = SBX(4,J)
     SBZK(5,K,J) = SBX(6,J)
217 CONTINUE
847  SBZK(6,K,1) = -(K1(IND,NTS)*SBX(4,NTS)+SBX(6,NTS)*C21(IND))
     IF(NOSB .GT. 0) SBZK(6,K,1) = CMPLX(0.,0.)

```

C

```
201 CONTINUE
```

C

```

401  NIR = NP1 + 1
     IF(ICAL .EQ. 1 .OR. ICAL .EQ. 4) NIR = NP1
     IF(NOSB .GT. 0) CHD1 = 0.
     IF(NOSB .GT. 0) CHD2 = 0.
     DO 23 K=NTS,NIR
       IF(K .EQ. NTS) GO TO 372
       DO 100 I=1,NP1
         CA(I) = CMPLX(0.,0.)
         CB(I) = CMPLX(0.,0.)
         CC(I) = CMPLX(0.,0.)
100 CONTINUE

```

C.....* CLACULATE THE PARAMETERS FOR THE VOID-FRACTION PERTURBATION
C.....

```

VAR4 = CMPLX(1.,0.)
KLOW = K - 1
DO 25 I=NTS,KLOW
  IF(I .EQ. KLOW) GO TO 26
  VAR3 = CMPLX(1.,0.)
  JU = K - I - 1
  DO 27 J=1,JU
    JP = K - J
    VAR3 = VAR3*CX3(JP)
27 CONTINUE
  CA(I) = VAR3 * CX1(I)
  CB(I) = VAR3 * CX2(I)
  CBS(I) = VAR3*CXS2(I)
  GO TO 66
26  CA(I) = CX1(KLOW)
   CB(I) = CX2(KLOW)
   CBS(I) = CXS2(I)
66  VAR4 = VAR4 * CX3(I)
   CC(K) = VAR4
25 CONTINUE

```

C

```

VAR5 = CMPLX(0.,0.)
DO 28 I=NTS,KLOW
28  VAR5 = VAR5 + CA(I)
   CK11(K) = (1.-K1(IND,NTS)*M1)*VAR5 - C21(IND)*CC(K)*M1

```

```

C.....
  A01 = CKIN(IND,K)/(DZ(IND,K)*COH(IND,K)*K1(IND,K)*SC7)
  B01 = CSB2(IND,K)*ZETA(IND,K)
  B02 = EXP(B01) - EXP(CSB2(IND,K))
  SIN7 = CMLPX(1.,0.)
  A04 = G1FN2(SIN7,CSB2(IND,K),ZETA(IND,K))
  A05 = G1FN2(STC1(K),CSB2(IND,K),ZETA(IND,K))
  U1K = A01 * (1.-WK(1,K))
  U2K = -A01*WK(2,K) + CSB10(IND,K)/SC7
  U3K = A01 * (-WK(3,K)+(SC8/CSB2(IND,K))*B02+SC9*A04+SC10*A05)
  U4K = A01 * (-WK(4,K)+CSB6(IND,K)*(1.-ZETA(IND,K))+B02*
1      (SC11/CSB2(IND,K))+SC12*A04+SC13*A05)
  U5K = A01 * (-WK(5,K)+(SC16/CSB2(IND,K))*B02+SC14*A05)
C.....
C  * TRANSFER FUNCTIONS FOR SUBCOOLED BOILING NODE AVERAGE
C  REACTION FREQUENCY PERTURBATION
C.....
  YOK = 1. - CSBF(IND,K)*U4K + CSBG(IND,K)*PAR2(K)
  YK(1,K) = CSBE(IND,K)*CHD2 / YOK
  YK(2,K) = (CSBQ(IND,K)*CSBD(IND,K)/QO(IND,K) + CSBF(IND,K)*
1      U2K) / YOK
  YK(3,K) = CSBF(IND,K)*U1K/YOK
  YK(4,K) = (U3K*CSBF(IND,K) - CSBG(IND,K)*PAR1(K)) / YOK
  YK(5,K) = (U5K*CSBF(IND,K) - CSBG(IND,K)*PAR3(K)) / YOK
  YK(6,K) = CSBE(IND,K)*CHD1/YOK
  SB1X = YK(1,K)
  SB2X(K) = YK(3,K) * ZLK(1,K,1)
  SB7X = YK(6,K)
  DO 213 J=3,6
    JM1 = J-1
    DO 213 JJ=NTS,K
      IF(JJ.EQ. K) GO TO 214
      SBX(J,JJ) = YK(3,K)*ZLK(JM1,K,JJ)
      GO TO 213
214  IF(J.EQ. 5) GO TO 213
      SBX(J,JJ) = YK(JM1,K)
      IF(J.EQ. 4) SBX(J,JJ) = YK(J,K)
213  CONTINUE
C
  SBZK(1,K,1) = SB1X + SBX(4,NTS)
  IF(NOSB.GT. 0) SBZK(1,K,1) = SB1X + SBX(4,NTS)
  IF(K.EQ. NTS) GO TO 876
  DO 299 J=NTS,KM1
299  SBZK(4,K,J) = SBX(5,J)
876  DO 215 J=NTS,K
    IF(J.EQ. NTS) GO TO 216
    SBZK(2,K,J) = SBX(3,J)
    GO TO 215
216  SBZK(2,K,J) = SBX(3,J) + SB7X
    IF(NOSB.GT. 0) SBZK(2,K,J) = SBX(3,J) + SB7X

```

```

    CKI21(K) = -(VAR5 + CC(K)/(RHOG*CKIN(IND,NTS)*VFG1)) *
1      K1(IND,NTS) * M2
    SKI1(K) = VAR5
    DO 29 I=NTS,KLOW
    IF(I .EQ. KLOW) GO TO 30
    IH = I + 1
    VAR6 = CMPLX(0.,0.)
    DO 31 J=IH,KLOW
31  VAR6 = VAR6 + CA(J)
    CKI22(K,I) = C5(IND)*VAR6*Z3(I)*DZ(IND,I) + CB(I)
    SKI2(K,I) = VAR6*DZ(IND,I) + CBS(I)
    GO TO 29
30  CKI22(K,I) = CB(I)
    SKI2(K,I) = CBS(I)
29  CONTINUE
32  CKI3(K) = -(VAR5 + CC(K)/(RHOG*VFG1*CKIN(IND,NTS))) *
1      K1(IND,NTS) * M3
    SKI3(K) = -VAR5*K1(IND,NTS) - CC(K)*C21(IND)

```

C

```

    IF(IOSUB .EQ. 0) GO TO 202
    IF(K .GE. NFB2) GO TO 225
    SUMS1 = CMPLX(0.,0.)
    SUMS2 = CMPLX(0.,0.)
    DO 218 J=NSP1,K
    SUMS1 = SUMS1 + (SBZK(3,K,J) + SBZK(5,K,J)*SKI1(J))
    SUMS2 = SUMS2 + (SBZK(3,K,J)*K1(IND,NTS) - SBZK(5,K,J)*
1      SKI3(J))
218 CONTINUE
    SBTk(1,K,1) = SBZK(1,K,1) + SUMS1
    SBTk(3,K,1) = SBZK(6,K,1) - SUMS2
    SBTk(5,K,1) = SB2X(K)
    DO 219 J=NTS,K
    SBTk(2,K,J) = SBZK(2,K,J)
219 CONTINUE
    DO 220 J=NTS,KLOW
    SUMS3 = CMPLX(0.,0.)
    JP1 = J+1
    DO 221 JJ=JP1,K
    SUMS3 = SUMS3 + SBZK(3,K,JJ)*DZ(IND,J)+SKI2(JJ,J)*SBZK(5,K,JJ)
221 CONTINUE
    SETK(4,K,J) = SUMS3 + SBZK(4,K,J)
220 CONTINUE

```

C

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    DO 222 J=NSP1,K
    IF(J .EQ. K) GO TO 223
    SUMS3 = CMPLX(0.,0.)
    DO 298 JJ=J,KLOW
    SUMS3 = SUMS3 + SBTk(4,K,JJ)*SGAM(JJ,J)
298 CONTINUE
    SGAM(K,J) = SUMS3

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```

      GO TO 222
223  SGAM(K,J) = CMPLX(1.,0.)
222  CONTINUE
C
      SUMS1 = CMPLX(0.,0.)
      SUMS2 = CMPLX(0.,0.)
      SUMS3 = CMPLX(0.,0.)
      DO 230 J=NSP1,K
        SUMS1 = SUMS1 + SGAM(K,J)*(SBTK(1,J,1) + SBTK(4,J,NTS)*
1      (YK(1,NTS)+YK(3,NTS)*CHD2+YK(4,NTS)))
        SUMS2 = SUMS2 + SGAM(K,J)*(SBTK(3,J,1) - SBTK(4,J,NTS)
1      *(K1(IND,NTS)*(YK(4,NTS)+YK(3,NTS)*CHD2+YK(1,NTS))
2      + YK(5,NTS)*C21(IND)))
        SUMS3 = SUMS3 + SGAM(K,J)*SBTK(3,J,1)
230  CONTINUE
      SBM1(K) = SUMS1 + SUMS2*M1 + SUMS3*TH1
      SBM21(K) = SUMS2*M2 + SUMS3*TH2
      SBM3(K) = SUMS2*M3 + SUMS3*TH3
      DO 231 J=NTS,K
        IF(J.EQ. NTS) GO TO 232
        SUMS3 = CMPLX(0.,0.)
        DO 233 JJ=J,K
          SUMS3 = SUMS3 + SGAM(K,JJ)*SBTK(2,JJ,J)
233  CONTINUE
        SBM2(K,J) = SUMS3 * Z3(J)
        GO TO 231
232  SUMS3 = CMPLX(0.,0.)
        DO 234 JJ=NSP1,K
          SUMS3 = SUMS3 + SGAM(K,JJ)*(SBTK(2,JJ,NTS) + SBTK(4,JJ,NTS)*
1      (YK(2,NTS)+YK(6,NTS)+YK(3,NTS)*CHD1))
234  CONTINUE
        SBM2(K,J) = SUMS3*Z3(J) + M4*SUMS2
231  CONTINUE
      GO TO 228
C
225  SBM1(K) = CMPLX(0.,0.)
      SBM21(K) = CMPLX(0.,0.)
      SBM3(K) = CMPLX(0.,0.)
      DO 226 JJ=NTS,K
        IF(K.EQ. NIR) GO TO 4829
        IF(JJ.EQ. K) GO TO 227
4829  SBM2(K,JJ) = CMPLX(0.,0.)
        GO TO 226
227  SBM2(K,JJ) = C5(IND)*Z3(JJ)
226  CONTINUE
C.....
C  * TRANSFER FUNCTIONS FOR NODE INLET VELOCITY & VOID FRACTION
C      PERTURBATIONS
C      SBJ1,21,2,3 ; T.F. FOR NODE INLET VELOCITY PERTURBATION
C      SBM1,21,2,3 ; T.F. FOR NODE CHARACTERISTIC FREQUENCY PERTURBATION

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C CK11,21,2,3 ; T.F. FOR NODE INLET VOID FRACTION PERUTRBATION

C.....

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228 SUMS1 = CMPLX(0.,0.)
    SUMS3 = CMPLX(0.,0.)
    SUMS4 = CMPLX(0.,0.)
    DO 250 J=NTS,KLOW
        SUMS1 = SUMS1 + DZ(IND,J)*SBM1(J)
        SUMS3 = SUMS3 + DZ(IND,J)*SBM3(J)
        SUMS4 = SUMS4 + DZ(IND,J)*SBM21(J)
        SUMS2 = CMPLX(0.,0.)
        DO 251 JJ=J,KLOW
            SUMS2 = SUMS2 + DZ(IND,JJ)*SBM2(JJ,J)
251 CONTINUE
    SBJ2(K,J) = SUMS2
    IF(J.EQ. NTS) SBJ2(K,J) = SUMS2 - K1(IND,J)*M4
250 CONTINUE
    SBJ1(K) = SUMS1 + 1. - K1(IND,NTS)*M1
    SBJ3(K) = -K1(IND,NTS)*M3 + SUMS3
    SBJ21(K) = -K1(IND,NTS)*M2 + SUMS4

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C

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SUMS1 = CMPLX(0.,0.)
SUMS3 = CMPLX(0.,0.)
SUMS4 = CMPLX(0.,0.)
DO 252 J=NTS,KLOW
    SUMS1 = SUMS1 + SK12(K,J)*SBM1(J)
    SUMS3 = SUMS3 + SK12(K,J)*SBM3(J)
    SUMS4 = SUMS4 + SK12(K,J)*SBM21(J)
    SUMS2 = CMPLX(0.,0.)
    DO 253 JJ=J,KLOW
        SUMS2 = SUMS2 + SK12(K,JJ)*SBM2(JJ,J)
253 CONTINUE
    CK122(K,J) = SUMS2
    IF(J.EQ. NTS) CK122(K,J) = SUMS2 + SK13(K)*M4
252 CONTINUE
    CK11(K) = SUMS1 + SK11(K) + SK13(K)*M1
    CK13(K) = SUMS3 + SK13(K)*M3
    CK121(K) = SUMS4 + SK13(K)*M2
    GO TO 255

```

C

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202 SBJ1(K) = 1. - K1(IND,NTS)*M1
    SBJ3(K) = -K1(IND,NTS)*M3
    DO 254 J=NTS,KLOW
        SBJ2(K,J) = C5(IND)*DZ(IND,J)*Z3(J)
254 CONTINUE
    SBJ21(K) = -K1(IND,NTS)*M2
    SBM1(K) = CMPLX(0.,0.)
    SBM3(K) = CMPLX(0.,0.)
    DO 402 J=1,K
        SBM2(K,J) = CMPLX(0.,0.)
        IF(J.EQ. K) SBM2(K,J) = C5(IND)*Z3(J)

```

402 CONTINUE
GO TO 255

C.....
C * FOR THE BOUNDARY NODE WITH SUBCOOLED BOILING

C.....

372 IF(10SUB .EQ. 0) GO TO 378
CSM1 = YK(1,K) + YK(3,K)*CHD2 + YK(4,K)
CSM2 = YK(6,K) + YK(3,K)*CHD1 + YK(2,K)
CSM3 = K1(IND,K)*(YK(1,K) + YK(3,K)*CHD2 + YK(4,K) +
1 C21(IND)*YK(5,K))
SBM1(K) = CSM1 - CSM3*M1
SBM21(K) = -CSM3*M2
SBM2(K,K) = CSM2*Z3(K) - CSM3*M4
SBM3(K) = -CSM3*M3
GO TO 379

C.....
C * FOR THE BOUNDARY NODE WITHOUT SUBCOOLED BOILING

C.....

378 SBM1(K) = CMPLX(0.,0.)
SBM21(K) = CMPLX(0.,0.)
SBM2(K,K) = C5(IND)*Z3(K)
SBM3(K) = CMPLX(0.,0.)

C.....

379 SBJ1(K) = 1.-K1(IND,K)*M1
SBJ21(K) = -K1(IND,K)*M2
SBJ2(K,K) = CMPLX(0.,0.)
IF(10SUB .EQ. 1) SBJ2(K,K) = -K1(IND,K)*M4
SBJ3(K) = -K1(IND,K)*M3
CK11(K) = -C21(IND)*M1
CK121(K) = -C21(IND)*M2
CK122(K,K) = CMPLX(0.,0.)
IF(10SUB .EQ. 1) CK122(K,K) = -C21(IND)*M4
CK13(K) = -C21(IND)*M3

C.....

255 IF(ICAL .EQ. 1) GO TO 389
IF(ICAL .EQ. 4) GO TO 389
IF(ICAL .GT. 1 .AND. K .EQ. NIR) GO TO 23

C.....
C * THE COMPONENTS OF THE PRESSURE DROP PERTURBATION IN EACH NODE

C.....

389 DP1 = (1.-S/(COH(IND,K)*K1(IND,K))) * ALOG(ZETA(IND,K))
DP2 = CEXP(DP1) - 1.
DP3 = S*CKIN(IND,K) / GC
DP4 = COH(IND,K)*K1(IND,K) - S
DP1V = DP3 * (TG(1,K)*ALOG(ZETA(IND,K))/(COH(IND,K)*K1(IND,K)) +
1 TG(2,K)*DP2/DP4)
DP1Q = DP3 * ((TG(3,K)*(ZETA(IND,K)-1.) + TG(4,K)*
1 ALOG(ZETA(IND,K)))/(COH(IND,K)*K1(IND,K)) +TG(5,K)*DP2/DP4)
DP1H = DP3 * TG(6,K)*DP2/DP4

C.....

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DP2V = (TB2(1,K) - TB1(1,K)) / GC
DP2Q = (TB2(2,K) - TB1(2,K)) / GC
DP2H = (TB2(3,K) - TB1(3,K)) / GC

C
SO1 = (CKIN(IND,K)*FRICMO(IND)*GO(IND)) / (GC*DENSF*DH(IND)*
1 COH(IND,K)*K1(IND,K))
DP5 = (2.*COH(IND,K)*K1(IND,K) - S) / (COH(IND,K)*K1(IND,K))
DP6 = DP5 * ALOG(ZETA(IND,K))
DP7 = CEXP(DP6) - 1.
DP3V = SO1 * ( C8(IND,K)*ALOG(ZETA(IND,K))*TG(1,K) + C9(IND,K)*
1 TG(1,K)*(ZETA(IND,K)-1.) + C8(IND,K)*TG(2,K)*COH(IND,K)*
2 K1(IND,K)*DP2/DP4 + C9(IND,K)*TG(2,K)*DP7/DP5 )
DP3Q = SO1 * ( C8(IND,K)*TG(4,K)*ALOG(ZETA(IND,K)) + (C8(IND,K)
1 *TG(3,K) + C9(IND,K)*TG(4,K))*(ZETA(IND,K)-1.)
2 + (C9(IND,K)*TG(3,K)/2.)*(ZETA(IND,K)**2-1.)
2 + C8(IND,K)*TG(5,K)*COH(IND,K)*K1(IND,K)*DP2/DP4
3 + C9(IND,K)*TG(5,K)*DP7/DP5 )
DP3H = SO1 * TG(6,K) * ( C8(IND,K)*COH(IND,K)*K1(IND,K)*DP2/DP4 +
1 C9(IND,K)*DP7/DP5 )

C
SO2 = CKIN(IND,K)*FRICMO(IND)*GO2(IND) / (2.*GC*DH(IND)*
1 COH(IND,K)*K1(IND,K)*DENSF)
DP4V = SO2 * ( TF(1,K)*(ZETA(IND,K)-1.) + TF(2,K)*
1 ALOG(ZETA(IND,K)) + COH(IND,K)*K1(IND,K)*TF(3,K)*DP2/DP4
2 + TF(4,K)*DP7/DP5 )
DP4Q = SO2 * ( TF(5,K)*(ZETA(IND,K)-1.) + TF(6,K)*ALOG(
1 ZETA(IND,K)) + TF(7,K)*(ZETA(IND,K)**2-1.)/2. + COH(IND,K)
2 *K1(IND,K)*TF(8,K)*DP2/DP4 + TF(9,K)*DP7/DP5 )
DP4H = SO2 * ( COH(IND,K)*K1(IND,K)*TF(10,K)*DP2/DP4 + TF(11,K)*
1 DP7/DP5 )

C
SO3 = G1*C4*CKIN(IND,K)*STC2(K)/GC
DP5V = SO3 * ( (1.-1./ZETA(IND,K)) + (1./CSTB1(K)-1.)/STC1(K) )
DP5Q = -DP5V / (COH(IND,K)*K1(IND,K)) * CKIN(IND,K)
DP5H = (SO3/STC2(K)/S) * (1./CSTB1(K)-1.)

C
DP6V = ( (TR2(1,K)-TR1(1,K)) - TR2(2,K)*DP2/ZETA(IND,K)**2 ) / GC
DP6Q = ( TR2(3,K)*(1.-ZETA(IND,K))-TR2(4,K)*DP2/ZETA(IND,K)**2 )
1 / GC
DP6H = ( TR2(5,K)/CSTB2(K) - TR1(5,K) ) / GC

C
GT2V = DP1V + DP2V + DP3V + DP4V + DP5V + DP6V
GT2Q = DP1Q + DP2Q + DP3Q + DP4Q + DP5Q + DP6Q
GT2H = DP1H + DP2H + DP3H + DP4H + DP5H + DP6H

C - - - - -
VAR1 = C22(IND)
MM4 = CMPLX(0.,0.)
IF(10SUB.EQ.1.AND.K.EQ.NTS) MM4 = VAR1*MM4
IF(K.GT.NTS) VAR1 = CMPLX(0.,0.)

C.....

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C      * PRESSURE DROP TRANSFER FUNCTIONS IN THE TWO-PHASE REGION
C.....
      PINOD1(K) = GT2V*SBJ1(K)+GT2Q*SBM1(K)+GT2H*CKI1(K) - VAR1*M1
C
      IF(NOSB .GT. 0) GO TO 2010
      DO 33 I=1,NSF
      PINOD2(K,I) = (GT2V*SBJ21(K)+GT2H*CKI21(K)+GT2Q*SBM21(K)
1          -VAR1*M2) * HS(I)
      33 CONTINUE
      2010 IF(K .EQ. NTS) GO TO 2040
      DO 34 J=NTS,KLOW
      PINOD2(K,J) = GT2V*SBJ2(K,J) + GT2Q*SBM2(K,J) + GT2H*CKI22(K,J)
      34 CONTINUE
      2040 PINOD2(K,K) = SBM2(K,K)*GT2Q - MM4
C
      PINOD3(K) = GT2V*SBJ3(K)+GT2H*CKI3(K)-VAR1*M3+GT2Q*SBM3(K)
C - - - - -
      23 CONTINUE
C.....
C      * TOTAL TWO-PHASE PRESSURE DROP PERTURBATION WHICH DOES NOT
C      INCLUDE THE SPACER EFFECT
C.....
      SUMP1 = CMPLX(0.,0.)
      DO 36 I=1,NP1
      36 SUMP2(I) = CMPLX(0.,0.)
      SUMP3 = CMPLX(0.,0.)
C
      DO 35 K=NTS,NP1
      SUMP1 = SUMP1 + PINOD1(K)
      SUMP3 = SUMP3 + PINOD3(K)
      35 CONTINUE
      DO 67 I=1,NP1
      DO 67 K=NTS,NP1
      SUMP2(I) = SUMP2(I) + PINOD2(K,I)
      67 CONTINUE
C.....
C      * CALCULATE THE PRESSURE DROP PERTURBATION DUE TO SPACERS
C.....
      NSPAC = N1PSP(IND)
      NPLUS = NP1 + 1
      DO 37 K=NTS,NPLUS
      KK = K
      IF(K .EQ. NPLUS) GO TO 645
      NNSP = NUMBSP(IND, KK)
      IF(NNSP .EQ. 0) GO TO 37
      645 IF(K .EQ. NPLUS) NNSP = 1
      DO 377 JJJ=1,NNSP
      NSPAC = NSPAC + 1
C
      IF(K .EQ. NPLUS) GO TO 646

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        SLOSS = KLOSS(NSPAC)
        GO TO 647
646  Y2 = ZETA(IND, NP1)
        KK = NP1
        SLOSS = XKEXIT(IND)
        GO TO 648
647  Y2 = ZETSP(IND, NSPAC)
648  VV1 = -STC1(KK) * ALOG(Y2)
        Y3 = CEXP(VV1)
        VV2 = (1. - STC1(KK)) * ALOG(Y2)
        Y4 = CEXP(VV2)
        Y5 = SLOSS*G02(IND) / (2.*GC*DENSF)
        Y6 = SLOSS*VIN(IND)*COR2PH(IND, KK)/GC
C
        SPA1 = Y6*(TG(1, KK)/Y2 + TG(2, KK)*Y3)
        SPA2 = Y6*(TG(3, KK) + TG(4, KK)/Y2 + TG(5, KK)*Y3)
        SPA3 = Y6*TG(6, KK)*Y3
        SPB1 = Y5*(TF(1, KK) + TF(2, KK)/Y2 + TF(3, KK)*Y3 + TF(4, KK)*Y4)
        SPB2 = Y5*(TF(5, KK) + TF(6, KK)/Y2 + TF(7, KK)*Y2 + TF(8, KK)*Y3
1         + TF(9, KK)*Y4)
        SPB3 = Y5*(TF(10, KK)*Y3 + TF(11, KK)*Y4)
C
        B1 = SPA1 + SPB1
        B2 = SPA2 + SPB2
        B3 = SPA3 + SPB3
C
        SPK1(NSPAC) = B1*SBJ1(KK) + B2*SBM1(KK) + B3*CK11(KK)
        IF(NOSB .GT. 0) GO TO 2011
        DO 39 I=1, NSF
39  SPK2(NSPAC, I) = (B1*SBJ21(KK) + B3*CKI21(KK) + B2*SBM21(KK))
1         * HS(I)
2011 DO 40 J=NTS, KK
        IF(J .EQ. KK) GO TO 41
        SPK2(NSPAC, J) = B1*SBJ2(KK, J) + B2*SBM2(KK, J) + B3*CKI22(KK, J)
        GO TO 40
41  SPK2(NSPAC, J) = B2*SBM2(KK, J)
40  CONTINUE
        SPK3(NSPAC) = B1*SBJ3(KK) + B3*CKI3(KK) + B2*SBM3(KK)
377 CONTINUE
37  CONTINUE
C.....
C  * TOTAL SPACER EFFECT
C.....
        SPT1 = CMPLX(0., 0.)
        DO 43 I=1, NP1
43  SPT2(I) = CMPLX(0., 0.)
        SPT3 = CMPLX(0., 0.)
C
        IF(NSP .EQ. 0) GO TO 1919
        KTSP = K2PSP(IND)

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      DO 44 J=KTSP, NSPAC
      SPT1 = SPT1 + SPK1(J)
      SPT3 = SPT3 + SPK3(J)
44  CONTINUE
      DO 46 I=1, NP1
      DO 46 J=KTSP, NSPAC
      SPT2(I) = SPT2(I) + SPK2(J, I)
46  CONTINUE
C.....
C  * TOTAL TWO-PHASE PRESSURE DROP PERTURBATION IN THE CORE
C.....
1919 PI1(IND) = SUMP1 + SPT1
      PI3(IND) = SUMP3 + SPT3
      DO 45 I=1, NP1
      PI2(IND, I) = SUMP2(I) + SPT2(I)
45  CONTINUE
C.....
C  * CHANNEL EXIT FLOW VELOCITY & VOID FRACTION PERTURBATION
C.....
      CXJ1(IND) = SBJ1(NIR)
      CXJ3(IND) = SBJ3(NIR)
      CXA1(IND) = CKI1(NIR)
      CXA3(IND) = CKI3(NIR)
      IF(NOSB .GT. 0) GO TO 52
      DO 69 I=1, NSF
      CXJ2(IND, I) = SBJ21(NIR)*HS(I)
      CXA2(IND, I) = CKI21(NIR)*HS(I)
69  CONTINUE
52  DO 53 I=NTS, NP1
      CXJ2(IND, I) = SBJ2(NIR, I)
      CXA2(IND, I) = CKI22(NIR, I)
53  CONTINUE
C
      IF(ICAL .EQ. 6) GO TO 8879
C.....
C  * CALCULATE THE VOID FRACTION PERTURBATION IN EACH NODE *
C.....
      DO 47 K=NTS, NP1
      DO 48 I=1, NP1
48  TALP2(K, I) = CMLPX(0., 0.)
C
      TALP1(IND, K) = (PAR1(K)*SBJ1(K)+PAR2(K)*SBM1(K)+PAR3(K)*CKI1(K))
1      /((DENSF*AXS(IND))
      IF(NOSB .GT. 0) GO TO 2020
      DO 49 I=1, NSF
49  TALP2(K, I) = (CKI21(K)*PAR3(K)+PAR1(K)*SBJ21(K)+SBM21(K)*
1      PAR2(K)) * HS(I)
2020 DO 50 I=NTS, K
      IF(I .EQ. K) GO TO 51
      TALP2(K, I) = PAR3(K)*CKI22(K, I)+PAR1(K)*SBJ2(K, I)+PAR2(K)*

```

```

1          SBM2(K, I)
GO TO 50
51 TALP2(K, I) = SBM2(K, I)*PAR2(K)
50 CONTINUE
TALP3(IND, K) = PAR1(K)*SBJ3(K) + PAR3(K)*CKI3(K) + PAR2(K)*
1          SBM3(K)
TSUM2(IND, K) = CMPLX(0., 0.)
DO 55 J=1, K
TSUM2(IND, K) = TSUM2(IND, K) + TALP2(K, J)*BEE(IND, J)
55 CONTINUE
47 CONTINUE
C.....
C * TRANSFER FUNCTION FOR THE CHANNEL AVERAGE VOID FRACTION
C.....
C IF(ICAL .GE. 4) GO TO 8879
TAU1(IND) = CMPLX(0., 0.)
DO 61 K=1, NP1
61 SUM2(K) = CMPLX(0., 0.)
DO 62 K=NTS, NP1
TAU1(IND) = TAU1(IND) + TALP1(IND, K)*DZ(IND, K)
62 CONTINUE
TAU1(IND) = TAU1(IND) / ALHEAT
DO 64 K=1, NP1
DO 63 J=K, NP1
63 SUM2(K) = SUM2(K) + TALP2(J, K)*DZ(IND, J)
SUM2(K) = SUM2(K) / ALHEAT
64 CONTINUE
C
TAU2(IND) = CMPLX(0., 0.)
DO 65 K=1, NP1
TAU2(IND) = TAU2(IND) + SUM2(K)*BEE(IND, K)
65 CONTINUE
C
8879 RETURN
END
C
C
C
C
C*****
SUBROUTINE DPLP(ICAL, JLL, JRR, S)
C*****
C
C * CALCULATE THE PRESSURE DROP PERTURBATION IN THE LOOP
C
COMPLEX HUB1(200), HUB2(200), RR1, RR2, RR3, CX12(200), RT1, RT2,
1 DPUP1, DPUP2, DPUP3, CX7(200), CX8(200), CX9, CX10, CX11,
2 SH1, SH2, SH3, SH5, UPC1, UPC2, CXJ1, CXJ2, CXJ3, CXA1, CXA2,
3 CXA3, SUP1(200), SUP2(200), SUP3(200), SUPT, CR1, CR2, RX2,
4 DWSW1, DWSW2, DWSW3, T1, CC1, CC2, CC7, EPV, WC1, WC2, DTHET,

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5      DPIZ,DPIE,DDD, TLP1,TLP2, DPH1, S, RX1, SUP5
COMMON/CONST1/ C1(200),C2(200),C3(200),C4,C5(200),C8(200,30),
1      C9(200,30),C18(200), C21(200), C22(200),C25(200),
2      C26(200), T6, V7(200), DD1, CK1, CMP
COMMON/CONST2/ P,VCH,VIN(200),AXS(200),DH(200),DHIN(200),
1      PH(200),TIN,TSATP,ENTHT,DENSI,SIGM,ENTHP,VISC,CPF,KF,
2      DENSF,VFG1,RHOG,G0(200),G02(200),H0(200),GC,G1,KLOSS(30),
3      FRICM0(200),VGJH(200,30),COH(200,30),CZERO,VGJ,DPTS,
4      G02RF(200),HFG1,ZSP(30),NUMBSP(200,30),ALHEAT,CXF(200),
5      AVEQ,CHOM01,CHOM02,XKIN(200),XKEXIT(200)
COMMON/CONSS1/ QDIS(200,30), Q0(200,30), DZ(200,30),Z(200,30),
1      K1(200,30), CKIN(200,30), ZETA(200,30), DOIN(200,30),
2      DOOUT(200,30), ALPIN(200,30),BEE(200,30), CPI1(200,30),
3      COR2PH(200,30), ZETSP(200,30), WIN
COMMON/CONSS2/ NTOT(200),NBB(200),NBB1(200),NSP,N1PSP(200),
1      K2PSP(200), NDP(200), NDP1(200), ISUB(200)
COMMON /RISER/ COR,VGJR,CKR0,RL,AR,DRIN,DR,PI,CL1,CL2,CL3,CL4,
1      CL5, CL6, CR5, CR6, UPJ1, UPJ2, RO11, RO12,
2      RO21, RO22, XROUT, UPJIN
COMMON /CLOOP/ SLOOP, SFLOOP, RLOOP,AA, VL1, VL2, VL3, DPLPT,
1      RATW
COMMON /CUPPER/ RKIN, RKEXIT, AP, RPO, RP1, RP2, CL10,CL11,
1      CLT,AXSCH,RAR,AD,DL,DHDL,FDL, F1(200),F2(200),
2      RJ1(200),RJ2(200),RJ3(200),F3(200)
COMMON /CDELH1/ HFW, ADC, PHV, DKV, CPV, DENV, TEMV, TEMINV,
1      THV, HOD, PLM, AHLF, THLP, HOLP, WO, DLENG
COMMON /CDELH2/ CH1, CH2, CH3, CH4, CH5, CH7, CH8, CH9, CH10
COMMON /CXCH/ CXJ1(200),CXJ2(200,30),CXJ3(200), CXA1(200),
1      CXA2(200,30),CXA3(200)
COMMON /CXLP/ RR1(200), RR2, RR3, DPUP1(200), DPUP2, DPUP3,
1      DWSW1(200), DWSW2, DWSW3, T1, DPH1

```

C

```

DO 1 I=JLL,JRR
NP1 = NTOT(I)
HUB1(I) = CMPLX(0.,0.)
HUB2(I) = CMPLX(0.,0.)
DO 2 J=1,NP1
HUB1(I) = HUB1(I) + CXJ2(I,J)*BEE(I,J)
HUB2(I) = HUB2(I) + CXA2(I,J)*BEE(I,J)
2 CONTINUE
1 CONTINUE

```

C.....

C (1) FOR THE RISER

```

SUP2(I) = RJ2(I)*RT1 + F2(I)*RT2*SUP1
SUP3(I) = RJ3(I)*RT1 + F3(I)*RT2*SUP1
10 CONTINUE
RR2 = CMPLX(0.,0.)
RR3 = CMPLX(0.,0.)
DO 11 I=JLL,JRR
RR1(I) = (SUP1(I)*CXJ1(I) + SUP2(I)*CXA1(I))/AXS(I)/DENSF +
1      SUP3(I)
RR2 = RR2 + (SUP1(I)*HUB1(I) + SUP2(I)*HUB2(I))
RR3 = RR3 + (SUP1(I)*CXJ3(I) + SUP2(I)*CXA3(I))
11 CONTINUE

```

C.....

C (2) FOR THE UPPER PLENUM

```

SUP2(I) = RJ2(I)*RT1 + F2(I)*RT2*SUP1
SUP3(I) = RJ3(I)*RT1 + F3(I)*RT2*SUP1

```

```

10 CONTINUE
  RR2 = CMPLX(0.,0.)
  RR3 = CMPLX(0.,0.)
  DO 11 I=JLL,JRR
    RR1(I) = (SUP1(I)*CXJ1(I) + SUP2(I)*CXA1(I))/AXS(I)/DENSF
    1 SUP3(I)
    RR2 = RR2 + (SUP1(I)*HUB1(I) + SUP2(I)*HUB2(I))
    RR3 = RR3 + (SUP1(I)*CXJ3(I) + SUP2(I)*CXA3(I))
  11 CONTINUE
C.....
C (2) FOR THE UPPER PLENUM
C.....
  UPC1 = -S*(RP2-ALHEAT)/UPJIN
  UPC2 = (GC*C4*UPJIN/G1/S) * (CEXP(UPC1)-1.)
  DPUP2 = CMPLX(0.,0.)
  DPUP3 = CMPLX(0.,0.)
  DO 12 I=JLL,JRR
    DPUP1(I) = ((F1(I)*CXJ1(I) + F2(I)*CXA1(I))/AXS(I)/DENSF +
    1 F3(I)) * UPC2
    DPUP2 = DPUP2 + (F1(I)*HUB1(I) + F2(I)*HUB2(I))*UPC2
    DPUP3 = DPUP3 + (F1(I)*CXJ3(I) + F2(I)*CXA3(I))*UPC2
  12 CONTINUE
C.....
C * PRESSURE DROP PERTURBATION BY THE DOWNCOMER LENGTH PERTURBATION
C.....
  CC7 = CH2 * CEXP(CR1)
  DO 30 I=JLL,JRR
    CX7(I) = CH1*(R011*RJ1(I)+R012*SUPT*F1(I)) - CC7*(R021*RJ1(I)
    1 +R022*SUPT*F1(I))
    CX8(I) = CH1*(R011*RJ2(I)+R012*SUPT*F2(I)) - CC7*(R021*RJ2(I)
    1 +R022*SUPT*F2(I))
    CX12(I) = CH1*(R011*RJ3(I)+R012*SUPT*F3(I)) -
    1 CC7*(R021*RJ3(I)+R022*SUPT*F3(I))
  30 CONTINUE
  SH5 = CH10 + DL*S/GC/AD + CH9/(DENSF*AD*S)
  CX10 = CMPLX(0.,0.)
  CX11 = CMPLX(0.,0.)
  DO 31 I=JLL,JRR
    CX9 = (CX7(I)*CXJ1(I) + CX8(I)*CXA1(I))/AXS(I)/DENSF + CX12(I)
    DWSW1(I) = SH5*CX9 - CH9/(DENSF*AD*S)*RA1W
    CX10 = CX10 + (CX7(I)*HUB1(I) + CX8(I)*HUB2(I))
  31 CONTINUE

```

```

CX11 = CX11 + (CX7(1)*CXJ3(1) + CX8(1)*CXA3(1))
31 CONTINUE
DWSW2 = SH5*CX10
DWSW3 = SH5*CX11
C.....
C * PRESSURE DROP IN THE UNHEATED LOOP
C.....
C T1 = VL1*S + VL2 - VL3
C
C CC7 = CH2 * CEXP(CR1)
C IF(ICAL.EQ. 3 .OR. ICAL.EQ. 5) GO TO 200
C GO TO 100
C.....
C * CALCULATE THE INLET ENTHALPY PERTURBATION
C.....
200 EPV = S*DENV*CPV/DKV
EPV = CSQRT(EPV)
WC1 = EPV*THV
CC1 = DKV*EPV/(DKV*EPV + HOD/CCOTH(WC1))
DPI = DENS1*ADC*S/WO + (PHV*HOD/WO/CPF)*CC1
DTHET = -(CH5*PHV/WO) * (0.8*CC1-1.)
DPIZ = -DPI*DLENG
DPIE = CEXP(DPIZ)
DBIZ = -CH3*DLENG
DBIE = EXP(DBIZ)
DDD = DTHET*(DBIE-DPIE)/(DPI-CH3)/WO + CH4*DPIE
C.....
C * FOR THE LOWER PLENUM
C.....
C WC2 = EPV*THLP
C CC2 = DKV*EPV/(DKV*EPV + HOLP/CCOTH(WC2))
C TLP1 = WO*DDD + (CH7-ENTHT) - CC2*AHLP*0.8*CH8/WO
C TLP2 = PLM*S + WO + CC2*HOLP*AHLP/CPF
C DPH1 = (TLP1/TLP2)*DENSF*AXS(IND)*RATW
C
100 RETURN
END
C
C
C
C
C*****
C SUBROUTINE VDTF(ICAL,JLL,JRR,NCH)
C*****
C
C * CALCULATE THE TOTAL PRESSURE DROP INCLUDING THE LOOP
C AND THE THERMAL-HYDAULIC TRANSFER FUNCTION DUE TO THE VOID
C FRACTION AND FLOW RATE FEEDBACK
C
C DIMENSION FPV(30)

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DIMENSION FPV(30)
COMPLEX GAM1,GAM2,GAM3, RR1,RR2,RR3, DPUP1,DPUP2,DPUP3, DWSW1,
1 DWSW2,DWSW3, T1, TGAM,TPI, DPH1, CXL,DWF,
2 TALP1,TALP3, SUM1,SUM2, FPV,FALF, F11,F1, TSUM2,
3 TAU1,TAU2, P11,P12,P13, TLP1(200),TLP2,TLP3,TLP4,
4 TGAM1,TPI1

C
COMMON /DPCON1/GAM1(200),GAM2(200,30),GAM3(200), P11(200),
1 P12(200,30),P13(200), TALP1(200,30),
2 TSUM2(200,30),TAU1(200),TAU2(200),TALP3(200,30)
COMMON /CXLP/ RR1(200), RR2, RR3, DPUP1(200), DPUP2, DPUP3,
1 DWSW1(200), DWSW2, DWSW3, T1, DPH1
COMMON/CONST2/ P,VCH,VIN(200),AXS(200),DH(200),DHIN(200),
1 PH(200),TIN,TSATP,ENTHT,DENSI,SIGM,ENTHP,VISC,CPF,KF,
2 DENSF,VFG1,RHOG,G0(200),G02(200),H0(200),GC,G1,KLOSS(30),
3 FRICMO(200),VGJH(200,30),COH(200,30),CZERO,VGJ,DPTS,
4 G02RF(200),HFG1,ZSP(30),NUMBSP(200,30),ALHEAT,CXF(200),
5 AVEQ,CHOMO1,CHOMO2,XKIN(200),XKEXIT(200)
COMMON/CONSS1/ QDIS(200,30), QO(200,30), DZ(200,30),Z(200,30),
1 K1(200,30), CKIN(200,30), ZETA(200,30), DOIN(200,30),
2 DOOUT(200,30), ALPIN(200,30),BEE(200,30), CPI1(200,30),
3 COR2PH(200,30), ZETSP(200,30), WIN
COMMON/CONSS2/ NTOT(200),NBB(200),NBB1(200),NSP,N1PSP(200),
1 K2PSP(200), NDP(200), NDP1(200), ISUB(200)
COMMON /CDELH1/ HFW, ADC, PHV, DKV, CPV, DENV, TEMV, TEMINV,
1 THV, HOD, PLM, AHLF, THLP, HOLP, WO, DLENG
COMMON/VOIDPT/FALF(200,30),F1(200),TGAM(200),TPI(200)
COMMON /CGHT/ F11
COMMON /RESULT/XZ, SS1, SS2
COMMON /DIM1/ DELX, DELZ, CHLAMB(200), ALFNOD(200,30),
1 BBLAMB(200)
C*****
DO 1000 I=JLL,JRR
NP1 = NTOT(I)

C.....
C * TOTAL CHANNEL PRESSURE DROP PERTURBATION CORRESPONDING TO
C THE CHANNEL INLET FLOW RATE PERTURBATION
C.....
TGAM(I) = (GAM1(I)+P11(I))/AXS(I)/DENSF + (GAM3(I)+P13(I))*DPH1
C.....
C * TOTAL CHANNEL PRESSURE DROP PERTURBATION CORRESPONDING TO
C THE POWER PERTURBATION
C.....
CXL = CMPLX(0.,0.)
DO 10 K=1,NP1
CXL = CXL + (GAM2(I,K)+P12(I,K))*BEE(I,K)
10 CONTINUE
C.....
C * TOTAL LOOP PRESSURE DROP PERTURBATION DUE TO CHANNEL INLET
C FLOW RATE PERTURBATIONS

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C.....TLP1(I) = RR1(I)+DWSW1(I)+DPUP1(I)+T1 + (RR3+DWSW3+DPUP3)*
      1      DPH1
C
C 1000 CONTINUE
C.....* TOTAL LOOP PRESSURE DROP PERTURBATION DUE TO POWER
C      PERTURBATIONS
C.....TLP2 = RR2 + DPUP2 + DWSW2
C.....*** CALCULATE VOID-FRACTION PERTURBATION IN EACH NODE ***
C.....
C      DO 3000 I=JLL,JRR
C      NP1 = NTOT(I)
C      NOSB = ISUB(I)
C      IF(NOSB.EQ. 0) NSF = NDP(I)
C      NTS = NDP1(I)
C      IF(NOSB.GT. 0) GO TO 31
C      DO 30 K=1,NSF
C      FPV(K) =CMPLX(0.,0.)
C      FALF(I,K)=CMPLX(0.,0.)
C 30 CONTINUE
C.....* CHANNEL INLET FLOW RATE FEEDBACK CORRESPONDING TO POWER
C      PERTURBATIONS
C.....
C 31 TLP3 = CMPLX(0.,0.)
C      TLP4 = CMPLX(0.,0.)
C      DO 32 J=JLL,JRR
C      IF(J.EQ. 1) GO TO 32
C      TLP3 = TLP3 + TLP1(J)*(TPI(I)-TPI(J))/TGAM(J)
C      TLP4 = TLP4 + TLP1(J)*TGAM(I)/TGAM(J)
C 32 CONTINUE
C      DWF = (TPI(I)+TLP2+TLP3) / (TGAM(I)+TLP1(I)+TLP4)
C      IF(ICAL.EQ. 6) GO TO 50
C.....* TRANSFER FUNCTION FOR THE NODE VOID FRACTION
C.....
C      DO 45 K=NTS,NP1
C      KK = K
C      IF(NP1.GT.NCH .AND. K.GT.NDP1(I)) KK=K-1
C.....* INCLUDE THE EFFECT OF DELHI
C.....
C      IF(ICAL.EQ. 3 .OR. ICAL.EQ. 5) GO TO 40
C      GO TO 41
C 40 TALP1(I,KK) = TALP1(I,KK) + TALP3(I,KK)*DPH1
C 41 IF(ICAL.GE. 4) GO TO 43
C      FALF(I,KK)=TSUM2(I,KK)-TALP1(I,KK)*DWF

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```

      IF(NP1.EQ. NCH) GO TO 45
      IF(K.EQ. NDP1(1)) FALF(1,K-1) = FALF(1,K)*DZ(1,K)/DELZ
      GO TO 45
C
C 43 SUM2 = CMPLX(0.,0.)
      FPV(K) = TSUM2(1,K) - TALP1(1,K)*DWF
C 45 CONTINUE
C.....
C * POWER-TO-VOID PERTURBATION
C.....
      IF(ICAL.LT. 4) GO TO 60
      NCON = NP1
      XZ = Z(1,NCON)*30.478513
C      F11 = FPV(NCON)
      F11 = TAU2(1) - TAU1(1)*DWF
      GO TO 51
C 50 F11 = -DWF*(AVEQ/W0)
C 51 SS1 = CABS(F11)
      SS2 = ANGL(F11)
      GO TO 2000
C.....
C * TRANSFER FUNCTION FOR THE CHANNEL AVERAGE VOID FRACTION
C.....
C 60 F1(1) = TAU2(1) - TAU1(1)*DWF
C
C 3000 CONTINUE
C 2000 RETURN
C      END
C
C
C
C
C*****
C      SUBROUTINE WALLDY(S, INODE)
C*****
C
C      * CALCULATION OF HEATED WALL DYNAMICS
C      (1) I=1 ; LUMPED PARAMETER MODEL
C      (2) I=2 ; PARALLEL PLATE MODEL
C      (3) I=3 ; CYLINDRICAL TUBE MODEL
C      (4) I=4 ; BWR FUEL ROD
C
C
C      COMPLEX Z1,Z2,Z3, S, EP, WC,WC1,WC2,WDEN, CCOTH, EP1,EP2,EPF,
C      1 EPC, BS10,BS11,BSK0,BSK1
C      COMMON/OPTION/ IOSUB, IOPT, KOPT, IP1LO, ISLIP, IRW
C      COMMON /CONWD1/ CPH,TKH,DENSH,CPC,TKC,DENSC,CRS,CRI,CRO,
C      1 GAPC, V22(200,30), THICKH
C      COMMON/CONST2/ P,VCH,VIN(200),AXS(200),DH(200),DHIN(200),
C      1 PH(200),TIN,TSATP,ENTHT,DENSI,SIGM,ENTHP,VISC,CPF,KF,

```

```

2      DENSF,VFG1,RHOG,GO(200),G02(200),H0(200),GC,G1,KLOSS(30),
3      FRICMO(200),VGJH(200,30),COH(200,30),CZERO,VGJ,DPTS,
4      G02RF(200),HFG1,ZSP(30),NUMBSP(200,30),ALHEAT,CXF(200),
5      AVEQ,CHOM01,CHOM02,XKIN(200),XKEXIT(200)
COMMON /WD2/Z1, Z2, Z3(30)
COMMON/CONSS2/ NTOT(200),NBB(200),NBB1(200),NSP,N1PSP(200),
1      K2PSP(200),NDP(200),NDP1(200),ISUB(200)

```

C

```

W = AIMAG(S)
N1 = NDP1(INODE)
N2 = NTOT(INODE)
IF(IOPT.EQ. 2) GO TO 1
IF(IOPT.EQ. 3) GO TO 2
IF(IOPT.EQ. 4) GO TO 3

```

C.....

C * LUMPED PARAMETER MODEL

C.....

```

Z1 = -PH(INODE)/(DENS*CXF(INODE)*CPH*S)
Z2 = 1./(DENS*CPH*S)
GO TO 100

```

C.....

C * PARALLEL PLATE MODEL

C.....

```

1 EP = S*DENS*CPH/TKH
EP = CSQRT(EP)
WC = EP*THICKH
Z1 = -CCOTH(WC)/(EP*TKH)
Z2 = 1. / (DENS*CPH*S)
GO TO 100

```

C.....

C * CYLINDRICAL TUBE MODEL

C.....

```

2 EP1 = S*DENS*CPH/TKH
SU = W*DENS*CPH/TKH
EP = CSQRT(EP1)
RI = SU*CR1
RO = SU*CRO
WC1 = BSK1(R2)*BSI0(R2) + BSI1(R2)*BSK0(R2)
WC2 = BSI1(R1)*BSK1(R2) - BSK1(R1)*BSI1(R2)
Z1 = - (WC1/WC2) / (EP*TKH)
Z2 = 1./(DENS*CPH*S)
GO TO 100

```

C.....

C * BWR FUEL ROD MODEL

C.....

```

3 EP1 = S*DENS*CPH/TKH
EP2 = S*DENS*CPG/TKC
EPF = CSQRT(EP1)
EPC = CSQRT(EP2)
SUF1 = W*DENS*CPH/TKH

```

```

SUC1 = W*DENSC*CPC/TKC
SUF2 = SQRT(SUF1)
SUC2 = SQRT(SUC1)
RS = SUF2*CRS
R1 = SUC2*CR1
RO = SUC2*CRO
RSI = CR1/CRS
WC = EPC*TKC*(BS10(RS)/(TKH*EPF*BS11(RS))*RSI + 1./GAPC)
WC1 = BS10(R1) - WC*BS11(R1)
WC2 = BSK0(R1) + WC*BSK1(R1)
WDEN = WC2*BS11(RO) + WC1*BSK1(RO)
C
Z1 = (1./EPC/TKC) * (-WC2*BS10(RO) + WC1*BSK0(RO)) / WDEN
Z2 = (1./((DENSH*CPH*S)) * (BS10(RO)*BSK1(RO)+BSK0(RO)*BS11(RO))
1 / WDEN
C
100 IF(KOPT .EQ. 0) GO TO 4
DO 10 I=N1,N2
Z3(I) = V22(INODE,I)*Z2/(1. - V22(INODE,I)*Z1)
C
10 CONTINUE
GO TO 101
C
4 DO 11 I=N1,N2
Z3(I) = CMPLX(0.,0.)
11 CONTINUE
C
101 RETURN
END
C
C
C
C
C*****
SUBROUTINE STABTY(S,IK,RATIO,AMRAT,ARRAT,NCH1,ICOUNT,IBODE)
C*****
C
C * CALCULATION OF THE OPEN-LOOP TRANSFER FUNCTION, GH(S)
C * RATION = GH(S)
C * AMRAT = ABS(GH(S))
C * ARRAT = ANG(GH(S))
C
C
C COMPLEX S,ZPK,RATIO,GAM1,GAM2,GAM3,PI1,PI2,PI3,TAU1,TAU2,TAU3
COMPLEX F1,TGAM,TPI1,FALF,AAA,F22,ZPKP,ZPK1,RATIO1
COMPLEX CXL,CST1,CST2,CST3,RR1,RR2,RR3,DPUP1,DPUP2,DPUP3,
1 DWSW1,DWSW2,DWSW3,T1,DPH1
COMPLEX RANI,GAMM,ZN1,BI,RK1,XZN1,XBM,XRKM
COMPLEX WW1,WW2,TZ1,TZ2,TWO,THREE
DIMENSION CAL1(30),CAL2(30)
C

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```

COMMON /PERT/ DELVI, DELQO, DELK
COMMON /PTKO/ZPK, ZPK1, ZPKP
COMMON /DPCON1/GAM1(200), GAM2(200,30), GAM3(200), P11(200),
1      P12(200,30), P13(200), TALP1(200,30),
2      TSUM2(200,30), TAU1(200), TAU2(200), TALP3(200,30)
COMMON /CXLP/ RR1(200), RR2, RR3, DPUP1(200), DPUP2, DPUP3,
1      DWSW1(200), DWSW2, DWSW3, T1, DPH1
COMMON /CONSS2/ NTOT(200), NBB(200), NBB1(200), NSP, N1PSP(200),
1      K2PSP(200), NDP(200), NDP1(200), ISUB(200)
COMMON /CONSS1/ QDIS(200,30), QO(200,30), DZ(200,30), Z(200,30),
1      K1(200,30), CKIN(200,30), ZETA(200,30), DOIN(200,30),
2      DOOUT(200,30), ALPIN(200,30), BEE(200,30), CPI1(200,30),
3      COR2PH(200,30), ZETSP(200,30), WIN
COMMON /CONST2/ P, VCH, VIN(200), AXS(200), DH(200), DHIN(200),
1      PH(200), TIN, TSATP, ENTHT, DENSI, SIGM, ENTHP, VISC, CPF, KF,
2      DENSF, VFG1, RHOG, GO(200), GO2(200), HO(200), GC, G1, KLOSS(30),
3      FRICMO(200), VGJH(200,30), COH(200,30), CZERO, VGJ, DPTS,
4      GO2RF(200), HFG1, ZSP(30), NUMBSP(200,30), ALHEAT, CXF(200),
5      AVEQ, CHOMO1, CHOMO2, XKIN(200), XKEXIT(200)
COMMON /SIM1/ IMAX, JMAX, KMAX, ICASE, ISPEC, JSPEC, INUCLR, XKEFF
COMMON /SIM2/ JMX(20), NFT(15,15,30), AL(15,15), TAL(15,15),
1      BAL(15,15), ASRC(15,15), SRC(15,15,30), AEXP(15,15),
2      REXP(15,15,30), AXSRC(30), XXSRC(30)
COMMON /SIM3/ JJD(15,15), DZ1(200), DZ2(200), NF(200,30), NB(200),
1      SC(200,30,6), XEXP(200,30), SIG1(200,30,11),
2      CSIG1(200,30,11)
COMMON /KIN3/ RANI(200,4), GANM(200,30,6), ZNI(200,4), B1(200)
COMMON /KIN5/ RKI(200), XZNI(200,30,6), XBM(200,30), XRKM(200,30)
COMMON /DIM1/ DELX, DELZ, CHLAMB(200), ALFNOD(200,30), BBLAMB(200)
COMMON /VOIDPT/ FALF(200,30), F1(200), TGAM(200), TP11(200)
COMMON /PTK1/ AAA(200)
COMMON /TWOG2/ WW1(100,100), WW2(100,100), TZ1(100,100),
1      TZ2(100,100), TWO(100,100), THREE(100,100)

C      IF(DELVI) 100,100,600
100     IF(DELQO) 200,200,700
200     IF(DELK) 1000,1000,800
C.....
C      * FOR FLOW VELOCITY PERTURBATION .....
C.....
600 IF(IK.EQ.1) GO TO 602
C      * NO NUCLEAR COUPLING
      RATIO = P11(NCH1) / GAM1(NCH1)
      GO TO 900
602 IF(ICASE.EQ.1) GO TO 603
      IF(ICASE.NE.9) GO TO 200
603 CTS1 = P11(NCH1) + (P13(NCH1)+RR3+DPUP3)*DPH1
      NP1 = NTOT(NCH1)
      CXL = CMPLX(0.,0.)
      DO 604 K=1,NP1

```

```

        CXL = CXL + (GAM2(NCH1,K)+PI2(NCH1,K))*BEE(NCH1,K)
604 CONTINUE
        CTS2 = CXL+RR2+DPUP2
        CTS3 = GAM1(NCH1)+DWSW1(NCH1)+T1+DWSW3*DPH1
        RATIO = CST1 + CTS2*TAU1(NCH1)*ZPKP/(1.-ZPKP*TAU2(NCH1))
C
        GO TO 900
C.....
C * FOR Q'ii' PERTURBATIONS (ONLY FOR NUCLEAR COUPLING)
C.....
700 IF(1K.NE. 1) GO TO 200
    IF(ICASE.EQ.2.OR.ICASE.EQ.11) GO TO 710
    IF(ICASE.EQ.4.OR.ICASE.EQ.10) GO TO 720
    IF(ICASE.EQ.5.OR.ICASE.EQ.6.OR.ICASE.EQ.13) GO TO 730
    IF(ICASE.EQ.14.OR.ICASE.EQ.15) GO TO 730
    IF(ICASE.EQ.3.OR.ICASE.EQ.7) GO TO 740
    IF(ICASE.EQ.8) GO TO 750
    WRITE(6,701) ZPKP,F1(NCH1)
701 FORMAT(5X,'ZPKP = ',2E12.4,5X,'F1 = ',2E12.4)
C
    IF(1BODE.EQ. 1) GO TO 705
    RATIO = - ZPKP * F1(NCH1)
    GO TO 900
705 RATIO = ZPKP*F1(NCH1) / (1.-ZPKP*F1(NCH1))
    GO TO 900
710 CONTINUE
C.....
C *** POINT KINETICS ***
C *** ICASE = 2, NON-UNIFORM RADIAL ***
C *** ICASE = 11, CHECKER-BOARD PROBLEM ***
C.....
    NCH = NCH1 - 1
    RATIO = CMPLX(0.,0.)
    DO 711 I=1,IMAX
        JR=JMX(I)
        DO 711 J=1,JR
            M=JJD(I,J)
711 RATIO = RATIO - AAA(M)*F1(M)/FLOAT(NCH)
        IF(1BODE.EQ. 1) GO TO 712
        GO TO 900
712 RATIO = -RATIO/(1.+RATIO)
        GO TO 900
720 CONTINUE
C.....
C *** COUPLED KINETICS ***
C *** ICASE = 4, RADIAL COUPLING(2-D) ***
C *** ICASE = 10, CHECKER-BOARD PROBLEM ***
C.....
    CALL OPENTF(S,RATIO,NCH1,ICOUNT)
    IF(1BODE.EQ. 1) GO TO 721

```

GO TO 900
 721 RATIO = -RATIO/(1+RATIO)
 GO TO 900
 730 CONTINUE

C
 C ***** AXIALLY COUPLED KINETICS *****
 C ***** ICASE = 5 : SPECIFIC CHANNEL *****
 C ***** ICASE = 6 : AVERAGE CHANNEL *****
 C ***** ICASE = 13 : HOT CHANNEL, TWO GROUP *****

C
 CALL OPENTF(S,RATIO,NCH1,ICOUNT)
 IF(IBODE.EQ.1) GO TO 731
 GO TO 900
 731 RATIO = -RATIO/(1+RATIO)
 740 CONTINUE

C
 C ***** POINT KINETICS *****
 C ***** ICASE = 3 : NON-UNIFORM AXIAL *****
 C ***** ICASE = 7 : SPECIFIC CHANNEL *****

C
 RATIO = CMPLX(0.,0.)
 IF(ICASE.EQ.3) NCC=NCH1
 IF(ICASE.EQ.7) NCC=JJD(1SPEC,JSPEC)
 DO 741 K=1,KMAX
 KP1=K+1
 C111=CABS(FALF(NCC,KP1))
 F22=FALF(NCC,K)
 IF(C111.NE.0.) F22=FALF(NCC,KP1)
 RATIO = RATIO - AAA(K)*F22/FLOAT(KMAX)
 741 CONTINUE
 GO TO 900

C
 750 CONTINUE

C
 C *** GENERAL KINETICS ***
 C *** ICASE = 8, 3-D COUPLING ***

C
 CALL OPENTF(S,RATIO,NCH1,ICOUNT)
 IF(IBODE.EQ.1) GO TO 751
 GO TO 900
 751 RATIO = -RATIO/(1+RATIO)
 GO TO 900

C
 C * FOR KEFF PERTURBATIONS

C
 800 IF(ICASE.EQ.1) GO TO 801
 IF(ICASE.NE.9) GO TO 1000
 801 IF(IBODE.EQ.0) GO TO 802
 ZPKP = CMPLX(0.,0.)
 ZPK = ZPK*1.045


```

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, XSLT, YSLT, PWIDTH, LENGTH
      DATA IBLNK /1H /, CHAR /      1H1, 1H2, 1H3, 1H4, 1H5, 1H6, 1H7,
1      1H8, 1H9, 1H0/
      PWIDTH = 100
      LENGTH = 60
C.....
C      DETERMINATION 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
      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
C
C
C
C
C*****
      SUBROUTINE LINE(X11, Y11, X22, Y22)
C*****
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      TO 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 = MIN0(I11,I22)
      I2 = I11 + I22 - I1
      DO 21 I = I1, I2
      21 IP(I,J1) = IDOT
      RETURN
C
      END

```

```

C
C
C
C*****
SUBROUTINE XLINE(Y)
C*****
C
C
C
C      PLOTS HORIZONTAL AXES
C
C      INTEGER PWIDTH
C      DIMENSION IP(100,60)
C      COMMON /PLOT/ IP, XORG, YORG, XSLOT, YSLOT, PWIDTH, LENGTH
C      DATA MINUS /1H-/
C
C      J = LENGTH + 1 - IFIX(YORG + Y*YSLOT)
C      DO 1 I = 1, PWIDTH
C      1  IP(I,J) = MINUS
C      RETURN
C      END
C
C
C
C*****
SUBROUTINE YLINE(X)
C*****
C
C
C
C      PLOTS VERTICAL LINES
C
C      INTEGER PWIDTH
C      DIMENSION IP(100,60)
C      COMMON /PLOT/ IP, XORG, YORG, XSLOT, YSLOT, PWIDTH, LENGTH
C      DATA IBAR /1HI/
C
C      I = IFIX(XORG + X*XSLOT)
C      DO 1 J = 1, LENGTH
C      1  IP(I,J) = IBAR
C      RETURN
C      END
C
C
C
C*****
SUBROUTINE PTY(X, Y, IC)
C*****
C
C
C
C      PLOTS A POINT ON THE LINE PRINTER
C
C      INTEGER PWIDTH
C      DIMENSION IP(100,60)
C      COMMON /PLOT/ IP, XORG, YORG, XSLOT, YSLOT, PWIDTH, LENGTH
C
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
C
C
C*****
      SUBROUTINE PRTPL4(NO,B,N,NL,KX,JX,MPLT,YSC)
C*****
C
C      NO - TITLE OF GRAPH (A10)
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      MPLT - ORDER OF VARIABLE TO BE PLOTTED
C      YSC - RANGE OF ORDINATE OF GRAPH (CORRECTED INTERNALLY IF NOT
C            ADEQUATE).
C
      DIMENSION OUT(101), YPR(12), B(KX,JX), A(200)
      DATA ANG/1H*/ , BLANK /1H /
C
      1 FORMAT(11, 60X,9H PLOT OF , A10/)
      2 FORMAT(1HZ,F11.4 , 5X, 101A1, E12.4)
      3 FORMAT(1HZ,117X, 112)
      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
      MPLT1 = MPLT + 1
      WRITE(6,1) IADV, NO
C.....
C      CONVERT ABSCISSAS TO LOG COORDINATES AND STORE IN ARRAY-A
C.....
      DO 10 I = 1,N
      10 A(I) = -ALOG(B(I,1))
C.....
C      DETERMINE EXTREMA
C.....
      YMIN = 1.0E75

```

```

      YMAX = -1.0E75
      DO 40 K = 1, N
      IF(B(K,MPL0T1) .GT. YMAX) YMAX = B(K,MPL0T1)
      IF(B(K,MPL0T1) .LT. YMIN) YMIN = B(K,MPL0T1)
40 CONTINUE
C.....
C      FIND SCALES FOR PLOTTING
C.....
      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,MPL0T1) - YMIN)/YSCAL) + 1
      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
C
C
C*****
      SUBROUTINE ASSIGN(N1, N2, X, IND, INODE, IB)
C*****
C
C      * NODE REDISTRIBUTION
C
      DIMENSION XDZ(30), XQDIS(30), XCO(30), XVGJ(30)
      COMMON/CONSS1/ QDIS(200,30), QO(200,30), DZ(200,30), Z(200,30),
1      K1(200,30), CKIN(200,30), ZETA(200,30), DOIN(200,30),
2      DOOUT(200,30), ALPIN(200,30), BEE(200,30), CPI1(200,30),
3      COR2PH(200,30), ZETSP(200,30), WIN
      COMMON/CONST2/ P, VCH, VIN(200), AXS(200), DH(200), DHIN(200),

```

```

1      PH(200), TIN, TSATP, ENTHT, DENS1, SIGM, ENTHP, VISC, CPF, XF,
2      DENSF, VFG1, RHOG, GO(200), G02(200), H0(200), GC, G1, XLOSS(30),
3      FRICM0(200), VGJH(200, 30), COH(200, 30), CZERO, VGJ, DPTS,
4      G02RF(200), HFG1, ZSP(30), NUMBSP(200, 30), ALHEAT, CXF(200),
5      AVEQ, CHOM01, CHOM02, XKIN(200), XKEXIT(200)

```

C

```

      DO 100 I=N1, N2
        XDZ(I) = DZ(INODE, I)
        XQDIS(I) = QDIS(INODE, I)
        IF(IB .EQ. 0) GO TO 100
        XCO(I) = COH(INODE, I)
        XVGJ(I) = VGJH(INODE, I)
100 CONTINUE

```

C

```

      NBB2 = N1 - 1
      INN1 = N1 + 1
      INN2 = N2 + 1
      NBBS = INN1 + 1
      DO 101 I=INN1, INN2
        IN = I - 1
        QDIS(INODE, I) = XQDIS(IN)
        IF(IB .EQ. 0) GO TO 103
        COH(INODE, I) = XCO(IN)
        VGJH(INODE, I) = XVGJ(IN)
103  IF(I .EQ. INN1) GO TO 101
        DZ(INODE, I) = XDZ(IN)
101 CONTINUE

```

C

```

      IF(IND .EQ. 0) GO TO 500
      GO TO 200
500  IF(NBB2 .NE. 0) GO TO 200
        DZ(INODE, N1) = X
        Z(INODE, N1) = X
        DZ(INODE, INN1) = XDZ(N1) - DZ(INODE, N1)
        Z(INODE, INN1) = Z(INODE, N1) + DZ(INODE, INN1)
      GO TO 201
200  DZ(INODE, N1) = X - Z(INODE, NBB2)
        Z(INODE, N1) = Z(INODE, NBB2) + DZ(INODE, N1)
        DZ(INODE, INN1) = XDZ(N1) - DZ(INODE, N1)
        Z(INODE, INN1) = Z(INODE, N1) + DZ(INODE, INN1)

```

C

```

201  DO 102 I=NBBS, INN2
        IN = I - 1
        Z(INODE, I) = Z(INODE, IN) + DZ(INODE, I)
102 CONTINUE
      RETURN
      END

```

C
C
C

```
C*****
SUBROUTINE NUCLER
```

C#####

**C
C
C
C**

C
C

```
IN=7
READ(IN,500) TITLE
```

```

      READ(IN,502) IMAX,JMAX,KMAX, INUCLR,NFTYPE, ICHEK
      READ(IN,504) ( PLAMDA(JJ),JJ=1,6)
      READ(IN,505) ( FPDF(JJ),JJ=1,11)
      READ(IN,505) ( FPLAM(JJ),JJ=1,11)
      READ(IN,506) ( JMX(I), I=1,IMAX)
      READ(IN,506) ( JJMX(I), I=1,IMAX)
      READ(IN,500) TITL1
C
      ID=0
      DO 15 I=1,IMAX
      JR=JMX(I)
      DO 14 J=1,JR
      JJD(I,J)=ID+J
14  CONTINUE
      ID=JJD(I,JR)
15  CONTINUE
C
      DO 20 I=1,IMAX
      JJR=JJMX(I)
      READ(IN,506) (NFUEL(I,J),J=1,JJR)
20  CONTINUE
C
      READ(IN,500)
      DO 22 I=1,IMAX
      JJR=JJMX(I)
      READ(IN,506) (NCONTL(I,J),J=1,JJR)
22  CONTINUE
C
      DO 28 I=1,IMAX
      JJR=JJMX(I)
      DO 28 J=1,JJR
      KCC=KMAX-NCONTL(I,J)
      KL=KCC+1
      IF(KCC.EQ.KMAX) GO TO 24
      DO 23 K=KL,KMAX
23  NFT(I,J,K)=NFUEL(I,J)
C
      IF(KCC.EQ.0) GO TO 28
24  CONTINUE
C
      DO 25 K=1,KCC
25  NFT(I,J,K)=NFUEL(I,J)+NFTYPE
28  CONTINUE
C
      READ(IN,500) TITL2
C
      DO 30 I=1,IMAX
      JJR=JJMX(I)
      READ(IN,514) (AL(I,J),J=1,JJR)
30  CONTINUE

```

```

C      READ(IN,500) TITL3
C
C      DO 35 I=1,IMAX
C      JJR=JIMX(I)
C      READ(IN,514) (TAL(I,J),J=1,JJR)
35 CONTINUE
C
C      READ(IN,500) TITL4
C
C      DO 40 I=1,IMAX
C      JJR=JIMX(I)
C      READ(IN,514) (BAL(I,J),J=1,JJR)
40 CONTINUE
C
C      READ(IN,500) TITL5
C
C      DO 45 I=1,IMAX
C      JJR=JIMX(I)
C      READ(IN,512) IL,(ASRC(I,J),J=1,JJR)
45 CONTINUE
C
C      READ(IN,500) TITL6
C
C      DO 50 I=1,IMAX
C      READ(IN,500)
C      JJR=JIMX(I)
C      DO 50 KK=1,KMAX
C      K=KMAX-KK+1
C      READ(IN,512) IL,(SRC(I,J,K),J=1,JJR)
50 CONTINUE
C
C      READ(IN,500) TITL7
C
C      DO 65 I=1,IMAX
C      JJR=JIMX(I)
C      READ(IN,512) IL,(AEXP(I,J),J=1,JJR)
65 CONTINUE
C
C      READ(IN,500) TITL8
C
C      DO 70 I=1,IMAX
C      READ(IN,500)
C      JJR=JIMX(I)
C      DO 70 KK=1,KMAX
C      K=KMAX-KK+1
C      READ(IN,512) IL,(REXP(I,J,K),J=1,JJR)
70 CONTINUE
C

```

```

C
C
C 76 CONTINUE
C      READ(IN,513) (AXSRC(K),K=1,KMAX)
C      IF(ICHEK.EQ.1) GO TO 110
C
C      DO 100 I=1,IMAX
C      INV=IMAX-I+1
C      JJR=JMX(I)
C      JR=JMX(I)
C      DO 100 J=1,JJR
C      JNV=IMAX-J+1
C
C      DO 80 K=1,KMAX
C      NFT(JNV,INV,K)=NFT(I,J,K)
C      SRC(JNV,INV,K)=SRC(I,J,K)
C      REXP(JNV,INV,K)=REXP(I,J,K)
C 80 CONTINUE
C
C      AL(JNV,INV)=AL(I,J)
C      TAL(JNV,INV)=TAL(I,J)
C      BAL(JNV,INV)=BAL(I,J)
C      ASRC(JNV,INV)=ASRC(I,J)
C      AEXP(JNV,INV)=AEXP(I,J)
C 100 CONTINUE
C
C 110 CONTINUE
C      RETURN
C      END
C
C*****
C      SUBROUTINE XSMODL
C*****
C
C      * THIS ROUTINE CALCULATES FITTING COEFFICIENTS OF DATA AT
C      CERTAIN EXPOSURE AND VOID FRACTION
C
C      DIMENSION FLUX(2,3,3),SIGA(2,3,3),SIGF(2,3,3),TITLE(80),
C 1          VN2(2,3,3),BT(3,3,6),XSC(3,3,11),REFE(3),REFU(3),
C 2          DIFF(2,3,3),SIG12(2,3,3)
C
C
C      COMMON/SIM1/IMAX,JMAX,KMAX,ICASE,ISPEC,JSPEC,INUCLR,XKEFF
C      COMMON/COEF1/C1(10,2,11),C2(10,2,11),C3(10,2,11),C4(10,2,11),
C 1          C5(10,2,11),C6(10,2,11),C7(10,2,11),C8(10,2,11),
C 2          C9(10,2,11),C10(10,2,11),C11(10,2,11)
C      COMMON/COEF2/D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D11,D12,SUMSRC
C      COMMON/COEF3/NFTMX
C
C

```

```

500 FORMAT(80A1)
515 FORMAT(3F10.4,50X)
510 FORMAT(10I3,50X)
520 FORMAT(20X,3E15.6)
530 FORMAT(20X,6E10.4)
620 FORMAT(20X,4E15.6)
C
    IN=4
    READ(IN,510) NFTMX
    READ(IN,515) (REFE(IE),IE=1,3)
    READ(IN,515) (REFU(IU),IU=1,3)
C
    DO 100 NF=1,NFTMX
    READ(IN,500) TITLE
    DO 30 IU=1,3
    READ(IN,500)
    DO 20 IG=1,2
    READ(IN,520) (FLUX(IG,IE,IU),IE=1,3)
    READ(IN,520) (SIGA(IG,IE,IU),IE=1,3)
    READ(IN,520) (SIGF(IG,IE,IU),IE=1,3)
    READ(IN,520) (VN2(IG,IE,IU),IE=1,3)
    READ(IN,520) (DIFF(IG,IE,IU),IE=1,3)
    READ(IN,520) (SIG12(IG,IE,IU),IE=1,3)
20 CONTINUE
C
    DO 25 IE=1,3
    READ(IN,530) (BT(IE,IU,IGR),IGR=1,6)
    DO 22 IGR=1,6
    IX=IGR+4
    XSC(IE,IU,IX)=BT(IE,IU,IGR)
22 CONTINUE
25 CONTINUE
30 CONTINUE
C
    IF(ICASE.EQ.13.OR.ICASE.EQ.14.OR.ICASE.EQ.15) GO TO 37
    NX=10
    NG=1
    GO TO 39
37 CONTINUE
    NX=11
    NG=2
    GO TO 41
39 CONTINUE
C.....
C * COLLAPSING TWO GROUP DATA TO ONE GROUP DATA
C.....
    DO 40 IE=1,3
    DO 40 IU=1,3
    FL1=FLUX(1,IE,IU)
    FL2=FLUX(2,IE,IU)

```



```

FLXX=FL1+FL2
XSC(IE,IU,1)=(SIGA(1,IE,IU)*FL1+SIGA(2,IE,IU)*FL2)/FLXX
XSC(IE,IU,2)=(SIGF(1,IE,IU)*FL1+SIGF(2,IE,IU)*FL2)/FLXX
XSC(IE,IU,3)=(DIFF(1,IE,IU)*FL1+DIFF(2,IE,IU)*FL2)/FLXX
XSC(IE,IU,4)=FLXX/(FL1/VN2(1,IE,IU)+FL2/VN2(2,IE,IU))

```

40 CONTINUE

C

41 CONTINUE

C

```

DO 50 IG=1,NG
IF(ICASE.EQ.13.OR.ICASE.EQ.14.OR.ICASE.EQ.15) GO TO 45
GO TO 42

```

45 CONTINUE

```

DO 43 IE=1,3
DO 43 IU=1,3
XSC(IE,IU,1)=SIGA(IG,IE,IU)
XSC(IE,IU,2)=SIGF(IG,IE,IU)
XSC(IE,IU,3)=DIFF(IG,IE,IU)
XSC(IE,IU,4)=VN2(IG,IE,IU)
XSC(IE,IU,11)=SIG12(IG,IE,IU)

```

43 CONTINUE

42 CONTINUE

```

DO 50 IX=1,NX
C1(NF,IG,IX)=XSC(1,1,IX)
C2(NF,IG,IX)=XSC(3,1,IX)-C1(NF,IG,IX)
C3(NF,IG,IX)=XSC(1,3,IX)-C1(NF,IG,IX)
C4(NF,IG,IX)=XSC(3,3,IX)-XSC(1,3,IX)
C5(NF,IG,IX)=XSC(3,3,IX)-XSC(3,1,IX)
C6(NF,IG,IX)=XSC(1,2,IX)-C1(NF,IG,IX)
C7(NF,IG,IX)=XSC(3,2,IX)-XSC(1,2,IX)-C2(NF,IG,IX)
C8(NF,IG,IX)=XSC(2,2,IX)-XSC(2,1,IX)-C6(NF,IG,IX)
C9(NF,IG,IX)=C4(NF,IG,IX)-C2(NF,IG,IX)
C10(NF,IG,IX)=XSC(2,3,IX)-XSC(2,1,IX)-C3(NF,IG,IX)
C11(NF,IG,IX)=XSC(2,1,IX)-C1(NF,IG,IX)

```

50 CONTINUE

C

C

75 CONTINUE

100 CONTINUE

C

```

CON1=REFU(3)-REFU(2)
CON2=REFU(3)-REFU(1)
CON3=REFU(2)-REFU(1)
D1=1./CON1/CON2
D2=-1./CON1/CON3
D3=REFU(1)*REFU(2)*D1
D4=REFU(1)*REFU(3)*D2
D5=-(REFU(1)+REFU(2))*D1
D6=-(REFU(1)+REFU(3))*D2
CON4=REFE(3)-REFE(2)

```

```

CON5=REFE(3)-REFE(1)
CON6=REFE(2)-REFE(1)
D7=1./CON4/CON5
D8=-1./CON4/CON6
D9=REFE(1)*REFE(2)*D7
D10=REFE(1)*REFE(3)*D8
D11=-(REFE(1)+REFE(2))*D7
D12=-(REFE(1)+REFE(3))*D8

```

```

C      RETURN
      END

```

```

C*****
      SUBROUTINE XDATA
C*****

```

```

C      COMMON/SIM1/IMAX,JMAX,KMAX,ICASE,ISPEC,JSPEC,INUCLR,XKEFF
      COMMON/SIM2/JMX(20),NFT(15,15,30),AL(15,15),TAL(15,15),
1      BAL(15,15),ASRC(15,15),SRC(15,15,30),AEXP(15,15),
2      REXP(15,15,30),AXSRC(30),XXSRC(30)
      COMMON/SIM3/JJD(15,15),DZ1(200),DZ2(200),NF(200,30),NB(200),
1      SC(200,30,6),XEXP(200,30),SIG1(200,30,11),
2      CSIG1(200,30,11)
      COMMON/COEF1/C1(10,2,11),C2(10,2,11),C3(10,2,11),C4(10,2,11),
1      C5(10,2,11),C6(10,2,11),C7(10,2,11),C8(10,2,11),
2      C9(10,2,11),C10(10,2,11),C11(10,2,11)
      COMMON/COEF2/D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D11,D12,SUMSRC
      COMMON/DIM1/DX,DZT,RAMBDA(200),ALFA(200,30),BBLAMB(200)
      COMMON/TWOG1/SIG2(200,30,11),CSIG2(200,30,11),TFLX(2,4,30)
      COMMON/CONSS2/NTOT(200),NBB(200),NBB1(200),NSP,N1PSP(200),
1      K2PSP(200),NDP(200),NDP1(200),ISUB(200)
      COMMON/CONSS1/QDIS(200,30),QO(200,30),DZ(200,30),Z(200,30),
1      K1(200,30),CKIN(200,30),ZETA(200,30),DOIN(200,30),
2      DOOUT(200,30),ALPIN(200,30),BEE(200,30),CPI1(200,30),
3      COR2PH(200,30),ZETSP(200,30),WIN

```

```

C      IF(ICASE.EQ.5.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 25
      IL = 1
      IR = IMAX
      GO TO 26
25  IL = ISPEC
      IR = ISPEC
26  CONTINUE

```

```

C      DO 80 I=IL,IR
      IF(ICASE.EQ.5.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 60
      JL=1

```

```

      JR=JMX(1)
      GO TO 65
60    JL=JSPEC
      JR=JSPEC
65    CONTINUE
C
      DO 80 J=JL,JR
      M=JJD(1,J)
      KK = 1
      DO 80 K=1,KMAX
      KP1=KK+1
      IF(NTOT(M) .EQ. KMAX) GO TO 20
      IF(NTOT(M) .EQ. KMAX+1) GO TO 30
20    U = ALFA(M,K)
      GO TO 40
30    IF(DZ(M,KK) .LT. DZT) GO TO 50
      U = ALFA(M,KK)
      GO TO 45
50    U = (ALFA(M,KK)*DZ(M,KK) + ALFA(M,KP1)*DZ(M,KP1))/DZT
      GO TO 46
45    KK = KK + 1
      GO TO 40
46    KK = KK + 2
40    U2=U*U
      N=NFT(1,J,K)
      G1E=D9+D11*REXP(1,J,K)+D7*REXP(1,J,K)**2
      G2E=D10+D12*REXP(1,J,K)+D8*REXP(1,J,K)**2
      F1U=D3+D5*U+D1*U2
      F2U=D4+D6*U+D2*U2
      DF1DU=D5+2.*D1*U
      DF2DU=D6+2.*D2*U
C
      NX=10
      IF( ICASE.EQ.13.OR. ICASE.EQ.14.OR. ICASE.EQ.15) NX=11
      DO 70 IX=1,NX
      FFA=C3(N,1,IX)+C9(N,1,IX)*G1E+C10(N,1,IX)*G2E
      FFB=C6(N,1,IX)+C7(N,1,IX)*G1E+C8(N,1,IX)*G2E
      SIG1(M,K,IX)=C1(N,1,IX)+C2(N,1,IX)*G1E+C11(N,1,IX)*G2E+
1      F1U*FFA+F2U*FFB
      CSIG1(M,K,IX)=FFA*DF1DU+FFB*DF2DU
      IF( ICASE.EQ.13.OR. ICASE.EQ.14.OR. ICASE.EQ.15) GO TO 68
      GO TO 70
68    CONTINUE
      FFA=C3(N,2,IX)+C9(N,2,IX)*G1E+C10(N,2,IX)*G2E
      FFB=C6(N,2,IX)+C7(N,2,IX)*G1E+C8(N,2,IX)*G2E
      SIG2(M,K,IX)=C1(N,2,IX)+C2(N,2,IX)*G1E+C11(N,2,IX)*G2E+
1      F1U*FFA+F2U*FFB
      CSIG2(M,K,IX)=FFA*DF1DU+FFB*DF2DU
70    CONTINUE
80    CONTINUE

```

```

C      RETURN
C      END
C
C
C
C
C*****
C      SUBROUTINE COEFT(S,ICOUNT)
C*****
C      *   THIS ROUTINE CALCULATES TEE, RHOX, RHOZ, RX, RZ, FOR
C          STEADY-STATE AND PERTURBED STATE(FUNCTION OF FREQUENCY)
C
C      COMPLEX S,BR3,BR4,TEE
C      DIMENSION BR2(15,15,30),CC(15,15,30),F22(15,15,30),
C1      ZZZ(15,15,30)
C      COMMON/SIM1/IMAX,JMAX,KMAX,ICASE,ISPEC,JSPEC,INUCLR,XKEFF
C      COMMON/SIM2/JMX(20),NFT(15,15,30),AL(15,15),TAL(15,15),
C1      BAL(15,15),ASRC(15,15),SRC(15,15,30),AEXP(15,15),
C2      REXP(15,15,30),AXSRC(30),XXSRC(30)
C      COMMON/SIM3/JJD(15,15),DZ1(200),DZ2(200),NF(200,30),NB(200),
C1      SC(200,30,6),XEXP(200,30),SIG1(200,30,11),
C2      CSIG1(200,30,11)
C      COMMON/SIM4/TEE(15,15,30)
C      COMMON/SIM6/RHOX(15,15,30),RHOZ(15,15,30),RX(15,15,30),
C1      RZ(15,15,30),TEEO(15,15,30),PLAMDA(6),FPDF(15),
C2      FPLAM(15)
C      COMMON/DIM1/DX,DZT,RAMBDA(200),ALFA(200,30),BBLAMB(200)
C
C      IF(ICOUNT.EQ.1) GO TO 15
C      IF(ICASE.EQ.1.OR.ICASE.EQ.3.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 35
C      IF(ICASE.EQ.11.OR.ICASE.EQ.12) GO TO 35
C15 CONTINUE
C      DZZ=DZT*30.48
C      A=0.3
C      A3=3.*A
C      AM=1.-A
C
C      IF(ICASE.EQ.5.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 16
C      IL=1
C      IR=IMAX
C      GO TO 17
C16 IL=ISPEC
C      IR=ISPEC
C17 CONTINUE
C
C      DO 30 I=IL,IR
C      IF(ICASE.EQ.5.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 18
C      JL=1

```

```

      JR=JMX(1)
      GO TO 19
18  JL=JSPEC
      JR=JSPEC
19  CONTINUE

C      DO 30 J=JL,JR
      M=JJD(1,J)
C      WRITE(6,670) 1,J,NB(M),DZ1(M),DZ2(M)
      DO 30 K=1,KMAX
      DZ=DZZ
      DF=SIG1(M,K,3)
      XOD25=.25/DF
      HOD=DZ*XOD25
      DXOD=DX*XOD25
      XO1D=1./(1.+DXOD)
      ZO1D=1./(1.+HOD)
      BR1=2.*XO1D/DX
      FA=ZO1D/DZ+BR1
      FB=XO1D/DX+2.*ZO1D/DZ
      XXK=SIG1(M,K,2)/SIG1(M,K,1)
      SIGA=SIG1(M,K,1)
      SIGF=SIG1(M,K,2)
      VL=SIG1(M,K,4)
      IF(1NUCLR.EQ.1) GO TO 22
      R=DX*DX/DZ/DZ
      BDEN=A3+AM*(R+2.)
      XOB=1./BDEN
      BB=A3*XOB
      CC(1,J,K)=.25*AM*XOB
      F22(1,J,K)=BB+2.*CC(1,J,K)*(4.*XO1D+2.*R*ZO1D)
      QT=CC(1,J,K)*(SIGA-SIGF)/DF
      BR2(1,J,K)=FA+(SIGA-SIGF)*F22(1,J,K)
22  CONTINUE
      RHOX(1,J,K)=(DXOD-1.)*XO1D
      RHOZ(1,J,K)=(HOD-1.)*ZO1D
      RX(1,J,K)=XO1D/DX/FA/2.
      RZ(1,J,K)=ZO1D/DZ/FB/2.
      IF(1NUCLR.EQ.1) GO TO 25
      ZZZ(1,J,K)=2.*XO1D*DX+ZO1D*DZ
      TEE0(1,J,K)=(FA-QT*ZZZ(1,J,K))/BR2(1,J,K)
23  TEE(1,J,K)=(TEE0(1,J,K)*BR2(1,J,K)-S*ZZZ(1,J,K)*CC(1,J,K)/
1      SIG1(M,K,4)/SIG1(M,K,3))/(BR2(1,J,K)+S/SIG1(M,K,4)*
2      F22(1,J,K))
      IF(1COUNT.GT.1) GO TO 30
      TEE0=TEE0(1,J,K)
      IF(TEE00.EQ.1..AND.XXK.LT.1.) TEE0(1,J,K)=0.9999
      IF(TEE00.EQ.1..AND.XXK.GE.1.) TEE0(1,J,K)=1.0001
      GO TO 30
25  CONTINUE

```

```

      TEE0(I,J,K)=FA/(FA+SIGA-SIGF)
      TEE(I,J,K)=FA/(FA+SIGA+S/VL-SIGF)
      TEE00=TEE0(I,J,K)
      IF(TEE00.EQ.1..AND.XXK.LT.1.) TEE0(I,J,K)=0.9999
      IF(TEE00.EQ.1..AND.XXK.GE.1.) TEE0(I,J,K)=1.0001
30  CONTINUE
      IF(ICASE.NE.5) GO TO 35
      IF(ICOUNT.GT.1) GO TO 33
      IF(INRUN.GT.0) GO TO 35

```

```

C
      WRITE(6,600) (RHOX(ISPEC,JSPEC,K),K=4,19)
      WRITE(6,600) (RHOZ(ISPEC,JSPEC,K),K=4,19)
      WRITE(6,600) (RX(ISPEC,JSPEC,K),K=4,19)
      WRITE(6,600) (TEE0(ISPEC,JSPEC,K),K=4,19)
33  WRITE(6,610) (TEE(ISPEC,JSPEC,K),K=5,9)
600  FORMAT(1X,15F8.4)
610  FORMAT(1X,10E12.5)
35  CONTINUE
      RETURN
      END

```

```

C
C
C
C
C*****
      SUBROUTINE KINET(S,ICOUNT,DELK)
C*****

```

```

C
C      * THIS ROUTINE GENERATES KINETICS PARAMETERS FOR ANY
C      GEOMETRIES
C

```

```

C
C      *** ICASE = 1 POINT KINETICS(UNIFORM), CORE AVERAGE
C                  = 2 POINT KINETICS(NON-UNIFORM RADIAL)
C                  = 3 POINT KINETICS(NON-UNIFORM AXIAL)
C                  = 4 RADIALLY COUPLED KINETICS(2-D)
C                  = 5 AXIALLY COUPLED KINETICS(1-D), IDENTICAL CHANNEL
C                  = 6 AXIALLY COUPLED KINETICS(1-D), AVERAGED CHANNEL
C                  = 7 POINT KINETICS(NON-UNIFORM AXIAL), SPECIFIC CHANNEL
C                  = 8 GENERAL SPACE NODAL KINETICS(3-D)
C                      (CHECKER-BOARD PROBLEM ONLY)
C                  = 9 POINT KINETICS(UNIFORM), SPECIFIC CHANNEL
C                  =10 RADIALLY COUPLED KINETICS(2-D)
C                      (CHECKER-BOARD PROBLEM ONLY)
C                  =11 POINT KINETICS(NON-UNIFORM RADIAL)
C                      (CHECKER-BOARD PROBLEM ONLY)
C                  =12 POINT KINETICS(UNIFORM CASE)
C                      (CHECKER-BOARD PROBLEM)
C                  =13 TWO GROUP AXIALLY COUPLED KINETICS, HOT CHANNEL
C                      (COARSE MESH DIFFUSION THEORY ONLY)
C

```

C
C
C
C
C
C

=14 TWO GROUP CHECKER BOARD, 2-D
(CMDT ONLY)
=15 TWO GROUP CHECKER BOARD, 3-D
(CMDT ONLY)

COMPLEX S, SUM1, SUM2, T, TT, SAIN, SANI, SAMR, AMN, ANM, AMR, RAIN, RANI,
1 SAKN, SANK, RAIR, GAMN, GANM, PPSI, ZPK, ZPKP, AAA, B, ZPK1, TEE,
2 XAIN, ZNI, XZNI, BI, RKI, XBM, XRKM, WW1, WW2, TZ1, TZ2, TWO, THREE
COMPLEX TB11(4, 30), TB12(4, 30), TK11(4, 30), TK12(4, 30), TGI(4, 30),
1 TRIJ2(4, 30, 2), TZN1(4, 30, 2), TZN2(4, 30, 2), TFI(4, 30),
2 TRIJ1(4, 30, 2), CXK, CXXK, CXXN, CFP, SFP
DIMENSION SIGA(15, 15, 30), SUMBJ(6), DMDU(6), TO(200, 30, 6),
1 XKN(200, 30, 6), XFS(200, 30, 6), BBT(6), DBTDU(6), REAC(200),
2 GTIME(200), CAL(200), XSGF(200), XVEL(200), CXGF(200),
3 CXVL(200), CLAM(200), PBET(200, 6), CBET(200, 6), PBETA(6),
4 CBETA(6), SUMBL(6), SUMCBL(6), SAION(6), SANOI(6), CBBT(6),
5 AMON(6), ANOM(6), RBET(200, 6), R(200, 30, 6), RO(200, 30, 6),
6 RCBT(200, 6), RAIOR(200), RAION(200, 4), SAKON(2), SANOK(2),
7 AXA(30), AXF(30), AV(30), ACXA(30), ACXF(30), ACV(30),
8 GAMON(200, 30, 6), SUMXRC(4), XKEF(200), XTFLX(2, 4, 30)
DIMENSION BIJO1(4, 30, 2), BIJO2(4, 30, 2), DJOK1(4, 30, 2), DJOK2(4, 30, 2),
1 DDC1(4, 30, 2), DDC2(4, 30, 2), DIJO1(4, 30, 2), DIJO2(4, 30, 2),
2 DDOF1(4, 30, 2), DDOF2(4, 30, 2), TCXFJ1(4, 30, 2), TCXFJ2(4, 30, 2),
3 TFLX1(4, 30, 2), TFLXT(4, 30, 2), TXFJ1(4, 30, 2), TXFJ2(4, 30, 2)
DIMENSION XXA(4, 2), XXF(4, 2), XXD(4, 2), XXV(4, 2), XXR(4, 2),
1 CXXA(4, 2), CXXF(4, 2), CXXD(4, 2), CXXV(4, 2), CXXR(4, 2),
2 SUMBT(6), SUMCB1(6), SUMCB2(6), ATFLX(4, 2)

C

COMMON/CONST2/ P, VCH, VIN(200), AXS(200), DH(200), DHIN(200),
1 PH(200), TIN, TSATP, ENTHI, DENSI, SIGM, ENTHP, VISC, CPF, KF,
2 DENSF, VFG1, RHOG, GO(200), GO2(200), HO(200), GC, G1, KLOSS(30),
3 FRICMO(200), VGJH(200, 30), COH(200, 30), CZERO, VGJ, DPTS,
4 GO2RF(200), HFG1, ZSP(30), NUMBSP(200, 30), ALHEAT, CXF(200),
5 CHFO, CHOM01, CHOM02, XKIN(200), XKEXIT(200)

C

COMMON/SIM1/IMAX, JMAX, KMAX, ICASE, ISPEC, JSPEC, INUCLR, XKEFF
COMMON/SIM2/JMX(20), NFT(15, 15, 30), AL(15, 15), TAL(15, 15),
1 BAL(15, 15), ASRC(15, 15), SRC(15, 15, 30), AEXP(15, 15),
2 REXP(15, 15, 30), AXSRC(30), XXSRC(30)
COMMON/SIM3/JJD(15, 15), DZ1(200), DZ2(200), NF(200, 30), NB(200),
1 SC(200, 30, 6), XEXP(200, 30), SIG1(200, 30, 11),
2 CSIG1(200, 30, 11)
COMMON/SIM4/TEE(15, 15, 30)
COMMON/SIM5/RXA(15, 15), RXF(15, 15), RV(15, 15), RCXF(15, 15),
1 RCXA(15, 15), RCV(15, 15)
COMMON/SIM6/RHOX(15, 15, 30), RHOZ(15, 15, 30), RX(15, 15, 30),
1 RZ(15, 15, 30), TEO(15, 15, 30), PLAMDA(6), FPDF(15),
2 FPLAM(15)
COMMON/KIN1/XKINF(15, 15, 30), SIGF(15, 15, 30)

```

COMMON/KIN2/RDF(15,15),RCDF(15,15),RANO1(200,4),ADF(30),
1 ACDF(30),GANOM(200,30,6),CFP
COMMON/KIN3/RANI(200,4),GANM(200,30,6),ZNI(200,4),BI(200)
COMMON/KIN5/RKI(200),XZNI(200,30,6),XBM(200,30),XRKM(200,30)
COMMON/PTK0/ZPK, ZPK1, ZPKP
COMMON/PTK1/AAA(200)
COMMON/DIM1/DX,DZT,RAMBDA(200),ALFA(200,30),BBLAMB(200)
COMMON/XX/T(200,30,6),SANI(6),SAIN(6),AMN(6),ANM(6),RAIR(200),
1 RAIN(200,4),SAKN(2),SANK(2),GAMN(200,30,6)
COMMON/TWOG1/SIG2(200,30,11),CSIG2(200,30,11),TFLX(2,4,30)
COMMON/TWOG2/WW1(100,100),WW2(100,100),TZ1(100,100),
1 TZ2(100,100),TWO(100,100),THREE(100,100)
COMMON/TEST/CXK(15,15,30),CXKN(200,30,6)

```

```

C
C
660 FORMAT(20X,'ICASE = ',I3)
610 FORMAT(5X,10E12.5)
C
WRITE(6,660) ICASE
DZ=DZT*30.48
TSAR=DX*DX
BSAR=TSAR
VOL=DX*DX*DZ
ANR=DX*DZ
ANT=DX*DX
C
IF(ICASE.EQ.13.OR.ICASE.EQ.14.OR.ICASE.EQ.15) GO TO 1785
C
IF(ICASE.EQ.5.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 88
IL=1
IR=IMAX
GO TO 90
88 IL=ISPEC
IR=ISPEC
90 CONTINUE
C
JL=1
DO 110 I=IL,IR
IF(ICASE.EQ.5.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 103
JR=JMX(I)
GO TO 105
103 JL=JSPEC
JR=JSPEC
105 CONTINUE
C
DO 110 J=JL,JR
M=JJD(I,J)
DO 110 K=1,KMAX
SUM1 = CMPLX(0.,0.)
DO 107 JJ=1,6
MV = JJ + 4

```



```

SUM1 = SUM1 + S*SIG1(M,K,MV)/(S + PLAMDA(JJ))
107 CONTINUE
  SIGA(I,J,K)=SIG1(M,K,1)
  SIGF(I,J,K)=SIG1(M,K,2)
  XKINF(I,J,K)=SIGF(I,J,K)/SIGA(I,J,K)
  CXK(I,J,K) = XKINF(I,J,K) * (1.-SUM1) / (1.+S/SIG1(M,K,4)
1
110 CONTINUE
C.....
C  * ADD THE FISSION PRODUCT EFFECT
C  CFP ; THE FACTOR OF F.P. EFFECT
C.....
  SFP = CMPLX(0.,0.)
  TDF = 0.
  DO 106 I=1,11
    TDF = TDF + FPDF(I)
    SFP = SFP + FPLAM(I)*FPDF(I)/(S+FPLAM(I))
106 CONTINUE
  CFP = 1.-TDF + SFP
C
  IF(ICOUNT.EQ.1) GO TO 40
  IF(ICASE.EQ.13.OR.ICASE.EQ.14.OR.ICASE.EQ.15) GO TO 1785
  IF(ICASE.EQ.1.OR.ICASE.EQ.2.OR.ICASE.EQ.3.OR.ICASE.EQ.7.OR.
1 ICASE.EQ.9.OR.ICASE.EQ.11.OR.ICASE.EQ.12) GO TO 199
  GO TO 120
40 CONTINUE
C
  DADU=0.
  DBDU=0.
  DCDU=0.
  DDDU=0.
  DEDU=0.
  DFDU=0.
  SUMA=0.
  SUMB=0.
  SUMC=0.
  SUMD=0.
  SUME=0.
  SUMF=0.
C
  DO 115 JJ=1,6
    SUMBJ(JJ)=0.
    DM DU(JJ)=0.
115 CONTINUE
120 CONTINUE
C
  IF(ICASE.EQ.5.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 122
  IL=1
  IR=IMAX
  GO TO 123

```

```

122 IL=ISPEC
    IR=ISPEC
123 CONTINUE
C
    DO 200 I=IL,IR
        IM1=I-1
        IP1=I+1
        IF(ICASE.EQ.5.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 124
        JL=1
        JR=JMX(I)
        GO TO 125
124 JL=JSPEC
        JR=JSPEC
125 CONTINUE
C
        IF(I.GT.1) JIM1=JMX(IM1)
        DO 200 J=JL,JR
            JM1=J-1
            JP1=J+1
            M=JJD(I,J)
            AH=AL(I,J)
            BAH=BAL(I,J)
            TAH=TAL(I,J)
C
            DO 200 K=1,KMAX
                KM1=K-1
                KP1=K+1
C
                IF(ICASE.EQ.8.OR.ICASE.EQ.10.OR.ICASE.EQ.11) GO TO 155
                IF(ICASE.EQ.12) GO TO 155
                IF(ICASE.EQ.5.OR.ICASE.EQ.6.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 176
C
                IF(I.NE.1) GO TO 130
126 CONTINUE
                IF(I.EQ.1) GO TO 128
                IF(J.EQ.JR.AND.J.EQ.JIM1) GO TO 132
128 CONTINUE
                IF(ICOUNT.GT.1) GO TO 135
                T(M,K,1)=CMPLX(0.,0.)
                SC(M,K,1)=0.
                TO(M,K,1)=0.
                R(M,K,1)=0.
                RO(M,K,1)=AH
                XKN(M,K,1)=1.
                CXKN(M,K,1)=CMPLX(1.,0.)
                XFS(M,K,1)=0.
                GO TO 135
130 CONTINUE
C

```

```

      IF(J.EQ.JR) GO TO 126
      IF(J.LT.JR.AND.J.GT.JIM1) GO TO 126
132 CONTINUE

```

C
C

```

      T(M,K,1)=TEE(IM1,J,K)
      CXKN(M,K,1) = CXK(IM1,J,K)
      IF(ICOUNT.GT.1) GO TO 135
      SC(M,K,1)=SRC(IM1,J,K)
      TO(M,K,1)=TEEO(IM1,J,K)
      R(M,K,1)=RX(IM1,J,K)
      RO(M,K,1)=RHOX(IM1,J,K)
      XKN(M,K,1)=XKINF(IM1,J,K)
      XFS(M,K,1)=SIGF(IM1,J,K)
135 CONTINUE

```

C

```

      IF(J.NE.1) GO TO 137
      T(M,K,2)=TEE(I,J,K)
      CXKN(M,K,2) = CXK(I,J,K)
      IF(ICOUNT.GT.1) GO TO 140
      SC(M,K,2)=SRC(I,J,K)
      TO(M,K,2)=TEEO(I,J,K)
      R(M,K,2)=RX(I,J,K)
      RO(M,K,2)=RHOX(I,J,K)
      XKN(M,K,2)=XKINF(I,J,K)
      XFS(M,K,2)=SIGF(I,J,K)
      GO TO 140

```

137 CONTINUE

C

```

      T(M,K,2)=TEE(I,JM1,K)
      CXKN(M,K,2) = CXK(I,JM1,K)
      IF(ICOUNT.GT.1) GO TO 140
      SC(M,K,2)=SRC(I,JM1,K)
      TO(M,K,2)=TEEO(I,JM1,K)
      R(M,K,2)=RX(I,JM1,K)
      RO(M,K,2)=RHOX(I,JM1,K)
      XKN(M,K,2)=XKINF(I,JM1,K)
      XFS(M,K,2)=SIGF(I,JM1,K)

```

140 CONTINUE

C

```

      IF(I.NE.IMAX) GO TO 142
      T(M,K,3)=TEE(I,J,K)
      CXKN(M,K,3) = CXK(I,J,K)
      IF(ICOUNT.GT.1) GO TO 144
      SC(M,K,3)=SRC(I,J,K)
      TO(M,K,3)=TEEO(I,J,K)
      R(M,K,3)=RX(I,J,K)
      RO(M,K,3)=RHOX(I,J,K)
      XKN(M,K,3)=XKINF(I,J,K)
      XFS(M,K,3)=SIGF(I,J,K)

```

```

GO TO 144
142 CONTINUE
C
  T(M,K,3)=TEE(IP1,J,K)
  CXKN(M,K,3) = CXK(IP1,J,K)
  IF(ICOUNT.GT.1) GO TO 144
  SC(M,K,3)=SRC(IP1,J,K)
  TO(M,K,3)=TEEO(IP1,J,K)
  R(M,K,3)=RX(IP1,J,K)
  RO(M,K,3)=RHOX(IP1,J,K)
  XKN(M,K,3)=XKINF(IP1,J,K)
  XFS(M,K,3)=SIGF(IP1,J,K)
144 CONTINUE
C
  IF(J.NE.JR) GO TO 146
  IF(ICOUNT.GT.1) GO TO 148
  SC(M,K,4)=0.
  TO(M,K,4)=0.
  T(M,K,4)=CMPLX(0.,0.)
  CXKN(M,K,4) = CMPLX(1.,0.)
  R(M,K,4)=0.
  RO(M,K,4)=AH
  XKN(M,K,4)=1.
  XFS(M,K,4)=0.
  GO TO 148
146 CONTINUE
C
  T(M,K,4)=TEE(I,JP1,K)
  CXKN(M,K,4) = CXK(I,JP1,K)
  IF(ICOUNT.GT.1) GO TO 148
  SC(M,K,4)=SRC(I,JP1,K)
  TO(M,K,4)=TEEO(I,JP1,K)
  R(M,K,4)=RX(I,JP1,K)
  RO(M,K,4)=RHOX(I,JP1,K)
  XKN(M,K,4)=XKINF(I,JP1,K)
  XFS(M,K,4)=SIGF(I,JP1,K)
148 CONTINUE
  GO TO 176
C
155 CONTINUE
C.....
C * CHECKER-BOARD PROBLEM ONLY
C (ICASE = 8, 10, OR 11)
C.....
  IF(I.NE.1) GO TO 160
156 CONTINUE
  IF(I.EQ.1) GO TO 158
  IF(J.EQ.JR.AND.J.EQ.JIM1) GO TO 161
158 CONTINUE
  T(M,K,1)=TEE(IP1,J,K)

```

```

CXKN(M,K,1) = CXK(IP1,J,K)
IF(ICOUNT.GT.1) GO TO 162
SC(M,K,1)=SRC(IP1,J,K)
TO(M,K,1)=TEEO(IP1,J,K)
R(M,K,1)=RX(IP1,J,K)
RO(M,K,1)=RHOX(IP1,J,K)
XKN(M,K,1)=XKINF(IP1,J,K)
XFS(M,K,1)=SIGF(IP1,J,K)
GO TO 162
160 CONTINUE
C
IF(J.EQ.JR) GO TO 156
IF(J.LT.JR.AND.J.GT.JIM1) GO TO 156
161 CONTINUE
C
T(M,K,1)=TEE(IM1,J,K)
CXKN(M,K,1) = CXK(IM1,J,K)
IF(ICOUNT.GT.1) GO TO 162
SC(M,K,1)=SRC(IM1,J,K)
TO(M,K,1)=TEEO(IM1,J,K)
R(M,K,1)=RX(IM1,J,K)
RO(M,K,1)=RHOX(IM1,J,K)
XKN(M,K,1)=XKINF(IM1,J,K)
XFS(M,K,1)=SIGF(IM1,J,K)
162 CONTINUE
C
IF(J.NE.1) GO TO 164
T(M,K,2)=TEE(I,JP1,K)
CXKN(M,K,2) = CXK(I,JP1,K)
IF(ICOUNT.GT.1) GO TO 166
SC(M,K,2)=SRC(I,JP1,K)
TO(M,K,2)=TEEO(I,JP1,K)
R(M,K,2)=RX(I,JP1,K)
RO(M,K,2)=RHOX(I,JP1,K)
XKN(M,K,2)=XKINF(I,JP1,K)
XFS(M,K,2)=SIGF(I,JP1,K)
GO TO 166
164 CONTINUE
C
T(M,K,2)=TEE(I,JM1,K)
CXKN(M,K,2) = CXK(I,JM1,K)
IF(ICOUNT.GT.1) GO TO 166
SC(M,K,2)=SRC(I,JM1,K)
TO(M,K,2)=TEEO(I,JM1,K)
R(M,K,2)=RX(I,JM1,K)
RO(M,K,2)=RHOX(I,JM1,K)
XKN(M,K,2)=XKINF(I,JM1,K)
XFS(M,K,2)=SIGF(I,JM1,K)
166 CONTINUE

```

```

C      IF(I.NE.IMAX) GO TO 170
        T(M,K,3)=TEE(IM1,J,K)
        CXKN(M,K,3) = CXK(IM1,J,K)
        IF(ICOUNT.GT.1) GO TO 172
        SC(M,K,3)=SRC(IM1,J,K)
        TO(M,K,3)=TEEO(IM1,J,K)
        R(M,K,3)=RX(IM1,J,K)
        RO(M,K,3)=RHOX(IM1,J,K)
        XKN(M,K,3)=XKINF(IM1,J,K)
        XFS(M,K,3)=SIGF(IM1,J,K)
        GO TO 172
170 CONTINUE
C      T(M,K,3)=TEE(IP1,J,K)
        CXKN(M,K,3) = CXK(IP1,J,K)
        IF(ICOUNT.GT.1) GO TO 172
        SC(M,K,3)=SRC(IP1,J,K)
        TO(M,K,3)=TEEO(IP1,J,K)
        R(M,K,3)=RX(IP1,J,K)
        RO(M,K,3)=RHOX(IP1,J,K)
        XKN(M,K,3)=XKINF(IP1,J,K)
        XFS(M,K,3)=SIGF(IP1,J,K)
172 CONTINUE
C      IF(J.NE.JR) GO TO 174
        T(M,K,4)=TEE(I,JM1,K)
        CXKN(M,K,4) = CXK(I,JM1,K)
        IF(ICOUNT.GT.1) GO TO 176
        SC(M,K,4)=SRC(I,JM1,K)
        TO(M,K,4)=TEEO(I,JM1,K)
        R(M,K,4)=RX(I,JM1,K)
        RO(M,K,4)=RHOX(I,JM1,K)
        XKN(M,K,4)=XKINF(I,JM1,K)
        XFS(M,K,4)=SIGF(I,JM1,K)
        GO TO 176
174 CONTINUE
C      T(M,K,4)=TEE(I,JP1,K)
        CXKN(M,K,4) = CXK(I,JP1,K)
        IF(ICOUNT.GT.1) GO TO 176
        SC(M,K,4)=SRC(I,JP1,K)
        TO(M,K,4)=TEEO(I,JP1,K)
        R(M,K,4)=RX(I,JP1,K)
        RO(M,K,4)=RHOX(I,JP1,K)
        XKN(M,K,4)=XKINF(I,JP1,K)
        XFS(M,K,4)=SIGF(I,JP1,K)
176 CONTINUE
        IF(ICASE.EQ.4.OR.ICASE.EQ.10) GO TO 200
C

```

```

IF(K.NE.1) GO TO 180
IF(ICOUNT.GT.1) GO TO 182
SC(M,K,5)=0.
TO(M,K,5)=0.
T(M,K,5)=CMPLX(0.,0.)
CXKN(M,K,5) = CMPLX(1.,0.)
R(M,K,5)=0.
RO(M,K,5)=BAH
XKN(M,K,5)=1.
XFS(M,K,5)=0.
GO TO 182

```

180 CONTINUE

C

```

T(M,K,5)=TEE(I,J,KM1)
CXKN(M,K,5) = CXK(I,J,KM1)
IF(ICOUNT.GT.1) GO TO 182
SC(M,K,5)=SRC(I,J,KM1)
TO(M,K,5)=TEEO(I,J,KM1)
R(M,K,5)=RZ(I,J,KM1)
RO(M,K,5)=RHOZ(I,J,KM1)
XKN(M,K,5)=XKINF(I,J,KM1)
XFS(M,K,5)=SIGF(I,J,KM1)

```

182 CONTINUE

C

```

IF(K.NE.KMAX) GO TO 185
IF(ICOUNT.GT.1) GO TO 188
SC(M,K,6)=0.
TO(M,K,6)=0.
T(M,K,6)=CMPLX(0.,0.)
CXKN(M,K,6) = CMPLX(1.,0.)
R(M,K,6)=0.
RO(M,K,6)=TAH
XKN(M,K,6)=1.
XFS(M,K,6)=0.
GO TO 188

```

185 CONTINUE

C

```

T(M,K,6)=TEE(I,J,KP1)
CXKN(M,K,6) = CXK(I,J,KP1)
IF(ICOUNT.GT.1) GO TO 188
SC(M,K,6)=SRC(I,J,KP1)
TO(M,K,6)=TEEO(I,J,KP1)
R(M,K,6)=RZ(I,J,KP1)
RO(M,K,6)=RHOZ(I,J,KP1)
XKN(M,K,6)=XKINF(I,J,KP1)
XFS(M,K,6)=SIGF(I,J,KP1)

```

188 CONTINUE

C

```

200 CONTINUE
199 CONTINUE

```

```

C
C
ANT=DX*DX
IF(ICASE.EQ.1.OR.ICASE.EQ.2.OR.ICASE.EQ.11) GO TO 201
IF(ICASE.EQ.12) GO TO 201
IF(ICASE.EQ.4.OR.ICASE.EQ.10) GO TO 305
IF(ICASE.EQ.3.OR.ICASE.EQ.6.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 405
IF(ICASE.EQ.5.OR.ICASE.EQ.8) GO TO 705

```

```

C
201 CONTINUE

```

```

C.....
C * POINT KINETICS PARAMETERS(UNIFORM, OR NON-UNIFORM RADIAL)
C.....

```

```

IF(ICOUNT.GT.1) GO TO 303
DO 300 I=1,IMAX
JR=JMX(I)
DO 300 J=1,JR
M=JJD(I,J)
IF(ICASE.EQ.1.OR.ICASE.EQ.12) GO TO 204
DADU=0.
DBDU=0.
DCDU=0.
DDDU=0.
DEDU=0.
SUMA=0.
SUMB=0.
SUMC=0.
SUMD=0.
SUME=0.

```

```

C
DO 203 JJ=1,6
SUMBJ(JJ)=0.
DMDU(JJ)=0.
203 CONTINUE
204 CONTINUE

```

```

C
DO 295 K=1,KMAX

```

```

C.....
C * DEFINE TEMPORARY VARIABLES
C.....

```

```

XK=XKINF(I,J,K)
SSRC=SRC(I,J,K)
SGF=SIG1(M,K,2)
SOFX=SSRC/SGF
SOSF=SOFX*SOFX
V=SIG1(M,K,4)
DVDU=CSIG1(M,K,4)
VARU=(2./XK-1.)*CSIG1(M,K,2)-CSIG1(M,K,1)

```

```

C
DO 208 JJ=1,6

```



```

      IX=JJ+4
      BBT(JJ)=SIG1(M,K,IX)
      DBTDU(JJ)=CSIG1(M,K,IX)
208 CONTINUE
C.....
C * CALCULATION OF XLEAK(NET CURRENT ON 6 FACES OF NODE
C      (I,J,K)
C.....
      CURIN=0.
      CUROT=0.
      XLKI=SSRC*TEEO(I,J,K)/(TEEO(I,J,K)-1.)*(XK-1.)/XK
C
      DO 210 N=1,4
      XLKN=SC(M,K,N)*TO(M,K,N)/(TO(M,K,N)-1.)*(XKN(M,K,N)-1.)/
1      XKN(M,K,N)
      CURIN=CURIN+XLKN*R(M,K,N)*(1.-RO(M,K,N))/(1.-RO(M,K,N))*
1      RHOX(I,J,K))*ANR
      CUROT=CUROT+XLKI*RX(I,J,K)*(1.-RHOX(I,J,K))/(1.-RO(M,K,N))*
1      RHOX(I,J,K))*ANR
210 CONTINUE
C
      DO 215 N=5,6
      XLKN=SC(M,K,N)*TO(M,K,N)/(TO(M,K,N)-1.)*(XKN(M,K,N)-1.)/
1      XKN(M,K,N)
      CURIN=CURIN+XLKN*R(M,K,N)*(1.-RO(M,K,N))/(1.-RO(M,K,N))*
1      RHOZ(I,J,K))*ANT
      CUROT=CUROT+XLKI*RZ(I,J,K)*(1.-RHOZ(I,J,K))/(1.-RO(M,K,N))*
1      RHOZ(I,J,K))*ANT
215 CONTINUE
C
      XLEAK=CURIN-CUROT
C
C.....
C * SUMMATION TO GET A, B, AND C OVER ALL DIRECTIONS
C.....
      S2SF=SSRC*SOFX
      SUMA=SUMA+S2SF*(1.-1./XK)*VOL
      SUMB=SUMB+SOFX*XLEAK
      SUMC=SUMC+S2SF*VOL
      SUMD=SUMD+SOSF/V*VOL
      SUME=SUME+SOSF*VOL
C
      DO 220 JJ=1,6
      SUMBJ(JJ)=SUMBJ(JJ)+S2SF*BBT(JJ)*VOL
      DMDU(JJ)=DMDU(JJ)+SOSF*VOL*(SGF*DBTDU(JJ)-BBT(JJ))*
1      CSIG1(M,K,2))
220 CONTINUE
C.....
C * DERIVATIVES OF A, B, C WRT VOID FRACTION
C.....

```

```

DADU=DADU+SOSF*VARU*VOL
DBDU=DBDU-SOSF*CSIG1(M,K,2)*XLEAK/SSRC
DCDU=DCDU-SOSF*CSIG1(M,K,2)*VOL
DDDU=DDDU-(SOSF/V/V*DVDU+2.*SOSF/SGF/V*CSIG1(M,K,2))*VOL
DEDU=DEDU-2.*SOSF/SGF*CSIG1(M,K,2)*VOL

```

295 CONTINUE

C

```

IF(ICASE.EQ.1.OR.ICASE.EQ.12) GO TO 298
REAC(M)=(SUMA+SUMB)/SUMC
XKEF(M)=1./(1.-REAC(M))
GTIME(M)=SUMD/SUMC
CAL(M)=(DADU+DBDU-REAC(M)*DCDU)/SUMC
XSGF(M)=SUMC/SUME
XVEL(M)=SUME/SUMD
CXGF(M)=(DCDU-XSGF(M)*DEDU)/SUME
CXVL(M)=(DEDU-XVEL(M)*DDDU)/SUMD
CLAM(M)=(DDDU-GTIME(M)*DCDU)/SUMC

```

C

```

WRITE(6,610) REAC(M),GTIME(M),CAL(M),XSGF(M),CXGF(M),CXVL(M),
1 CLAM(M),XKEF(M)
DO 297 JJ=1,6
PBET(M,JJ)=(1.-REAC(M))*SUMBJ(JJ)/SUMC
CBET(M,JJ)=((1.-REAC(M))*DMDU(JJ)-SUMBJ(JJ)*CAL(M)-
1 PBET(M,JJ)*DCDU)/SUMC

```

297 CONTINUE

298 CONTINUE

300 CONTINUE

C

```

IF(ICASE.EQ.2.OR.ICASE.EQ.11) GO TO 302
REACT=(SUMA+SUMB)/SUMC
XKEFF=1./(1.-REACT)
PCAPLA=SUMD/SUMC
DRDU=(DADU+DBDU-REACT*DCDU)/SUMC
CALPHA=(DADU+DBDU)/SUMC
ASGF=SUMC/SUME
AVEL=SUME/SUMD
CSGF=(DCDU-ASGF*DEDU)/SUME
CVL=(DEDU-AVEL*DDDU)/SUMD
CLAMD=(DDDU-PCAPLA*DCDU)/SUMC

```

C

```

DO 301 JJ=1,6
PBETA(JJ)=SUMBJ(JJ)/SUMC
CBETA(JJ)=(DMDU(JJ)-PBETA(JJ)*DCDU)/SUMC

```

301 CONTINUE

302 CONTINUE

C

```

IF(ICASE.EQ.2.OR.ICASE.EQ.11) GO TO 303
IF(INRUN.GT.0) GO TO 303
WRITE(6,610) REACT,PCAPLA,DRDU,CALPHA,ASGF,AVEL,CSGF,CVL,
1 CLAMD,XKEFF

```

```

303 CONTINUE
  IF( ICASE.EQ.1.OR.ICASE.EQ.12) GO TO 1000
  IF( ICASE.EQ.2.OR.ICASE.EQ.11) GO TO 1100
C
305 CONTINUE
C.....
C * RADIALLY COUPLED KINETICS PARAMETERS CALCULATION(2-D)
C.....
  DO 350 I=1,IMAX
    JR=JMX(I)
    DO 350 J=1,JR
      M=JJD(I,J)
C
      DO 306 N=1,4
        SAIN(N)=CMPLX(0.,0.)
        SANI(N)=CMPLX(0.,0.)
        SAION(N)=0.
        SANOI(N)=0.
        SUMXRC(N)=0.
306 CONTINUE
C
        SAMR=CMPLX(0.,0.)
        SAMOR=0.
        SUMSR=0.
        IF( ICOUNT.GT.1) GO TO 310
        SUMCDF=0.
        SUMCV=0.
        SUMCXA=0.
        SUMCXF=0.
        SUMDF=0.
        SUMV=0.
        SUMVV=0.
        SMTHE=0.
        SUMWW=0.
        SUMXA=0.
        SUMXX=0.
C
        DO 308 JJ=1,6
          SUMBL(JJ)=0.
          SUMCBL(JJ)=0.
308 CONTINUE
310 CONTINUE
C
        DO 340 K=1,KMAX
          CXXK = CXK(I,J,K)
          XK=XKINF(I,J,K)
          SSRC=SRC(I,J,K)
          DO 312 N=1,4
            SUMXRC(N)=SUMXRC(N)+SC(M,K,N)*VOL
312 CONTINUE

```

```

      IF(ICOUNT.GT.1) GO TO 322
C.....
C * DEFINE TEMPORARY VARIABLES
C.....
      V=SIG1(M,K,4)
      SGF=SIG1(M,K,2)
      DF=SIG1(M,K,3)
      SGA=SIG1(M,K,1)
      CV=CSIG1(M,K,4)
      CSGF=CSIG1(M,K,2)
      CSGA=CSIG1(M,K,1)
      CDF=CSIG1(M,K,3)
C
      DO 315 JJ=1,6
      IX=JJ+4
      BBT(JJ)=SIG1(M,K,IX)
      CBBT(JJ)=CSIG1(M,K,IX)
315 CONTINUE
C
C
      SUMCV=SUMCV+SSRC*VOL*CV/SGF/V/V
      SUMV=SUMV+SSRC*VOL/SGF/V
      SUMSR=SUMSR+SSRC*VOL
      SMTHE=SMTHE+SSRC*VOL/SGF
      SUMXA=SUMXA+SSRC*VOL/XK
      SUMDF=SUMDF+SSRC*VOL*DF/SGF
      SUMCXF=SUMCXF+SSRC*VOL*CSGF/SGF/SGF
      SUMCXA=SUMCXA+SSRC*VOL*CSGA/SGF
      SUMCDF=SUMCDF+SSRC*VOL*CDF/SGF
      SUMXX=SUMXX+SSRC*VOL*CSGF/SGF/XK
      SUMVV=SUMVV+SSRC*VOL*CSGF/SGF/V/SGF
      SUMWW=SUMWW+SSRC*VOL*DF*CSGF/SGF/SGF
C
      DO 320 JJ=1,6
      SUMBL(JJ)=SUMBL(JJ)+SSRC*VOL*BBT(JJ)
      SUMCBL(JJ)=SUMCBL(JJ)+SSRC*VOL*CBBT(JJ)
320 CONTINUE
C
322 IF(ICOUNT.GT.1) SUMSR=SUMSR+SSRC*VOL
C
      DO 325 N=1,4
      XNU=ANR/(1.-RO(M,K,N)*RHOX(I,J,K))
      AMN(N)=TEE(I,J,K)/(TEE(I,J,K)-1.)*(CXK-1.)/CXK*RX(I,J,K)*
1      (1.-RHOX(I,J,K))*XNU
      ANM(N)=T(M,K,N)/(T(M,K,N)-1.)*(CXKN(M,K,N)-1.)/CXKN(M,K,N)*
1      R(M,K,N)*(1.-RO(M,K,N))*XNU
      AMON(N)=TEEO(I,J,K)/(TEEO(I,J,K)-1.)*(XK-1.)/XK*RX(I,J,K)*
1      (1.-RHOX(I,J,K))*XNU
      ANOM(N)=TO(M,K,N)/(TO(M,K,N)-1.)*(XKN(M,K,N)-1.)/XKN(M,K,N)*
1      R(M,K,N)*(1.-RO(M,K,N))*XNU

```

```

SAIN(N)=SAIN(N)+AMN(N)*SSRC
SANI(N)=SANI(N)+ANM(N)*SC(M,K,N)
SAION(N)=SAION(N)+AMON(N)*SSRC
SANOI(N)=SANOI(N)+ANOM(N)*SC(M,K,N)

```

```

325 CONTINUE

```

```

C

```

```

SAH=1.
IF(K.EQ.1) SAH=BAH
IF(K.EQ.KMAX) SAH=TAH
AMR=TEE(I,J,K)/(TEE(I,J,K)-1.)*(CXXK-1.)/CXXK*RZ(I,J,K)*
1 (1.-SAH)/(1.-SAH*RHOZ(I,J,K))*TSAR
AMOR=TEEO(I,J,K)/(TEEO(I,J,K)-1.)*(XK-1.)/XK*RZ(I,J,K)*
1 (1.-SAH)/(1.-SAH*RHOZ(I,J,K))*TSAR
SAMR=SAMR+AMR*SSRC
SAMOR=SAMOR+AMOR*SSRC

```

```

335 CONTINUE

```

```

C

```

```

C

```

```

340 CONTINUE

```

```

C

```

```

IF(ICOUNT.GT.1) GO TO 344

```

```

C

```

```

RXA(I,J)=SUMXA/SMTHE
RXF(I,J)=SUMSR/SMTHE
RV(I,J)=SMTHE/SUMV
RCXF(I,J)=SUMCXF*RXF(I,J)/SMTHE
RCXA(I,J)=(SUMCXA+RXA(I,J)*SUMCXF-SUMXX)/SMTHE
RCV(I,J)=(SUMVV+SUMCV)*RV(I,J)-SUMCXF/SUMV
RDF(I,J)=SUMDF/SMTHE
RCDF(I,J)=(SUMCDF+RDF(I,J)*SUMCXF-SUMWW)/SMTHE
WRITE(6,610) RXA(I,J),RXF(I,J),RV(I,J),RCXF(I,J),RCXA(I,J),
1 RCV(I,J),RDF(I,J),RCDF(I,J)

```

```

C

```

```

DO 343 JJ=1,6
RBET(M,JJ)=SUMBL(JJ)/SUMSR
RCBT(M,JJ)=SUMCBL(JJ)/SUMSR

```

```

343 CONTINUE

```

```

344 CONTINUE

```

```

C

```

```

RAIR(M)=SAMR/SUMSK
RAIOR(M)=SAMOR/SUMSR

```

```

C

```

```

DO 346 N=1,4
IF(SUMXRC(N).EQ.0.) SUMXRC(N)=1.
RAIN(M,N)=SAIN(N)/SUMSR
RANI(M,N)=SANI(N)/SUMXRC(N)
RAION(M,N)=SAION(N)/SUMSR
RANOI(M,N)=SANOI(N)/SUMXRC(N)

```

```

346 CONTINUE

```

```

C

```

```

350 CONTINUE
C.....
C *   RADIALLY COUPLED KINETICS(2-D)
C.....
      DO 395 I=1, IMAX
        IM1=I-1
        IP1=I+1
        IF(I.GT.1) JIM1=JMX(IM1)
        JR=JMX(I)
        DO 395 J=1, JR
          M=JJD(I,J)
          JM1=J-1
          JP1=J+1
          SUM1=CMPLX(0.,0.)
          SUM2=CMPLX(0.,0.)
C
          DO 355 JJ=1,6
            SUM1=SUM1+S*RBET(M,JJ)/(S+PLAMDA(JJ))
            SUM2=SUM2+S*RCBT(M,JJ)/(S+PLAMDA(JJ))
          355 CONTINUE
C
          XAIN=CMPLX(0.,0.)
          XAION=0.
C
          DO 390 N=1,4
            XAIN=XAIN+RAIN(M,N)
            XAION=XAION+RAION(M,N)
            IF(N.EQ.1) GO TO 361
            IF(N.EQ.2) GO TO 364
            IF(N.EQ.4) GO TO 365
            IF(N.EQ.3) GO TO 366
          361 IF(I.EQ.1) GO TO 362
C
            IF(J.GT.JIM1.AND.J.LE.JR) GO TO 362
            ZNI(M,N)=RCXF(IM1,J)/RXF(IM1,J)*RANI(M,N)
            GO TO 390
          362 ZNI(M,N)=CMPLX(0.,0.)
            IF(ICASE.EQ.10) ZNI(M,N)=RCXF(IP1,J)/RXF(IP1,J)*RANI(M,N)
            GO TO 390
C
          364 IF(J.NE.1) ZNI(M,N)=RCXF(I,JM1)/RXF(I,JM1)*RANI(M,N)
            IF(J.EQ.1.AND.ICASE.EQ.10) ZNI(M,N)=RCXF(I,JP1)/RXF(I,JP1)*
              RANI(M,N)
            IF(J.EQ.1.AND.ICASE.EQ.4) ZNI(M,N)=RCXF(I,J)/RXF(I,J)*
              RANI(M,N)
            GO TO 390
C
          365 IF(J.EQ.JR.AND.ICASE.EQ.10) ZNI(M,N)=RCXF(I,JM1)/RXF(I,JM1)*
              RANI(M,N)
            IF(J.EQ.JR.AND.ICASE.EQ.4) ZNI(M,N)=CMPLX(0.,0.)

```

```

      IF(J.NE.JR) ZNI(M,N)=RCXF(I,JP1)/RXF(I,JP1)*RANI(M,N)
      GO TO 390
366 IF(I.EQ.IMAX.AND.ICASE.EQ.10) ZNI(M,N)=RCXF(IM1,J)/RXF(IM1,J)*
      1 RANI(M,N)
      IF(I.EQ.IMAX.AND.ICASE.EQ.4) ZNI(M,N)=RCXF(I,J)/RXF(I,J)*
      1 RANI(M,N)
      IF(I.NE.IMAX) ZNI(M,N)=RCXF(IP1,J)/RXF(IP1,J)*RANI(M,N)
390 CONTINUE
C
C      BI(M)=(RXA(I,J)+S/RV(I,J))/RXF(I,J)+RAIR(M)+(SUM1-1.)/XKEFF+
      1 XAIN
      RKI(M)=((1.-SUM1)/XKEFF+BI(M))*RCXF(I,J)/RXF(I,J)-SUM2/XKEFF-
      1 (RAIOR(M)+XAION)*RCDF(I,J)/RDF(I,J)-
      2 (RCXA(I,J)-S*RCV(I,J)/RV(I,J)**2)/RXF(I,J)
395 CONTINUE
C
C      GO TO 2000
C
405 CONTINUE
C.....
C * POINT KINETICS(FOR NON-UNIFORM AXIAL, OR SPECIFIC CHANNEL),
C OR AXIALLY COUPLED KINETICS(AVERAGE CHANNEL)
C (ICASE=3, 6, OR 7)
C.....
      I37=0
      IF(ICASE.EQ.3.OR.ICASE.EQ.7.OR.ICASE.EQ.9) I37=1
      IF(ICOUNT.GT.1.AND.I37.EQ.1) GO TO 485
      DO 480 K=1,KMAX
      IF(ICASE.EQ.3.OR.ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 408
      DO 406 N=1,2
      SAKN(N)=CMPLX(0.,0.)
      SANK(N)=CMPLX(0.,0.)
      SAKON(N)=0.
      SANOK(N)=0.
      SUMXRC(N)=0.
406 CONTINUE
C
      SAMR=CMPLX(0.,0.)
      SAMOR=0.
      SUMSR=0.
      IF(ICOUNT.GT.1) GO TO 410
      SUMCDF=0.
      SUMCV=0.
      SUMCXA=0.
      SUMCXF=0.
      SUMDF=0.
      SUMV=0.
      SUMVV=0.

```

SMTHE=0.
SUMWW=0.
SUMXA=0.
SUMXX=0.

C
DO 407 JJ=1,6
SUMBL(JJ)=0.
SUMCBL(JJ)=0.
407 CONTINUE

C
GO TO 410
408 CONTINUE

C.....
C * ICASE=3 POINT KINETICS, NON-UNIFORM AXIAL
C.....

IF(ICASE.EQ.9) GO TO 410
DADU=0.
DBDU=0.
DCDU=0.
DDDU=0.
DEDU=0.
DFDU=0.
SUMA=0.
SUMB=0.
SUMC=0.
SUMD=0.
SUME=0.
SUMF=0.

C
DO 409 JJ=1,6
SUMBJ(JJ)=0.
DMDU(JJ)=0.
409 CONTINUE

C
410 CONTINUE
IF(ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 411
IL=1
IR=IMAX
GO TO 412
411 IL=ISPEC
IR=ISPEC
412 CONTINUE
JL=1
IF(ICASE.EQ.7.OR.ICASE.EQ.9) JL=JSPEC
DO 470 I=IL,IR
IM1=I-1
IF(I.GT.1) JIM1=JMX(IM1)
JR=JMX(I)
IF(ICASE.EQ.7.OR.ICASE.EQ.9) JR=JSPEC
DO 470 J=JL,JR


```

      CXXK = CXK(I,J,K)
      M=JJD(I,J)
      SSRC=SRC(I,J,K)
      IF(K.NE.1) SUMXRC(1)=SUMXRC(1)+SC(M,K,5)*VOL
      IF(K.NE.KMAX) SUMXRC(2)=SUMXRC(2)+SC(M,K,6)*VOL
      XK=XKINF(I,J,K)
      IF(ICOUNT.GT.1) GO TO 446
C.....
C * DEFINE TEMPORARY VARIABLES
C.....
      V=SIG1(M,K,4)
      SGF=SIG1(M,K,2)
      DF=SIG1(M,K,3)
      SGA=SIG1(M,K,1)
      CV=CSIG1(M,K,4)
      CSGF=CSIG1(M,K,2)
      CSGA=CSIG1(M,K,1)
      CDF=CSIG1(M,K,3)
      VARU=(2./XK-1.)*CSIG1(M,K,2)-CSIG1(M,K,1)
C
      DO 420 JJ=1,6
      IX=JJ+4
      BBT(JJ)=SIG1(M,K,IX)
      CBBT(JJ)=CSIG1(M,K,IX)
      DBTDU(JJ)=CBBT(JJ)
420 CONTINUE
C
      SOFX=SSRC/SGF
      SOSF=SOFX*SOFX
C
      IF(ICASE.EQ.6) GO TO 440
C.....
C * CALCULATION OF POINT KINETICS PARAMETERS FOR NON-UNIFORM
C AXIAL CASE
C.....
      CURIN=0.
      CUROT=0.
      XLK1=SSRC*TEEO(I,J,K)/(TEEO(I,J,K)-1.)*(XK-1.)/XK
C
      IF(ICASE.EQ.7.OR.ICASE.EQ.9) GO TO 426
C
      DO 425 N=1,4
      XLKN=SC(M,K,N)*TO(M,K,N)/(TO(M,K,N)-1.)*(XKN(M,K,N)-1.)/
1      XKN(M,K,N)
      CURIN=CURIN+XLKN*R(M,K,N)*(1.-RO(M,K,N))/(1.-RO(M,K,N))*
1      RHOX(I,J,K))*ANR
      CUROT=CUROT+XLK1*RX(I,J,K)*(1.-RHOX(I,J,K))/(1.-RO(M,K,N))*
1      RHOX(I,J,K))*ANR
425 CONTINUE
C

```

```

426 CONTINUE
DO 430 N=5,6
  XLKN=SC(M,K,N)*TO(M,K,N)/(TO(M,K,N)-1.)*(XKN(M,K,N)-1.)/
  1 XKN(M,K,N)
  CURIN=CURIN+XLKN*R(M,K,N)*(1.-RO(M,K,N))/(1.-RO(M,K,N)*
  1 RHOZ(I,J,K))*ANT
  CUROT=CUROT+XLKI*RZ(I,J,K)*(1.-RHOZ(I,J,K))/(1.-RO(M,K,N)*
  1 RHOZ(I,J,K))*ANT

```

```

430 CONTINUE

```

C

```

  XLEAK=CURIN-CUROT

```

C

```

  * SUMMATION TO GET A, B, AND C OVER ALL DIRECTIONS

```

C

```

  S2SF=SSRC*SOFX
  SUMA=SUMA+S2SF*(1.-1./XK)*VOL
  SUMB=SUMB+SOFX*XLEAK
  SUMC=SUMC+S2SF*VOL
  SUMD=SUMD+SOSF/V*VOL
  SUME=SUME+SOSF*VOL
  SUMF=SUMF+SGA*SOSF*VOL

```

C

```

DO 435 JJ=1,6
  SUMBJ(JJ)=SUMBJ(JJ)+S2SF*BBT(JJ)*VOL
  DMDU(JJ)=DMDU(JJ)+SOSF*VOL*(SGF*DBTDU(JJ)-BBT(JJ))*
  1 CSIG1(M,K,2)

```

```

435 CONTINUE

```

C

```

  * DERIVATIVES OF A, B, C WRT VOID FRACTION

```

C

```

  DADU=DADU+SOSF*VARU*VOL
  DBDU=DBDU-SOSF*CSIG1(M,K,2)*XLEAK/SSRC
  DCDU=DCDU-SOSF*CSIG1(M,K,2)*VOL
  DDDU=DDDU-(SOSF/V/V*CV+2.*SOSF/SGF/V*CSIG1(M,K,2))*VOL
  DEDU=DEDU-2.*SOSF/SGF*CSIG1(M,K,2)*VOL
  DFDU=DFDU+SOSF*VOL*(CSGA-2./XK*CSGF)
  GO TO 470

```

```

440 CONTINUE

```

C

```

  SUMCV=SUMCV+SSRC*VOL*CV/SGF/V/V
  SUMV=SUMV+SSRC*VOL/SGF/V
  SUMSR=SUMSR+SSRC*VOL
  SMTHE=SMTHE+SSRC*VOL/SGF
  SUMXA=SUMXA+SSRC*VOL/XK
  SUMDF=SUMDF+SSRC*VOL*DF/SGF
  SUMCXF=SUMCXF+SSRC*VOL*CSGF/SGF/SGF
  SUMCXA=SUMCXA+SSRC*VOL*CSGA/SGF
  SUMCDF=SUMCDF+SSRC*VOL*CDF/SGF
  SUMXX=SUMXX+SSRC*VOL*CSGF/SGF/XK
  SUMVV=SUMVV+SSRC*VOL*CSGF/SGF/V/SGF

```

```

SUMWW=SUMWW+SSRC*VOL*DF*CSGF/SGF/SGF
C
DO 445 JJ=1,6
SUMBL(JJ)=SUMBL(JJ)+SSRC*VOL*BBT(JJ)
SUMCBL(JJ)=SUMCBL(JJ)+SSRC*VOL*CBBT(JJ)
445 CONTINUE
446 IF(ICASE.EQ.6.AND.ICOUNT.GT.1) SUMSR=SUMSR+SSRC*VOL
C
C
DO 448 NN=1,2
N=NN+4
XNU=ANT/(1.-RO(M,K,N)*RHOZ(I,J,K))
AMN(NN)=TEE(I,J,K)/(TEE(I,J,K)-1.)*(CXK-1.)/CXK*RZ(I,J,K)*
1 (1.-RHOZ(I,J,K))*XNU
ANM(NN)=T(M,K,N)/(T(M,K,N)-1.)*(CXKN(M,K,N)-1.)/CXKN(M,K,N)*
1 R(M,K,N)*(1.-RO(M,K,N))*XNU
AMON(NN)=TEEO(I,J,K)/(TEEO(I,J,K)-1.)*(XK-1.)/XK*RZ(I,J,K)*
1 (1.-RHOZ(I,J,K))*XNU
ANOM(NN)=TO(M,K,N)/(TO(M,K,N)-1.)*(XKN(M,K,N)-1.)/XKN(M,K,N)*
1 R(M,K,N)*(1.-RO(M,K,N))*XNU
SAKN(NN)=SAKN(NN)+AMN(NN)*SSRC
SANK(NN)=SANK(NN)+ANM(NN)*SC(M,K,N)
SAKON(NN)=SAKON(NN)+AMON(NN)*SSRC
SANOK(NN)=SANOK(NN)+ANOM(NN)*SC(M,K,N)
448 CONTINUE
C
IF(ICASE.GT.1) GO TO 449
WRITE(10,9999) I,J,K,AMN(1),AMN(2),ANM(1),ANM(2),TEE(I,J,K),XK,
1 XNU
9999 FORMAT(1X,3I3,1X,12E10.3)
449 CONTINUE
C
IF(I.EQ.1) GO TO 450
IF(J.EQ.JR.OR.J.GT.JIM1) GO TO 450
GO TO 460
450 CONTINUE
SAR=ANR
AH=AL(I,J)
IF(J.EQ.JR) SAR=2.*ANR
IF(I.EQ.1) GO TO 453
IF(J.EQ.JR.AND.J.EQ.JIM1) SAR=ANR
453 CONTINUE
AMR=TEE(I,J,K)/(TEE(I,J,K)-1.)*(CXK-1.)/CXK*RX(I,J,K)*
1 (1.-AH)/(1.-AH*RHOX(I,J,K))*SAR
AMOR=TEEO(I,J,K)/(TEEO(I,J,K)-1.)*(XK-1.)/XK*RX(I,J,K)*
1 (1.-AH)/(1.-AH*RHOX(I,J,K))*SAR
SAMR=SAMR+AMR*SSRC
SAMOR=SAMOR+AMOR*SSRC
460 CONTINUE
C

```

```

470 CONTINUE
C
  IF(ICASE.EQ.6) GO TO 473
  IF(ICASE.EQ.9) GO TO 480
  REAC(K)=(SUMA+SUMB)/SUMC
  XKEF(K)=1./(1.-REAC(K))
  GTIME(K)=SUMD/SUMC
  CAL(K)=(DADU+DBDU-REAC(K)*DCDU)/SUMC
  XSGF(K)=SUMC/SUME
  XVEL(K)=SUME/SUMD
  CXGF(K)=(DCDU-XSGF(K)*DEDU)/SUME
  CXVL(K)=(DEDU-XVEL(K)*DDDU)/SUMD
  CLAM(K)=(DDDU-GTIME(K)*DCDU)/SUMC
C
  IF(INRUN.GT.0) GO TO 4870
  WRITE(6,610) REAC(K), GTIME(K), CAL(K), XSGF(K), XVEL(K), CXGF(K),
1      CXVL(K), CLAM(K), XKEF(K)
4870 CONTINUE
  DO 472 JJ=1,6
  PBET(K,JJ)=(1.-REAC(K))*SUMBJ(JJ)/SUMC
  CBET(K,JJ)=((1.-REAC(K))*DMDU(JJ)-SUMBJ(JJ)*CAL(K)-
1      PBET(K,JJ)*DCDU)/SUMC
472 CONTINUE
473 CONTINUE
  IF(ICOUNT.GT.1) GO TO 477
C
  IF(ICASE.EQ.3.OR.ICASE.EQ.7) GO TO 476
  AXA(K)=SUMXA/SMTHE
  AXF(K)=SUMSR/SMTHE
  AV(K)=SMTHE/SUMV
  ACXF(K)=SUMCXF*AXF(K)/SMTHE
  ACXA(K)=(SUMCXA+AXA(K)*SUMCXF-SUMXX)/SMTHE
  ACV(K)=(SUMVV+SUMCV)*AV(K)-SUMCXF/SUMV
  ADF(K)=SUMDF/SMTHE
  ACDF(K)=(SUMCDF+ADF(K)*SUMCXF-SUMWW)/SMTHE
C
  IF(INRUN.GT.0) GO TO 4890
  WRITE(6,610) AXA(K), AXF(K), AV(K), ACXF(K), ACXA(K), ACV(K),
1      ADF(K), ACDF(K)
4890 CONTINUE
  DO 474 JJ=1,6
  RBET(K,JJ)=SUMBL(JJ)/SUMSR
  RCBT(K,JJ)=SUMCBL(JJ)/SUMSR
474 CONTINUE
477 CONTINUE
C
  RAIK(K)=SAMR/SUMSR
  RAIOR(K)=SAMOR/SUMSR
C
  IF(K.EQ.1) SUMXRC(1)=1.

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```

      IF(K.EQ.KMAX) SUMXRC(2)=1.
      DO 475 N=1,2
      RAIN(K,N)=SAKN(N)/SUMSR
      RANI(K,N)=SANK(N)/SUMXRC(N)
      RAIOR(K,N)=SAKON(N)/SUMSR
      RANOI(K,N)=SANOK(N)/SUMXRC(N)
475  CONTINUE
      WRITE(10,9991)
9991  FORMAT(2X,' K, SAMR(CMPLX), SUMSR, SAMOR, RAIOR, RAIR,
1     RAIN(K,1), RAIN(K,2)')
      WRITE(10,9997) K, SAMR, SUMSR, SAMOR, RAIOR(K), RAIR(K), RAIN(K,1),
1     RAIN(K,2)
9997  FORMAT(2X, I3, 11E11.4)
476  CONTINUE
480  CONTINUE
      IF(ICASE.NE.9) GO TO 485
      REACT=(SUMA+SUMB)/SUMC
      PCAPLA=SUMD/SUMC
      DRDU=(DADU+DBDU-REACT*DCDU)/SUMC
      CALPHA=(DADU+DBDU)/SUMC
      ASGF=SUMC/SUME
      ASGA=SUMF/SUME
      AVEL=SUME/SUMD
      CSGF=(DCDU-ASGF*DEDU)/SUME
      CSA=(DFDU-ASGA*DEDU)/SUME
      CVL=(DEDU-AVEL*DDDU)/SUMD
      CLAMD=(DDDU-PCAPLA*DCDU)/SUMC
      DO 490 JJ=1,6
      PBETA(JJ)=SUMBJ(JJ)/SUMC*(1.-REACT)
      CBETA(JJ)=((1.-REACT)*DMDU(JJ)-SUMBJ(JJ)*DRDU-PBETA(JJ)*DCDU)/SUMC
490  CONTINUE
      IF(INRUN.GT.0) GO TO 485
      WRITE(6,671) REACT, PCAPLA, DRDU, CALPHA, ASGF, AVEL, CSGF, CVL,
1     CLAMD, ASGA, CSA
671  FORMAT(5X, 'REACT', 5X, 'PCAPLA', 5X, 'DRDU', 5X, 'CALPHA', 5X, 'ASGF',
1     5X, 'AVEL', 5X, 'CSGF', 5X, 'CVL', 5X, 'CLAMD', 5X, 'ASGA', 5X,
2     'CSA', //, 5X, 11E11.4)
485  CONTINUE
      IF(ICASE.EQ.9) GO TO 1000
      GO TO 1199
705  CONTINUE
C.....
C * GENERAL SPACE KINETICS(3-D) OR AXIALLY COUPLED KINETICS.....
C (1-D, IDENTICAL CHANNEL) PARAMETERS CALCULATION
C.....
      IF(ICASE.EQ.8) GO TO 706
      IL=ISPEC
      IRR=ISPEC
      GO TO 708
706  IL=1

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```

      IRR=IMAX
708 CONTINUE
C
      DO 760 I=IL,IRR
      IF(ICASE.EQ.8) GO TO 710
      JL=JSPEC
      JR=JSPEC
      GO TO 715
710 JL=1
      JR=JMX(1)
715 CONTINUE
C
      DO 760 J=JL,JR
      M=JJD(1,J)
      DO 760 K=1,KMAX
C
      CXXK = CXX(1,J,K)
      XK=XKINF(1,J,K)
      XTO=TEEO(1,J,K)
      XRO=RHOX(1,J,K)
      ZRO=RHOZ(1,J,K)
      XR=RX(1,J,K)
      ZR=RZ(1,J,K)
C
      IF(ICASE.EQ.5) GO TO 745
C
      DO 740 N=1,4
      GAMN(M,K,N)=TEE(1,J,K)/(TEE(1,J,K)-1.)*(CXXK-1.)/CXXK*XR*
1      (1.-XRO)/(1.-XRO*RO(M,K,N))*ANR/VOL
      GANM(M,K,N)=T(M,K,N)/(T(M,K,N)-1.)*(CXKN(M,K,N)-1.)/CXKN(M,K,N)*
1      R(M,K,N)*(1.-RO(M,K,N))/(1.-XRO*RO(M,K,N))*
2      ANR/VOL
      IF(ICOUNT.GT.1) GO TO 740
      GAMON(M,K,N)=XTO/(XTO-1.)*(XK-1.)/XK*XR*(1.-XRO)/(1.-XRO*
1      RO(M,K,N))*ANR/VOL
      GANOM(M,K,N)=TO(M,K,N)/(TO(M,K,N)-1.)*(XKN(M,K,N)-1.)/
1      XKN(M,K,N)*R(M,K,N)*(1.-RO(M,K,N))/(1.-RO(M,K,N))*
2      XRO)*ANR/VOL
740 CONTINUE
745 CONTINUE
C
      DO 750 NN=5,6
      N=NN
      IF(ICASE.EQ.5) N=NN-4
      GAMN(M,K,N)=TEE(1,J,K)/(TEE(1,J,K)-1.)*(CXXK-1.)/CXXK*ZR*
1      (1.-ZRO)/(1.-ZRO*RO(M,K,NN))*ANT/VOL
      GANM(M,K,N)=T(M,K,NN)/(T(M,K,NN)-1.)*(CXKN(M,K,NN)-1.)/
1      CXKN(M,K,NN)*R(M,K,NN)*(1.-RO(M,K,NN))/(1.-ZRO*RO(M,K,NN))*
2      ANT/VOL
      IF(ICOUNT.GT.1) GO TO 750

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      GAMON(M,K,N)=XTO/(XTO-1.)*(XK-1.)/XK*ZR*(1.-ZRO)/(1.-ZRO*
1      RO(M,K,NN))*ANT/VOL
      GANOM(M,K,N)=TO(M,K,NN)/(TO(M,K,NN)-1.)*(XKN(M,K,NN)-1.)/
1      XKN(M,K,NN)*R(M,K,NN)*(1.-RO(M,K,NN))/(1.-RO(M,K,NN))*
2      ZRO)*ANT/VOL
750 CONTINUE
760 CONTINUE
      IF(ICASE.EQ.5) GO TO 1400
      IF(ICASE.EQ.8) GO TO 1700
C
1000 CONTINUE
C.....
C * ZERO POWER POINT KINETICS(UNIFORM)
C.....
      SUM1=CMPLX(0.,0.)
      SUM2=CMPLX(0.,0.)
C
      DO 1070 I=1,6
      SUM1=SUM1+PBETA(I)*S/(S+PLAMDA(I))
      SUM2=SUM2+CBETA(I)*S/(S+PLAMDA(I))
1070 CONTINUE
      PPSI=SUM1/PCAPLA
C
      IF(DELK.NE.0.) GO TO 1092
      IF(ICASE.EQ.9) GO TO 1091
      ZPK=CHFO/PCAPLA/(PPSI+S)
      ZPKP=CHFO*(CSGF/ASGF+CVL/AVEL)+ZPK*(DRDU-SUM2+PPSI*CLAMD)
      ZPKP = CFP*ZPKP
1090 CONTINUE
C
      GO TO 2000
1091 ZPK=CHFO/PCAPLA/(PPSI+S)
      ZPKP=CHFO*(CSGF/ASGF+CVL/AVEL)+ZPK*(DRDU-SUM2+CLAMD*PPSI)
      ZPKP = CFP*ZPKP
      GO TO 2000
1092 IF(ICASE.EQ.1) GO TO 1093
      CKEF = 1./(1.-REACT)
      GO TO 1094
1093 CKEF = REAC(M)
1094 ZPK1 = CHFO/CKEF/PCAPLA/(PPSI+S)
      ZPK=ZPK1*DRDU
      ZPKP = CHFO*(CSGF/ASGF+CVL/AVEL-SUM2/(PCAPLA*S+SUM1))+
1      CLAMD*SUM1/PCAPLA/(PCAPLA*S+SUM1))
      GO TO 2000
C
1100 CONTINUE
C.....
C * POINT KINETICS(NON-UNIFORM RADIAL)
C.....
      DO 1150 I=1,IMAX

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```

JR=JMX(I)
DO 1150 J=1,JR
M=JJD(I,J)
SUM1=CMPLX(0.,0.)
SUM2=CMPLX(0.,0.)
C
DO 1130 JJ=1,6
SUM1=SUM1+PBET(M,JJ)*S/(S+PLAMDA(JJ))
SUM2=SUM2+CBET(M,JJ)*S/(S+PLAMDA(JJ))
1130 CONTINUE
C
A=CXGF(M)/XSGF(M)+CXVL(M)/XVEL(M)
B=CAL(M)-SUM2+CLAM(M)/GTIME(M)*SUM1
AAA(M)=(A+B/(GTIME(M)*S+SUM1))*ASRC(I,J)*CHFO*CFP
1150 CONTINUE
C
GO TO 2000
1199 CONTINUE
C
IF(ICASE.EQ.6) GO TO 1500
C.....
C * POINT KINETICS(NON-UNIFORM AXIAL)
C      ICASE = 3 : NON-UNIFORM AXIAL
C      ICASE = 7 : SPECIFIC CHANNEL
C.....
DO 1290 K=1,KMAX
SUM1=CMPLX(0.,0.)
SUM2=CMPLX(0.,0.)
C
DO 1270 JJ=1,6
SUM1=SUM1+PBET(K,JJ)*S/(S+PLAMDA(JJ))
SUM2=SUM2+CBET(K,JJ)*S/(S+PLAMDA(JJ))
1270 CONTINUE
C
A=CXGF(K)/XSGF(K)+CXVL(K)/XVEL(K)
B=CAL(K)-SUM2+CLAM(K)/GTIME(K)*SUM1
IF(ICASE.EQ.3) AAA(K)=(A+B/(GTIME(K)*S+SUM1))*AXSRC(K)*CHFO*CFP
IF(ICASE.EQ.7) AAA(K)=(A+B/(GTIME(K)*S+SUM1))*SRC(ISPEC,
1 JSPEC,K)*CHFO*CFP
1290 CONTINUE
C
GO TO 2000
1400 CONTINUE
C
C.....
C * AXIALLY COUPLED KINETICS, IDENTICAL CHANNEL(1-D)
C.....
M=JJD(ISPEC,JSPEC)
C
DO 1450 K=1,KMAX

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SUM1=CMPLX(0.,0.)
SUM2=CMPLX(0.,0.)
C
DO 1420 JJ=1,6
JL=JJ+4
SUM1=SUM1+S*SIG1(M,K,JL)/(S+PLAMDA(JJ))
SUM2=SUM2+S*CSIG1(M,K,JL)/(S+PLAMDA(JJ))
1420 CONTINUE
C
XAIN=CMPLX(0.,0.)
XAION=0.
KM1=K-1
KP1=K+1
C
DO 1430 N=1,2
XAIN=XAIN+GANM(M,K,N)
XAION=XAION+GAMON(M,K,N)
C
IF(N.EQ.1) GO TO 1425
IF(N.EQ.2) GO TO 1428
1425 IF(K.EQ.1) ZN1(K,N)=CMPLX(0.,0.)
IF(K.NE.1) ZN1(K,N)=CSIG1(M,KM1,2)/SIG1(M,KM1,2)*GANM(M,K,N)
GO TO 1430
1428 IF(K.EQ.KMAX) ZN1(K,N)=CMPLX(0.,0.)
IF(K.NE.KMAX) ZN1(K,N)=CSIG1(M,KP1,2)/SIG1(M,KP1,2)*GANM(M,K,N)
1430 CONTINUE
C
BI(K)=(SIG1(M,K,1)+S/SIG1(M,K,4))/SIG1(M,K,2)+
1 XAIN+(SUM1-1.)/XKEFF
RK1(K)=((1.-SUM1)/XKEFF+BI(K))*CSIG1(M,K,2)/SIG1(M,K,2)-
1 SUM2/XKEFF-XAION*CSIG1(M,K,3)/SIG1(M,K,3)-
2 (CSIG1(M,K,1)-S*CSIG1(M,K,4))/SIG1(M,K,4)**2/SIG1(M,K,2)
1450 CONTINUE
C
GO TO 2000
1500 CONTINUE
C
C.....
C * AXIALLY COUPLED KINETICS, AVERAGE CHANNEL(1-D)
C.....
DO 1560 K=1,KMAX
SUM1=CMPLX(0.,0.)
SUM2=CMPLX(0.,0.)
C
DO 1520 JJ=1,6
SUM1=SUM1+S*RBET(K,JJ)/(S+PLAMDA(JJ))
SUM2=SUM2+S*RCBT(K,JJ)/(S+PLAMDA(JJ))
1520 CONTINUE
C
XAIN=CMPLX(0.,0.)

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```

XAION=0.
KM1=K-1
KP1=K+1
C
DO 1530 N=1,2
XAIN=XAIN+RAIN(K,N)
XAION=XAION+RAION(K,N)
C
IF(N.EQ.1) GO TO 1525
IF(N.EQ.2) GO TO 1528
1525 IF(K.EQ.1) ZNI(K,N)=CMPLX(0.,0.)
IF(K.NE.1) ZNI(K,N)=ACXF(KM1)/AXF(KM1)*RANI(K,N)
GO TO 1530
1528 IF(K.EQ.KMAX) ZNI(K,N)=CMPLX(0.,0.)
IF(K.NE.KMAX) ZNI(K,N)=ACXF(KP1)/AXF(KP1)*RANI(K,N)
1530 CONTINUE
C
BI(K)=(AXA(K)+S/AV(K))/AXF(K)+RAIR(K)+(SUM1-1.)/XKEFF+XAIN
RKI(K)=((1.-SUM1)/XKEFF+BI(K))*ACXF(K)/AXF(K)-SUM2/XKEFF-
1 (RAIOR(K)+XAION)*ACDF(K)/ADF(K)-
2 (ACXA(K)-S*ACV(K)/AV(K)**2)/AXF(K)
1560 CONTINUE
C
GO TO 2000
1600 CONTINUE
1700 CONTINUE
C
C.....
C * GENERAL SPACE NODAL KINETICS(3-D)
C.....
C
DO 1780 I=1,IMAX
IM1=I-1
IP1=I+1
IF(I.GT.1) JIM1=JMX(IM1)
JR=JMX(I)
DO 1780 J=1,JR
JM1=J-1
JP1=J+1
M=JJD(I,J)
IF(I.NE.1) MIM1=JJD(IM1,J)
IF(I.NE.IMAX) MIP1=JJD(IP1,J)
IF(J.NE.1) MJM1=JJD(I,JM1)
IF(J.NE.JR) MJP1=JJD(I,JP1)
C
DO 1780 K=1,KMAX
SUM1=CMPLX(0.,0.)
SUM2=CMPLX(0.,0.)
C
DO 1710 JJ=1,6
JL=JJ+4

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```

SUM1=SUM1+S*SIG1(M,K,JL)/(S+PLAMDA(JJ))
SUM2=SUM2+S*CSIG1(M,K,JL)/(S+PLAMDA(JJ))
1710 CONTINUE
C
XAIN=CMPLX(0.,0.)
XAION=0.
KM1=K-1
KP1=K+1
C
DO 1750 N=1,6
XAIN=XAIN+GAMN(M,K,N)
XAION=XAION+GAMON(M,K,N)
C
IF(N.EQ.1) GO TO 1715
IF(N.EQ.2) GO TO 1720
IF(N.EQ.3) GO TO 1725
IF(N.EQ.4) GO TO 1730
IF(N.EQ.5) GO TO 1735
IF(N.EQ.6) GO TO 1740
1715 IF(I.EQ.1) GO TO 1717
IF(J.GT.JIM1.AND.J.LE.JR) GO TO 1717
XZNI(M,K,N)=CSIG1(MIM1,K,2)/SIG1(MIM1,K,2)*GANM(M,K,N)
GO TO 1750
1717 XZNI(M,K,N)=CSIG1(MIP1,K,2)/SIG1(MIP1,K,2)*GANM(M,K,N)
C1717 XZNI(M,K,N)=CMPLX(0.,0.)
GO TO 1750
C1720 IF(J.EQ.1) XZNI(M,K,N)=CSIG1(M,K,2)/SIG1(M,K,2)*GANM(M,K,N)
1720 IF(J.EQ.1) XZNI(M,K,N)=CSIG1(MJP1,K,2)/SIG1(MJP1,K,2)*GANM(M,K,N)
IF(J.NE.1) XZNI(M,K,N)=CSIG1(MJM1,K,2)/SIG1(MJM1,K,2)*GANM(M,K,N)
GO TO 1750
C1725 IF(I.EQ.IMAX) XZNI(M,K,N)=CSIG1(M,K,2)/SIG1(M,K,2)*GANM(M,K,N)
1725 IF(I.EQ.IMAX) XZNI(M,K,N)=CSIG1(MIM1,K,2)/SIG1(MIM1,K,2)*
1 GANM(M,K,N)
IF(I.NE.IMAX) XZNI(M,K,N)=CSIG1(MIP1,K,2)/SIG1(MIP1,K,2)*
1 GANM(M,K,N)
GO TO 1750
C1730 IF(J.EQ.JR) XZNI(M,K,N)=CMPLX(0.,0.)
1730 IF(J.EQ.JR) XZNI(M,K,N)=CSIG1(MJM1,K,2)/SIG1(MJM1,K,2)*GANM(M,K,N)
IF(J.NE.JR) XZNI(M,K,N)=CSIG1(MJP1,K,2)/SIG1(MJP1,K,2)*GANM(M,K,N)
GO TO 1750
1735 IF(K.EQ.1) XZNI(M,K,N)=CMPLX(0.,0.)
IF(K.NE.1) XZNI(M,K,N)=CSIG1(M,KM1,2)/SIG1(M,KM1,2)*GANM(M,K,N)
GO TO 1750
1740 IF(K.EQ.KMAX) XZNI(M,K,N)=CMPLX(0.,0.)
IF(K.NE.KMAX) XZNI(M,K,N)=CSIG1(M,KP1,2)/SIG1(M,KP1,2)*GANM(M,K,N)
1750 CONTINUE
C
XBM(M,K)=(SIG1(M,K,1)+S/SIG1(M,K,4))/SIG1(M,K,2)+
1 XAIN+(SUM1-1.)/XKEFF
XRKM(M,K)=((1.-SUM1)/XKEFF+XBM(M,K))*CSIG1(M,K,2)/SIG1(M,K,2)-

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      1      SUM2/XKEFF-XAION*CSIG1(M,K,3)/SIG1(M,K,3)-
      2      (CSIG1(M,K,1)-S*CSIG1(M,K,4)/SIG1(M,K,4)**2)/SIG1(M,K,2)
1780 CONTINUE
      GO TO 2000
1785 CONTINUE
C
C.....
C *   ICASE = 13, 14, 15  TWO GROUP COUPLING
C.....
      SSSUM=0.
      DO 1786 I=1, IMAX
      JR=JMX(I)
      DO 1786 J=1, JR
      M=JJD(I, J)
      DO 1786 K=1, KMAX
      SSSUM=SSSUM+SIG1(M, K, 2)*TFLX(1, M, K)+SIG2(M, K, 2)*TFLX(2, M, K)
1786 CONTINUE
C
      AAAAA=FLOAT(KMAX)*FLOAT(IMAX)*FLOAT(JMAX)/SSSUM
      DO 1788 I=1, IMAX
      JR=JMX(I)
      DO 1788 J=1, JR
      M=JJD(I, J)
      DO 1788 K=1, KMAX
      XQ11=AAAAA*SIG1(M, K, 2)*TFLX(1, M, K)
      XQ12=AAAAA*SIG2(M, K, 2)*TFLX(2, M, K)
      TOTQ1=XQ11+XQ12
      XMULT=SRC(I, J, K)/TOTQ1
      XTFLX(1, M, K)=XQ11*XMULT
      XTFLX(2, M, K)=XQ12*XMULT
1788 CONTINUE
C
      IF(ICASE.EQ.14) GO TO 1851
C
      AOV=ANT/VOL*2./DX
      BIJ01(1,1,1)=0.
      BIJ02(1,1,1)=0.
      DIJ01(1,1,1)=0.
      DIJ02(1,1,1)=0.
      DJOK1(1,1,1)=0.
      DJOK2(1,1,1)=0.
      TXFJ1(1,1,1)=1.
      TXFJ2(1,1,1)=1.
      TCXFJ1(1,1,1)=0.
      TCXFJ2(1,1,1)=0.
      DDC1(1,1,1)=0.
      DDC2(1,1,1)=0.
      DDOF1(1,1,1)=0.
      DDOF2(1,1,1)=0.
      TFLX1(1,1,1)=0.

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```

TFLXT(1,1,1)=0.
N=KMAX
BIJ01(1,N,2)=0.
BIJ02(1,N,2)=0.
DIJ01(1,N,2)=0.
DIJ02(1,N,2)=0.
DJOK1(1,N,2)=0.
DJOK2(1,N,2)=0.
TXFJ1(1,N,2)=1.
TXFJ2(1,N,2)=1.
TCXFJ1(1,N,2)=0.
TCXFJ2(1,N,2)=0.
DDC1(1,N,2)=0.
DDC2(1,N,2)=0.
DDOF1(1,N,2)=0.
DDOF2(1,N,2)=0.
TFLX1(1,N,2)=0.
TFLXT(1,N,2)=0.

```

C
C

```

DO 1830 I=1,IMAX
JR=JMX(I)
DO 1830 J=1,JR
M=JJD(I,J)
DO 1830 K=1,KMAX
KM1=K-1
KP1=K+1
SUM1=CMPLX(0.,0.)
SUM2=SUM1

```

C

```

DO 1790 NN=1,6
N=NN+4
SUM1=SUM1+SIG1(M,K,N)*S/(S+PLAMDA(NN))
1790 SUM2=SUM2+CSIG1(M,K,N)*S/(S+PLAMDA(NN))

```

C
C

```

IF(K.EQ.1) GO TO 1792
BIJ01(M,K,1)=AOV*SIG1(M,K,3)*SIG1(M,KM1,3)/(SIG1(M,K,3)+
1 SIG1(M,KM1,3))
BIJ02(M,K,1)=AOV*SIG2(M,K,3)*SIG2(M,KM1,3)/(SIG2(M,K,3)+
1 SIG2(M,KM1,3))
DJOK1(M,K,1)=SIG1(M,KM1,3)
DJOK2(M,K,1)=SIG2(M,KM1,3)
DIJ01(M,K,1)=AOV/(SIG1(M,K,3)+SIG1(M,KM1,3))**2
DIJ02(M,K,1)=AOV/(SIG2(M,K,3)+SIG2(M,KM1,3))**2
DDOF1(M,K,1)=(DJOK1(M,K,1)**2)*DIJ01(M,K,1)/SIG1(M,KM1,2)
DDOF2(M,K,1)=(DJOK2(M,K,1)**2)*DIJ02(M,K,1)/SIG2(M,KM1,2)
DDC1(M,K,1)=(SIG1(M,K,3)**2)*DIJ01(M,K,1)*CSIG1(M,KM1,3)
DDC2(M,K,1)=(SIG2(M,K,3)**2)*DIJ02(M,K,1)*CSIG2(M,KM1,3)
TXFJ1(M,K,1)=SIG1(M,KM1,2)

```

TXFJ2(M,K,1)=SIG2(M,KM1,2)
 TCXFJ1(M,K,1)=CSIG1(M,KM1,2)
 TCXFJ2(M,K,1)=CSIG1(M,KM1,2)
 TFLX1(M,K,1)=XTFLX(1,M,KM1)
 TFLXT(M,K,1)=SRC(1,J,KM1)

C

1792 IF(K.EQ.KMAX) GO TO 1795
 BIJO1(M,K,2)=AOV*SIG1(M,K,3)*SIG1(M,KP1,3)/(SIG1(M,K,3)+
 1 SIG1(M,KP1,3))
 BIJO2(M,K,2)=AOV*SIG2(M,K,3)*SIG2(M,KP1,3)/(SIG2(M,K,3)+
 1 SIG2(M,KP1,3))
 DJOK1(M,K,2)=SIG1(M,KP1,3)
 DJOK2(M,K,2)=SIG2(M,KP1,3)
 DIJO1(M,K,2)=AOV/(SIG1(M,K,3)+SIG1(M,KP1,3))**2
 DIJO2(M,K,2)=AOV/(SIG2(M,K,3)+SIG2(M,KP1,3))**2
 DDOF1(M,K,2)=(DJOK1(M,K,2)**2)*DIJO1(M,K,2)/SIG1(M,KP1,2)
 DDOF2(M,K,2)=(DJOK2(M,K,2)**2)*DIJO2(M,K,2)/SIG2(M,KP1,2)
 DDC1(M,K,2)=(SIG1(M,K,3)**2)*DIJO1(M,K,2)*CSIG1(M,KP1,3)
 DDC2(M,K,2)=(SIG2(M,K,3)**2)*DIJO2(M,K,2)*CSIG2(M,KP1,3)
 TXFJ1(M,K,2)=SIG1(M,KP1,2)
 TXFJ2(M,K,2)=SIG2(M,KP1,2)
 TCXFJ1(M,K,2)=CSIG1(M,KP1,2)
 TCXFJ2(M,K,2)=CSIG1(M,KP1,2)
 TFLX1(M,K,2)=XTFLX(1,M,KP1)
 TFLXT(M,K,2)=SRC(1,J,KP1)

C

1795 CONTINUE

C

TXF1=SIG1(M,K,2)
 TXF2=SIG2(M,K,2)
 TEMP1=SIG1(M,K,1)+SIG1(M,K,11)+BIJO1(M,K,1)+BIJO1(M,K,2)
 TEMP2=SIG2(M,K,1)+BIJO2(M,K,1)+BIJO2(M,K,2)
 TGAM1=1./TXF1/SIG1(M,K,4)
 TGAM2=1./TXF2/SIG2(M,K,4)
 TCXF1=CSIG1(M,K,2)
 TCXF2=CSIG2(M,K,2)
 CDD1=CSIG1(M,K,3)*((DJOK1(M,K,1)**2)*DIJO1(M,K,1)+
 1 (DJOK1(M,K,2)**2)*DIJO1(M,K,2))
 CDD2=CSIG2(M,K,3)*((DJOK2(M,K,1)**2)*DIJO2(M,K,1)+
 1 (DJOK2(M,K,2)**2)*DIJO2(M,K,2))

C

C

TB11(M,K)=S*TGAM1+TEMP1/TXF1
 TF1(M,K)=(1.-SUM1)/XKEFF
 TK11(M,K)=((TEMP1*TCXF1/TXF1-CSIG1(M,K,1)-CSIG1(M,K,11)-CDD1+
 1 S*(SIG1(M,K,4)*TCXF1+TXF1*CSIG1(M,K,4))*TGAM1**2)*
 2 XTFLX(1,M,K)/TXF1+CSIG1(M,K,3)*(DDOF1(M,K,1)*TFLX1(M,K,1)+
 3 DDOF1(M,K,2)*TFLX1(M,K,2))-SUM2*SRC(1,J,K)/XKEFF)*CHFO

C

DO 1800 N=1,2

```

TRI J1(M,K,N)=(-DDC1(M,K,N)/TXF1*(XTFLX(1,M,K)-TFLX1(M,K,N))+
1 BIJ01(M,K,N)*TCXFJ1(M,K,N)/(TXFJ1(M,K,N)**2)*TFLX1(M,K,N))*CHFO
TRI J2(M,K,N)=(DDC2(M,K,N)*((TFLXT(M,K,N)-TFLX1(M,K,N))/
1 TXFJ2(M,K,N)-XTFLX(2,M,K)/TXF2)-BIJ02(M,K,N)*TCXFJ2(M,K,N)/
2 (TXFJ2(M,K,N)**2)*(TFLXT(M,K,N)-TFLX1(M,K,N)))*CHFO
TZN1(M,K,N)=BIJ01(M,K,N)/TXFJ1(M,K,N)
TZN2(M,K,N)=BIJ02(M,K,N)/TXFJ2(M,K,N)

```

1800 CONTINUE

C

```

TGI(M,K)=-S*TGAM2-TEMP2/TXF2
TBI2(M,K)=TGI(M,K)-SIG1(M,K,11)/TXF1
TKI2(M,K)=((-SIG2(M,K,4)*TCXF2+TXF2*CSIG2(M,K,4))*S*TGAM2**2+
1 (CSIG2(M,K,1)-TCXF2/TXF2*TEMP2+CDD2)/TXF2)*
2 (-XTFLX(2,M,K))+(CSIG1(M,K,11)-SIG1(M,K,11)*TCXF1/
3 TXF1)*XTFLX(1,M,K)/TXF1+CSIG1(M,K,3)*(DDOF2(M,K,1)*
4 (TFLXT(M,K,1)-TFLX1(M,K,1))+DDOF2(M,K,2)*(TFLXT(M,K,2)-
5 TFLX1(M,K,2))))*CHFO

```

C

1830 CONTINUE

C

C

C

* MATRICES FORMATION, WW1, WW2, TZ1, TZ2, TWO, THREE

C

```

DO 1832 K=1, KMAX
DO 1832 J=1, KMAX
WW1(K,J)=CMPLX(0.,0.)
WW2(K,J)=CMPLX(0.,0.)
TZ1(K,J)=CMPLX(0.,0.)
TZ2(K,J)=CMPLX(0.,0.)
TWO(K,J)=CMPLX(0.,0.)
THREE(K,J)=CMPLX(0.,0.)

```

1832 CONTINUE

C

C

```

DO 1850 K=1, KMAX
KM1=K-1
KP1=K+1
DO 1850 J=1, KMAX
IF(J.NE.K) GO TO 1835
WW1(K,J)=TBI1(1,K)
WW2(K,J)=TBI2(1,K)
TZ1(K,J)=TKI1(1,K)
TZ2(K,J)=TKI2(1,K)
TWO(K,J)=TFI(1,K)
THREE(K,J)=TGI(1,K)
GO TO 1850

```

C

1835 CONTINUE

C

IF(J.EQ.KM1.OR.J.EQ.KP1) GO TO 1840

```

      GO TO 1850
1840 CONTINUE
      IF(K.EQ.1) GO TO 1842
      WW1(K,KM1)=-TZN1(1,K,1)
      WW2(K,KM1)=TZN2(1,K,1)
      TZ1(K,KM1)=TRIJ1(1,K,1)
      TZ2(K,KM1)=TRIJ2(1,K,1)
      THREE(K,KM1)=TZN2(1,K,1)
1842 IF(K.EQ.KMAX) GO TO 1850
      WW1(K,KP1)=-TZN1(1,K,2)
      WW2(K,KP1)=TZN2(1,K,2)
      TZ1(K,KP1)=TRIJ1(1,K,2)
      TZ2(K,KP1)=TRIJ2(1,K,2)
      THREE(K,KP1)=TZN2(1,K,2)
1850 CONTINUE
      GO TO 2000
1851 CONTINUE
C.....
C * ICASE = 14, TWO GROUP CHECKER BOARD, 2-D
C.....
      AOV=ANR/VOL*2./DZ
      DO 1856 I=1,IMAX
      JR=JMX(I)
      DO 1856 J=1,JR
      M=JJD(I,J)
      SUM1A=0.
      SUM1F=0.
      SUM2A=0.
      SUM2F=0.
      SUM1D=0.
      SUM1V=0.
      SUM2D=0.
      SUM2V=0.
      SUM1R=0.
      SUMSC=0.
      SUM1CA=0.
      SUM1CF=0.
      SUM2CA=0.
      SUM2CF=0.
      SUM1CD=0.
      SUM1CV=0.
      SUM2CD=0.
      SUM2CV=0.
      SUM1CR=0.
      SUMTF1=0.
      SUMTF2=0.
      SUMFX1=0.
      SUMFX2=0.
C
      DO 1852 JJ=1,6

```


SUMBT(JJ)=0.
 SUMCB1(JJ)=0.
 1852 SUMCB2(JJ)=0.

C

DO 1854 K=1,KMAX
 TFF1=XTFLX(1,M,K)
 TFF2=XTFLX(2,M,K)
 SUMFX1=SUMFX1+TFF1
 SUMFX2=SUMFX2+TFF2
 SUM1A=SUM1A+SIG1(M,K,1)*TFF1
 SUM1F=SUM1F+SIG1(M,K,2)*TFF1
 SUM1D=SUM1D+SIG1(M,K,3)*TFF1
 SUM1V=SUM1V+SIG1(M,K,4)*TFF1
 SUM1R=SUM1R+SIG1(M,K,11)*TFF1
 SUM2A=SUM2A+SIG2(M,K,1)*TFF2
 SUM2F=SUM2F+SIG2(M,K,2)*TFF2
 SUM2D=SUM2D+SIG2(M,K,3)*TFF2
 SUM2V=SUM2V+SIG2(M,K,4)*TFF2
 SUM1CA=SUM1CA+CSIG1(M,K,1)*TFF1
 SUM1CF=SUM1CF+CSIG1(M,K,2)*TFF1
 SUM1CD=SUM1CD+CSIG1(M,K,3)*TFF1
 SUM1CV=SUM1CV+CSIG1(M,K,4)*TFF1
 SUM1CR=SUM1CR+CSIG1(M,K,11)*TFF1
 SUM2CA=SUM2CA+CSIG2(M,K,1)*TFF2
 SUM2CF=SUM2CF+CSIG2(M,K,2)*TFF2
 SUM2CD=SUM2CD+CSIG2(M,K,3)*TFF2
 SUM2CV=SUM2CV+CSIG2(M,K,4)*TFF2

C

DO 1853 JJ=1,6
 JJJ=JJ+4
 SUMBT(JJ)=SUMBT(JJ)+SIG1(M,K,JJJ)*(SIG1(M,K,2)*TFF1+
 1 SIG2(M,K,2)*TFF2)
 SUMCB1(JJ)=SUMCB1(JJ)+CSIG1(M,K,JJJ)*(SIG1(M,K,2)*TFF1+
 1 SIG2(M,K,2)*TFF2)
 1853 SUMCB2(JJ)=SUMCB2(JJ)+CSIG1(M,K,2)*TFF1+CSIG2(M,K,2)*TFF2

C

SUMTF1=SUMTF1+TFF1
 SUMTF2=SUMTF2+TFF2
 SUMSC=SUMSC+SIG1(M,K,2)*TFF1+SIG2(M,K,2)*TFF2

1854 CONTINUE

C

ATFLX(M,1)=SUMFX1/FLOAT(KMAX)
 ATFLX(M,2)=SUMFX2/FLOAT(KMAX)
 XXA(M,1)=SUM1A/SUMTF1
 XXF(M,1)=SUM1F/SUMTF1
 XXD(M,1)=SUM1D/SUMTF1
 XXV(M,1)=SUM1V/SUMTF1
 XXR(M,1)=SUM1R/SUMTF1
 XXA(M,2)=SUM2A/SUMTF2
 XXF(M,2)=SUM2F/SUMTF2

```

XXD(M,2)=SUM2D/SUMTF2
XXV(M,2)=SUM2V/SUMTF2
CXXA(M,1)=SUM1CA/SUMTF1
CXXF(M,1)=SUM1CF/SUMTF1
CXXD(M,1)=SUM1CD/SUMTF1
CXXV(M,1)=SUM1CV/SUMTF1
CXXR(M,1)=SUM1CR/SUMTF1
CXXA(M,2)=SUM2CA/SUMTF2
CXXF(M,2)=SUM2CF/SUMTF2
CXXD(M,2)=SUM2CD/SUMTF2
CXXV(M,2)=SUM2CV/SUMTF2

```

C

```

DO 1855 JJ=1,6
PBET(M,JJ)=SUMBT(JJ)/SUMSC
1855 CBET(M,JJ)=(SUMCB1(JJ)-PBET(M,JJ)*SUMCB2(JJ))/SUMSC
1856 CONTINUE

```

C

```

DO 1880 I=1,IMAX
JR=JMX(I)
IF(I.EQ.1) IPR=2
IF(I.EQ.2) IPR=1
DO 1880 J=1,JR
IF(J.EQ.1) JPR=2
IF(J.EQ.2) JPR=1
SUM1=CMPLX(0.,0.)
SUM2=SUM1
M=JJD(I,J)
MIPR=JJD(IPR,J)
MJPR=JJD(I,JPR)
BIJ01(M,1,1)=AOV*XXD(M,1)*XXD(MIPR,1)/(XXD(M,1)+XXD(MIPR,1))
BIJ02(M,1,1)=AOV*XXD(M,2)*XXD(MIPR,2)/(XXD(M,2)+XXD(MIPR,2))
BIJ01(M,1,2)=AOV*XXD(M,1)*XXD(MJPR,1)/(XXD(M,1)+XXD(MJPR,1))
BIJ02(M,1,2)=AOV*XXD(M,2)*XXD(MJPR,2)/(XXD(M,2)+XXD(MJPR,2))
DJOK1(M,1,1)=XXD(MIPR,1)
DJOK2(M,1,1)=XXD(MIPR,2)
DJOK1(M,1,2)=XXD(MJPR,1)
DJOK2(M,1,2)=XXD(MJPR,2)
DIJ01(M,1,1)=AOV/(XXD(M,1)+XXD(MIPR,1))**2
DIJ02(M,1,1)=AOV/(XXD(M,2)+XXD(MIPR,2))**2
DIJ01(M,1,2)=AOV/(XXD(M,1)+XXD(MJPR,1))**2
DIJ02(M,1,2)=AOV/(XXD(M,2)+XXD(MJPR,2))**2
DDOF1(M,1,1)=(DJOK1(M,1,1)**2)*DIJ01(M,1,1)/XXF(MIPR,1)
DDOF2(M,1,1)=(DJOK2(M,1,1)**2)*DIJ02(M,1,1)/XXF(MIPR,2)
DDOF1(M,1,2)=(DJOK1(M,1,2)**2)*DIJ01(M,1,2)/XXF(MJPR,1)
DDOF2(M,1,2)=(DJOK2(M,1,2)**2)*DIJ02(M,1,2)/XXF(MJPR,2)
DDC1(M,1,1)=(XXD(M,1)**2)*DIJ01(M,1,1)*CXXD(MIPR,1)
DDC2(M,1,1)=(XXD(M,2)**2)*DIJ02(M,1,1)*CXXD(MIPR,2)
DDC1(M,1,2)=(XXD(M,1)**2)*DIJ01(M,1,2)*CXXD(MJPR,1)
DDC2(M,1,2)=(XXD(M,2)**2)*DIJ02(M,1,2)*CXXD(MJPR,2)
TXFJ1(M,1,1)=XXF(MIPR,1)

```

```

TXFJ2(M,1,1)=XXF(MIPR,2)
TXFJ1(M,1,2)=XXF(MJPR,1)
TXFJ2(M,1,2)=XXF(MJPR,2)
TCXFJ1(M,1,1)=CXXF(MIPR,1)
TCXFJ2(M,1,1)=CXXF(MIPR,2)
TCXFJ1(M,1,2)=CXXF(MJPR,1)
TCXFJ2(M,1,2)=CXXF(MJPR,2)
TFLX1(M,1,1)=ATFLX(MIPR,1)
TFLX1(M,1,2)=ATFLX(MJPR,1)
TFLXT(M,1,1)=ASRC(I,PR,J)
TFLXT(M,1,2)=ASRC(I,J,PR)
TXF1=XXF(M,1)
TXF2=XXF(M,2)
TEMP1=XXA(M,1)+XXR(M,1)+2.*(BIJ01(M,1,1)+BIJ01(M,1,2))
TEMP2=XXA(M,2)+2.*(BIJ02(M,1,1)+BIJ02(M,1,2))
TGAM1=1./TXF1/XXV(M,1)
TGAM2=1./TXF2/XXV(M,2)
TCXF1=CXXF(M,1)
TCXF2=CXXF(M,2)
CDD1=CXXD(M,1)*2.*((DJOK1(M,1,1)**2)*DIJ01(M,1,1)+
1 (DJOK1(M,1,2)**2)*DIJ01(M,1,2))
CDD2=CXXD(M,2)*2.*((DJOK2(M,1,1)**2)*DIJ02(M,1,1)+
1 (DJOK2(M,1,2)**2)*DIJ02(M,1,2))
C
DO 1870 JJ=1,6
SUM1=SUM1+S*PBET(M,JJ)/(S+PLAMDA(JJ))
1870 SUM2=SUM2+S*CBET(M,JJ)/(S+PLAMDA(JJ))
C
C
TBI1(M,1)=S*TGAM1+TEMP1/TXF1
TFI(M,1)=(1.-SUM1)/XKEFF
TKI1(M,1)=((TEMP1*TCXF1/TXF1-CXXA(M,1)-CXXR(M,1)-CDD1+
1 S*(XXV(M,1)*TCXF1+TXF1*CXXV(M,1))*TGAM1**2)*
2 ATFLX(M,1)/TXF1+CXXD(M,1)*2.*(DDOF1(M,1,1)*TFLX1(M,1,1)+
3 DDOF1(M,1,2)*TFLX1(M,1,2))-SUM2*ASRC(I,J)/XKEFF)*CHFO
C
DO 1872 N=1,2
TRI1(M,1,N)=(-DDC1(M,1,N)/TXF1*(ATFLX(M,1)-TFLX1(M,1,N))+
1 BIJ01(M,1,N)*TCXFJ1(M,1,N)/(TXFJ1(M,1,N)**2)*TFLX1(M,1,N))*CHFO
TRI2(M,1,N)=(DDC2(M,1,N)*((TFLXT(M,1,N)-TFLX1(M,1,N))/
1 TXFJ2(M,1,N)-ATFLX(M,2)/TXF2)-BIJ02(M,1,N)*TCXFJ2(M,1,N)/
2 (TXFJ2(M,1,N)**2)*((TFLXT(M,1,N)-TFLX1(M,1,N))*CHFO
TZN1(M,1,N)=BIJ01(M,1,N)/TXFJ1(M,1,N)
TZN2(M,1,N)=BIJ02(M,1,N)/TXFJ2(M,1,N)
1872 CONTINUE
C
TGI(M,1)=-S*TGAM2-TEMP2/TXF2
TBI2(M,1)=TGI(M,1)-XXR(M,1)/TXF1
TKI2(M,1)=((-XXV(M,2)*TCXF2+TXF2*CXXV(M,2))*S*TGAM2**2+
1 (CXXA(M,2)-TCXF2/TXF2*TEMP2+CDD2)/TXF2)*

```

```

2      (-ATFLX(M,2))+(CXXR(M,1)-XXR(M,1)*TCXF1/
3      TXF1)*ATFLX(M,1)/TXF1+CXXD(M,1)*2.*(DDOF2(M,1,1)*
4      (TFLXT(M,1,1)-TFLX1(M,1,1))+DDOF2(M,1,2)*(TFLXT(M,1,2)-
5      TFLX1(M,1,2)))*CHFO

```

C
1880 CONTINUE

C
C

```

DO 1890 K=1,4
DO 1890 J=1,4
WW1(J,K)=CMPLX(0.,0.)
WW2(J,K)=CMPLX(0.,0.)
TZ1(J,K)=CMPLX(0.,0.)
TZ2(J,K)=CMPLX(0.,0.)
TWO(J,K)=CMPLX(0.,0.)
THREE(J,K)=CMPLX(0.,0.)

```

1890 CONTINUE

C

```

DO 1895 K=1,4
DO 1895 J=1,4
IF(J.NE.K) GO TO 1895
WW1(K,J)=TB11(K,1)
WW2(K,J)=TB12(K,1)
TZ1(K,J)=TK11(K,1)
TZ2(K,J)=TK12(K,1)
TWO(K,J)=TF1(K,1)
THREE(K,J)=TG1(K,1)

```

1895 CONTINUE

C

```

WW1(1,2)=-2.*TZN1(1,1,2)
WW2(1,2)=2.*TZN2(1,1,2)
TZ1(1,2)=2.*TRI1(1,1,2)
TZ2(1,2)=2.*TRI2(1,1,2)
THREE(1,2)=2.*TZN2(1,1,2)

```

C

```

WW1(1,3)=-2.*TZN1(1,1,1)
WW2(1,3)=2.*TZN2(1,1,1)
TZ1(1,3)=2.*TRI1(1,1,1)
TZ2(1,3)=2.*TRI2(1,1,1)
THREE(1,3)=2.*TZN2(1,1,1)

```

C

```

WW1(2,1)=-2.*TZN1(2,1,2)
WW2(2,1)=2.*TZN2(2,1,2)
TZ1(2,1)=2.*TRI1(2,1,2)
TZ2(2,1)=2.*TRI2(2,1,2)
THREE(2,1)=2.*TZN2(2,1,2)

```

C

```

WW1(2,4)=-2.*TZN1(2,1,1)
WW2(2,4)=2.*TZN2(2,1,1)
TZ1(2,4)=2.*TRI1(2,1,1)

```

```

      TZ2(2,4)=2.*TRIJ2(2,1,1)
      THREE(2,4)=2.*TZN2(2,1,1)
C
      WW1(3,1)=-2.*TZN1(3,1,1)
      WW2(3,1)=2.*TZN2(3,1,1)
      TZ1(3,1)=2.*TRIJ1(3,1,1)
      TZ2(3,1)=2.*TRIJ2(3,1,1)
      THREE(3,1)=2.*TZN2(3,1,1)
C
      WW1(3,4)=-2.*TZN1(3,1,2)
      WW2(3,4)=2.*TZN2(3,1,2)
      TZ1(3,4)=2.*TRIJ1(3,1,2)
      TZ2(3,4)=2.*TRIJ2(3,1,2)
      THREE(3,4)=2.*TZN2(3,1,2)
C
      WW1(4,2)=-2.*TZN1(4,1,1)
      WW2(4,2)=2.*TZN2(4,1,1)
      TZ1(4,2)=2.*TRIJ1(4,1,1)
      TZ2(4,2)=2.*TRIJ2(4,1,1)
      THREE(4,2)=2.*TZN2(4,1,1)
C
      WW1(4,3)=-2.*TZN1(4,1,2)
      WW2(4,3)=2.*TZN2(4,1,2)
      TZ1(4,3)=2.*TRIJ1(4,1,2)
      TZ2(4,3)=2.*TRIJ2(4,1,2)
      THREE(4,3)=2.*TZN2(4,1,2)
C
C
C 2000 CONTINUE
C
      RETURN
      END
C
C
C
C *****
      SUBROUTINE OPENTF(S,RATIO,NCH1,ICOUNT)
C *****
C
C *** CALCULATE OPEN-LOOP TRANSFER FUNCTION ***
C *** S = FREQUENCY
C *** RATIO = OPEN-LOOP TRANSFER FUNCTION
C
C
      COMPLEX S,RATIO,DD(30,30),FINV(30,30),DUMMY(30,30),
1      FF(30,30),XL(30,30),F11(30,30),A(30,30),XT(30,30)
      COMPLEX FALF,RANI,GANM,ZNI,BI,RKI,XZNI,XBM,XRKM,F1
      COMPLEX THEOT,APIP(15,200),XUM(15),XUML,TGAM1,TPI1,
1      ZL(200,5),AX(200,5),DENO,DENO1,XYZ,Y4,A11,AIP1,AIP2,
2      AIP4,FG(100),CFP

```

```

COMPLEX DQ(200),TQ,YP(200),Y(200),AP(30)
COMPLEX EE(30,30),WWZ(30,30)
COMPLEX CWW1(30,30),CWW2(30,30),CTZ1(30,30),CTWO(30,30)
COMPLEX WW1,WW2,TZ1,TZ2,TWO,THREE,WINV(30,30),WWT(30,30)
COMMON/SIM1/IMAX,JMAX,KMAX,ICASE,ISPEC,JSPEC,INUCLR,XKEFF
COMMON/SIM2/JMX(20),NFT(15,15,30),AL(15,15),TAL(15,15),
1      BAL(15,15),ASRC(15,15),SRC(15,15,30),AEXP(15,15),
2      REXP(15,15,30),AXSRC(30),XXSRC(30)
COMMON/SIM3/JJD(15,15),DZ1(200),DZ2(200),NF(200,30),NB(200),
1      SC(200,30,6),XEXP(200,30),SIG1(200,30,11),
2      CSIG1(200,30,11)
COMMON/KIN2/RDF(15,15),RCDF(15,15),RANO1(200,4),ADF(30),
1      ACDF(30),GANOM(200,30,6),CFP
COMMON/KIN3/RAN1(200,4),GANM(200,30,6),ZNI(200,4),B1(200)
COMMON/KIN5/RK1(200),XZNI(200,30,6),XBM(200,30),XRKM(200,30)
COMMON/CONST2/ P,VCH,VIN(200),AXS(200),DH(200),DHIN(200),
1      PH(200),TIN,TSATP,ENTHT,DENSI,SIGM,ENTHP,VISC,CPF,KF,
2      DENSF,VFG1,RHOG,GO(200),GO2(200),HO(200),GC,G1,KLOSS(30),
3      FRICMO(200),VGJH(200,30),COH(200,30),CZERO,VGJ,DPTS,
4      GO2RF(200),HFG1,ZSP(30),NUMBSP(200,30),ALHEAT,CXF(200),
5      AVEQ,CHOM01,CHOM02,XKIN(200),XKEXIT(200)
COMMON/CONSS1/QDIS(200,30),QO(200,30),DZ(200,30),Z(200,30),
1      K1(200,30),CKIN(200,30),ZETA(200,30),DOIN(200,30),
2      DOOUT(200,30),ALPIN(200,30),BEE(200,30),CP11(200,30),
3      COR2PH(200,30),ZETSP(200,30),WIN
COMMON/VOIDPT/FALF(200,30),F1(200),TGAM1(200),TP11(200)
COMMON/TWOG2/WW1(100,100),WW2(100,100),TZ1(100,100),
1      TZ2(100,100),TWO(100,100),THREE(100,100)

```

C
C

```

KKMAX=KMAX
IF(ICASE.EQ.14) KKMAX=4
MM=KKMAX+1
TC=CMPLX(0.,0.)
IF(ICASE.EQ.4) GO TO 1199
IF(ICASE.EQ.8) GO TO 400
IF(ICASE.EQ.10) GO TO 300
IF(ICASE.EQ.13.OR.ICASE.EQ.14.OR.ICASE.EQ.15) GO TO 1500
IF(ICASE.EQ.5) M=JJD(ISPEC,JSPEC)
IF(ICASE.EQ.6) M=NCH1

```

C

```

DO 30 K=1,KMAX
KP1=K+1
F11(K,1)=FALF(M,K)
C11=CABS(FALF(M,KP1))
IF(C11.NE.0.) F11(K,1)=FALF(M,KP1)
A(1,K)=1./FLOAT(KMAX)
DO 30 J=1,KMAX
FF(J,K)=CMPLX(0.,0.)
XL(J,K)=CMPLX(0.,0.)

```

30 CONTINUE

C

```
DO 60 K=1, KMAX
  FF(K,K)=B1(K)
  KM1=K-1
  KP1=K+1
  IF(K.EQ.1) GO TO 35
  IF(K.EQ.KMAX) GO TO 40
  IF(ICASE.EQ.6) GO TO 33
  FF(K,KM1)=-GANM(M,K,1)
  FF(K,KP1)=-GANM(M,K,2)
  XL(K,K)=(RK1(K)*SRC(1SPEC,JSPEC,K)+CSIG1(M,K,3)/SIG1(M,K,3)*
1    (GANOM(M,K,1)*SRC(1SPEC,JSPEC,KM1)+
2    GANOM(M,K,2)*SRC(1SPEC,JSPEC,KP1)))*AVEQ
  XL(K,KM1)=-ZNI(K,1)*SRC(1SPEC,JSPEC,KM1)*AVEQ
  XL(K,KP1)=-ZNI(K,2)*SRC(1SPEC,JSPEC,KP1)*AVEQ
  GO TO 60
33 FF(K,KM1)=-RANI(K,1)
  FF(K,KP1)=-RANI(K,2)
  XL(K,K)=(RK1(K)*AXSRC(K)+ACDF(K)/ADF(K)*
1    (RANO1(K,1)*AXSRC(KM1)+RANO1(K,2)*AXSRC(KP1)))*
2    AVEQ
  XL(K,KM1)=-ZNI(K,1)*AXSRC(KM1)*AVEQ
  XL(K,KP1)=-ZNI(K,2)*AXSRC(KP1)*AVEQ
  GO TO 60
35 CONTINUE
  IF(ICASE.EQ.6) GO TO 38
  FF(K,KP1)=-GANM(M,K,2)
  XL(K,K)=(RK1(K)*SRC(1SPEC,JSPEC,K)+CSIG1(M,K,3)/SIG1(M,K,3)*
1    GANOM(M,K,2)*SRC(1SPEC,JSPEC,KP1))*AVEQ
  XL(K,KP1)=-ZNI(K,2)*SRC(1SPEC,JSPEC,KP1)*AVEQ
  GO TO 60
38 FF(K,KP1)=-RANI(K,2)
  XL(K,K)=(RK1(K)*AXSRC(K)+ACDF(K)/ADF(K)*
1    RANO1(K,2)*AXSRC(KP1))*AVEQ
  XL(K,KP1)=-ZNI(K,2)*AXSRC(KP1)*AVEQ
  GO TO 60
40 CONTINUE
  IF(ICASE.EQ.6) GO TO 50
  FF(K,KM1)=-GANM(M,K,1)
  XL(K,K)=(RK1(K)*SRC(1SPEC,JSPEC,K)+CSIG1(M,K,3)/SIG1(M,K,3)*
1    GANOM(M,K,1)*SRC(1SPEC,JSPEC,KM1))*AVEQ
  XL(K,KM1)=-ZNI(K,1)*SRC(1SPEC,JSPEC,KM1)*AVEQ
  GO TO 60
50 FF(K,KM1)=-RANI(K,1)
  XL(K,K)=(RK1(K)*AXSRC(K)+ACDF(K)/ADF(K)*
1    RANO1(K,1)*AXSRC(KM1))*AVEQ
  XL(K,KM1)=-ZNI(K,1)*AXSRC(KM1)*AVEQ
60 CONTINUE
DO 61 K=1, KMAX
```

```

      DO 61 J=1, KMAX
      XL(K, J) = CFP*XL(K, J)
61  CONTINUE
C
      WRITE(8, 620)
      DO 80 K=1, KMAX
      KM1=K-1
      KP1=K+1
      IF(K.EQ.1) GO TO 73
      IF(K.EQ.KMAX) GO TO 75
      WRITE(8, 660) K, XL(K, KM1), XL(K, K), XL(K, KP1), F11(K, 1)
      GO TO 80
73  WRITE(8, 670) K, XL(K, K), XL(K, KP1), F11(K, 1)
      GO TO 80
75  WRITE(8, 680) K, XL(K, KM1), XL(K, K), F11(K, 1)
80  CONTINUE
C
620  FORMAT(/, 5X, 'K ', 8X, 'XL(K, KM1)', 16X, 'XL(K, K)', 16X,
1      'XL(K, KP1)', 16X, 'F11(1, K)'/)
660  FORMAT(5X, 12, 8E12.5)
670  FORMAT(5X, 12, 24X, 6E12.5)
680  FORMAT(5X, 12, 4E12.5, 24X, 2E12.5)
C
      DO 260 K=1, KMAX
      KM1=K-1
      KP1=K+1
      IF(K.EQ.1) GO TO 250
      IF(K.EQ.KMAX) GO TO 255
      Y(K)=XL(K, KM1)*F11(KM1, 1)+XL(K, K)*F11(K, 1)+XL(K, KP1)*F11(KP1, 1)
      YP(K)=(YP(KM1)*FF(K, KM1)-Y(K))/(AP(KM1)*FF(K, KM1)-FF(K, K))
      AP(K)=-FF(K, KP1)/(AP(KM1)*FF(K, KM1)-FF(K, K))
      GO TO 260
250  Y(1)=XL(1, 1)*F11(1, 1)+XL(1, 2)*F11(2, 1)
      YP(1)=Y(1)/FF(1, 1)
      AP(1)=FF(1, 2)/FF(1, 1)
      GO TO 260
255  Y(K)=XL(K, K)*F11(K, 1)+FF(K, KM1)*F11(KM1, 1)
      YP(K)=(YP(KM1)*FF(K, KM1)-Y(K))/(AP(KM1)*FF(K, KM1)-FF(K, K))
      DQ(K)=YP(K)
260  CONTINUE
C
C
      AP(KMAX)=CMPLX(0., 0.)
      TQ=CMPLX(0., 0.)
      DO 280 K=1, KMAX
      KI=KMAX-K
      KIP1=KI+1
      IF(KI.EQ.0) GO TO 280
      DQ(KI)=YP(KI)-AP(KI)*DQ(KIP1)
280  CONTINUE

```



```

C
DO 290 K=1,KMAX
TQ=TQ+DQ(K)*A(1,K)
290 CONTINUE
GO TO 2000
300 CONTINUE
C
C.....
C ***** ICASE = 11, RADIAL COUPLING(2-D) *****
C ***** CHECKER BOARD PROBLEM ONLY *****
C.....
DO 303 N=1,4
303 FG(N)=F1(N)
C
DO 320 I=1,IMAX
IPR=I+1
JR=JMX(I)
IF(I.EQ.IMAX) IPR=I-1
DO 320 J=1,JR
JPR=J+1
IF(J.EQ.JR) JPR=J-1
M=JJD(I,J)
AX(M,M)=BI(M)
C
ANOMQ=(RANOI(M,1)+RANOI(M,3))*ASRC(IPR,J)+(RANOI(M,2)+
1 RANOI(M,4))*ASRC(I,JPR)
ZL(M,M)=(RKI(M)*ASRC(I,J)+RCDF(I,J)/RDF(I,J)*ANOMQ)*AVEQ
C
DO 310 MM=1,4
IF(MM.EQ.M) GO TO 310
MPMM=M+MM
IF(MPMM.EQ.3.OR.MPMM.EQ.7) GO TO 305
IF(MPMM.EQ.5) GO TO 308
AX(M,MM)=-RANI(M,1)-RANI(M,3)
ZL(M,MM)=(-ZNI(M,1)-ZNI(M,3))*ASRC(IPR,J)
GO TO 310
305 AX(M,MM)=-RANI(M,2)-RANI(M,4)
ZL(M,MM)=(-ZNI(M,2)-ZNI(M,4))*ASRC(I,JPR)
GO TO 310
308 AX(M,MM)=CMPLX(0.,0.)
ZL(M,MM)=CMPLX(0.,0.)
310 CONTINUE
DO 311 MM=1,4
ZL(M,MM) = CFP*ZL(M,MM)
311 CONTINUE
C
Y(M)=ZL(M,1)*F1(1)+ZL(M,2)*F1(2)+ZL(M,3)*F1(3)+ZL(M,4)*F1(4)
320 CONTINUE
C
C

```

```

      APIP(1,1)=AX(1,2)/AX(1,1)
      APIP(2,1)=AX(1,3)/AX(1,1)
      YP(1)=Y(1)/AX(1,1)
C
      DENO=APIP(1,1)*AX(2,1)-AX(2,2)
      APIP(1,2)=AX(2,1)*APIP(2,1)/DENO
      APIP(2,2)=-AX(2,4)/DENO
      YP(2)=(YP(1)*AX(2,1)-Y(2))/DENO
C
      DENO=APIP(1,1)*APIP(1,2)*AX(3,1)-APIP(2,1)*AX(3,1)+AX(3,3)
      APIP(1,3)=(APIP(1,1)*APIP(2,2)*AX(3,1)+AX(3,4))/DENO
      YP(3)=(APIP(1,1)*AX(3,1)*YP(2)-AX(3,1)*YP(1)+Y(3))/DENO
C
      DENO=APIP(1,2)*AX(4,2)-AX(4,3)
      DQ(4)=(YP(3)*DENO-YP(2)*AX(4,2)+Y(4))/(APIP(1,3)*DENO-
1      APIP(2,2)*AX(4,2)+AX(4,4))
      DQ(3)=YP(3)-DQ(4)*APIP(1,3)
      DQ(2)=YP(2)-DQ(3)*APIP(1,2)-DQ(4)*APIP(2,2)
      DQ(1)=YP(1)-DQ(2)*APIP(1,1)-DQ(3)*APIP(2,1)
      TQ=(DQ(1)+DQ(2)+DQ(3)+DQ(4))/4.
C
      GO TO 2000
400 CONTINUE
C
C.....
C * ICASE = 8 , 3D COUPLED KINETICS TRANSFER FUNCTION
C CHECKER-BOARD PROBLEM ONLY
C.....
      DO 450 K=1,KMAX
      KM1=K-1
      DO 450 I=1,IMAX
      JR=JMX(I)
      DO 450 J=1,JR
      M=JJD(I,J)
      ANOMQ=0.
      MT=M+KM1*4
      FG(MT)=FALF(M,K)
      DO 402 N=1,6
402 ANOMQ=ANOMQ+GANOM(M,K,N)*SC(M,K,N)
C
      IF(K.EQ.1) GO TO 420
      AX(MT,5)=CMPLX(0.,0.)
      AX(MT,1)=-GANM(M,K,5)
      ZL(MT,5)=CMPLX(0.,0.)
      ZL(MT,1)=-XZNI(M,K,5)*SC(M,K,5)*AVEQ
      IF(K.NE.KMAX) GO TO 404
      GO TO 405
404 AX(MT,5)=-GANM(M,K,6)
      ZL(MT,5)=-XZNI(M,K,6)*SC(M,K,6)*AVEQ
405 IF(I.EQ.1.AND.J.EQ.1) GO TO 407

```

IF(I.EQ.1.AND.J.EQ.2) GO TO 410
IF(I.EQ.2.AND.J.EQ.1) GO TO 415

C
AX(MT,2)=-GANM(M,K,1)-GANM(M,K,3)
ZL(MT,2)=(-XZNI(M,K,1)*SC(M,K,1)-XZNI(M,K,3)*SC(M,K,3))*AVEQ
AX(MT,3)=-GANM(M,K,2)-GANM(M,K,4)
ZL(MT,3)=(-XZNI(M,K,2)*SC(M,K,2)-XZNI(M,K,4)*SC(M,K,4))*AVEQ
AX(MT,4)=XBM(M,K)
ZL(MT,4)=(XRKM(M,K)*SRC(I,J,K)+CSIG1(M,K,3)/SIG1(M,K,3)*
1 ANOMQ)*AVEQ
GO TO 450

C
407 AX(MT,4)=-GANM(M,K,1)-GANM(M,K,3)
ZL(MT,4)=(-XZNI(M,K,1)*SC(M,K,1)-XZNI(M,K,3)*SC(M,K,3))*AVEQ
AX(MT,3)=-GANM(M,K,2)-GANM(M,K,4)
ZL(MT,3)=(-XZNI(M,K,2)*SC(M,K,2)-XZNI(M,K,4)*SC(M,K,4))*AVEQ
AX(MT,2)=XBM(M,K)
ZL(MT,2)=(XRKM(M,K)*SRC(I,J,K)+CSIG1(M,K,3)/SIG1(M,K,3)*
1 ANOMQ)*AVEQ
GO TO 450

C
410 AX(MT,4)=-GANM(M,K,1)-GANM(M,K,3)
ZL(MT,4)=(-XZNI(M,K,1)*SC(M,K,1)-XZNI(M,K,3)*SC(M,K,3))*AVEQ
AX(MT,2)=-GANM(M,K,2)-GANM(M,K,4)
ZL(MT,2)=(-XZNI(M,K,2)*SC(M,K,2)-XZNI(M,K,4)*SC(M,K,4))*AVEQ
AX(MT,3)=XBM(M,K)
ZL(MT,3)=(XRKM(M,K)*SRC(I,J,K)+CSIG1(M,K,3)/SIG1(M,K,3)*
1 ANOMQ)*AVEQ
GO TO 450

C
415 AX(MT,2)=-GANM(M,K,1)-GANM(M,K,3)
ZL(MT,2)=(-XZNI(M,K,1)*SC(M,K,1)-XZNI(M,K,3)*SC(M,K,3))*AVEQ
AX(MT,4)=-GANM(M,K,2)-GANM(M,K,4)
ZL(MT,4)=(-XZNI(M,K,2)*SC(M,K,2)-XZNI(M,K,4)*SC(M,K,4))*AVEQ
AX(MT,3)=XBM(M,K)
ZL(MT,3)=(XRKM(M,K)*SRC(I,J,K)+CSIG1(M,K,3)/SIG1(M,K,3)*
1 ANOMQ)*AVEQ
GO TO 450

C
420 CONTINUE
AX(MT,5)=-GANM(M,K,6)
ZL(MT,5)=-XZNI(M,K,6)*SC(M,K,6)*AVEQ
IF(I.EQ.1.AND.J.EQ.1) GO TO 425
IF(I.EQ.1.AND.J.EQ.2) GO TO 430
IF(I.EQ.2.AND.J.EQ.1) GO TO 435

C
AX(MT,1)=CMPLX(0.,0.)
ZL(MT,1)=CMPLX(0.,0.)

C
AX(MT,2)=-GANM(M,K,1)-GANM(M,K,3)

```

ZL(MT,2)=(-XZNI(M,K,1)*SC(M,K,1)-XZNI(M,K,3)*SC(M,K,3))*AVEQ
AX(MT,3)=-GANM(M,K,2)-GANM(M,K,4)
ZL(MT,3)=(-XZNI(M,K,2)*SC(M,K,2)-XZNI(M,K,4)*SC(M,K,4))*AVEQ
AX(MT,4)=XBM(M,K)
ZL(MT,4)=(XRKM(M,K)*SRC(I,J,K)+CSIG1(M,K,3)/SIG1(M,K,3))*
1 ANOMQ)*AVEQ
GO TO 450

```

C

```

425 AX(MT,3)=-GANM(M,K,1)-GANM(M,K,3)
ZL(MT,3)=(-XZNI(M,K,1)*SC(M,K,1)-XZNI(M,K,3)*SC(M,K,3))*AVEQ
AX(MT,2)=-GANM(M,K,2)-GANM(M,K,4)
ZL(MT,2)=(-XZNI(M,K,2)*SC(M,K,2)-XZNI(M,K,4)*SC(M,K,4))*AVEQ
AX(MT,1)=XBM(M,K)
ZL(MT,1)=(XRKM(M,K)*SRC(I,J,K)+CSIG1(M,K,3)/SIG1(M,K,3))*
1 ANOMQ)*AVEQ
AX(MT,4)=CMPLX(0.,0.)
ZL(MT,4)=CMPLX(0.,0.)
GO TO 450
430 AX(MT,4)=-GANM(M,K,1)-GANM(M,K,3)
ZL(MT,4)=(-XZNI(M,K,1)*SC(M,K,1)-XZNI(M,K,3)*SC(M,K,3))*AVEQ
AX(MT,1)=-GANM(M,K,2)-GANM(M,K,4)
ZL(MT,1)=(-XZNI(M,K,2)*SC(M,K,2)-XZNI(M,K,4)*SC(M,K,4))*AVEQ
AX(MT,2)=XBM(M,K)
ZL(MT,2)=(XRKM(M,K)*SRC(I,J,K)+CSIG1(M,K,3)/SIG1(M,K,3))*
1 ANOMQ)*AVEQ
AX(MT,3)=CMPLX(0.,0.)
ZL(MT,3)=CMPLX(0.,0.)
GO TO 450

```

C

```

435 AX(MT,1)=-GANM(M,K,1)-GANM(M,K,3)
ZL(MT,1)=(-XZNI(M,K,1)*SC(M,K,1)-XZNI(M,K,3)*SC(M,K,3))*AVEQ
AX(MT,4)=-GANM(M,K,2)-GANM(M,K,4)
ZL(MT,4)=(-XZNI(M,K,2)*SC(M,K,2)-XZNI(M,K,4)*SC(M,K,4))*AVEQ
AX(MT,3)=XBM(M,K)
ZL(MT,3)=(XRKM(M,K)*SRC(I,J,K)+CSIG1(M,K,3)/SIG1(M,K,3))*
1 ANOMQ)*AVEQ
AX(MT,2)=CMPLX(0.,0.)
ZL(MT,2)=CMPLX(0.,0.)
450 CONTINUE
DO 451 M=1,MT
DO 451 J=1,5
ZL(M,J) = CFP*ZL(M,J)
451 CONTINUE

```

C
C

```

DO 460 K=1,KMAX
KM1=K-1
DO 460 I=1,IMAX
JR=JMX(I)
DO 460 J=1,JR

```

```

M=JJD(1,J)
MT=M+KM1*4
MTP4=MT+4
IF(K.NE.1) GO TO 453
Y(MT)=ZL(MT,1)*FG(1) + ZL(MT,2)*FG(2) + ZL(MT,3)*FG(3) +
1 ZL(MT,4)*FG(4) + ZL(MT,5)*FG(MTP4)
GO TO 460

```

```

C
453 CONTINUE
MTP1=MT+1
MTM1=MT-1
MTP2=MT+2
MTM2=MT-2
MTM4=MT-4

```

```

C
IF(1.EQ.1.AND.J.EQ.1) THEOT=ZL(MT,2)*FG(MT)+ZL(MT,3)*FG(MTP1)+
1 ZL(MT,4)*FG(MTP2)
IF(1.EQ.1.AND.J.EQ.2) THEOT=ZL(MT,2)*FG(MTM1)+ZL(MT,3)*FG(MT)+
1 ZL(MT,4)*FG(MTP2)
IF(1.EQ.2.AND.J.EQ.1) THEOT=ZL(MT,2)*FG(MTM2)+ZL(MT,3)*FG(MT)+
1 ZL(MT,4)*FG(MTP1)
IF(1.EQ.2.AND.J.EQ.2) THEOT=ZL(MT,2)*FG(MTM2)+ZL(MT,3)*
1 FG(MTM1)+ZL(MT,4)*FG(MT)

```

```

C
Y(MT)=ZL(MT,1)*FG(MTM4)+ZL(MT,5)*FG(MTP4)+THEOT
460 CONTINUE

```

```

C
C
APIP(1,1)=AX(1,2)/AX(1,1)
APIP(2,1)=AX(1,3)/AX(1,1)
APIP(3,1)=CMPLX(0.,0.)
APIP(4,1)=AX(1,5)/AX(1,1)
YP(1)=Y(1)/AX(1,1)

```

```

C
DENO=APIP(1,1)*AX(2,1) - AX(2,2)
APIP(1,2)=APIP(2,1)*AX(2,1)/DENO
APIP(2,2)=-AX(2,4)/DENO
APIP(3,2)=APIP(4,1)*AX(2,1)/DENO
APIP(4,2)=-AX(2,5)/DENO
YP(2)=(YP(1)*AX(2,1)-Y(2))/DENO

```

```

C
DENO=(APIP(1,1)*APIP(1,2)-APIP(2,1))*AX(3,1)+AX(3,3)
APIP(1,3)=(APIP(1,1)*APIP(2,2)*AX(3,1)+AX(3,4))/DENO
APIP(2,3)=(APIP(1,1)*APIP(3,2)-APIP(4,1))*AX(3,1)/DENO
APIP(3,3)=APIP(1,1)*APIP(4,2)*AX(3,1)/DENO
APIP(4,3)=AX(3,5)/DENO
YP(3)=((YP(2)*APIP(1,1)-YP(1))*AX(3,1)+Y(3))/DENO

```

```

C
DENO=APIP(1,3)*(APIP(1,2)*AX(4,2)-AX(4,3))-APIP(2,2)*AX(4,2)+
1 AX(4,4)

```

```

    APIP(1,4)=(APIP(2,3)*(APIP(1,2)*AX(4,2)-AX(4,3))-APIP(3,2)*
1    AX(4,2))/DENO
    APIP(2,4)=(APIP(3,3)*(APIP(1,2)*AX(4,2)-AX(4,3))-APIP(4,2)*
1    AX(4,2))/DENO
    APIP(3,4)=APIP(4,3)*(APIP(1,2)*AX(4,2)-AX(4,3))/DENO
    APIP(4,4)=AX(4,5)/DENO
    YP(4)=(YP(3)*(APIP(1,2)*AX(4,2)-AX(4,3))-YP(2)*AX(4,2)+Y(4))/
1    DENO

```

C
C

```

DO 490 K=2, KMAX
KM1=K-1
DO 490 I=1, IMAX
JR=JMX(I)
DO 490 J=1, JR
M=JJD(I,J)
MT=M+KM1*4
MTM1=MT-1
MTM2=MT-2
MTM3=MT-3
MTM4=MT-4
XYZ=APIP(1,MTM4)*APIP(1,MTM3)-APIP(2,MTM4)
IF(I.EQ.1.AND.J.EQ.2) GO TO 463
IF(I.EQ.2.AND.J.EQ.1) GO TO 467
IF(I.EQ.2.AND.J.EQ.2) GO TO 471

```

C

```

    DENO=APIP(1,MTM2)*XYZ-APIP(1,MTM4)*APIP(2,MTM3)+APIP(3,MTM4)-
    APIP(4,MTM2)*XYZ-APIP(1,MTM4)*APIP(3,MTM3)+APIP(4,MTM4)-
1    AX(MT,2)/AX(MT,1))/DENO
    AIP1=(APIP(3,MTM2)*XYZ-APIP(1,MTM4)*APIP(4,MTM3)-AX(MT,3)/
1    AX(MT,1))/DENO
    AIP2=(APIP(4,MTM2)*XYZ-AX(MT,4)/AX(MT,1))/DENO
    IF(K.EQ.KMAX) GO TO 462
    AIP4=-AX(MT,5)/AX(MT,1)/DENO
462 Y4=(YP(MTM2)*XYZ-YP(MTM3)*APIP(1,MTM4)+YP(MTM4)-
1    Y(MT)/AX(MT,1))/DENO
    GO TO 475

```

C

463 CONTINUE

C

```

    DENO=APIP(1,MTM2)*XYZ-APIP(1,MTM4)*APIP(2,MTM3)+APIP(3,MTM4)-
1    AX(MT,2)/AX(MT,1)
    AIP1=(APIP(2,MTM2)*XYZ-APIP(1,MTM4)*APIP(3,MTM3)-
1    AX(MT,3)/AX(MT,1))/DENO
    AIP1=(APIP(3,MTM2)*XYZ-APIP(1,MTM4)*APIP(4,MTM3))/DENO
    AIP2=(APIP(4,MTM2)*XYZ-AX(MT,4)/AX(MT,1))/DENO
    IF(K.EQ.KMAX) GO TO 465
    AIP4=-AX(MT,5)/AX(MT,1)/DENO
465 Y4=(YP(MTM2)*XYZ-YP(MTM3)*APIP(1,MTM4)+YP(MTM4)-
1    Y(MT)/AX(MT,1))/DENO

```

GO TO 475

C

467 CONTINUE

C

DENO=APIP(1,MTM2)*(XYZ+AX(MT,2)/AX(MT,1))-APIP(1,MTM4)*

1 APIP(2,MTM3)+APIP(3,MTM4)

A11=(APIP(2,MTM2)*(XYZ+AX(MT,2)/AX(MT,1))-APIP(1,MTM4)*

1 APIP(3,MTM3)+APIP(4,MTM4)-AX(MT,3)/AX(MT,1))/DENO

AIP1=(APIP(3,MTM2)*(XYZ+AX(MT,2)/AX(MT,1))-APIP(1,MTM4)*

1 APIP(4,MTM3)-AX(MT,4)/AX(MT,1))/DENO

IF(K.EQ.KMAX) GO TO 469

AIP2=APIP(4,MTM2)*(XYZ+AX(MT,2)/AX(MT,1))/DENO

AIP4=-AX(MT,5)/AX(MT,1)/DENO

469 Y4=(YP(MTM2)*(XYZ+AX(MT,2)/AX(MT,1))-YP(MTM3)*APIP(1,MTM4)+

1 YP(MTM4)-Y(MT)/AX(MT,1))/DENO

GO TO 475

C

471 CONTINUE

C

DENO=APIP(1,MTM2)*(XYZ+AX(MT,2)/AX(MT,1))-APIP(1,MTM4)*

1 APIP(2,MTM3)+APIP(3,MTM4)-AX(MT,3)/AX(MT,1)

A11=(APIP(2,MTM2)*(XYZ+AX(MT,2)/AX(MT,1))-APIP(1,MTM4)*

1 APIP(3,MTM3)+APIP(4,MTM4)-AX(MT,4)/AX(MT,1))/DENO

IF(K.EQ.KMAX) GO TO 473

AIP1=(APIP(3,MTM2)*(XYZ+AX(MT,2)/AX(MT,1))-APIP(1,MTM4)*

1 APIP(4,MTM3))/DENO

AIP2=APIP(4,MTM2)*(XYZ+AX(MT,2)/AX(MT,1))/DENO

AIP4=-AX(MT,5)/AX(MT,1)/DENO

473 Y4=(YP(MTM2)*(XYZ+AX(MT,2)/AX(MT,1))-YP(MTM3)*APIP(1,MTM4)+

1 YP(MTM4)-Y(MT)/AX(MT,1))/DENO

475 CONTINUE

C

C

DENO1=APIP(1,MTM1)-A11

IF(1.EQ.2.AND.J.EQ.2.AND.K.EQ.KMAX) GO TO 480

APIP(1,MT)=(APIP(2,MTM1)-AIP1)/DENO1

IF(1.EQ.2.AND.J.EQ.1.AND.K.EQ.KMAX) GO TO 480

APIP(2,MT)=(APIP(3,MTM1)-AIP2)/DENO1

IF(1.EQ.1.AND.J.EQ.2.AND.K.EQ.KMAX) GO TO 480

APIP(3,MT)=APIP(4,MTM1)/DENO1

IF(1.EQ.1.AND.J.EQ.1.AND.K.EQ.KMAX) GO TO 480

APIP(4,MT)=-AIP4/DENO1

480 YP(MT)=(YP(MTM1)-Y4)/DENO1

490 CONTINUE

C

TQ=CMPLX(0.,0.)

C

DO 498 KK=1,KMAX

K=KMAX+1-KK

KM1=K-1

```

DO 498 II=1, IMAX
I=IMAX+1-II
JR=JMX(I)
DO 498 JJ=1, JR
J=JR+1-JJ
M=JJD(I, J)
MT=M+KM1*4
MTP1=MT+1
MTP2=MT+2
MTP3=MT+3
MTP4=MT+4
IF(K.NE.KMAX) GO TO 492
IF(I.EQ.IMAX.AND.J.EQ.JR) DQ(MT)=YP(MT)
IF(I.EQ.IMAX.AND.J.EQ.1) DQ(MT)=YP(MT)-APIP(1,MT)*YP(MTP1)
IF(I.EQ.1.AND.J.EQ.2) DQ(MT)=YP(MT)-APIP(1,MT)*YP(MTP1)-
1 APIP(2,MT)*YP(MTP2)
1 IF(I.EQ.1.AND.J.EQ.1) DQ(MT)=YP(MT)-APIP(1,MT)*YP(MTP1)-
APIP(2,MT)*YP(MTP2)-APIP(3,MT)*YP(MTP3)
GO TO 494
492 CONTINUE
DQ(MT)=YP(MT)-APIP(1,MT)*YP(MTP1)-APIP(2,MT)*YP(MTP2)-
1 APIP(3,MT)*YP(MTP3)-APIP(4,MT)*YP(MTP4)
494 CONTINUE
C
TQ=TQ+DQ(MT)/FLOAT(KMAX)/4.
498 CONTINUE
GO TO 2000
1199 CONTINUE
C
C.....
C * ICASE = 4, RADIALLY COUPLED KINETICS
C.....
F1(NCH1)=CMPLX(0.,0.)
C
DO 1200 I=1, IMAX
JR=JMX(I)
IM1=I-1
IP1=I+1
IF(I.NE.1) JIM1=JMX(IM1)
DO 1200 J=1, JR
JM1=J-1
JP1=J+1
M=JJD(I, J)
C
DO 1115 N=1, 5
AX(M, N)=CMPLX(0.,0.)
1115 ZL(M, N)=CMPLX(0.,0.)
C
IF(I.EQ.1) GO TO 1117
IF(J.LE.JR.AND.J.GT.JIM1) GO TO 1117

```



```

      IF(I.NE.1) MIM1=JJD(IM1,J)
1117 IF(I.NE.IMAX) MIP1=JJD(IP1,J)
      IF(J.NE.1) MJM1=JJD(1,JM1)
      IF(J.NE.JR) MJP1=JJD(1,JP1)

```

C

```

      IF(I.EQ.1) GO TO 1120
      IF(I.EQ.IMAX) GO TO 1130
      IF(J.EQ.1) GO TO 1140
      IF(J.EQ.JR) GO TO 1150
      IF(J.LT.JR.AND.J.GT.JIM1) GO TO 1160
      ANOMQ=RANOI(M,1)*ASRC(IM1,J)+RANOI(M,2)*ASRC(1,JM1)+
1      RANOI(M,3)*ASRC(IP1,J)+RANOI(M,4)*ASRC(1,JP1)
      AX(M,1)=-RANI(M,1)
      ZL(M,1)=-ZNI(M,1)*ASRC(IM1,J)*AVEQ
      AX(M,2)=-RANI(M,2)
      ZL(M,2)=-ZNI(M,2)*ASRC(1,JM1)*AVEQ
      AX(M,3)=BI(M)
      ZL(M,3)=(RK1(M)+RCDF(1,J)/RDF(1,J)*ANOMQ)*AVEQ
      AX(M,4)=-RANI(M,4)
      ZL(M,4)=-ZNI(M,4)*ASRC(1,JP1)*AVEQ
      AX(M,5)=-RANI(M,3)
      ZL(M,5)=-ZNI(M,3)*ASRC(IP1,J)*AVEQ
      Y(M)=ZL(M,1)*F1(MIM1)+ZL(M,2)*F1(MJM1)+ZL(M,3)*F1(M)+
1      ZL(M,4)*F1(MJP1)+ZL(M,5)*F1(MIP1)
      GO TO 1180

```

C

C

```

***** I = 1 *****

```

C

```

1120 AX(M,5)=-RANI(M,3)
      ZL(M,5)=-ZNI(M,3)*ASRC(IP1,J)*AVEQ
      IF(J.EQ.1) GO TO 1124
      AX(M,1)=-RANI(M,2)
      ZL(M,1)=-ZNI(M,2)*ASRC(IM1,J)*AVEQ
      AX(M,2)=BI(M)
      IF(J.EQ.JR) GO TO 1126
      ANOMQ=RANOI(M,2)*ASRC(1,JM1)+
1      RANOI(M,3)*ASRC(IP1,J)+RANOI(M,4)*ASRC(1,JP1)
      ZL(M,2)=(RK1(M)+RCDF(1,J)/RDF(1,J)*ANOMQ)*AVEQ
      AX(M,3)=-RANI(M,4)
      ZL(M,3)=-ZNI(M,4)*ASRC(1,JP1)*AVEQ
      Y(M)=ZL(M,1)*F1(MJM1)+ZL(M,2)*F1(M)+
1      ZL(M,3)*F1(MIP1)+ZL(M,5)*F1(MJP1)
      GO TO 1180

```

C

C

```

***** I = 1, J = 1 *****

```

C

```

1124 ANOMQ=RANOI(M,2)*ASRC(1,J)+RANOI(M,3)*ASRC(IP1,J)+
1      RANOI(M,4)*ASRC(1,JP1)
      AX(M,1)=BI(M)-RANI(M,2)
      ZL(M,1)=(RK1(M)+RCDF(1,J)/RDF(1,J)*ANOMQ-ZNI(M,2)*ASRC(1,J))*AVEQ

```

```

AX(M,2)=-RANI(M,4)
ZL(M,2)=-ZNI(M,4)*ASRC(1,JP1)*AVEQ
Y(M)=ZL(M,1)*F1(M)+ZL(M,2)*F1(MJP1)+ZL(M,5)*F1(MIP1)
GO TO 1180

```

```

C
C ***** I = 1, J = JR *****
C

```

```

1126 ANOMQ=RANO1(M,2)*ASRC(1,JM1)+RANO1(M,3)*ASRC(1P1,J)
ZL(M,2)=(RK1(M)+RCDF(1,J)/RDF(1,J)*ANOMQ)*AVEQ
Y(M)=ZL(M,1)*F1(MJM1)+ZL(M,2)*F1(M)+ZL(M,5)*F1(MIP1)
GO TO 1180

```

```

C
C ***** I = IMAX *****
C

```

```

1130 AX(M,1)=-RANI(M,1)
ZL(M,1)=-ZNI(M,1)*ASRC(IM1,J)*AVEQ
IF(J.EQ.1) GO TO 1133
AX(M,2)=-RANI(M,2)
ZL(M,2)=-ZNI(M,2)*ASRC(1,JM1)*AVEQ
AX(M,3)=BI(M)-RANI(M,3)
IF(J.EQ.JR) GO TO 1136
ANOMQ=RANO1(M,1)*ASRC(IM1,J)+RANO1(M,2)*ASRC(1,JM1)+
1 RANO1(M,3)*ASRC(1,J)+RANO1(M,4)*ASRC(1,JP1)
ZL(M,3)=(RK1(M)+RCDF(1,J)/RDF(1,J)*ANOMQ)*AVEQ
AX(M,4)=-RANI(M,4)
ZL(M,4)=-ZNI(M,4)*ASRC(1,JP1)*AVEQ
Y(M)=ZL(M,1)*F1(MIM1)+ZL(M,2)*F1(MJM1)+ZL(M,3)*F1(M)+
1 ZL(M,4)*F1(MJP1)
GO TO 1180

```

```

C
C ***** J = 1, I = IMAX *****
C

```

```

1133 ANOMQ=RANO1(M,1)*ASRC(IM1,J)+RANO1(M,2)*ASRC(1,J)+
1 RANO1(M,3)*ASRC(1,J)+RANO1(M,4)*ASRC(1,JP1)
AX(M,3)=BI(M)-RANI(M,2)-RANI(M,3)
ZL(M,3)=(RK1(M)+RCDF(1,J)/RDF(1,J)*ANOMQ-(ZNI(M,2)+
1 ZNI(M,3))*ASRC(1,J))*AVEQ
AX(M,4)=-RANI(M,4)
ZL(M,4)=-ZNI(M,4)*ASRC(1,JP1)*AVEQ
Y(M)=ZL(M,1)*F1(MIM1)+ZL(M,4)*F1(MJP1)+ZL(M,3)*F1(M)
GO TO 1180

```

```

C
C ***** J = JR, I = IMAX *****
C

```

```

1136 ANOMQ=RANO1(M,1)*ASRC(IM1,J)+RANO1(M,2)*ASRC(1,JM1)+
1 RANO1(M,3)*ASRC(1,J)
ZL(M,3)=(RK1(M)+RCDF(1,J)/RDF(1,J)*ANOMQ-ZNI(M,3)*ASRC(1,J))*AVEQ
Y(M)=ZL(M,1)*F1(MIM1)+ZL(M,2)*F1(MJM1)+ZL(M,3)*F1(M)
GO TO 1180

```

```

C

```

C ***** J = 1, I.NE.1, I.NE.IMAX *****

C

```

1140 AX(M,1)=-RANI(M,1)
      ZL(M,1)=-ZNI(M,1)*ASRC(IM1,J)*AVEQ
      AX(M,4)=-RANI(M,4)
      ZL(M,4)=-ZNI(M,4)*ASRC(I,JP1)*AVEQ
      AX(M,5)=-RANI(M,3)
      ZL(M,5)=-ZNI(M,3)*ASRC(IP1,J)*AVEQ
      ANOMQ=RANOI(M,1)*ASRC(IM1,J)+RANOI(M,2)*ASRC(I,J)+
1      RANOI(M,3)*ASRC(IP1,J)+RANOI(M,4)*ASRC(I,JP1)
      AX(M,3)=BI(M)-RANI(M,2)
      ZL(M,3)=(RKI(M)+RCDF(I,J)/RDF(I,J)*ANOMQ-ZNI(M,2)*
1      ASRC(I,J))*AVEQ
      Y(M)=ZL(M,1)*F1(MIM1)+ZL(M,3)*F1(M)+
1      ZL(M,4)*F1(MJP1)+ZL(M,5)*F1(MIP1)
      GO TO 1180

```

C

***** J = JR, I.NE.1, I.NE.IMAX *****

C

```

1150 AX(M,2)=-RANI(M,2)
      ZL(M,2)=-ZNI(M,2)*ASRC(I,JM1)*AVEQ
      AX(M,3)=BI(M)
      AX(M,5)=-RANI(M,3)
      ZL(M,5)=-ZNI(M,3)*ASRC(IP1,J)*AVEQ
      IF(J.EQ.JIM1) GO TO 1153
      ANOMQ=RANOI(M,2)*ASRC(I,JM1)+RANOI(M,3)*ASRC(IP1,J)
      ZL(M,3)=(RKI(M)+RCDF(I,J)/RDF(I,J)*ANOMQ)*AVEQ
      Y(M)=ZL(M,2)*F1(MJM1)+ZL(M,3)*F1(M)+ZL(M,5)*F1(MIP1)
      GO TO 1180
1153 ANOMQ=RANOI(M,1)*ASRC(IM1,J)+RANOI(M,2)*ASRC(I,JM1)+
1      RANOI(M,3)*ASRC(IP1,J)
      AX(M,1)=-RANI(M,1)
      ZL(M,1)=-ZNI(M,1)*ASRC(IM1,J)*AVEQ
      ZL(M,3)=(RKI(M)+RCDF(I,J)/RDF(I,J)*ANOMQ)*AVEQ
      Y(M)=ZL(M,1)*F1(MIM1)+ZL(M,2)*F1(MJM1)+ZL(M,3)*F1(M)+
1      ZL(M,5)*F1(MIP1)
      GO TO 1180

```

C

***** J.LT.JR.AND.J.GT.JIM1, I.NE.1, I.NE.IMAX *****

C

```

1160 AX(M,2)=-RANI(M,2)
      ZL(M,2)=-ZNI(M,2)*ASRC(I,JM1)*AVEQ
      ANOMQ=RANOI(M,2)*ASRC(I,JM1)+
1      RANOI(M,3)*ASRC(IP1,J)+RANOI(M,4)*ASRC(I,JP1)
      AX(M,3)=BI(M)
      ZL(M,3)=(RKI(M)+RCDF(I,J)/RDF(I,J)*ANOMQ)*AVEQ
      AX(M,4)=-RANI(M,4)
      ZL(M,4)=-ZNI(M,4)*ASRC(I,JP1)*AVEQ
      AX(M,5)=-RANI(M,3)
      ZL(M,5)=-ZNI(M,3)*ASRC(IP1,J)*AVEQ

```

```

      Y(M)=ZL(M,2)*F1(MJM1)+ZL(M,3)*F1(M)+
      1      ZL(M,4)*F1(MJP1)+ZL(M,5)*F1(MIP1)
1180 CONTINUE
C
      DO 1161 N=1,5
      ZL(M,N) = CFP*ZL(M,N)
1161 CONTINUE
C
      DQ(M)=CMPLX(0.,0.)
      YP(M)=CMPLX(0.,0.)
      DO 1185 JPO=1,JMAX
1185 APIP(JPO,M)=CMPLX(0.,0.)
C
1200 CONTINUE
C
C
      DO 1300 I=1,IMAX
      JR=JMX(I)
      IM1=I-1
      IP1=I+1
      IF(I.NE.IMAX) JIP1=JMX(IP1)
      IF(I.GT.1) JIM1=JMX(IM1)
      DO 1300 J=1,JR
      M=JJD(I,J)
      JM1=J-1
      JP1=J+1
      JRM1=JR-1
      IF(I.EQ.1) GO TO 1207
      IF(J.LE.JR.AND.J.GT.JIM1) GO TO 1207
      MIM1=JJD(IM1,J)
      MIM1P1=MIM1+1
1207 IF(I.NE.IMAX) MIP1=JJD(IP1,J)
      IF(J.NE.1) MJM1=JJD(I,JM1)
      IF(J.NE.JR) MJP1=JJD(I,JP1)
      IF(I.NE.1) GO TO 1216
C
C ***** I = 1 *****
C
      IF(J.NE.1) GO TO 1210
      APIP(1,1)=AX(1,2)/AX(1,1)
      APIP(JR,1)=AX(1,5)/AX(1,1)
      YP(1)=Y(1)/AX(1,1)
      GO TO 1300
C
1210 CONTINUE
      DENO=APIP(1,JM1)*AX(J,1)-AX(J,2)
      APIP(JR,J)=-AX(J,5)/DENO
      IF(J.EQ.JR) GO TO 1211
      APIP(1,J)=-AX(J,3)/DENO
      GO TO 1212

```

```

1211 APIP(1,J)=AX(J,1)*APIP(1,JM1)/DENO
C
1212 CONTINUE
    DO 1213 J1=2,JRM1
        J1P1=J1+1
1213 APIP(J1,J)=AX(J,1)*APIP(J1P1,JM1)/DENO
    YP(J)=(AX(J,1)*YP(JM1)-Y(J))/DENO
    GO TO 1300
C
C
1216 CONTINUE
    JH=JIM1/2
    JHM=JIM1-JH*2
    IF(J.GT.JIM1.AND.J.LE.JR) GO TO 1235
    XUM(1)=AX(M,1)*(APIP(1,MIM1)*APIP(1,MIM1P1)-APIP(2,MIM1))
    NUU=JIM1-1
    MMN=M-NUU
    NUM1=NUU-1
C
    DO 1219 N1=2,NUU
        N1P1=N1+1
        NH=N1/2
        NHM=N1-NH*2
        XUML=((-1)**NHM*APIP(N1P1,MIM1)-(-1)**NHM*APIP(1,MIM1))*
1        APIP(N1,MIM1P1))*AX(M,1)
        IF(N1.EQ.NUU) XUML=XUML+(-1)**JHM*AX(M,3)
        IF(N1.EQ.NUM1) XUML=XUML-(-1)**JHM*AX(M,2)
        XUM(N1)=CMPLX(0.,0.)
        N1M1=N1-1
C
    DO 1218 N2=1,N1M1
        N2M1=N2-1
        N3=N1M1-N2M1
        MMN2=MMN+N1-N2
        MH=N2/2
        MHM=N2-MH*2
1218 XUM(N1)=XUM(N1)-XUM(N3)*APIP(N2,MMN2)*(-1)**MHM
    XUM(N1)=XUM(N1)+XUML
1219 CONTINUE
C
C
    APIP(JR,M)=(-1)**JHM*AX(M,5)/XUM(NUU)
    NZ=NUM1/2
    NZM=NUM1-NZ*2
    MMJIM1=M-JIM1
C
    DO 1220 N1=1,NUM1
        N2=NUU-N1+1
        N3=M-NUU+N1
        NH=N1/2

```

```

      NHM=N1-NH*2
      IF(NZM.EQ.1) NHM=NHM+1
      IF(1.EQ.IMAX.AND.J.EQ.JR) GO TO 1220
      APIP(1,M)=APIP(1,M)+(-1)**NHM*XUM(N1)*APIP(N2,N3)/XUM(NUU)
1220 YP(M)=YP(M)+(-1)**NHM*XUM(N1)*YP(N3)
      APIP(1,M)=APIP(1,M)+(-1)**JHM*(AX(M,1)*APIP(1,MIM1)*
1      APIP(JIM1,MIM1P1)+AX(M,4))/XUM(NUU)
      YP(M)=(YP(M)+(-1)**JHM*(AX(M,1)*APIP(1,MIM1)*YP(MIM1P1)+
1      Y(M))-(-1)**JHM*AX(M,1)*YP(MIM1))/XUM(NUU)
      IF(1.EQ.IMAX.AND.J.EQ.JR) GO TO 1225
      IF(1.NE.IMAX) GO TO 1221
      JRM1=JR-J
      IF(JRM1.LT.2) GO TO 1225
C
1221 CONTINUE
      DO 1224 N1=2,JRM1
      DO 1222 NA=1,NUM1
      N2=NUU+N1-NA
      N3=M-NUU+NA
      NH=NA/2
      NHM=NA-NH*2
      IF(NZM.EQ.1) NHM=NHM+1
1222 APIP(N1,M)=APIP(N1,M)+(-1)**NHM*XUM(NA)*APIP(N2,N3)/
1      XUM(NUU)
1224 CONTINUE
1225 CONTINUE
      GO TO 1300
1235 CONTINUE
C
C ***** J.NE.JR.AND.J.GT.JMX(IM1) *****
C
      DENO=AX(M,2)*APIP(1,MJM1)-AX(M,3)
      IF(J.EQ.JR) APIP(1,M)=AX(M,2)*APIP(2,MJM1)/DENO
      IF(J.NE.JR) APIP(1,M)=-AX(M,4)/DENO
      JRM1=JR-1
      DO 1238 N1=2,JRM1
      N1P1=N1+1
1238 APIP(N1,M)=AX(M,2)*APIP(N1P1,MJM1)/DENO
C
      APIP(JR,M)=-AX(M,5)/DENO
      YP(M)=(AX(M,2)*YP(MJM1)-Y(M))/DENO
C
1300 CONTINUE
C
      NCH=NCH1-1
      DQ(NCH)=YP(NCH)
      DO 1350 II=1,IMAX
      I=IMAX-II+1
      JR=JMX(I)
      DO 1350 JJ=1,JR

```

```

      J=JR-JJ+1
      JJR=JR
      M=JJD(1,J)
      IF(M.EQ.NCH) GO TO 1330
      IF(1.EQ.IMAX) JJR=JR-J
      DO 1320 N5=1,JJR
      MPN5=M+N5
1320 DQ(M)=DQ(M)+API P(N5,M)*DQ(MPN5)
C
      DQ(M)=YP(M)-DQ(M)
1330 CONTINUE
      TQ=TQ+DQ(M)/FLOAT(NCH)
1350 CONTINUE
      GO TO 2000
1500 CONTINUE
C
C.....
C * TWO GROUP AXIAL COUPLING (ICASE = 13): MATRIX OPERATION
C.....
C
      K=KKMAX
      DO 1510 I=1,KKMAX
      DO 1510 J=1,KKMAX
      CWW1(I,J)=WW1(I,J)
      CWW2(I,J)=WW2(I,J)
      CTWO(I,J)=TWO(I,J)
      CTZ1(I,J)=TZ1(I,J)
1510 CONTINUE
      CALL MATXIN(K,MM,WINV,CWW1,ICOUNT)
      CALL MATMUL(K,K,K,K,CWW2,WINV,CTWO,WWT,1,ICOUNT)
      CALL MATMUL(K,K,K,K,CWW2,WINV,CTZ1,WWZ,1,ICOUNT)
C
      DO 1520 I=1,KKMAX
      IF(ICASE.EQ.14) F11(I,1)=F1(I)
      IF(ICASE.EQ.13) F11(I,1)=FALF(1,1)
      A(1,1)=1./FLOAT(KKMAX)
      DO 1520 J=1,KKMAX
      FF(I,J)=WWT(I,J)-THREE(I,J)
1520 XL(I,J)=TZ2(I,J)-WWZ(I,J)
C
      CALL MATXIN(K,MM,FINV,FF,ICOUNT)
      CALL MATMUL(1,K,K,K,A,FINV,DUMMY,DD,0,ICOUNT)
      CALL MATMUL(1,K,K,K,DD,XL,DUMMY,EE,0,ICOUNT)
      CALL MATMUL(1,1,K,K,EE,F11,DUMMY,XT,0,ICOUNT)
      TQ=XT(1,1)
C
2000 RATIO=-TQ
C
      WRITE(8,7505) TQ, RATIO
7505 FORMAT(/10X,2(5X,2(2X,E10.4)))

```

```

C      RETURN
C      END
C
C
C
C
C*****
C      SUBROUTINE MATXIN(N,M,X,XI,ICOUNT)
C*****
C      * MATRIX INVERSION BY MATRIX PARTITION METHOD
C      * XI(I,J) : (N X N) MATRIX
C      * X(I,J) : INVERTED MATRIX
C      * M = N + 1
C
C      COMPLEX X(30,30), XI(30,30), Y(30,30)
C
C      IF(ICOUNT.GT.1) GO TO 1000
C      WRITE(9,54)
C      54 FORMAT(10X,'MATRIX A')
C      DO 50 I=1,N
C      50 WRITE(9,1) (XI(I,J), J=1,N)
C      1 FORMAT(/5X,3(3X,2(2X,E10.3)))
C      1000 CONTINUE
C
C      K = 0
C      DO 10 J=1,N
C      10 Y(1,J) = 0.
C      Y(1,M) = 1.
C      DO 11 I=1,N
C      11 Y(I,1) = 0.
C      Y(M,1) = 1.
C      200 DO 20 I=2,M
C      11 = I - 1
C      DO 20 J=2,M
C      JJ = J - 1
C      Y(I,J) = XI(11,JJ)
C      20 CONTINUE
C
C      DO 30 I=1,N
C      DO 30 J=1,N
C      X(I,J) = Y(I,J) - Y(I,M)*Y(M,J)/Y(M,M)
C      30 CONTINUE
C
C      K = K+1
C      IF(K.EQ. N) GO TO 100
C      DO 40 I=1,N
C      DO 40 J=1,N
C      XI(I,J) = X(I,J)
C      40 CONTINUE

```



```

      GO TO 200
C
100 DO 89 I=1,N
    DO 89 J=1,N
      X(I,J) = -X(I,J)
    89 CONTINUE
      IF(ICOUNT.GT.1) GO TO 66
      WRITE(9,88)
    88 FORMAT(/////5X,' INVERSE A')
      DO 60 I=1,N
    60 WRITE(9,2) (X(I,J), J=1,N)
      2 FORMAT(/5X,3(3X,2(2X,E10.3)))
    66 RETURN
      END
C
C
C
C*****
      SUBROUTINE MATMUL(N,L,KN,M,A,B,C,D,NOP,ICOUNT)
C*****
C      * MATRIX MULTIPLICATION
C      * NOP=0 ; D(N,L) = A(N,K) X B(K,L)
C      *      =1 ; D(N,M) = A(N,K)*B(K,L)*C(L,M)
C
      COMPLEX A(30,30),B(30,30),C(30,30),D(30,30)
      COMPLEX SUM1,SUM2,F(30,30)
C
      DO 10 I=1,N
      DO 10 J=1,L
      SUM1 = CMPLX(0.,0.)
      DO 20 K=1,KN
    20 SUM1 = SUM1 + A(I,K)*B(K,J)
      F(I,J) = SUM1
    10 CONTINUE
      IF(NOP.EQ. 1) GO TO 15
      DO 16 I=1,N
      DO 16 J=1,L
    16 D(I,J) = F(I,J)
      GO TO 17
C
    15 DO 30 I=1,N
      DO 30 J=1,M
      SUM2 = CMPLX(0.,0.)
      DO 40 K=1,N
    40 SUM2 = SUM2 +F(I,K)*C(K,J)
      D(I,J) = SUM2
    30 CONTINUE
C
    17 CONTINUE
      IF(ICOUNT.GT.1) GO TO 67

```

```

WRITE(9,1)
DO 50 I=1,N
50 WRITE(9,2) (A(I,J),J=1,KN)
WRITE(9,3)
DO 51 I=1,KN
51 WRITE(9,2) (B(I,J), J=1,L)
IF(NOP.EQ. 0) GO TO 21
WRITE(9,5)
DO 52 I=1,L
52 WRITE(9,2) (C(I,J), J=1,M)
21 IF(NOP.EQ. 0) M=L
WRITE(9,6)
DO 53 I=1,N
53 WRITE(9,2) (D(I,J), J=1,M)
CC
1 FCRMAT(///10X,'MATRIX A(N,N)')
3 FORMAT(///10X,'MATRIX B(N,N)')
5 FORMAT(///10X,'MATRIX C(N,N+1)')
6 FORMAT(///10X,'MATRIX D(N,N+1) = A X B X C')
2 FORMAT(/5X,3(3X,2(2X,E10.3)))
67 RETURN
END

```

APPENDIX XVIII
NUFREQ-N ERROR MESSAGES

Error No.	Contents
E1	EXIT QUALITY IS GREATER THAN 1. The channel power is too high, or the channel inlet velocity or inlet sub- cooling is too low. Thus such conditions are not suitable to test.
E2	NO FORCING FUNCTION WAS SPECIFIED. Check input CARD19 and specify any of external forcing functions.
E3	ITERATION FOR FLOW REDISTRIBUTION DOES NOT CONVERGE. Check input data and especially, input CARD
E4	ITERATION FOR THE SUBCOOLED BOILING DOES NOT CONVERGE. Check channel thermal-hydraulic parame- ters and increase the number of node.
E5	SAME AS E1