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Dynamic Simulation of the Fast Flux Test Facility Primary System

Prepared by M. R. Sands

Department of Nuclear and Energy Engineering
The University of Arizona

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3 September 1981
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ABSTRACT

Using the lumped parameter methodology, a computer model simulating the primary heat transport system (PHTS) of the Fast Flux Test Facility (FFTF) is developed. The three primary loops are simulated by two loops; a single and a double loop. The conservation of mass, energy and momentum are the physical foundations of the model FATFAD (FAst Flux Test FAcility Dynamics).

To test FATFAD, three transients are initiated, (1) a ten cent step input of reactivity, (2) a ten cent step reactivity input plus a 50 °K rise in the secondary sodium temperature entering the IHX, and (3) a 25% reduction in Loop One's primary pump speed. The results show that FATFAD inexpensively and accurately simulates the PHTS of the FFTF.

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CHAPTER 1

INTRODUCTION

The computer model FATFAD, Fast Flux Test Facility Dynamics, was developed out of a need for accurate, inexpensive, plant transient analyses. Implicit in this model description is the necessity for keeping code size to a minimum. To accomplish this, space dependence may be represented by suitable averaging (i.e., limiting the number of spatial zones), and similar components are combined together, resulting in fewer state and algebraic equations, thus reducing run cost. This type of computer modeling is called lumped-parameter modeling, and is the technique used for the development of FATFAD.

Using the lumped parameter methodology, FATFAD has on the order of 60 coupled non-linear first order ordinary differential equations plus approximately 1000 algebraic equations. A system this size can be easily integrated by the DAREP simulation language, developed by Dr. Granino Korn and Dr. John V. Wait at The University of Arizona.

In Fig. 1.1, a schematic of the Fast Flux Test Facility (FFTF), primary system, as modeled in FATFAD, is shown. There are two primary loops connecting the reactor and the intermediate heat exchanger. Loop One is the model of a single heat transport loop. Loop Two incorporates the second and third primary heat transport systems of the actual FFTF complex. Components shown on the schematic are those which make up

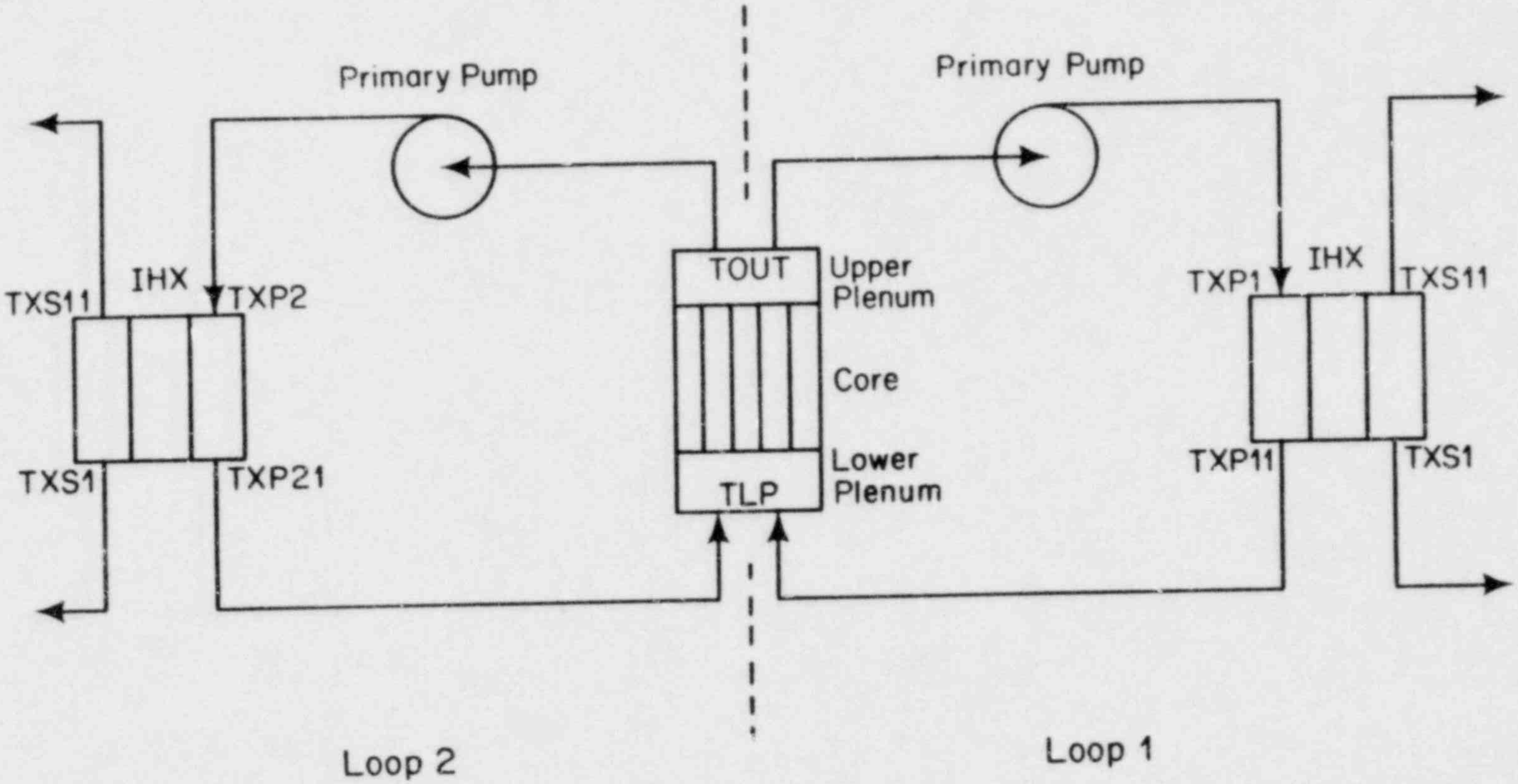


Figure 1.1 Schematic diagram of the FFTF.

FATFAD. It is important to note that the IHX and pump of Loop Two are actually two IHX's and two pumps combined, as is the case for the piping. Three physical laws are used in the model development of all these components: conservation of mass, energy, and momentum.

Important tools which aided in the development of FATFAD were steady state solving routines for each major component. Often steady-state values of variables would be unknown, and determination of these parameters was necessary. To accomplish this, state variables would be set to their steady state values (i.e., their derivatives set equal to zero), and the unknown term could be solved for algebraically.

All momentum equations have a friction factor term which is an effective parameter representing overall flow resistances (i.e., elbows, pipe roughness, etc.). These friction factors can be found by making their steady state values match known design values of the other parameters comprising the momentum equations. One method of finding these state friction factors is by setting up dummy differential equations. These dummy equations are actually momentum equations with the left hand side of the equation altered. Replacing dw/dt by df/dt, where w is the mass flow rate and f is the friction factor in question, the derivative will approach zero as f approaches the desired steady state value.

The following chapters will deal with the development of each of the components of the FFTF primary heat transport system, various transient runs, and results and conclusions.

CHAPTER 2

INTERMEDIATE HEAT EXCHANGER (IHX)

In Loop One the IHX is represented by one tube and its associated primary and secondary sodium flows. This representation assumes that all tubes and flow channels behave the same thermally. Total thermal response due to the transient is accomplished by magnifying the effect of the one tube by the number of tubes which make up the IHX.

There are three radial regions and one axial region comprising the IHX model. Primary sodium, tube wall, and secondary sodium make up the three radial sections. Although there is only one axial region, the option of adding more regions is built into the model.

Loop Two has an IHX which is modeled similarly to Loop One's IHX except for one major difference: dimensions. Since this unit is actually two IHX's, the tube size must accommodate twice the flow rate of the single IHX. To do this, the tube area is assumed to be twice the size of its counterpart.

Energy Balance

Before proceeding directly to the energy equations for each region and deriving the resulting differential equations for temperature, algebraic expressions for the input parameters will be determined.

Primary cross-sectional flow area per tube is calculated from the equation

$$\text{Area} = \text{CAXP1} = \pi\left[b^2 - \left(\frac{a}{2}\right)^2\right] \tag{2.1}$$

where a and b are shown in Fig. 2.1, and are the tube outside diameter and equivalent radius, respectively.

Density of the primary liquid sodium can be approximated by Eq. (2.2),

$$\text{Density} = \text{ROXP11} = 16.02(59.533 - 0.008333*\text{FAP11}) \tag{2.2}$$

with FAP11 being the average liquid sodium temperature in °F, on the primary side. Since all temperatures are calculated in °K, the equivalent temperature expressed in °F must be determined. The constant out front in Eq. (2.2) is the conversion factor from English to SI units.

Knowing the density and cross-sectional flow area, the liquid sodium velocity can be calculated from the mass flow rate equation.

$$\text{Velocity} = \text{VXP11} = \text{WPD1}/(\text{ROXP11}*\text{CAXP1})*\text{ENXP1} \tag{2.3}$$

WPD1 is the mass flow rate through the primary side of the IHX and is calculated from the momentum equation (Ch. 4). The number of IHX tubes is given by ENXP1.

Next, relationships for specific heat, dynamic viscosity, thermal conductivity, convective heat transfer coefficient, and resistance must be determined (Additon et al., 1976).

Eq. (2.4) is the expression for specific heat of the primary sodium (CPXP1), identical in form with the equation for specific heat of the secondary sodium (CPXS1).

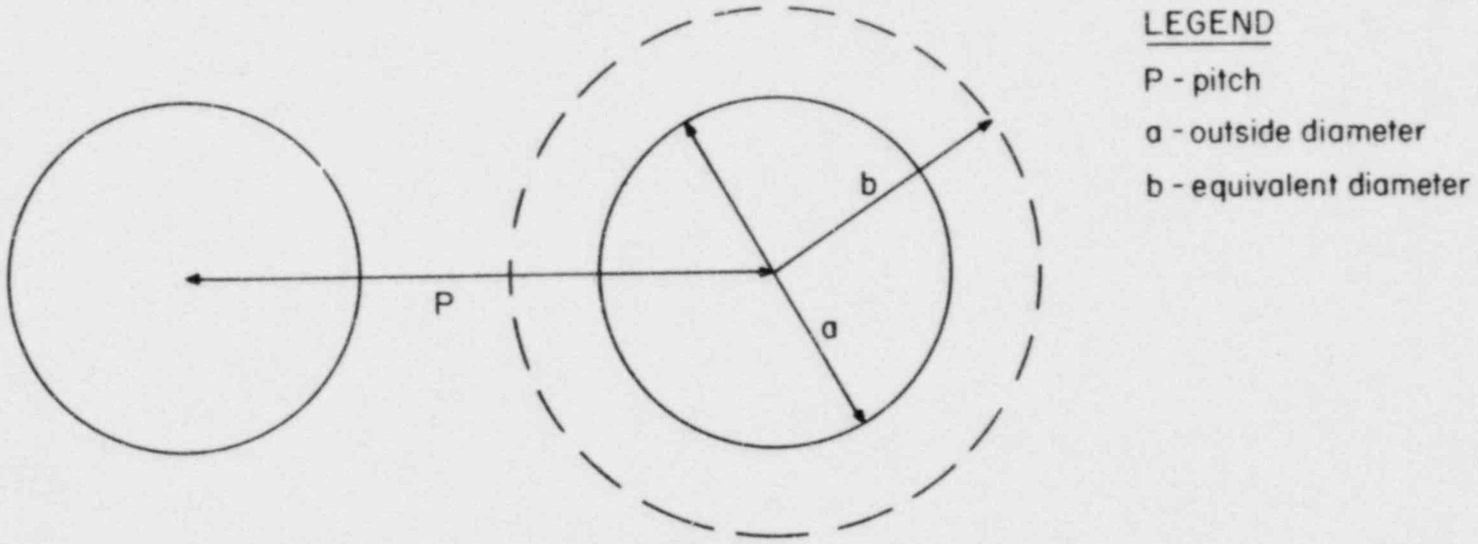


Figure 2.1. Top view of IHX flow channel.

$$\text{Specific Heat} = \text{CPXP1} = 4.1868\text{E+3}(0.34574 - 7.9226\text{E-5} * \text{FAP11} + 3.4086\text{E-8} * \text{FAP11}^2) \qquad (2.4)$$

The factor in front is the conversion factor from English to SI units. For the case of secondary sodium, FAP11 is replaced by FAS11. Specific heat of the tube wall is assumed to be constant.

Thermal conductivity must be calculated for the tube wall and liquid sodium film. From Additon et al. (1976), the wall thermal conductivity is

$$\text{Thermal Conductivity} = \text{TCXW11} = 1.73073(7.7388464 + 0.40721437\text{E-2} * \text{TXF11}) \qquad (2.5)$$

where TXF11 is the wall temperature expressed in °F. The empirical relationship for the sodium film thermal conductivity is given to be

$$\text{Film Thermal Conductivity} = \text{TCXP11} = 1.73073(54.306 - 1.878\text{E-2} * \text{FAP11} + 2.0914\text{E-6} * \text{FAP11}^2) \qquad (2.6)$$

Once again, the constant in front is a conversion factor to SI units. A similar expression is used for the sodium thermal conductivity on the secondary side (TCXS11). Viscosity can be determined from the following equation,

$$\log\left(\frac{\text{UMXP11}}{1.867\text{E-4}}\right) = 1.0203 + 397.17/\text{RP11} - 0.4925 * \log(\text{RP11}) \qquad (2.7)$$

Taking the antilog of both sides

$$\text{Viscosity} = \text{UMXP11} = 1.867\text{E-}4\{10.0^{**}[1.0203 + 397.17/\text{RP11} - 0.4925^{*}\log(\text{RP11})]\} \quad (2.8)$$

with RP11 being the average sodium temperature expressed in terms of °R, and the constant in front being the conversion factor. When determining the viscosity for the secondary side, replace UMXP11 and RP11 by UMXS11 and RS11, respectively.

The convective heat transfer coefficient, $\bar{h}_c$, has the form

$$\text{Convective Heat Transfer Coefficient} = \text{HXP11} = (\text{TCXP11}/\text{DH})^{*}\text{UNXP1} \quad (2.9)$$

where TCXP11 is the primary sodium thermal conductivity, DH is the hydraulic diameter, and UNXP1 is the Nusselt number of the primary sodium, given by Eq. (2.10) (Additon et al., 1976).

$$\text{Nusselt Number} = \text{UNXP1} = A+B(\text{REXP11})^{C}(\text{PRXP11})^{D} \quad (2.10)$$

The constants A, B, C, and D are dependent upon the geometry of the system, with REXP11 being the Reynolds number and PRXP11 the Prandit number. In calculating the Reynolds number, the following relation is used

$$\text{Reynolds Number} = \text{REXP11} = \text{ROXP11} * \text{VXP11} * \text{DH}/\text{UMXP11} \quad (2.11)$$

where ROXP11, VXP11, and UMXP11 are given by Eqs. (2.3), (2.2), and (2.8), respectively. The Prandit number is just

$$\text{Prandit Number} = \text{PRXP11} = \text{CPXP11}^{*}\text{UMXP11}/\text{TCXP11} \quad (2.12)$$

with CPXP11 given by Eq. (2.4).

Thermal resistance of the tube wall is

$$\text{Wall Thermal Resistance} = \text{RW11} = \ell n(\text{DOT/DCT})/(2.0*\text{PI}*\text{TL}*\text{TC}*\text{W11}) \tag{2.13}$$

DOT being the outside diameter, DCT the point inside the tube wall where the wall temperature (TXW) is measured, PI the value of π and TL the tube length. Thermal conductivity of the tube wall, TCXW11, is given by Eq. (2.5).

Temperatures of the primary sodium, tube wall, and secondary sodium are solved for by the energy conservation law. Performing the energy balance on region I (Fig. 2.2),

$$\frac{dU}{dt} = \dot{m}\ c_p\ T)_{in} - \dot{m}\ c_p\ T)_{out} - q \tag{2.14}$$

where $q = \overline{h}_c\ A\Delta T$, with ΔT being the temperature difference between sodium and tube wall. Also,

$$\frac{dU}{dt} = m\frac{du}{dt} \tag{2.15}$$

and

$$du = \left.\frac{\partial u}{\partial T}\right)_\nu dT + \left.\frac{\partial u}{\partial \nu}\right)_T d\nu \tag{2.16}$$

Since incompressible flow is being assumed, the second term on the right side is zero. Rewriting the first term,

$$\left.\frac{\partial u}{\partial T}\right)_\nu dT = C_\nu\ dT = C_p\ dT \tag{2.17}$$

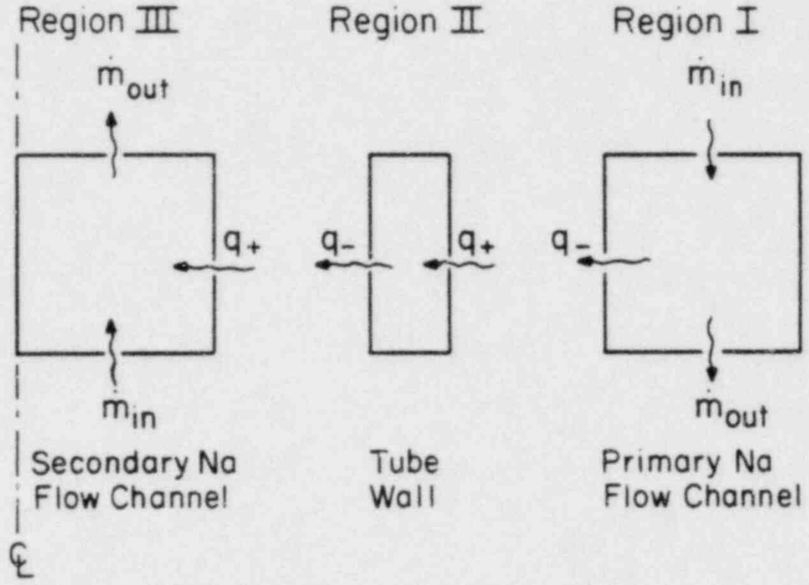


Figure 2.2. Exploded cutaway view of IHX as modeled with heat and mass flows.

again using the assumption of incompressible flow. Rewriting Eq. (2.15),

$$\frac{dU}{dt} = mc_p \frac{dT}{dt} \tag{2.18}$$

and combining Eqs. (2.18) and (2.14), the result becomes

$$mc_p \frac{dT}{dt} = \dot{m}c_p(T_1 - T_2) - \bar{h}_c A\Delta T \tag{2.19}$$

or,

$$\text{Temperature} = \frac{d}{dt}(\text{TXP11})_{out} = [\text{WPD1*CPXP11*}(\text{TXP11}_{in} - \text{TXP11}_{out}) - \text{UXP11*}(\text{TAVP11} - \text{TXW11})]/\text{WP11} \tag{2.20}$$

The variables in Eq. (2.20) are TXP11_{in} and TXP11_{out}, the liquid sodium temperatures into and out of the IHX respectively, UXP11, the overall heat transfer coefficient between the liquid sodium and tube wall, WP11, the product of primary sodium mass and primary sodium specific heat, and TAVP11 and TXW11, the average sodium temperature and wall temperature respectively. UXP11 may be expressed as

$$\text{Overall Heat Transfer Coefficient} = \text{UXP11} = [1.0/(\text{RX11} + \text{RW11})]\text{*ENXT1} \tag{2.21}$$

where RW11 is given by Eq. (2.13), and RX11 equals the inverse of the product of convective heat transfer coefficient (Eq. 2.9) and tube area (PAREA).

Analysis for Region II, the IHX tube wall (Fig. 2.2), is performed in a similar manner as for Region I.

$$\frac{dU}{dt} = q_+ - q_- \qquad (2.22)$$

There is assumed to be no axial heat flow. All three terms of Eq. (2.22) are expressed in the same form as the terms in Eq. (2.14),

$$mc_p \frac{dT}{dt} = \overline{h}_c\ A\Delta T)_{in} - \overline{h}_c\ A\Delta T)_{out} \qquad (2.23)$$

or,

$$\text{Wall Temperature} = \frac{d}{dt}(\text{TXW11}) = [\text{UXP11}*(\text{TAVP11} - \text{TXW11})$$

$$- \text{UXS11}*(\text{TXW11} - \text{TAVS11})]/\text{WW11} \qquad (2.24)$$

UXS11 is the secondary overall heat transfer coefficient, TAVS11 the average sodium temperature on the secondary side, and WW11 is the inverse of the product of tube wall mass and tube wall specific heat. Like UXP11, the overall heat transfer coefficient for the secondary side can be expressed as

$$\text{Overall Heat Transfer Coefficient} = \text{UXS11} =$$

$$[1.0/(\text{RXS11} + \text{RF} + \text{RW211})]*\text{ENXT1} \qquad (2.25)$$

where RW211 is given by Eq. (2.13) with one modification: the term ℓn(DOT/DCT) is replaced by ℓn(DCT/DIT), DIT being the inside tube diameter. RXS11 is similar to RX11 except primary terms are replaced by their appropriate secondary counterpart. Lastly, RF is the fouling resistance on the secondary side, and is assumed to be constant.

Doing the same thing for Region III (secondary sodium, Fig. 2.2), and assuming similar expressions for dU/dt and q,

$$\frac{dU}{dt} = \dot{m}c_p\ T_2)_{in} - \dot{m}c_p\ T_1)_{out} + q \qquad (2.26)$$

$$mc_p \frac{dT}{dt} = \dot{m}c_p(T_2 - T_1) + \overline{h}_c\ A\Delta T \qquad (2.27)$$

The secondary liquid sodium temperature is thus expressed by Eq. (2.28):

$$\text{Secondary Sodium Temperature} = \frac{d}{dt}\ (\text{TXS11}) =$$

$$[\text{WSD1*CXPS1*}(\text{TXS11}_{out}-\text{TXS11}_{in})$$

$$+ \text{UXS11*}(\text{TXW11} - \text{TAVS11})]/\text{WS11} \qquad (2.28)$$

Secondary mass flow rate is given by WSD1, and WS11 is the product of secondary sodium mass and sodium specific heat.

Determination of steady state values of IHX variables is given in Appendix A.

CHAPTER 3

REACTOR

There are three major components making up the reactor model: lower plenum, core, and upper plenum. For both upper and lower plenum models, perfect mixing is assumed. As seen in Fig. 3.1, there are five regions making up the core: three fuel regions, one control region, and one region including everything else (reflector, structure material, etc.). In addition, there is a center pin calculation which is used to show whether a transient is severe enough to cause localized fuel melting.

Scram conditions have also been built into the code for automatically scraming the reactor. If certain primary and/or secondary operating conditions are violated, the system will drop all the primary and/or secondary control rod banks, respectively.

Control rod positioning during operation is determined by the flux control system, and reactor power is determined using the prompt-jump approximation.

Lower and Upper Plenum

With perfect mixing of the sodium assumed, both models are nothing more than the energy conservation law. From Fig. 3.1, the physical representation of both plenums are shown.

Applying the conservation of energy to the lower plenum,

$$\Delta U = Q_{in} - Q_{out} \tag{3.1}$$

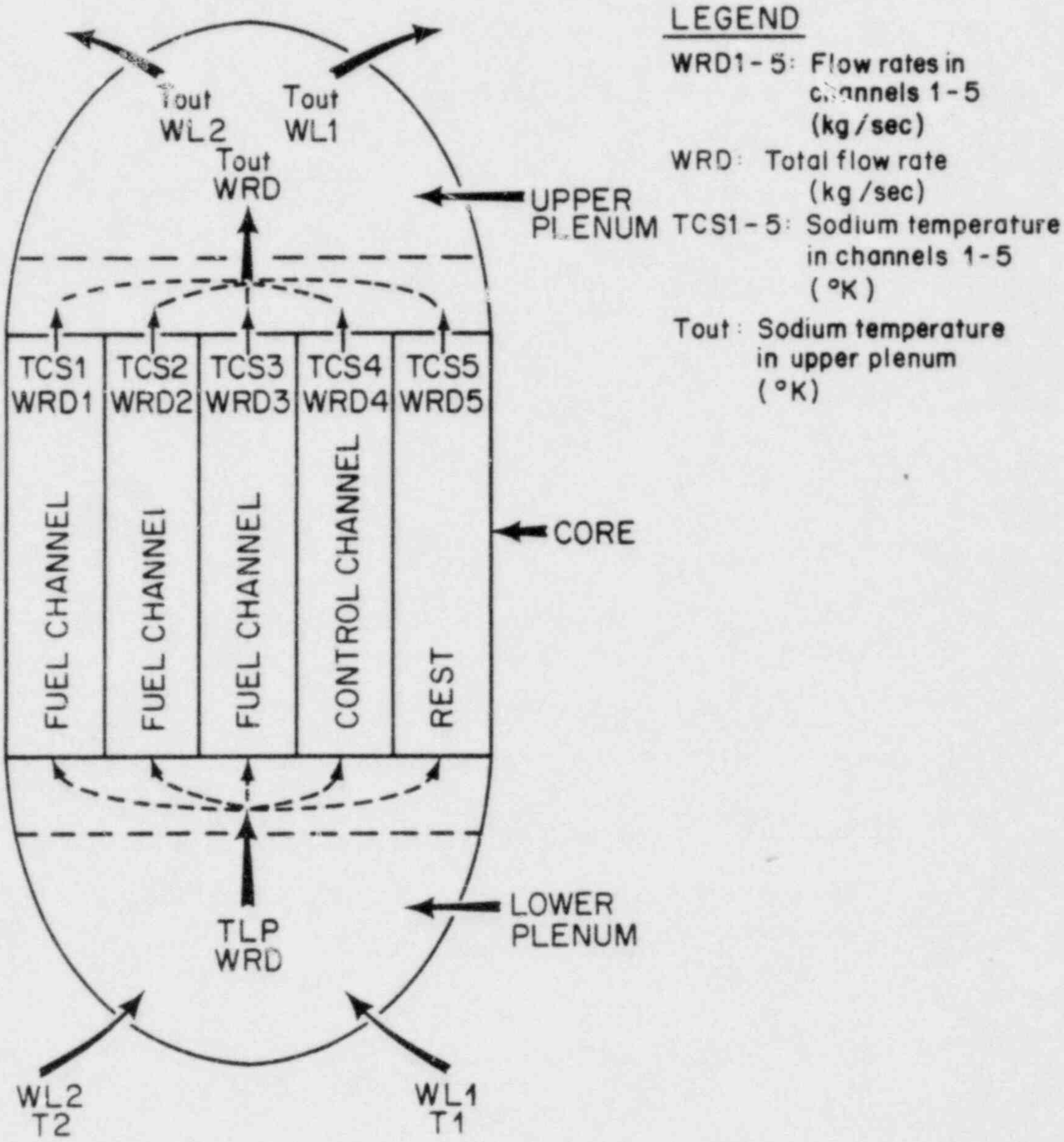


Figure 3.1. Schematic representation of the 5-channel core.

or

$$m\frac{du}{dt} = \dot{m}h)_{in} - \dot{m}h)_{out} \qquad (3.2)$$

But $h=c_pT$ for incompressible fluids, so Eq. (3.2) becomes

$$m\frac{du}{dt} = \dot{m}c_pT)_{in} - \dot{m}c_pT)_{out} \qquad (3.3)$$

Since there are two primary inflows, the first term on the R.H.S. of Eq. (3.3) is rewritten to incorporate both flows,

$$m\frac{du}{dt} = \dot{m}c_pT)_1 + \dot{m}c_pT)_2 - \dot{m}c_pT)_{out} \qquad (3.4)$$

Also, specific internal energy is a function of volume and temperature, with its differential expressed by

$$du = \left.\frac{\partial u}{\partial T}\right)_v dT = \left.\frac{\partial u}{\partial v}\right)_T dv \qquad (3.5)$$

However, from the assumption of incompressible flow, the second term on the R.H.S. of Eq. (3.5) is zero and $C_v \equiv \left.\frac{\partial u}{\partial T}\right)_v = C_p$ (derived in Chapter 2). Therefore

$$m\frac{du}{dt} = mc_p\left.\frac{dT}{dt}\right)_{out} = \dot{m}c_pT)_1 + \dot{m}c_pT)_2 - \dot{m}c_pT)_{out} \qquad (3.6)$$

finally,

$$\left.\frac{dT}{dt}\right)_{out} = [\dot{m}c_pT)_1 + \dot{m}c_pT)_2 - \dot{m}c_pT)_{out}]/mc_p)_{out} \qquad (3.7)$$

As expressed in FATFAD, Eq. (3.7) is written

$$\text{Lower Plenum Temperature} = \frac{d}{dt}\,(\text{TLP}) = (\text{QLOOP1} +$$

$$\text{QLOOP2 - WRD*CPSLP*TLP)/(RHOLP*VOLLP*CPSLP)} \qquad (3.8)$$

QLOOP1 and QLOOP2 represent the heat brought into the lower plenum from loops one and two respectively. Specific heat of sodium is given by CPSLP, mass flow rate into the core by WRD, sodium density in the lower plenum by RHOLP, and lower plenum volume by VOLLP.

Liquid sodium temperature in the upper plenum is derived the same way.

$$m\left.\frac{du}{dt}\right)_{out} = \dot{m}h)_{in} - h(\dot{m}_1 + \dot{m}_2)\Big)_{out} \qquad (3.9)$$

Enthalpy is the same for both exits from the upper plenum because the temperature is assumed to be the same at both exits. Using similar reasoning as used for the case of the lower plenum (incompressible flow), Eq. (3.9) can be expressed in a manner similar to Eq. (3.6)

$$mc_p\left.\frac{dT}{dt}\right)_{out} = \dot{m}c_pT)_{in} - (\dot{m}_1 + \dot{m}_2)c_pT)_{out} \qquad (3.10)$$

or

$$\left.\frac{dT}{dt}\right)_{out} = [\dot{m}c_pT)_{in} - (\dot{m}_1 + \dot{m}_2)c_pT)_{out}]/m\,c_p)_{out} \qquad (3.11)$$

The equivalent expression for the upper plenum is shown below,

$$\text{Upper Plenum Outlet Temperature} = \frac{d}{dt}\,(\text{TUPO}) =$$

$$\text{[WRD*CPOUT*TOUT - (WL11+WL21)*CPOUT*TUPO]/}$$

$$\text{(RHOUP*VOLUP*CPUPO)} \qquad (3.12)$$

Mass flow rates from the upper plenum to the one and two loop systems are given by WL11 and WL21, respectively. Liquid sodium specific heat and temperature at the core outlet are represented as CPOUT and TOUT, respectively, while the same two thermodynamic properties for upper plenum outlet are given by CPUPO and TUPO, respectively. Finally, the sodium density in the upper plenum is RHOUP, and the upper plenum volume is VOLUP.

Core

Temperature at the exit of the core, TOUT, is determined by an energy balance between sodium exit temperatures from the five core channels and the upper plenum inlet temperature, Fig. 3.1.

For five channels,

$$Q_{in} = \dot{m}h)_1 + \dot{m}h)_2 + \dot{m}h)_3 + \dot{m}h)_4 + \dot{m}h)_5 \tag{3.13}$$

$$Q_{out} = \dot{m}h)_{out} \tag{3.14}$$

remembering $h=c_pT$ for incompressible flows and $\frac{dU}{dt} = \dot{m}c_p \frac{dT}{dt}$ (see Eq. 2.15 through Eq. 2.18), the energy equation becomes,

$$mc_p \left.\frac{dT}{dt}\right)_{out} = [\dot{m}c_pT)_1 + \dot{m}c_pT)_2 + \dot{m}c_pT)_3 + \dot{m}c_pT)_4$$

$$+ \dot{m}c_pT)_5] - \dot{m}c_pT)_{out} \tag{3.15}$$

Dividing by $mc_p)_{out}$,

$$\text{Core Outlet Temperature} = \frac{d}{dt}(\text{TOUT}) = (\text{T1+T2+T3+T4+T5}$$

$$-\ \text{WRD*CPOUT*TOUT})/(\text{RHOUT*VOLC*CPOUT}) \qquad (3.16)$$

where T1-5 are the product of flow rate, specific heat, and temperature in each of the five channels, Eq. (3.17). Core volume is given by VOLC and RHOUT is the sodium density from the core exit.

$$\text{T(1-5)} = \text{WRD(1-5)*CPS(1-5)*TCS(1-5)} \qquad (3.17)$$

Channels 1-3

As mentioned earlier, three of the five channels are fuel channels. Each of these channels are divided into three radial regions as shown in Fig. 3.2: fuel-gap, clad, and coolant. Relations for temperature will once again be derived for each of these regions, using energy conservation.

Following the same format as in Chapter 2, all pertinent thermodynamic quantities will be determined before deriving the equations for fuel, clad, and coolant temperatures.

Heat output per unit length per fuel pin is determined in the following manner.

QT = total power output of core

η = fraction of power due to active core area

QA = actual power produced by active core area

ENRC = number of fuel elements in core

QP = power produced per fuel pin

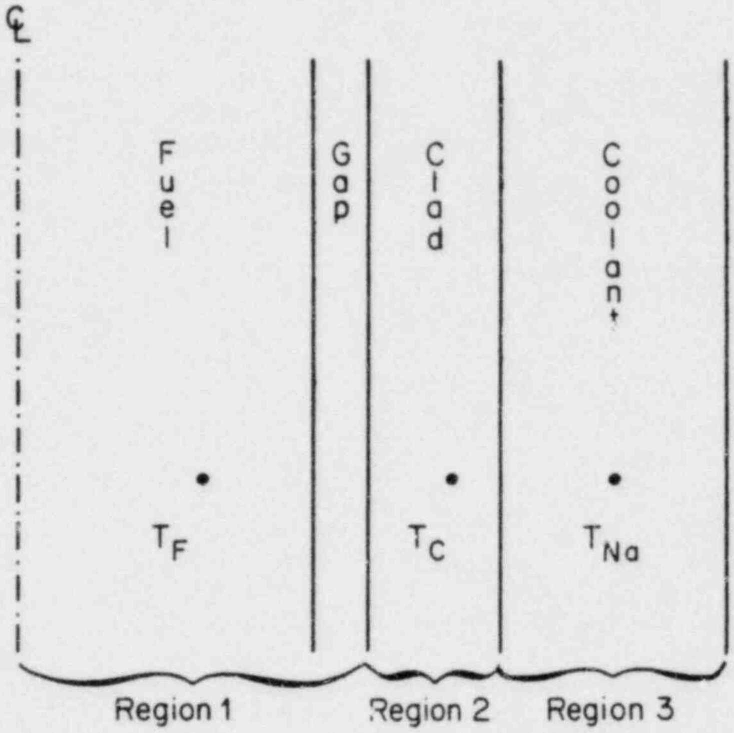


Figure 3.2. Detailed break-up of fuel channels.

QL = power produced per unit length of fuel pin

L = active length of fuel pin

Relation among these quantities are:

$$QA = QT^{*}\eta \tag{3.18}$$

$$QF = QA/ENRC = QT^{*}\eta/ENRC \tag{3.19}$$

$$QL = QP/L = QT^{*}\eta/(ENRC^{*}PL) \tag{3.20}$$

or

$$QLP(1\text{-}3) = QT^{*}FPC(1\text{-}3)/(ENRC^{*}PL) \tag{3.21}$$

where $FPC=\eta$.

Two other properties needed for the fuel are its thermal conductivity and specific heat. Eq. (3.22) gives an empirical relationship for the thermal conductivity (Shinaishin, 1976).

$$k_f = F(D)^{*}\left[\frac{38.24}{T + 129.2} + 6.1256E\text{-}13^{*}T^3\right] \tag{3.22}$$

where

$$T = 273 + 5/9\ (\overline{T}_f - 32) \tag{3.23}$$

$$F(D) = 1.079\ ^{*}\left[\frac{D}{1 + 0.5^{*}(1\text{-}D)}\right] \tag{3.24}$$

with D being the ratio of fuel density to theoretical density. Rewriting Eq. (3.22) as it appears in FATFAD, Fuel Temperature Conductivity = TCCF(1-3) =

$$100\left\{F(1\text{-}3)*\left[\frac{38.24}{TCF(1\text{-}3)+129.2} + 6.1256E\text{-}13*TCF(1\text{-}3)^3\right]\right\} \tag{3.25}$$

where TCF(1-3) are the fuel temperatures for channels 1-3, given by Eq. (3.23), and F(1-3) are defined by Eq. (3.24), with D written as FRO.

Specific heat of the fuel is also given by an empirical relationship (Shinaishin, 1976) where the fuel temperature is in degrees C.

$$C_{p_f} = 0.1091351924 + 7.75289753E\text{-}5*T - 6.121778E\text{-}8*T^2 + 2.046305E\text{-}11*T^3 \tag{3.26}$$

Rewriting,

$$\text{Fuel Specific Heat} = CPCF = 4.1868E{+}3*(0.1091351924 + 7.75289753E\text{-}5*TCF - 6.121778E\text{-}8*TCF^2 + 2.046305E\text{-}11*TCF^3) \tag{3.27}$$

with TCF being expressed in degrees C, and the constant in front being the conversion factor from English to SI units.

The gap between the fuel and the cladding has a convective heat transfer coefficient expressed by Eq. (3.28) (Shinaishin, 1976),

$$h_g = 0.132 + \frac{0.1167\ T_g^{\frac{1}{2}} - 2.36}{G/D_p} + 0.6391\left(\frac{B}{1+B}\right) \tag{3.28}$$

where

$$T_g = T_c + 273 + 0.2723*(1 + 0.08*G/D_p)*q' \tag{3.29}$$

$$B = \mathrm{Exp}(-7.0 + 0.035*q' - 6.3*G/D_p) \qquad (3.30)$$

and G/D_p is the cold gap to pellet diametral ratio expressed in percent.

$$\text{Gap Convective Heat Transfer Coefficient} = \mathrm{HCG}(1\text{-}3) =$$
$$\Big\{0.132 + (0.1167*\mathrm{TG}(1\text{-}3)^{\frac{1}{2}} - 2.36)/\mathrm{CGPDR} + 0.6391 * [\mathrm{B}(1\text{-}3)/(1.0+\mathrm{B}(1\text{-}3))]\Big\}\ 1.0\ \mathrm{E}{+}4 \qquad (3.31)$$

with

$$\mathrm{TG}(1\text{-}3) = \mathrm{TCC}(1\text{-}3) + 273.0 + 0.2723*(1.0+0.08*\mathrm{CGPDR}) * \mathrm{QLP}(1\text{-}3) \qquad (3.32)$$

$$\mathrm{B}(1\text{-}3) = \mathrm{Exp}(-7.0 + 0.035*\mathrm{QLP}(1\text{-}3) - 6.3*\mathrm{CGPDR}) \qquad (3.33)$$

TG is the temperature of the gas in the gap, TCC is the temperature of the cladding, and CGPDR is G/D_p. Again, the constant in front is the conversion factor from English to SI units.

Next, the cladding specific heat and thermal conductivity must be found. The cladding material is SS-316 and both thermodynamic properties (Goldsmith, Waterman and Hirschhorn, 1961) are expressed by an empirical fit, found using SUPER LEAST, a least squares fitting program. Eq. (3.34) gives the relationship for specific heat, while thermal conductivity is given by Eq. (3.35).

$$\text{Cladding Specific Heat} = \mathrm{CPCC}(1\text{-}3) = 4.1868\mathrm{E}{+}3 * (0.14937593\quad 0.39506964\mathrm{E}{-}4*\mathrm{TFCC}(1\text{-}3) + 0.2678125\mathrm{E}{-}7*\mathrm{TFCC}(1\text{-}3)^2) \qquad (3.34)$$

where TFCC is the cladding temperature expressed in degrees F and the constant in front is the conversion factor.

$$\text{Cladding Thermal Conductivity} = \text{TCCC}(1\text{-}3) = 1.73073*(7.7388464 + 0.40721437\text{E-}2*\text{TFCC}(1\text{-}3)) \quad (3.35)$$

with the conversion factor in front.

For liquid sodium, many of the properties are similar in form to those found in Chapter 2, and only the variable names are changed. These parameters are thermal conductivity (TCCS), Eq. (2.6), average specific heat (CPAS), Eq. (2.4), viscosity (UMCS), Eq. (2.8), density (RHOCS), Eq. (2.2), Reynolds number (RECS), Eq. (2.11), and Prandit number (PRCS), Eq. (2.12). The temperatures in each of the above equations are also different. They are TFS for thermal conductivity, TCSA for specific heat, TRS for viscosity, and TFS for density, with units being the same as their counterparts in Chapter 2. The Nusselt number for liquid sodium is given by the relation found in Eq. (3.36) (Additon et al., 1976).

$$\text{Sodium Nusselt Number} = \text{UNCS}(1\text{-}3) = 4.0 + 0.16*(\text{PC/DHC})^{5} + 0.006288*(\text{PC/DHC})^{3.8}*\text{PCCS}(1\text{-}3)^{0.86} \quad (3.36)$$

where DHC and PC are the hydraulic diameter and resulting perimeter of the sodium channel, respectively, and

$$\text{PCCS}(1\text{-}3) = \text{RECS}(1\text{-}3)*\text{PRCS}(1\text{-}3) \quad (3.37)$$

The convective film heat transfer coefficient is given by

$$h_f = (Nu * k)/D_h \tag{3.38}$$

or

Convective Film Heat Transfer Coefficient = HCS(1-3) =

UNCS(1-3)*TCCS(1-3)/DHC (3.39)

Next the sodium temperature (TCS), cladding temperature (TCC), and fuel temperature (TCF) will be derived, using energy conservation. Fig. 3.3.

Performing the same steps as in Chapter 2, Eqs. (2.14) through (2.18), the sodium temperature can be evaluated.

$$\Delta U = q'_{in} + q_{in} - q_{out} \tag{3.40}$$

With incompressible flow Eq. (3.40) becomes

$$mc_p \left.\frac{dT}{dt}\right)_{out} = q'_{in} + \dot{m}\bar{c}_p(T_{in}-T_{out}) \tag{3.41}$$

or

Sodium Temperature = $\frac{d}{dt}$ (TCS) = [QNA*CPAS*(TLP-TCS)]/

(CPAS*XMASS) (3.42)

where CPAS, XMASS, and WRDPP are the sodium average specific heat, mass, and mass flow rate, per pin, for a fuel region. QNA is the heat generated per pin which reaches the sodium region. The sodium mass is just the sodium density (RHOCS) multiplied by sodium flow volume

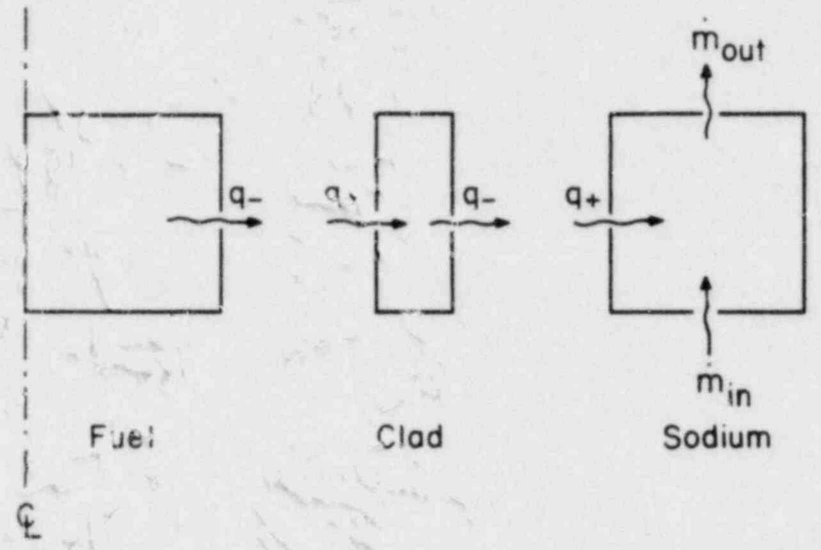


Figure 3.3. Exploded cutaway view of fuel pin and flow channel with heat and mass flows.

(VOL/ENRC), where ENRC is the number of pins per region and VOL, the total sodium flow volume of the region.

Once again applying the conservation of energy, and assuming no axial heat flow, the equation for cladding temperature is

$$mc_p \frac{d\bar{T}_c}{dt} = q' = \left[\frac{1}{A_c h_c} + \frac{\ln(D_{oc}/D_c)}{2k_c \pi L_c} \right]^{-1} (\bar{T}_c - \bar{T}_s) \qquad (3.43)$$

This can also be written

$$\text{Cladding Temperature} = \frac{d}{dt}(\text{TCC}) = [\text{QF-UAC*(TCC-TCSA)}]/$$

$$\text{(CM*CPCC)} \qquad (3.44)$$

Here, CM and CPCC are the cladding mass and specific heat, respectively. Average sodium temperature is given by TCSA, and UAC is the overall heat transfer coefficient, represented by Eq. (3.45). QF is the heat reaching the cladding from the fuel. It should be noted that TCC is an area weighted average cladding temperature, and is evaluated at the point where both inside and outside cladding areas are equal (see Fig. 3.2).

$$\text{Overall Heat Transfer Coefficient} = \text{UAC} =$$

$$\left[\frac{1.0}{\text{HSC*CAREA2}} + \frac{\text{ALOG(DOC/DC)}}{\text{2.0*TCC*PI*PL}} \right]^{-1} \qquad (3.45)$$

where DC is the diameter of the cladding at whatever point TCC is evaluated, DOC is the cladding outer diameter, and CAREA2 is the cladding surface area.

Finally, the fuel temperature takes on the form given by Eq. (3.46).

$$mc_p \frac{d\overline{T}_f}{dt} = q' - \left[\frac{1}{8\pi k_f L} + \frac{1}{h_g A} + \frac{\ln(D_c/D_{Ic})}{2k_c \pi L_c} \right]^{-1} (\overline{T}_f - \overline{T}_c) \quad (3.46)$$

which is rewritten in the following form

$$\text{Fuel Temperature} = \frac{d}{dt}\,(\text{TCF}) = [\text{QP-UAF*(TCF-TCC)}]/(\text{FM*CPCF}) \quad (3.47)$$

Once again, fuel mass and specific heat are given by FM and CPCF, respectively. Also, UAF is the overall heat transfer coefficient shown in the next equation.

$$\text{Overall Heat Transfer Coefficient} = \text{UAF} =$$

$$\left[\frac{1.0}{\text{8.0*PI*PL*TCCF}} + \frac{1.0}{\text{HCG*CAREAI}} + \frac{\text{ALOG(DC/DIC)}}{\text{2.0*TCCC*PI*PL}} \right]^{-1} \quad (3.48)$$

where DIC is the cladding inner surface diameter, CAREAI is the surface area of the gap space, HCG is the gap convective heat transfer coefficient (Eq. 3.31), and TCCF is the fuel thermal conductivity (Eq. 3.25).

Channels 4 and 5

Determination of sodium temperatures in channels 4 and 5 is approached as in channels 1 through 3. In this case, however, there is no heat generation due to fuel. Instead, a certain fractional power output was found (Westinghouse Hanford Company, 1975) due to each region during normal operation. It is assumed that this fractional power (FPC4, FPC5) remains constant even during transient operation. Knowing this, the temperature equations take on the same form as for the fuel region case (Eq. 3.42). The only difference is that the variables have other values; different mass, specific heat, and mass flow rate.

Determination of the center pin fuel, cladding, and sodium temperatures is done in the same manner as for the three fuel channels. Results of this analysis are shown below.

$$\text{Hot Channel Sodium Temperature} = \frac{d}{dt}(\mathrm{TCSHC}) =$$

$$\frac{1.0}{\mathrm{CPASHC*XMASHC}} * \left\{\mathrm{QNAHC+WRDHC*[CPASHC*(TLP-TCSHC)]}\right\} \tag{3.49}$$

$$\text{Hot Channel Cladding Temperature} = \frac{d}{dt}(\mathrm{TCCHC}) =$$

$$\mathrm{[QFHC-UACHC*(TCCHC-TCSAHC)]/(CM*CPCCHC)} \tag{3.50}$$

$$\text{Hot Channel Fuel Temperature} = \frac{d}{dt}(\mathrm{TCFHC}) =$$

$$\mathrm{[QPHC-UAFHC*(TCFHC-TCCHC)]/(FM*CPCFHC)} \tag{3.51}$$

All of the above variables have the same meaning and form as the variables used for the three fuel regions. What makes this calculation different, however, is the mass flow rate (WRDHC) and the heat produced by the pin (QPHC). For the center pin, the mass flow rate is 95 percent of that used in Region One and the heat produced per pin is 6 percent higher than that used in Region One.

Reactor Scram

There are eight conditions built into the simulator which can cause the reactor to scram. Four of these are primary conditions and four are secondary conditions, as summarized in Tables 3.1 and 3.2 (Westinghouse Hanford Company, 1975).

Table 3.1. Primary scram conditions with setpoints.

Primary Wide Range nuclear - high	≤ 112% Full Power
Primary Wide Range nuclear - low	≤ 10% Full Power
IHX Primary Outlet Temperature	≤ 50°F
Reactor Coolant Level	≤ 5" below operating level

Table 3.2. Secondary scram conditions with setpoints.

Reactor Outlet Temperature	≤ 75°F
Low Primary Loop Flow	≥ 60% Full Flow
Low Secondary Loop Flow	≥ 55% Full Flow
High Primary Flow	≤ 112% Full Flow

If a transient situation causes a setpoint condition to be violated, that particular scram signal will be initiated, and, with the appropriate time response delay, the reactor will be scramed. There is also a one second time delay for the control rods to be fully inserted.

Each primary rod bank is worth eight dollars, and there are six rod banks. The secondary rod bank is worth \$1.88, and there are three secondary banks.

Kinetics

In this simulator the reactor power is determined using the point-reactor kinetics equations, Eqs. (3.52) and (3.53), except that the prompt-jump approximation is assumed.

$$\frac{dn(t)}{dt} = \frac{\rho-\beta}{\ell} n(t) + \sum_i \lambda_i C_i + q(t) \qquad (3.52)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta}{\ell} n(t) - \lambda_i C_i(t) \qquad (3.53)$$

By normalizing the neutron power, n(t), and delayed precursor concentration, $C_i(t)$, the resulting equations for power and precursor concentration become

$$N(t) = \sum_i \frac{\beta_i}{\beta} D_i(t)/(1 - \rho/\beta) \qquad (3.54)$$

$$\frac{d\, D_i(t)}{dt} = \lambda_i [N(t) - D_i(t)] \qquad (3.55)$$

where

$$N(t) = n(t)/n(o) \tag{3.56}$$

$$D_i(t) = C_i(t)/C_i(o) \tag{3.57}$$

and i runs from 1 to 6 (the number of delayed neutron groups). In the model, Eqs. (3.54) and (3.55) take on the following form

$$\text{Neutron Power} = \text{EN} = \text{BDOB}/(1.0 - \text{ROD}) \tag{3.58}$$

$$\text{Precursor Concentration} = \frac{d}{dt}(\text{CN}) = \text{AMDA}*(\text{EN-CN}) \tag{3.59}$$

where AMDA is the precursor half life, BDOB is the sum of the products of each of the precursor yields and its half life, divided by the total delayed neutron fraction. Reactivity, ROD, is expressed in dollars and is given by Eq. (3.60).

$$\text{Reactivity} = \text{ROD} = \text{ROCRD} + \text{ROFBD} + \text{ROEXCD} + \text{ROAUTO} \tag{3.60}$$

when ROCRD is the reactivity worth given to the system, ROFBD is the feedback reactivity (Eq. 3.59) (Shinaishin, 1976), ROEXCD is the excess reactivity needed at steady state to offset the negative reactivity given the system by ROFBD, and ROAUTO is the reactivity, determined by the flux controller, which keeps the reactor critical at the new operating point.

$$\begin{aligned}\text{Feedback Reactivity} = \text{ROFBD} = [&100.0*(\text{DOPC/BETAT})* \\ &\text{ALOG(TVAFR/TIR)} + \text{SODDC}*(\text{TVAS-TI}) + \text{AXEC}* \\ &(\text{TVAF-TI}) + \text{REC}*(\text{TVAS-TI})]/100.0\end{aligned} \tag{3.61}$$

The symbols in Eq. (3.61) are (Project Management Corporation, 1975)

DOPC = Doppler Coefficient

SODDC = Sodium density expansion coefficient (¢/°K)

AXEC = Axial expansion coefficient (¢/°K)

REC = Radial expansion coefficient (¢/°K)

BETAT = Total delayed neutron fraction

TVAFR = Averaged fuel temperature in degree R

TVAS = Volume averaged sodium temperature in degree K

TVAF = Volume averaged fuel temperature in degree K

TIR = Cold Stand-by temperature

Determination of steady state values of reactor variables is given in Appendix B.

CHAPTER 4

MOMENTUM AND PRESSURE EQUATIONS

Momentum Equations

All the momentum equations in FATFAD have the same general form, therefore the momentum equation will be derived for a general case and then applied to each component. For the case of a cylindrical flow channel, Fig. 4.1, the momentum equation looks like Eq. (4.1).

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \frac{\partial}{\partial x} (\rho \vec{v} \cdot \vec{v}) = - \vec{\nabla} P - \rho \vec{g} - \vec{\nabla} \tau \tag{4.1}$$

Noting that $\rho v = \dot{m}/A$, Eq. (4.1) becomes

$$\frac{1}{A} \frac{\partial \dot{m}}{\partial t} + \frac{1}{A} \vec{\nabla} \cdot (\dot{m} \vec{v}) = - \vec{\nabla} P - \rho \vec{g} - \vec{\nabla} \tau \tag{4.2}$$

Using the vector identity

$$\vec{\nabla} \cdot (\dot{m} \vec{v}) = \dot{m} \vec{\nabla} \cdot \vec{v} + \vec{v} \cdot \vec{\nabla} \dot{m}$$

and realizing that for incompressible flow $\vec{\nabla} \dot{m} = 0$, Eq. (4.2) reduces to

$$\frac{1}{A} \frac{\partial \dot{m}}{\partial t} + \frac{\omega}{A} \vec{\nabla} \cdot \vec{v} = - \vec{\nabla} P - \rho \vec{g} - \vec{\nabla} \tau \tag{4.3}$$

or

$$\frac{1}{A} \frac{\partial \dot{m}}{\partial t} + \frac{\dot{m}}{\rho A^2} \vec{\nabla} \cdot \dot{m} = - \vec{\nabla} \quad - \rho \vec{g} - \vec{\nabla} \tau \tag{4.4}$$

Rewriting the gradient and divergence terms

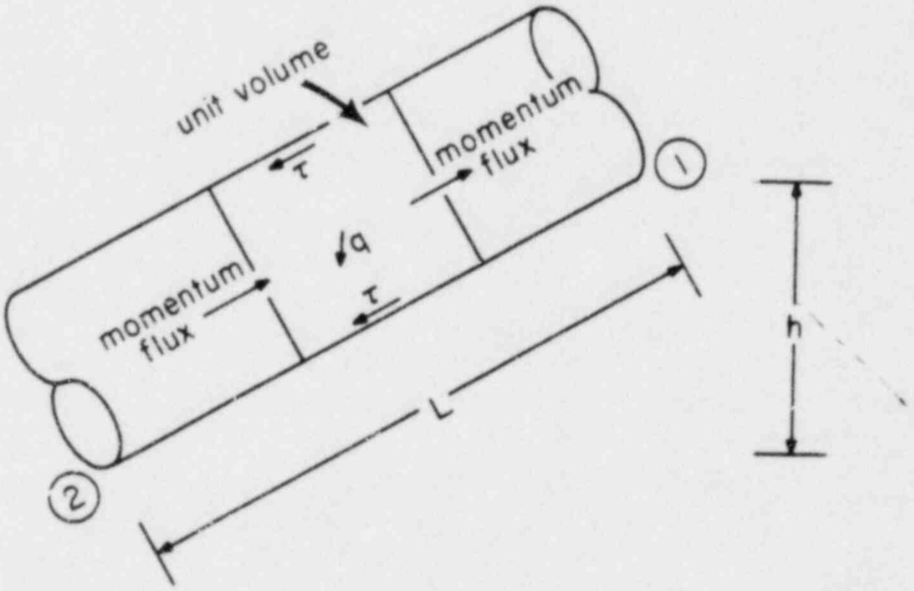


Figure 4.1. Pipe section with forces for momentum balance.

$$\frac{1}{A}\frac{\partial \dot{m}}{\partial t} - \left.\frac{\dot{m}^2}{\rho A^2}\right)_2 + \left.\frac{\dot{m}^2}{\rho A^2}\right)_1 = P_2 - P_1 - \rho g h - P_f \tag{4.5}$$

the general form of the differential equation becomes,

$$\frac{\partial \dot{m}}{\partial t} = \frac{A}{L}\left[\left.\frac{\dot{m}^2}{\rho A^2}\right)_2 - \left.\frac{\dot{m}^2}{\rho A^2}\right)_1 + P_2 - P_1 - \rho g h - P_f\right] \tag{4.6}$$

All the terms in Eq. (4.6) except one are self explanatory; P_f is the pressure loss due to friction along the sides of the channel.

With the momentum equation as derived, mass flow rates can be expressed for all the necessary components.

Reactor Core

$$\text{Flow Rate} = \frac{d}{dt}(\text{WRD}) = \text{AOL}^*\Big[\text{PLP-PUP-YC*G*RHOC}$$

$$+\left(\frac{\text{WRD}}{\text{AC}}\right)^2 * (1.0/\text{RHOLP} - 1.0/\text{RHOC} - \text{F12*AC}^2)\Big] \tag{4.7}$$

Since the core has five channels, there are five equations such as Eq. (4.7). All the variables have the suffix 1 through 5. PLP and RHOLP are pressure and density in the lower plenum, respectively. Upper plenum pressure is PUP, density at the outlet of the core is RHOC, and F12 is the friction term. Lastly, AC is the cross-sectional flow area, AOL is the cross-sectional area divided by the active core length, and YC is the height from the lower plenum inlet to the core outlet.

IHX

$$\text{Flow Rate} = \frac{d}{dt}\,(\text{WIXP}) = \text{AOLXP}*\Bigg[\text{POUT12-PIN13-RHOXP*G*Y}$$
$$+\left(\frac{\text{WIXP}}{\text{PAXP1}}\right)^2 * \left(\frac{1.0}{\text{ROUT12}} - \frac{1.0}{\text{ROIN13}} - \text{FXP1*PAXP1}^2\right)\Bigg] \qquad (4.8)$$

All the variables have the same meanings as in Eq. (4.7), except that the suffix 2 pertains to the IHX inlet side and 3 to the IHX outlet size; see Fig. 4.2. The 1 used in the suffix stands for the one loop side, whereas the two loop side is represented by 2.

Piping

For each pipe section (see Fig. 4.2), there is a momentum equation having the general form given by Eq. (4.6). Equation (4.9) models sodium flow rate for the one loop side, but the two loop model uses the same equation with different piping dimensions and notation (suffix 1 instead of 2).

$$\text{Piping Flow Rate} = \frac{d}{dt}\,(\text{WL1}) = \text{AOL1}*\Bigg[\text{PIN1-POUT1-RHOL1*G*YL1}$$
$$+\left(\frac{\text{WL1}}{\text{PAL1}}\right)^2 * \left(\frac{1.0}{\text{ROIN1}} - \frac{1.0}{\text{ROUT1}} - \text{FL1*PAL1}^2\right)\Bigg] \qquad (4.9)$$

Once again, all variables have the same meaning as their counterparts in Eq. (4.7); only the dimensions have changed. To represent each pipe segment, each variable has a suffix 1, 2, or 3, depending on which segment is being considered (ex., WL11 is the flow rate in the first pipe segment).

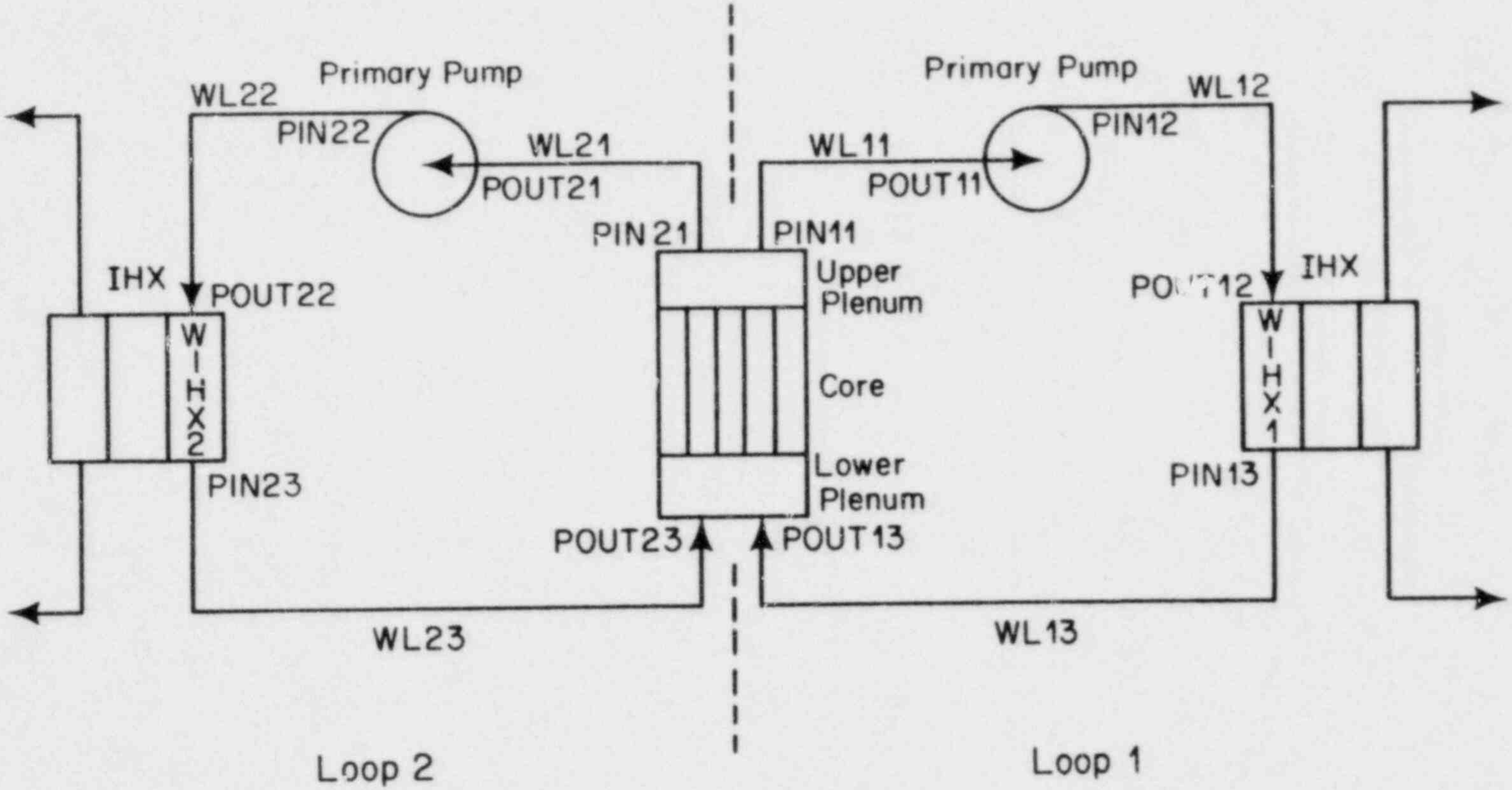


Figure 4.2. Primary HTS with pipe connections.

Pressure Equations

To determine pressures at the various divisions (see Fig. 4.2), a system of 13 algebraic equations and 13 unknowns must be solved. The 13 algebraic equations are the right hand sides of all the momentum equations presented in the previous section. By equating the right hand sides, conservation of mass is assumed throughout the primary system.

Realizing that the flow rate from the core is equal to the sodium flow out of the upper plenum, the following equality is formed.

$$\sum_{i=1}^{5} \mathrm{AOL}_i * (\mathrm{PLP}-\mathrm{PUP}-\mathrm{RHOC}_i * G * \mathrm{YC} + \mathrm{T3}_i) =$$

$$\sum_{j=1}^{2} \mathrm{AOL}_j 3 * (\mathrm{PIN}_j 3 - \mathrm{POUT}_j 3 - \mathrm{RHOL}_j 3 * G * \mathrm{YL}_j 3 + \mathrm{REST}_j 3) \qquad (4.10)$$

The two variables $\mathrm{T3}_i$ and $\mathrm{REST}_j 3$, are shorthand notation for the last term of the momentum equation for the reactor core and piping, respectively (see Eqs. 4.7 and 4.9). Knowing that the pressure into the lower plenum is

$$\text{Pressure Into Lower Plenum} = \mathrm{POUT}_j 3 = \mathrm{PLP}+\mathrm{DELP}_j 3 \qquad (4.11)$$

the lower plenum pressure at the inlet to the core, PLP, can be determined by substituting Eq. (4.11) into Eq. (4.10) and rearranging terms.

$$\begin{aligned}
&\mathrm{PLP} * \left(1.0 + \frac{\mathrm{AOL13+AOL23}}{\mathrm{AOLR}}\right) = \frac{\mathrm{AOL13}}{\mathrm{AOLR}} * (\mathrm{PIN13-DELP13-RHOL13}* \\
&\quad \mathrm{G*YL13} + \mathrm{REST13}) + \frac{\mathrm{AOL23}}{\mathrm{AOLR}} * (\mathrm{PIN23-DELP23-RHOL23*G*YL23} \\
&\quad + \mathrm{REST23}) - \frac{\mathrm{AOL1}}{\mathrm{AOLR}} * (\mathrm{-PUP-RHOC1*G*YC+T31}) - \frac{\mathrm{AOL2}}{\mathrm{AOLR}} * \\
&\quad (\mathrm{-PUP-RHOC2*G*YC+T32}) - \frac{\mathrm{AOL3}}{\mathrm{AOLR}} * (\mathrm{-PUP-RHOC3*G*YC+T33}) \\
&\quad - \frac{\mathrm{AOL4}}{\mathrm{AOLR}} * (\mathrm{-PUP-RHOC4*G*YC+T34}) - \frac{\mathrm{AOL5}}{\mathrm{AOLR}} * (\mathrm{-PUP-RHOC5*G*YC} \\
&\quad + \mathrm{T35}) \qquad (4.12)
\end{aligned}$$

where

$$\mathrm{AOLR} = \mathrm{AOL1} + \mathrm{AOL2} + \mathrm{AOL3} + \mathrm{AOL4} + \mathrm{AOL5} \qquad (4.13)$$

All the terms on the R.H.S. in Eq. (4.12) are known except PIN13 and PIN23, the pressures at the inlet of the pipe which connects the IHX to the reactor for the one and two loop sides, respectively.

By equating the R.H.S. of the momentum equations for the section of pipe between the reactor and the pump (WL11) and for the section between the IHX and the reactor (WL13), an expression for PIN13 can be determined.

$$\begin{aligned}
&\text{Pressure into Pipe Section 3} = \mathrm{PIN13} = \frac{\mathrm{AOL11}}{\mathrm{AOL13}} * \\
&\quad (\mathrm{PIN11-POUT11-RHOL11*G*YL11+REST11}) + \mathrm{POUT13} \\
&\quad + \mathrm{RHOL13*G*YL13} - \mathrm{REST13} \qquad (4.14)
\end{aligned}$$

In this equation, the only unknown is POUT11, the pressure at the exit of the pipe connecting the reactor with the pump. The pressure at the inlet of this pipe, PIN11, is

$$\text{Pressure into Pipe Section 1} = \text{PIN11} = \text{PUP-DELP11} \qquad (4.15)$$

where PUP is the pressure at the core exit, determined by the sum of the cover gas pressure and the hydrostatic pressure of the upper plenum sodium, and DELP11 is the pressure difference due to height change between the top of the core and the upper plenum exit. The two loop pressure, PIN23, has the same form.

A relation for POUT11 is obtained by taking the momentum equations for the piping between the reactor and the pump, and between the pump and the IHX, and equating their right hand sides. The result is

$$\begin{aligned} \text{Pressure out of Pipe Section 1} &= \text{POUT11}*\left(1.0 + \frac{\text{AOL12}}{\text{AOL11}}\right) \\ &= \text{PIN11-RHOL11*G*YL11+REST11} - \frac{\text{AOL12}}{\text{AOL11}} * \\ &\quad \text{(PUMP1-POUT12-RHOL12*G*YL12+REST12)} \qquad (4.16) \end{aligned}$$

In Eq. (4.16), the only unknown is POUT12, the pressure on the outlet side of the pipe connecting the pump and the IHX. PUMP1 is the pressure drop across the pump, determined by the pump model (Boadu, 1981).

In obtaining Eq. (4.16), we also used Eq. (4.17) relating PUMP1 with PIN12, the pressure at the pipe inlet connecting the pump and IHX.

$$\text{Pressure into Pipe Section 2} = \text{PIN12-POUT11+PUMP1} \qquad (4.17)$$

Once again, the unknown pressure is determined by setting the right hand sides of two momentum equations equal to each other and solving for the desired pressure. For POUT12, flow rates WIHX1 and WL13 are equated.

$$\text{Pressure out of Pipe Section 2} = \text{POUT12} = \frac{\text{AOL13}}{\text{AOLXP1*ENXT1}} * \\ (\text{PIN13-POUT13-RHOL13*G*YL13+REST13}) \\ + \text{PIN13+RHOXP1*G*YXP1-RESTX1} \qquad (4.18)$$

PIN13, the unknown in Eq. (4.18), must be solved for in a slightly different manner. First Eq. (4.18) is substituted into Eq. (4.16). Then the resulting expression, Eq. (4.19), is substituted into Eq. (4.14). Substituting,

$$\text{POUT11*}\left(1.0 + \frac{\text{AOL12}}{\text{AOL11}}\right) = \text{PIN11-RHOL11*G*YL11+REST11} - \frac{\text{AOL12}}{\text{AOL11}} * \\ \Bigg[\text{PUMP1} - \frac{\text{AOL13}}{\text{AOLXP1*ENXT1}} * (\text{PIN13-POUT13-RHOL13*G*YL13} \\ + \text{REST13}) - \text{PIN13-RHOXP1*G*YXP1+RESTX1-RHOL12*G*YL12} \\ + \text{REST12}\Bigg] \qquad (4.19)$$

By performing the second substitution, PIN13, the inlet pressure for the pipe connecting the IHX to the reactor, takes on the final form given by Eq. (4.20).

$$\begin{aligned}
&\mathrm{PIN13}*\Big[1.0+\Big(\frac{\mathrm{AOL12}}{\mathrm{AOLXP1*ENXT1}}+\frac{\mathrm{AOL12}}{\mathrm{AOL13}}\Big)/\Big(1.0+\frac{\mathrm{AOL12}}{\mathrm{AOL11}}\Big)\Big]\\
&=\frac{\mathrm{AOL11}}{\mathrm{AOL13}}*\Big[\mathrm{PIN11}-\{\mathrm{PIN11}-\mathrm{RHOL11}*\mathrm{G}*\mathrm{YL11}+\mathrm{REST11}-\frac{\mathrm{AOL12}}{\mathrm{AOL11}}*\\
&[\mathrm{PUMP1}-\frac{\mathrm{AOL13}}{\mathrm{AOLXP1*ENXT1}}*(-\mathrm{POUT13}-\mathrm{RHOL13}*\mathrm{G}*\mathrm{YL13}+\mathrm{REST13})\\
&-\mathrm{RHOXP1}*\mathrm{G}*\mathrm{YXP1}+\mathrm{RESTX1}-\mathrm{RHOL12}*\mathrm{G}*\mathrm{YL12}+\mathrm{REST12}]\}/\\
&\Big(1.0+\frac{\mathrm{AOL12}}{\mathrm{AOL11}}\Big)-\mathrm{RHOL11}*\mathrm{G}*\mathrm{YL11}\Big]+\mathrm{POUT13}+\mathrm{RHOL13}*\mathrm{G}*\mathrm{YL13}\\
&-\mathrm{REST13}
\end{aligned}\tag{4.20}$$

The pressure out of the pipe connecting the IHX to the reactor, POUT13, is the only unknown. POUT13 is given by Eq. (4.10), which is a function of PLP, so that upon substituting Eqs. (4.20) and (4.11) into Eq. (4.12) an expression for PLP is obtained in which all terms are known. Performing the above steps and collecting like terms, the equation for PLP becomes

$$\begin{aligned}
&\text{Pressure at Core Inlet} = \mathrm{PLP} = \Bigg(\mathrm{AOL13}*\Big(\Big(\Big(\frac{\mathrm{AOL11}}{\mathrm{AOL13}}*\Big(\mathrm{PIN11}-\\
&\Big(\mathrm{PIN11}-\mathrm{RHOL11}*\mathrm{G}*\mathrm{YL11}+\mathrm{REST11}-\frac{\mathrm{AOL12}}{\mathrm{AOL11}}*\Big(\mathrm{PUMP1}+\frac{\mathrm{AOL13}}{\mathrm{AOLXP1*ENXT1}}*\\
&(\mathrm{DELP13}+\mathrm{RHOL13}*\mathrm{G}*\mathrm{YL13}-\mathrm{REST13})-\mathrm{RHOXP1}*\mathrm{G}*\mathrm{YXP1}+\mathrm{RESTX1}-\mathrm{RHOL12}*\mathrm{G}*\mathrm{YL12}+\\
&\mathrm{REST12}\Big)\Big)/\Big(1.0+\frac{\mathrm{AOL12}}{\mathrm{AOL11}}\Big)-\mathrm{RHOL11}*\mathrm{G}*\mathrm{YL11}+\mathrm{REST11}\Big)+\mathrm{DELP13}+\\
&\mathrm{RHOL13}*\mathrm{G}*\mathrm{YL13}-\mathrm{REST13}\Big)/\Big(1.0+\Big(\frac{\mathrm{AOL12}}{\mathrm{AOLXP1*ENXT1}}+\frac{\mathrm{AOL12}}{\mathrm{AOL13}}\Big)/\Big(1.0+\frac{\mathrm{AOL12}}{\mathrm{AOL11}}\Big)\Big)\\
&-\mathrm{DELP13}-\mathrm{RHOL13}*\mathrm{G}*\mathrm{YL13}+\mathrm{REST13}\Big)+\mathrm{AOL23}*\Big(\Big(\Big(\frac{\mathrm{AOL21}}{\mathrm{AOL23}}*\Big(\mathrm{PIN21}-\Big(\mathrm{PIN21}-\\
&\mathrm{RHOL21}*\mathrm{G}*\mathrm{YL21}+\mathrm{REST21}-\frac{\mathrm{AOL22}}{\mathrm{AOL21}}*\Big(\mathrm{PUMP2}+\frac{\mathrm{AOL23}}{\mathrm{AOLXP2*ENXT2}}*
\end{aligned}$$

$$
\begin{aligned}
&(\mathrm{DELP23+RHOL23\ast G\ast YL23-REST23}) - \mathrm{RHOXP2\ast G\ast YXP2+RESTX2-RHOL22\ast G\ast YL22} +\\
&\mathrm{REST22}\Big)\Big) / \left(1.0 + \frac{\mathrm{AOL22}}{\mathrm{AOL21}}\right) - \mathrm{RHOL21\ast G\ast YL21+REST21}\Bigg) + \mathrm{DELP23+RHOL23\ast G}\ast\\
&\mathrm{YL23-REST23}\Bigg) / \Big(1.0 + \left(\frac{\mathrm{AOL22}}{\mathrm{AOLXP2\ast ENXT2}} + \frac{\mathrm{AOL22}}{\mathrm{AOL23}}\right) / \left(1.0 + \frac{\mathrm{AOL22}}{\mathrm{AOL21}}\right)\Big)\\
&- \mathrm{DELP23-RHOL23\ast G\ast YL23+REST23}\Bigg) + \mathrm{AOL1\ast(PUP+RHOC1\ast G\ast YC-T31)} + \mathrm{AOL2}\ast\\
&\mathrm{(PUP+RHOC2\ast G\ast YC-T32)} + \mathrm{AOL3}\ast\mathrm{(PUP+RHOC3\ast G\ast YC-T33)} + \mathrm{AOL4}\ast\\
&\mathrm{(PUP+RHOC4\ast G\ast YC-T34)} + \mathrm{AOL5}\ast\mathrm{(PUP+RHOC5\ast G\ast YC-T35)}\Bigg)\Bigg/\Bigg(\mathrm{AOLR+AOL13}+\\
&\mathrm{AOL23} - \Big(\mathrm{AOL13}/\Big(1.0 + \left(\frac{\mathrm{AOL12}}{\mathrm{AOLXP1\ast ENXT1}} + \frac{\mathrm{AOL12}}{\mathrm{AOL13}}\right)/\left(1.0 + \frac{\mathrm{AOL12}}{\mathrm{AOL11}}\right)\Big)\Big)\ast\\
&\Big(1.0 + \mathrm{AOL11\ast AOL12}/\big(\mathrm{AOLXP1\ast ENXT1\ast(AOL11+AOL12)}\big)\Big) - \Big(\mathrm{AOL23}/\Big(1.0 +\\
&\left(\frac{\mathrm{AOL22}}{\mathrm{AOLXP2\ast ENXT2}} + \frac{\mathrm{AOL22}}{\mathrm{AOL23}}\right)/\left(1.0 + \frac{\mathrm{AOL22}}{\mathrm{AOL21}}\right)\Big)\Big)\ast\Big(1.0 + \mathrm{AOL21\ast AOL22}/\\
&\big(\mathrm{AOLXP2\ast ENXT2\ast(AOL21+AOL22)}\big)\Big)\Bigg)
\end{aligned}
\tag{4.21}
$$

With Eq. (4.21), the system of algebraic equations describing the pressures at various points is closed. In summary, the pressure equations incorporated in FATFAD are Eqs. (4.11), (4.15), (4.17), (4.18), (4.19), (4.20), and (4.21).

Determination of steady state values of momentum and pressure variables (i.e., mass flow rates, friction factors, etc.) is given in Appendix C.

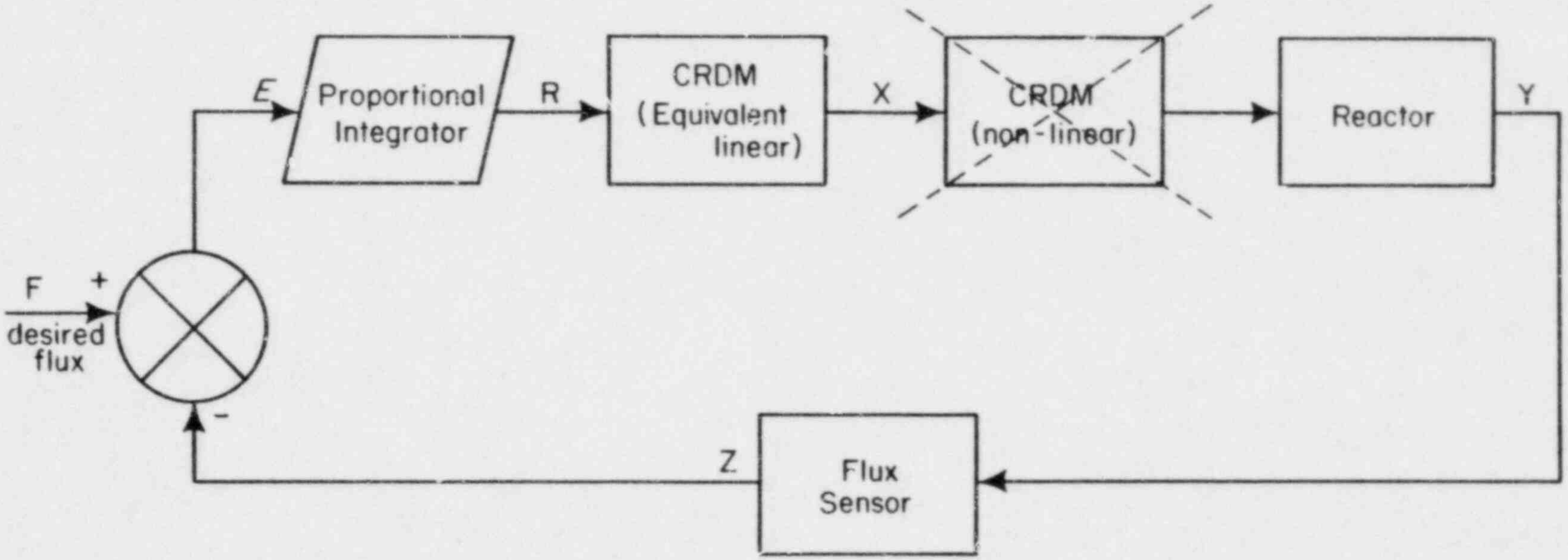
CHAPTER 5

FLUX CONTROL SYSTEM

To maintain the flux at its desired operating point, a flux control system is installed. The system is shown schematically in Fig. 5.1 (Schade, 1980). However, two changes had to be made to this system before implementation. The first is the omission of the non-linear control rod drive transfer function block. This is done because of the large increase in run time that the non-linear control rod drive mechanism (CRDM) causes, with no additional accuracy. Second, when no information could be obtained pertaining to the type of flux controller used in the FFTF, a proportional integral, PI, controller was assumed. Gains for this PI controller are unknown and must be determined. This problem is the subject of the rest of the chapter.

Gain Constant Determination

A schematic of the control scheme with its appropriate transfer functions is shown in Fig. 5.2. Determination of the gain constant for the proportional integral controller is performed using the Nichols Chart method (Kuo, 1975). Analysis of a control scheme by the Nichols method requires that there be no magnification of the desired output. For this system, the Flux Sensor transfer function is not unity, so a transformation of the control scheme must be performed. A generalized representation of the flux control scheme in the FFTF is shown in Fig. 5.3. Here F(s) is



Note: The non-linear CRDM will initially not be used because of the greatly increased run time needed and the many glitches which it causes on all output variables.

Figure 5.1. Block diagram for flux control system.

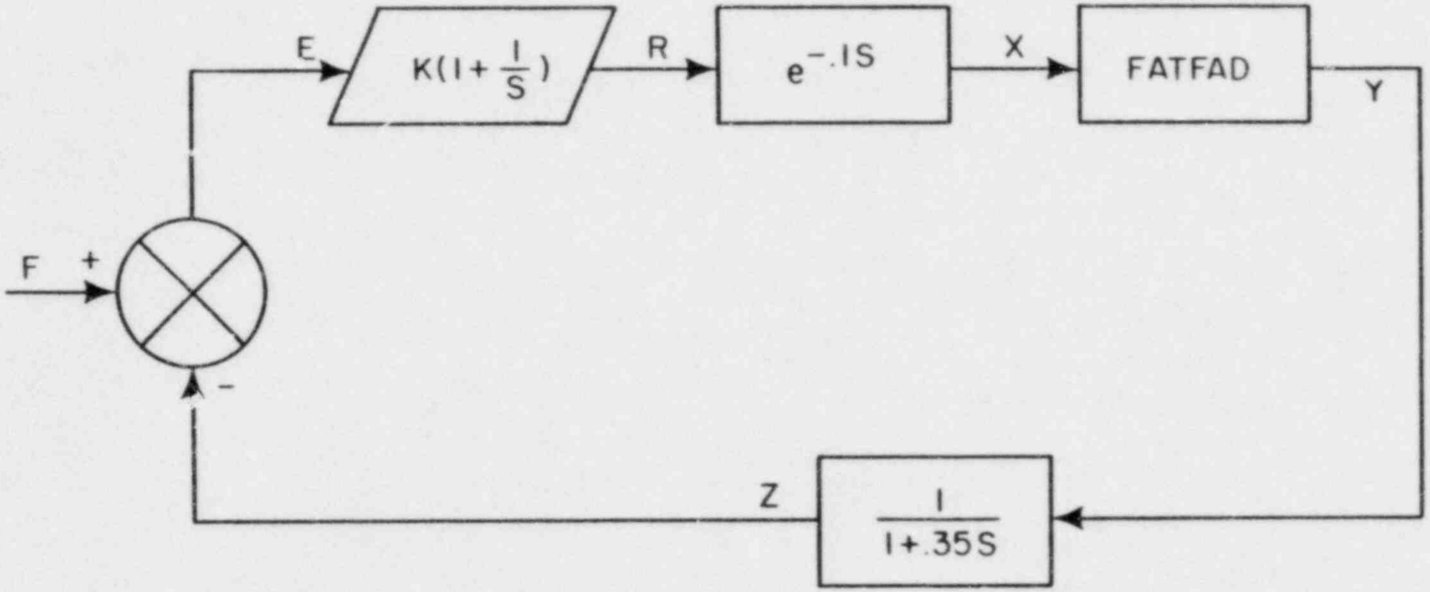


Figure 5.2. Transfer functions of flux control system.

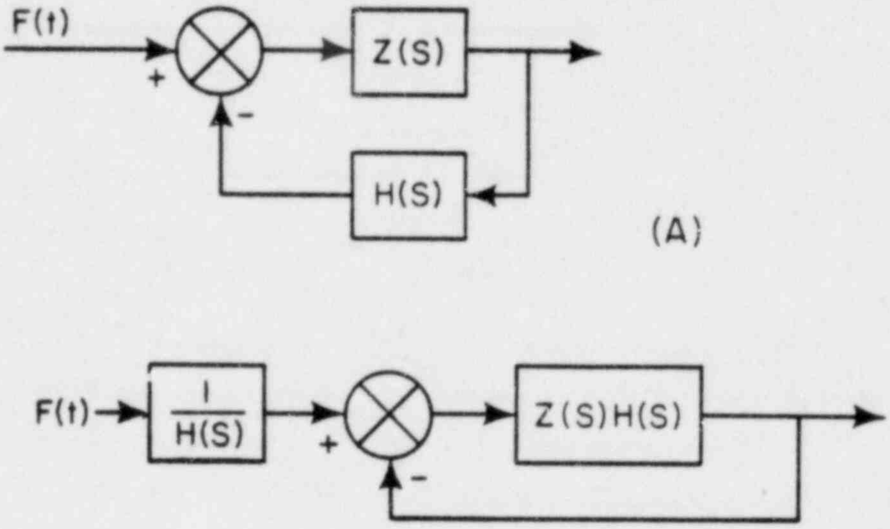


Figure 5.3. Equivalent representations of the flux control system.

(a) General control system with non-unity feedback.
(b) Transformed control system to give unity feedback.

the Laplace Transform of the desired flux, H(s) the transfer function for the Flux Sensor, and Z(s) is the product of the transfer functions for the PI Controller, CRDM (equivalent linear), and reactor. Performing this transformation, the control system to be analyzed is shown in Fig. 5.3.

All the differential equations describing the control scheme are shown below (for detailed derivation, see Appendix D).

$$\frac{d}{dt}(U1) = U2 \tag{5.1}$$

$$\frac{d}{dt}(U2) = PIOP-60.0*U2-1200.0*U1 \tag{5.2}$$

$$ZROD = \frac{d}{dt}(U2)-60.0*U2+1200.0*U1 \tag{5.3}$$

$$PIOP = CONST*ERR+WD \tag{5.4}$$

$$\frac{d}{dt}(WD) = ERR \tag{5.5}$$

$$\frac{d}{dt}(FLUX) = (EN-FLUX)/0.35 \tag{5.6}$$

$$ERR = FEN(ROCRD) - FLUX \tag{5.7}$$

The variable CONST in Eq. (5.4) is the gain constant which is to be determined from the Nichols method. Eq. (5.4) is also the equation which must be altered in accordance with the transformation illustrated in Fig. 5.3. This new equation for PIOP is

$$\frac{d}{dt}\,(\mathrm{PIOP}) = (\mathrm{ERR*CONST+WD-PIOP})/0.35 \tag{5.8}$$

The error signal, Eq. (5.7), is also altered; it becomes a function of the desired flux only. In determining the gain, the desired flux is a sinusoidal function. Due to difficulties caused by the control rod position equation, Eq. (5.3), ZROD is set equal to the proportional integral controller output PIOP (for the gain determination only).

With all necessary equations determined, several computer runs are made, each with a different frequency for the sinusoidally varying desired flux. Plotted are the reactor power, ENPR, and the transformed desired flux, FENDPP (output from transfer block on L.H.S. of the junction of transformed control system), against time. From each run, the period of oscillation for ENPR and FENDPP is determined, along with the phase angle between them. Using Eq. (5.9), the magnitude for that frequency is calculated.

$$\text{Magnitude} = M = 20\,\log_{10}\left(\frac{\mathrm{ENPR}}{\mathrm{FENDPP}}\right) \tag{5.9}$$

With the results from these runs, Bode plots for magnitude and phase are drawn, Figs. 5.4 and 5.5 respectively. Also, a plot of magnitude vs. phase is produced by combining the magnitude and phase curves, eliminating the frequency. Since the former analysis does not include the CRDM transfer function, it must now be added.

Using the Padé Approximation, the control rod drive transfer function can be represented as a ratio of two polynomials,

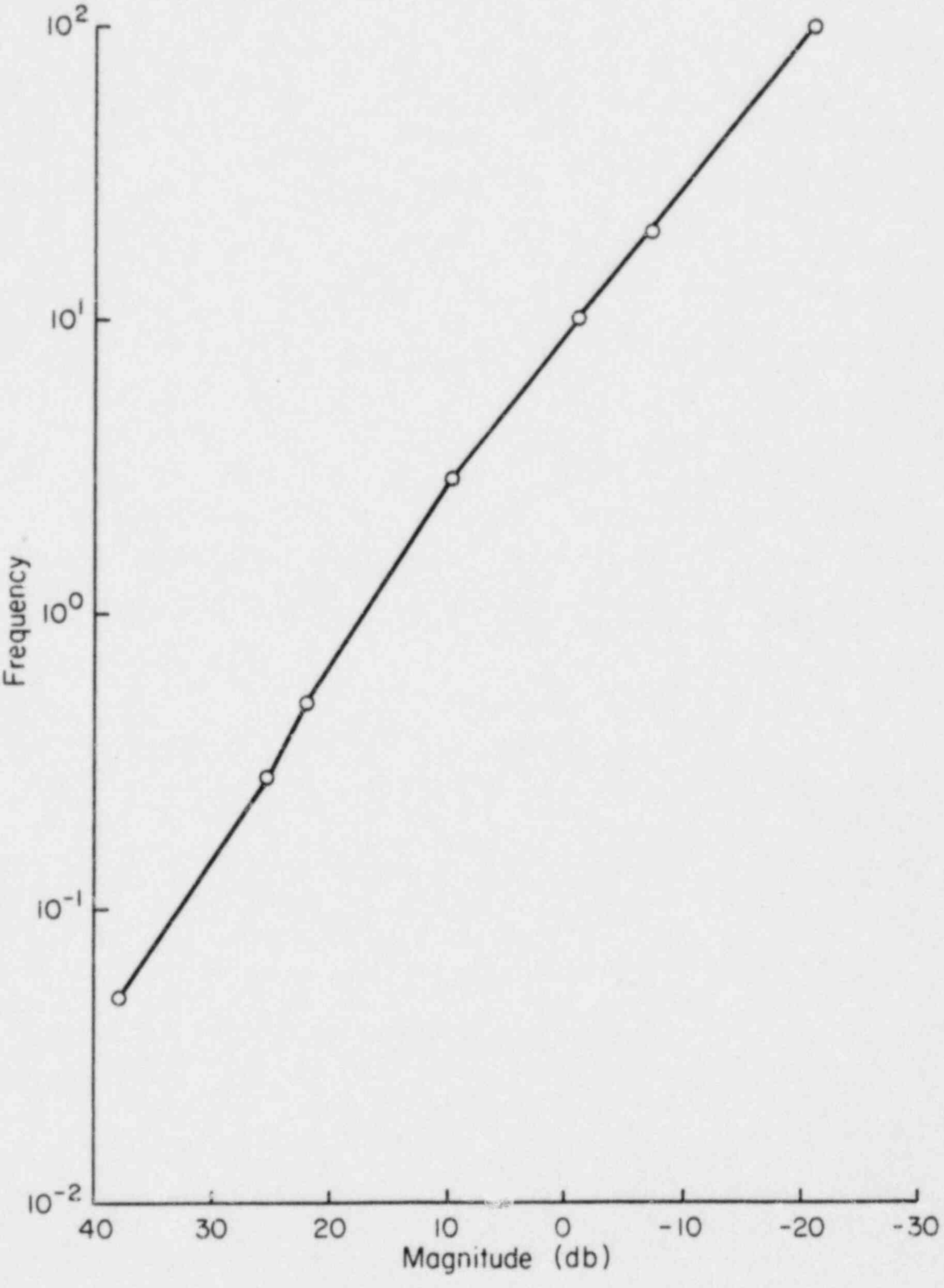


Figure 5.4. Frequency versus Magnitude (without CRDM).

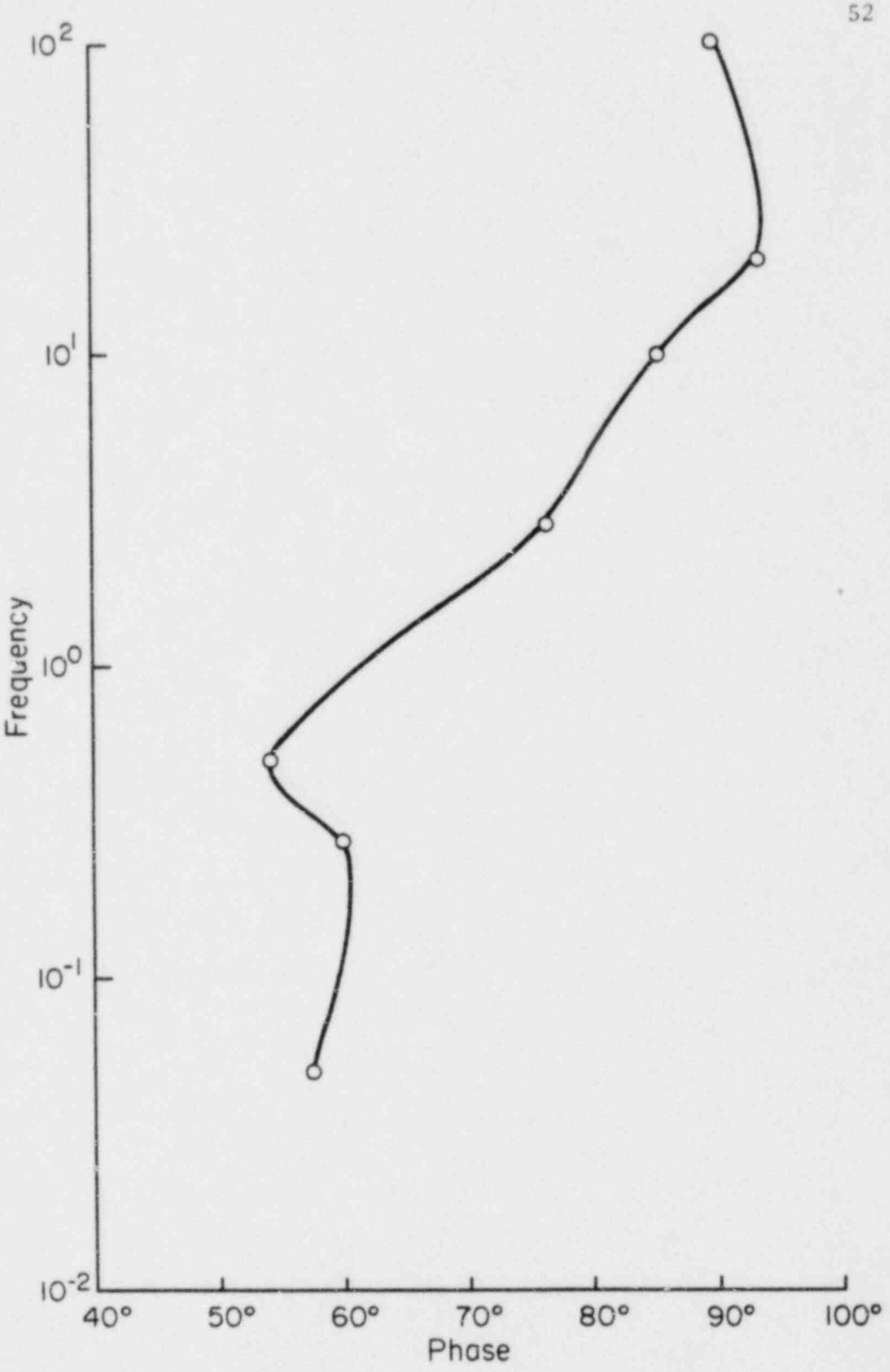


Figure 5.5. Frequency versus Phase (without CRDM).

$$G(s) = \frac{s^2 - as + b}{s^2 + as + b} \qquad (5.10)$$

where a=60 and b=1200. G(s) can be written in terms of two transfer functions (see Appendix D), with the following forms

$$G(s)_1 = 1.0/[1+(2\xi_1/\omega_1)s + (s/\omega_1)^2] \qquad (5.11)$$

and

$$G(s)_2 = 1+(2\xi_2/\omega_2)s + (s/\omega_2)^2 \qquad (5.12)$$

with

$$G(s) = G(s)_1\ G(s)_2 \qquad (5.13)$$

where

$\omega_1 = \omega_2 = \sqrt{b}$ (natural frequency)

$\xi_1 = a\omega_1/2b$

$\xi_2 = -a\omega_2/2b$

From Eq. (5.11) Bode plots for magnitude and phase are determined for $G(s)_1$, $G(s)_2$, and $G(s)$, Figs. 5.6 and 5.7 respectively. Combining graphs, a magnitude vs. phase plot is formed and is superimposed upon a similar plot for the other portion of the control scheme. Fig. 5.8 shows both curves for the flux control scheme with and without the CRDM, respectively. It is the former graph which is superimposed on a Nichols Chart for gain determination in Fig. 5.9.

The gain margin for this system is -5.75 db with a phase margin of 46 degrees (assuming a gain of one). However, control systems usually operate with larger gain and phase margins, so an adjustment is needed.

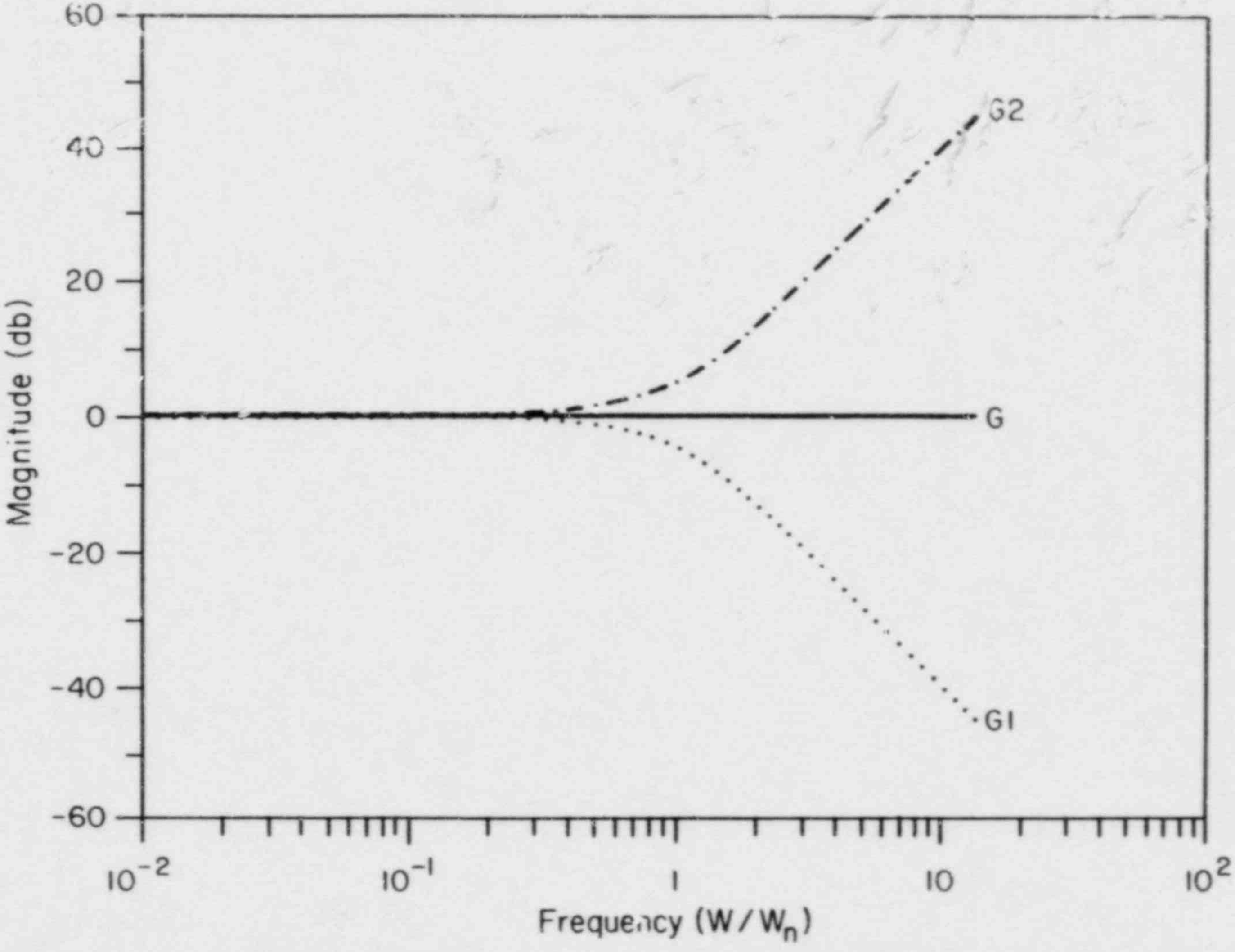


Figure 5.6. Magnitude versus Frequency for CRDM.

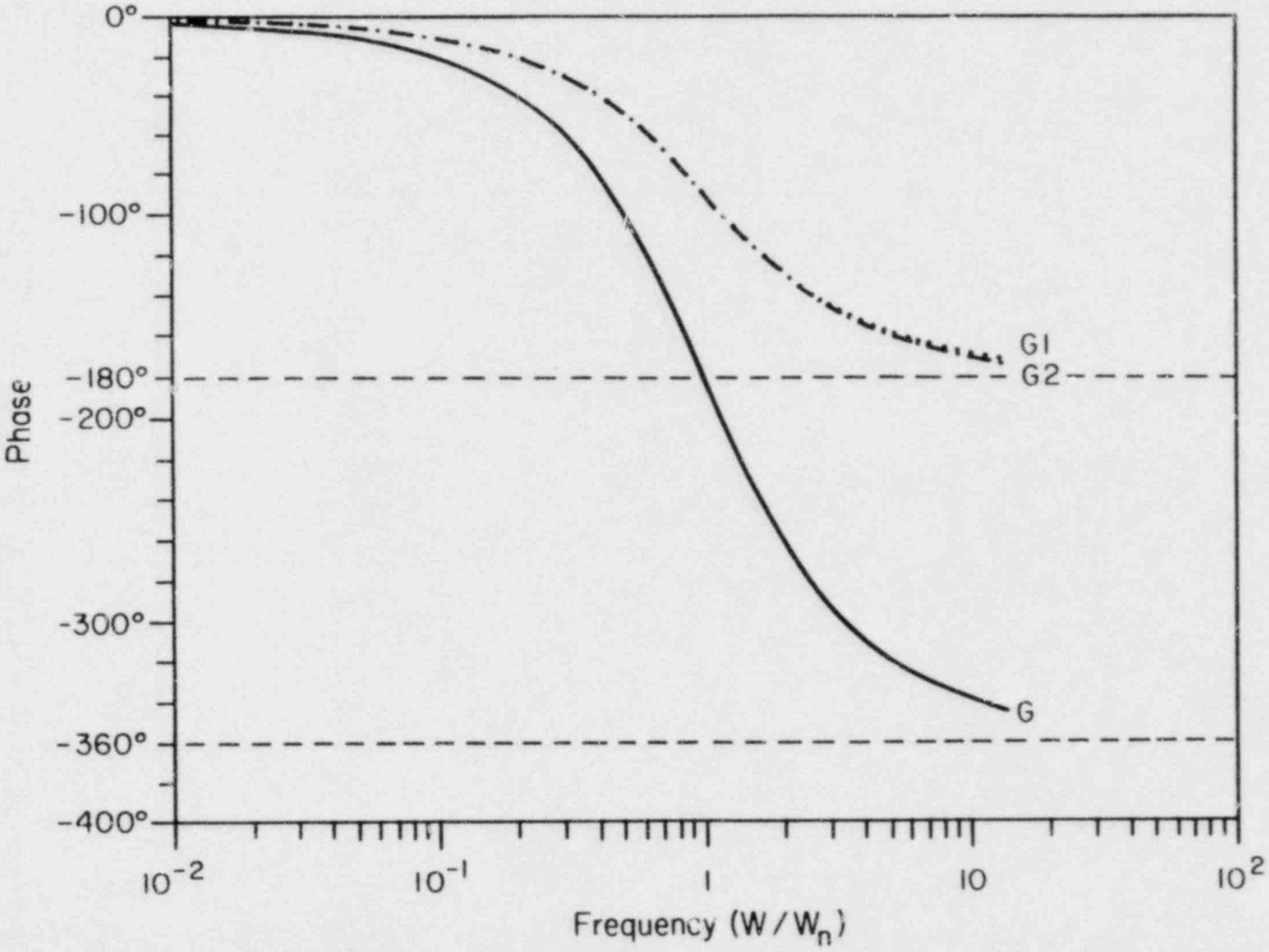


Figure 5.7. Phase versus Frequency for CRDM.

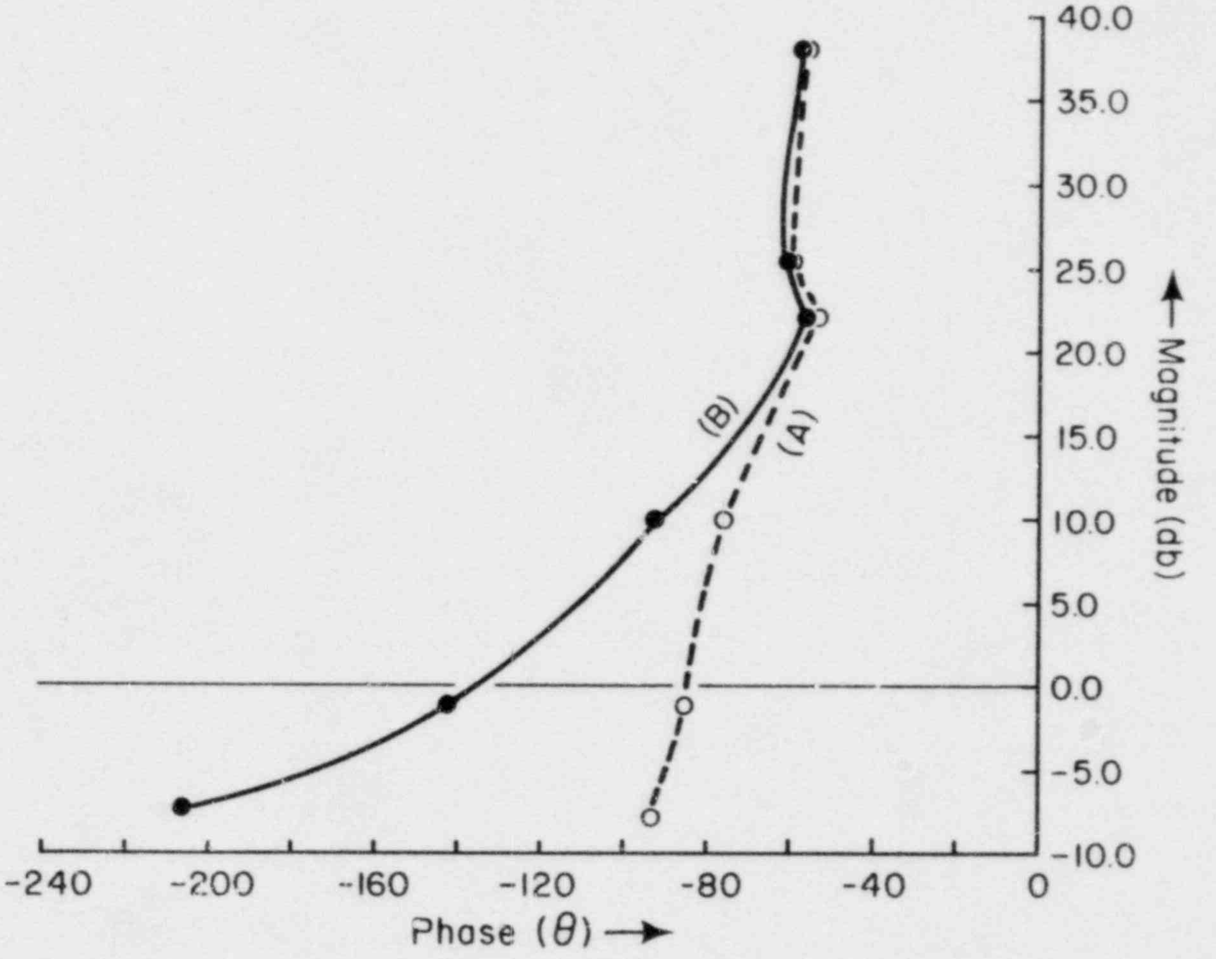


Figure 5.8. Magnitude versus Phase (A) without CRDM and (B) with CRDM.

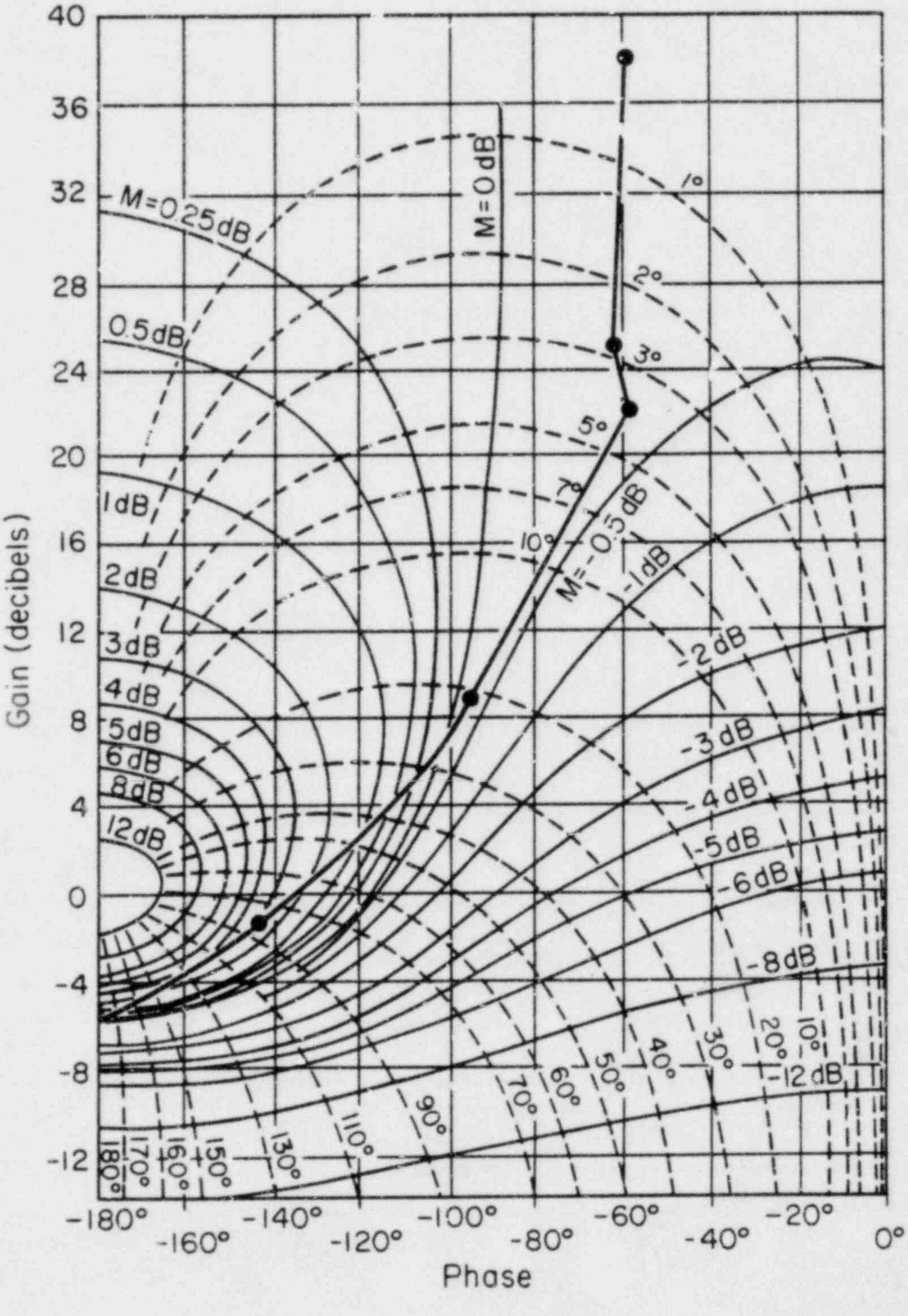


Figure 5.9. Nichols plot of flux control system of FFTF.

Deciding on a gain margin of -10.0 db, a new plot is found by shifting the existing plot down by -4.25 db on the Nichols chart. This new plot, Fig. 5.10, has a phase margin of 70 degrees and a band width of approximately 11 Hz. With this shift, the gain constant for the flux control scheme is calculated to be CONST=.3162.

As a sideline, it should be mentioned that phase lag and phase lead networks can be added to control schemes to provide smaller or larger band widths, respectively. In the case of this control scheme, a phase lead network could be added, since a larger band width would be desirable. However, this adjustment was not considered necessary for the purposes of this study.

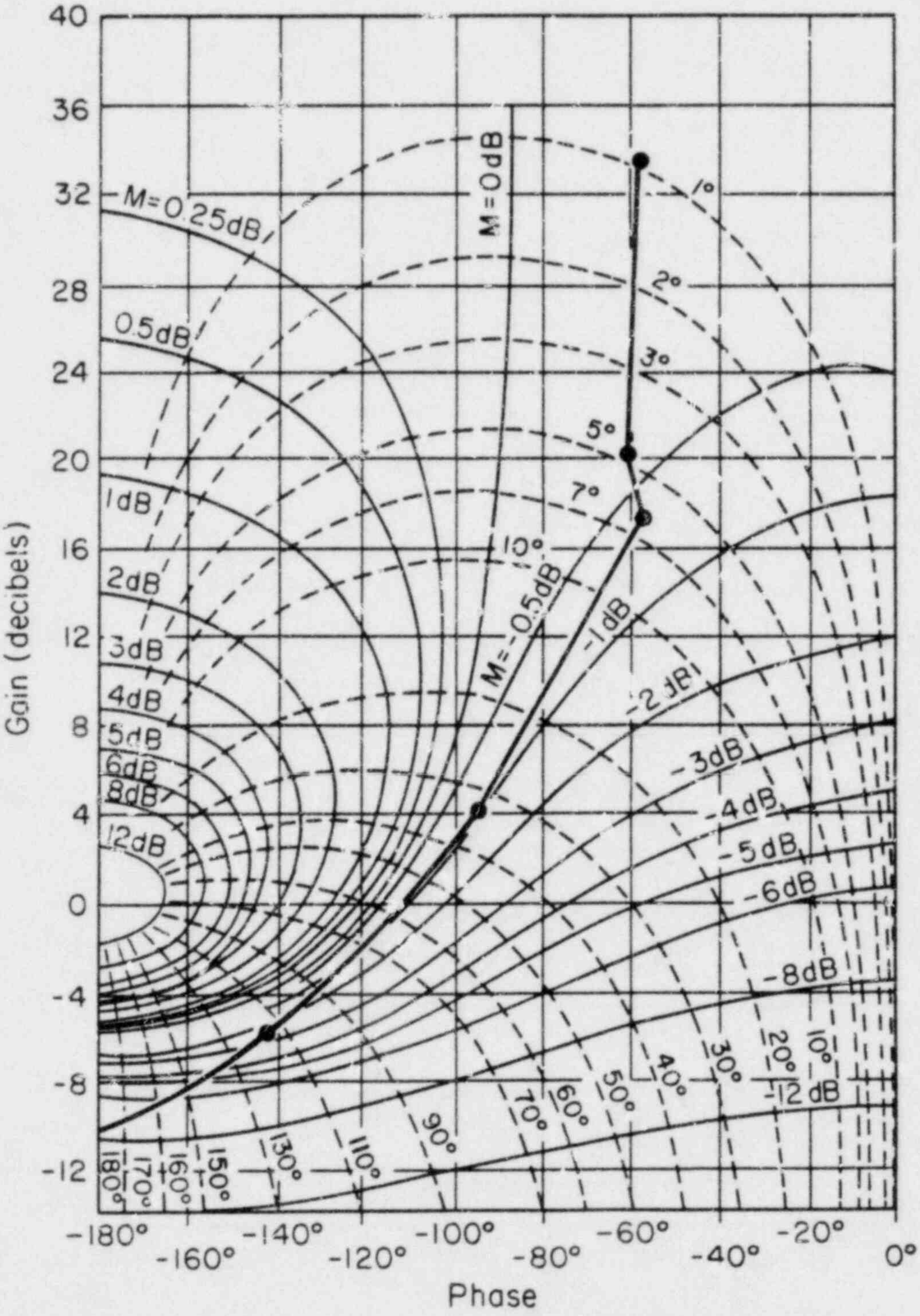


Figure 5.10. Nichols plot with larger phase margin.

CHAPTER 6

RESULTS AND CONCLUSION

Results

Three transients were selected to demonstrate the overall performance of FATFAD in simulating responses of the FFTF. The first transient consists of a ten cent reactivity step insertion. The second transient has a ten cent reactivity step input plus a 50° K rise of the inlet temperature to the secondary side of the IHX. Finally, the third transient is a 25% reduction of the pump speed in Loop One.

Ten Cent Step Input

A ten cent step input of reactivity at t=5.0 seconds initiated the first transient. Fig. 6.1 illustrates the plant response over the first 200 seconds.

Following the reactivity step, the fuel temperatures (TCF1-3) rise to their new steady state temperatures. Which causes the cladding and sodium temperatures to increase (TCC1-3 and TCS1-5, respectively). As the sodium temperatures rise in the core channels, so does the reactor outlet temperature (TUPO), with TXP1, the inlet temperature to the IHX, following suit (allowing for the transport time delay). The increase in TXP1 is felt on the secondary side of the IHX where its outlet temperature, TXS11, begins to rise. However, not all of the added heat can be transported to the secondary side, thus resulting in a slight increase

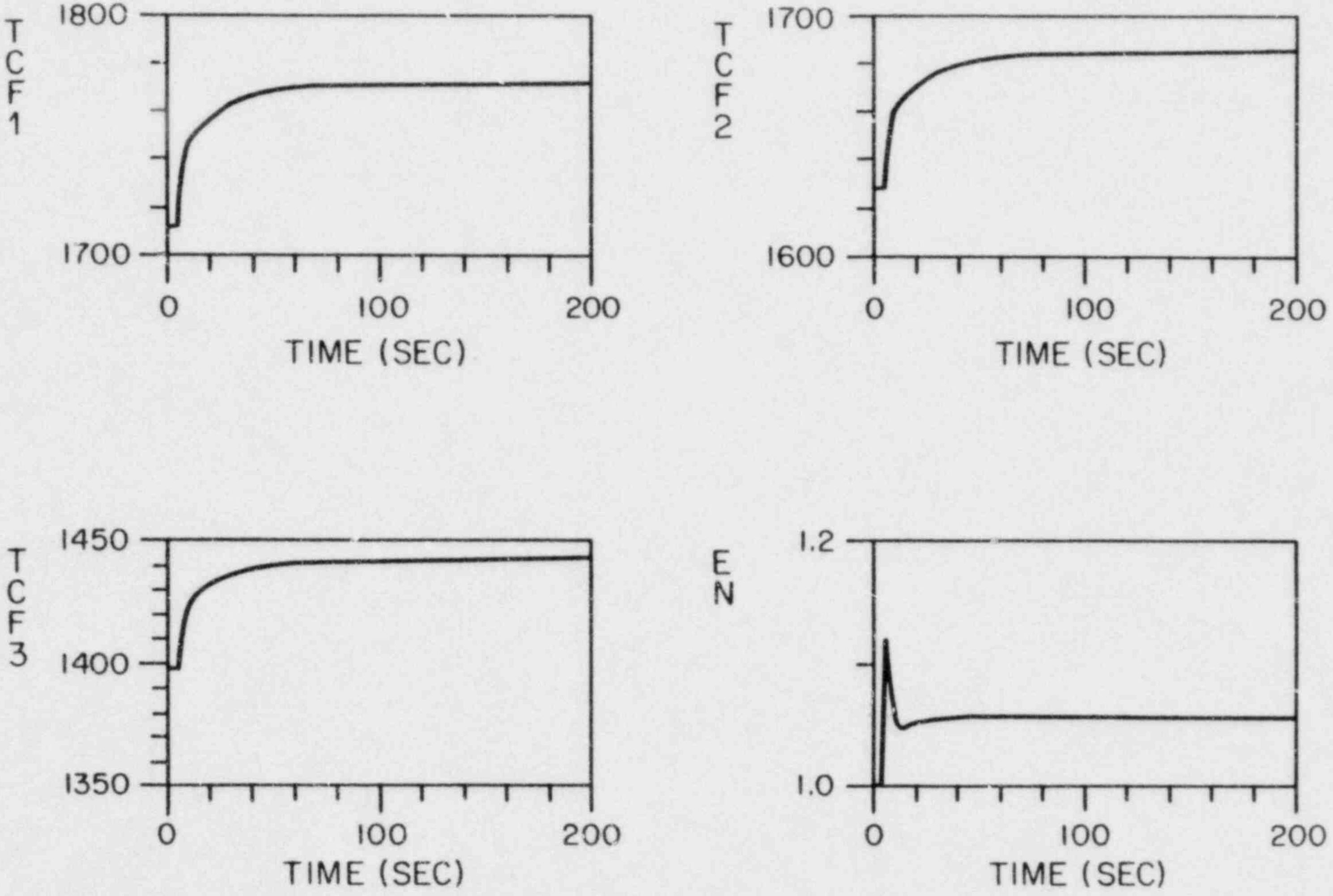


Figure 6.1. Transient response to a 10 cent reactivity step input.

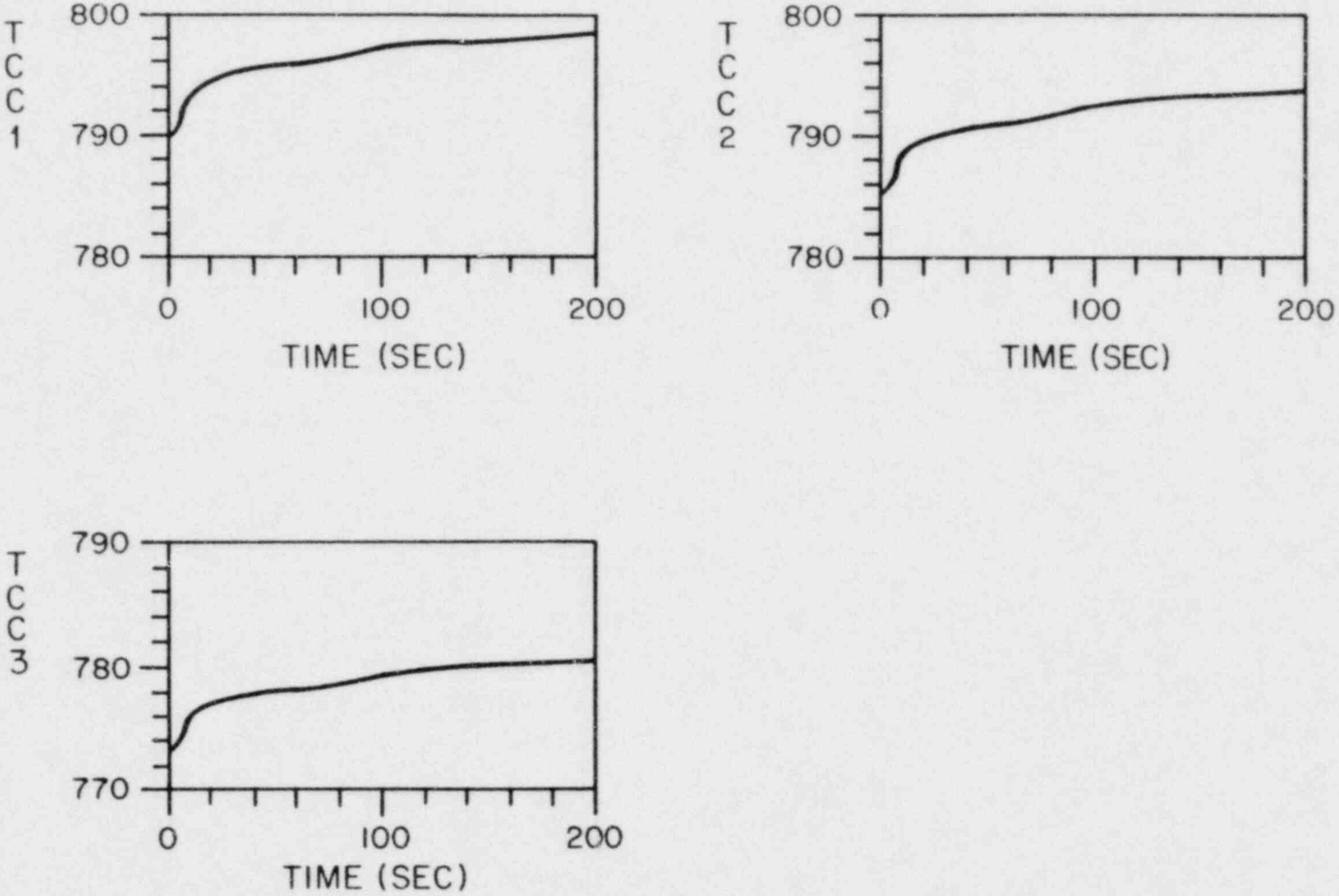
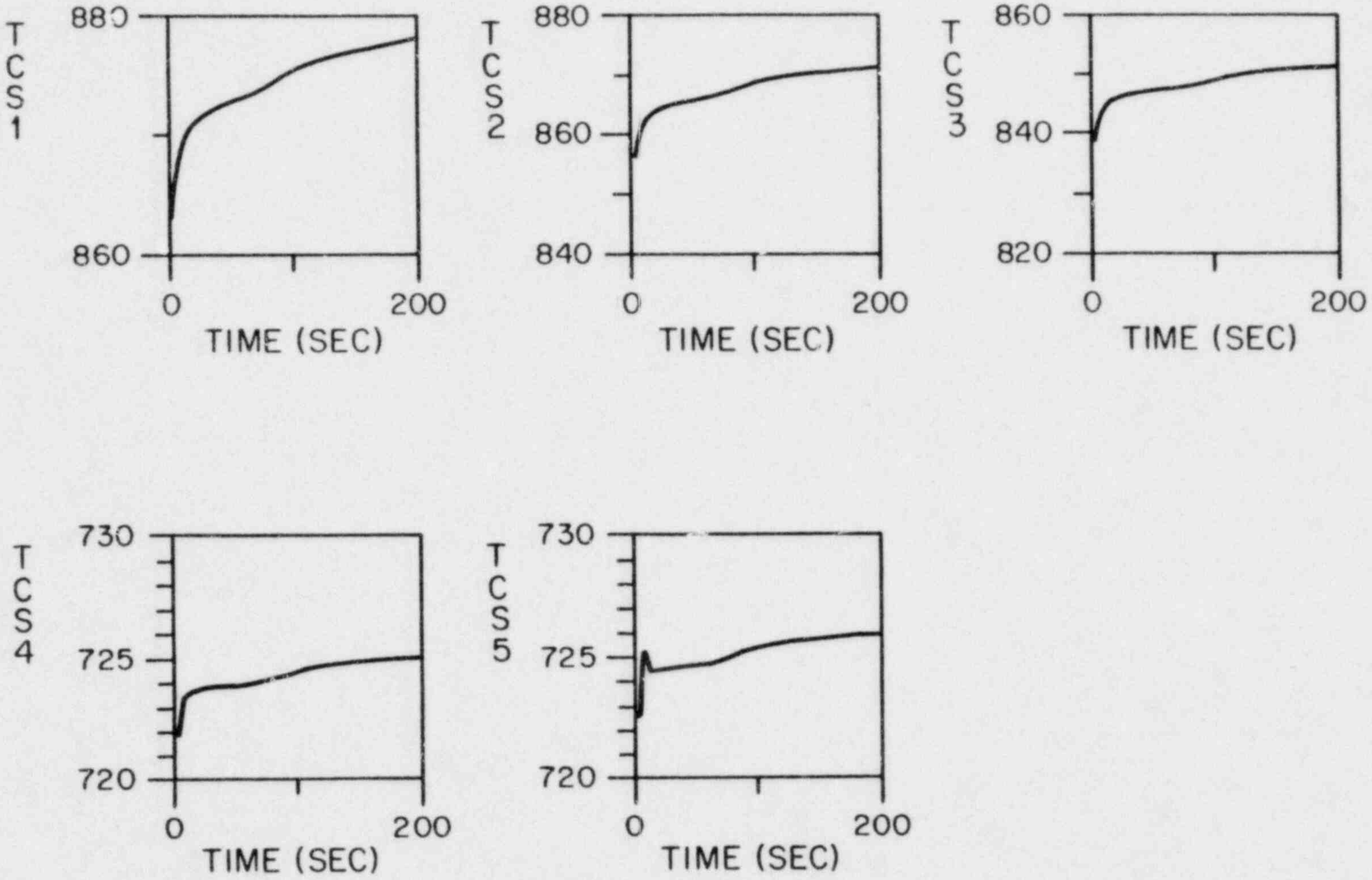


Figure 6.1.--Continued



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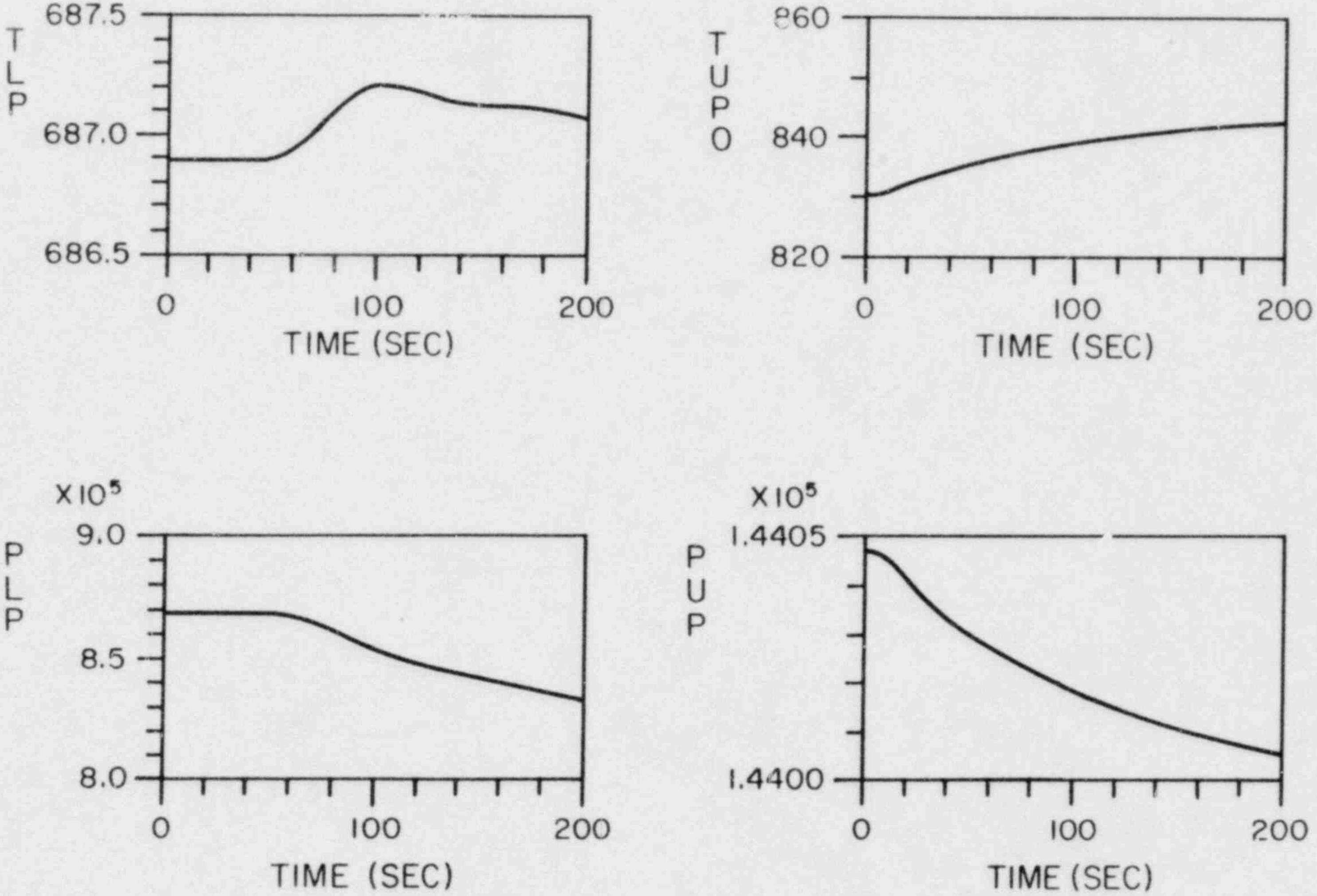

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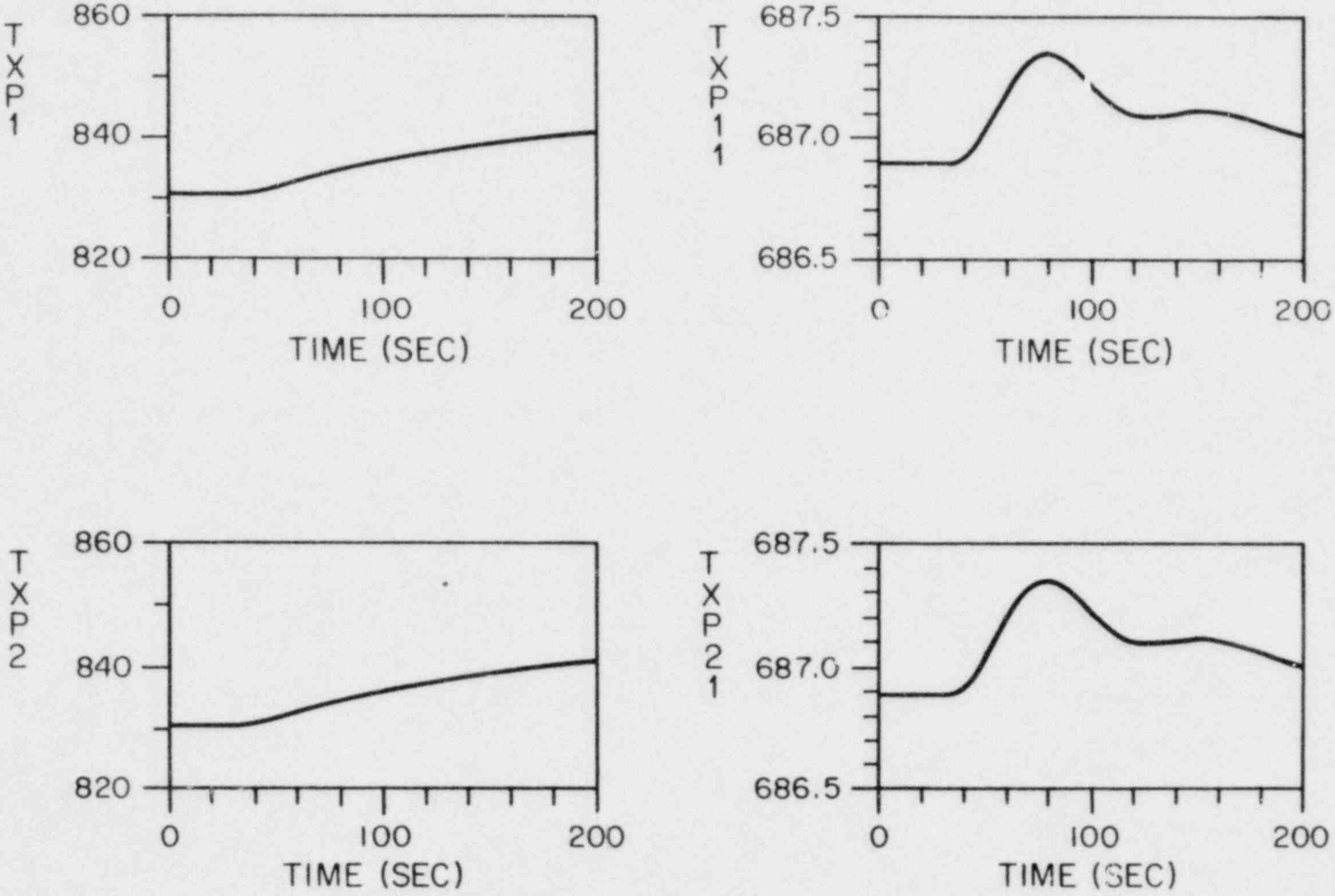

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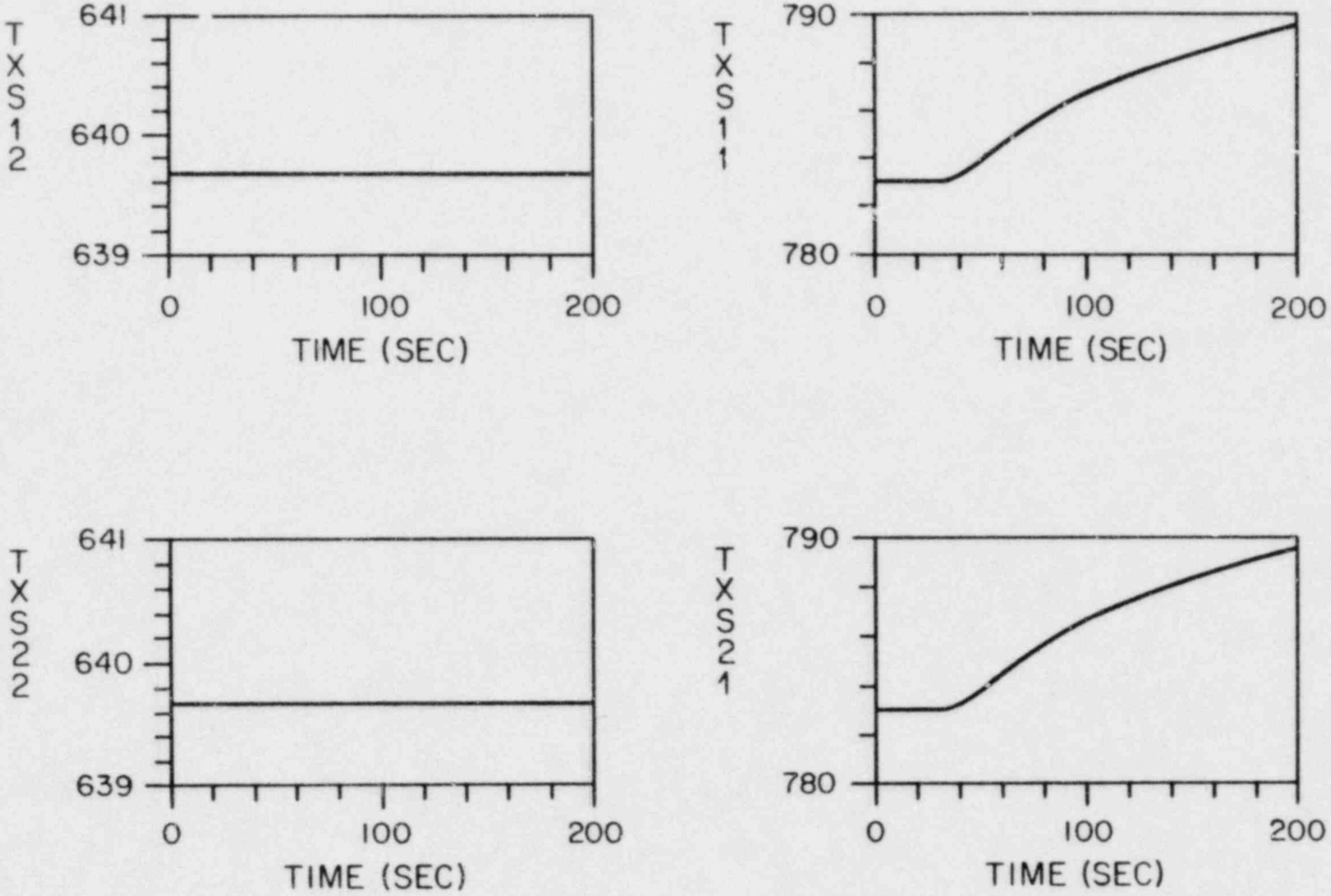


Figure 6.1.--Continued

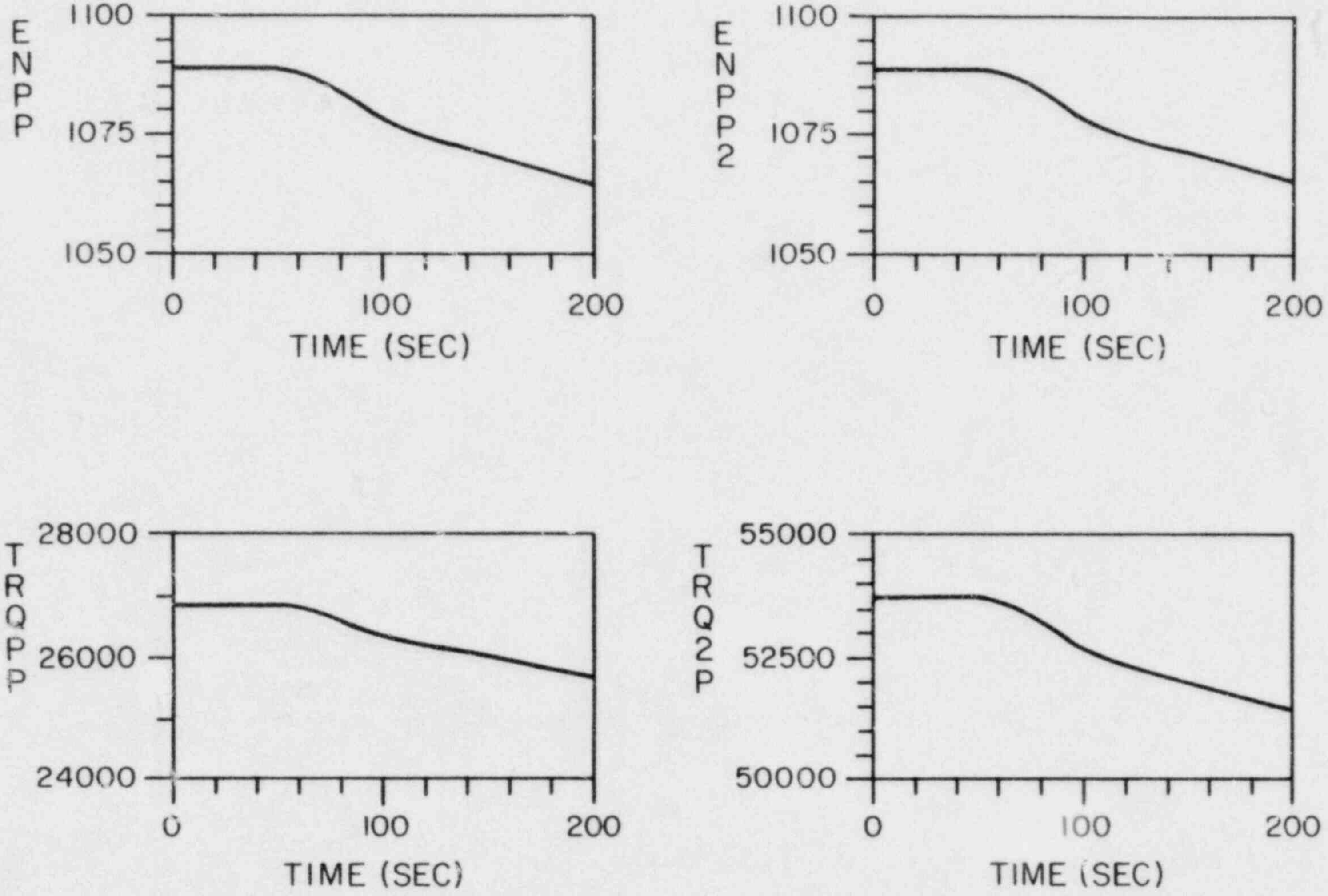


Figure 6.1.--Continued

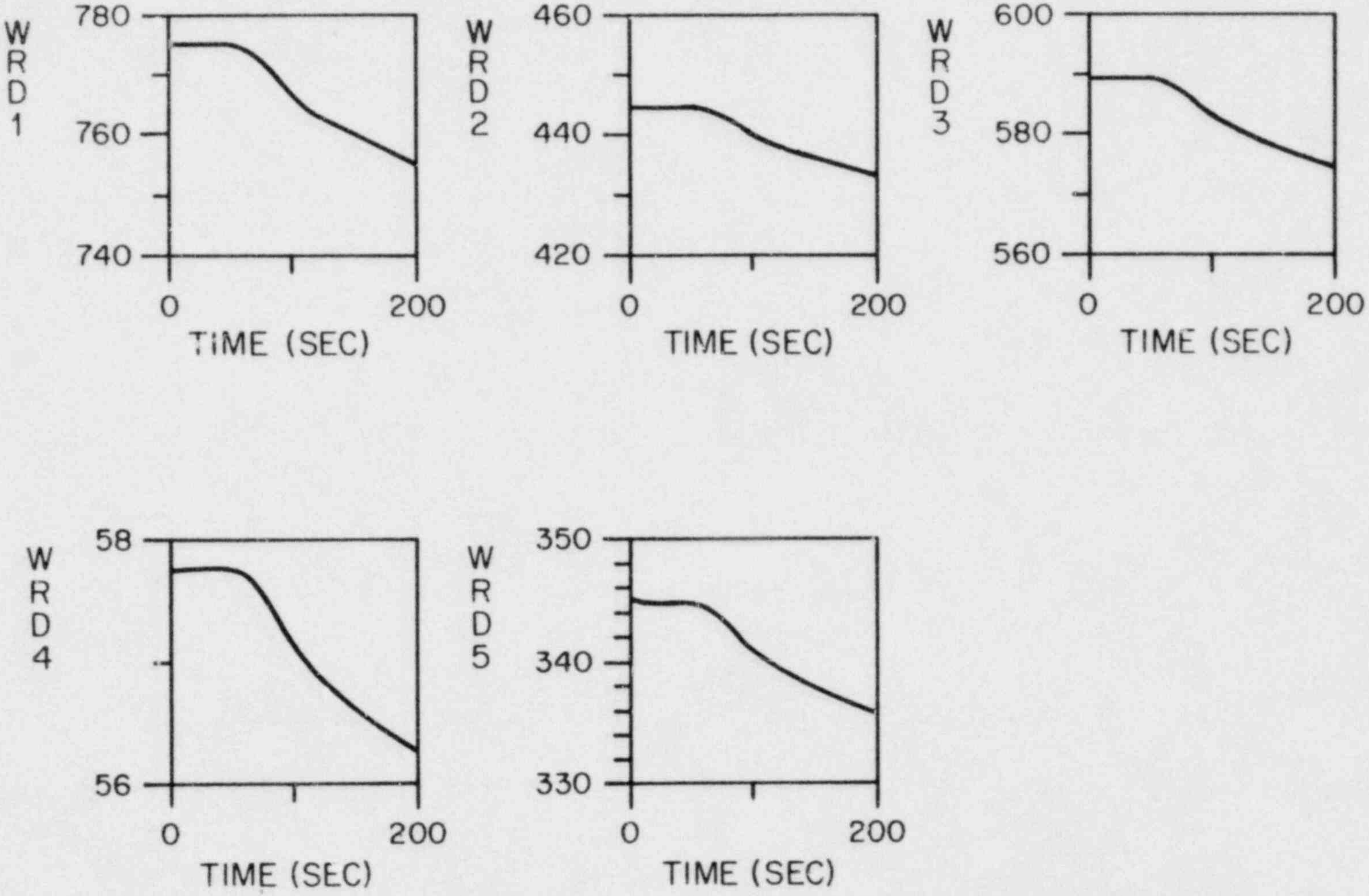


Figure 6.1.--Continued

in the sodium temperature at the outlet of the IHX primary side (TXP11). Once again allowing for the transport time delay, TLP, the lower plenum temperature, begins to rise. Because TLP is an input to the primary pump control scheme the temperature increase causes the pumps to reduce speed (ENPP) thus decreasing the flow rate. This decrease of flow is felt instantaneously throughout the system and is illustrated by the core flow rates, WRD1-5. It is this decrease in flow rate which causes the core sodium and the cladding temperatures to begin their second temperature rise and plateau. The reduction in total flow rate also accounts for the leveling off the subsequent decrease in TXP11.

By the end of this run, the system has almost reached a new operating point. It should be mentioned that since this is a symmetric transient, both loops should behave identically, as is seen in the graphs.

Ten Cent Step Input Plus a 50° K Rise in the IHX Secondary Inlet Temperature

For the second transient, a 10 cent reactivity step input at 5 seconds was accompanied by a 50° K rise in the secondary sodium inlet temperature to the IHX, over a ten second period. Fig. 6.2 illustrates the primary heat transport system (PHTS) response to this imbalance over the first 200 seconds.

At t=0, TXS12 begins the 50° K increase over a period of 10 seconds, which causes TXP11 (IHX primary sodium outlet temperature) to rise. During this rise in TXS12, a 10 cent step input of reactivity is initiated at t=5.0 seconds causing the fuel temperatures to rise (TCF1-3).

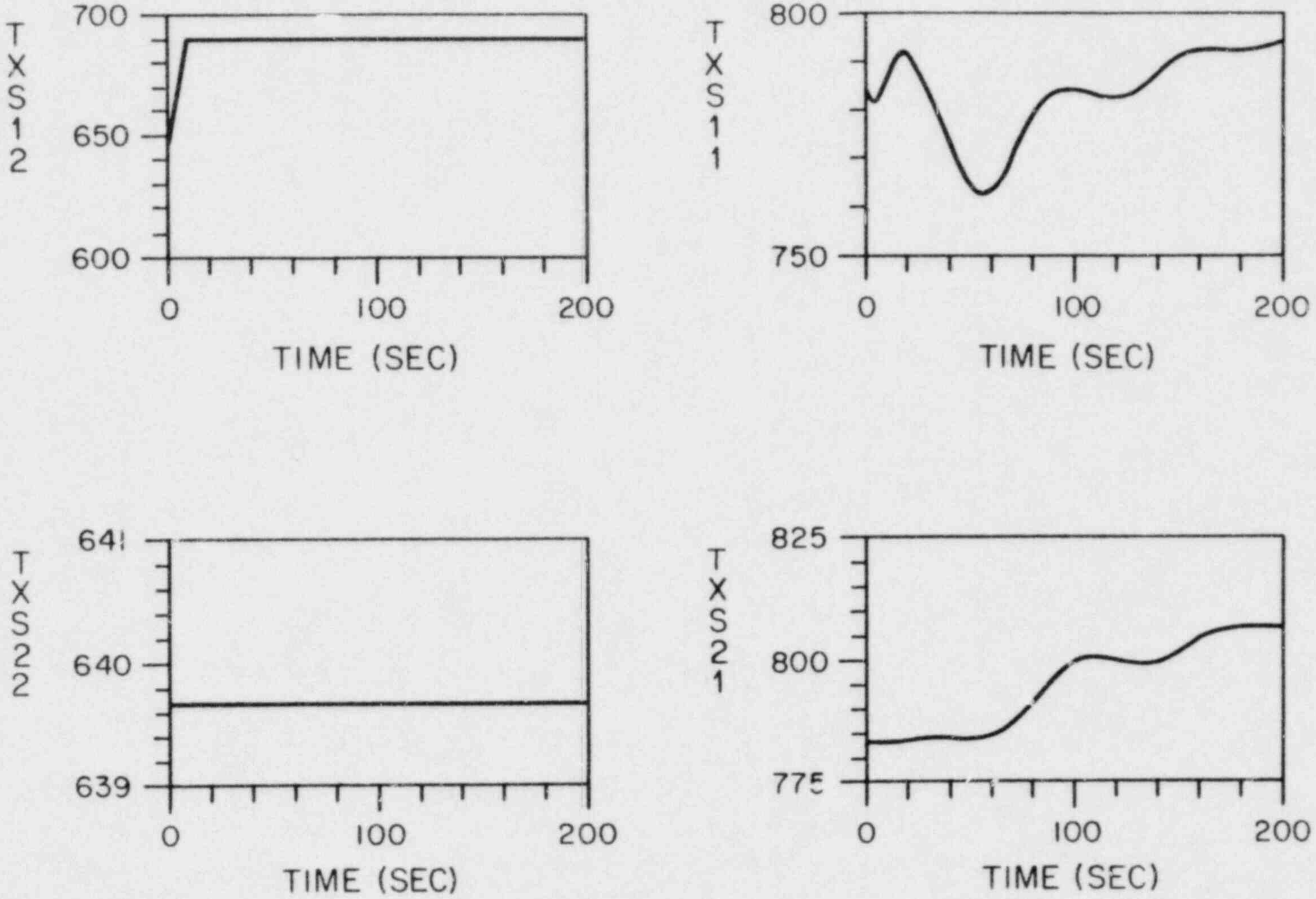
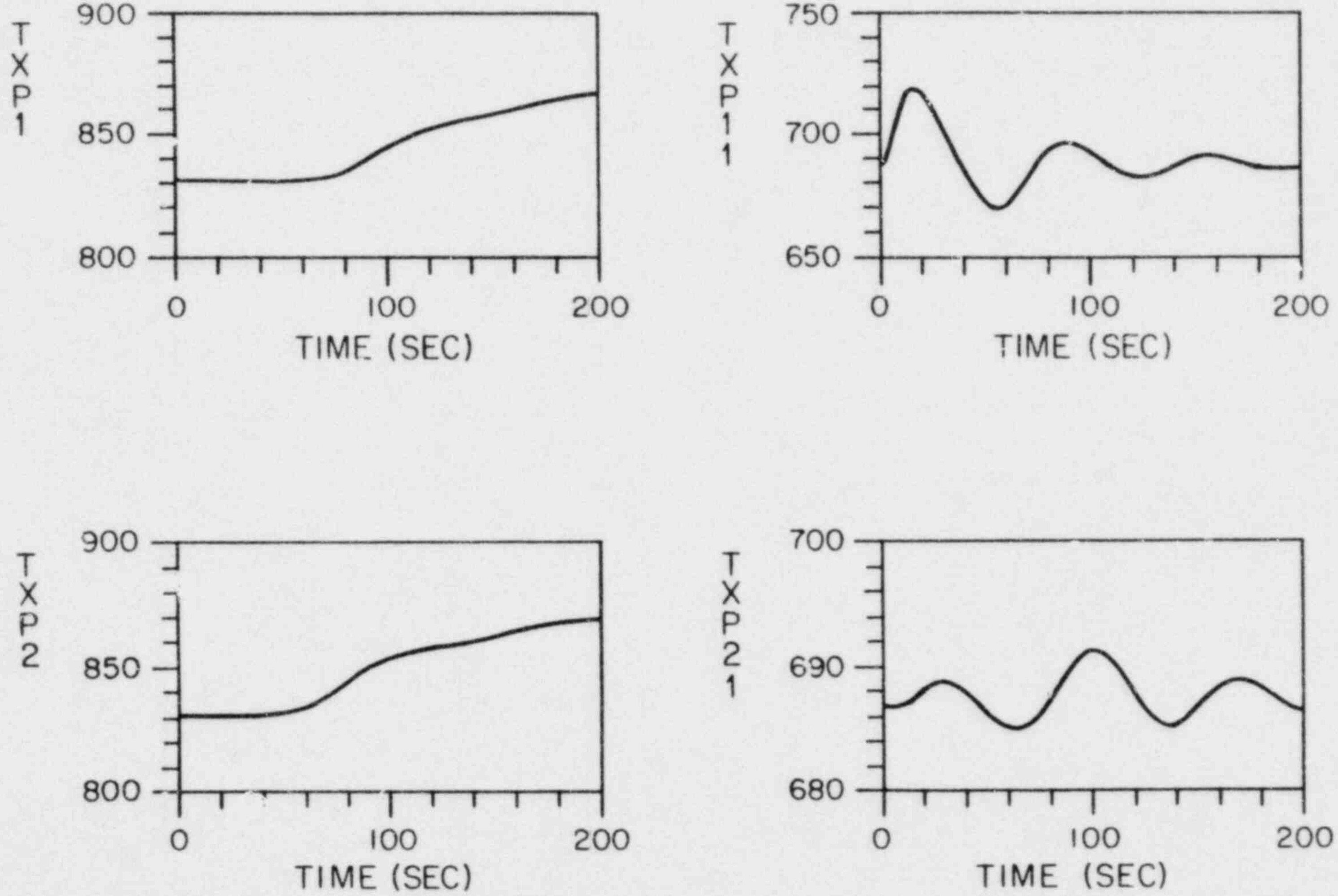


Figure 6.2. Transient response to a 10 cent reactivity step input plus 50 °K rise in TXS12.



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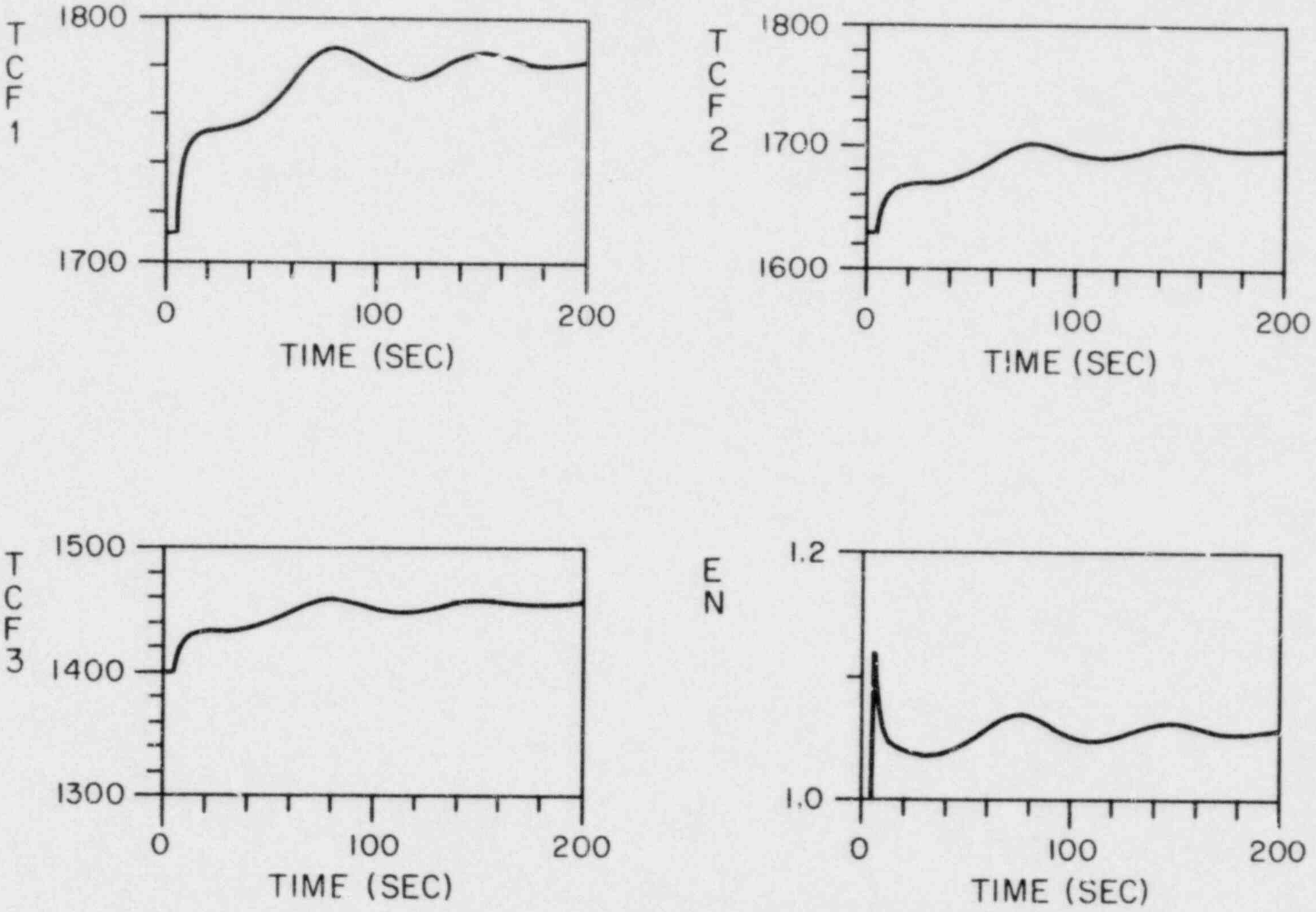
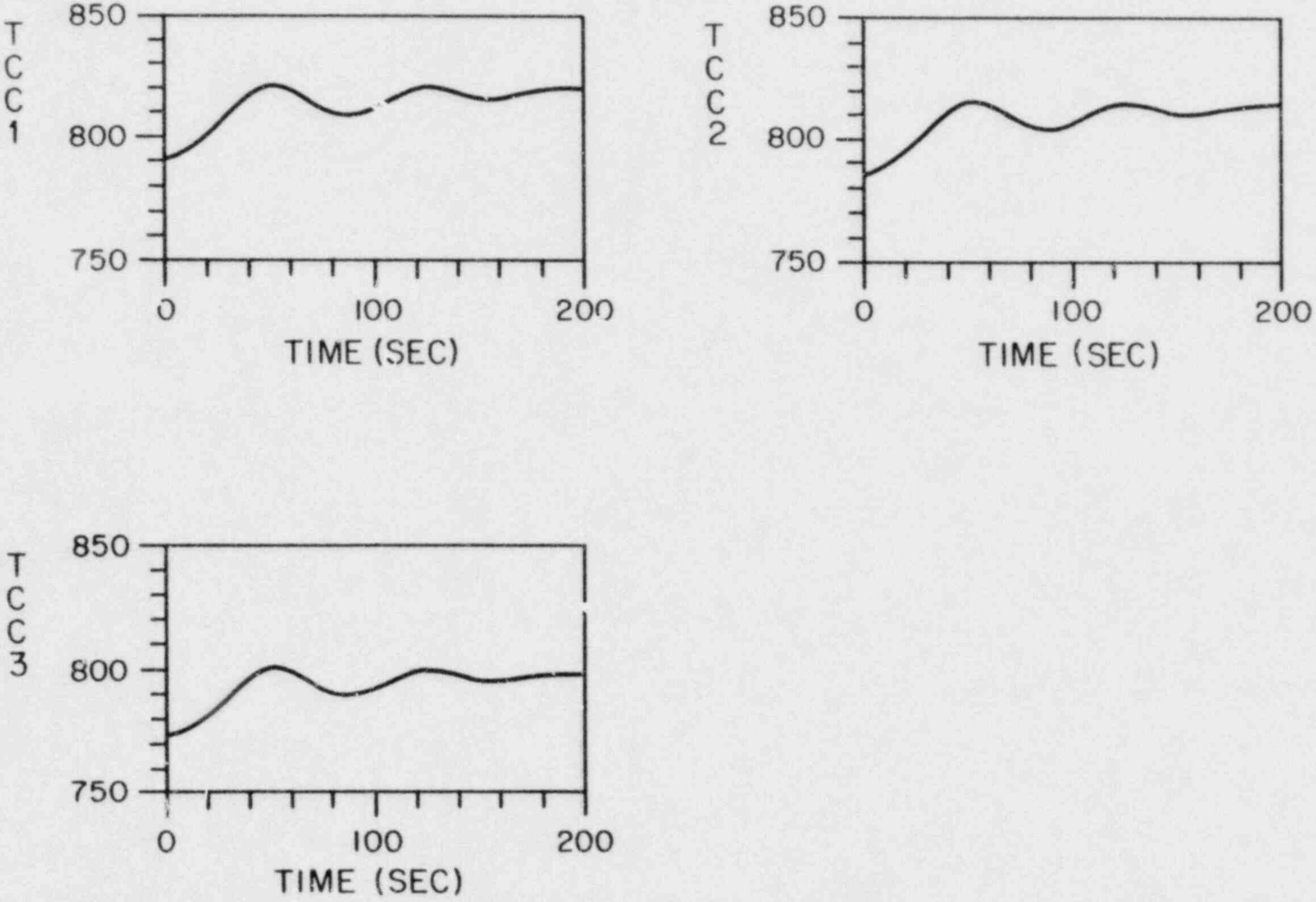


Figure 6.2.--<u>Continued</u>



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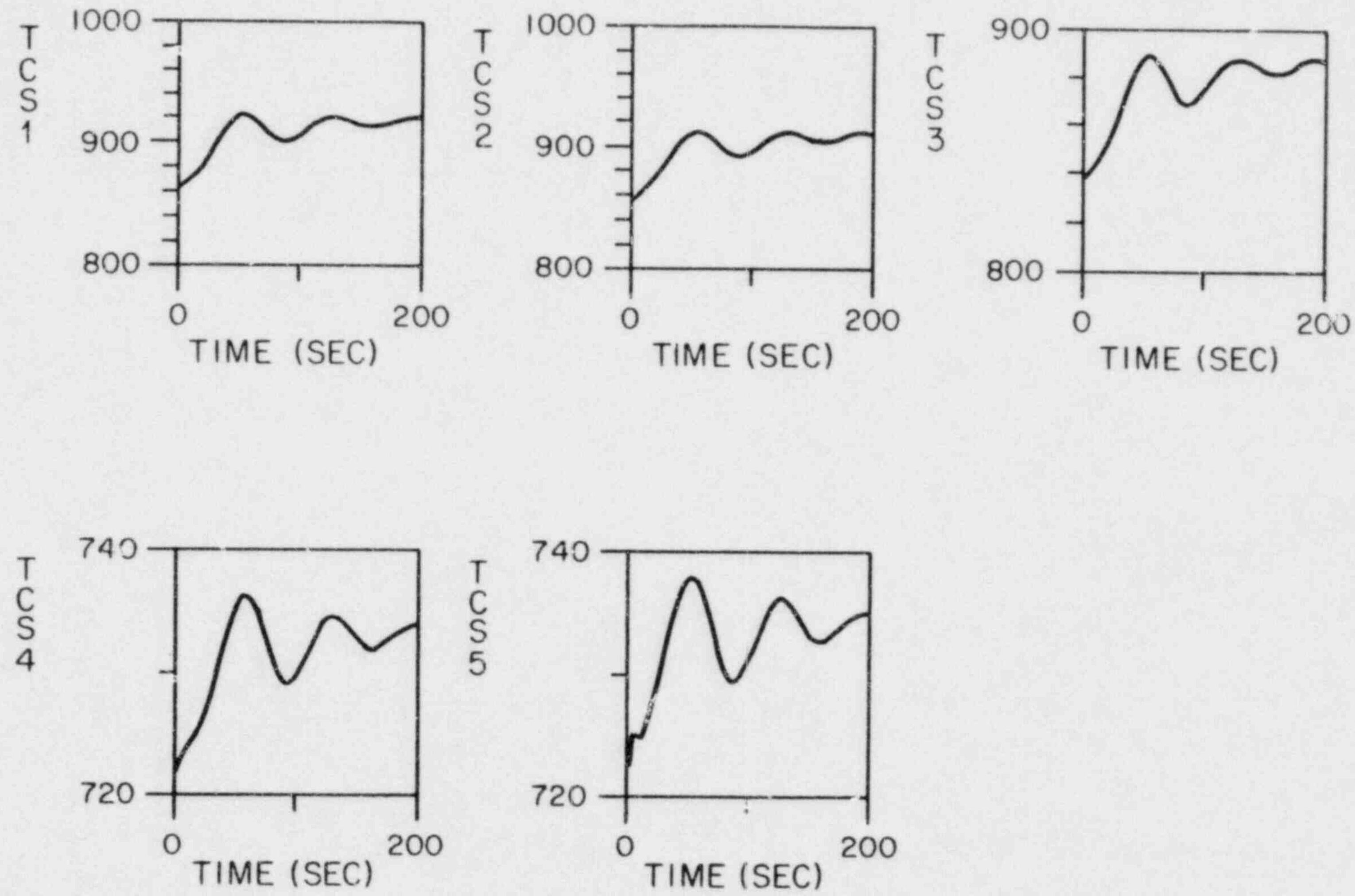

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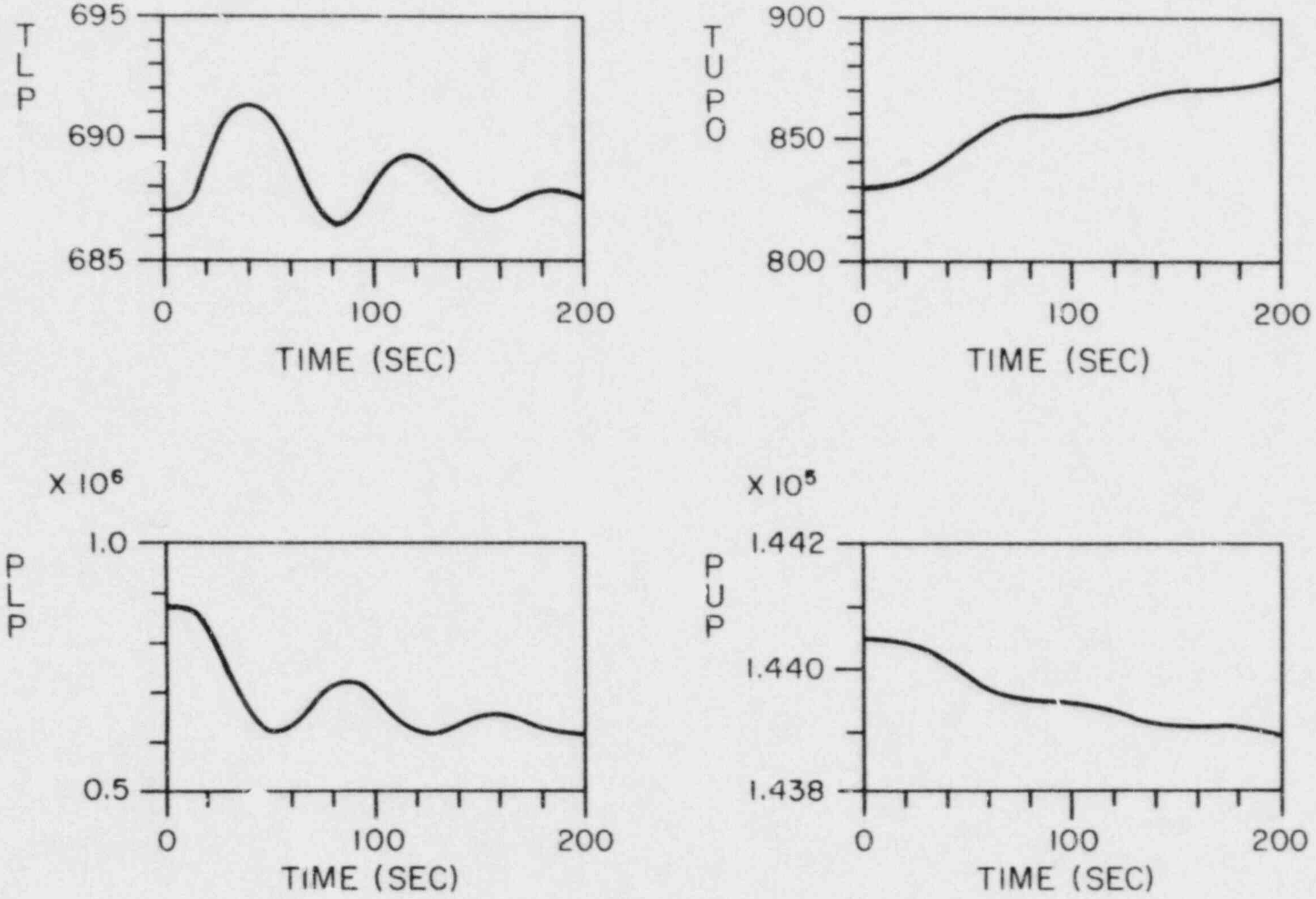

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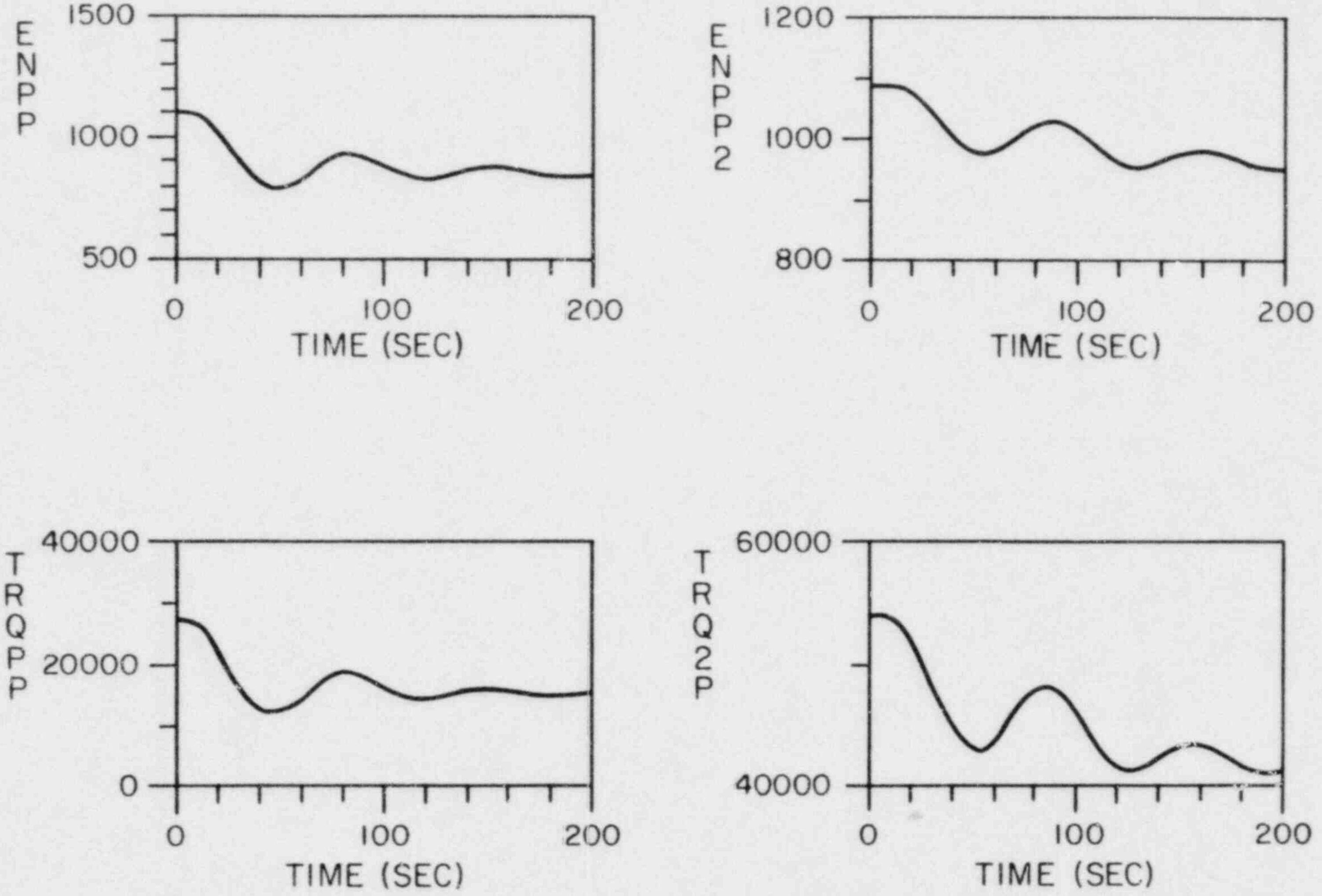

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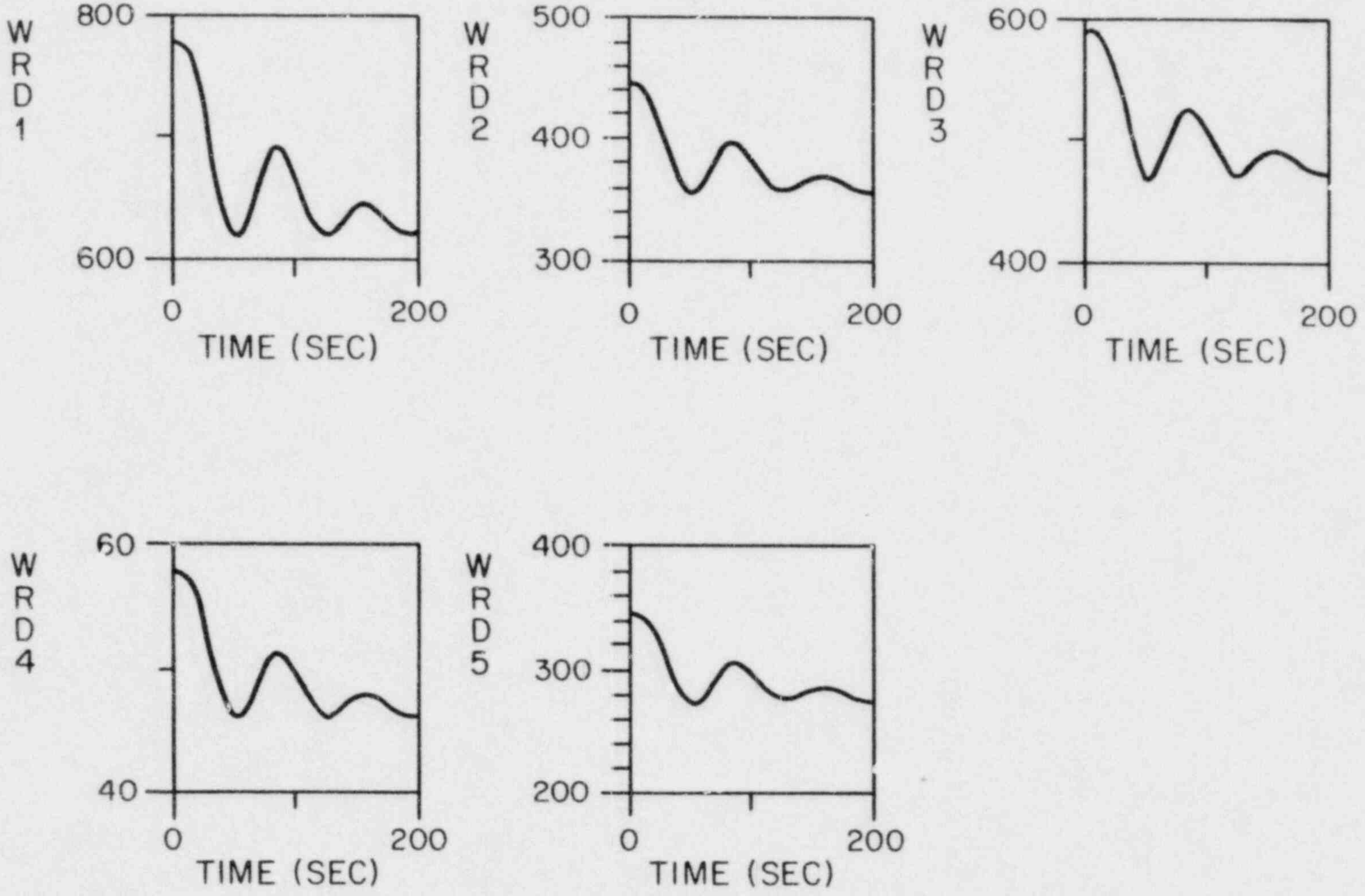

Figure 6.2.--Continued

Following the fuel temperature rise are the cladding and sodium temperatures (TCC1-3 and TCS1-5, respectively). Their initial increases are identical to the responses they had for the 10 cent step input (first transient case). However, soon afterwards, the cladding and sodium temperatures depart from their expected behaviors; both temperatures begin to increase much more rapidly instead of leveling off as in the first case. The reason for this results from the temperature rise in the lower plenum inlet temperature for Loop One, TLP1. Taking into account the transport time delay between the IHX primary outlet and lower plenum inlet, the lower plenum temperature (TLP) begins climbing when the cladding and sodium temperatures begin their second increase. TLP in turn depends upon the sodium temperatures entering the lower plenum from the two primary loops (TLP1 and TLP2). These temperatures are in turn inputs to the control systems of the primary pumps. When the sodium entering the lower plenum from the single loop begins to show an increase in temperature, the pump in that loop reduces its speed (ENPP), thus decreasing flow rate. This decrease in flow rate is felt instantaneously throughout the system, including the core flow rates (WRD1-5). It is the reduction in flow rates through the core which causes the increase in sodium and cladding temperatures.

Initially, when the flow is reduced in the single loop, the double loop tries to take up the slack. This causes the IHX primary outlet sodium temperature in the double loop (TXP21) to increase (less time spent in the IHX). But the flow rate is another input into the pump control system; therefore, the pump on the two loop-side reduces speed (ENP , causing TXP21 to level off and drop.

The "ripples" seen in various quantities are due to the pump controllers decreasing and increasing pump speed (i.e., flow rate) in accordance with the sodium temperature. It is this undulation in the sodium temperature which causes the power (EN) to fluctuate. Feedback reactivity increases due to rising sodium temperature and vice versa, causing power to oscillate with fuel temperatures following.

During this time, TUPO, the upper plenum outlet temperature, rises. This is followed by a rise in the IHX primary sodium inlet temperatures, TXP1 and TXP2 (allowing for the transport time delay). It is the rise in TXP1 and TXP2 which make TXS11 and TXS21 increase, respectively (IHX secondary outlet sodium temperature for the single and double loop, respectively).

Backing up momentarily, note that before TXS11 displays its increasing trend, there is a large dip in the temperature. This dip results from the secondary flow remaining constant while the primary flow decreases. Less hot sodium enters the IHX per unit time, thus decreasing the amount of heat flow to the secondary side, and resulting in a lower outlet temperature for the IHX secondary side. For this reason, TXP11 displays a temperature drop during the same time interval. With primary flow reduced, the sodium spends more time in the IHX, transferring more heat than usual and thus decreasing the primary outlet temperature from the IHX. Once this lower temperature is "felt" at the lower plenum inlet, the pump begins to increase speed and flow rate.

Therefore the pump speed fluctuates, as mentioned earlier, causing all other quantities to follow.

Looking at the behavior of all the variables plotted, it can be seen that by the end of 200 seconds, most of the undulations have died away, with the control systems bringing the plant to a new steady state.

25% Reduction in Loop One's Primary Pump Speed

At time t=0 a 25% coast down in the pump speed for the single loop (ENPP) takes place, with the responses shown in Fig. 6.3. Flow rates in Loop One immediately respond by slowing down, including the flow rates through the core channels (WRD1-5). A lowering of the core flow rates causes the core sodium and cladding temperatures (TCS1-5 and TCC1-3, respectively) to increase. This in turn provides for a larger negative reactivity feedback, causing the reactor power (EN) to fall sharply with fuel temperatures (TCF1-3) following.

Initially, after the speed reduction, the two-loop side tries to take up the slack, with its flow rate increasing sharply. This causes the IHX primary sodium outlet temperature, TXP21, to increase. The IHX secondary sodium outlet temperature for Loop Two (TXS21) also rises initially because more hot primary sodium is entering the IHX, resulting in more heat flow (i.e., higher TXS21).

The opposite is happening in Loop One; TXP11 decreases because the flow rate drops, allowing the sodium to stay within the IHX longer and to give up more of its energy in the form of heat transfer. Also, TXS11 decreases since less hot sodium is entering the IHX on the primary

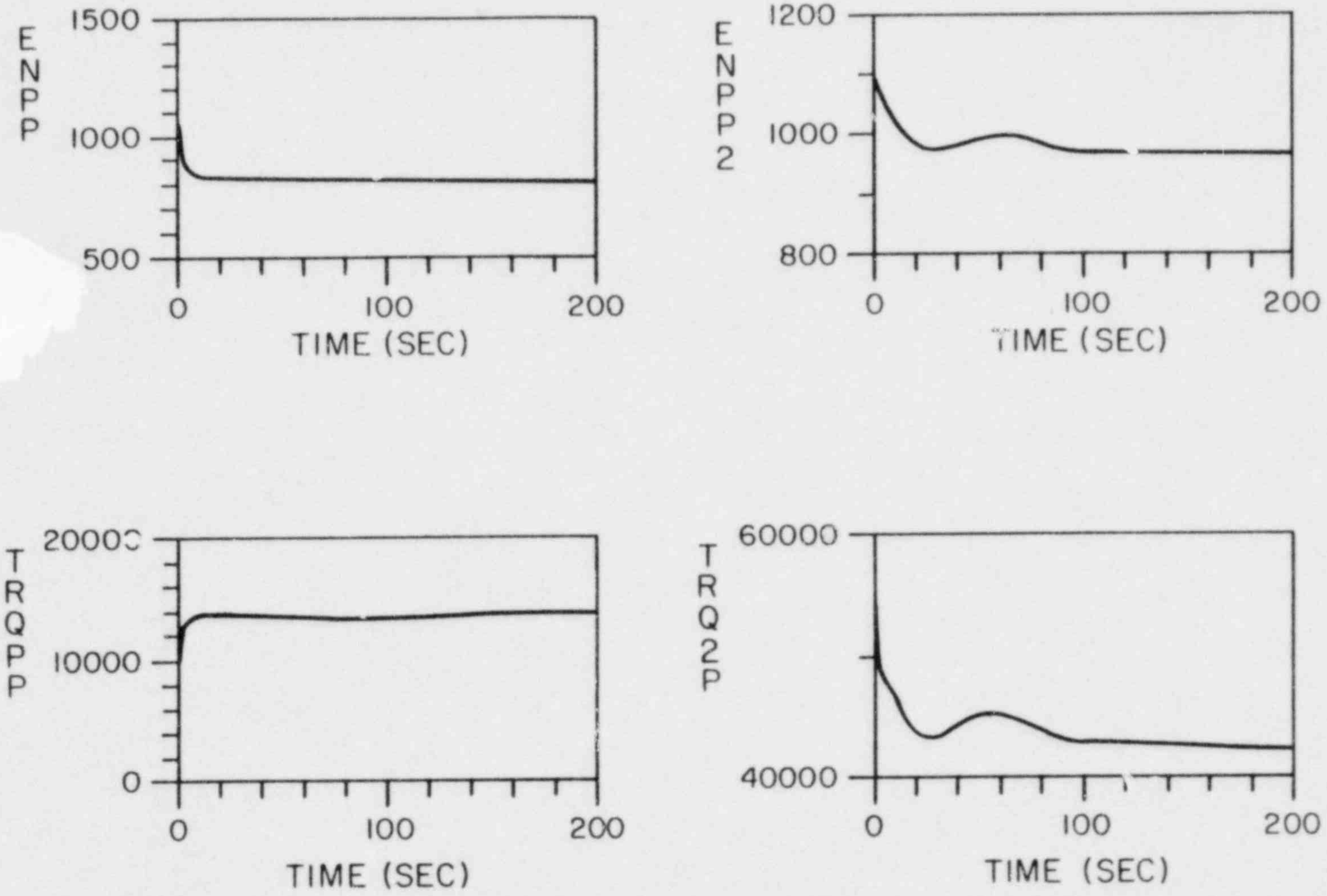

Figure 6.3. Transient response to a 25% reduction in Loop One's pump speed.

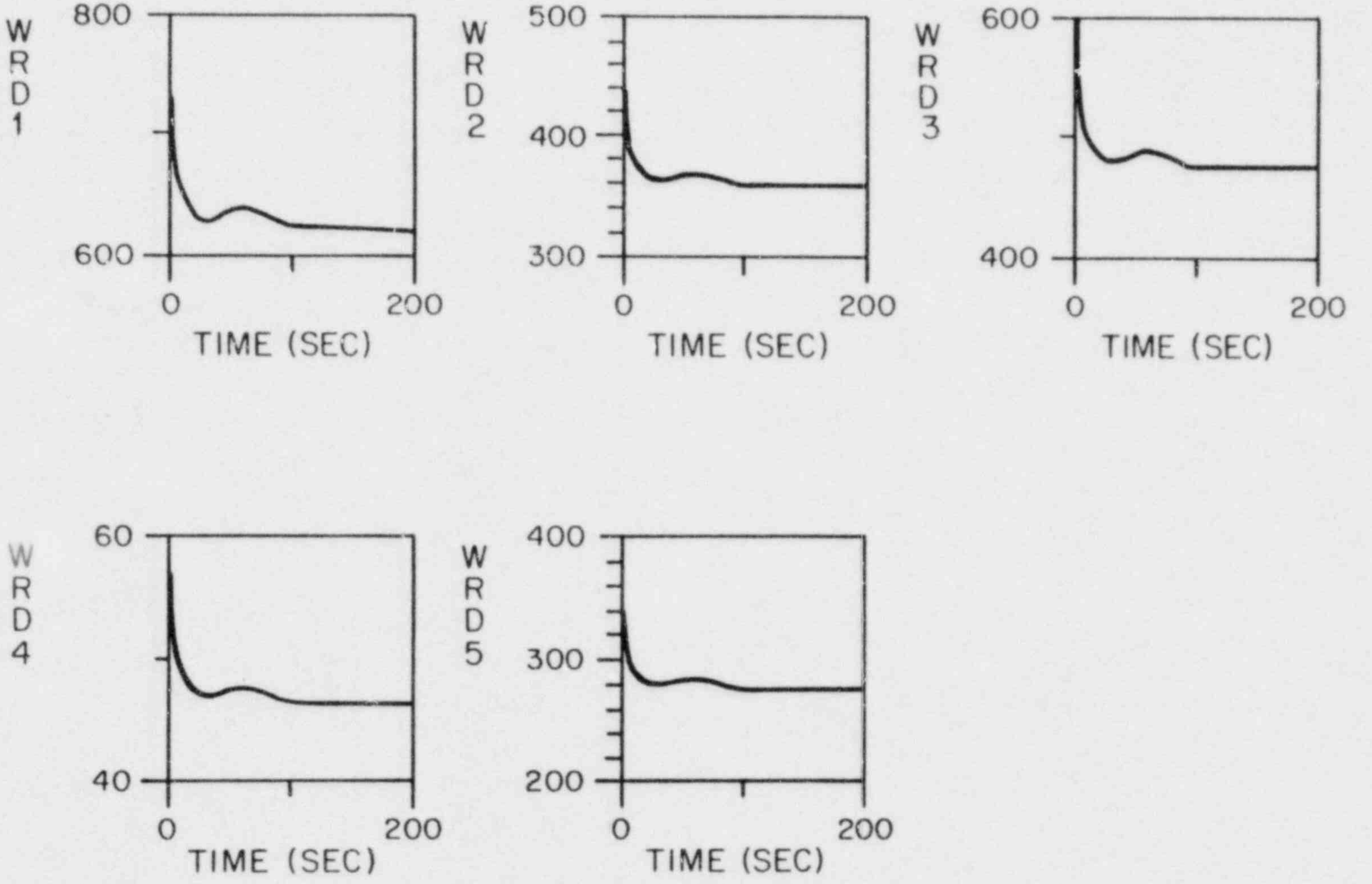

Figure 6.3.--Continued

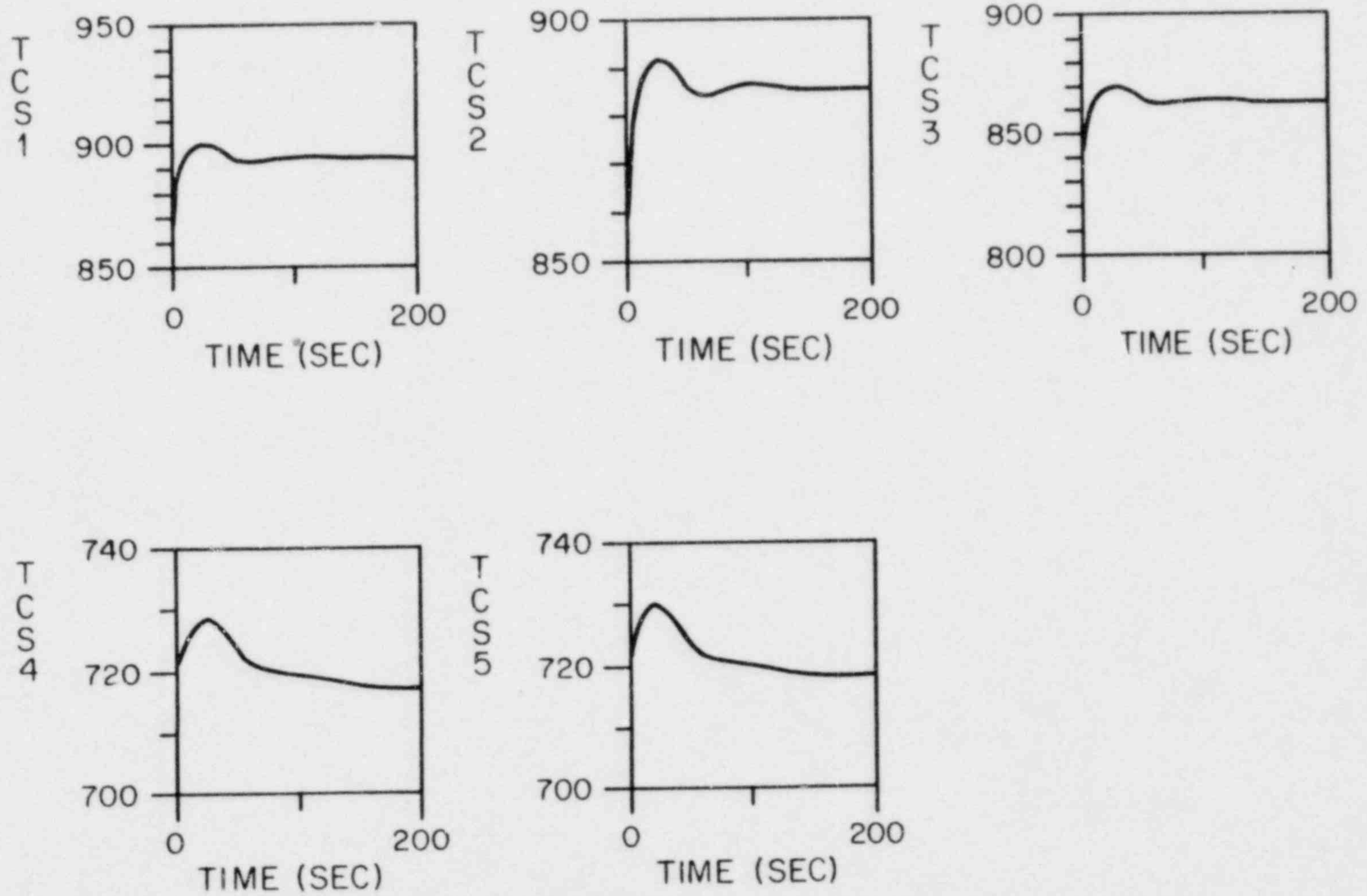

Figure 6.3.--Continued

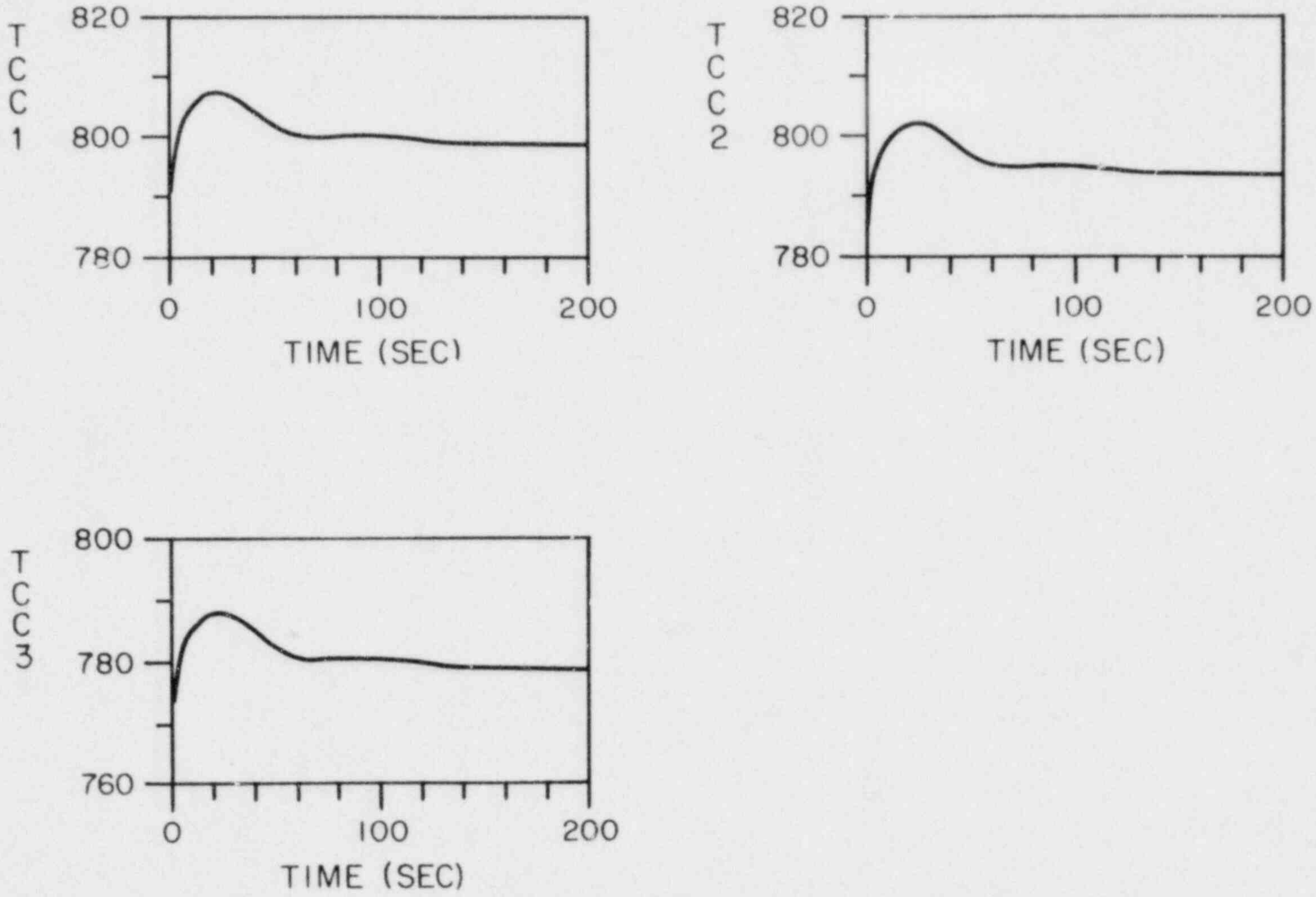

Figure 6.3.--Continued

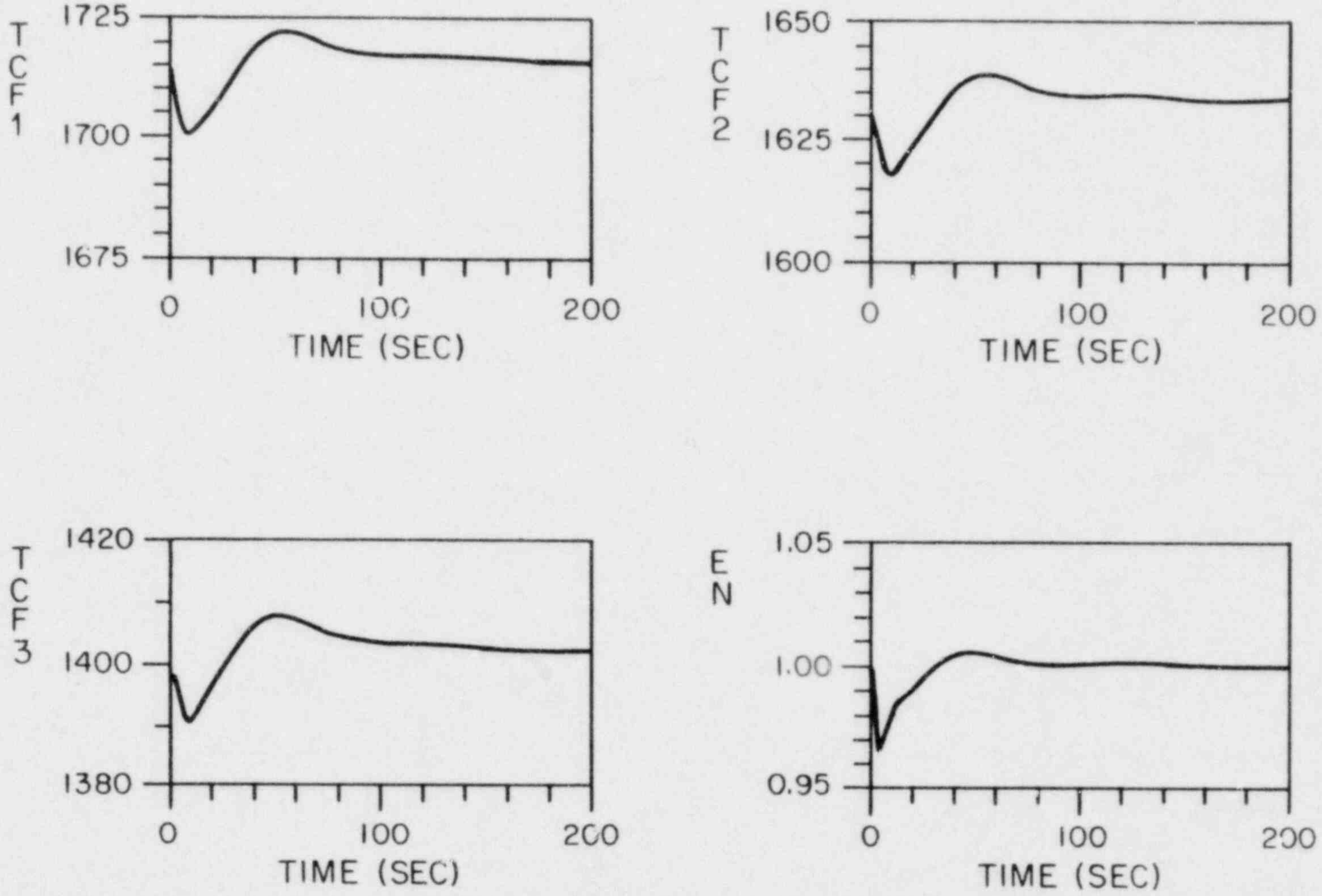

Figure 6.3.--Continued

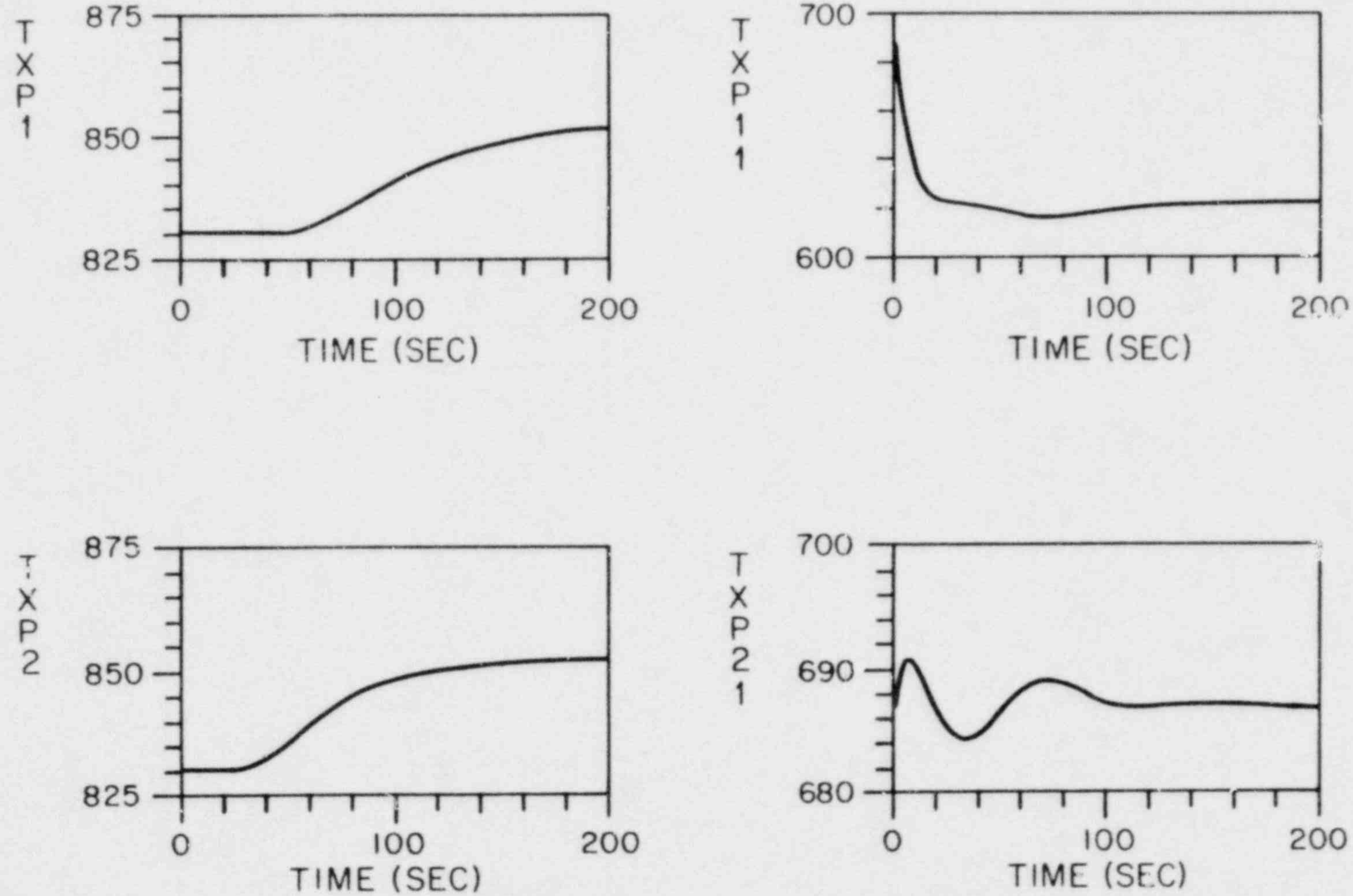

Figure 6.3.--Continued

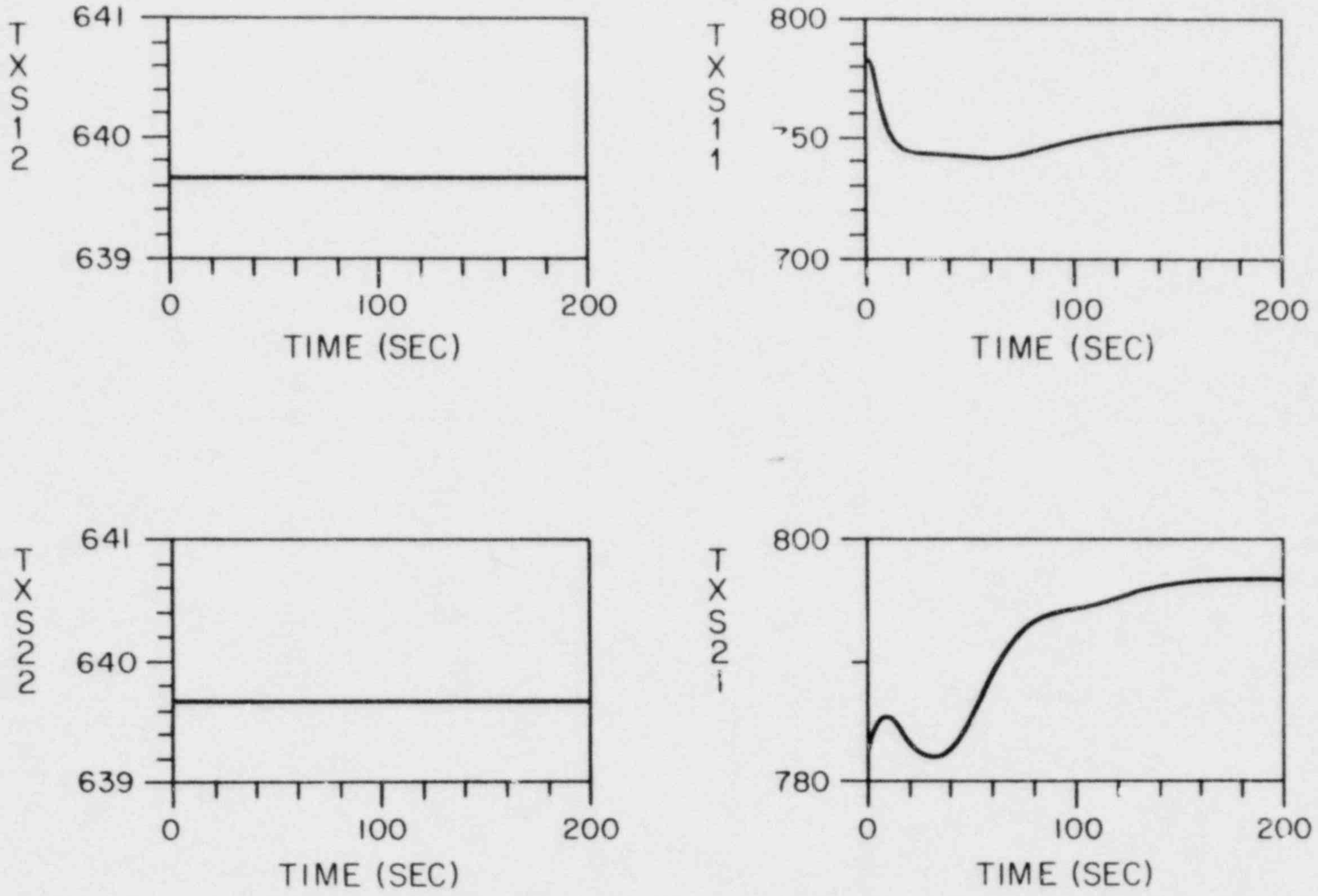

Figure 6.3.--Continued

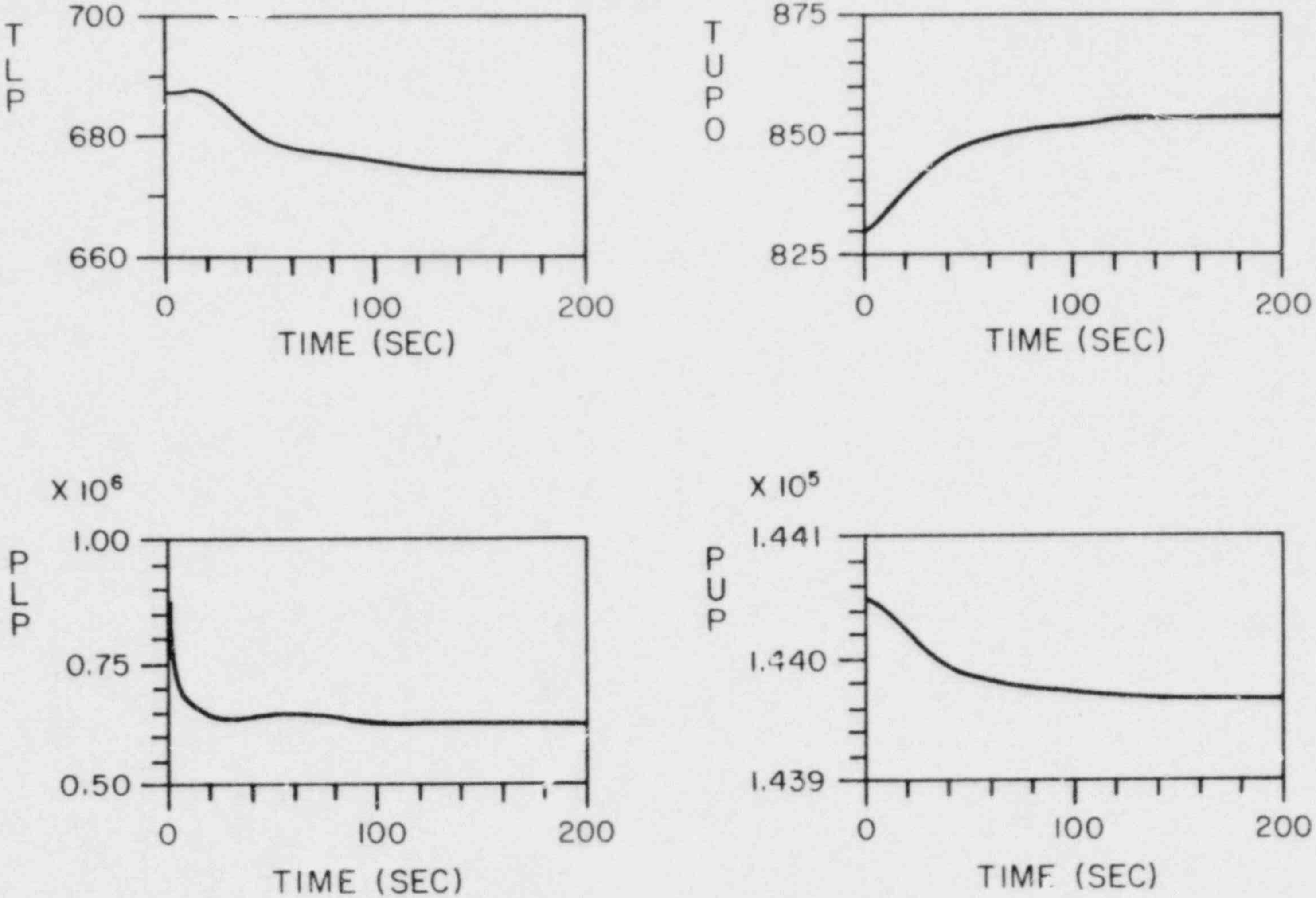

Figure 6.3.--Continued

side. The secondary sodium does not gain as much energy per unit time, in the form of heat flow as in the steady state situation.

When the reactor power deviates from its normal operating condition, the flux control scheme will correct any deviation. In this case the control system pulls out control rods until the power starts climbing toward its original operating condition. The power also rises with the fuel temperatures. The sodium and cladding temperatures in turn will follow the rise in fuel temperatures. However, TCS4 and TCS5 have a slightly different temperature profile; the lower temperature at the end is due to the lower plenum temperature (TLP), which has decreased during the transient.

During this time, the upper plenum sodium exit temperature (TUPO) increases, which in turn causes the rise in TXP1 and TXP2 (IHX primary inlet temperature for the single and double loop, respectively). This is felt on the secondary side by heat transfer across the IHX's with both TXS11 and TXS21 increasing.

The undulations seen in some of the variables are due to the control scheme for the pump in Loop Two.

Conclusion

The objective of this work was to develop a fast-running and accurate model of the FFTF. In all three runs discussed previously, the total execution time ranged from 150 CP seconds to approximately 160 CP seconds. Since all runs were for 200 seconds simulation time, the code runs faster than real time and is indeed fast.

Although there are no comparisons on which to judge the accuracy of the results, physical reasoning was adequate to interpret the runs. All the components were modeled separately and tested thoroughly, and there is no reason to doubt the results obtained.

However, it should be remembered that only the primary system has been modeled. The secondary system is set up now to remove whatever heat is necessary to maintain the IHX secondary sodium inlet temperature at the normal steady state operating point. It is the lack of a model for the secondary side (i.e., DHX, Dump Heat Exchanger) which would cause the results to change by any appreciable amount from the transient responses reported here.

In summary, FATFAD has been shown to be an inexpensive, fast and reliable lumped parameter model of the FFTF primary heat transport system.

For a listing of FATFAD and an index of variable names with definitions see Appendix E.

APPENDIX A

IHX

As in Chapter 2 the parameters which go into the energy equation for the IHX will be considered first. Values found here for transient varying parameters are calculated for the steady state case.

Primary cross-sectional flow area per tube (Eq. 2.1):

$$CAXP1 = \pi[b^2-(a/2)^2]$$

$b = 1.763 \cdot 10^{-2}$m (equivalent diameter),

$a = 2.223 \cdot 10^{-2}$m (outside diameter).

Substituting,

$$CAXP1 = 5.883 \cdot 10^{-2}\text{m}$$

Sodium density (Eq. 2.2):

$$ROXP11 = 16.02\ (59.533-.008333*FAP11)$$

FAP11 (average sodium temperature) = $(T_{in}-T_{out})/2$

$T_{in} = 830.2222$ °K

$T_{out} = 686.8889$ °K

so,

$FAP11 = 906.0$ °F

$ROXP11 = 832.77\ \text{kg/m}^3$

From CAXP1 and ROXP11, the sodium velocity through the IHX can be found.

Sodium velocity (Eq. 2.3):

VXP11 = WRD1/(ROXP11*CAXP1*ENXP1)

ENXP1 = 1540 tubes

WRD1 = 737.066278 kg/sec

VXP11 = .978 m/sec

Specific heat of sodium (Eq. 2.4):

$$CPXP1 = 4.1868\cdot10^{3}\ (.34574-7.9226\cdot10^{-5}*FAP11+3.4086\cdot10^{-8}*FAP11^{2})$$

Using the value of FAP11 determined earlier,

CPXP1 = 1264.16 KJ/kg °K

Thermal conductivity for tube wall and sodium:

Tube wall (Eq. 2.5)

$$TCXW11 = 1.73073\ (7.7388464+.40721437\cdot10^{-2}*TXF11)$$

TXF11 (tube wall temperature in °F) = 878.01 °F

TCXW11 = 19.5818 J/sec m °K

Sodium (Eq. 2.6)

$$TCXP11 = 1.73073\ (54.306-1.878\cdot10^{-2}*FAP11+2.0914\cdot10^{-6}*FAP11^{2})$$

With the steady state value for FAP11 given previously, the sodium thermal conductivity becomes

$$\text{TCXP11} = 67.5123 \text{ J/sec m °K}$$

Sodium viscosity (Eq. 2.8):

$$\text{UMXP11} = 1.867 \cdot 10^{-4} \cdot 10.0^{[1.0203+(397.17/\text{RP11})-.4925\log(\text{RP11})]}$$

where

$$\text{RP11 (average sodium temperature in °R)} = \text{FAP11}+460.0$$

$$\text{RP11} = 1366.0 \text{ °R}$$

and

$$\text{UMXP11} = 1.0914 \cdot 10^{-4} \text{ N sec/m}^3$$

With the thermodynamic properties calculated for both tube wall and sodium, the convective heat transfer coefficients can be determined. The general form of $\bar{h}_c$ is,

$$\bar{h}_c = \frac{k}{D_h} Nu_D \tag{2.9}$$

where

$$Nu_D = A+BRe^C Pr^D \tag{2.10}$$

and

$$Re = \frac{\rho V D_n}{\mu}$$

$$Pr = \frac{C_p \mu}{k}$$

$\overline{h}_c$ for primary (shell) side:

The Reynolds number and Prandlt number are given by Eqs. (2.11) and (2.12) respectively. Also, the constants for the Nusselt number are,

$A = 28.16$,

$B = 3.893 \cdot 10^{-11}$,

$C = D = 0.86$

Substituting everything into the equation for $\overline{h}_c$,

$$HXP11 = \frac{TCXP11}{DH} \left[28.16 + (3.893 \cdot 10^{-11}) REXP11^{.86} \; PRXP11^{.86}\right]$$

$$HXP11 = 5.6422 \cdot 10^{-4} \text{ J/sec m}^2 \; ^\circ\text{k}$$

where

DH (hydraulic diameter) $= 3.36953 \cdot 10^{-2}$ m

$\overline{h}_c$ for secondary (tube) side:

Reynolds number and Prandlt number are again by Eqs. (2.11) and (2.12) respectively. The constants for the Nusselt number are now,

$A = 5.0$,

$B = 0.025$,

$C = D = 0.8$

and the expression for $\overline{h}_c$ becomes

$$HXS11 = \frac{TCXS11}{D} \left[5.0 + (.025) REXS11^{.8} \; PRXS11^{.8}\right]$$

$$HSX11 = 3.1919 \cdot 10^{-4} \text{ J/sec m}^2 \; ^\circ\text{K}$$

where

D (inside diameter of tube) = $1.96\cdot 10^{-2}$m

The tube wall has a thermal resistance associated with it:

$$RW11 = \ln(DOT/DIT)/(2.0*\pi*TCXW11*TL)$$

$$RW11 = 2.4973\cdot 10^{-4} \text{ sec °K/J}$$

where,

$DIT = D = 1.96\cdot 10^{-2}$m

$DOT = 2.223\cdot 10^{-2}$m

This is the total resistance through the wall. It is split into two parts in the model, with the interior point placed where the wall temperature is determined.

Temperatures for each of the three regions (primary, wall, secondary) can now be derived for using the energy equation (see Chapter 2).

Primary region (Eq. 2.20):

$$\frac{d}{dt}(TXP11)_{out} = [WPD1*CPXP11*(TXP11_{in}-TXP11_{out}) - UXP11*(TAVP11-TXW11)]/WP11$$

where,

TAVP11 (Average sodium temperature) = 758.5556 °K

The steady state value of $TXP11_{in}$ is 830.2222 °K and of $TXP11_{out}$ is 686.8889 °K.

Tube wall (Eq. 2.24):

$$\frac{d}{dt}(TXW11) = [UXP11(TAVP11-TXW11) - UXS11(TXW11-TAVS11)]/WW11$$

where

TAVS11 (average sodium temperature on secondary side) = 711.333 °K

The overall heat transfer coefficient for the secondary side (UXS11) contains the fouling resistance RF. This resistance takes into account the buildup of particulate matter on the tube walls, and its value is considered constant. RF had to be determined simultaneously with the wall temperature since one is a function of the other, and neither quantity had a known steady state value. To sustain steady state conditions throughout the system, TXW11 and RF were found to have the values,

$TXW11 = 743.00326844$ °K

$RF = 1.0774167599\cdot 10^{-4}$ sec °K/J

Secondary region (Eq. 2.28):

$$\frac{d}{dt}(TXS11)_{in} = [WSD1*CPXS1(TXS11_{out} - TXS11_{in}) + UXS11(TXW11-TAVS11)]/WS11$$

The steady state values of $TXS11_{in}$ and $TXS11_{out}$ are 639.6667 °K and 783.0 °K, respectively.

APPENDIX B

REACTOR

Lower and Upper Plenum

With a perfect mixing model assumed for both plenums, the only state variable which is of concern is the sodium temperature.

For the lower plenum, sodium temperature is given by Eq. (3.8).

$$\frac{d}{dt}(\text{TLP}) = (\text{QLOOP1}+\text{QLOOP2}-\text{WRD}*\text{CPSLP}*\text{TLP})/(\text{RHOLP}*\text{VOLLP}*\text{CPSLP})$$

WRD (total sodium flow rate) = 2211.198834 kg/sec

VOLLP = 66.09 m^3

The density (RHOLP) and specific heat (CPSLP) are both given by the same expressions as those used for the IHX.

$$\text{QLOOP}(1,2) = \text{WL}(1,2)3*\text{CPL}(1,2)*\text{TLP}(1,2)$$

Since all the above parameters have known steady state values, the system of equations is closed.

TLP = 686.8889 °K

also,

TLP1 = TLP2 = 686.8889 °K

WL13 = 737.066278 kg/sec

WL23 = 1474.132556 kg/sec

Sodium temperature for the upper plenum is given by Eq. (3.12).

$$\frac{d}{dt}\text{(TUPO)} = \text{[WRD*CPOUT*TOUT-(WL11-WL21)*CPOUT*TUPO]/} \\ \text{(RHOUP*VOLUP*VPUPO)}$$

Once again, the density (RHOUP) and specific heats (CPOUT and CPUPO) are found using Eq. (2.2) with the appropriate temperature substitution.

VOLUP (volume of upper plenum) = 95.09 m^3

The steady state value for the upper plenum temperature is

TUPO = 830.2222 °K

also,

WL11 = WL13

WL21 = WL23

Core

By using the energy conservation law, the core outlet temperature (TOUT) can be expressed by Eq. (3.16).

$$\frac{d}{dt}\text{(TOUT)} = \text{(T1+T2+T3+T4+T5-WRD*CPOUT*TOUT)/} \\ \text{(RHOUT*VOLC*CPOUT)}$$

where

VOLC = 2.519691942 m^3

and where T(1-5) is given by Eq. (3.17). Knowing the sodium steady state temperatures in all five channels (given later in this appendix), the sodium steady state temperature at the core outlet becomes

$$\mathrm{TOUT} = 830.2222\ ^\circ\mathrm{K}$$

The five sodium temperatures mentioned above are also determined using the energy equation for each channel. There are also many thermodynamic properties of fuel, cladding, and sodium which appear in the temperature equations. Therefore, as in Appendix A, these thermodynamic properties will be considered first.

Fuel thermal conductivity (Eq. 3.25):

$$\mathrm{TCCF}(1\text{-}3) = 100.0\{\mathrm{F}(1\text{-}3)[38.24/(\mathrm{TCF}(1\text{-}3)+129.2) + 6.1256\cdot 10^{-13} * \mathrm{TCF}(1\text{-}3)\}]$$

where

$$\mathrm{F}(1\text{-}3) = 1.079[\mathrm{FRO}/(1+.5(1-\mathrm{FRO}))] = 0.9387$$

and

$$\mathrm{FRO} = 0.9094$$

Fuel specific heat (Eq. 3.27):

$$\mathrm{CPCF} = 4.1868\cdot 10^{3}(0.1091351924+7.75289753\cdot 10^{-5} * \mathrm{TCF} - 6.121778\cdot 10^{-8} * \mathrm{TCF}^{2}+2.046305\cdot 10^{-11} * \mathrm{TCF}^{3})$$

therefore

$$\mathrm{CPCF} = 648.458\ \mathrm{KJ/kg}\ ^\circ\mathrm{K}$$

The value of CPCF for the other two fuel channels will differ since the fuel temperatures differ.

Gap convective heat transfer coefficient (Eq. 3.31):

$$HCG(1\text{-}3) = 10^4\{0.132+(0.1167*TG(1\text{-}3)^{\frac{1}{2}} -2.36)/$$
$$CGPDR+0.6391[B(1\text{-}3)/(1.0+B(1\text{-}3))]\}$$

with $TG(1\text{-}3)$ given by Eq. (3.32) and $B(1\text{-}3)$ by Eq. (3.33). For the first fuel channel, in steady state,

$$CGPDR = 1.651\cdot 10^{-4}/4.9149\cdot 10^{-3} = 3.359\%$$

$$TG1 = 1125.5\ °K$$

$$B1 = 4.04\cdot 10^{-9}$$

so,

$$HCG1 = 5.95\cdot 10^4\ J/sec\ m^2\ °K$$

Cladding specific heat (Eq. 3.34):

$$CPCC(1\text{-}3) = 4.1868\cdot 10^3[0.14937593-0.39506964\cdot 10^{-4}$$
$$*TFCC(1\text{-}3)+0.2678125\cdot 10^{-7}*TFCC(1\text{-}3)^2]$$

For Channel 1 in steady state,

$TFCC1$ (clad temperature in °F) = 962.59 °F

therefore

$$CPCC1 = 5.701\cdot 10^2\ KJ/kg\ °K \qquad (S.S.\text{-}316)$$

Cladding thermal conductivity (Eq. 3.35):

$$TCCC(1\text{-}3) = 1.73073\ (7.7388464+0.40721437\cdot 10^{-2}*TFCC(1\text{-}3))$$

In steady state,

$$TCC1 = 20.178 \text{ J/sec m}^2 \text{ °K} \qquad \text{(S.S.-316)}$$

It should be mentioned that since the cladding temperature and thermal conductivity are functions of one another, and neither were known, a trial and error method was used to obtain the steady state values.

Sodium heat transfer coefficient (Eq. 3.39):

The convective film heat transfer coefficient for sodium is

HCS(1-3) = UNCS(1-3)*TCSS(1-3)/DHC

where UNCS is the sodium Nusselt number, given by Eq. (3.36), and DHC, the hydraulic diameter, has the value

DHC = 4 · cross-sectional flow area/wetted perimeter

$DHC = 4.106381678 \cdot 10^{-3}$ m

$HCS1 = 1.0539 \cdot 10^{7}$ J/sec m^2 °K (steady state)

At this point, all necessary thermodynamic quantities are assembled and the expressions for fuel, cladding, and sodium temperatures can be formulated. By use of energy conservation, the above three temperatures are given by Eqs. (3.47), (3.44), and (3.42), respectively. The overall heat transfer coefficients are,

Clad-Sodium (Eq. 3.45):

$$UAC(1\text{-}3) = [1.0/(HCS(1\text{-}3)*CAREA2)+ALOG(DOC/DC)/$$
$$(2.0*TCCC(1\text{-}3)*PI*PL)]^{-1}$$

In steady state,

TCCC1 = 20.0937 J/sec m °K

Using

CAREA2 = $1.678215171\cdot10^{-2}$ m

DOC (cladding outer diameter) = $5.842\cdot10^{-3}$ m

DC (diameter where TCC is evaluated = $5.474222066\cdot10^{-3}$ m

PI = π

PL = .9144 m

we have

UAC1 = $1.7578\cdot10^{-3}$ J/sec m °K

Fuel-Clad (Eq. 3.48):

UAF(1-3) = [1.0/(8.0*PI*PL*TCCF(1-3))+1.0/(HCG(1-3)*CAREA1)

+ ALOG(DC/DIC)/(2.0*TCCC(1-3)*PI*PL)]$^{-1}$

In steady state,

TCCF1 = 2.30578 J/sec m °K

HCG1 = $5.95\cdot10^{4}$ J/sec m^2 °K

using

CAREA1 = $1.45931754\cdot10^{-2}$

DIC = $5.08\cdot10^{-3}$ m

we find

UAF1 = $1.4945\cdot10^{3}$ J/sec m °K

Temperature calculations for the center pin are done in a similar fashion as for the three fuel regions. The resulting equations have the same form, and only the values for various parameters change; see Eqs. (3.49), (3.50), and (3.51). Table B.1 lists the steady state temperatures of the 5 channels and hot channel.

Table B.1. Steady state temperatures for 5 channel core.

	Steady State Temperatures (°K)		
Cladding	Fuel	Cladding	Sodium
Hot	1776.7583707	801.08287055	883.70062324
1	1711.0141904	789.99552822	863.1161984
2	1628.1658722	785.57202418	856.4841221
3	1397.9035084	773.31133087	838.4591702
4	---	---	721.8784246
5	---	---	722.5928366

Kinetics

The total reactivity, used in the prompt jump approximation (Eq. 3.56), is given by Eq. (3.58),

$$\text{ROD} = \text{ROCRD}+\text{ROFBD}+\text{ROEXCD}+\text{ROAUTO}$$

where,

$$\text{ROEXCD} = -\text{ROFBD}$$

with

$$\text{ROFBD} = [100.0(\text{DOPC}/\text{BETAT})*\ell n(\text{TVAFR}/\text{TIR})+\text{SODDC}*(\text{TVAS}-\text{TI})$$
$$+ \text{AXEC}*(\text{TVAF}-\text{TI})+\text{REC}*(\text{TVAS}-\text{TI})]/100.0$$

$\text{BETAT} = 3.34991 \cdot 10^{-3}$

$\text{DOPC} = -.005$

$\text{SODDC} = -.0882$ ¢/°K

$\text{AXEC} = -.0684$ ¢/°K

$\text{REC} = -.378$ ¢/°K

$\text{TI} = 477.4444$ °K

$\text{TIR} = 860.0$ °R

In steady state,

ROFBD = -2.6839411896366 dollars

ROCRD = 0.0 dollars

ROAUTO = 0.0 dollars

APPENDIX C

MOMENTUM AND PRESSURE EQUATIONS

Steady state values of terms in the momentum equations were, for the most part, found in various volumes of the FSAR for FFTF. Only one term, the friction factor, required an alternate method for steady state determination. The method employed involves rewriting the momentum equation which contains the unknown friction factor, and solving the new differential equation that results.

To illustrate this technique, the momentum equation for the IHX is reproduced below.

$$\frac{d}{dt}\,(\text{WIXP}) = \text{AOLXP}*[\text{POUT12-PIN13-RHOXP*G*Y}+(\text{WIXP/PAXP1})^2* (1.0/\text{ROUT12}-1.0/\text{ROIN13}-\text{FXP1*PAXP1}^2)]$$

All the terms on the R.H.S. of this equation have known steady state values except FXP1. The steady state value of FXP1 is found by replacing the actual momentum equation with a fictitious equation.

$$\frac{d}{dt}\,(\text{FXP1}) = \text{AOLXP}*[\text{POUT12-PIN13-RHOXP*G*Y}+(\text{WIXP/PAXP1})^2* (1.0/\text{ROUT12}-1.0/\text{ROIN13}-\text{FXP1*PAXP1}^2)] \tag{C.1}$$

As can be seen, Eq. (C.1) looks identical to the original equation. The only alteration comes from the L.H.S. of the momentum equation. Instead of having $d(\dot{m})/dt$, $d(f)/dt$ is substituted in its place, with f being the friction factor, FXP1 in this case. By pegging all other terms at their steady state values and solving Eq. (C.1), the integration routine will determine the value of the friction term which gives a derivative of zero.

In the case of FXP1, the result of using this steady state solver is

FXP1 = 281561.182617841

Below is a list of the friction factors, all of which were obtained using the fictitious differential equation method.

Reactor:

F121 = 1.153853889592

F122 = 3.506702498715

F123 = 1.9966364878736

F124 = 207.89525748858

F125 = 5.6344305986404

IHX:

FXP1 = 283026.28367793 one-loop

FXP2 = 70764.297116279 two-loop

Piping:

FL11 = 0.0152114170078

FL12 = 0.0341751154091 one-loop

FL13 = 0.1818751139653

FL21 = 0.00380285425196

FL22 = 0.00854377885226 two-loop

FL23 = 0.04546877849133

APPENDIX D

FLUX CONTROL SYSTEM

Determination of Differential Equations of Flux Controller

(A) CRDM (Equivalent Linear)

$$\frac{\text{OUTPUT}}{\text{INPUT}} = \frac{X(s)}{R(s)} = e^{-0.1s}$$

In order to solve this the exponent must be expanded. This is done using the Padé approximation (for small negative argument),

$$\frac{\text{OUTPUT}}{\text{INPUT}} = \frac{s^2T^2-6sT+12}{s^2T^2+6sT+12} = \frac{s^2 - \frac{6}{T}s + \frac{12}{T^2}}{s^2 + \frac{6}{T}s + \frac{12}{T^2}}$$

Let

$a = 6/T$

$b = \frac{12}{T^2}$

$T = 0.1$ (not -0.1)

then

$$\frac{X(s)}{R(s)} = \frac{s^2-as+b}{s^2+as+b} \qquad (D.1)$$

or

$$X(s)(s^2+as+b) = R(s)(s^2-as+b) \qquad (D.2)$$

Let X(s) have the following form,

$$X(s) = u(s)(s^2-as+b) \tag{D.3}$$

Substituting Eq. (D.3) into Eq. (D.2),

$$u(s)(s^2-as+b)(s^2+as+b) = R(s)(s^2-as+b) \tag{D.4}$$

reducing,

$$u(s)(s^2+as+b) = R(s) \tag{D.5}$$

The equations which must now be solved are Eqs. (D.3) and (D.5). Determining the appropriate differential equations,

$$x(t) = \frac{d^2u}{dt^2} - a\frac{du}{dt} + b[u(t)] \tag{D.6}$$

$$r(t) = \frac{d^2u}{dt^2} + a\frac{du}{dt} + b[u(t)] \tag{D.7}$$

Letting

$$u_1(t) = u(t), \quad \frac{du}{dt} = u_2(t)$$

we have

$$\frac{d^2u}{dt^2} = \frac{du_2}{dt}$$

Substituting these relations back into Eqs. (D.6) and (D.7),

$$x(t) = \frac{du_2}{dt} - au_2 + bu_2 \tag{D.8}$$

where

$$\frac{du_2}{dt} = r(t) - au_2 - bu_2 \tag{D.9}$$

The needed equations are thus

$$\frac{du_2}{dt} = u_2 \qquad \text{(D.10)}$$

$$\frac{du_2}{dt} = r(t) - au_2 - bu_2 \qquad \text{(D.11)}$$

$$x(t) = \frac{du_2}{dt} - au_2 + bu_2 \qquad \text{(D.12)}$$

where Eqs. (D.10), (D.11), and (D.12) correspond to Eqs. (5.1), (5.2), and (5.3), respectively.

(B) Flux Sensor

$$\frac{Z(s)}{Y(s)} = \frac{1}{1+0.35s}$$

or

$$Z(s)(1+0.35s) = Y(s) \qquad \text{(D.13)}$$

The differential equation for Eq. (D.13) becomes,

$$\frac{dZ}{dt} = [y(t)-Z(t)]/0.35 \qquad \text{(D.14)}$$

where Eq. (D.14) corresponds to Eq. (5.6).

(C) Proportional Integrator

$$r(t) = k_1e(t)+k_2 \int_0^t e(t)dt \qquad \text{(D.15)}$$

Rewriting Eq. (D.15) in a more convenient form,

$$\frac{d\omega}{dt} = k_2 e(t) \tag{D.16}$$

$$r(t) = k_1 e(t) = \omega(t) \tag{D.17}$$

with Eq. (D.16) given by Eq. (5.5) and Eq. (D.17) by Eq. (5.4). The constant k_2 is assumed to equal one, leaving only k_1 to be determined using the Nichols Chart method.

Determination of Gain (K)

Before actually determining k_1, the control system has to be transformed into an equivalent system, but with a feedback of unity (see Fig. 5.3). With H(s) as the Flux Sensor transfer function and Z(s) the PI transfer function, Eq, (5.4) becomes

$$PIOP/ERR = (K + 1/s)/(1 + 0.35s) \qquad \text{(D.18}$$

or

$$PIOP(1+0.35s) = ERR(K + 1/s) \tag{D.19}$$

where the equivalent differential equation is

$$\frac{d}{dt}\,(PIOP) = (ERR{*}K + \int ERR\ dt - PIOP)/0.35 \tag{D.20}$$

Since $\omega(t) = \int ERR\ dt$, Eq. (D.20) can be written as

$$\frac{d}{dt}\,(PIOP) = (ERR{*}K + \omega(t) - PIOP)/0.35 \tag{D.21}$$

which is Eq. (5.8).

With this transformation, the desired flux entering the summation junction is also altered. Let FEND be the desired flux going into the transfer block, and FENDP the desired flux coming out of the block. The differential equation is then

$$\mathrm{FENDP/FEND} = 1 + 0.35s$$

$$\frac{d}{dt}(\mathrm{FEND}) = (\mathrm{FENP-FEND})/0.35 \tag{D.22}$$

Turning to the linear CRDM transfer function, Eq. (5.10) can be represented as a product of two other transfer functions each having the form expressed by Eq. (5.11). Rewriting Eq. (5.10),

$$G(s) = (\omega_2^2/\omega_1^2)(\omega_1^2/\omega_2^2)[(s^2-as+b)/(s^2+as+b)]$$

$$= (\omega_2^2/\omega_1^2)\ G(s)_1\ G(s)_2 \tag{D.23}$$

where,

$$G(s)_1 = \omega_1^2/(s^2+as+b)$$

$$G(s)_2 = (s^2-as+b)/\omega_2^2$$

Both transfer functions can be represented by Eq. (5.11) using the following definitions,

$$\xi_1 = a\omega_1/2b = 0.866$$

$$\xi_2 = -a\omega_2/2b = -0.866$$

$$\omega_1 = \omega_2 = \sqrt{b} = 34.64$$

Since ω_1 equals ω_2, Eq. (D.23) can be written as

$$G(s) = G(s)_1\ G(s)_2 \tag{D.24}$$

Before deriving the expressions for magnitude and phase angle of G(s), it should be mentioned that the analysis is only good for linear systems. Because this control scheme is nonlinear, the results obtained from the following treatment hold for small transients about the normal operating point only.

The magnitude, in decibels, is,

$$|G(s)|_{db} = 20\ \log_{10}|G(\text{[illegible]} \tag{D.25}$$

But

$$|G(s)| = |G(s)_1\ G(s)_2|$$

therefore

$$\begin{aligned} |G(s)|_{db} &= 20\ \log_{10}|G(s)_1\ G(s)_2| \\ &= 20\ \log_{10}|G(s)_1| + 20\ \log_{10}|G(s)_2| \end{aligned}$$

$$|G(s)|_{db} = |G(s)_1|_{db} + |G(s)_2|_{db} \tag{D.26}$$

where, using $s=j\omega$,

$$|G(j\omega)_1|_{db} = -20\ \log_{10}\{[1-(\omega/\omega_1)^2]^2 + 4\xi_1^2(\omega/\omega_1)^2\}^{\frac{1}{2}} \tag{D.27}$$

$$|G(j\omega)_2|_{db} = 20\ \log_{10}\{[1-(\omega/\omega_2)^2]^2 + 4\xi_2^2(\omega/\omega_2)^2\}^{\frac{1}{2}} \tag{D.28}$$

In determining a relationship for phase angle, complex number theory is useful. Putting $G(s)_1$ and $G(s)_2$ into a more useful form,

$$G(j\omega)_1 = M_1[(-\omega^2+b)-ja\omega] \tag{D.29}$$

$$G(j\omega)_2 = M_2[(-\omega^2+b)-ja\omega] \tag{D.30}$$

with M_1 and M_2 being the resulting constants after rationalizing the denominators of $G(j\omega)_1$ and $G(j\omega)_2$, respectively. Looking at only the complex portion of Eqs. (D.29) and (D.30), they can be rewritten in the form

$$Z = x+jy = \rho(\cos\theta + j\,\sin\theta)$$

where $\rho = \sqrt{x^2+y^2}$ and $\theta=\tan^{-1}(y/x)$. Using a power series expansion, it can be shown that

$$e^{i\theta} = \cos\theta + j\,\sin\theta$$

Hence

$$Z = \rho e^{i\theta} \tag{D.31}$$

with ρ being the magnitude and θ the phase angle. Therefore,

$$G(j\omega)_1 = \rho_1\, e^{i\theta_1} \tag{D.32}$$

$$G(j\omega)_2 = \rho_2\, e^{i\theta_2} \tag{D.33}$$

Using Eq. (D.24),

$$G(j\omega) = \rho_1\rho_2\, e^{i(\theta_1+\theta_2)} \tag{D.34}$$

where $\theta = \theta_1+\theta_2$ is the total phase angle. Alternately,

$$\underline{/G(j\omega)} = \underline{/G(j\omega)_1} + \underline{/G(j\omega)_2} \tag{D.35}$$

with

$$\theta_1 = -\tan^{-1}\left\{\frac{2\xi_1\omega}{\omega_1} \Big/ \left[1-\left(\frac{\omega}{\omega_1}\right)^2\right]\right\} \tag{D.36}$$

$$\theta_2 = \tan^{-1}\left\{\frac{2\xi_2\omega}{\omega_2} \Big/ \left[1-\left(\frac{\omega}{\omega_2}\right)^2\right]\right\} \tag{D.37}$$

From Eqs. (D.26) and (D.34), a plot of magnitude vs. phase is superimposed on a similar graph for the control system without the CRDM (Fig. 5.8). The resulting graph is placed on a Nichols chart and the gain constant is read directly from the chart. As mentioned in Chapter 5, the gain comes out to be 0.3162.

APPENDIX E

GLOSSARY OF VARIABLE NAMES AND FATFAD LISTING

The following is an alphabetical list of variables used in FATFAD. All variables are in SI units unless otherwise stated. As mentioned in Chapters 2 through 5, various schemes have been adopted for variable naming. For example, the suffix 1 and 2 signifies whether that variable is used for the one or two loop model, respectively. Other schemes are used and explained in various chapters, therefore they will not be reproduced here.

Immediately following the glossary is a listing of FATFAD, a DARE P input file.

AC1	CROSS-SECTIONAL FLOW AREA IN CORE CHANNEL 1
AC2	CROSS-SECTIONAL FLOW AREA IN CORE CHANNEL 2
AC3	CROSS-SECTIONAL FLOW AREA IN CORE CHANNEL 3
AC4	CROSS-SECTIONAL FLOW AREA IN CORE CHANNEL 4
AC5	CROSS-SECTIONAL FLOW AREA IN CORE CHANNEL 5
AMDA1	DECAY CONSTANT FOR GROUP 1
AMDA2	DECAY CONSTANT FOR GROUP 2
AMDA3	DECAY CONSTANT FOR GROUP 3
AMDA4	DECAY CONSTANT FOR GROUP 4
AMDA5	DECAY CONSTANT FOR GROUP 5
AMDA6	DECAY CONSTANT FOR GROUP 6
ADL1	AREA DIVIDED BY LENGTH FOR CORE CHANNEL 1
ADL11	AREA DIVIDED BY LENGTH OF PIPE SECTION 1, LOOP 1
ADL12	AREA DIVIDED BY LENGTH OF PIPE SECTION 2, LOOP 1
ADL13	AREA DIVIDED BY LENGTH OF PIPE SECTION 3, LOOP 1
ADL2	AREA DIVIDED BY LENGTH FOR CORE CHANNEL 2
ADL21	AREA DIVIDED BY LENGTH OF PIPE SECTION 1, LOOP 2
ADL22	AREA DIVIDED BY LENGTH OF PIPE SECTION 2, LOOP 2
ADL23	AREA DIVIDED BY LENGTH OF PIPE SECTION 3, LOOP 2
ADL3	AREA DIVIDED BY LENGTH FOR CORE CHANNEL 3
ADL4	AREA DIVIDED BY LENGTH FOR CORE CHANNEL 4
ADL5	AREA DIVIDED BY LENGTH FOR CORE CHANNEL 5
ADLXP1	AREA DIVIDED BY LENGTH OF IHX TUBE, LOOP 1
ADLXP2	AREA DIVIDED BY LENGTH FO IHX TUBE, LOOP 2
AXEC	AXIAL EXPANSION COEFFICIENT
BETA1	DELAYED NEUTRON FRACTION FOR GROUP 1
BETA2	DELAYED NEUTRON FRACTION FOR GROUP 2
BETA3	DELAYED NEUTRON FRACTION FOR GROUP 3
BETA4	DELAYED NEUTRON FRACTION FOR GROUP 4
BETA5	DELAYED NEUTRON FRACTION FOR GROUP 5
BETA6	DELAYED NEUTRON FRACTION FOR GROUP 6
BETAT	TOTAL DELAYED NEUTRON FRACTION
CAREA1	HEAT TRANSFER AREA, GAP-CLADDING INTERFACE
CAREA2	HEAT TRANSFER AREA, CLAD-SODIUM INTERFACE
CAXP1	IHX X-SECT. FLOW AREA, PRIMARY SIDE(LOOP 1)
CAXP2	IHX X-SECT. FLOW AREA, PRIMARY SIDE, LOOP 2
CAXS1	IHX X-SECT. FLOW AREA, SECONDARY SIDE(LOOP 1)
CAXS2	IHX X-SECT. FLOW AREA, SECONDARY SIDE, LOOP 2
CGPDR	COLD GAP TO PELLET DIAMETRAL RATIO(*%)
CM	CLADDING MASS PER PIN
CN1	NORMALIZED CONCENTRATION OF 1ST DELAY GROUP
CN2	NORMALIZED CONCENTRATION OF 2ND DELAY GROUP
CN3	NORMALIZED CONCENTRATION OF 3RD DELAY GROUP
CN4	NORMALIZED CONCENTRATION OF 4TH DELAY GROUP
CN5	NORMALIZED CONCENTRATION OF 5TH DELAY GROUP
CN6	NORMALIZED CONCENTRATION OF 6TH DELAY GROUP
CNLROD	ROD WORTH FOR CONTROL RODS
CONST	GAIN CONSTANT FOR FLUX CONTROL SYSTEM
CPAS1	AV. SODIUM SPECIFIC HEAT OF CORE CHANNEL 1
CPAS2	AV. SODIUM SPECIFIC HEAT OF CORE CHANNEL 2
CPAS3	AV. SODIUM SPECIFIC HEAT OF CORE CHANNEL 3
CPAS4	AV. SODIUM SPECIFIC HEAT OF CORE CHANNEL 4
CPAS5	AV. SODIUM SPECIFIC HEAT OF CORE CHANNEL 5
CPASHC	AV. SODIUM SPECIFIC HEAT IN CORE HOT CHANNEL
CPCC1	SPECIFIC HEAT OF CLAD IN CORE CHANNEL 1
CPCC2	SPECIFIC HEAT OF CLAD IN CORE CHANNEL 2
CPCC3	SPECIFIC HEAT OF CLAD IN CORE CHANNEL 3
CPCCHC	SPECIFIC HEAT OF CLAD IN CORE HOT CHANNEL
CPCF1	SPECIFIC HEAT OF FUEL IN CORE CHANNEL 1
CPCF2	SPECIFIC HEAT OF FUEL IN CORE CHANNEL 2
CPCF3	SPECIFIC HEAT OF FUEL IN CORE CHANNEL 3
CPCFHC	SPECIFIC HEAT OF FUEL IN CORE HOT CHANNEL
CPL1	IHX EXIT PRIMARY SODIUM SPECIFIC HEAT, LOOP 1
CPL2	IHX EXIT PRIMARY SODIUM SPECIFIC HEAT, LOOP 2

CPOUT	UPPER PLENUM INLET SODIUM SPECIFIC HEAT
CPS1	SODIUM SPECIFIC HEAT OF CORE CHANNEL 1
CPS2	SODIUM SPECIFIC HEAT OF CORE CHANNEL 2
CPS3	SODIUM SPECIFIC HEAT OF CORE CHANNEL 3
CPS4	SODIUM SPECIFIC HEAT OF CORE CHANNEL 4
CPS5	SODIUM SPECIFIC HEAT OF CORE CHANNEL 5
CPSLP	LOWER PLENUM SODIUM SPECIFIC HEAT
CPLPO	UPPER PLENUM OUTLET SODIUM SPSCIFIC HEAT
CPXP11	IHX PRIMARY SODIUM SPECIFIC HEAT, LOOP 1
CPXP21	IHX PRIMARY SODIUM SPECIFIC HEAT, LOOP 2
CPXS11	IHX SECONDARY SODIUM SPECIFIC HEAT, LOOP 1
CPXS21	IHX SECONDARY SODIUM SPECIFIC HEAT, LOOP 2
CPXW1	SPECIFIC HEAT OF IHX TUBE
CSFA	CROSS-SECTIONAL FLOW AREA PER FUEL ELEMENT
D	IHX TUBE DIAMETER
DC	CLADDING DIAMETER WHERE TEMP. IS FOUND
DCT	IHX TUBE DIAMETER WHERE WALL TEMP. IS MEASURED
DELP11	UPPER PLENUM PRESSURE DIFFERENCE, LOOP 1
DELP13	LOWER PLENUM PRESSURE DIFFERENCE, LOOP 1
DELP21	UPPER PLENUM PRESSURE DIFFERENCE, LOOP 2
DELP23	LOWER PLENUM PRESSURE DIFFERENCE, LOOP 2
DH	HYDRAULIC DIAMETER PER TUBE CELL IN IHX
DHC	HYDRAULIC DIAMETER OF SODIUM CHANNEL PER PIN
DIC	CLADDING INSIDE DIAMETER
DIT	IHX TUBE INSIDE DIAMETER
DOC	CLADDING OUTSIDE DIAMETER
DOPC	DOPPLER COEFFICIENT
DOT	IHX TUBE OUTSIDE DIAMETER
EN	NORMALIZED FLUX
ENRC1	NUMBER OF FUEL PINS IN CORE CHANNEL 1
ENRC2	NUMBER OF FUEL PINS IN CORE CHANNEL 2
ENRC3	NUMBER OF FUEL PINS IN CORE CHANNEL 3
ENRC4	NUMBER OF CONTROL PINS IN CORE CHANNEL 4
ENRC5	NUMBER OF PINS IN CORE CHANNEL 5
ENXT1	NUMBER OF IHX TUBES IN LOOP 1
ENXT2	NUMBER OF IHX TUBES IN LOOP 2
ERR	ERROR SIGNAL FOR THE FLUX CONTROL SYSTEM
FI21	FRICTION FACTOR FOR CORE CHANNEL 1
FI22	FRICTION FACTOR FOR CORE CHANNEL 2
FI23	FRICTION FACTOR FOR CORE CHANNEL 3
FI24	FRICTION FACTOR FOR CORE CHANNEL 4
FI25	FRICTION FACTOR FOR CORE CHANNEL 5
FAP11	AV. PRIMARY SODIUM TEMP.(F) IN IHX, LOOP 1
FAP21	AV. PRIMARY SODIUM TEMP. IN IHX, LOOP 2
FAS11	AV. SECONDARY SODIUM TEMP.(F) IN IHX, LOOP 1
FAS21	AV. SECONDARY SODIUM TEMP. IN IHX, LOOP 2
FL11	FRICTION FACTOR FOR PIPE SECTION 1, LOOP 1
FL12	FRICTION FACTOR FOR PIPE SECTION 2, LOOP 1
FL13	FRICTION FACTOR FOR PIPE SECTION 3, LOOP 1
FL21	FRICTION FACTOR FOR PIPE SECTION 1, LOOP 2
FL22	FRICTION FACTOR FOR PIPE SECTION 2, LOOP 2
FL23	FRICTION FACTOR FOR PIPE SECTION 3, LOOP 2
FLUX	NORMALIZED FLUX
FM	FUEL MASS PER PIN
FPC1	FRACTIONAL POWER OUTPUT IN CORE CHANNEL 1
FPC2	FRACTIONAL POWER OUTPUT IN CORE CHANNEL 2
FPC3	FRACTIONAL POWER OUTPUT IN CORE CHANNEL 3
FPC4	FRACTIONAL POWER OUTPUT IN CORE CHANNEL 4
FPC5	FRACTIONAL POWER OUTPUT IN CORE CHANNEL 5
FRO	FUEL DENSITY DIVEDED BY THEORETICAL DENSITY
FV1	CORE SODIUM VOLUME FRACTION FOR CORE CHANNEL 1
FV2	CORE SODIUM VOLUME FRACTION FOR CORE CHANNEL 2
FV3	CORE SODIUM VOLUME FRACTION FOR CORE CHANNEL 3
FV4	CORE SODIUM VOLUME FRACTION FOR CORE CHANNEL 4
FV5	CORE SODIUM VOLUME FRACTION FOR CORE CHANNEL 5
FVF1	FUEL VOLUME FRACTION FOR CORE CHANNEL 1

FVF2	FUEL VOLUME FRACTION FOR CORE CHANNEL 2
FVF3	FUEL VOLUEM FRACTION FOR CORE CHANNEL 3
FWRD1	FRACTION OF TOTAL FLOW THROUGH CORE CHANNEL 1
FWRD2	FRACTION OF TOTAL FLOW THROUGH CORE CHANNEL 2
FWRD3	FRACTION OF TOTAL FLOW THROUGH CORE CHANNEL 3
FWRD4	FRACTION OF TOTAL FLOW THROUGH CORE CHANNEL 4
FWRD5	FRACTION OF TOTAL FLOW THROUGH CORE CHANNEL 5
FXP1	FRICTION FACTOR FOR IHX TUBE IN LOOP 1
FXP2	FRICTION FACTOR FOR IHX TUBE IN LOOP 2
G	ACCELERATION DUE TO GRAVITY
HCG1	FUEL GAP HEAT TRANSFER COEFF. OF CORE CHANNEL 1
HCG2	FUEL GAP HEAT TRANSFER COEFF. OF CORE CHANNEL 2
HCG3	FUEL GAP HEAT TRANSFER COEFF. OF CORE CHANNEL 3
HCGHC	GAP HEAT TRANSFER COEFF. IN CORE HOT CHANNEL
HCS1	SODIUM HEAT TRANSFER COEFF. IN CORE CHANNEL 1
HCS2	SODIUM HEAT TRANSFER COEFF. IN CORE CHANNEL 2
HCS3	SODIUM HEAT TRANSFER COEFF. IN CORE CHANNEL 3
HCSHC	SODIUM HEAT TRANSFER COEFF. OF CORE HOT CHANNEL
HXP11	IHX PRIMARY SODIUM HEAT TRANSFER COEFF., LOOP 1
HXP21	IHX PRIMARY SODIUM HEAT TRANSFER COEFF., LOOP 2
HXS11	IHX SECONDARY HEAT TRANSFER COEFF., LOOP 1
HXS21	IHX SECONDARY NA HEAT TRANSFER COEFF., LOOP 2
P	PERIMETER OF AN IHX TUBE
PAL11	X-SECTIONAL FLOW AREA OF PIPE SECTION 1, LOOP 1
PAL12	X-SECTIONAL FLOW AREA OF PIPE SECTION 2, LOOP 1
PAL13	X-SECTIONAL FLOW AREA OF PIPE SECTION 3, LOOP 1
PAL21	X-SECTIONAL FLOW AREA OF PIPE SECTION 1, LOOP 2
PAL22	X-SECTIONAL FLOW AREA OF PIPE SECTION 2, LOOP 2
PAL23	X-SECTIONAL FLOW AREA OF PIPE SECTION 3, LOOP 2
PAREA	HEAT TRANSFER AREA OF AN IHX TUBE
PAXP1	IHX TUBE AREA, PRIMARY SIDE IN LOOP 1
PAXP2	IHX TUBE AREA, PRIMARY SIDE IN LOOP 2
PCCS1	SODIUM PECLET NUMBER IN CORE CHANNEL 1
PCCS2	SODIUM PECLET NUMBER IN CORE CHANNEL 2
PCCS3	SODIUM PECLET NUMBER IN CORE CHANNEL 3
PCCSHC	SODIUM PECLET NUMBER OF CORE HOT CHANNEL
PCG	UPPER PLENUM COVER GAS PRESSURE
PEXP11	IHX PRIMARY SODIUM PECLET NUMBER, LOOP 1
PEXP21	IHX PRIMARY SODIUM PECLET NUMBER, LOOP 2
PEXS11	IHX SECONDARY SODIUM PECLET NUMBER, LOOP 1
PEXS21	IHX SECONDARY SODIUM PECLET NUMBER, LOOP 2
PIN11	PRESSURE AT PIPE SECTION 1 INLET, LOOP 1
PIN12	PRESSURE AT INLET OF PIPE SECTION 2, LOOP 1
PIN13	PRESSURE AT INLET OF PIPE SECTION 3, LOOP 1
PIN21	PRESSURE AT PIPE SECTION 1 INLET, LOOP 2
PIN22	PRESSURE AT INLET OF PIPE SECTION 2, LOOP 2
PIN23	PRESSURE AT INLET OF PIPE SECTION 3, LOOP 2
PIOP	PROPORTIONAL INTEGRALL OUTPUT SIGNAL
PL	ACTIVE FUEL PIN LENGTH
PLL11	LENGTH OF PIPE SECTION 1 IN LOOP 1
PLL12	LENGTH OF PIPE SECTION 2 IN LOOP 1
PLL13	LENGTH OF PIPE SECTION 3 IN LOOP 1
PLL21	LENGTH OF PIPE SECTION 1 IN LOOP 2
PLL22	LENGTH OF PIPE SECTION 2 IN LOOP 2
PLL23	LENGTH OF PIPE SECTION 3 IN LOOP 2
PLP	LOWER PLENUM PRESSURE
POUT11	PRESSURE AT EXIT OF PIPE SECTION 1, LOOP 1
POUT12	PRESSURE AT EXIT OF PIPE SECTION 2, LOOP 1
POUT13	PRESSURE AT PIPE SECTION 3 EXIT, LOOP 1
POUT21	PRESSURE AT EXIT OF PIPE SECTION 1, LOOP 2
POUT22	PRESSURE AT EXIT OF PIPE SECTION 2, LOOP 2
POUT23	PRESSURE AT PIPE SECTION 3 EXIT, LOOP 2
PRCS1	SODIUM PRANDLT NUMBER IN CORE CHANNEL 1
PRCS2	SODIUM PRANDLT NUMBER IN CORE CHANNEL 2
PRCS3	SODIUM PRANDLT NUMBER IN CORE CHANNEL 3
PRCSHC	SODIUM PRANDLT NUMBER OF CORE HOT CHANNEL

PRXP11	IHX PRIMARY SODIUM PRANDLT NUMBER, LOOP 1
PRXP21	IHX PRIMARY SODIUM PRANDLT NUMBER, LOOP 2
PRXS11	IHX SECONDARY SODIUM PRANDLT NUMBER, LOOP 1
PRXS21	IHX SECONDARY SODIUM PRANDLT NUMBER, LOOP 2
PUP	UPPER PLENUM PRESSURE
Q1	POWER PRODUCED IN CORE CHANNEL 1
Q2	POWER PRODUCED IN CORE CHANNEL 2
Q3	POWER PRODUCED IN CORE CHANNEL 3
Q4	POWER PRODUCED IN CORE CHANNEL 4
Q5	POWER PRODUCED IN CORE CHANNEL 5
QF1	HEAT FLOW REACHING CLAD OF CORE CHANNEL 1
QF2	HEAT FLOW REACHING CLAD OF CORE CHANNEL 2
QF3	HEAT FLOW REACHING CLAD OF CORE CHANNEL 3
QFHC	HEAT FLOW REACHING CLAD OF CORE HOT CHANNEL
QHOT	POWER PRODUCED IN CORE CHANNEL 1
QL1	POWER PRODUCED PER PIN LENGTH IN CORE CHANNEL 1
QL2	POWER PRODUCED PER PIN LENGTH IN CORE CHANNEL 2
QL3	POWER PRODUCED PER PIN LENGTH IN CORE CHANNEL 3
QLHC	POWER PRODUCED PER PIN LENGTH, CORE HOT CHANNEL
QLOOP1	HEAT FLOW ENTERING LOWER PLENUM FROM LOOP 1
QLOOP2	HEAT FLOW ENTERING LOWER PLENUM FROM LOOP 2
QLP1	SAME AS QL1
QLP2	SAME AS QL2
QLP3	SAME AS QL3
QLPHC	POWER PRODUCED PER PIN LENGTH, CORE HOT CHANNEL
QNA1	HEAT FLOW REACHING SODIUM IN CORE CHANNEL 1
QNA2	HEAT FLOW REACHING SODIUM IN CORE CHANNEL 2
QNA3	HEAT FLOW REACHING SODIUM IN CORE CHANNEL 3
QNA4	HEAT FLOW REACHING SODIUM IN CORE CHANNEL 4
QNA5	HEAT FLOW REACHING SODIUM IN CORE CHANNEL 5
QNAHC	HEAT FLOW REACHING SODIUM IN CORE HOT CHANNEL
QP1	POWER PRODUCED PER PIN IN CORE CHANNEL 1
QP2	POWER PRODUCED PER PIN IN CORE CHANNEL 2
QP3	POWER PRODUCED PER PIN IN CORE CHANNEL 3
QPHC	POWER PRODUCED IN CORE HOT CHANNEL
QT	OPERATING POWER
QTOT	RATED THERMAL POWER OUTPUT
R11	RADIUS OF PIPE SECTION 1 IN LOOP 1
R12	RADIUS OF PIPE SECTION 2 IN LOOP 1
R13	RADIUS OF PIPE SECTION 3 IN LOOP 1
R21	RADIUS OF PIPE SECTION 1 IN LOOP 2
R22	RADIUS OF PIPE SECTION 2 IN LOOP 2
R23	RADIUS OF PIPE SECTION 3 IN LOOP 2
RC11	THERMAL RESISTANCE OF CLAD IN CORE CHANNEL 1
RC12	THERMAL RESISTANCE OF CLAD IN CORE CHANNEL 2
RC13	THERMAL RESISTANCE OF CLAD IN CORE CHANNEL 3
RC1HC	CLAD THERMAL RESISTANCE OF CORE HOT CHANNEL
RC21	THERMAL RESISTANCE OF CLAD IN CORE CHANNEL 1
RC22	THERMAL RESISTANCE OF CLAD IN CORE CHANNEL 2
RC23	THERMAL RESISTANCE OF CLAD IN CORE CHANNEL 3
RC2HC	CLAD THERMAL RESISTANCE OF CORE HOT CHANNEL
REL	RADIAL EXPANSION COEFFICIENT
RECS1	SODIUM REYNOLDS NUMBER IN CORE CHANNEL 1
RECS2	SODIUM REYNOLDS NUMBER IN CORE CHANNEL 2
RECS3	SODIUM REYNOLDS NUMBER IN CORE CHANNEL 3
RECSHC	SODIUM REYNOLDS NUMBER OF CORE HOT CHANNEL
REXP11	IHX PRIMARY SODIUM REYNOLDS NUMBER, LOOP 1
REXP21	IHX PRIMARY SODIUM REYNOLDS NUMBER, LOOP 2
REXS11	IHX SECONDARY SODIUM REYNOLDS NUMBER, LOOP 1
REXS21	IHX SECONDARY SODIUM REYNOLDS NUMBER, LOOP 2
RF	FAULING RESISTANCE FOR IHX TUBE
RF1	THERMAL RESISTANCE OF FUEL IN CORE CHANNEL 1
RF2	THERMAL RESISTANCE OF FUEL IN CORE CHANNEL 2
RF3	THERMAL RESISTANCE OF FUEL IN CORE CHANNEL 3
RFHC	FUEL THERMAL RESISTANCE OF CORE HOT CHANNEL
RG1	THERMAL RESISTANCE OF GAP IN CORE CHANNEL 1

RG2	THERMAL RESISTANCE OF GAP IN CORE CHANNEL 2
RG3	THERMAL RESISTANCE OF GAP IN CORE CHANNEL 3
RGHC	GAP THERMAL RESISTANCE OF CORE HOT CHANNEL
RHOC1	DENSITY OF SODIUM IN CORE CHANNEL 1
RHOC2	DENSITY OF SODIUM IN CORE CHANNEL 2
RHOC3	DENSITY OF SODIUM IN CORE CHANNEL 3
RHOC4	DENSITY OF SODIUM IN CORE CHANNEL 4
RHOC5	DENSITY OF SODIUM IN CORE CHANNEL 5
RHOCS1	AV. SODIUM DENSITY OF CORE CHANNEL 1
RHOCS2	AV. SODIUM DENSITY OF CORE CHANNEL 2
RHOCS3	AV. SODIUM DENSITY OF CORE CHANNEL 3
RHOHC	DENSITY OF SODIUM IN CORE HOT CHANNEL
RHOL11	DENSITY OF SODIUM IN PIPE SECTION 1, LOOP 1
RHOL12	DENSITY OF SODIUM IN PIPE SECTION 2, LOOP 1
RHOL13	DENSITY OF SODIUM IN PIPE SECTION 3, LOOP 1
RHOL21	DENSITY OF SODIUM IN PIPE SECTION 1, LOOP 2
RHOL22	DENSITY OF SODIUM IN PIPE SECTION 2, LOOP 2
RHOL23	DENSITY OF SODIUM IN PIPE SECTION 3, LOOP 2
RHOLP	DENSITY OF SODIUM IN THE LOWER PLENUM
RHOMAX	MAXIMUM REACTIVITY OF CONTROL BUNDLE
RHOUP	DENSITY OF SODIUM AT UPPER PLENUM OUTLET
RHOUT	DENSITY OF SODIUM AT UPPER PLENUM INLET
RHOXP1	SODIUM DENSITY IN IHX, LOOP 1
RHOXP2	SODIUM DENSITY IN IHX, LOOP 2
ROAUTO	REACTIVITY FROM FLUX CONTROL SYSTEM
ROCRD	CONTROL ROD REACTIVITY
ROO	TOTAL REATIVITY
ROEXCD	ECCENTRIC CONTROL ROD REACTIVITY
ROFBD	FEEDBACK REACTIVITY IN DOLLARS
ROIN11	SODIUM DENSITY AT PIPE SECTION 1 INLET, LOOP 1
ROIN12	SODIUM DENSITY AT PIPE SECTION 2 INLET, LOOP 1
ROIN13	SODIUM DENSITY AT PIPE SECTION 3 INLET, LOOP 1
ROIN21	SODIUM DENSITY AT PIPE SECTION 1 INLET, LOOP 2
ROIN22	SODIUM DENSITY AT PIPE SECTION 2 INLET, LOOP 2
ROIN23	SODIUM DENSITY AT PIPE SECTION 3 INLET, LOOP 2
ROSAHC	SODIUM DENSITY OF CORE HOT CHANNEL
ROUT11	SODIUM DENSITY AT PIPE SECTION 1 EXIT, LOOP 1
ROUT12	SODIUM DENSITY AT PIPE SECTION 2 EXIT, LOOP 1
ROUT13	SODIUM DENSITY AT PIPE SECTION 3 EXIT, LOOP 1
ROUT21	SODIUM DENSITY AT PIPE SECTION 1 EXIT, LOOP 2
ROUT22	SODIUM DENSITY AT PIPE SECTION 2 EXIT, LOOP 2
ROUT23	SODIUM DENSITY AT PIPE SECTION 3 EXIT, LOOP 2
ROXP11	IHX PRIMARY SODIUM DENSITY, LOOP 1
ROXP21	IHX PRIMARY SODIUM DENSITY, LOOP 2
ROXS11	IHX SECONDARY SODIUM DENSITY, LOOP 1
ROXS21	IHX SECONDARY SODIUM DENSITY, LOOP 2
RP11	AV. PRIMARY SODIUM TEMP.(R) IN IHX, LOOP 1
RP21	AV. PRIMARY SODIUM TEMP. IN IHX, LOOP 2
RS1	THERMAL RESISTANCE OF SODIUM IN CORE CHANNEL 1
RS11	AV. SECONDARY SODIUM TEMP.(R) IN IHX, LOOP 1
RS2	THERMAL RESISTANCE OF SODIUM IN CORE CHANNEL 2
RS21	AV. SECONDARY SODIUM TEMP. IN IHX, LOOP 2
RS3	THERMAL RESISTANCE OF SODIUM IN CORE CHANNEL 3
RSHC	SODIUM THERMAL RESISTANCE OF CORE HOT CHANNEL
RW11	IHX TUBE WALL THERMAL RESISTANCE, LOOP 1
RW21	IHX TUBE WALL THERMAL RESISTANCE, LOOP 2
RW211	IHX TUBE WALL THERMAL RESISTANCE, LOOP 1
RW221	IHX TUBE WALL THERMAL RESISTANCE, LOOP 2
RX11	IHX PRIMARY SODIUM THERMAL RESISTANCE, LOOP 1
RX21	IHX PRIMARY SODIUM THERMAL RESISTANCE, LOOP 2
RXS11	IHX SECONDARY SODIUM THERMAL RESISTANCE, LOOP 1
RXS21	IHX SECONDARY SODIUM THERMAL RESISTANCE, LOOP 2
SAFROD	ROD WORTH FOR SAFTY RODS
SAREA	IHX CELL HEAT TRANSFER AREA ON SECONDARY SIDE
SODDC	SODIUM DENSITY COEFFICIENT
TAULP1	TRANSPORT TIME DELAY FOR LOWER PLENUM, LOOP 1

TAULP2	TRANSPORT TIME DELAY FOR LOWER PLENUM, LOOP 2
TAUP11	TRANSPORT TIME DELAY FOR PUMP, LOOP 1
TAUP21	TRANSPORT TIME DELAY FOR PUMP, LOOP 2
TAUXP1	TRANSPORT TIME DELAY FOR IHX, LOOP 1
TAUXP2	TRANSPORT TIME DELAY FOR IHX, LOOP 2
TAVL11	AV. SODIUM TEMP. IN PIPE SECTION 1, LOOP 1
TAVL12	AV. SODIUM TEMP. IN PIPE SECTION 1, LOOP 2
TAVL13	AV. SODIUM TEMP. IN PIPE SECTION 3, LOOP 1
TAVL21	AV. SODIUM TEMP. IN PIPE SECTION 2, LOOP 1
TAVL22	AV. SODIUM TEMP. IN PIPE SECTION 2, LOOP 2
TAVL23	AV. SODIUM TEMP. IN PIPE SECTION 3, LOOP 2
TAVP11	AV. PRIMARY SODIUM TEMP. IN IHX, LOOP 1
TAVP21	AV. PRIMARY SODIUM TEMP. IN IHX, LOOP 2
TAVS11	AV. SECONDARY SODIUM TEMP. IN IHX, LOOP 1
TAVS21	AV. SECONDARY SODIUM TEMP. IN IHX, LOOP 2
TAVXP1	AV. SODIUM TEMP. IN THE IHX, LOOP 1
TAVXP2	AV. SODIUM TEMP. IN THE IHX, LOOP 2
TCC1	CLADDING TEMPERATURE FOR CORE CHANNEL 1
TCC2	CLADDING TEMPERATURE FOR CORE CHANNEL 2
TCC3	CLADDING TEMPERATURE FOR CORE CHANNEL 3
TCCC1	THERMAL CONDUCTIVITY OF CLAD IN CORE CHANNEL 1
TCCC2	THERMAL CONDUCTIVITY OF CLAD IN CORE CHANNEL 2
TCCC3	THERMAL CONDUCTIVITY OF CLAD IN CORE CHANNEL 3
TCCCHC	CLAD THERMAL CONDUCTIVITY IN CORE HOT CHANNEL
TCCF1	THERMAL CONDUCTIVITY OF FUEL IN CORE CHANNEL 1
TCCF2	THERMAL CONDUCTIVITY OF FUEL IN CORE CHANNEL 2
TCCF3	THERMAL CONDUCTIVITY OF FUEL IN CORE CHANNEL 3
TCCFHC	FUEL THERMAL CONDUCTIVITY IN CORE HOT CHANNEL
TCCHC	CLADDING TEMPERATURE IN CORE HOT CHANNEL
TCCS1	SODIUM THERMAL CONDUCTIVITY OF CORE CHANNEL 1
TCCS2	SODIUM THERMAL CONDUCTIVITY OF CORE CHANNEL 2
TCCS3	SODIUM THERMAL CONDUCTIVITY OF CORE CHANNEL 3
TCCSHC	SODIUM THERMAL CONDUCTIVITY OF CORE HOT CHANNEL
TCF1	FUEL TEMPERATURE FOR CORE CHANNEL 1
TCF2	FUEL TEMPERATURE FOR CORE CHANNEL 2
TCF3	FUEL TEMPERATURE FOR CORE CHANNEL 3
TCFHC	FUEL TEMPEARATURE IN CORE HOT CHANNEL
TCS1	SODIUM TEMPERATURE IN CORE CHANNEL 1
TCS2	SODIUM TEMPERATURE IN CORE CHANNEL 2
TCS3	SODIUM TEMPERATURE IN CORE CHANNEL 3
TCS4	SODIUM TEMPERATURE IN CORE CHANNEL 4
TCS5	SODIUM TEMPERATURE IN CORE CHANNEL 5
TCSA1	AV. SODIUM TEMPERATURE OF CORE CHANNEL 1
TCSA2	AV. SODIUM TEMPERATURE OF CORE CHANNEL 2
TCSA3	AV. SODIUM TEMPERATURE OF CORE CHANNEL 3
TCSA4	AV. SODIUM TEMPERATURE OF CORE CHANNEL 4
TCSA5	AV. SODIUM TEMPERATURE OF CORE CHANNEL 5
TCSAHC	AV. SODIUM TEMPERATURE IN CORE HOT CHANNEL
TCSHC	SODIUM TEMPERATURE IN CORE HOT CHANNEL
TCXP11	IHX PRIMARY SODIUM THERMAL CONDUCTIVITY, LOOP 1
TCXP21	IHX PRIMARY SODIUM THERMAL CONDUCTIVITY, LOOP 2
TCXS11	IHX SECONDARY SODIUM THERMAL CONDUCT., LOOP 1
TCXS21	IHX SECONDARY NA THERMAL CONDUCTIVITY, LOOP 2
TCXW11	IHX TUBE WALL THERMAL CONDUCTIVITY, LOOP 1
TCXW21	IHX TUBE WALL THERMAL CONDUCTIVITY, LOOP 2
TDLAY1	TIME DELAY FOR 1ST SCRAM INITIATOR
TDLAY2	TIME DELAY FOR 2ND SCRAM INITIATOR
TDLAY3	TIME DELAY FOR 3RD SCRAM INITIATOR
TDLAY4	TIME DELAY FOR 4TH SCRAM INITIATOR
TDLA	TIME DELAY FOR 5TH SCRAM INITIATOR
TDLAY6	TIME DELAY FOR 6TH SCRAM INITIATOR
TDLAY7	TIME DELAY FOR 7TH SCRAM INITIATOR
TDLAY8	TIME DELAY FOR 8TH SCRAM INITIATOR
TFC1	FUEL TEMP.(C) OF CORE CHANNEL 1
TFC2	FUEL TEMP.(C) OF CORE CHANNEL 2
TFC3	FUEL TEMP.(C) OF CORE CHANNEL 3

TFCL1	CLADDING TEMP.(F) OF CORE CHANNEL 1
TFCL2	CLADDING TEMP.(F) OF CORE CHANNEL 2
TFCCHC	CLAD TEMP.(F) IN CORE HOT CHANNEL
TFF1	FUEL TEMP.(F) OF CORE CHANNEL 1
TFF2	FUEL TEMP.(F) OF CORE CHANNEL 2
TFF3	FUEL TEMP.(F) OF CORE CHANNEL 3
TFFC3	CLADDING TEMP.(F) OF CORE CHANNEL 3
TFP1	IHX PRIMARY SODIUM INLET TEMP.(F) IN LOOP 1
TFP11	IHX PRIMARY SODIUM TEMP.(F) IN LOOP 1
TFP2	PRIMARY SODIUM IHX INLET TEMP.(F), LOOP 2
TFP21	IHX PRIMARY SODIUM TEMP.(F), LOOP 2
TFS1	AV. SODIUM TEMP.(F) OF CORE CHANNEL 1
TFS11	IHX SECONDARY SODIUM TEMP.(F), LOOP 1
TFS12	IHX SECONDARY SODIUM OUTLET TEMP.(F) IN LOOP 1
TFS2	AV. SODIUM TEMP.(F) OF CORE CHANNEL 2
TFS21	IHX SECONDARY SODIUM TEMP.(F), LOOP 2
TFS22	IHX INLET INTERMEDIATE SODIUM TEMP.(F), LOOP 2
TFS3	AV. SODIUM TEMP.(F) OF CORE CHANNEL 3
TFSHC	AV. SODIUM TEMP.(F) OF CORE HOT CHANNEL
TG1	FUEL GAP TEMP. OF CORE CHANNEL 1
TG2	FUEL GAP TEMP. OF CORE CHANNEL 2
TG3	FUEL GAP TEMP. OF CORE CHANNEL 3
TGHC	GAP TEMP. IN CORE HOT CHANNEL
TI	COLD STAND-BY TEMPERATURE
TINP1	SODIUM TEMP. ENTERING PUMP, LOOP 1
TINP2	SODIUM TEMP. ENTERING PUMP, LOOP 2
TIR	COLD STAND-BY TEMPERATURE(R)
TL	IHX TUBE LENGTH
TLP	LOWER PLENUM SODIUM TEMPERATURE
TLP1	SODIUM TEMP. ENTERING LOWER PLENUM, LOOP 1
TLP2	SODIUM TEMP. ENTERING LOWER PLENUM, LOOP 2
TOP1	SODIUM TEMP. EXITING PUMP IN LOOP 1
TOP2	SODIUM TEMP. EXITING PUMP IN LOOP 2
TOUT	SODIUM TEMPERATURE LEAVING THE CORE
TRP1	IHX PRIMARY SODIUM INLET TEMP.(R) IN LOOP 1
TRP11	IHX PRIMARY SODIUM TEMP.(R) IN LOOP 1
TRP2	PRIMARY SODIUM IHX INLET TEMP.(R), LOOP 2
TRP21	IHX PRIMARY SODIUM TEMP.(R), LOOP 2
TRS1	AV. SODIUM TEMP.(R) OF CORE CHANNEL 1
TRS11	IHX SECONDARY SODIUM TEMP.(R), LOOP 1
TRS12	IHX SECONDARY SODIUM OUTLET TEMP.(R) IN LOOP 1
TRS2	AV. SODIUM TEMP.(R) OF CORE CHANNEL 2
TRS21	IHX SECONDARY SODIUM TEMP.(R), LOOP 2
TRS22	IHX INLET INTERMEDIATE SODIUM TEMP.(R), LOOP 2
TRS3	AV. SODIUM TEMP.(R) OF CORE CHANNEL 3
TRSHC	AV. SODIUM TEMP.(R) OF CORE HOT CHANNEL
TSPNAH	UPPER PLENUM SODIUM HEIGHT TRIP POINT
TUPO	UPPER PLENUM SODIUM OUTLET TEMPERATURE
TVAF	VOLUME AVERAGED FUEL TEMPERATURE
TVAFR	VOLUME AVERAGED FUEL TEMPERATURE(F)
TVAS	VOLUME AVERAGED SODIUM TEMPERATURE
TXF11	IHX TUBE WALL TEMP.(F), LOOP 1
TXF21	IHX TUBE WALL TEMP.(F), LOOP 2
TXP1	IHX INLET PRIMARY SODIUM TEMP. IN LOOP 1
TXP11	IHX PRIMARY SODIUM OUTLET TEMP. FOR LOOP 1
TXP2	IHX PRIMARY SODIUM INLET TEMP., LOOP 2
TXP21	IHX PRIMARY SODIUM OUTLET TEMP. FOR LOOP 2
TXS1	IHX INLET SECONDARY SODIUM TEMP. IN LOOP 1
TXS11	SECONDARY SODIUM TEMP. AT IHX INLET IN LOOP 1
TXS21	INTERMEDIATE SODIUM TEMP. AT IHX EXIT(LOOP 2)
TXS22	IHX SECONDARY SODIUM INLET TEMP., LOOP 2
TXW11	IHX TUBE WALL TEMPERATURE IN LOOP 1
TXW21	IHX TUBE WALL TEMPERATURE IN LOOP 2
U1	CONTROL VARIABLE SIGNAL FOR ROD MOVEMENT
U2	CONTROL VARIABLE SIGNAL FOR ROD MOVEMENT
UAC1	OVERALL CLAD-NA HEAT TRANS. COEFF., CORE CH. 1

UAC2	OVERALL CLAD-NA HEAT TRANS. COEFF., CORE CH. 2
UAC3	OVERALL CLAD-NA HEAT TRANS. COEFF., CORE CH. 3
UACHC	OVERALL CLAD-NA HEAT TRANS. COEFF., CORE HOT CH.
UAF1	OVERALL FUEL HEAT TRANS. COEFF., CORE CH. 1
UAF2	OVERALL FUEL HEAT TRANS. COEFF., CORE CH. 2
UAF3	OVERALL FUEL HEAT TRANS. COEFF., CORE CH. 3
UAFHC	OVERALL FUEL-CLAD HEAT TRANS. COEFF. HOT CORE CH
UAT1	TOTAL OVERALL HEAT TRANS. COEFF., CORE CH. 1
UAT2	TOTAL OVERALL HEAT TRANS. COEFF., CORE CH. 2
UAT3	TOTAL OVERALL HEAT TRANS. COEFF., CORE CH. 3
UMCS1	AV. SODIUM VISCOSITY OF CORE CHANNEL 1
UMCS2	AV. SODIUM VISCOSITY OF CORE CHANNEL 2
UMCS3	AV. SODIUM VISCOSITY OF CORE CHANNEL 3
UMCSHC	SODIUM VISCOSITY OF CORE HOT CHANNEL
UMXP11	IHX PRIMARY SODIUM VISCOSITY, LOOP 1
UMXP21	IHX PRIMARY SODIUM VISCOSITY, LOOP 2
UMXS11	IHX SECONDARY SODIUM VISCOSITY, LOOP 1
UMXS21	IHX SECONDARY SODIUM VISCOSITY, LOOP 2
UNCS1	SODIUM NUSSELT NUMBER IN CORE CHANNEL 1
UNCS2	SODIUM NUSSELT NUMBER IN CORE CHANNEL 2
UNCS3	SODIUM NUSSELT NUMBER IN CORE CHANNEL 3
UNCSHC	SODIUM NUSSELT NUMBER OF CORE HOT CHANNEL
UNXS11	IHX SECONDARY SODIUM NUSSELT NUMBER, LOOP 1
UNXS21	IHX SECONDARY SODIUM NUSSELT NUMBER, LOOP 2
UPNAH	UPPER PLENUM SODIUM HEIGHT
UXP11	IHX PRIMARY OVERALL HEAT TRANSFER COEFF., LOOP 1
UXP21	IHX PRIMARY OVERALL HEAT TRANSFER COEFF., LOOP 2
UXS11	IHX SECONDARY OVERALL HEAT TRANSFER COEFF LOOP 1
UXS21	IHX SECONDARY OVERALL HEAT TRANSFER COEFF LOOP 2
VCS1	SODIUM VELOCITY PER PIN IN CORE CHANNEL 1
VCS2	SODIUM VELOCITY PER PIN IN CORE CHANNEL 2
VCS3	SODIUM VELOCITY PER PIN IN CORE CHANNEL 3
VCSHC	SODIUM VELOCITY OF CORE HOT CHANNEL
VOL1	SODIUM VOLUME IN CORE CHANNEL 1
VOL2	SODIUM VOLUME IN CORE CHANNEL 2
VOL3	SODIUM VOLUME IN CORE CHANNEL 3
VOL4	SODIUM VOLUME IN CORE CHANNEL 4
VOL5	SODIUM VOLUME IN CORE CHANNEL 5
VOLC	TOTAL CORE SODIUM VOLUME
VOLHC	SODIUM VOLUME IN CORE HOT CHANNEL
VOLLP	LOWER PLENUM VOLUME
VOLP1	VOLUME OF PUMP IN LOOP 1
VOLP2	VOLUME OF PUMP IN LOOP 2
VOLT	TOTAL SODIUM CORE VOLUME
VOLUP	UPPER PLENUM VOLUME
VXP11	IHX PRIMARY SODIUM VELOCITY, LOOP 1
VXP21	IHX PRIMARY SODIUM VELOCITY, LOOP 2
VXS11	IHX SECONDARY SODIUM VELOCITY, LOOP 1
VXS21	IHX SECONDARY SODIUM VELOCITY, LOOP 2
WD	INTEGRAL OF ERROR SIGNAL FOR FLUX CONTROLLER
WIXP1	PRIMARY FLOW RATE THROUGH IHX IN LOOP 1
WIXP2	PRIMARY FLOW RATE THROUGH IHX IN LOOP 2
WL1	SODIUM FLOW RATE FOR LOOP ONE
WL11	FLOW RATE THROUGH PIPE SECTION 1, LOOP 1
WL12	FLOW RATE THROUGH PIPE SECTION 2, LOOP 1
WL13	FLOW RATE THROUGH PIPE SECTION 3, LOOP 1
WL21	FLOW RATE THROUGH PIPE SECTION 1, LOOP 2
WL22	FLOW RATE THROUGH PIPE SECTION 2, LOOP 2
WL23	FLOW RATE THROUGH PIPE SECTION 3, LOOP 2
WPD1	PRIMARY FLOW RATE THROUGH IHX IN LOOP 1
WPD2	PRIMARY FLOW RATE THROUGH IHX, LOOP 2
WRD	TOTAL SODIUM FLOW RATE
WRD1	SODIUM FLOW RATE IN CORE CHANNEL 1
WRD2	SODIUM FLOW RATE IN CORE CHANNEL 2
WRD3	SODIUM FLOW RATE IN CORE CHANNEL 3
WRD4	SODIUM FLOW RATE IN CORE CHANNEL 4

WRO5	SODIUM FLOW RATE IN CORE CHANNEL 5
WROF	FRACTION OF TOTAL PRIMARY FLOW
WROHC	SODIUM FLOW RATE IN CORE HOT CHANNEL
WROPP1	SODIUM FLOW RATE PER PIN IN CORE CHANNEL 1
WROPP2	SODIUM FLOW RATE PER PIN IN CORE CHANNEL 2
WROPP3	SODIUM FLOW RATE PER PIN IN CORE CHANNEL 3
WROPP4	SODIUM FLOW RATE PER PIN IN CORE CHANNEL 4
WROPP5	SODIUM FLOW RATE PER PIN IN CORE CHANNEL 5
WSD1	SECONDARY FLOW RATE THROUGH IHX IN LOOP 1
WSD2	SECONDARY FLOW RATE THROUGH IHX, LOOP 2
WSDF	FRACTION OF TOTAL SECONDARY FLOW
WXP1	SODIUM FLOW RATE PER IHX TUBE IN LOOP 1
WXS1	IHX SECONDARY SODIUM FLOW RATE IN LOOP 1
WXW1	MASS OF IHX TUBE
XMASHC	SODIUM MASS IN CORE HOT CHANNEL
XMASS1	SODIUM MASS PER UNIT CELL FOR CORE CHANNEL 1
XMASS2	SODIUM MASS PER UNIT CELL FOR CORE CHANNEL 2
XMASS3	SODIUM MASS PER UNIT CELL FOR CORE CHANNEL 3
XMASS4	SODIUM MASS PER UNIT CELL FOR CORE CHANNEL 4
XMASS5	SODIUM MASS PER UNIT CELL FOR CORE CHANNEL 5
XNASS1	NUMBER OF FUEL ASSEMBLIES IN CORE CHANNEL 1
XNASS2	NUMBER OF FUEL ASSEMBLIES IN CORE CHANNEL 2
XNASS3	NUMBER OF FUEL ASSEMBLIES IN CORE CHANNEL 3
XNASS4	NUMBER OF CONTROL ASSEMBLIES IN CORE CHANNEL 4
XNASS5	NUMBER OF ASSEMBLIES IN CORE CHANNEL 5
XNPPA1	NUMBER OF PINS PER ASSEMBLY IN CORE CHANNEL 1
XNPPA2	NUMBER OF PINS PER ASSEMBLY IN CORE CHANNEL 2
XNPPA3	NUMBER OF PINS PER ASSEMBLY IN CORE CHANNEL 3
XNPPA4	NUMBER OF PINS PER ASSEMBLY IN CORE CHANNEL 4
XNPPA5	NUMBER OF PINS PER ASSEMBLY IN CORE CHANNEL 5
YC	ACTIVE CORE HEIGHT
YL11	HEIGHT ABOVE LOWER PLENUM INLET FOR PLL11
YL12	HEIGHT ABOVE LOWER PLENUM INLET FOR PLL12
YL13	HEIGHT ABOVE LOWER PLENUM INLET FOR PLL13
YL21	HEIGHT ABOVE LOWER PLENUM INLET FOR PLL21
YL22	HEIGHT ABOVE LOWER PLENUM INLET FOR PLL22
YL23	HEIGHT ABOVE LOWER PLENUM INLET FOR PLL23
YUP	HEIGHT OF UPPER PLENUM, FROM CORE EXIT
YXP1	IHX HEIGHT ABOVE LOWER PLENUM INLET, LOOP 1
YXP2	IHX HEIGHT ABOVE LOWER PLENUM INLET, LOOP 2
ZMAX	MAXIMUM CONTROL ROD WITHDRAWL DISTANCE

```
$M1
$D1

*************************** FATFAD *************************************

*************************** FATFAD *************************************

*************************** FATFAD *************************************

************************************************************************
***** TEN CENT STEP INCREASE WITH 50 DEGREE RISE OF IHX SECONDARY
***** INLET
************************************************************************
$P
        DISPLAY TCS1


    IHX FOR THE FFTF(ONE AXIAL REGION)

    ALL PARAMETERS USED HERE HAVE THE SAME MEANING AS THOSE USED FOR
    THE TWO IHX MODEL.  THE ONLY CHANGE COMES IN REPLACING THE SUFFIX 2
    WITH 1 TO SHOW THAT THIS MODEL IS FOR ONE IHX WHILE THE 2 SIGNIFIES
    TWO IHXS.



      PROCED  TXP1=ENTXP1,DTTXP1,TXP1I,STXP1,T
      IF(ENTXP1.EQ.0.0)  TXP1=PDELAY(TOP1,TAUXP1,3,TXP1I)
      IF(ENTXP1.EQ.1..AND.T.EQ.0.0)  TXP1=PDELAY(TOP1,TAUXP1,3,TXP1I)
      IF(ENTXP1.EQ.1..AND.T.NE.0.0)  TXP1=TXP1I+DTTXP1
      IF(ENTXP1.EQ.2..AND.T.LE.STXP1)  TXP1=TXP1I+DTTXP1*T
      ENDPRO



      PROCED  TXS12=ENTXS1,DTTXS1,TXS1I,STXS1,T
      IF(ENTXS1.EQ.0.0)  TXS12=TXS1I
      IF(ENTXS1.EQ.1..AND.T.EQ.0.0)  TXS12=TXS1I
      IF(ENTXS1.EQ.1..AND.T.NE.0.0)  TXS12=TXS1I+DTTXS1
      IF(ENTXS1.EQ.2..AND.T.LE.STXS1)  TXS12=TXS1I+DTTXS1*T
      ENDPRO


      PROCED  WPD1=ENWPD1,DTWPD1,WL12L,T,SWPD1
      IF(ENWPD1.EQ.0.0)  WPD1=WL12L
      IF(ENWPD1.EQ.1.AND.T.EQ.0.)  WPD1=WL12L
      IF(ENWPD1.EQ.1.AND.T.NE.0.)  WPD1=WL12L*(1.+DTWPD1/100.0)
      IF(ENWPD1.EQ.2.0.AND.T.LE.SWPD1)  WPD1=WL12L*(1.+DTWPD1*T/100.0)
      ENDPRO


      PROCED  WSD1=ENWSD1,DTWSD1,WSD1I,T,SWSD1
      IF(ENWSD1.EQ.0.0)  WSD1=WSD1I
      IF(ENWSD1.EQ.1.AND.T.EQ.0.)  WSD1=WSD1I
      IF(ENWSD1.EQ.1.AND.T.NE.0.)  WSD1=WSD1I*(1.+DTWSD1/100.0)
      IF(ENWSD1.EQ.2.0.AND.T.LE.SWSD1)  WSD1=WSD1I*(1.+DTWSD1*T/100.0)
      ENDPRO

   PARAMETERS NEEDED FOR THE CALCULATION OF HXP1$(CONVECTIVE HEAT
   TRANSFER COEFFICIENT BETWEEN THE PRIMARY SODIUM AND THE TUBE WALL.


      REPEAT 1
      TAVP1$=(TXP1$+TXP1$(-1))/2.0
```

```
  TFP1$=(TXP1$-273.0)*(9.0/5.0)+32.0
  FAP1$=(TFP1$+TFP1$(-1))/2.0
  TRP1$=TFP1$+460.0
  RP1$=(TRP1$+TRP1$(-1))/2.0
  ROXP1$=16.02*(59.533-.00833*FAP1$)
  VXP1$=WPD1/(ROXP1$*(CAXP1*(ENXT1-ENTUB1)))
  CPXP1$=4.1868E+03*(.34574-7.9226E-05*FAP1$+3.4086E-08*(FAP1$**2))
  TCXP1$=1.73073*(54.306-1.878E-02*FAP1$+2.0914E-06*(FAP1$**2))
  UMXP1$=4.134E-04*(10.0**(1.0203+(397.17/RP1$)-.4925*ALOG10(RP1$)))
  REXP1$=(ROXP1$*VXP1$*DH)/(UMXP1$)
  PRXP1$=(CPXP1$*UMXP1$)/(TCXP1$)
  PEXP1$=REXP1$*(PRXP1$)
  HXP1$=H1(PEXP1$,TCXP1$,REXP1$,PRXP1$,P,DH)
  ENDREP
```

THE PRIMARY SODIUM TEMPERTURE DISTRIBUTION IS GIVEN BY TXP1$.

```
  REPEAT 1
  UXP1$=(1.0/(RX1$+RW1$))*(ENXT1-ENTUB1)
  RX1$=1.0/(HXP1$*PAREA)
  RW1$=ALOG(DOT/DCT)/(2.0*PI*TL*TCXW1$)
  WP1$=(WXP$*(CPXP1$))*(ENXT1-ENTUB1)
  DTXP1$=(WPD1*CPXP1$*(TXP1$(-1)-TXP1$)-UXP1$*(TAVP1$-TXW1$))/(WP1$)
  TXP1$.=(DTXP1$)
  ENDREP
```

PARAMETERS NEEDED FOR THE CALCULATION OF UXS1$(CONVECTIVE HEAT TRANSFER COEFFICIENT BETWEEN THE TUBE WALL AND THE SECONDARY SODIUM.

```
  REPEAT 1
  TXF1$=(TXW1$-273.0)*(9.0/5.0)+32.0
  TAVS1$=(TXS1$(+1)+TXS1$)/2.0
  TFS1$=(TXS1$-273.0)*(9.0/5.0)+32.0
  FAS1$=(TFS1$+TFS1$(+1))/2.0
  TRS1$=TFS1$+460.0
  RS1$=(TRS1$+TRS1$(+1))/2.0
  ROXS1$=16.02*(59.533-.00833*FAS1$)
  VXS1$=WSD1/(ROXS1$*CAXS1)
  CPXS1$=4.1868E+03*(.34574-7.9226E-05*FAS1$+3.4086E-08*(FAS1$**2))
  TCXS1$=1.73073*(54.306-1.878E-02*FAS1$+2.0914E-06*(FAS1$**2))
  TCXW1$=1.73073*(7.7388464+.40721437E-02*TXF1$)
  UMXS1$=4.134E-04*(10.0**(1.0203+(397.17/RS1$)-.4925*ALOG10(RS1$)))
  REXS1$=(ROXS1$*VXS1$*D)/(UMXS1$)
  PRXS1$=(CPXS1$*UMXS1$)/(TCXS1$)
  PEXS1$=REXS1$*(PRXS1$)
  UNXS1$=5.0+.025*(PEXS1$**.8)
  HXS1$=(TCXS1$/D)*(UNXS1$)
  RXS1$=1.0/(HXS1$*SAREA)
  UXS1$=(1.0/(RXS1$+RF+RW21$))*ENXT1
  RW21$=ALOG(DCT/DIT)/(2.0*PI*TCXW1$*TL)
  RF$=((ENXT1/UXS1$)-RXS1$-RW21$)
  ENDREP
```

WHERE RF IS THE FOULING RESISTANCE ON THE SECONDARY SIDE.

THE SECONDARY SODIUM TEMPERATURE DISTRIBUTION IS GIVEN BY TXS1$..

```
  REPEAT 1
  WS1$=(WXS$*(CPXS1$))*ENXT1
  DTXS1$=(WSD1*CPXS1$*(TXS1$(+1)-TXS1$)+UXS1$*(TXW1$-TAVS1$))/(WS1$)
  TXS1$.=(DTXS1$)
  ENDREP
```

THE TUBE WALL TEMPERATURE DISTRIBUTION IS GIVEN BY TXW1$.

```
  REPEAT 1
```

```
  WW1S=(WXWS*(CPXWS))*ENXT1
  DTXW1S=UXP1S*(TAVP1S-TXW1S)/WW1S-UXS1S*(TXW1S-TAVS1S)/(WW1S)
  TXW1S.=(DTXW1S)
  ENDREP
```

IHX FOR THE FFTF(ONE AXIAL REGION)
FFTF2 IS A LUMPED PARAMETER MODEL OF TWO OF THE THREE IHXS FOR THE FFTF. ALL PARAMETERS ARE CALCULATED ON A PER TUBE BASIS. MASS FLOW RATES AND TOTAL HEAT TRANSFER COEFFICIENTS ARE THEN MULTIPLIED BY THE APPROPRIATE NUMBER OF TUBES (ENXT2) TO SIMULATE THE NUMBER OF DESIRED IHXS.

ENTXP2,DTTXP2,STXP2,AND T ARE SWITCH VARIABLES USED FOR SIMULATING TEMPERATURE TRANSIENTS (IN THIS CASE INLET TEMPERATURE TRANSIENTS ON THE PRIMARY SIDE OF THE IHX). TXP2I IS THE PRIMARY, STEADY STATE, INLET TEMPERATURE OF THE IHX. TXP2 IS THE NEW INLET TEMPERATURE DUE TO A TRANSIENT.

```
  PROCED  TXP2=ENTXP2,DTTXP2,TXP2I,STXP2,T
  IF(ENTXP2.EQ.0.0)  TXP2=PDELAY(TOP2,TAUXP2,4,TXP2I)
  IF(ENTXP2.EQ.1..AND.T.EQ.0.0)  TXP2=PDELAY(TOP2,TAUXP2,4,TXP2I)
  IF(ENTXP2.EQ.1..AND.T.NE.0.0)  TXP2=TXP2I+DTTXP2
  IF(ENTXP2.EQ.2..AND.T.LE.STXP2)  TXP2=TXP2I+DTTXP2*T
  ENDPRO
```

ENTXS2,DTTXS2,STXS2, AND T ARE SWITCH VARIABLES USED FOR SIMULATING TEMPERATURE TRANSIENTS (IN THIS CASE INLET TEMPERATURE TRANSIENTS ON THE SECONDARY SIED OF THE IHX). TXS2I IS THE SECONDARY, STEADY STATE INLET TEMPERATURE OF THE IHX. TXS2 IS THE NEW INLET TEMPERATURE DUE TO A TRANSIENT.

```
  PROCED  TXS22=ENTXS2,DTTXS2,TXS2I,STXS2,T
  IF(ENTXS2.EQ.0.0)  TXS22=TXS2I
  IF(ENTXS2.EQ.1..AND.T.EQ.0.0)  TXS22=TXS2I
  IF(ENTXS2.EQ.1..AND.T.NE.0.0)  TXS22=TXS2I+DTTXS2
  IF(ENTXS2.EQ.2..AND.T.LE.STXS2)  TXS22=TXS2I+DTTXS2*T
  ENDPRO
```

ENWPD2, DTWPD2,SWPD2, AND T ARE SWITCH VARIABLES USED FOR SIMULATING MASS FLOW RATE TRANSIENTS (ON THE PRIMARY SIDE OF THE IHX). WPD2I IS THE PRIMARY, STEADY STATE, MASS FLOW RATE OF THE IHX. WPD2 IS THE NEW MASS FLOW RATE DUE TO A TRANSIENT.

```
  PROCED  WPD2=ENWPD2,DTWPD2,WL22L,T,SWPD2
  IF(ENWPD2.EQ.0.0)  WPD2=WL22L
  IF(ENWPD2.EQ.1.AND.T.EQ.0.)  WPD2=WL22L
  IF(ENWPD2.EQ.1.AND.T.NE.0.)  WPD2=WL22L*(1.+DTWPD2/100.0)
  IF(ENWPD2.EQ.2.0.AND.T.LE.SWPD2)  WPD2=WL22L*(1.+DTWPD2*T/100.0)
  ENDPRO
```

ENWSD2, DTWSD2, SWSD2,AND T ARE SWITCH VARIABLES USED FOR SIMULATING MASS FLOW RATE TRANSIENTS (ON THE SECONDARY SIDE OF THE IHX). WSD2I IS THE SECONDARY, STEADY STATE, MASS FLOW RATE OF THE IHX. WSD2 IS THE NEW MASS FLOW RATE DUE TO A TRANSIENT.

```
  PROCED  WSD2=ENWSD2,DTWSD2,WSD2I,T,SWSD2
  IF(ENWSD2.EQ.0.0)  WSD2=WSD2I
  IF(ENWSD2.EQ.1.AND.T.EQ.0.)  WSD2=WSD2I
```

```
   IF(ENWSD2.EQ.1.AND.T.NE.0.)  WSD2=WSD2I*(1.+DTWSD2/100.0)
   IF(ENWSD2.EQ.2.0.AND.T.LE.SWSD2)  WSD2=WSD2I*(1.+DTWSD2*T/100.0)
   ENDPRJ

PARAMETERS NEEDED FOR THE CALCULATION OF HXP2$(CONVECTIVE HEAT
TRANSFER COEFFICIENT BETWEEN THE PRIMARY SODIUM AND THE TUBE WALL.

TAVP2: AVERAGE SODIUM TEMPERATURE (K) FOR EACH REGION.
TFP2 : INLET SODIUM TEMPERATURE (F) FOR EACH REGION.
FAP2 : AVARAGE SODIUM TEMPERATURE (F) FOR EACH REGION.
TRP2 : INLET SODIUM TEMPERATURE (R) FOR EACH REGION.
RP2  : AVERAGE SODIUM TEMPERATURE (R) FOR EACH REGION.
ROXP2: SODIUM DENSITY FOR EACH REGION.
VXP2 : SODIUM VELOCITY FOR EACH REGION.
CPXP2: SODIUM SPECIFIC HEAT FOR EACH REGION.
TCXP2: SODIUM THERMAL CONDUCTIVITY FOR EACH REGION.
UMXP2: SODIUM VISCOSITY FOR EACH REGION.
REXP2: SODIUM REYNOLDS NUMBER FOR EACH REGION.
PRXP2: SODIUM PRANDTL NUMBER FOR EACH REGION.
PEXP2: SODIUM PECLET NUMBER FOR EACH REGION.
HXP2 : SODIUM UNIT HEAT TRANSFER COEDDICIENT FOR EACH REGION.

   REPEAT 1
   TAVP2$=(TXP2$+TXP2$(-1))/2.0
   TFP2$=(TXP2$-273.0)*(9.0/5.0)+32.0
   FAP2$=(TFP2$+TFP2$(-1))/2.0
   TRP2$=TFP2$+460.0
   RP2$=(TRP2$+TRP2$(-1))/2.0
   ROXP2$=16.02*(59.533-.00833*FAP2$)
   VXP2$=WPD2/(ROXP2$*(CAXP2*(ENXT1-ENTUB2)))
   CPXP2$=4.1868E+03*(.34574-7.9226E-05*FAP2$+3.4086E-08*(FAP2$**2))
   TCXP2$=1.73073*(54.306-1.878E-02*FAP2$+2.0914E-06*(FAP2$**2))
   UMXP2$=4.134E-04*(10.0**(1.0203+(397.17/RP2$)-.4925*ALOG10(RP2$)))
   REXP2$=(ROXP2$*VXP2$*DH)/(UMXP2$)
   PRXP2$=(CPXP2$*UMXP2$)/(TCXP2$)
   PEXP2$=REXP2$*(PRXP2$)
   HXP2$=H2(PEXP2$,TCXP2$,REXP2$,PRXP2$,P,DH)
   ENDREP

THE PRIMARY SODIUM TEMPERTURE DISTRIBUTION IS GIVEN BY TXP2$.

UXP2 : SODIUM OVERALL HEAT TRANSFER COEFFICIENT FOR EACH REGION
SODIUM MASS TIMES SPECIFIC HEAT FOR EACH REGION.

   REPEAT 1
   UXP2$=(1.0/(RX2$+RW2$))*(ENXT2-ENTUB2)
   RX2$=1.0/(HXP2$*PAREA)
   RW2$=ALOG(DOT/DCT)/(2.0*PI*TL*TCXW2$)
   WP2$=(WXP$*(CPXP2$))*(ENXT2-ENTUB2)
   DTXP2$=(WPD2*CPXP2$*(TXP2$(-1)-TXP2$)-UXP2$*(TAVP2$-TXW2$))/(WP2$)
   TXP2$.=(DTXP2$)
   ENDREP

PARAMETERS NEEDED FOR THE CALCULATION OF UXS2$(CONVECTIVE HEAT
TRANSFER COEFFICIENT BETWEEN THE TUBE WALL AND THE SECONDARY SODIUM.

THE BELOW PARAMETERS HAVE THE SAME MEANING AS THEIR PRIMARY
COUNTERPARTS, EXCEPT THESE ARE FOR THE SECONDARY SIDE OF THE IHX.
UNXS2 IS THE SODIUM NUSSELT NUMBER, AND RXS2 IS THE RESISTANCE FOR
EACH REGION ON THE SECONDARY SIDE.  D IS THE I.D. OF EACH TUBE.

   REPEAT 1
   TAVS2$=(TXS2$(+1)+TXS2$)/2.0
   TFS2$=(TXS2$-273.0)*(9.0/5.0)+32.0
   TXF2$=(TXW2$-273.0)*(9.0/5.0)+32.0
   FAS2$=(TFS2$+TFS2$(+1))/2.0
```

```
    TRS2$=TFS2$+460.0
    RS2$=(TRS2$+TRS2$(+1))/2.0
    ROXS2$=16.02*(59.533-.00833*FAS2$)
    VXS2$=WSD2/(ROXS2$*CAXS2)
    CPXS2$=4.1868E+03*(.34574-7.9226E-05*FAS2$+3.4086E-08*(FAS2$**2))
    TCXS2$=1.73073*(54.306-1.878E-02*FAS2$+2.0914E-06*(FAS2$**2))
    TCXW2$=1.73073*(7.7388464+.40721437E-02*TXF2$)
    UMXS2$=4.134E-04*(10.0**(1.0203+(397.17/RS2$)-.4925*ALOG10(RS2$)))
    REXS2$=(ROXS2$*VXS2$*D)/(UMXS2$)
    PRXS2$=(CPXS2$*UMXS2$)/(TCXS2$)
    PEXS2$=REXS2$*(PRXS2$)
    UNXS2$=5.0+.025*(PEXS2$**.8)
    HXS2$=(TCXS2$/D)*(UNXS2$)
    RXS2$=1.0/(HXS2$*SAREA)
    UXS2$=(1.0/(RXS2$+RF+RW22$))*ENXT2
    RW22$=ALOG(DCT/DIT)/(2.0*PI*TCXW2$*TL)

  WHERE RF IS THE FOULING RESISTANCE ON THE SECONDARY SIDE.

  THE SECONDARY SODIUM TEMPERATURE DISTRIBUTION IS GIVEN BY TXS2$..

  WS2 : SODIUM MASS TIMES SPECIFIC HEAT FOR EACH REGION ON SECONDARY
  SIDE.

    REPEAT 1
    WS2$=(WXS$*(CPXS2$))*ENXT2
    DTXS2$=(WSD2*CPXS2$*(TXS2$(+1)-TXS2$)+UXS2$*(TXW2$-TAVS2$))/(WS2$)
    TXS2$.=(DTXS2$)
    ENDREP

  THE TUBE WALL TEMPERATURE DISTRIBUTION IS GIVEN BY TXW2$.

  WW2 : TUBE WALL MASS TIMES ITS SPECIFIC HEAT FOR EACH REGION.

    REPEAT 1
    WW2$=(WXW$*(CPXW$))*ENXT2
    DTXW2$=UXP2$*(TAVP2$-TXW2$)/WW2$-UXS2$*(TXW2$-TAVS2$)/(WW2$)
    TXW2$.=(DTXW2$)
    ENDREP

    THIS IS A 5 CHANNEL REACTOR MODEL OF THE FFTF.

***************************SCRAM CONDITIONS*************  *************


    PROCED ROCRD=TROD,DLTROC,SROC,TXP11I,TXP11,TXP1I,TUPO,WROF,
   $WSOF,TSPNAH,T,UPNAH,CNLROD,SAFROD,SCRAM1,SCRAM2,SCRAM3,SCRAM4,
   $SCRAM5,SCRAM6,SCRAM7,SCRAM8,TDLAY1,TDLAY2,TDLAY3,TDLAY4,TDLAY5,
   $TDLAY6,TDLAY7,TDLAY8,DT

    PRIMARY SCRAM CONDITIONS

    IF(T.EQ.0.0) FLUX=1.0
    IF(SCRAM5.EQ.0.0.OR.SCRAM6.EQ.0.0.OR.SCRAM7.EQ.0.0.OR.SCRAM8.EQ.
   $0.0) GO TO 21
    IF(FLUX.GE.1.12.AND.RLDONE) GO TO 1
    IF(SCRAM1.EQ.0.0) GO TO 2
    IF(FLUX.LE..10.AND.RLDONE) GO TO 3
    IF(SCRAM2.EQ.0.0) GO TO 4
    IF(TXP11.GE.TXP11I+283.0.AND.RLDONE) GO TO 5
    IF(SCRAM3.EQ.0.0) GO TO 6
    IF(UPNAH.LE.TSPNAH.AND.RLDONE) GO TO 7
    IF(SCRAM4.EQ.0.0) GO TO 8

    SECONDARY SCRAM CONDITIONS
```

```
21    CONTINUE
      IF(TUPO.GE.TXP1I+296.89.AND.RLDONE) GO TO 9
      IF(SCRAM5.EQ.0.0) GO TO 10
      IF(WRDF.GE.1.12.AND.RLDONE) GO TO 11
      IF(SCRAM6.EQ.0.0) GO TO 12
      IF(WRDF.LE..60.AND.RLDONE) GO TO 13
      IF(SCRAM7.EQ.0.0) GO TO 14
      IF(WSDF.LE..55.AND.RLDONE) GO TO 15
      IF(SCRAM8.EQ.0.0) GO TO 16

      IF(T.GE.TROD) ENROC=1.0
      IF(ENROC.EQ.0.0) ROCRD=0.0
      IF(ENROC.EQ.1.0.AND.T.EQ.0.0) ROCRD=0.0
      IF(ENROC.EQ.1.0.AND.T.NE.0.0) ROCRD=DLTROC/100.0
      IF(ENROC.EQ.2.0.AND.T.LE.SROC) ROCRD=(DLTROC*T)/100.0
      TNEW=T
      ROCRDI=ROCRD
      GO TO 50
1     SCRAM1=0.0
2     TSCRAM=TNEW+DT+TDLAY1
      GO TO 17
3     SCRAM2=0.0
4     TSCRAM=TNEW+DT+TDLAY2
      GO TO 17
5     SCRAM3=0.0
6     TSCRAM=TNEW+DT+TDLAY3
      GO TO 17
7     SCRAM4=0.0
8     TSCRAM=TNEW+DT+TDLAY4
17    IF(T.LT.TSCRAM) GO TO 50
      IF(T.GT.TSCRAM+1.0) GO TO 18
      ROCRD=ROCRDI-(T-TSCRAM)*(CNLROD*6.0)
      GO TO 50
18    ROCRD=ROCRDI-CNLROD*6.0
      GO TO 50

9     SCRAM5=0.0
10    TSCRAM=TNEW+DT+TDLAY5
      GO TO 19
11    SCRAM6=0.0
12    TSCRAM=TNEW+DT+TDLAY6
      GO TO 19
13    SCRAM7=0.0
14    TSCRAM=TNEW+DT+TDLAY7
      GO TO 19
15    SCRAM8=0.0
16    TSCRAM=TNEW+DT+TDLAY8
19    IF(T.LT.TSCRAM) GO TO 50
      IF(T.GT.TSCRAM+1.0) GO TO 20
      ROCRD=ROCRDI-(T-TSCRAM)*(SAFROD*3.0)
      GO TO 50
20    ROCRD=ROCRDI-SAFROD*3.0
50    CONTINUE
      ENDPRO

      WRDF=WRD/(WPD1I+WPD2I)
      WSDF=(WSD1+WSD2)/(WSD1I+WSD2I)
      TSPNAH=YUP-(5.0/12.0)


*************************************************************************
      REPEAT 3
      QS=QT*FPCS
      QPS=QS ENRCS
```

```
      QL$=QP$/PL
      QLP$=QL$/100.0
      ENDREP

      Q4=QTOT*FPC4*EN
      Q5=QTOT*FPC5*EN
      QNA4=Q4/ENRC4
      QNA5=Q5/ENRC5

      QT=QTOT*EN

      VOLT=VOL1+VOL2+VOL3+VOL4+VOL5

      REPEAT 5
      FV$=VOL$/VOLT
      ENDREP

      REPEAT 6
      CN$.=AMDA$*(EN-CN$)
      ENDREP

      BD=BETA1*CN1+BETA2*CN2+BETA3*CN3+BETA4*CN4+BETA5*CN5+BETA6*CN6
      BDOB=BD/BETAT

      ROFB=100.0*(DOPC/BETAT)*ALOG(ABS(TVAFR/TIR))+SODOC*(TVAS-TI)+EXC
      EXC=AXEC*(TVAF-TI)+REC*(TVAS-TI)
      ROFBD=ROFB/100.0
      TVAFR=((TVAF-273.0)/1.8)+492.0
      TVAS=TCS1*FV1+TCS2*FV2+TCS3*FV3+TCS4*FV4+TCS5*FV5
      TVAF=TCF1*FVF1+TCF2*FVF2+TCF3*FVF3
      ROD=ROCRD+ROFBD+ROEXCD+ROAUTO

*****************************************************************
********************** FLUX CONTROL SYSTEM **********************
*****************************************************************

      U1D=U2
      U1.=U1D
      U2D=PIOP-60.0*U2-1200.0*U1
      U2.=U2D
      ZROD=(U2D-60.0*U2+1200.0*U1)*.0254
       ZROD=PIOP
       PIOPD=(ERR*CONST+WD-PIOP)/.35
       PIOP.=PIOPD
      PIOP=CONST*ERR+WD
      WDD=ERR
      WD.=WDD
       FENDP=FEND+.35*FENDD
       FENDD=AA*W*PI*COS(W*PI*T)
       ERR=FENDF
      FLUXD=(EN-FLUX)/.35
      FLUX.=FLUXD
      FEND=FEN(ROCRD)
      ERR=FEND-FLUX
       FEND=1.0+AA*SIN(W*PI*T)

      PROCED ROAUTO=RHOMAX,ZROD,ZMAX,PI,TSCRAM
      IF(T.EQ.0.0) TSCRAM=1000.0
      IF(T.GE.TSCRAM) GO TO 111
      ROAUTO=RHOMAX*ZROD/ZMAX*(1.0-(1.0/(2.0*PI))*SIN(2.0*PI*ZROD/ZMAX))
      GO TO 112
111   ROAUTO=0.0
112   CONTINUE
      ENDPRO

*****************************************************************
```

```
   PROCED EN=BDOB,T
   EN=BDOB/(1.0-ROD)
   IF(T.EQ.0.0) EN=1.0
   ENDPRO
   ENN=EN-1.0
   ENE=EN-1.0

   REPEAT 5
   TCS$D=(1.0/(CPAS$*XMASS$))*(QNA$+WRDPP$*DELT$)
   DELT$=CPAS$*(TLP-TCS$)
   XMASS$=RHOC$*(VOL$/ENRC$)
   TCS$.=TCS$D
   ENDREP

   REPEAT 5
   WRD$D=ADL$*((PLP-PUP)-YC*G*RHOC$+T3$)
   T3$=(WRD$/AC$)**2*(1.0/RHOLP-1.0/RHOC$-F12$*AC$**2)
   WRD$.=WRD$D
   ENDREP

   WROTH=WRD1+WRD2+WRD3+WRD4+WRD5
   REPEAT 5
   WRDL$=SATAM(WRD$,1.0E-03,1.0E+30)
   ENDREP

   REPEAT 5
   FWRD$=WRD$/WRD
   ENDREP
   FWRD=FWRD1+FWRD2+FWRD3+FWRD4+FWRD5



   REPEAT 3
   WL1$D=ADL1$*((PIN1$-POUT1$)-RHOL1$*G*YL1$+REST1$)
   REST1$=(WL1$D/PAL1$)**2*(1.0/ROIN1$-1.0/ROUT1$-FL1$*PAL1$**2)
   WL1$.=WL1$D
   ENDREP

      PRIMARY  AND  INTERMEDIATE  LOOPS  MOMENTUM  EQUATIONS


   PROCED XCOM,ALPHA,RNEWAL,ALNEW,END,
  $ QNEW,BVT,BVD,BAD,BAN,BVN,BVR,BAR,BAT,
  $ HVT,HVD,HAD,HAN,HVN,HVR,HAR,HAT,TFRIC,THYD,HOPP
  $  =T, ENPP,WL11,RHOTP4,RHOTPR,TRATED,HRAT,ENFPR,WL11D1,WL11R
    CALL PUMP(ENPP,WL11,RHOTP4,RHOTPR,TRATED,HRAT,ENPPR,WL11D1,
  $ WL11R,ALPHA,RNEWAL,ALNEW,END,
  $ QNEW,BVT,BVD,BAD,BAN,BVN,BVR,BAR,BAT,
  $ HVT,HVD,HAD,HAN,HVN,HVR,HAR,HAT,TFRIC,THYD,HOPP,T,XCOM)
    ENDPRO
    PUMP1=HOPP*ROIN12*9.806*CORE1
    DRENPP=(9.5493/AIPP)*(TRQPP-THYD-TFRIC)
    ENPP.=DENPP

PRIMARY PUMP HEAD AT DESIRED VALUE

   PROCED XCOMD,DLPHA.DNEWAL,DLNEW,DEND,
  $ DQNEW,BVTD,BVDD,BADD,BAND,BVND,BVRD,BARD,BATD,
  $ HVTD,HVDD,HADD,HAND,HVND,HVRD,HARD,HATD,TFRICD,THYDD,HOPPD
  $ =T,ENPPD1,WL11D1,RHOTP4,RHOTPR,TRATED,HRAT,ENPPR,WL11D1,WL11R
    CALL PUMP(ENPPD1,WL11D1,RHOTP4,RHOTPR,TRATED,HRAT,ENPPR,WL11D1,
  $ WL11R,DLPHA,DNEWAL,DLNEW,DEND,
  $ DQNEW,BVTD,BVDD,BADD,BAND,BVND,BVRD,BARD,BATD,
```

```
 $ HVTD,HVDD,HADD,HAND,HVND,HVRD,HARD,HATD,TFRICD,THYDD,HOPPD,T
 $,XCOMD)
  ENDPRO

     PRIMARY PUMP SPEED CONTROLLER


  TR1M.=(1./TTR1)*(TLP: TR1M)
  ETR1=TR1O-TR1M
  ETR1I.=ETR1

  WPSAC=WL11D1+AETR1*(ETR1+ETR1I/TETR1)

PRIMARY PUMP FLOW S.P. (SWWPS)

  PROCED  EWPS=SWWPS,WPSAC,WPSMC,WPSM
  IF(SWWPS.EQ.0.0)  EWPS=WPSAC-WPSM
  IF(SWWPS.NE.0.0)  EWPS=WPSMC-WPSM
  ENDPRO
  WPSM.=(1./TWPS)*(WL11-WPSM)

  EWPSI.=EWPS
  ENPPDD=ENPPD1+AEWPS*(EWPS+EWPSI/TEWPS)

  PROCED  ENPPAC=ENPPDD,ENPPMX
  IF(ENPPDD.LE.0.0)  ENPPAC=0.0
  IF(ENPPDD.GT.0.0.AND.ENPPDD.LE.ENPPMX)  ENPPAC=ENPPDD
  IF(ENPPDD.GT.ENPPMX)  ENPPAC=ENPPMX
  ENDPRO

PRIMARY PUMP SPEED S.P. (SWENPP)

  PROCED  EENPP=SWENPP,ENPPMC,ENPPAC,ENPP,TSCRAM
  IF(T.EQ.0.0) TSCRAM=2000.0
  IF(T.GE.TSCRAM) SWENPP=1.0
  IF(SWENPP.EQ.0.0)  EENPP=ENPPAC-ENPP
  IF(SWENPP.NE.0.0)  EENPP=ENPPMC-ENPP
  ENDPRO

  ENPPI.=EENPP
  EENPPC=EENPP+ENPPI/TEENPP

     ETRQP=ATRQP*EENPPC

  TRQPD=THYDD+TFRICD

  TRQPDD=TRQPD+ETRQP

  PROCED  TRQPAC=TRQPDD,TRQPMX
  IF(TRQPDD.LE.0.0)  TRQPAC=0.0
  IF(TRQPDD.GT.0.0.AND.TRQPDD.LE.TRQPMX)  TRQPAC=TRQPDD
   IF(TRQPDD.GE.TRQPMX)  TRQPAC=TRQPMX
  ENDPRO

PRIMARY PUMP TORQUE S.P. (SWTRQP)

  PROCED  TRQPP=SWTRQP,TRQPAC,TRQPMC,TSCRAM
  IF(T.EQ.0.0) TSCRAM=2000.0
  IF(SWTRQP.EQ.0.0)  TRQPP=TRQPAC
  IF(SWTRQP.NE.0.0)  TRQPP=TRQPMC
  IF(T.GE.TSCRAM) TRQPP=0.0
  ENDPRO


  PROCED  DENPP=ENWP,DRENPP
  IF(ENWP.EQ.0.0)  DENPP=DRENPP
```

```
      IF(ENWP.NE.0.0)  DENPP=0.0
      ENDPRO


      REPEAT 3
      WL2$D=ADL2$*((PIN2$-POUT2$)-RHOL2$*G*YL2$+REST2$)
      REST2$=(WL2$B/PAL2$)**2*(1.0/ROIN2$-1.0/ROUT2$-FL2$*PAL2$**2)
      WL2$.=WL2$D
      ENDREP

      PROCED WL11B,WL12B,WL13B,ELOSS1=WL11,WL12,WL13,FWL11,FWL12,
     $  FWL13,ENWL1,STWL1
      IF(ENWL1.EQ.0.0)GO TO 100
      IF(ENWL1.EQ.1.0.AND.T.LT.STWL1)GO TO 100
      IF(ENWL1.EQ.1.0.AND.T.GE.STWL1)GO TO 200
100   WL11B=WL11
      WL12B=WL12
      WL13B=WL13
      ELOSS1=0.0
      GO TO 300
200   WL11B=WL11*(1.0-FWL11)
      WL12B=WL12*(1.0-FWL12)
      WL13B=WL13*(1.0-FWL13)
      ELOSS1=(WL11*FWL11+WL12*FWL12+WL13*FWL13)*(T-STWL1)
300   CONTINUE
      ENDPRO

      PROCED WL21B,WL22B,WL23B,ELOSS2=WL21,WL22,WL23,FWL21,FWL22,
     $  FWL23,ENWL2,STWL2
      IF(ENWL2.EQ.0.0)GO TO 400
      IF(ENWL2.EQ.1.0.AND.T.LT.STWL2)GO TO 400
      IF(ENWL2.EQ.1.0.AND.T.GE.STWL2)GO TO 500
400   WL21B=WL21
      WL22B=WL22
      WL23B=WL23
      ELOSS2=0.0
      GO TO 600
500   WL21B=WL21*(1.0-FWL21)
      WL22B=WL22*(1.0-FWL22)
      WL23B=WL23*(1.0-FWL23)
      ELOSS2=(WL21*FWL21+WL22*FWL22+WL23*FWL23)*(T-STWL2)
600   CONTINUE
      ENDPRO


       PROCED XCOM2,ALPHA2,RNEWA2,ALNEW2,END2,
     $ QNEW2,BVT2,BVD2,BAD2,BAN2,BVN2,BVR2,BAR2,BAT2,
     $ HVT2,HVD2,HAD2,HAN2,HVN2,HVR2,HAR2,HAT2,TFRIC2,THYD2,HOPP2
     $  =T, ENPP2,WL21,RHOTP4,RHOTPR,TRATE2,HRAT,ENPPR,WL21D2,WL21R
       CALL PUMP(ENPP2,WL21,RHOTP4,RHOTPR,TRATE2,HRAT,ENPPR,WL21D2,
     $ WL21R,ALPHA2,RNEWA2,ALNEW2,END2,
     $ QNEW2,BVT2,BVD2,BAD2,BAN2,BVN2,BVR2,BAR2,BAT2,
     $ HVT2,HVD2,HAD2,HAN2,HVN2,HVR2,HAR2,HAT2,TFRIC2,THYD2,HOPP2,T
     $,XCOM2)
       ENDPRO
       PUMP2=HOPP2*ROIN22*9.806*CORE2
       DREN2P=(9.5493/AI2P)*(TRQ2P-THYD2-TFRIC2)
       ENPP2.=DEN2P

      PROCED XCOMD2,DLPHA2,DNEWA2,DLNEW2,DEND2,
     $ DQNEW2,BVTD2,BVDD2,BADD2,BAND2,BVND2,BVRD2,BARD2,BATD2,
     $ HVTD2,HVDD2,HADD2,HAND2,HVND2,HVRD2,HARD2,HATD2,TFRID2,THYDD2,
     $HOPPD2,=T,ENPPD2,WL21D2,RHOTP4,RHOTPR,TRATE2,HRAT,ENPPR,WL21D2,
     $WL21R
       CALL PUMP(ENPPD2,WL21D2,RHOTP4,RHOTPR,TRATE2,HRAT,ENPPR,WL21D2,
     $ WL21R,DLPHA2,DNEWA2,DLNEW2,DEND2,
```

```
$ DQNEW2,BWTD2,BVDD2,BADD2,BAND2,BVND2,BVRD2,BARD2,BATD2,
$ HVTD2,HVDD2,HADD2,HAND2,HVND2,HVRD2,HARD2,HATD2,TFRID2,THYDD2,
$HOPPD2,T,XCOMD2)
 ENDPRO

    INTERMEDIATE PUMP SPEED CONTROLLER


 TR2M.=(1./TTR2)*(TLP2-TR2M)
 ETR2=TR2D-TR2M
 ETR2I.=ETR2
 W2SAC=WL21D2+AETR2*(ETR2+ETR2I/TETR2)




 PROCED  EW2S=SWW2S,W2SMC,W2SAC
 IF(SWW2S.EQ.0.0)  EW2S=W2SAC-W2SM
 IF(SWW2S.NE.0.0)  EW2S=W2SMC-W2SM
 ENDPRO
 W2SM.=(1./TW2S)*(WL21-W2SM)

 EW2SI.=EW2S
 EN2PDD=ENPPD2+AEW2S*(EW2S+EW2SI/TEW2S)

 PROCED  EN2PAC=EN2PDD,ENPPMX
 IF(EN2PDD.LE.0.0)  EN2PAC=0.0
 IF(EN2PDD.GT.0.0.AND.EN2PDD.LE.ENPPMX)  EN2PAC=EN2PDD
 IF(EN2PDD.GT.ENPPMX)  EN2PAC=ENPPMX
 ENDPRO


 PROCED  EEN2P=SWEN2P,EN2PMC,EN2PAC,ENPP2,TSCRAM
 IF(T.EQ.0.0) TSCRAM=2000.0
 IF(T.GE.TSCRAM) SWEN2P=1.0
 IF(SWEN2P.EQ.0.0)  EEN2P=EN2PAC-ENPP2
 IF(SWEN2P.NE.0.0)  EEN2P=EN2PMC-ENPP2
 ENDPRO

 PROCED ENPPD1,ENPPD2=TSCRAM
 IF(T.EQ.0.0) TSCRAM=2000.00
 ENPPD1=1068.47
 ENPPD2=1068.47
 IF(T.GE.TSCRAM) ENPPD1=81.64
 IF(T.GE.TSCRAM) ENPPD2=81.64
 ENDPRO

 EN2PI.=EEN2P
 EEN2PC=EEN2P+EN2PI/TEEN2P

    ETRQ2=ATRQ2*EEN2PC

 TRQ2D=THYDD2+TFRID2

 TRQ2DD=TRQ2D+ETRQ2

 PROCED  TRQ2AC=TRQ2DD,TRQ2MX
 IF(TRQ2DD.LE.0.0)  TRQ2AC=0.0
 IF(TRQ2DD.GT.0.0.AND.TRQ2DD.LE.TRQ2MX)  TRQ2AC=TRQ2DD
 IF(TRQ2DD.GT.TRQ2MX)  TRQ2AC=TRQ2MX
 ENDPRO

 PROCED  TRQ2P=SWTRQ2,TRQ2AC,TRQ2MC,TSCRAM
```

```
 IF(T.EQ.0.0) TSCRAM=2000.0
 IF(SWTRQ2.EQ.0.0)  TRQ2P=TRQ2AC
 IF(SWTRQ2.NE.0.0)  TRQ2P=TRQ2MC
 IF(T.GE.TSCRAM) TRQ2P=0.0
 ENDPRO


 PROCED  DEN2P=ENW2,DREN2P
 IF(ENW2.EQ.0.0)  DEN2P=DREN2P
 IF(ENW2.NE.0.0)  DEN2P=0.0
 ENDPRO




 REPEAT 2
 PIN$2=POUT$1+PUMP$
 POUT$1=(PIN$1+SUM$1-C$*(PUMP$-POUT$2+SUM$2))/(1.0+C$)
 POUT$2=S$*(PIN$2-POUT$3+SUM$3)+PIN$3-SUMX$
 PIN$3=(D$*(PIN$1-ADD$+SUM$1)+POUT$3-SUM$3)*PART$/AOL$3
 ADD$=(PIN$1+SUM$1-C$*(PUMP$-S$*(-POUT$3+SUM$3)+AD$))/(1.0+C$)
 AD$=SUMX$+SUM$2

 A$=AOL$2/(AOLXP$*ENXT$)
 Y$=AOL$2/AOL$3
 C$=AOL$2/AOL$1
 D$=AOL$1/AOL$3
 E$=AOL$3/AOL$1
 G$=AOL$3/AOLR
 S$=AOL$3/(AOLXP$*ENXT$)

 PART$=AOL$3/(1.0+(A$+Y$)/(1.0+C$))
 PIECE$=1.0+AOL$1*AOL$2/(AOLXP$*ENXT$*(AOL$1+AOL$2))

 DENOM$=PART$*PIECE$
 SUMX$=-RHOXP$*G*YXP$+RESTX$

 ENDREP

 REPEAT 3

 SUM1$=-RHOL1$*G*YL1$+REST1$
 SUM2$=-RHOL2$*G*YL2$+REST2$

 ENDREP

 BUMER=QUEER1+QUEER2+QUEER3+QUEER4+QUEER5



 PLP=(AOL13*((D1*(PIN11-(PIN11+SUM11-C1*(PUMP1+S1*(DELP13-SUM13)+
$SUMX1+SUM12))/(1.0+C1)+SUM11)+DELP13-SUM13)/(1.0+(A1+Y1)/(1.0+C1))
$-DELP13+SUM13)+AOL23*((D2*(PIN21-(PIN21+SUM21-C2*(PUMP2+S2*
$(DELP23-SUM23)+SUMX2+SUM22))/(1.0+C2)+SUM21)+DELP23-SUM23)
$/(1.0+(A2+Y2)/(1.0+C2))-DELP23+SUM23)+BUMER)/(AOLR+AOL13+
$AOL23-DENOM1-DENOM2)

 AOLR=AOL1+AOL2+AOL3+AOL4+AOL5

 REPEAT 5
 QUEER$=AOL$*(PUP+YC*G*RHOC$-T3$)
 ENDREP

 WRD=WL13+WL23
```

```
REPEAT 2
WIXP$D=ADLXP$*((POUT$2-PIN$3)-RHOXP$*G*YXP$+RESTX$)
RESTX$=(WIXP$/PAXP$)**2*(1.0/ROUT$2-1.0/ROIN$3-FXP$*(PAXP$**2))
WIXP$.=WIXP$D
WIXPL$=SATAM(WIXP$,1.0E-03,1.0E+30)
WIHX$=WIXP$*(ENXT1-ENTUB$)
ENDREP

REPEAT 5
T$=WROL$*CPS$*TCS$
ENDREP


TUPOD=(WRD*CPOUT*TOUT-(WL11+WL21)*CPOUT*TUPO)/RVC
RVC=RHOUP*VOLUP*CPUPO
TUPO.=TUPOD
TOUTD=(T1+T2+T3+T4+T5-WRD*CPOUT*TOUT)/(RHOUT*VOLC*CPOUT)
TOUT.=TOUTD

TLPD=(QLOOP1+QLOOP2-WRD*CPSLP*TLP)/(RHOLP*VOLLP*CPSLP)
TLP.=TLPD

QLOOP1=WL13L*CPL1*TLP1
QLOOP2=WL23L*CPL2*TLP2

CPL1=CP(TXP11,1)
CPL2=CP(TXP21,1)
CPUPO=CP(TUPO,1)
CPOUT=CP(TOUT,1)
CPSLP=CP(TLP,1)
REPEAT 5
CPS$=CP(TCS$,1)
CPAS$=CP(TCSA$,1)
TCSA$=(TCS$+TLP)/2.0
ENDREP



 PUP=UPNAH*G*RHOUP+PCG
 PLP1=PUP+7.241E05

 REPEAT 2
 TAVL$1=(TUPO+TINP$)/2.0
 TAVL$2=(TOP$+TXP$)/2.0
 TAVL$3=(TXP$1+TLP$)/2.0
 TAVXP$=(TXP$+TXP$1)/2.0
 ENDREP

 REPEAT 5
 RHOC$=RHONA(TCS$)
 ENDREP


 REPEAT 2
 RHOAP$=(ROUT$1+ROIN$2)/2.0
 ENDREP

 PROCED RHOLP,RHOUT,RHOUP,RHOL11,RHOL12,RHOL13,RHOL21,RHOL22,
$RHOL23,ROIN11,ROIN12,ROIN13,ROUT11,ROUT12,ROUT13,ROIN21,
$ROIN22,ROIN23,ROUT21,ROUT22,ROUT23,RHOXP1,RHOXP2=T
 RHOLP=RHONA(TLP)
 RHOUT=RHONA(TOUT)
 RHOUP=RHONA(TUPO)
 RHOL11=RHONA(TAVL11)
```

```
RHOL12=RHONA(TAVL12)
RHOL13=RHONA(TAVL13)
RHOL21=RHONA(TAVL21)
RHOL22=RHONA(TAVL22)
RHOL23=RHONA(TAVL23)
ROIN11=RHONA(TUPO)
ROIN12=RHONA(TOP1)
ROIN13=RHONA(TXP11)
ROUT11=RHONA(TINP1)
ROUT12=RHONA(TXP1)
ROUT13=RHONA(TLP1)
ROIN21=RHONA(TUPO)
ROIN22=RHONA(TOP2)
ROIN23=RHONA(TXP21)
ROUT21=RHONA(TINP2)
ROUT22=RHONA(TXP2)
ROUT23=RHONA(TLP2)
RHOXP1=RHONA(TAVXP1)
RHOXP2=RHONA(TAVXP2)
ENDPRO

REPEAT 2
TOP$D=(WL$1/(RHOAP$*VOLP$))*(TINP$-TOP$)
TOP$.=TOP$D
ENDREP

REPEAT 3
PAL1$=PI*(R1$**2)
PAL2$=PI*(R2$**2)
AOL1$=PAL1$/PLL1$
AOL2$=PAL2$/PLL2$
ENDREP

PIN11=PUP-DELP11
PIN21=PUP-DELP21

POUT13=PLP+DELP13
POUT23=PLP+DELP23


REPEAT 3
TFS$=(TCSA$-273.0)*(9.0/5.0)+32.0
TRS$=TFS$+460.0
TCCS$=1.73073*(54.306-1.878E-02*TFS$+2.0914E-06*(TFS$**2))


RHOCS$=16.02*(59.533-.00833*TFS$)
UMCS$=4.134E-04*(10.0**(1.0203+(397.17/TRS$)-.4925*ALOG10(TRS$)))
ENDREP

REPEAT 3
TFF$=(TCF$-273.0)*(9.0/5.0)+32
TFC$=(TFF$-32.0)*(5.0/9.0)

CPCF$=CP(TCF$,2)

TCCF$=100.0*(F$*(38.24/(TCF$+129.2)+6.1256E-13*(TCF$**3)))
F$=1.079*(FRO/(1.0+.5*(1.0-FRO)))
ENDREP

REPEAT 3
TFCC$=(TCC$-273.0)*(9.0/5.0)+32.0
TCCC$=1.73073*(7.7388464+.40721437E-02*TFCC$)

CPCC$=CP(TCC$,3)
```

```
ENDREP

REPEAT 3
TGS=TCCS+.2723*(1.0+.08*CGPDR)*QLPS
BS=EXP(-7.0+.035*QLPS-6.3*CGPDR)
HCS=.132+(.1167*SQRT(TGS)-2.36)/CGPDR+.6391*(BS/(1.0+BS))
HCGS=(1.0E+04*HCS)
ENDREP

REPEAT 3
QFS=UAFS*(TCFS-TCCS)
QNAS=UACS*(TCCS-TCSAS)

DTCCS=(1.0/(CM*CPCCS))*(QFS-UACS*(TCCS-TCSAS))
TCCS.=(DTCCS)
TCS=(QPS/UACS)+TCSAS
UACS=1.0/(RC2S+RSS)
RC2S=ALOG(DOC/DC)/(2.0*TCCCS*PI*PL)
RSS=1.0/(HCSS*CAREA2)
ENDREP


REPEAT 3
UATS=1.0/((1.0/UAFS)+(1.0/UACS))
ENDREP
REPEAT 3
DTCFS=(1.0/(FM*CPCFS))*(QPS-UAFS*(TCFS-TCCS))
TCFS.=(DTCFS)
TFS=(QPS/UATS)+TCSAS
UAFS=1.0/(RFS+RGS+RC1S)
RFS=1.0/(8.0*PI*PL*TCCFS)
RGS=1.0/(HCGS*CAREA1)
RC1S=ALOG(DC/DIC)/(2.0*TCCCS*PI*PL)
ENDREP

REPEAT 5
ENRCS=XNASSS*XNPPAS
WROPPS=WRDLS/ENRCS
ENDREP
REPEAT 3
VCSS=WRDPPS/(RHOCSS*CSFA)
RECSS=(RHOCSS*VCSS*DHC)/(UMCSS)
PRCSS=(CPASS*UMCSS)/(TCCSS)
PCCSS=(RECSS*PRCSS)
UNCSS=4.0+.16*((PC/DHC)**5)+.006288*((PC/DHC)**3.8)*PCCSS**.86
HCSS=(UNCSS*TCCSS)/DHC
ENDREP



TLP1=PDELAY(TXP11,TAULP1,1,TL1)
WL13L=SATAM(WL13,1.0E-03,1.0E+30)
TAULP1=(ROXP11*4.2733)/WL13L

TLP2=PDELAY(TXP21,TAULP2,2,TL2)
WL23L=SATAM(WL23,1.0E-03,1.0E+30)
TAULP2=(ROXP21*2.0*4.2733)/WL23L

TINP1=PDELAY(TUPO,TAUP11,5,TINP1I)
WL11L=SATAM(WL11,1.0E-03,1.0E+30)
TAUP11=(ROUT11*16.0744)/WL11L

TINP2=PDELAY(TUPO,TAUP21,6,TINP2I)
WL21L=SATAM(WL21,1.0E-03,1.0E+30)
TAUP21=(ROUT11*2.0*16.0744)/WL21L
```

```
WL12L=SATAM(WL12,1.0E-03,1.0E+30)
TAUXP1=(RHOL12*1.7263)/WL12L
WL22L=SATAM(WL22,1.0E-03,1.0E+30)
TAUXP2=(RHOL22*2.0*1.7263)/WL22L

THE FOLLOWING EQUATIONS ARE USED IN THE CALCULATION OF THE HOT
CHANNEL FUEL, CLADDING, AND SODIUM TEMPERATURES.

QHOT=QT*FPC1
QPHC=(QHOT/ENRC1)*1.06
QLHC=QPHC/PL
QLPHC=QLHC/100.0

QNAHC=UACHC*(TCCHC-TCSAHC)
TCSHCD=(1.0/(CPASHC*XMASHC))*(QNAHC+WRDHC*(CPASHC*(TLP-TCSHC)))
XMASHC=RHOHC*VOLHC
VOLHC=VOL1/ENRC1
TCSHC.=TCSHCD

WRDHC=WRDPP1*.95
TCSAHC=(TCSHC+TLP)/2.0
CPASHC=CP(TCSAHC,1)
CPCCHC=CP(TCCHC,3)
CPCFHC=CP(TCFHC,2)
RHOHC=RHONA(TCSHC)

TCCFHC=100.0*(FHC*(38.24/(TCFHC+129.2)+6.1256E-13*(TCFHC**3)))
FHC=1.079*(FRO/(1.0+.5*(1.0-FRO)))
TFCCHC=(TCCHC-273.0)*1.8+32.0
TCCCHC=1.73073*(7.7388464+.40721437E-02*TFCCHC)

TGHC=TCCHC+.2723*(1.0+.08*CGPDR)*QLPHC
BHC=EXP(-7.0+.035*QLPHC-6.3*CGPDR)
HCHC=.132+(.1167*SQRT(TGHC)-2.36)/CGPDR+.6391*(BHC/(1.0+BHC))
HCGHC=1.0E+04*HCHC

VCSHC=WRDHC/(ROSAHC*CSFA)
RECSHC=(ROSAHC*VCSHC*DHC)/UMCSHC
PRCSHC=(CPASHC*UMCSHC)/TCCSHC
PCCSHC=RECSHC*PRCSHC
UNCSHC=4.0+.16*((PC/DHC)**5)+.006288*((PC/DHC)**3.8)*PCCSHC**.86
HCSHC=(UNCSHC*TCCSHC)/DHC

TFSHC=(TCSAHC-273.0)*1.8+32.0
TRSHC=TFSHC+460.0
TCCSHC=1.73073*(54.306-1.878E-02*TFSHC+2.0914E-06*(TFSHC**2))
ROSAHC=16.02*(59.533-.00833*TFSHC)
UM=10.0**(1.0203+(397.17/TRSHC)-.4925*ALOG10(TRSHC))
UMCSHC=4.134E-04*UM

QFHC=UAFHC*(TCFHC-TCCHC)

TCCHCD=(1.0/(CM*CPCCHC))*(QFHC-UACHC*(TCCHC-TCSAHC))
TCCHC.=TCCHCD
UACHC=1.0/(RC2HC+RSHC)
RC2HC=ALOG(DOC/DC)/(2.0*TCCCHC*PI*PL)
RSHC=1.0/(HCSHC*CAREA2)

TCFHCD=(1.0/(FM*CPCFHC))*(QPHC-UAFHC*(TCFHC-TCCHC))
TCFHC.=TCFHCD
UAFHC=1.0/(RFHC+RGHC+RC1HC)
RFHC=1.0/(8.0*PI*PL*TCCFHC)
RGHC=1.0/(HCGHC*CAREA1)
RC1HC=ALOG(DC/DIC)/(2.0*TCCCHC*PI*PL)
```

```
      THE FOLLOWING SECTION CALCULATES THE TOTAL SODIUM MASS IN
      THE PRIMARY SIDE OF FFTF AT ALL TIMES.  BY KEEPING TRACK OF
      THIS MASS PIPE BREAKS WILL BE POSSIBLE TO MODEL AND THE
      SODIUM HEIGHT IN THE UPPER PLENUM WILL BE KEPT TRACK OF.
      ALSO, THIS SECTION CALCULATES THE SODIUM UPPER PLENUM HEIGHT.

      REPEAT 3
      ENAM1$=ENAV1$*RHOL1$
      ENDREP

      REPEAT 3
      ENAM2$=ENAV2$*RHOL2$
      ENDREP

      ENAXM1=ENAVX1*RHOXP1
      ENAXM2=ENAVX2*RHOXP2
      ENPPM1=ENVPP1*ROIN12
      ENPPM2=ENVPP2*ROIN22
      ENAVM1=ENAVV1*RHOL13+ENAHV1*RHOL11
      ENAVM2=ENAVV2*RHOL23+ENAHV2*RHOL21
      ENALPM=ENAVLP*RHOLP

      ENACM=VOL1*RHOC1+VOL2*RHOC2+VOL3*RHOC3+VOL4*RHOC4+VOL5*RHOC5
      ENAMAS=TNAMAS-ENMLOS
      ENMLOS=ELOSS1+ELOSS2
      UPNAMV=95.09-ENMLOS/RHOUP

      UPNAH=UPNAMV/(PI*UPRAD**2)



      STORE WRD1,WRD2,WRD3,WRD4,WRD5,WRD,WL11,WL12,WL13,WL21,
     $WL22,WL23,PIN11,POUT11,PIN12,POUT12,PIN13,POUT13,PIN21,
     $POUT21,PIN22,POUT22,PIN23,POUT23,PLP,PUP,TCS1,TCS2,TCS3,
     $TCS4,TCS5,TCSHC,TCCHC,TCFHC,TCC1,TCC2,TCC3,TCF1,TCF2,TCF3,
     $WIXP1,WIXP2,TLP,TUPO,ROD,TXP11,TXP21,TXS11,TXS21,EN,ENN,
     $PUMP1,PUMP2,HOPP2,ENPP2,TRQPP,TRQ2P,HOPP,ENPP,ERR,PIOP,ZROD,
     $FLUX,U1,U2,ROAUTO,WD,TXS1I,TXS2I,TXP1,TXP2,FWRD,FWRD1,FWRD2,
     $FWRD3,FWRD4,FWRD5,TXS12,TXS22


*F

      FUNCTION H2(PEXP2,TCXP2,REXP2,PRXP2,P,DH)
      IF(PEXP2.LT.60.0) GO TO 10
      IF(PEXP2.GE.60.0.AND.PEXP2.LE.500.0) GO TO 20
      IF(PEXP2.GT.500.0) GO TO 30
10    H2=(TCXP2/DH)*(3.31+4.29*(P/DH)+.888*(P/DH)**2)
      RETURN
20    RE2=ALOG10(REXP2)
      UNXPP2=-2.79+3.97*(P/DH)+1.025*((P/DH)**2)+3.12*RE2-.265*(RE2**2)
      V2=EXP(-6.4612+.94182*ALOG(REXP2)+1.3*ALOG(1.38/(P/DH)))
      PSI2=1.0-1.82/(PRXP2*(V2**1.4))
      IF(PSI2.LT.1.0E-10) PSI2=1.0E-10
      X2=.0155*(PSI2**.86)
      W2=6.66+(P/DH)*(3.126+1.184*(P/DH))
      UNXP2=W2+X2*(PEXP2**.86)
      IF(UNXPP2.LT.UNXP2) UNXP2=UNXPP2
      H2=(TCXP2/DH)*UNXP2
      RETURN
30    V2=EXP(-6.4612+.94182*ALOG(REXP2)+1.3*ALOG(1.38/(P/DH)))
      PSI2=1.0-1.82/(PRXP2*(V2**1.4))
      IF(PSI2.LT.1.0E-10) PSI2=1.0E-10
      X2=.0155*(PSI2**.86)
      W2=6.66+(P/DH)*(3.126+1.184*(P/DH))
      UNXP2=W2+X2*(PEXP2**.86)
```

```
      H2=(TCXP2/DH)*UNXP2
      RETURN
      END
$F

      FUNCTION H1(PEXP1,TCXP1,REXP1,PRXP1,P,DH)
      IF(PEXP1.LT.60.0) GO TO 10
      IF(PEXP1.GE.60.0.AND.PEXP1.LE.500.0) GO TO 20
      IF(PEXP1.GT.500.0) GO TO 30
10    H=(TCXP1/DH)*(3.31+4.29*(P/DH)+.988*(P/DH)**2)
      RETURN
20    RE1=ALOG10(REXP1)
      UNXPP1=-2.79+3.97*(P/DH)+1.025*((P/DH)**2)+3.12*RE1-.265*(RE1**2)
      V1=EXP(-6.4612+.94182*ALOG(REXP1)+1.3*ALOG(1.38/(P/DH)))
      PSI1=1.0-1.82/(PRXP1*(V1**1.4))
      IF(PSI1.LT.1.0E-10) PSI1=1.0E-10
      X1=.0155*(PSI1**.86)
      W1=6.66+(P/DH)*(3.126+1.184*(P/DH))
      UNXP1=W1+X1*(PEXP1**.86)
      IF(UNXPP1.LT.UNXP1) UNXP1=UNXPP1
      H1=(TCXP1/DH)*UNXP1
      RETURN
30    V1=EXP(-6.4612+.94182*ALOG(REXP1)+1.3*ALOG(1.3/(P/DH)))
      PSI1=1.0-1.82/(PRXP1*(V1**1.4))
      IF(PSI1.LT.1.0E-10) PSI1=1.0E-10
      X1=.0155*(PSI1**.86)
      W1=6.66+(P/DH)*(3.126+1.184*(P/DH))
      UNXP1=W1+X1*(PEXP1**.86)
      H1=(TCXP1/DH)*UNXP1
      RETURN
      END
$F
      FUNCTION CP(TK,X)
      TF=(TK-273.0)*1.8+32.0
      IF(X.EQ.1.0) GO TO 10
      IF(X.EQ.2.0) GO TO 20
      IF(X.EQ.3.0) GO TO 30
10    CP=4.1868E+03*(.34574-.79226E-04*TF+.34086E-07*(TF**2))
      RETURN
20    TC=(TF-32.0)*(5.0/9.0)
      CP1=4.1868E+03*(.1091351924+7.75289753E-05*TC)
      CP2=4.1868E+03*(-6.121778E-08*(TC**2)+2.046305E-11*(TC**3))
      CP=CP1+CP2
      RETURN
30    CP=4.1868E+03*(.14937593-.39506964E-04*TF+.2678125E-07*(TF**2))
      RETURN
      END

       SUBROUTINE PUMP(ENPP,WPS,RHO,RHOR,TRATED,HRAT,ENPPR,WPSD,WPSR
     1 ,ALPHA,RNEWAL,ALNEW,END,
     2 WNEW,BVT,BVD,BAD,BAN,BVN,BVR,BAR,BAT,
     3 HVT,HVD,HAD,HAN,HVN,HVR,HAR,HAT,TFRIC,THYD,HOPP,T,XCOM)
       DATA COHVN,C1HVN,C2HVN,C3HVN,C4HVN,C5HVN,COHVR,C1HVR,C2HVR,
     1C3HVR,C4HVR,C5HVR,COHAR,C1HAR,C2HAR,C3HAR,C4HAR,C5HAR/-0.55392
     2 ,0.85376,0.62906,-3.7106,7.0593,-3.4776,-0.55392,0.66362,
     3-0.036081,-0.93928,-0.57381,0.0,0.62307,0.14665,-4.1896
     4,-2.4828,0.8973,0.0/
       DATA COHAT,C1HAT,C2HAT,C3HAT,C4HAT,C5HAT,COHAN,C1HAN,C2HAN
     1,C3HAN,C4HAN,C5HAN,COHAD,C1HAD,C2HAD,C3HAD,C4HAD,C5HAD/0.62307
     2,0.20178,-0.30242,0.76603,-0.48077,0.19231,1.264041,0.061907
     3,-.17327,-0.57294,0.033762,0.3865,1.264041,0.061907,-0.17327
     4,-0.57294,0.033762,0.3865/
      DATA COHVD,C1HVD,C2HVD,C3HVD,C4HVD,C5HVD,COHVT,C1HVT,C2HVT,
     1C3HVT,C4HVT,C5HVT,COBVT,C1BVT,C2BVT,C3BVT,C4BVT,C5BVT/
     20.68211,0.43961,0.68459,-0.24701,0.63156,-0.20833,0.68211,
     3-0.46132,0.92592,-0.4306,0.50845,-0.22436,0.8658,-0.60816
```

```
     4,3.1497,-4.3647,10.4180,-4.0064/
      DATA COBVD,C1BVD,C2BVD,C3BVD,C4BVD,C5BVD,COBAD,C1BAD,C2BAD,
     1C3BAD,C4BAD,C5BAD,COBAN,C1BAN,C2BAN,C3BAN,C4BAN,C5BAN/
     20.8658,0.28437,-0.22348,0.45083,-0.70586,0.21562,0.447841,
     3 0.5065,0.59643,-0.64055,-0.025531,0.11531,0.447841,0.5065,
     4 0.59643,-0.64055,-0.025531,0.11531/
      DATA COBVN,C1BVN,C2BVN,C3BVN,C4BVN,C5BVN,COBVR,C1BVR,C2BVR,
     1C3BVR,C4BVR,C5BVR/-0.37111,
     20.41741,3.8511,-7.6752,7.0695,-2.2917,-0.3711,2.3716,-0.56147
     3,0.0,0.0,0.0/
      DATA COBAR,C1BAR,C2BAR,C3BAR,C4BAR,C5BAR,COBAT,C1BAT,C2BAT,
     1C3BAT,C4BAT,C5BAT/-0.684,2.0342,-0.95477,-0.42286,0.0,0.0,
     2-0.68468,1.8495,0.96871,-8.9653,12.045,-4.7546/
       DATA COFRIC,C1FRIC,C2FRID/0.012,0.023,0.0/
       DATA AOFRIC,A1FRIC,A2FRIC/0.117,-8.97,0.0/
       DATA BOFRIC,B1FRIC,B2FRIC/0.0,14.77,0.0/
       ALPHA=ENPP/ENPPR
       QNEW=(WPS/RHO)/(WPSR/RHOR)
        WRITE(6,2001)(ENPP,ENPPR,WPS,WPSR,RHO,RHOR)
 2001  FORMAT(1H0,*ENPP,ENPPR,WPS,WPSR,RHO,RHOR*,6F10.2)
       RNEWAL=QNEW/ALPHA
       ALNEW=ALPHA/QNEW
               XCOM=ALNEW
        WRITE(6,2002)(ALPHA,QNEW,RNEWAL,ALNEW,XCOM)
 2002  FORMAT(1H0,*ALPHA,QNEW,RNEWAL,ALNEW,XCOM*,5F10.2)
        IF(ALNEW.GT.1.0) XCOM=RNEWAL
        IF(RNEWAL.GT.1.0) XCOM=ALNEW
       ALPHA2=ALPHA*ALPHA
       QNEW2=QNEW*QNEW
       RNEWA2=RNEWAL*RNEWAL
       RNEWA3=RNEWA2*RNEWAL
       RNEWA4=RNEWA3*RNEWAL
       RNEWA5=RNEWA4*RNEWAL
       ALNEW2=ALNEW*ALNEW
       ALNEW3=ALNEW2*ALNEW
       ALNEW4=ALNEW3*ALNEW
       ALNEW5=ALNEW4*ALNEW
       IF(ALPHA.GT.0.0117) GO TO 200
       IF(ALPHA.LE.0.0117.AND.ALPHA.GT.0.005) GO TO 210
       IF(ALPHA.GT.0.0.AND.ALPHA.LE.0.005) GO TO 220
       IF(ALPHA.LT.0.0) GO TO 230


 00     TFRIC=TRATED*(COFRIC + C1FRIC*ALPHA + C2FRIC*ALPHA*ALPHA)
         GO TO 221


 10     TFRIC=TRATED*(AOFRIC + A1FRIC*ALPHA + A2FRIC*ALPHA*ALPHA)
        GO TO 221


 20     TFRIC=TRATED*(BOFRIC+B1FRIC*ALPHA+B2FRIC*ALPHA*ALPHA)
        GO TO 221


 30     TFRIC=-TRATED*(COFRIC+C1FRIC*ALPHA+C2FRIC*ALPHA*ALPHA)


 21    CONTINUE
       IF(T.LE.0.0) END=1.0
       IF(ALNEW.EQ.1.0) GO TO 231
       IF((ALNEW.LT.1.0.AND.ALNEW.GT.0.0).AND.(END.EQ.1.0.OR.END.EQ.2.0.O
      $R.END.EQ.8.0)) GO TO 231
       IF((ALNEW.LT.0.0.AND.ALNEW.GE.(-1.0)).AND.(END.EQ.1.0.OR.END.EQ.3.
      $.OR.END.EQ.2.0)) GO TO 238
       IF((RNEWAL.LT.0.0.AND.RNEWAL.GT.(-1.0)).AND.(END.EQ.2.0.OR.END.EQ.
```

```
     $4.0.OR.END.EQ.3.0)) GO TO 237
      IF((RNEWAL.GE.0.0.AND.RNEWAL.LT.1.0).AND.(END.EQ.3.0.OR.END.EQ.5.0
     $.OR.END.EQ.4.0)) GO TO 236
      IF((ALNEW.LT.1.0.AND.ALNEW.GT.0.0).AND.(END.EQ.6.0.OR.END.EQ.4.0.
     $OR.END.EQ.5.0)) GO TO 235
      IF((ALNEW.LT.0.0.AND.ALNEW.GE.(-1.0)).AND.(END.EQ.5.0.OR.END.EQ.
     $7.0.OR.END.EQ.6.0)) GO TO 234
      IF((RNEWAL.LT.0.0.AND.RNEWAL.GT.(-1.0)).AND.(END.EQ.8.0.OR.END.
     $EQ.6.0.OR.END.EQ.7.0)) GO TO 233
      IF((RNEWAL.GE.0.0.AND.RNEWAL.LT.1.0).AND.(END.EQ.1.0.OR.END.EQ.
     $7.0.OR.END.EQ.8.0)) GO TO 232
  231 HVN=C0HVN+C1HVN*ALNEW+C2HVN*ALNEW2+C3HVN*ALNEW3+C4HVN*ALNEW4+
     $C5HVN*ALNEW5
      HOPP=HRAT*HVN*QNEW2
      BVN=C0BVN+C1BVN*ALNEW+C2BVN*ALNEW2+C3BVN*ALNEW3+C4BVN*ALNEW4+
     $C5BVN*ALNEW5
      THYD=TRATED*BVN*QNEW2
      HVR=0.0
      BVR=0.0
      END=1.0
      GO TO 248
  232 HVR=C0HVR+C1HVR*ALNEW+C2HVR*ALNEW2+C3HVR*ALNEW3+C4HVR*ALNEW4+
     $C5HVR*ALNEW5
      HOPP=HRAT*HVR*QNEW2
      BVR=C0BVR+C1BVR*ALNEW+C2BVR*ALNEW2+C3BVR*ALNEW3+C4BVR*ALNEW4+
     $C5BVR*ALNEW5
      THYD=TRATED*BVR*QNEW2
      HVN=0.0
      BVN=0.0
      END=2.0
      GO TO 248
  237 HAR=C0HAR+C1HAR*RNEWAL+C2HAR*RNEWA2+C3HAR*RNEWA3+C4HAR*RNEWA4+
     $C5HAR*RNEWA5
      HOPP=HRAT*HAR*ALPHA2
      BAR=C0BAR+C1BAR*RNEWAL+C2BAR*RNEWA2+C3BAR*RNEWA3+C4BAR*RNEWA4+
     $C5BAR*RNEWA5
      THYD=TRATED*BAR*ALPHA2
      END=3.0
      GO TO 248
  236 HAT=C0HAT+C1HAT*RNEWAL+C2HAT*RNEWA2+C3HAT*RNEWA3+C4HAT*RNEWA4+
     $C5HAT*RNEWA5
      HOPP=HRAT*HAT*ALPHA2
      BAT=C0BAT+C1BAT*RNEWAL+C2BAT*RNEWA2+C3BAT*RNEWA3+C4BAT*RNEWA4+
     $C5BAT*RNEWA5
      THYD=TRATED*BAT*ALPHA2
       END=4.0
      GO TO 248
  235 HVT=C0HVT+C1HVT*ALNEW+C2HVT*ALNEW2+C3HVT*ALNEW3+C4HVT*ALNEW4+
     $C5HVT*ALNEW5
      HOPP=HRAT*HVT*QNEW2
      BVT=C0BVT+C1BVT*ALNEW+C2BVT*ALNEW2+C3BVT*ALNEW3+C4BVT*ALNEW4+
     $C5BVT*ALNEW5
      THYD=TRATED*BVT*QNEW2
      END=5.0
      GO TO 248
  234 HVD=C0HVD+C1HVD*ALNEW+C2HVD*ALNEW2+C3HVD*ALNEW3+C4HVD*ALNEW4+
     $C5HVD*ALNEW5
      HOPP=HRAT*HVD*QNEW2
      BVD=C0BVD+C1BVD*ALNEW+C2BVD*ALNEW2+C3BVD*ALNEW3+C4BVD*ALNEW4+
     $C5BVD*ALNEW5
      THYD=TRATED*BVD*QNEW2
      END=6.0
      GO TO 248
  233 HAD=C0HAD+C1HAD*RNEWAL+C2HAD*RNEWA2+C3HAD*RNEWA3+C4HAD*RNEWA4+
     $C5HAD*RNEWA5
      HOPP=HRAT*HAD*ALPHA2
```

```
      BAD=C0BAD+C1BAD*RNEWAL+C2BAD*RNEWA2+C3BAD*RNEWA3+C4BAD*RNEWA4+
     $C5BAD*RNEWA5
      THYD=TRATED*BAD*ALPHA2
      END=7.0
      GO TO 248
 232  HAN=C0HAN+C1HAN*RNEWAL+C2HAN*RNEWA2+C3HAN*RNEWA3+C4HAN*RNEWA4+
     $C5HAN*RNEWA5
      HUPP=HRAT*HAN*ALPHA2
      BAN=C0BAN+C1BAN*RNEWAL+C2BAN*RNEWA2+C3BAN*RNEWA3+C4BAN*RNEWA4+
     $C5BAN*RNEWA5
      THYD=TRATED*BAN*ALPHA2
      END=8.0
      GO TO 248
 248   CONTINUE
       RETURN
       END

$F
      FUNCTION RHONA(T)
      RHONA=919.536-.07415*T
      RETURN
      END

$T1
      FEN , 5
                0.0,        1.0000
                .050,       1.0283
                .100,       1.0568
                .150,       1.0857
                .200,       1.1148
END
      TMAX=200.0,           DTMIN=1.0E-08,            EMAX=1.0E-05
      NPOINT=201,           SY(9)=22,                 DTMAX=.03
      QTOT=3.98596E+08,     FPC1=.432375,             FPC2=.23877
      FPC3=.28308,          FPC4=.00645,              FPC5=.039325
      TCS1=863.1161984,     TCS2=856.4841221,         TCS3=838.4591702
      TCS4=721.8764246,     TCS5=722.5928366,         TLP=686.8889
      TCSHC=883.70062324,  TCCHC=801.08287055,        TCFHC=1776.7583707
      WRD1=774.654985,      WRD2=444.49272,           WRD3=589.12924
      WRD4=57.736177,       VOL1=.4486296212,         WRD5=344.985818
      VOL2=.2691777727,     VOL3=.4187209796,         VOL4=.403163568
      VOL5=.980,            TOUT=830.222,             VOLUP=95.09
      PCG=1.03E+05,         YUP=16.0*12.0*2.54/100.0
      G=9.81,               AC1=.1296,                AC2=.07776
      AC3=.12096,           AC4=.02754,               AC5=.00432
      AOL1=.03543,          AOL2=.021258,             AOL3=.033068
      AOL5=1.181E-03
      WL1=737.066278,       AOL4=7.5306E-03
      YC=.9144*4.0,         NLOOP=2.0,                WLN=WL1
      VOLLP=66.09,          TXP11=686.8889,           TXP21=TXP11
      TL1=TXP11,            TL2=TXP21,                WL2=NLOOP*WLN
      TUPO=830.222,         VOLC=2.519691942
      TCF1=1711.0141904,   TCF2=1628.1658722,         TCF3=1397.9035084
      TCC1=789.99552822,   CAREA1=1.45931754E-02,  CAREA2=1.67821517E-02
      FRO=.9094,            TCC2=785.52702418,         TCC3=773.31133087
      PI=ACOS(-1.0),        CSFA=1.88412949E-05
      CGPDR=3.359,           FM=.170870725,          CM=4.798E-02
      DIC=5.08E-03,          DOC=5.842E-03,          DC=5.474222066E-03
      BETA1=8.531E-05,           BETA2=7.169E-04,    BETA3=6.266E-04
      BETA4=1.212E-03,           BETA5=5.352E-04,    BETA6=1.739E-04
      BETAT=3.34991E-03,         AMDA1=.013,         AMDA2=.0314
      AMDA3=.135,                AMDA4=.345,         AMDA5=1.37
      AMDA6=3.75,                DOPC=-.005,         SODDC=-.0882
      AXEC=-.0684,               REC=-.378,          TI=477.4444
      TIR=860.0,               PCG=1.03E+05
      TROD=5.000,               DLTROC=10.0,           SROC=3.0+TROD
```

```
PL=.9144,              RDEXCD=2.6839411896366
XNASS1=30.0,           XNASS2=18.0,            XNASS3=28.0
XNASS4=9.0,            XNASS5=1.0
XNPPA1=217.0,          XNPPA2=XNPPA1,          XNPPA3=XNPPA1
PC=1.835318428E-02,    XNPPA4=61.0,            XNPPA5=1.0
DHC=4.106381678E-03
CN1=1.0,               CN2=1.0,                CN3=1.0
CN4=1.0,               CN5=1.0,                CN6=1.0
FVF1=.395,             FVF2=.237,              FVF3=.368
ENAV11=16.09,          ENAV12=1.73,            ENAV13=4.28
ENVPP1=13.88,          ENAVX1=14.16,           ENAVV1=1.47
ENAV21=ENAV11*2.0,     ENAV22=ENAV12*2.0,      ENAV23=ENAV13*2.0
ENVPP2=ENVPP1*2.0,     ENAVX2=ENAVX1*2.0,      ENAVV2=ENAVV1*2.0
ENAVLP=66.09,          ENAVUP=95.09,           TNAMAS=2.603670823E+05
ENAHV1=2.32,           ENAHV2=ENAHV1*2.0,      UPRAD=2.4913

FWL11=0.0,             FWL12=0.00,             FWL13=0.0
FWL21=0.0,             FWL22=0.00,             FWL23=0.0
F121=1.1538538689592, F122=3.5067024987150,  F123=1.9966364878736
F121=1.154320245412, F122=3.5061196915866,   F123=1.9974432344055
F124=207.69525748858,F125=5.6344305986404
F124=207.97925418712,F125=5.6367832417284
F124=207.97925418712,F125=5.8253618530609
DH=3.36953E-02,          P=.105857,         WPD1I=737.066278
PAREA=.2855659656,       TXP1I=830.2222
WXP1=2.633,              ENXT1=1540.0
TXS11=783.0,              TXS1I=639.6667,     D=1.96E-02
FNTXS1=2.0,              DTTXS1=5.0,        STXS1=10.0
WSD1I=732.8656434,        SAREA=.2517810563
TXW11=743.00326844,       TFP1=1035.0,        TRP1=1495.0
TFS12=692.0,              TRS12=1152.0
WXS1=1.02,               RF=1.0771167599E-04
CPXW1=4.605E+02,         WXW1=2.822
CAXS1=.4646465801,       CAXP1=5.883376E-04
DCT=2.095629858E-02,      DOT=2.223E-02,      DIT=1.96E-02
TL=4.089
ENWSD1=0.0,               DTWSD1= 5.0,        SWSD1=5.0
WPD2I=1474.132574
TXP2I=830.2222
ENXT2=3080.0
TXS21=783.0,             TXS2I=639.6667,      TXP11I=666.8889
WSD2I=1465.7316868
TXW21=743.00326844,       TFP2=1035.0,        TRP2=1495.0
TFS22=692.0,             TRS22=1152.0
CAXS2=.9292931602,       CAXP2=1.1766752E-03
ENWSD2=0.0,              DTWSD2= 5.0,        SWSD2=5.0
R11=.34605,            R12=.19365,             R13=.19365
R21=.6921,             R22=.3873,              R23=.3873
PLL11=44.1,            PLL12=18.75,            PLL13=36.97
PLL21=44.1,            PLL22=18.75,            PLL23=36.97
YL11=-1.6,             YL12=6.8,               YL13=-2.7
YL21=-1.6,             YL22=6.8,               YL23=-2.7
TOP1=830.2222,         WIXP1=.478614466,       WIXP2=WIXP1*2.0
TOP2=830.2222,       DELP11=8.213E+03,       DELP21=8.213E+03
DELP13=1.49973E+05,    DELP23=1.49973E+05,     WL11=WL1
WL12=WL11,             WL13=WL11,              WL21=WL2
WL22=WL21,             WL23=WL21
VOLP1=13.867,          VOLP2=2.0*13.867
TINP11=830.2222,         TINP2I=830.2222
ENP1=0.0,              DLP1=-5.0,               SP1=10.0
ENP2=0.0,              DLP2=-5.0,               SP2=10.0
ENPCG=0.0,             DLPCG=20.0,              SPCG=10.0
ENTUB1=0.0,            ENTUB2=0.0
ENWL1=0.0,             STWL1=0.0
ENWL2=0.0,             STWL2=5.0
AOLXP1=1.435E-04,      YXP1=-6.8,              PAXP1=5.883E-04
```

```
      SCRAM1=1.0,           SCRAM2=1.0,           SCRAM3=1.0
      SCRAM4=1.0,           SCRAM5=1.0,           SCRAM6=1.0
      SCRAM7=1.0,           SCRAM8=1.0
      TDLAY1=.11,           TDLAY2=.175,          TDLAY3=2.1
      TDLAY4=.60,           TDLAY5=2.1,           TDLAY6=.50
      TDLAY7=.50,           TDLAY8=.50
      CNLROD=6.00,          SAFROD=1.88
      ADLXP2=5.744E-04,     YXP2=-6.8,            PAXP2=2.3532E-03
      FENPP=1.0,            PIOP=0.0,             U1=0.0
      U2=0.0,               AA=.010,              W=.05
      ZMAX=.9144,           RHOMAX=8.0,           CONST=.3162
      ZMAX=.9144,           RHOMAX=8.0,           CONST=10.0
      FLUX=1.0
      POUT11=1.4272E+05,    PIN12=1.1769E+06,     POUT12=1.1011E+06
      PIN13=1.0942E+06,     POUT21=POUT11,        PIN22=PIN12
      POUT22=POUT12,        PIN23=PIN13
      PLP=8.68147E+05
      FL11=.0152114170078, FL12=.0341751154091, FL13=.1818751139653
      FL21=.0038028542519б, FL22=.00854377885226, FL23=.04546877849133
      FXP1=263026.28367793, FXP2=70764.297116279
      FXP1=297699.634016493, FXP2=74474.9085041233
      FXP1=281561.182617841, FXP2=70382.5694576646
      FFEN1=.118722036744235, FFEN2=.0296772513867912
      TTR1=5.0, TETR1=10.0
      AEWPS=2.0,      TR1D=686.889,  TR1=686.889
      TR1M=TR1D,       HRAT=153.31,   TRATED=26927.
      ENPPR=1170,     WL11D1=WL11,     WL11R=WL11D1
            WPSM=WL11,  CORE1=0.8388599, CORE2=CORE1
      RHOTP4=857.97504,    RHOTPR=RHOTP4, AETR1=5.0
      ENPP=1088.47,  DEND=1.0,        END=1.0
      ENPFMX=1110,   TRQPMX=37107.591,  TEENPP=10.0
      TWPS=0.5,    TEWPS=10.0,  ATRQP=25.0

      ENPP2=1088.47, AETR2=10.0,     TR2=TR1
      DEND2=1.0,  END2=1.0, TTR2=TTR1
      TRATE2=TRATED*2.0, WL21D2=WL11D1*2.0, AIPP=1180.0
      WL21R=WL11R*2.0, W2SM=WPSM*2.0, AI2P=AIPP*2.0
      AEW2S=1.0,     TEW2S=TEWPS,  TW2S=TWPS
       TRQ2=ATRQP*2.0, TRQ2MX=TRQPMX*2.0, TEEN2P=TEENPP
      TR2D=TR1D,    TR2M=TR2D,  TETR2=10.0
      ENPPMC=81.64
      ENPPMC=816.35
      SWENPP=0.0
END
       REACTOR
TEK,  EN,ENN,ROD
TEK,  TCS1,TCS2,TCS3,TCS4,TCS5
TEK,  TCC1,TCC2,TCC3
TEK,  TCF1,TCF2,TCF3,EN
TEK,  TCSHC,TCCHC,TCFHC
TEK,  TLP,TUPO,PLP,PUP
TEK,  WRD1,WRD2,WRD3,WRD4,WRD5
TEK,  FWRD1,FWRD2,FWRD3,FWRD4,FWRD5,FWRD
        PUMPS
TEK,  ENPP,ENPP2,TRQPP,TRQ2P
TEK,  HOPP,HOPP2,PUMP1,PUMP2
        IHX
TEK,  TXP1,TXP11,TXP2,TXP21
TEK,  TXS12,TXS11,TXS22,TXS21
TEK,  WIXP1,WIXP2,WRD
        PIPING
TEK,  WL11,WL12,WL13
TEK,  WL21,WL22,WL23
TEK,  PIN11,POUT11,PIN12,POUT12,PIN13,POUT13
TEK,  PIN21,POUT21,PIN22,POUT22,PIN23,POUT23
      FLUX CONTROLERS
```

```
TEK, ERR,PIOP,ZROD,FLUX
TEK, U1,U2,ROAUTO,WD
       REACTOR
LIST, EN,ENN,ROD
LIST, TCS1,TCS2,TCS3,TCS4,TCS5
LIST, TCC1,TCC2,TCC3
LIST, TCF1,TCF2,TCF3
LIST, TCSHC,TCCHC,TCFHC
LIST, TLP,TUPO,PLP,PUP
LIST, WRD1,WRD2,WRD3,WRD4,WRD5
LIST, FWRD1,FWRD2,FWRD3,FWRD4,FWRD5,FWRD
       PUMPS
LIST, ENPP,ENPP2,TRQPP,TRQ2P
LIST, HOPP,HOPP2,PUMP1,PUMP2
       IHX
LIST. TXP1,TXP11,TXP2,TXP21
LIST, TXS1I,TXS11,TXS2I,TXS21
LIST, WIXP1,WIXP2,WRD
       PIPING
LIST, WL11,WL12,WL13
LIST, WL21,WL22,WL23
LIST, PIN11,POUT11,PIN12,POUT12,PIN13,POUT13
LIST, PIN21,POUT21,PIN22,POUT22,PIN23,POUT23
     FLUX CONTROLERS
LIST, ERR,PIOP,ZROD,FLUX
LIST, U1,U2,ROAUTO,WD
END
```

REFERENCES

Additon, S. L., et al., "Simulation of Overall FFTF Plant Performance," HEDL-TC-556, April 1976.

Boadu, H. O., "Simulation of Sodium Pumps for Nuclear Power Plants," M.S. Thesis, University of Arizona for the U.S. Nuclear Regulatory Commission, NUREG/CR-2188, August 1981.*

Goldsmith, Waterman, Hirschhorn, *Handbook of Thermalphysical Properties of Solid Materials*, The Macmillan Co., Vol. 2, New York, 1961.

Kuo, Benjamin C., *Automatic Control Systems*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1975.

Project Management Corporation, *Clinch River Breeder Reactor Project, Preliminary Safety Analysis Report*, 1975.

Schade, A. R., Hanford Engineering Development Laboratory, Richland, Washington, private communication, 1980.

Shinaishin, M. A., "Dynamic Simulation of a Sodium-Cooled Fast Reactor Power Plant," Ph.D. Dissertation, University of Arizona; NUREG-0110 (1976).*

Westinghouse Hanford Company, *Fast Flux Test Facility, Final Safety Analysis Report*, 1975.

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Using the lumped parameter methodology, a computer model simulating the primary heat transport system (PHTS) of the Fast Flux Test Facility (FFTF) is developed. The three primary loops are simulated by two loops; a single and a double loop. The conservation of mass, energy and momentum are the physical foundations of the model FATFAD (FAst Flux Test FAcility Dynamics).

To test FATFAD, three transients are initiated, (1) a ten cent step input of reactivity, (2) a ten cent step reactivity input plus a 50 °K rise in the secondary sodium temperature entering the IHX, and (3) a 25% reduction in Loop One's primary pump speed. The results show that FATFAD inexpensively and accurately simulates the PHTS of the FFTF.

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