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DYNAMIC SIMULATION OF A SODIUM-COOLED
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by

Mervat Abdel Monem Shinaishin

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF NUCLEAR ENGINEERING

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

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GRADUATE COLLEGE

I hereby recommend that this dissertation prepared under my
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ABSTRACT

Simulation of the dynamic behavior of the Clinch River Breeder Reactor Plant (CRBRP) is the subject of this dissertation. The range of transients under consideration extends from a moderate transient, of the type referred to as Anticipated Transient Without Scram (ATWS), to a transient initiated by an unexpected accident followed by reactor scram. The moderate range of transients can be simulated by a digital simulator referred to as the CRBRP ATWS simulator. Two versions of this simulator were prepared; in one, the plant controllers were not included, whereas, in the other, the controllers were incorporated. In addition to the usual assumption of lumped parameters, uniform heat transfer and point kinetics (prompt jump) have been the main approximations in this and other simulators (see below). Two different transport-delay models have also been installed in all simulators. The simulators were constructed using the DARE-P System, developed by the Electrical Engineering Department at The University of Arizona.

A simulator referred to as the CRBRP-DCHT simulator was constructed for studying transients due to unexpected accidents followed by reactor scram. In this simulator emphasis was placed on simulating the auxiliary heat removal system, in order to determine its capability to remove the after-shut down fission and decay heat. Also, in this DCHT simulator, a detailed model of the temperature distribution in the

reactor outlet plenum replaced the total mixing model used in the ATWS simulator. In this model, it is assumed that the reactor outlet plenum is occupied by three sodium regions at most. In the lower region, total mixing is postulated, and the length of this region is a direct function of the kinetic energy of the sodium entering this plenum. The middle region is a stratification region which is composed of sodium strata of progressively higher temperatures from its lower to its upper boundary. The upper region is a total mixing region which contains sodium at a higher temperature than that in the boundary layer beneath it.

A two-loop simulator was also constructed. This simulator has the capability of simulating transients following accidents which have different effects on the different heat transport loops in the plant (e.g., pipe leak, pump failure, etc.). However, it was not possible to test this simulator due to the local memory restrictions.

In the initial phase of this work, a steam generator simulator was constructed. In that simulator, approximate linear thermodynamic equations were used. However, when it became possible to use two-dimensional tables on the DARE system, a second version of this simulator was prepared; in this version the linear thermodynamic equations were replaced by standard data tables. A comparison of simulator transients from these two versions was conducted. Except for the subcooled water-related variables, the results from both versions are close. This gave an indication that the single slope approximate linear thermodynamic equations used in obtaining the subcooled water properties were not

adequate. The second version of this simulator was also used in comparing similar transients using different integration rules.

The transients studied using the two versions of the ATWS simulator include step and ramp reactivity perturbations, and an electrical load perturbation in the controlled plant. An uncontrolled control rod withdrawal followed by reactor scram was studied using the DCHT simulator, although the duration of this transient was restricted to 20 sec. because of computer limitations. The results agree very well with the expected physical behavior of the plant.

CHAPTER 1

INTRODUCTION

The objective of this work is the modeling of THE CLINCH RIVER BREEDER REACTOR PLANT (CRBRP) [1,2], and the simulation of its dynamics with emphasis on both model simplicity and simulator accuracy.

The CRBRP is a three loop heat transport system with the reactor vessel (RV), the turbogenerator, and the feedwater (FW) system common to all loops. Each loop has one intermediate heat exchanger (IHX), and one recirculation type steam generator (SG). The steam generator is composed of one superheater (SH), two evaporators (EVAP), and one steam drum (SD). In addition, each loop has one variable speed primary pump located on the primary hot leg, one variable speed intermediate pump on the intermediate cold leg, and one fixed speed recirculation pump on the downcomer from the steam drum. See Figure 1-1.1 which is a schematic diagram of these system components.

The requirement for simple representation of a complex system necessitates the reduction to a minimum (one per component) of the number of regions (and thus equations) representing each of the system components. However, it is natural to expect that this will not adequately represent the physical system. As a compromise between simplicity and accuracy, the reactor is represented by three axial regions: the inlet plenum, the core, and the outlet plenum. The core

CRBRP	CLINCH RIVER BREEDER-REACTOR PLANT
RV	REACTOR VESSEL
PP	PRIMARY PUMP
IHX	INTERMEDIATE HEAT EXCHANGER
SH	SUPERHEATER
EVAP	EVAPORATOR
IP	INTERMEDIATE PUMP
SD	STEAM DRUM
RCP	RECIRCULATION PUMP
FW	FEEDWATER
FWFCV	FEEDWATER FLOW CONTROL VALVE
T	TURBINE
G	GENERATOR
C	CONDENSER
TCV	TURBINE CONTROL VALVE
VDMP	DUMP VALVE
DS	DESUPERHEATER

Figure 1-1.1. Schematic Diagram of the CRBRP

is represented by an average channel in which the fuel in the middle is surrounded by the sodium coolant. The IHX is represented by one axial and two radial regions, primary and intermediate sodium, with no tube wall in between, since the wall mass heat capacity (MC_p) is considered small (see Section 2-5). However, in the SH the tube wall is relatively thick (due to the large pressure differential on the wall sides) and is taken into account in the SH representation; i.e., the SH is represented by three radial regions: intermediate sodium (on the shell side, i.e., outside the tube), tube wall, and superheated steam (inside the tube); and one axial region. In the EVAP where both one phase (subcooled water), and two phase mixture (steam/water) exist inside its tubes, and where the difference in the heat transfer properties between the one and the two phase fluids is large, it seemed necessary to represent the EVAP by at least two axial regions; however in the radial direction, the EVAP, as the SH, is represented by three radial regions. The SD is also represented by two vertical regions; in the lower region there is subcooled water, whereas the upper region contains saturated steam only (the boundary layer between the two regions is not included in the simulation). A schematic diagram of this system representation is shown in Figure 1-1.1.

In developing the model just described, the starting point was a 500 MW LMFBR model developed by the Argonne National Laboratory (ANL) [3], in which two axial regions in all components were used in the simulation. The system equations of the ANL model were implemented on the DARE P system, which is a digital simulation system developed at

The University of Arizona [4]. However, it was not possible to get any results from the EVAP section of the simulator even during the steady state. The equations of this EVAP section were then modified, and it was possible to simulate the steady state. However, another problem appeared during the transient. This is believed to be inherent in most system components in which change of phase takes place, and which becomes particularly severe when the boundary between the one phase and the two phase regions is allowed to be movable. In mathematical terms this contributes to the "stiffness" of the overall system nonlinear differential equations (i.e., to a wider spread in the spectrum of the system's time dependent eigenvalues). This problem became clear after a number of integration methods (e.g., the explicit fourth order Runge Kutta, variable step; the pseudo-implicit exponential rule (Pope's), variable step; the implicit fifth order Gear stiff method, variable step, etc.) failed to converge when applied to the EVAP.

Following this stage it became obvious that the degree of the system stiffness necessitates the use of other implicit integration methods (or modified versions of the ones mentioned above) more suitable for highly stiff systems. However, in any implicit integration method the Jacobian matrix calculation requires $n + 1$ evaluations of the derivative vector and a matrix inversion at many, if not all, time steps. In view of this, and realizing that it is an ultimate goal to construct a total plant simulator (i.e., one which include all plant components), it was decided to modify the ANL model to that described above and shown in Figure 1-1.1.

In the heat transfer model utilized by the ANL, the outlet temperature T_o of each region is obtained from:

$$T_o = 2 \bar{T} - T_I \quad (1-1.1)$$

where $\bar{T}$ is the average temperature in that region, obtainable from its energy balance equation, and T_I is the inlet temperature of the region. However, using these approximations in the one axial region components (e.g., IHX or SH), an increase in the inlet temperature of the component will result in an initial decrease in the outlet temperature of that component (this problem does not appear when all components are divided into two axial regions, which is the case in the ANL model, even though it remains a problem when considering each region separately). In a first attempt to overcome this problem, the average and outlet temperatures of each region were obtained from:

$$\bar{T} = \frac{T_I + T_o}{2} \quad (1-1.2)$$

and

$$\frac{dT_o}{dt} = 2 \frac{d\bar{T}}{dt} - \frac{dT_I}{dt} \quad (1-1.3)$$

and $\frac{d\bar{T}}{dt}$ is still obtained from the energy balance equation of that region, whereas $\frac{dT_I}{dt}$ for the one region components is obtained from:

$$\frac{dT_I}{dt} \approx \frac{T_{I-1} - T_I}{\tau_I} \quad (1-1.4)$$

where T_{I-1} is the outlet temperature of the preceding component in the loop (preceding in the sense of the flow direction in the loop including both components), and τ_I is the transport delay in the pipe lines between the two components, i.e.,

$$\tau_I(t) = \frac{\text{the mass of the fluid in these pipe lines at time } t}{\text{the mass flow rate in them at time } t} \quad (1-1.5)$$

Equation (1-1.4) is obtained by expanding $T_I(t + \tau_I(t))$ in Taylor's series, in the following equation:

$$T_I(t + \tau_I(t)) = T_{I-1}(t) \quad (1-1.6)$$

and neglecting higher than first order perturbations. Equation (1-1.3) can thus be rewritten as:

$$\frac{dT_o}{dt} = 2 \frac{d\bar{T}}{dt} - \frac{T_{I-1} - T_I}{\tau_I} \quad (1-1.7)$$

In this equation an increase in the inlet temperature of the component results in a continuous increase in the outlet temperature. However, it was quickly realized that updating T_o from Eq. (1-1.7) will result in a change in T_o due to a change in T_{I-1} even if T_I has not been changed yet, i.e., the system will behave in an anticipative manner which is not physically acceptable. This led to the search for another solution to the problem, which was done in the following way:

$$\bar{T} \approx \frac{T_I + T_o}{2} \quad (1-1.2)$$

thus

$$T_o - \bar{T} \approx \bar{T} - T_I \approx \frac{T_o - T_I}{2} \quad (1-1.8)$$

then let Q be the total heat transferred (not including the heat transported) to the region under consideration. This leads to

$$\frac{d\bar{T}}{dt} \approx \left(\frac{1}{MC_p}\right)[Q - W C_p (T_o - T_I)] \approx \left(\frac{1}{(M/2)C_p}\right)[Q/2 - W C_p (\bar{T} - T_I)] \quad (1-1.9)$$

Then by looking upon $\bar{T}$ as an outlet temperature of the region half closer to its inlet, and assuming a uniform heat transfer, we can deduce the following:

$$\frac{dT_o}{dt} = \left(\frac{1}{(M/2)C_p}\right)[Q/2 - W C_p (T_o - \bar{T})] \quad (1-1.10)$$

Comparing equations (1-1.9) and (1-1.10) we conclude that:

$$\frac{dT_o}{dt} \approx \frac{d\bar{T}}{dt}$$

On the other hand the inlet temperature $T_I(t)$ to any component in a closed loop of the system can be obtained from either of the following two delay models¹:

1. A Pure Transport Delay Model (FDELAY). In this model

$$T_I(t) = T_{I-1}(0) \quad t \leq \tau_I(0)$$

1. These delay models were developed by the author and implemented by G. Sowers and D. Clarke, graduate students at The University of Arizona.

and

$$T_I(t) = T_I^*(t) \quad t \geq \tau_I(0)$$

where

$$T_I^*(t_{\text{VALID}}(t,k)) = T_{I-1}(t_1(k)) \quad t \geq t_1(k), 1 \leq k \leq 100$$

$$t_{\text{VALID}}(t,k) = t_1(k) + \tau_I(t_1) \quad t \geq t_1(k), 1 \leq k \leq 100$$

in which, $t_1(k)$ is the first time at which the k^{th} entry is created in the one dimensional FDELAY array. In this array the independent variable is t and the dependent variable is $T_I(t)$. Linear interpolation is utilized in obtaining $T_I(t)$ when t falls between two entries of the t_{VALID} in the time column. It should be noted that $t_1(1) = 0$.

In the model listings this is implemented by equations of the form

$$T_I(t) = \text{FDELAY}(T_{I-1}, \tau_I(t), J, T_{I-1}(0))$$

Here T_I and T_{I-1} are as described above; J is an index that takes a value ranging between one and the maximum allowable in the DARE system (20 at the time of this writing), and must be different for different delayed variables.

This model is suitable for a relatively constant non-decreasing $\tau_I(t)$; the following model was developed for handling situations where $\tau_I(t)$ may either increase or decrease rather rapidly.

2. A Mixing Plus Transport Delay Model (PDELAY). In the simulator listings this model is implemented via the following equation

$$T_I(t) = \text{PDELAY}(T_{I-1}(t), \tau_I(t), J, T_{I-1}(o))$$

Two cases occur depending on whether $\tau_I(t)$ is increasing, constant, or decreasing:

2a. $\tau_I(t)$ Increasing or Constant: In this case

$$T_I(t) = T_{I-1}(o) \quad t \leq t_o$$

and

$$T_I(t) = T_I^*(t) \quad t > t_o$$

where

$$T_I^*(t_{\text{VALID}}(t,k)) = T_{I-1}(t_1(k)) \quad t \geq t_1(k), 1 \leq k \leq 100$$

$$t_{\text{VALID}}(t,k) = t_1(k) + \tau_I(t_1) \quad t = t_1(k), 1 \leq k \leq 100$$

and

$$t_{\text{VALID}}(t,k) = t + [t_{\text{VALID}}(t-\Delta t, k) - t] [\tau_I(t) / \tau_I(t-\Delta t)]$$

$$t > t_1(k), 1 \leq k \leq 100$$

where t_o is the time at which t equals $t_{\text{VALID}}(t,1)$. Other variables are as defined above. It should be noted that

$$t_o = \tau_I(o) \text{ if } \tau_I(t) \text{ is constant}$$

whereas

$$t_o > \tau_I(o) \text{ if } \tau_I(t) \text{ is increasing}$$

2b. $\tau_I(t)$ Decreasing. In this case a mixing model is superimposed on the transport delay just described, and $T_I(t)$ is obtained from

$$T_I(t) = T_{I-1}(o) \quad t \leq t_o$$

and

$$T_I(t) = [T_{I-1}(t) \Delta t + T_I(t - \Delta t) \tau_I(t)] / [\Delta t + \tau_I(t)] \quad t > t_o$$

where t_o is as in case (2a) above. However, it should be noted that in this case

$$t_o < \tau_I(o)$$

and that the second equation is a discretized form of

$$\frac{dT_I(t)}{dt} = [T_{I-1}(t) - T_I(t)] / \tau_I(t)$$

in which $\frac{dT_I(t)}{dt}$ was replaced by $[T_I(t) - T_I(t - \Delta t)] / \Delta t$.

In summary:

1. The inlet temperature to any component I in the closed system is obtained from:

$$T_I(t) = \text{FDELAY}(T_{I-1}(t), \tau_I(t), J, T_{I-1}(o)) \quad (1-1.11a)$$

or

$$T_I(t) = \text{PDELAY}(T_{I-1}(t), \tau_I(t), J, T_{I-1}(o)) \quad (1-1.11b)$$

2. The average temperature $\bar{T}$ in the region is obtained from:

$$\bar{T} = \frac{T_i + T_o}{2} \quad (1-1.2)$$

where T_i and T_o are the inlet and outlet temperatures of the region respectively.

3. The outlet temperature T_o of a region is obtainable from:

$$\frac{dT_o}{dt} = \frac{d\bar{T}}{dt} \quad (1-1.12a)$$

i.e.,

$$\frac{dT_o}{dt} = \frac{1}{MC_p} [\text{heat input to the region-heat removal}] \quad (1-1.12b)$$

This is how the sodium and the superheated steam temperatures are obtained. However, as is to be expected in the case of subcooled or saturated water or saturated steam, the region pressure (via the enthalpy and density) is the variable obtainable from the energy, mass and momentum equations, whereas the temperatures and enthalpies are obtained from steam tables or linearized thermodynamic equations.

The neutron kinetics model utilized in the simulator is based on the point kinetic, prompt jump approximation, with six delayed neutron groups.

In order to be able to investigate transients ranging from normal to those following an accident, without greatly complicating the simulator structure, it was preferred to construct more than one simulator: the first for the anticipated transients without reactor scram (ATWS), and the second for the transients following scram initiating accidents. In the first, which will be referred to as the "CRBRP-ATWS SIMULATOR," an advantage is made of the limited range of the transient to be studied by that simulator, which permits smaller data tables, fewer plant controllers, a simple mixing model in the reactor outlet plenum, and the ability to omit relief valves, isolation valves, and the auxiliary heat removal system. However, these simplifications are slightly offset by incorporating the options of isolating any of the main system components or subsystems, as well as any of the controllers already in the simulator, via the use of what will be referred to as the "SWITCH PARAMETERS" (S.P.'s), (see the user manual in Appendix E).

The second simulator which will be referred to as the "CRBRP-DCHT SIMULATOR" where DCHT is an abbreviation for decay heat, is most suitable for the study of transients following scram initiating accidents. The reason for referring to this simulator by decay heat stems from the fact that it is our main interest to investigate the capability of the heat removal system to dissipate the decay heat following reactor scram in the event of such an accident. This simulator is simplified relative to the first by eliminating the option of removing any of the main system components, except the

turbogenerator which is permanently isolated from the rest of the plant (and thus drastically reducing the number of the S.P.'s), and by reducing the number of the electronic controllers (see Chapters 4 and 5). However, it is more complicated because of the need to extend the dimensions of some of the tables, and to add others (e.g., the coast down pressure heads and the decay heat tables), as well as the need for a more detailed model of the outlet plenum of the reactor, and the need to include the isolation and relief valves, and the auxiliary heat removal system (including both short and long term heat removal subsystems).

In the next chapter the dynamic equations of the main system components are presented, followed by a chapter on the additional features exclusive to the DCHT simulator. The system controllers for the operating power level are discussed in Chapter 4, whereas those for the after scram transients are discussed in Chapter 5. In Chapter 6, discussion of results and recommendations for future work are followed by presentation of the results. The dissertation also includes eleven appendices, the first of which, Appendix A, concentrates on deducing the criteria used in Chapter 2, in addition to proving or deducing some of the final forms of the main system equations, and presenting the data available or assumed for the constants and the parameters appearing in the equations. Appendix B is similar to Appendix A but relates to the contents of Chapter 3. Appendices C and D are concerned with plant controllers. Appendices E and F are the user manuals for the ATWS and the DCHT simulators,

whereas Appendices G and H are listings of these simulators, respectively. Appendix I is a listing of the steam generator simulator utilizing linear thermodynamic equations. Appendix J is a listing of the ATWS simulator without plant controllers which is more suitable, on a cost basis, than the ATWS simulator with plant controllers, mentioned above, for studying transients of the uncontrolled plant, as well as transients of an isolated subsystem or component of the plant. Appendix K is a listing of a TWO-LOOP simulator which has been prepared for investigating the system behavior following perturbations initiated in one of the three heat transport loops (e.g., a pipe leak in one of the primary cold legs, a pump failure, etc.). The number of differential equations in the TWO-LOOP simulator is larger than the maximum of 70 allowable when the Episode integration rule is utilized; therefore it has not been possible to test this simulator at the present time. (Episode is the only integration rule presently available on the DARE-System that can be utilized without divergence in studying the transients of the total plant.)

CHAPTER 2

DYNAMICS OF THE PLANT MAIN UNITS

In this chapter the differential equations describing each component of the main system (see Figure 1-1.1) are presented along with the assumptions made. The numerical values of the system constants and the initial values of the variables are all given in Appendix A.

2-1 Turbogenerator

The CRBRP turbogenerator unit is quite complicated as could be seen from Figure 2-1.1a; however, in the simulation, this unit is simplified to the one shown in Figure 2-1.1b. The equivalence between these two representations is assisted by:

1. Neglecting the effect of the fluctuations in the pressure and the flow rates at the different steambleeding points on the turbo-dynamics.
2. Assuming an overall turbine efficiency such that, for the same inlet flow and inlet and exhaust steam conditions, the two subsystems produce the same mechanical and consequently electrical powers.

Applying Newton's second law of mechanics to the turbogenerator rotary system, the following power balance equation (which is known as "The Swing Equation," by power system engineers), is obtainable [3,5]:

Figure 2-1.1. Power Cycle Schematic for the Clinch River Breeder Reactor Project.

(b)

Figure 2-1.1. Continued.

$$\frac{d\omega_G}{dt} = \left(\frac{\alpha}{I_{TG} \omega_G} \right) (P_T - P_\omega - P_{GE} - P_{G\theta}) \quad (2-1.1)$$

where

ω_G = turbogenerator shaft speed (rad/sec).

I_{TG} = inertia of the turbogenerator (lb_f-ft-sec²/rad²)

$\alpha = 7.376 \times 10^5$ a conversion factor (lb_f-ft/sec/MW)

P_T = the turbine power actuating the shaft (MW)

P_ω = frictional power losses (MW)

P_{GE} = electrical power losses in the generator damper
windings (MW)

$P_{G\theta}$ = the electrical (real) power generated (MW)

The powers on the R.H.S. of Eq. (2-1.1) are obtainable from the following differential and algebraic equations:

$$\frac{dP_T}{dt} = \frac{STWMW - P_T}{\tau_T} \quad (2-1.2)$$

where

STWMW = steam work rate in MW

$$= 2.931 \times 10^{-7} \text{ STWBTU} \quad (2-1.3a)$$

STWBTU = steam work rate in BTU/hr

$$= \eta_T (h_{S9} - h_{EXH}) W_{S9} \quad (\text{see Figure 1-1.1}) \quad (2-1.3b)$$

η_T = turbine effective efficiency

τ_T = turbine time constant (a typical [5] value for a non-reheat turbine is ~0.5 sec).

$$h_{S9} = \text{HSH}(P_{S9}, T_{S9})$$

where HSH is a (two-dimensional) superheated steam enthalpy table incorporated in the simulators.

$$T_{S9}(t) = C_{TS9} \text{FDELAY}(T_{SC}(t), \tau_{TS9}(t), J, T_{SC}(o)) \quad (2-1.4a)$$

or

$$T_{S9}(t) = C_{TS9} \text{PDELAY}(T_{SC}(t), \tau_{TS9}(t), J, T_{SC}(o)) \quad (2-1.4b)$$

(See Chapter 1 for the meanings of the FDELAY and PDELAY operators.)

where

$$C_{TS9} = \text{constant}$$

and

$$\tau_{TS9}(t) = \sum_i \frac{M_{SCi}}{W_{SCS}(t)} \quad (2-1.5)$$

where

M_{SCi} = mass of superheated steam in the i^{th} section of the pipe lines extending from the exit of the superheater to the turbine-flow control valves (lb_m /three loops) (see Figure 2-1.2).

W_{SCS} = superheated steam flow rate at the exit of the superheater (lb_m /sec/three loops).

P_{S9} is obtained as follows: Let P_{V9} be the pressure behind the turbine control valve V9 (See Figure 1-1.1), thus:

$$P_{V9} = A_{V9} \left(\frac{W_{S9S}}{N_{S94}} \right) \quad (2-1.6)$$

where

A_{V9} = constant

N_{S94} = the number of the turbine control valves (normally four).

W_{S9S} = turbine flow (lb_m /sec), and is determined from:

$$W_{S9S} = W_{SCS} - W_{DMPS} \quad (\text{see Figure 1-1.1}) \quad (2-1.7)$$

where

Figure 2-1.2. Basic Flow Diagram--Main Steam and Steam Dump System

W_{DMPS} = dump flow (lb_m/sec) and is determined as follows
 (depending on whether this flow is controlled
or is due to accidental opening of one of the
 four parallel valves, see Figure 2-1.2).

1. Accidental opening of one dump valve:

$$W_{DMPS} = C_{DMP} S_{VDMP} P_{S9} \quad (2-1.8a)$$

2. Controlled bypassing of superheated steam to the main
 condenser:

This process is resorted to as a quick means of controlling
 the pressure P_{S9} . In this case W_{DMPS} is obtained from:

$$W_{DMPS} = 4 C_{DMP} S_{VDMP} P_{S9} \quad (2-1.8b)$$

where

$$C_{DMP} = \text{constant}$$

$$S_{VDMP} = \text{the normalized stroke of the dump-flow valve}$$

The next step toward obtaining P_{S9} is to make the definitions:

$$P_{S9C} \triangleq \frac{W_{S9S}/N_{S94}}{C_{S9} S_{V9}} \quad (2-1.9a)$$

and

$$P_{S9SC} \triangleq P_{V9} + \left(\frac{W_{S9S}/N_{S94}}{C_{V9} S_{V9}} \right)^2 \quad (2-1.9b)$$

where

$P_{S9} = P_{S9C}$ if there had been a critical flow through the turbine control valve V9.

$P_{S9} = P_{S9SC}$ if there had been supercritical flow.

C_{S9} and C_{V9} are constants (see Appendix A).

Noting that the initial value of P_{S9} is known and comparing $P_{V9}(t)$ with $P_{S9}(t - \Delta t)$, $P_{S9}(t)$ is obtained from one of the following two expressions:

$$\text{If } P_{V9}(t) \geq 0.55 P_{S9}(t - \Delta t) \quad P_{S9}(t) = P_{S9SC}(t) \quad (2-1.10a)$$

$$\text{If } P_{V9}(t) < 0.55 P_{S9}(t - \Delta t) \quad P_{S9}(t) = P_{S9C}(t) \quad (2-1.10b)$$

In order to minimize the number of numerical tables in the simulator, P_{EXH} is assumed to remain constant at 2 in. Hg. Consequently h_{EXH} will depend on X_{EXH} (the turbine exhaust quality, see Figure 2-1.1b) which in turn depends on S_{S9} , where

$$S_{S9} = S9(P_{S9}, T_{S9})$$

$S9$ is a superheated steam entropy (two-dimensional) table installed in the simulator.

For adiabatic expansion of the steam in the turbine, at 2 in.

Hg, exhaust pressure:

$$S_{EXH} = S_{S9} \quad (2-1.11)$$

$$X_{EXH} = (S_{EXH} - 0.1313)/1.8487 \quad (2-1.12)$$

$$h_{EXH} = 69 + 1036.5 X_{EXH} \quad (2-1.13)$$

Note that in evaluating η_T (see Appendix A), the fact that the expansion process deviates from being adiabatic is taken into account.

Other powers on the R.H.S. of Eq. (2-1.1), are obtainable [3,5] as follows:

$$P_{\omega} = A_{\omega} \omega_G \quad (2-1.15)$$

where A_{ω} is a friction coefficient, assumed to be constant, and

$$P_{GE} = A_{GE} (\omega_G - \omega_{GI}) \quad (2-1.15)$$

where

$$\begin{aligned} \omega_{GI} &= \text{turbogenerator synchronous speed} \\ &= 2\pi \times 60 \text{ (rad/sec)}. \end{aligned}$$

$$A_{GE} = \text{constant}$$

and

$$P_{G\theta} = \frac{VE}{X'} \sin\left(\frac{\pi\theta_G}{180}\right) + \frac{V^2}{2} \left(\frac{1}{X} - \frac{1}{X'}\right) \sin\left(\frac{2\pi\theta_G}{180}\right) \quad (2-1.16)$$

where θ_G , the power angle, is defined as the phase angle in degrees between E and V of the generator. It is also the angular rotor position relative to the network in a synchronized system. The symbols are:

V = stator terminal voltage (KV)

E = the stator e.m.f. (KV)

X = the q axis Blondel reactance [5] of the stator windings (ohm).

X' = the d axis Blondel reactance [5] (ohm).

In order to simplify the equations describing the generator dynamics, the following assumptions were made

1. The quadrature and the direct axes reactances X and X' are initially equal (this is equivalent to assuming that the rotor is nonsalient, i.e., a round rotor).
2. The field current is constant.
3. The rotor speed is relatively constant ($|\text{changes}| \leq 5\%$).

These lead to the following conclusions:

1. Constant E
2. Constant X'

$$3. \quad P_{G\theta} \approx \frac{VE}{X'} \sin\left(\frac{\pi\theta_G}{180}\right) \quad (2-1.17)$$

$$4. \quad V \approx \frac{V_I}{EMW_I} EMW \quad (2-1.18)$$

where

V_I = initial value of V (= 22 KV)

EMW = electric load in MW

The armature current and consequently the generator power factor are obtained as follows (see Figure A-1.1):

1. Slow transients (e.g., slow ramp load changes):

$$I_a = \left\{ \left[\frac{V}{X'} \sin\left(\frac{\pi\theta_G}{180}\right) \right]^2 + \left[\frac{E-V \cos\left(\frac{\pi\theta_G}{180}\right)}{X'} \right]^2 \right\}^{0.5} \quad (2-1.19a)$$

2. Fast transients (stepwise load changes):

$$I_a = \left\{ \left[\frac{V}{X'} \sin\left(\frac{\pi\theta_{GI}}{180}\right) \right]^2 + \left[\frac{E-V \cos\left(\frac{\pi\theta_{GI}}{180}\right)}{X'} \right]^2 \right\}^{0.5} \quad (2-1.19a)$$

where θ_{GI} is the initial value of θ_G .

The power factor PF_G is given by:

$$PF_G = \frac{P_{G\theta}}{I_a V} \quad (2-1.20)$$

and the power angle θ_G is obtained from:

$$\frac{d\theta_G}{dt} = \frac{\omega_G - \omega_{GI}}{(\pi/180)} \quad (2-1.21)$$

2-2 Superheater

The superheater is simulated by one axial and three radial (sodium, wall and superheated steam) regions as shown in Figure 1-1.1. Mass, energy and momentum conservation laws are all applied.

2-2.1 Mass Conservation

$$W_{IC} = W_{IA} \quad (1b_m/\text{hr}/\text{three loops}) \quad (2-2.1)$$

$$W_{SC} = W_{SA} \quad (1b_m/\text{hr}/\text{three loops}) \quad (2-2.2)$$

2-2.2 Energy Conservation

In reference to the approximation presented in Chapter 1 regarding the temperature rate of change, the time rate of change of a region outlet temperature is approximately equal to the time rate of change of the average temperature in that region, i.e.,

$$\frac{dT_o}{dt} = \frac{d\bar{T}}{dt} \quad (\text{see Eq. (1-1.12a)})$$

where

T_o = the fluid temperature at the exit of the region

and

$\bar{T}$ = the average temperature in that region

The following equations represent the energy balance in each of the three radial regions of the superheater:

$$\frac{dT_{SC}}{dt} = \left(\frac{1}{C_{PS} V_{SA} \bar{\rho}_{SA}} \right) [H_{SSA} (T_{WA} - \bar{T}_{SA}) - W_{SA} (h_{SC} - h_{SA})] \quad (2-2.3)$$

$$\frac{d\bar{T}_{WA}}{dt} = \left(\frac{1}{C_{PWA} M_{WA}} \right) [H_{WA} (\bar{T}_{IA} - \bar{T}_{WA}) - H_{SSA} (\bar{T}_{WA} - \bar{T}_{SA})] \quad (2-2.4)$$

$$\frac{dT_{IC}}{dt} = \left(\frac{1}{C_{PIA} V_{IA} \bar{\rho}_{IA}} \right) [C_{PIA} W_{IA} (T_{IA} - T_{IC}) - H_{WA} (\bar{T}_{IA} - \bar{T}_{WA})] \quad (2-2.5)$$

where

$$\bar{T}_{SA} = \frac{T_{SA} + T_{SC}}{2} \quad (2-2.6)$$

and

$$\bar{T}_{IA} = \frac{T_{IA} + T_{IC}}{2} \quad (2-2.7)$$

whereas the inlet temperatures T_{SA} and T_{IA} are obtained from:

$$T_{SA} = T_{sat}(P_{SA}) \quad (2-2.8)$$

where T_{sat} is the saturation temperature of the steam at the pressure P_{SA} , and

$$T_{IA}(t) = \text{FDELAY}(T_{I3}(t), \tau_{TIA}(t), J, T_{I3}(o)) \quad (2-2.9a)$$

or

$$T_{IA}(t) = \text{PDELAY}(T_{I3}(t), \tau_{TIA}(t), J, T_{I3}(o)) \quad (2-2.9b)$$

(See Chapter 1 for the meanings of the FDELAY and PDELAY operators.)

where

T_{I3} = IHX exit temperature,

$$\tau_{TIA}(t) = \sum_i \frac{M_{I3i}}{W_{IS}} \quad \text{lb}_m / (\text{lb}_m / \text{sec}) \quad (2-2.10)$$

and

W_{IS} = sodium flow in the intermediate loop ($\text{lb}_m / \text{sec} / \text{three}$ loops)

M_{I3i} = mass of sodium in the i^{th} section of the pipe lines
extending from the IHX exit to the superheater inlet

The steam inlet and exit enthalpies h_{SA} and h_{SC} respectively are obtained from:

$$h_{SA}(t) = \text{FDELAY}(h_{gS4}(t), \tau_{hSA}(t), J, h_{gS4}(o)) \quad (2-2.11a)$$

or

$$h_{SA}(t) = \text{PDELAY}(h_{gS4}(t), \tau_{hSA}(t), J, h_{gS4}(o)) \quad (2-2.11b)$$

where

$$h_{gs4} = h_g(\bar{P}_{s4}) \quad (2-2.12)$$

$\bar{P}_{s4}$ = average steam pressure in the steam drum

and

$$\tau_{hSA}(t) = \frac{M_{S7}}{W_{SAS}} \text{ sec} \quad (2-2.13)$$

where

M_{S7} = mass of saturated steam in the pipe lines extending
from the drum to the superheater

and

$$W_{SAS} = W_{SA}/3600 \quad \text{lb}_m/\text{sec} \quad (2-2.14)$$

(Notice that S at the end of the flow subscript means that the flow unit is lb_m/sec , while the absence of it means that the flow is in $\text{lb}_m/\text{hr.}$)

The exit enthalpy h_{SC} is obtained from:

$$h_{SC} = h_{SC}(P_{SC}, T_{SC}) \quad (2-2.15)$$

where P_{SC} is the pressure at the exit of the superheater (for the determination of P_{SC} , see the momentum conservation section below).

Approximate linear thermodynamic equations (see Table 2-1.1) as well as standard data tables are used in evaluating the steam and sodium thermodynamic properties, and the open loop steam generator transients in both cases are compared (see Section 6-1.1) for comparison of results). (The ranges of the independent variables in the steam and sodium properties tables are selected to cover the expected range of transient values. These tables are given in the simulator's listing, Appendices G, H.)

Table 2-2.1. Linear Thermodynamic State Equations[†]

Variable	Notation	Linear Approximation
<u>Superheated Steam</u>		
Enthalpy	h_s	$872.5 - 0.05066P + 0.703T$
Density	ρ_s	$3.92 + 0.001625P - 0.0046T$
Entropy	S_s	$1.2696 - 9.6 \times 10^{-5} P + 4.795 \times 10^{-4} T$
<u>Saturated Steam</u>		
Enthalpy	h_g	$1278.7 - 0.072323P$ *
Density	ρ_g	$-2.18 + 0.0037649P$
<u>Saturated Water</u>		
Enthalpy	h_f	$437.35 + 0.11674P$ *
Density	ρ_f	$56.6 - 0.009P$
Temperature	T_{sat}	$488 + 0.07346P$ *
<u>Subcooled-water</u>		
Temperature	T	$68.5 + 0.8788h$
Density	ρ	$74.046 - 0.05T$
<u>Sodium</u>		
Density		$59.533 - 0.008333T$

[†] English units are to be used, and the pressure is in psia.

* These are modified versions of the corresponding equations given in Reference [6].

The superheated steam specific heat C_{PS} is obtained from [3]:

$$C_{PS} = \frac{h_{SC} - h_{SA}}{T_{SC} - T_{SA}} \quad (2-2.16)$$

The heat transfer coefficients are obtained as follows:

$$h_{SSA} = \pi L_S N_S / \left[\frac{\ln(D_{OS}/D_{IS})}{4 k_{WA}} + \frac{1}{D_{IS} h_{FS}} + \frac{1}{D_{IS} h_{SS}} \right] \quad (2-2.17a)$$

where [7],

$$h_{SS} = \frac{k_{SA}}{D_{IS}} \left[0.0214 Re^{0.8} Pr^{1/3} \left(1 + \frac{2.3 D_{IS}}{L_S} \right) \right] \quad (2-2.17b)$$

and

$$h_{WA} = \pi L_S N_S / \left[\frac{\ln(D_{OS}/D_{IS})}{4 k_{WA}} + \frac{1}{D_{OS} h_{NS}} \right] \quad (2-2.18a)$$

where [6],

$$h_{NS} = \frac{k_{IA}}{D_{EIS}} \left\{ 1.3 \left[4 + 0.024 \left(\frac{W_D I_{EIS} C_{PIA}}{k_{IA} N_{SA} D_{IS}} \right)^{0.8} \right] \right\} \quad (2-2.18b)$$

In deriving Eqs. (2-2.17a, 18a), the average wall temperature is assumed to be located at midwall, thus only half the wall thermal resistance is taken into account.

In these equations

L_S = superheater effective tube length

D_{IS} = superheater tube inner diameter

D_{OS} = superheater tube outer diameter

A_{IS} = sodium effective cross sectional area per tube

$$D_{EIS} = \frac{4 A_{IS}}{\pi D_{OS}} = \text{sodium equivalent diameter}$$

N_S = number of tubes in the three superheaters (noting that

W_{SA} is the flow per three loops)

h_{FS} = steam side fouling heat transfer coefficient

(Note that the sodium side fouling resistance is neglected relative to other resistances. See Appendix A for the evaluation of h_{FS} .)

2-2.3 Momentum Conservation

Applying the general form of the momentum Eq. (2-4.17) to the superheater and neglecting the hydrostatic pressure head (less than 1% of $P_{SA} - P_{SC}$), one finds that:

$$\frac{dW_{SAS}}{dt} = \left(\frac{1}{\tau_{WSAC}} \right) [P_{SA} - P_{SC} - f_{SAC} \left(\frac{W_{SAS}}{N_L} \right)^2] \quad (2-2.19)$$

(Clearly τ_{WSAC} does not have time units; actually it has inverse length units, i.e., ft^{-1} or in^{-1} . See Section (A-4.2) for more details.)

Similarly the momentum balance equation of the flow rate in the pipe lines extending from the superheater exit to the turbine flow-control valves is:

$$\frac{dW_{SAS}}{dt} = \left(\frac{1}{\tau_{WSC9}}\right) [P_{SC} - P_{S9} - f_{SC1} \left(\frac{W_{SAS}}{N_L}\right)^2 - f_{SC2} \left(\frac{W_{SAS}}{N_{SC2}}\right)^2] \quad (2-2.20)$$

where f_{SC1} and f_{SC2} are the friction constants in the pipe lines extending from the superheater exit to the header (see Figure 2-1.2), and from the header to the turbine control valves respectively; whereas

N_L = number of the heat transport loops in the plant
(normally three)

and

N_{SC2} = number of the pipe lines extending from the header
to the valves (normally two)

and from the momentum balance of the steam flow in the pipe line connecting the drum to the superheater;

$$\frac{dW_{SAS}}{dt} = \left(\frac{1}{\tau_{WS7A}}\right) [\bar{P}_{S4} - P_{SA} + \frac{Y_{S7A} \rho_{gS4}}{144} - f_{S7A} \left(\frac{W_{SAS}}{N_L}\right)^2] \quad (2-2.21)$$

where $Y_{S7A} \rho_{gS4}$ is the hydrostatic pressure head, and

$$\rho_{gS4} = \frac{1}{V_{gS4}} \quad (2-2.22a)$$

where

$$V_{gS4} = V_g(\bar{P}_{S4}) \quad (2-2.22b)$$

Combining Eqs. (2-2.19, 20, 21), it is found that W_{SAS} can be obtained from:

$$\frac{dW_{SAS}}{dt} = \left(\frac{1}{\tau_{WSA}}\right) [\bar{P}_{S4} - P_{S9} + \frac{Y_{S7A} \rho_{gS4}}{144} - (f_{SAC} + f_{SC1}) \times \left(\frac{W_{SAS}}{N_L}\right)^2 - f_{SC2} \left(\frac{W_{SAS}}{N_{SC2}}\right)^2] \quad (2-2.23)$$

Then knowing $\frac{dW_{SAS}}{dt}$, P_{SC} and P_{SA} are determined from Eqs. (2-2.20, 21) respectively. (Values of f 's, τ 's and Y 's are given in Appendix A.)

2-3 Evaporator

Due to the large difference in magnitudes of the heat transfer coefficients of the one phase water and two phase steam/water mixture, two axial regions are chosen as a compromise between the increase in the number of the differential equations (there is a restrictive limit on this number in all implicit integration rules in which the Jacobian matrix rank is a direct function of the number of differential equations in the simulator) and the adequacy in simulating the evaporator. A moving boundary between these two regions corresponds to saturation conditions. Both the tube wall and the surrounding sodium are also represented by two axial regions of the same boundaries as those on the steam/water side.

2-3.1 Steam/Water Side

2-3.1.1 Mass Conservation.

a. Region AS1:

$$\frac{dL_{S1}}{dt} = \left(\frac{1}{\bar{\rho}_{S1} A_{S1}} \right) (W_{S1} - W_{S2}) \quad (2-3.1)$$

where

$\bar{\rho}_{S1}$ = the saturated water density at $\bar{T}_{S1}$

L_{S1} = the region length

and

$$A_{S1} = \frac{\pi}{4} D_{IE}^2 N_E$$

where

D_{IE} = inner diameter of the EVAP tubes

N_E = number of tubes in the EVAPS per three loops, since

W_{S1} and W_{S2} are the flow rates per three loops

In deriving Eq. (2-3.1) the term $A_{S1} L_{S1} \frac{d\bar{P}_{S1}}{dt}$ is neglected relative to $A_{S1} \bar{\rho}_{S1} \frac{dL_{S1}}{dt}$.

b. Region AS2:

$$A_{S2} \frac{d(L_{S2} \bar{\rho}_{S2})}{dt} = W_{S2} - W_{S3} \quad (2-3.2)$$

In addition:

$$A_{S2} = A_{S1}$$

$$\frac{dL_{S2}}{dt} = - \frac{dL_{S1}}{dt} \quad (2-3.3)$$

$$\bar{\rho}_{S2} = \bar{\alpha}_{S2} \rho_{gS2} + (1 - \bar{\alpha}_{S2}) \rho_{fS2} \quad (2-3.4)$$

where

$\bar{\alpha}_{S2}$ is the average void fraction in the region

Also

$$\frac{d\bar{\rho}_{S2}}{dt} \approx - (\rho_{fS2} - \rho_{gS2}) \frac{d\bar{\alpha}_{S2}}{dt} \quad (2-3.5)$$

In this equation, the terms in $\frac{d\rho_{fS2}}{dt}$ and $\frac{d\rho_{gS2}}{dt}$ have been neglected relative to other derivative terms because

$$\frac{\partial \rho_{fS2}}{\partial P_{S2}} \approx -0.009 \text{ and } \frac{\partial \rho_{gS2}}{\partial \bar{P}_{S2}} \approx 0.0376 \text{ (see Table 2-2.1).}$$

2-3.1.2 Energy Conservation.

a. Region AS1:

$$A_{S1} \bar{\rho}_{S1} \frac{d(L_{S1} \bar{h}_{S1})}{dt} = W_{S1} h_{S1} - W_{S2} h_{S2} + H'_{S1} L_{S1} (\bar{T}_{W1} - \bar{T}_{S1}) \quad (2-3.6)$$

where

$$\bar{T}_{S1} = \frac{T_{S1} + T_{sat}(\bar{P}_{S2})}{2} \quad (2-3.7a)$$

T_{S1} is the subcooled water temperature at the evaporator inlet and is obtained from:

$$T_{S1} = T_{sat}(h_{S1}) \quad (2-3.7b)$$

where $T_{sat}(h_{S1})$ is the saturated water temperature whose enthalpy is h_{S1} . The error in T_{S1} when obtained from Eq. (2-3.7b) without taking into account the corrections corresponding to the degree of subcooling is minor [7] in comparison with the error expected due to other approximations made.

h_{S1} is obtained from:

$$h_{S1}(t) = \text{FDELAY}(h_{S6}(t), \tau_{hS1}(t), J, h_{S6}(o)) \quad (2-3.8a)$$

or

$$h_{S1}(t) = \text{PDELAY}(h_{S6}(t), \tau_{hS1}(t), J, h_{S6}(o)) \quad (2-3.8b)$$

(See Chapter 1 for the meanings of the FDELAY and PDELAY operators.)

where

h_{S6} = the subcooled water enthalpy at the exit of the stream drum. See Section (2-4.2)

$$\tau_{hS1}(t) = \sum_i \frac{M_{S6i}}{W_{S1S}(t)} \quad (2-3.9)$$

where

M_{S6i} = mass of water in the i^{th} section of the pipe lines extending from the drum to the evaporator inlet (i.e., the downcomer, see Figures A-4.2, 3), and

W_{S1S} = the flow rate in (lb_m/sec)/three loops, in these pipe lines

whereas $\bar{h}_{S1}$ is obtained from:

$$\bar{h}_{S1} = \frac{h_{S1} + h_{fS2}}{2} \quad (2-3.10)$$

In addition, the following approximations were made:

$$1. \quad \frac{dh_{S1}}{dt} = \frac{h_{S6} - h_{S1}}{\tau_{hS1}} \quad (2-3.11)$$

which is obtained by making a Taylor expansion of $h_{S1}(t + \tau_{hS1}(t))$ and neglecting higher order terms.

2. Depending on how h_{fS2} is obtained, $\partial h_{fS2} / \partial \bar{P}_{S2}$ is obtained as follows:

2a. h_{fS2} is obtained from steam tables:

$$\frac{\partial h_{fS2}}{\partial \bar{P}_{S2}} \approx \frac{h_{fS2}(\bar{P}_{S2} + 50) - h_{fS2}(\bar{P}_S - 50)}{100} \quad (2-3.12a)$$

in which the pressure step (Δp) is chosen to be 100 psi because the pressure interval in the steam tables used in the simulators is ≥ 100 psi. (See simulator listings, Appendices G and H.) Actually any value of Δp such that $0 < \Delta P < 100$ yields the same accuracy since the interpolation between any two entries in any of the tables used in the simulators is linear.

2b. h_{fS2} is obtained from approximate linear thermodynamic equations: In this case $\partial h_{fS2} / \partial \bar{P}_{S2}$ is approximated by

$$\frac{\partial h_{fS2}}{\partial \bar{P}_{S2}} \approx 0.1167 \quad (2-3.12b)$$

Equations (2-3.11, 2-3.12a, 2-3.12b) are used in substituting for $\frac{dh_{S1}}{dt}$ and $\frac{\partial h_{fS2}}{\partial \bar{P}_{S2}}$ in Eq. (2-3.13) below which is subsequently used to substitute for $\frac{d\bar{h}_{S1}}{dt}$ in Eq. (2-3.6).

$$\frac{d\bar{h}_{S1}}{dt} = \frac{1}{2} \left(\frac{dh_{S1}}{dt} + \frac{\partial h_{fS2}}{\partial \bar{P}_{S2}} \frac{d\bar{P}_{S2}}{dt} \right) \quad (2-3.13)$$

The water film heat transfer coefficient per unit length H'_{S1} is given by:

$$H'_{S1} = \pi N_E / \left[\frac{\ln(D_{OE}/D_{IE})}{4 k_{WE}} + \frac{1}{D_{IE} h_{FE}} + \frac{1}{D_{IE} h_{WE}} \right] \quad (2-3.14)$$

where

N_E = number of tubes in the evaporators (normally 4542).

D_{IE} = inner diameter of the evaporator tubes

D_{OE} = outer diameter of the evaporator tubes

h_{FE} = steam/water side, evaporator fouling heat transfer coefficient

k_{WE} = wall thermal conductivity

h_{WE} = water heat transfer coefficient given by [7]

$$h_{WE} = \frac{k_{S1}}{D_{IE}} (0.023 Re_{S1}^{0.8} Pr_{S1}^{0.4}) \quad (2-3.15)$$

where

k_{S1} = water thermal conductivity

and where Re_{S1} and Pr_{S1} are Reynolds and Prandtl numbers (in region AS1) respectively.

b. Region AS2:

$$A_{S2} \frac{d(L_{S2} \rho h_{S2})}{dt} = w_{S2} h_{S2} - w_{S3} h_{S3} + H'_{S2} L_{S2} (\bar{T}_{W2} - T_{Sat}) \quad (2-3.16)$$

where

$$\rho h_{S2} = \bar{\alpha}_{S2} \rho_{gS2} h_{gS2} + (1 - \bar{\alpha}_{S2}) \rho_{fS2} h_{fS2} \quad (2-3.17)$$

in which,

$\bar{\alpha}_{S2}$ = average void fraction in the region

In addition

$$h_{S3} = x_{S3} h_{gS2} + (1 - x_{S3}) h_{fS2} \quad (2-3.18)$$

where

x_{S3} = evaporator steam exit quality

Also

$$h'_{S2} = \pi N_E / \left[\frac{\ln(D_{OE}/D_{IE})}{4 k_{WE}} + \frac{1}{D_{IE} h_{FE}} \right] \quad (2-3.19)$$

in obtaining this equation only nucleate boiling is assumed to exist, and the film heat transfer resistance is therefore approximately zero [8].

At this point it may be appropriate to mention that even though it is possible to obtain a differential equation in $\bar{\alpha}_{S2}$ that can be used in updating this variable (see Eq. A-3.2), one has to determine x_{S3} once $\bar{\alpha}_{S2}$ is known. Unfortunately even the simplest analytic expression relating x_{S3} to $\bar{\alpha}_{S2}$ is a logarithmic (see Eq. 2-3.22 below) transcendental equation in x_{S3} which makes it especially difficult in the DARE-System where all defined variables (i.e., variables obtainable from algebraic equations) must be expressed explicitly in terms of defined variables that do not depend on them

(constants and state variables are also permissible). Since it is not possible to obtain an explicit analytic expression for x_{S3} , the following approach was taken:

Provided that:

$$1. \quad \left| \frac{dP_{S2}}{dt} \right| \leq 100 \text{ psi/sec} \quad (2-3.20a)$$

$$2. \quad \left| \frac{dL_{S1}}{dt} \right| \leq 20 \text{ ft/sec} \quad (2-3.20b)$$

3. The heat flux is uniform

Less than + 5% max error in x_{S3} will result if x_{S3} is obtained from:

$$x_{S3} = \frac{H'_{S2} L_{S2} (\bar{T}_{W2} - T_{sat})}{w_{S3} (h_{gS2} - h_{fS2})} \quad (2-3.21)$$

(See Section A-3.1, for full details.)

However if the heat flux is uniform $\bar{\alpha}_{S2}$ is related to x_{S3} by the following equation [7]:

$$\bar{\alpha}_{S2} = \left[\frac{1}{x_{S3}^{1-\psi}} \right] [x_{S3}^{1-\psi} + \psi \ln \left(\frac{\psi}{\psi + (1-\psi)x_{S3}} \right)] \quad (2.3.22)$$

where

$$\psi = S \frac{\rho_{gS2}}{\rho_{fS2}} \quad (2-3.23)$$

in which

S = slip ratio (assumed to be one)

Even though Eq. (2-3.22) can be used as it is in obtaining $\bar{\alpha}_{S2}$ once x_{S3} is obtained, the logarithmic term seemed to cause some numerical difficulties due to the appearance of negative argument, even though physically not possible. An alternative approach is to substitute [7]:

$$x_{S3} = \frac{\psi \alpha_{S3}}{\psi \alpha_{S3} + (1 - \alpha_{S3})} \quad (2-3.24)$$

into Eq. (2-3.22). This leads to

$$\bar{\alpha}_{S2} = \left(\frac{1}{1-\psi}\right) \left[1 - \left(1 - \frac{1}{\alpha_{S3}(1-\psi)}\right) \ln [1 - \alpha_{S3}(1-\psi)]\right] \quad (2-3.25)$$

Then by expanding [9] the logarithmic term, the following was obtained (see Section A-3.1 for details).

$$\bar{\alpha}_{S2} \approx \alpha_{S3} \left[\frac{1}{2} + \frac{\alpha_{S3}(1-\psi)}{6} + \frac{[\alpha_{S3}(1-\psi)]^2}{12} \right] \quad (2-3.26)$$

where α_{S3} is the exit void fraction and is obtained from [7]:

$$\alpha_{S3} = \frac{x_{S3}}{\psi + (1-\psi)x_{S3}} \quad (2-3.27)$$

2-3.2 Wall

2-3.2.1 Energy Conservation.

a. Region AW1:

$$\frac{d(\bar{T}_{W1} L_{S1})}{dt} = \left(\frac{1}{A_{WE} \bar{\rho}_{WE} C_{PWE}} \right) [H'_{W1} (\bar{T}_{I8} - \bar{T}_{W1}) - H'_{S1} (\bar{T}_{W1} - \bar{T}_{S1})] + T_{W2} \frac{dL_{S1}}{dt} \quad (2-3.28)$$

The last term in this equation is due to the fact that L_{S1} is a function of time (see Section A-3.2 for the derivation of this equation).

In Eq. (2-3.28)

A_{WE} = an effective wall cross section for the evaporator tubes

$$T_{W2} = \frac{\bar{T}_{W1} L_{S1} + \bar{T}_{W2} L_{S2}}{L_{S1} + L_{S2}} \quad (2-3.29)$$

H'_{W1} = sodium to mid-wall heat transfer coefficient per unit length, obtained from:

$$H'_{W1} = \pi N_E / \left[\frac{\ln(D_{OE}/D_{IE})}{4 k_{WE}} + \frac{1}{D_{OE} h_{NE}} \right] \quad (2-3.30)$$

(Notice that the sodium fouling resistance is neglected relative to the others.)

In Eq. (2-3.30), h_{NE} is obtained from [3]:

$$h_{NE} = \frac{k_{IE}}{D_{EE}} \left\{ 1.3 \left[4 + 0.024 \left(\frac{W_I D_{EE} C_{PIE}}{k_{IE} N_E A_{IE}} \right)^{0.8} \right] \right\} \quad (2-3.31)$$

b. Region AW2:

$$\frac{d(\bar{T}_{W2} L_{S2})}{dt} = \left(\frac{1}{A_{WE} \bar{\rho}_{WE} C_{PWE}} \right) [H'_{WE} (\bar{T}_{I7} - \bar{T}_{W2}) - H'_{S2} (\bar{T}_{W2} - T_{sat})] + T_{W2} \frac{dL_{S2}}{dt} \quad (2-3.32)$$

where

$$H'_{W2} = H'_{W1} \quad (2-3.33)$$

2-3.3 Sodium

2-3.3.1 Mass Conservation.

a. Region AI7:

$$A_{IE} \bar{\rho}_{IE} \frac{dL_{S2}}{dt} = W_{I7} - W_{I8} \quad (2-3.34)$$

where

A_{IE} = an effective sodium cross section

$\bar{\rho}_{IE}$ = an average sodium density in the evaporator

and

$$W_{I7} = W_I \quad (2-3.35)$$

b. Region AI8:

$$A_{IE} \bar{\rho}_{IE} \frac{dL_{S1}}{dt} = W_{I8} - W_{I9} \quad (2-3.36)$$

From Eqs. (2-3.34, 2-3.35, 2-3.36) and Eq. (2-3.3)

$$W_{I9} = W_I \quad (2-3.37)$$

2-3.3.2 Energy Conservation.

a. Region AI7:

$$\begin{aligned} \frac{d(\bar{T}_{I7} L_{S2})}{dt} = & \left(\frac{1}{A_{IE} \bar{O}_{IE} C_{PIE}} \right) [W_I C_{PIE} T_{I7} - W_{I8} C_{PIE} T_{I8} \\ & - H'_{W2} L_{S2} (\bar{T}_{I7} - \bar{T}_{W2})] \end{aligned} \quad (2-3.38)$$

Expanding the L.H.S. of this equation and replacing $\frac{d\bar{T}_{I7}}{dt}$ by

$\frac{dT_{I8}}{dt}$ (see Eq. (1-1.12a)), it is found that:

$$\begin{aligned} \frac{dT_{I8}}{dt} = & \left(\frac{1}{A_{IE} \bar{O}_{IE} L_{S2} C_{PIE}} \right) [W_I C_{PIE} T_{I7} - W_{I8} C_{PIE} T_{I8} \\ & - H'_{W2} L_{S2} (\bar{T}_{I7} - \bar{T}_{W2}) + \frac{\bar{T}_{I7}}{L_{S2}} \frac{dL_{S1}}{dt} \end{aligned} \quad (2-3.39)$$

where

$$T_{I7}(t) = \text{FDELAY}(T_{IC}(t), \tau_{TI7}, J, T_{IC}(o)) \quad (2-3.40a)$$

$$T_{I7}(t) = \text{PDELAY}(T_{IC}(t), \tau_{TI7}(t), J, T_{IC}(o)) \quad (2-3.40b)$$

and

$$\tau_{TI7}(t) = \frac{M_{I7}}{W_{IS}(t)} \quad \text{sec} \quad (2-3.41)$$

where

M_{I7} = mass of sodium in the pipe lines extending from
the superheater to the evaporator

$$W_{IS} = W_I / 3600$$

and $\bar{T}_{I7}$ is obtained from:

$$\bar{T}_{I7} = \frac{T_{I7} + T_{I8}}{2} \quad (2-3.42)$$

b. Region AI8: Similar to T_{I8} (see Eq. (2-3.39)), T_{I9} is
obtained from:

$$\begin{aligned} \frac{dT_{I9}}{dt} = & \left(\frac{1}{A_{IE} \bar{\rho}_{IE} L_{S1} C_{PIE}} \right) [W_{I8} C_{PIE} T_{I8} - W_I C_{PIE} T_{I9} \\ & - H'_{W1} L_{S1} (\bar{T}_{I8} - \bar{T}_{W1})] - \frac{\bar{T}_{I8}}{L_{S1}} \frac{dL_{S1}}{dt} \end{aligned} \quad (2-3.43)$$

where

$$\bar{T}_{I8} = \frac{T_{I8} + T_{I9}}{2} \quad (2-3.44)$$

The momentum balance on the steam/water side of the evaporator will be deferred until the end of the steam drum section, since a closed loop including both the evaporator and the drum is necessary for complete momentum analysis. Also the sodium momentum balance in the evaporator is deferred until the end of the section on the IHX, where by then all components in the intermediate loop will have been presented.

2-4 Steam Drum

Even though the steam drum is regarded as two distinct regions, one containing subcooled water and the other containing saturated steam, the dynamics of the drum as a whole (see the mass and energy balance Eqs. (2-4.2, 2-4.7)) are investigated (otherwise the dynamics of the boundary layer separating the two regions would have to be considered).

In addition to the mass and the energy balance stated below, the water level in the drum must be known explicitly due to its essential role from the safety point of view. A relatively simple formula [3] relating this to the subcooled water mass in the drum is:

$$y_{S5} = \frac{D_{ID}}{2} \left\{ 1 + \sin \left[\frac{\pi}{2} \left(\frac{M_{S5}}{M_{S5I}} - 1 \right) \right] \right\} \quad (2-4.1)$$

where

D_{ID} = inner diameter of the drum

M_{S5} = mass of subcooled water in the drum

$M_{S5I} = M_{S5}(t=0)$

In obtaining Eq. (2-4.1) (see Section A-4.1), it is assumed that the initial water level in the drum is at the central plane and that the deviation of this level from its initial value is relatively small.

2-4.1 Mass Conservation

$$\frac{d(M_{S4} + M_{S5})}{dt} = (W_{S4} + W_{S5} - W_{S7} - W_{S6})/N_L \quad (2-4.2)$$

where

M_{S4} = mass of saturated steam in the drum (lb_m /drum)

W_{S4} = mass flow rate of the steam/water mixture entering
the drums (lb_m /hr/three loops)

W_{S5} = mass flow rate of feedwater (lb_m /hr/three loops)

W_{S7} = mass flow rate of saturated steam out of the
drums (lb_m /hr/three loops)

W_{S6} = subcooled water flow rate out of the drums
(lb_m /hr/three loops)

However [3],

$$\frac{M_{S4}}{\rho_{gS4}} + \frac{M_{S5}}{\rho_{fS4}} = V_D \quad (2-4.3)$$

where

V_D = drum volume

In order to separate M_{S4} from M_{S5} , without involving the pressure $\bar{P}_{S4}$ the following assumption was made

$$\frac{dM_{S4}}{dt} = \frac{M_{S4}(t) - M_{S4}(t-\tau)}{\tau} \quad (2-4.4)$$

where τ is a (suitable) constant time delay.

Equation (2-4.4) is used to substitute for $\frac{dM_{S4}}{dt}$ in Eq. (2-4.2), whereas M_{S4} is obtained from Eq. (2-4.3).

A differential equation for the average pressure $\bar{P}_{S4}$ in the drum is obtained by differentiating Eq. (2-4.3) which leads to:

$$\frac{d\bar{P}_{S4}}{dt} = -\frac{1}{D} \left(V_{gS4} \frac{dM_{S4}}{dt} + V_{fS4} \frac{dM_{S5}}{dt} \right) \quad (2-4.5a)$$

where

$$D = M_{S4} \frac{\partial V_{gS4}}{\partial \bar{P}_{S4}} + M_{S5} \frac{\partial V_{fS4}}{\partial \bar{P}_{S4}} \quad (2-4.5b)$$

2-4.2 Energy Conservation

$$\frac{d(M_{S5}\bar{h}_{S5} + M_{S4}h_{gS4})}{dt} = (W_{S4}h_{S4} + W_{S5}h_{S5} - W_{S7}h_{gS4} - W_{S6}h_{S6})/N_L \quad (2-4.7)$$

where

$$h_{S4}(t) = \text{FDELAY}(h_{S3}(t), \tau_{hS4}(t), J, h_{S3}(o)) \quad (2-4.8a)$$

$$\text{or } h_{S4}(t) = \text{PDELAY}(h_{S3}(t), \tau_{hS4}(t), J, h_{S3}(o)) \quad (2-4.8b)$$

and

$$\tau_{hS4}(t) = \sum_i \frac{M_{S3i}}{W_{S3S}} \text{ sec} \quad (2-4.9)$$

M_{S3i} = mass of the steam/water mixture in the i^{th} section
of the pipe lines extending from the evaporator
exit to the drum inlet

W_{S3S} = steam/water flow rate at the exit of the evaporator
(lb_m/sec/three loops)

also

$$W_{S4} = W_{S3} \quad (2-4.10)$$

$$W_{S7} = W_{SA} \quad (2-4.11)$$

$$W_{S6} = W_{S1} \quad (2-4.12)$$

and

$$h_{S5} = (w_{SC} h_{SC} - \frac{\gamma P_T}{\eta_{PT}}) / W_{S5} \quad (2-4.13)$$

where

$$\gamma = 3.412 \times 10^6 \text{ (BTU/hr)/MW}$$

η_{PT} = plant thermal efficiency (assumed to remain constant)

$$= \frac{\text{turbine net power}}{\text{thermal power generated}}$$

i.e.,

$$\eta_{PT} = \frac{387.6}{975} = 0.3975 \quad (\text{see Section A-1.1})$$

(W_{S5} is given in the next section on the momentum balance.)

Then by assuming complete mixing in the subcooled water region of the drum

$$h_{S6} = \bar{h}_{S5}$$

and Eq. (2-4.7) can be rearranged to the following:

$$\begin{aligned} \frac{dh_{S6}}{dt} = & \left(\frac{1}{N_L M_{S5}} \right) [W_{S4} h_{S4} + W_{S5} h_{S5} - W_{S6} h_{S6} - W_{S7} h_{gS4} \\ & - N_L (h_{gS4} \frac{dM_{S4}}{dt} + h_{S6} \frac{dM_{S5}}{dt} + M_{S4} \frac{\partial h_{gS4}}{\partial \bar{P}_{S4}} \frac{d\bar{P}_{S4}}{dt})] \end{aligned} \quad (2-4.14)$$

where, as in the evaporator, $\frac{\partial h_{gS4}}{\partial \bar{P}_{S4}}$ is approximated by:

$$\frac{\partial h_{gS4}}{\partial \bar{P}_{S4}} = \frac{hg(\bar{P}_{S4} + 50) - hg(\bar{P}_{S4} - 50)}{100} \quad (2-4.15)$$

2-4.3 Momentum Conservation in the Evaporator/Steam Drum Loop

This loop is considered to have the following regions:

1. The subcooled water region in the evaporator (starting at the evaporator inlet, not the beginning of the effective tube length).
2. The steam/water region in the evaporator (ending at the evaporator exit).
3. The riser (pipe lines from the evaporator to the steam drum).
4. The drum.

5. The downcomer (the pipe lines between the drum and the evaporator) including the recirculation pump.

In each region, the hydrostatic, friction and obstruction losses as well as the acceleration pressure heads are included in the momentum equations.

The general form of the momentum equations is:

$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = - \nabla P + \rho \vec{g} - \nabla \tau \quad (2-4.16)$$

which when integrated over the length of a region provided that the region boundaries are fixed (see Section A-4.4 for more details), gives:

$$\frac{L}{A} \frac{d \bar{W}_a}{dt} + \frac{W_{2a}^2}{\rho_2 A_2^2} - \frac{W_{1a}^2}{\rho_1 A_1^2} = P_1 - P_2 + Y_{12} \bar{\rho} g - \text{Losses} \quad (2-4.17)$$

Appearing in this equation is W_a which is the absolute flow (the flow across fixed boundaries), not W , which is the relative flow. (It is important to notice that especially in applying Eq. (2-4.17) in the variable boundary regions of the evaporator.)

2-4.3.1 Evaporator.

a. Frictional Losses [7]:

$$\Delta P_{S PH} = (8 f \frac{L}{D_{IE}} \frac{1}{144 \times 2 g A^2 \bar{\rho}}) \bar{W}_a^2 \quad (2-4.18)$$

where f is determined from [10]:

$$f = 8/Re \quad 10^3 \leq Re \quad (2-4.19a)$$

$$f = 0.05256/Re^{0.243} \quad 10^3 < Re \leq 10^5 \quad (2-4.19b)$$

$$f = 0.02117/Re^{0.164} \quad Re > 10^5 \quad (2-4.19c)$$

In the two phase regions a friction multiplier $R(\bar{P}, x_{EX})$ which is a function of both the average pressure in the region and the exit quality is obtained from a table (\$T9; RD, 3, 5, see Appendix G) whose entries are taken from Figure (12-13) of Reference [7].

b. Entrance, Exit, Bends and Obstruction Losses: All these losses are assumed to have the form:

$$\Delta P = \text{Constant } \bar{W}_a^2 \quad (2-4.20)$$

where the constant is determined from the momentum balance in the region at the initial steady state (see Section A-4.5).

2-4.3.2 Riser and Downcomer. Frictional and other losses are lumped into one term for each region. This has the form of Eq. (2-4.20).

Applying the momentum Eq. (2-4.17) to all regions in the loop (see Section A-4.6 for details), the flow rates at the inlet and exit of the evaporator are found to satisfy the following equations:

$$\frac{dW_{S1S}}{dt} = \frac{A_{22}(t) B_1(t) - A_{12}(t) B_2(t)}{\Delta} \quad (2-4.21)$$

and

$$\frac{dW_{S3S}}{dt} = \frac{A_{11}(t) B_2(t) - A_{21}(t) B_1(t)}{\Delta} \quad (2-4.22)$$

where

$$\Delta = A_{11}(t) A_{22}(t) - A_{12}(t) A_{21}(t) \quad (2-4.23)$$

and

$$A_{11}(t) = \frac{L_{S1}}{gA_{S1}} + \frac{L_{S2}}{2gA_{S1}} + \sum_{i=1}^4 \frac{L_{S6i}}{g N_{S6i} A_{S6i}} \quad (2-4.24)$$

where i refers to the i^{th} section of the pipe lines in the downcomer region, and

N_{S6i} = number of the pipe lines in the i^{th} section

whereas

$$A_{12}(t) = \frac{L_{S2T}}{2 gA_{S1}} + \sum_{i=1}^2 \frac{L_{S3i}}{g N_{S3i} A_{S3i}} \quad (2-4.25)$$

L_{S2T} = total length of the evaporator tube section
containing the two phase steam/water mixture

L_{S3i} and A_{S3i} are the pipe length and cross-section of
the i^{th} section in the Riser region

$$A_{21}(t) = \frac{L_{S2}}{4gA_{S1}} \quad (2-4.26)$$

$$A_{22}(t) = \frac{L_{S2T}}{4gA_{S1}} + \sum_{i=1}^2 \frac{L_{S3i}}{g N_{S3i} A_{S3i}} \quad (2-4.27)$$

and

$$B_1(t) = - (HDSPH + CHMPH - \Delta P_{RC} + FRPH) \quad (2-4.28)$$

where

$$\begin{aligned} HDSPH = & L_{S1} \bar{\rho}_{S1} + L_{S2} \bar{\rho}_{S2} + 10.2 \rho_{S3} - 52.72 \rho_{S6} \\ & - (Y_{S5} + (D_{OD} - D_{ID})/2) \rho_{S6} \end{aligned} \quad (2-4.29)$$

(See Section A-4.6 for details.)

$$CHMPH = \frac{1}{g A_{S1}^2} \left(\frac{W_{S3S}^2}{\rho_{S3}} - \frac{W_{S1S}^2}{\rho_{fS2}} \right) \quad (2-4.30)$$

$$\begin{aligned} FRPH = & (f_{S1a} L_{S1} + f_{ob1} + f_{S6} \left(\frac{N_E}{N_L} \right)^2) W_{S1S}'^2 \\ & + (f_{S2a} R L_{S2}) \bar{W}_{S2aS}'^2 + (f_{ob3} + (L_{S2T} - L_{S2}) \\ & \times (f_{S2a} R) W_{S3S}'^2 \end{aligned} \quad (2-4.31)$$

in which

$$W_{S1S}' = \frac{W_{S1S}}{N_E}$$

is the flow rate per evaporator tube, and

$$\bar{W}_{S2aS}' = \frac{W_{S1S}' + W_{S3S}'}{2} \quad (2-4.32)$$

$$f_{S1a} = \frac{8 f_{S1}}{2 g A_{S1}^2 \bar{\rho}_{S1} D_{IE}} \quad (2-4.33)$$

f_{S1} is obtainable from Eq. (2-4.19), in which Re is that for the subcooled water in the region (AS1).

f_{S2a} is similar to f_{S1a} except that Re is that for saturated rather than subcooled water.

f_{obl} is obstruction pressure loss constant coefficient in those regions (not including the downcomer) in which the flow rate is W_{S1S} .

f_{ob3} is similar to f_{obl} with S_{S3S} replacing W_{S1S} .

$R = RD(\bar{P}_{S2}, x_{S3})$ is the two phase friction multiplier.

f_{S6} is a constant pressure loss coefficient in the downcomer region.

ΔP_{RC} in Eq. (2-4.28) is the recirculation pump head. Since the recirculation flow is time dependent while the recirculation pump speed is fixed, and since the pump characteristics are not available, it is assumed that

$$\Delta P_{RC} = \Delta P_{RCSF} - f_{RC} (W_{S1S}/N_L)^2 \quad (2-4.34)$$

where ΔP_{RCSF} is the recirculation pump shut-off head and f_{RC} is a constant determined from the known [2] operating point of the recirculation pump and the assumed shut-off head (see Section A-4.6).

On the other hand $B_2(t)$ of Eqs. (2-4.21, 2-4.22) is obtained from:

$$B_2(t) = 144(\bar{P}_{S2} - \bar{P}_{S4}) - HSPH34 - CHMPH/2 - FRPH34 \quad (2-4.35)$$

where

$$HSPH34 = L_{S2} \bar{\rho}_{S2}/2 + 7.67 \rho_{S3} \quad (2-4.36)$$

$\equiv$ half the hydrostatic pressure head in the
two phase regions

$$\begin{aligned} \text{FRPH34} = f_{S2a} R L_{S2} (\bar{W}'_{S2aS})^2 / 2 + (4.834 R f_{S2a} \\ + f'_{ob3}) (W'_{S3S})^2 \end{aligned} \quad (2-4.37)$$

where

f'_{ob3} = obstruction pressure loss coefficient in the Riser

(See Section A-4.6 for the numerical values of this and other constants.)

Finally, Eqs. (2-4.21, 22) are modified to give the flow rates W'_{S1S} and W'_{S3S} rather than W_{S1S} and W_{S3S} , by dividing both sides of each equation by N_E (the number of tubes in the evaporators). This is found to add to the numerical stability since it attenuates (or scales down) the initial errors in the variables on the R.H.S's of the equations, i.e., Eqs. (2-4.21, 22) are replaced by:

$$\frac{d W'_{S1S}}{dt} = \frac{A_{22}(t)B_1(t) - A_{12}(t)B_2(t)}{N_E \Delta} \quad (2-4.38)$$

and

$$\frac{d W'_{S3S}}{dt} = \frac{A_{11}(t)B_2(t) - A_{21}(t)B_1(t)}{N_E \Delta} \quad (2-4.39)$$

2-4.4 Momentum Conservation in the Feedwater Loop (s)

Applying the general momentum Eq. (2-4.17) to the feedwater loop extending from the (main) feedwater header to the steam drum gives the following

$$\begin{aligned} \frac{d W_{S5S}}{dt} = & \left(\frac{1}{\tau_{WS5}} \right) [144 (\text{PHFW} - \bar{P}_{S4}) - 12.5 \rho_{S5} \\ & - f_{S5} \left(\frac{W_{S5S}}{N_L} \right)^2 - 144 \Delta P_{V5}] \end{aligned} \quad (2-4.40)$$

where

$$\tau_{WS5} = \frac{L_{S5}}{g N_L A_{S5}} \quad (2-4.41)$$

PHFW = pressure head in the main feedwater header (psia)

f_{S5} = constant pressure loss coefficient, in the pipe
lines (not including the valve losses)

ΔP_{V5} = feedwater flow control valve pressure loss, i.e.,

$$\Delta P_{V5} = f_{V5} \left(\frac{W_{S5S}}{N_L S_{V5}} \right)^2 \text{ psi} \quad (2-4.42)$$

where f_{V5} is a constant (see Section A-4.7 for its numerical value)

and S_{V5} is the normalized valve stroke.

2-5 Intermediate Heat Exchanger (IHX)

The IHX tube wall is much thinner than that of the evaporator or the superheater (since the pressure differential across the wall is

much less) and therefore has much lower mass heat capacity. Consequently, the wall energy storage is neglected and the IHX is simulated by one primary and one intermediate region with an overall heat transfer coefficient between the two radial regions. The film heat transfer coefficients are:

a. On the primary (shell) side [3]:

$$h_{NIP} = \frac{k_{NIP}}{D_{EI}} [1.3(4 + 0.024 Pe^{0.8})] \quad (2-5.1)$$

where

D_{EI} = primary sodium equivalent diameter per tube

Pe = Peclet number

$$= Re \cdot Pr$$

$$= \frac{W_P}{N_I} \frac{D_{EI}}{A_C} \frac{C_{PP}}{k_{NIP}}$$

where

N_I = number of tubes in the IHX(s)

A_C = primary sodium equivalent cross sectional area
per tube of the IHX.

b. On the intermediate (tube) side [3]:

$$h_{NII} = \frac{k_{NII}}{D_{II}} (4 + 0.024 Pe^{0.8}) \quad (2-5.2)$$

The overall heat transfer coefficient is obtained from:

$$H_I = \pi L_I N_I / \left[\frac{1}{D_{OI} h_{NIP}} + \frac{\ln(D_{OI}/D_{II})}{2 k_{WI}} + \frac{1}{D_{II} h_{FI}} + \frac{1}{D_{II} h_{NII}} \right] \quad (2-5.3)$$

where

k_{WI} = tube-wall thermal conductivity

h_{FI} = tube side (intermediate sodium side) fouling heat transfer coefficient. (On the intermediate side the sodium is colder, resulting in more precipitation of the impurities than on the primary side.)

The inlet temperatures on the primary and the intermediate sides respectively are:

$$T_{P5}(t) = FDELAY(T_{P4}(t), \tau_{TP5}(t), J, T_{P4}(o)) \quad (2-5.4a)$$

$$\text{or} \quad T_{P5}(t) = PDELAY(T_{P4}(t), \tau_{TP5}(t), J, T_{P4}(o)) \quad (2-5.4b)$$

(See Chapter 1 for the meanings of the FDELAY and PDELAY operators.)

$$\text{and} \quad T_{I1}(t) = FDELAY(T_{I9}(t), \tau_{TI1}(t), J, T_{I9}(o)) \quad (2-5.5a)$$

$$\text{or} \quad T_{I1}(t) = PDELAY(T_{I9}(t), \tau_{TI1}(t), J, T_{I9}(o)) \quad (2-5.5b)$$

where

$$\tau_{TP5}(t) = \sum_{i=1}^2 \frac{M_{P5i}}{W_{PS}(t)} \quad (2-5.6)$$

where

M_{P5i} = sodium mass in the i^{th} section of the hot legs in the primary loops

W_{PS} = primary flow (lb_m/sec/three loops)

Similarly,

$$\tau_{TII}(t) = \sum_{i=1}^2 \frac{M_{TIIi}}{W_{IS}} \quad (2-5.7)$$

where

M_{TIIi} = sodium mass in the i^{th} section of the cold legs in the intermediate loops

and

W_{IS} = intermediate flow rate (lb_m/sec/three loops)

In the following, mass and energy balances in the IHX and the momentum balance in the intermediate loop will be presented in that order.

2-5.1 Mass Conservation

$$W_{P5} = W_P \quad (2-5.8a)$$

$$W_{P7} = W_{P5} \quad (2-5.8b)$$

$$W_{I1} = W_I \quad (2-5.8c)$$

$$W_{I3} = W_{I1} \quad (2-5.8d)$$

Changes in the primary and the intermediate sodium masses are neglected.

2-5.2 Energy Conservation

a. Primary Sodium:

$$\frac{d T_{P7}}{dt} = \frac{1}{C_{PP} M_{P5}} [C_{PP} W_P (T_{P5} - T_{P7}) - H_I (\bar{T}_{P5} - \bar{T}_{I1})] \quad (2-5.9)$$

where

$$M_{P5} = \text{mass of sodium on the shell side of the IHXS} \\ (\text{lb}_m/\text{three loops})$$

and

$$\bar{T}_{P5} = \frac{T_{P5} + T_{P7}}{2} \quad (2-5.10)$$

$$T_{I1} = \frac{T_{I1} + T_{I3}}{2} \quad (2-5.11)$$

b. Intermediate Sodium:

$$\frac{d T_{I3}}{dt} = \frac{1}{C_{PI} M_{I1}} [C_{PI} W_I (T_{I1} - T_{I3}) + H_I (\bar{T}_{P5} - \bar{T}_{I1})] \quad (2-5.12)$$

2-5.3 Momentum Conservation in the Intermediate Loop(s)

As was done in the steam/water loop, the general momentum Eq. (2-4.17) is applied to all regions in the intermediate loop. An obvious choice of these regions is that each component represents a region as well as each pipe line interconnecting two components.

The intermediate flow rate (W_{IS}) is obtained from an overall momentum balance in the intermediate loop and is found to satisfy the following equation:

$$\begin{aligned} \frac{d W_{IS}}{dt} = & \left(\frac{1}{\tau_{WI}} \right) \{ (HOIP + 7.815) \rho_{NA}(T_{I1}) - 25.37 \rho_{NA}(\bar{T}_{I1}) \\ & - 17.862 \rho_{NA}(T_{I3}) + 35.416 [\rho_{NA}(\bar{T}_{IA}) + \rho_{NA}(\bar{T}_{IE}) \\ & - \rho_{NA}(T_{IC})] - [f_{I1}/N_{EVAP}^2 + f_{I2}/N_L^2] W_{IS}^2 \} \end{aligned} \quad (2-5.13)$$

where

$$\tau_{WI} = \sum_{i=1}^7 \frac{L_{Ii}}{N_{Ii} A_{Ii}} \quad (2-5.14a)$$

(Notice that the intermediate pump is considered one component and that the pipe lines extending from the evaporator to the pump suction represents a region separate from that extending from the pump discharge to the IHX entrance.)

Substituting the data available for the CRBRP, (see Section A-5.3), it is found that:

$$\tau_{WI} \approx \frac{2.443}{N_{EVAP}} + \frac{14.356}{N_L} \quad (2-5.14b)$$

where

N_{EVAP} = number of evaporators (normally 6)

f_{I1} and f_{I2} are friction coefficients, determined from the initial steady state values of the pressures and the temperatures in the intermediate loop.

and

HOIP = head of intermediate pump (ft)

2-6 Reactor

2-6.1 Reactor Kinetics

In the simulation, the two concentric cores (of different fuel enrichments) of the CRBR, are decoupled (kinetically) from other reactor regions (e.g., the blankets) and are regarded as one equivalent node. The point-kinetic, prompt-jump approximation with six delayed neutron groups is the model utilized in evaluating the neutron balance in the equivalent core. Hence the neutron balance equations are [3]:

$$0 = (\rho - \beta)n + \sum_{i=1}^6 \lambda_i C_i \ell \quad (2-6.1)$$

and

$$\frac{d C_i}{dt} = \frac{\beta_i n}{\ell} - \lambda_i C_i \quad i = 1, \dots, 6 \quad (2-6.2)$$

(All variables and parameters appearing in these equations are those conventionally used in reactor kinetics.)

The reactivity is

$$\rho = \rho_C + \rho_{FB} \quad (2-6.3)$$

in which

ρ_C = control rod reactivity

ρ_{FB} = feedback reactivity, which satisfies the following equation

$$\rho_{FB} = (100 \times DC/\beta) \ln\left(\frac{460 + \bar{T}_F}{460 + T_I}\right) + AXECC(\bar{T}_F - T_I) + SODDCC(\bar{T}_{P1} - T_I) + RECC(T_{P1} - T_I) \quad (2-6.4)$$

For $\bar{T}_F, \bar{T}_{P1}, T_{P1} \geq T_I$

where

DC = doppler constant $(\bar{T}_F \frac{dk}{dT_F})$

T_I = cold stand-by temperature (400°F)

AXECC = axial expansion coefficient (¢/F°)

SODDCC = sodium density coefficient (¢/F°)

RECC = radial expansion coefficient (¢/F°)

The neutron density and precursor concentrations in Eqs. (2-6.1, 2) are normalized relative to their initial values, and the following equations are obtained [3]:

$$N(t) = \sum_{i=1}^6 \frac{\beta_i}{\beta} D_i / (1 - \rho/\beta) \quad (2-6.5)$$

and

$$\frac{d D_i}{dt} = \lambda_i (N - D_i) \quad i = 1, \dots, 6 \quad (2-6.6)$$

where

$$N(t) = n(t)/n(0) \quad (2-6.7a)$$

and

$$D_i(t) = C_i(t)/C_i(0) \quad (2-6.7b)$$

where

$$C_i(0) = \beta_i n(0) / \lambda_i \ell \quad (2-6.8)$$

2-6.2 Reactor Thermodynamics

This section includes mass, energy and momentum balances in all regions of the reactor. These regions are:

- a. Lower plenum
- b. Upper plenum
- c. Equivalent core

2-6.2.1 Mass Conservation.

$$W_{P1} = FCC W_p \quad (2-6.9a)$$

$$W_{P3} = W_{P1} \quad (2-6.9b)$$

$$W_{P4} = W_p \quad (2-6.9c)$$

where

W_p = primary flow rate (lb_m/hr/three loops)

W_{P1} and W_{P3} are the flow rates at core inlet and core exit respectively

FCC = fraction of flow into the core

W_{P4} = flow leaving the outlet nozzle (the assumption made is that the sodium level in the upper plenum remains unchanged)

2-6.2.2 Energy Conservation. In both plena, complete mixing is assumed during normal transients.

a. Lower plenum:

$$\frac{d T_{P1}}{dt} = \frac{W_{PS}}{M_{P1}} (T_{R1} - T_{P1}) \quad (2-6.10)$$

where

$$T_{R1}(t) = \text{FDELAY}(T_{P7}(t), \tau_{TR1}(t), J, T_{P7}(o)) \quad (2-2.11a)$$

or

$$T_{R1}(t) = \text{PDELAY}(T_{P7}(t), \tau_{TR1}(t), J, T_{P7}(o)) \quad (2-6.11b)$$

where

$$\tau_{TR1}(t) = \frac{M_{R1} N_L}{W_{PS}} \quad (2-6.12)$$

in which

M_{R1} = mass of sodium in the primary cold leg

M_{P1} = mass of sodium in the lower plenum

b. Upper Plenum:

$$\frac{dT_{P4}}{dt} = \frac{W_{PS}}{M_{P4}} (T_{R3} - T_{P4}) \quad (2-6.13)$$

where

T_{R3} is an average (mixed) temperature at the entrance of the upper plenum, and is obtained from:

$$\frac{dT_{R3}}{dt} = \left\{ \frac{1}{1800 C_{PP} V_{NA} [\rho_{NA}(T_{P1}) + \rho_{NA}(T_{R3})]} \right\} [\epsilon N - C_{PP} W_P (T_{R3} - T_{P1})] \quad (2-6.14)$$

where

ϵ = the total reactor power at normal operation (BTU/hr)

C_{pp} = specific heat of the primary sodium (BTU/lb_m/°F)

V_{NA} = volume of sodium in the reactor vessel less that
in the lower and upper plena (~4928 ft³ from
reference [2]), and

M_{p4} = mass of sodium in the upper plenum

c. Core: The core is simulated by an average channel composed of central fuel region surrounded by sodium coolant. One axial region is assumed in both fuel and sodium.

1. Fuel: Even though neither the energy balance in the clad nor in the helium gap are considered explicitly, an estimate of the heat transfer impedance of both regions is necessary for fuel analysis. Given clad dimensions and material, it is easy to estimate its heat transfer resistance and inner surface temperature. However it is more complicated to estimate the gap conductance which can be obtained from [11]:

$$h_{GAP} = 0.132 + \frac{0.1167\sqrt{T_{GAP}} - 2.36}{G/D_p} + 0.6391 \frac{B}{1+B} \quad (2-6.15)$$

where

h_{GAP} = Gap conductance

$$T_{GAP} = T_{CLAD} + D + 273 + 0.2723 (1 + 0.08G/D_p) q' \quad (2-6.16)$$

$$B = \text{EXP}(-7 + 0.035q' - 6.3 G/D_p) \quad (2-6.17)$$

q' = linear power rating (watt/cm)

G/D_p = cold gap to pellet diametral ratio expressed in %

$$G = D_{I \text{ CLAD}} - D_p \quad (\text{not half this quantity}) \quad (2-6.18)$$

Equation (2-6.15) is limited to beginning of life conditions and to rods with G/D_p ranging from 1 to 4% and power not exceeding 20 kw/ft.

In addition to Eqs. (2-6.15) through (2-6.18) it is emphasized by the authors [11] that fuel thermal conductivity must be obtained from:

$$k'_F = F(D) \left[\frac{38.24}{T+129.2} + 6.1256 \times 10^{-13} T^3 \right] \quad (\text{w/cm/}^\circ\text{C}) \quad (2-6.19)$$

where

T = fuel temperature in K° , obtained from

$$T = 273 + \frac{5}{9} (\bar{T}_F - 32) \quad (2-6.20)$$

and

$$F(D) = 1.079 \left[\frac{D}{1 + 0.5(1-D)} \right] \quad (2-6.21)$$

where

D = fuel density/theoretical density

An overall heat transfer coefficient between the coolant and the fuel is given by

$$H_R = \pi N_P L_C / \left[\frac{1}{8 k_F} + \frac{1}{D_{IC} h'_G} + \frac{\ln(D_{OC}/D_{IC})}{2 k_C} + \frac{1}{D_{OC} h_C} \right] \quad (2-6.22)$$

where

h'_G = gap conductance [BTU/ hr/ft²/°F] (The notation h_G is preserved for the saturated steam enthalpy.)

h_C = sodium film heat transfer coefficient [BTU/ hr/ft²/°F] obtainable from

$$h_C = \frac{k_{NP}}{D_{EP}} [1.3(4 + 0.024 Pe^{0.8})] \quad (26.23)$$

where D_{EP} is the hydraulic diameter in the triangular fuel cell. The average fuel temperature is given by:

$$\frac{d\bar{T}_F}{dt} = \frac{1}{C_{PF} M_F} [FPGC \epsilon N-H_R(\bar{T}_F - \bar{T}_{P1})] \quad (26.24)$$

where

FPGC = fraction of power generated in the core

Because of the dependence of the fuel thermal conductivity on the fuel temperature and vice versa, a trial and error approach is used to obtain the initial steady state value of the fuel temperature (see Section A-6.2 for details).

2. Coolant:

$$\frac{dT_{p3}}{dz} = \frac{1}{C_{pp} M_{p \text{ core}}} [H_R (\bar{T}_F - \bar{T}_{p1}) - C_{pp} FFC W_p (T_{p1} - T_{p3})] \quad (2-6.25)$$

where

$$\bar{T}_{p1} = \frac{T_{p1} + T_{p3}}{2} \quad (2-6.26)$$

2-6.2.3 Maximum Temperatures in the Average and Hot Channels.

To get an estimate of the maximum temperatures in the average channel, the axial distribution of the volumetric heat generation is approximated by [7]:

$$q'''(z) = q_C''' \cos\left(\frac{\pi z}{H_e}\right) \quad (2-6.27)$$

where

q_C''' is the volumetric heat generation at the central plane of the average channel and is given by:

$$q_C''' = \text{heat generated in the core} / (A_p N_p \int_{-H/2}^{H/2} \cos \frac{\pi z}{H_e} dz)$$

i.e.,

$$q_C''' = \frac{\pi}{2 H_e} FPGC \epsilon N / (A_p N_p \sin \frac{\pi H}{2 H_e}) \quad (2-6.28)$$

where

A_p = cross sectional area of the fuel pin

H_e = core extrapolated height (an estimate of H_e is obtained from the axial flux distribution given by Figure (2-6) of reference [1], and is found to be ~ 4.737 ft.)

Then by assuming that transients are slow such that a sequence of quasi-static conditions prevails, the coolant temperature at the axial position z in the average channel is given by [7]:

$$T_p(z) = T_{p1} + \frac{q_C''' A_p H_e N_p}{\pi C_{pp} W_p} \left(\sin \frac{\pi z}{H_e} + \sin \frac{\pi H}{2 H_e} \right) \quad (2-6.29)$$

The clad outer surface temperature $T_C(z)$ is obtained from [7]:

$$T_C(z) = T_p(z) + q_C''' A_p \left(\frac{1}{\pi D_{OC} h_C} \right) \cos \frac{\pi z}{H_e} \quad (2-6.30)$$

Similarly the fuel surface temperature is obtained from:

$$T_S(z) = T_C(z) + q_C''' A_p \left(\frac{\ln(D_{OC}/D_{IC})}{2 \pi k_C} + \frac{1}{\pi D_{IC} h'_G} \right) \cos \frac{\pi z}{H_e} \quad (2-6.31)$$

and the fuel center line temperature is obtained from:

$$T_M(z) = T_S(z) + q_C''' A_p \left(\frac{1}{4 \pi k_F} \right) \cos \frac{\pi z}{H_e} \quad (2-6.32)$$

One of the main drawbacks of these approximations is the instantaneous response of the temperatures to any changes in the heat generation, which results in an over (or under) estimate of their

actual values, especially during the short period (few seconds) following the initiation of such transients (e.g., reactivity transients).

The maximum value of T_p , T_C , T_S and T_M and their locations are easily obtained from Eqs. (2-6.29) through (2-6.32). Both the maximum temperatures in the hot channel and their locations are dependent on the hot channel factors. The 3σ hot channel factors given in Table (4-4.2) of reference [2] are used to get the temperatures in the hot channel from those in the average channel. As is well known, these factors apply to temperature drops rather than the temperatures themselves. However, this does not apply to the coolant temperature according to reference [1], which states on page 2-18, "It should be noted that the factors corresponding to variations of inlet temperature and reactor coolant temperature rise are not utilized with plant thermal and hydraulic design conditions, since these conditions represent an absolute maximum." However, even though these temperatures are not given in that reference, the average channel coolant exit temperature can easily be determined from the thermal balance in that channel. But when comparing it with its counterpart of assembly 8, shown in Figure (4-4.1) of Reference [2], it was concluded that the 3σ coolant hot channel factor of Table (4-4.2) of reference [2] should be multiplied by the coolant exit temperature from the average channel (not by the temperature rise) in order to obtain a hot channel exit coolant temperature comparable to that of Figure (4-4.1) of reference [2]. (Note that other calculated hot channel temperatures agreed with those given in that figure.)

2-6.2.4 Momentum Conservation in the Primary Loop(s). The general momentum Eq. (2-4.17) is applied in each region of the primary loop(s). The main assumptions are that the sodium levels in both the reactor outlet plenum and the primary pump tank are fixed and that the gas pressure above the sodium surfaces is constant at 10 in H₂O.G. It was also assumed that the losses (frictional and others) in any region are proportional to the square of the flow in that region.

An overall momentum balance in the primary loop leads to the following equation (see Section A-6.5):

$$\begin{aligned} \frac{d W_{ps}}{dt} = & \left(\frac{1}{\tau_{wp}} \right) [15.839 \rho_{NA}(T_{p7}) - 11 \rho_{NA}(T_{p1}) - 3 \rho_{NA}(\bar{T}_{p1}) \\ & - 5.68 \rho_{NA}(T_{p3}) + (HOPP - 21.4) \rho_{NA}(T_{p4}) \\ & + 25.37 \rho_{NA}(\bar{T}_{p5}) - (f_{p1}/N_L^2 + f_{143}(FFC/N_{SUB})^2 \\ & + f_{p2})W_{ps}^2] \end{aligned} \quad (2.6.33)$$

in which

HOPP = head of primary pump

$$\tau_{wp} = \frac{3.55}{N_L} + \frac{6.55}{N_{SUB}} \cdot FFC \quad (2-6.34)$$

where N_{SUB} is the number of fuel subassemblies in the core and f_{p1} , f_{143} and f_{p2} are constants determined from the initial steady state values of the pressures and the temperature in the primary loop(s).

2-7 Pumps

Since primary, intermediate and feedwater pumps are variable speed pumps, and because of the variation of these pumps' flow rates during the transient, each pump head and efficiency is variable. For the primary and the intermediate pumps the pump head and efficiency at the main motor speed and the primary pump pony motor speed are given as functions of the flow rates in Figures (5-3.19), (5-4.3) and (5-3.21) of reference [2], respectively. These curves are generalized to other speeds and the generalized information is prepared in tabular form in which the pump head depends on both pump speed and flow rate. The following approximations [12] are used in calculating¹ the entries of these tables:

$$H_1 = H_2 \left(\frac{N_1}{N_2} \right)^2 \quad (2-7.1)$$

$$Q_1 = Q_2 \left(\frac{N_1}{N_2} \right) \quad (2-7.2)$$

where H_1 and H_2 are pump heads at speed N_1 and N_2 respectively, and Q_1 and Q_2 are pump flow rates (in 10^3 gpm).

Tables (2-7.1, 2-7.2) are usable for both primary and intermediate pumps. One table for each speed range is sufficient for both pumps because the heads of the two pumps differ by not more than $\pm 3\%$ at the same speed and flow rate.

1. Some of these calculations were done by G. Radda, a graduate student in the Nuclear Engineering Department.

Table 2-7.1. Main Motor Pump Head

Pump flow Pump rate speed (10 ³ gpm) (rpm)	0.0	4.0	8.0	12.0	16.0	20.0	24.0	28.0	32.0	36.0	40.0	44.0
1500.0	874.0	872.0	870.0	865.0	856.0	846.0	833.0	817.0	797.0	776.0	758.0	736.0
1400.0	775.0	773.0	770.0	765.0	758.0	749.0	738.0	723.0	705.0	684.0	658.0	634.0
1200.0	560.0	558.0	555.0	549.0	541.5	531.0	516.0	500.0	485.0	466.0	439.0	404.0
1170.0	532.0	531.0	528.0	522.0	514.0	504.0	489.0	472.0	463.61	431.58	410.0	375.0
1150.0	514.0	512.0	510.0	504.0	496.0	486.0	470.0	454.0	440.0	420.0	390.0	355.0
1030.0	419.0	418.0	415.0	410.0	404.0	393.0	380.0	364.0	343.0	319.0	288.0	253.0
1006.0	400.0	398.0	396.0	391.0	384.0	374.0	361.0	342.65	308.92	300.0	266.0	230.0
980.0	380.0	378.0	376.0	370.0	363.0	353.0	340.0	322.0	302.0	277.0	244.0	210.0
500.0	98.8	97.8	94.9	89.2	79.5	65.7	50.0	32.0	22.0	10.0	5.0	2.0
350.0	47.8	46.25	42.65	36.65	26.1	13.42	1.1	0.0	0.0	0.0	0.0	0.0
250.0	24.5	23.0	19.55	11.7	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
150.0	8.86	7.616	2.95	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
110.0	4.77	3.43	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2-7.2. Pony Motor Pump Head

Pump flow Pump rate speed (10 ³ gpm) (rpm)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
110.0	4.77	4.694	4.61	4.51	4.4	4.27	4.08	3.83	3.43
107.0	4.51	4.44	4.36	4.26	4.14	4.01	3.82	3.56	3.16
105.0	4.34	4.274	4.195	4.095	3.977	3.844	3.65	3.376	3.033
100.0	3.94	3.88	3.8	3.71	3.6	3.44	3.26	2.98	2.61
90.0	3.19	3.14	3.06	2.97	2.87	2.71	2.48	2.17	1.8
80.0	2.52	2.47	2.4	2.31	2.2	2.03	1.77	1.4	1.0
70.0	1.93	1.88	1.82	1.75	1.63	1.43	1.2	0.8	0.5
50.0	0.98	0.95	0.9	0.81	0.65	0.406	0.08	0.0	0.0
10.0	0.0394	0.0156	0.0	0.0	0.0	0.0	0.0	0.0	0.0

In generalizing the available data on pump efficiencies, a third-order least-square fit was chosen, which yields the following equations:

$$\begin{aligned}\eta_{pp} = & 0.01927 + 69.86 (Q_{pp}/N_{pp}) - 1970 (Q_{pp}/N_{pp})^2 \\ & + 16531.46 (Q_{pp}/N_{pp})^3\end{aligned}\quad (2-7.3)$$

and

$$\begin{aligned}\eta_{IP} = & 0.0063 + 72.025 (Q_{IP}/N_{IP}) - 2049 (Q_{IP}/N_{IP})^2 \\ & + 17671.51 (Q_{IP}/N_{IP})^3\end{aligned}\quad (2-7.4)$$

where N_{pp} and N_{IP} are the primary and intermediate pump speeds (rpm) respectively, and Q_{pp} and Q_{IP} are in 10^3 gpm, and are determined from:

$$Q_{pp} = 1.2465 \times 10^{-4} W_{pp}/\rho_{NA}(T_{p4}) \quad (10^3 \text{ gpm}) \quad (2-7.5)$$

and

$$Q_{IP} = 1.2465 \times 10^{-4} W_{IP}/\rho_{NA}(T_{I9}) \quad (10^3 \text{ gpm}) \quad (2-7.6)$$

where W_{pp} and W_{IP} are the primary and intermediate pump flow rates (lb_m/hr) respectively.

Pump speeds are obtained by applying Newton's second law of motion to the rotating system. This leads to

$$\frac{d N_{pp}}{dt} = \left(\frac{60/2\pi}{I_{pp}}\right) \left[\text{TRQP} - \frac{g W_{pp} \text{HOPP}/3600}{(2\pi/60) N_{pp} \eta_{pp}} \right] \quad (2-7.7)$$

and

$$\frac{d N_{IP}}{dt} = \left(\frac{60/2\pi}{I_{pp}} \right) \left[TRQI - \frac{g W_{IP} HOIP/3600}{(2\pi/60) N_{IP} \eta_{IP}} \right] \quad (2-7.8)$$

where

I_{pp} = primary (and intermediate) pump inertia
(lb_f-ft-sec²/rad²)

TRQP = primary pump motor torque (lb_f-ft/rad)

HOPP = head of primary pump (ft), obtained from either
of the following:

$$HOPP = HMM(N_{pp}, Q_{pp}) \quad N_{pp} > 110 \text{ rpm} \quad (2-7.9a)$$

$$HOPP = HPM(N_{pp}, Q_{pp}) \quad N_{pp} \leq 110 \text{ rpm} \quad (2-7.9b)$$

where HMM and HPM are the simulator names of tables (2-7.1, 2-7.2)
respectively.

Similarly

$$HOIP = HMM(N_{IP}, Q_{IP}) \quad N_{IP} > 110 \text{ rpm} \quad (2-7.10a)$$

$$HOIP = HPM(N_{IP}, Q_{IP}) \quad N_{IP} \leq 110 \text{ rpm} \quad (2-7.10b)$$

The pump inertia I_{pp} was estimated by comparing the primary coast down flow obtainable from Eq. (2-6.33) (in which the densities are held constant at their normal operation values), Eq. (2-7.7) (in

which TRQP was set to zero), Tables (2-7.1, 2-7.2) and Eq. (2-7.3) with the primary pump coast down characteristics given in Figure (5-3.22) of reference [2]. This estimate is

$$I_{pp} \approx 1.6 \times 10^4 \quad (\text{lb}_f\text{-ft-sec}^2/\text{rad}^2)$$

The operating points for the primary and intermediate pumps are summarized as follows:

a. At Main Motor Speeds:

$$(N_{pp}, Q_{pp}) = (1170, 33.42)$$

$$(N_{IP}, Q_{IP}) = (1006, 29.269)$$

$$\text{TRQP} \approx 575431.61$$

$$\text{TRQI} \approx 448790.3$$

b. At Pony Motor Speeds:

$$(N_{pp}, Q_{pp}) \approx (107, 3.342) \quad (\text{estimated})$$

$$(N_{IP}, Q_{IP}) \approx (92, 2.9269) \quad (\text{estimated})$$

$$\text{TRQP} \approx 5128.9$$

$$\text{TRQI} \approx 3992.61$$

CHAPTER 3

DECAY HEAT REMOVAL

As mentioned in Chapter 1, more than one simulator was constructed to permit the study of a large range of transients without excessively complicating the simulator. In the moderate transient range, the CRBRP-ATWS SIMULATOR is to be utilized, whereas in studying a transient following a scram initiating accident the CRBRP-DCHT SIMULATOR is to be utilized. This last simulator differs from the first one in the following aspects:

1. The turbogenerator system is permanently isolated from the rest of the plant.
2. The auxiliary short and long term heat removal subsystems are incorporated in the DCHT simulator, with forced or natural circulation in the steam/water recirculation loop and with the pony motors or natural circulation in the primary and intermediate loops.
3. Since the coast down characteristics of the main and the auxiliary feedwater pumps as well as those of the recirculation pumps are not available at this time and because of the need to use these characteristics in simulating the transient following reactor scram and pumps coast down, the necessity to assume or deduce these characteristics and to include them in the DCHT simulator is unavoidable. It was preferable to deduce these

coast down characteristics from the known [2] coast down characteristics of the primary pumps. Actually in the DCHT simulator the main and the auxiliary feedwater pumps' characteristics were substituted for by coast down time dependent pressure heads in the main and the auxiliary feedwater headers respectively (see Section on Momentum Balance for details). These deduced coast down time dependent heads of the feedwater headers and the recirculation pump are supplied to the DCHT simulator in tabular form (see Appendix H).

4. Both fission and decay heat are assumed to contribute to the total heat generation, whereas in the ATWS simulator all the reactor power is attributed to fission only.
5. A more detailed model of the outlet plenum in which the effects of the flow momentum and density changes are taken into account is implemented in this simulator; whereas in the ATWS simulator a total mixing model is used to evaluate the sodium temperature in the plena.
6. The existence of sodium voids is detected by comparing the sodium temperature at the hot channel exit with the saturation temperature at the local pressure (supplied in tabular form using standard [13] data tables of the sodium thermodynamic properties) and the simulator is forced to stop if boiling occurs, since the model will not adequately represent the physical system under these circumstances.

7. The control system is somewhat different from that used for normal operation and is automatically initiated after reactor scram.

Incorporating the auxiliary heat removal system in the DCHT simulator provides an opportunity to test this system's heat removal capability had the reactor been forced to scram due to one of the following events:

1. Total loss of off-site power with or without loss of on-site power.
2. Uncontrolled rod insertion.
3. Uncontrolled rod withdrawal from full power.
4. Loss of normal feedwater to all loops followed by reactor trip.
5. Turbine trip followed by reactor trip and failure of the steam bypass system valves to open.

As is clear from this selected list of events only those credible events which have symmetrical effects on all the heat transport loops can be investigated by the simulator. In addition to those listed above other scram initiators generating symmetrical transients in all loops can also be investigated.

The following sections include only those additional features mentioned in Items 1 to 6 above. Since the rest of the system equations are similar to those presented in the previous chapter. The control system (i.e., Item 7 above) will be presented separately in Chapter 5. The system constants, parameters and initial values of the

variables are all presented in Appendix B. The controllers, gains, time constants and initial control valves' strokes are presented in Appendix D.

3-1 Isolation of the Turbogenerator

Since the coupling between the turbogenerator unit and the rest of the plant is mainly via the superheated steam flow, isolation of the turbogenerator can be simulated by manipulating this variable. In this regard the following sequence of events may be postulated:

1. During the period before the reactor scram the superheated steam flow is assumed constant and equal to its rated value (this is a simplifying assumption due to the lack of the turbogenerator complementary set of equations).
2. Following the scram signal, the actuators of the isolation valves, on the exit lines from the superheaters, are initiated in order to close these valves. This will result in an increase in both the drum and the superheater exit pressures. This increase in the superheater exit pressure is allowed to continue until it reaches the set point (P_{SCMX}) of the pressure relief valves on the exit lines from the superheaters, at which point these valves fully open. Critical flow will continue across these valves until the heat load decreases to the level at which the long-term auxiliary heat removal subsystem (LTAHRS) can fully dissipate it, when the valves will reclose.

In order to simulate these events the following set of equations is used:

$$\frac{d S_{IVSC}}{dt} = (S_{IVSCD} - S_{IVSC})/\tau_{SIVSC} \quad (3-1.1)$$

where

S_{IVSC} = The normalized stroke of the isolation valve on the exit line from the superheater.

S_{IVSCD} = The desired value of the valve stroke. This is assumed to have the following discrete values:

$$S_{IVSCD} = 1 \quad t < t_{SCRAM} \quad (3-1.2a)$$

$$S_{IVSCD} = 0 \quad t \geq t_{SCRAM} \quad (3-1.2b)$$

where

t_{SCRAM} = The time at which the reactor scram is initiated.

τ_{SIVSC} = The valve actuator time constant.

The flow passing across this valve is assumed to be proportional to the valve stroke, i.e.,

$$W_{SAS1} = N_L \cdot A_{SIVSC} \cdot S_{IVSC} \quad (3-1.3)$$

Where W_{SAS1} is in $lb_m/sec/three\ loops$ and A_{SIVSC} is a constant determined from the initial values of W_{SAS1} and S_{IVSC} .

The dump flow from the pressure relief valves on the pipe line from the exit of the superheater is critical and is determined as follows:

1. From the beginning of the transient until P_{SC} approaches

P_{SCMX} :

$$W_{DMPS1} = 0 \quad (3-1.4a)$$

2. From the time P_{SC} is equal to P_{SCMX} until the heat load decreases to the level at which the LTAHRS can fully dissipate it:

$$W_{DMPS1} = N_L C_{DMP1} P_{SC} \quad (3-1.4b)$$

3. During the time in which the heat load falls within the capacity of the LTAHRS:

$$W_{DMPS1} = 0 \quad (3-1.4c)$$

W_{DMPS1} is the superheater dump flow in $lb_m/sec/three$ loops.

C_{DMP1} is a constant determined knowing that [2] the three parallel valves provide a relief capacity of 75% of rated superheated steam at P_{SCMX} (see Appendix B for more details).

P_{SCMX} is the high pressure set point (not necessarily the maximum P_{SC} attainable during the transient) of the pressure relief valves (~ 1600 psig).

Finally the total superheated steam flow rate is:

$$W_{SAS} = W_{SAS1} + W_{DMPS1} \quad (3-1.5)$$

3-2 The Auxiliary Heat Removal System (AHRS) and the Steam Drum

The AHRS is composed of a short-term and a long-term auxiliary heat removal subsystem (see Figure 3-2.1) both of which are automatically initiated (after reactor scram) under one of the following conditions:

1. Water level in the steam drum (Y_{S5}) is lower than a specified minimum (Y_{S5MN}); both subsystems are initiated.
2. The flow mismatch

$$E_{FLOW} = \frac{W_{S5} - W_{SA}}{W_{S5I}},$$

where W_{S5} and W_{SA} are the feedwater and superheated steam flow rates, is less than a specified negative value ($Flow_{MS}$); both subsystems are initiated.

3. If neither 1 nor 2 occurs before the power level approaches the capacity of the short-term heat removal subsystem (~ 120 MW(t) total) this subsystem will be initiated at this power level.
4. If neither 1 nor 2 occurs before the power level approaches the capacity of the long term heat removal subsystem (~ 45 MW(t) total) this subsystem will be initiated at this power level.

In all cases the short-term heat removal subsystem is deactivated when the power level approaches the capacity of the long term heat removal subsystem. On the other hand, whatever the initiator is, the long-term heat removal subsystem is de-energized once the plant temperatures approach the cold stand-by ($\sim 400^{\circ}\text{F}$).

In addition to the AHRS, another unit that should be discussed in this section, even though it was presented in the previous chapter, is the steam drum. This is because it is a coupling unit between the auxiliary feedwater system and the rest of the plant. Consequently some of the simulating equations for the drum variables (including the inlet water flow and enthalpy as well as the recirculated water enthalpy) will have to be modified, and additional drum variables (such as the recirculation flow from the drum to the recirculation heaters, the dump flow through the pressure relief valves on the drum outlet header, and the steam flow to the AFWP drive turbine) will have to be included.

In presenting the equations of this portion of the simulator, the sequence used in Chapter 2 will be followed; i.e., the conservation of mass, energy and momentum will be presented in that order.

3-2.1 Mass Balance

3-2.1.1 Mass Balance in the Recirculation Heater(s). See Figure 3-2.1.

$$W_{S5S2} = W_{APS} + W_{RCS} \quad (3-2.1)$$

where W_{S5S2} is the auxiliary feedwater flow ($\text{lb}_m/\text{sec}/\text{three loops}$) leaving the recirculation heaters to the steam drum; the flow rates on

the R.H.S. of Eq. (3-2.1) are obtainable from the momentum balance equations (see Section on Momentum Balance) and are defined as follows:

W_{APS} = the total flow from the AFWPS ($lb_m/sec/three\ loops$).

W_{RCS} = the recirculation flow ($lb_m/sec/three\ loops$) from the steam drums to the recirculation heaters.

In this mass balance it is assumed that the water levels in the recirculation heaters are fixed.

3-2.1.2 Mass Balance in the PACC. Only steam/water flow is simulated in the PACC, and by assuming that there is no mass storage in the PACC tubes it is found that:

$$W_{S5S3} = W_{S7S3} \quad (3-2.2)$$

where

W_{S7S3} = the saturated steam flow rate ($lb_m/sec/three\ loops$) from the steam drum to the PACC, obtainable from the momentum equation given below.

and

W_{S5S3} = the saturated water flow rate from the PACC to the steam drum.

3-2.1.3 Mass Balance in the Steam Drum.

$$\frac{d(M_{S4} + M_{S5})}{dt} = (W_{S4S} + W_{S5S} - W_{S1S} - W_{RCS} - W_{S7S})/N_L \quad (3-2.3a)$$

where

$$W_{S5S} = W_{S5S1} + W_{S5S2} + W_{S5S3} \quad (3-2.3b)$$

$$W_{S7S} = W_{SAS} + W_{DMPS2} + W_{APTS} + W_{S7S3} \quad (3-2.3c)$$

M_{S4} = mass of saturated steam in the drum (lb_m /drum),
given by Eq. (2-4.3); its first derivative is
given by Eq. (2-4.4).

M_{S5} = mass of subcooled water in the drum (lb_m /drum).

W_{S4S} = steam/water mixture flow rate into the drums
(lb_m /sec/three loops).

W_{S1S} = recirculation flow from the drums to the
evaporators (lb_m /sec/three loops).

W_{S1S} and W_{S4S} are obtainable from Eqs. (2-4.21, 22) respectively.

W_{S5S1} is the feedwater flow from the main feedwater system to
the drums, and is obtainable from the momentum balance Eq. (3-2.29)
given below.

W_{SAS} = superheated steam flow (see Eq. (3-1.5)).

W_{APTS} = auxiliary pump turbine flow rate (lb_m /sec)
obtainable from Eq. (3-2.38) below.

W_{DMPS2} = dump flow through the pressure relief valves on the drums' outlet headers ($lb_m/sec/three$ loops) and similar to W_{DMPS1} (see Eq. (3-1.4)). W_{DMPS2} is given by:

1. From the start of the transient until $\bar{P}_{S4}$ approaches $\bar{P}_{S4MX}$:

$$W_{DMPS2} = 0 \quad (3-2.4a)$$

2. From the time $\bar{P}_{S4}$ is equal to or exceeds $\bar{P}_{S4MX}$ until the heat load decreases to the level at which the LTAHRS can fully dissipate it:

$$W_{DMPS2} = N_L C_{DMP2} \bar{P}_{S4} \quad (3-2.4b)$$

3. During the period in which the heat load falls within the capacity of the LTAHRS:

$$W_{DMPS2} = 0 \quad (3-2.4c)$$

where C_{DMP2} is a constant determined by assuming that the relief valves on the outlet headers of the drums have a relief capacity of 25% of the rated flow at $\bar{P}_{S4MX}$ (see Appendix B for details).

$\bar{P}_{S4MX}$ is the high pressure set point of the pressure relief valves on the outlet header of the steam drum.

Even though the feedwater flow (W_{S5S}) to the steam drum is the sum of the main and the auxiliary feedwater flow rates, these flow rates are automatically controlled in the simulator and will not all

have their rated values at the same time. Before the activation of the auxiliary system both W_{S5S2} and W_{S5S3} will be zero and W_{S5S1} is at or near its rated value. Then once the coast down signals (following the scram signal by ~ 0.5 sec.) deactivate the main feedwater system, W_{S5S1} will be reduced gradually until it approaches zero. On the other hand, whenever the control system activates any or both of the auxiliary heat removal subsystems, the corresponding flow (W_{S5S2} and/or W_{S5S3}) will increase from its zero value to a value determined by the plant conditions (with W_{S5S3} much slower than W_{S5S2}). The same can be said about W_{S7S} , where each of its flow constituents is automatically controlled, e.g., W_{DMPS2} has different values depending on the pressure in the drum and W_{APTS} will be zero as long as the AFW drive turbine pressure control valve is closed even if the short term heat removal subsystem is activated. This corresponds to a situation in which only the motor driven pumps are operating whereas the turbine driven pump is, for some reason, inoperative. W_{S7S3} will be zero as long as the long term heat removal subsystem remains unactivated.

3-2.2 Energy Balance

3-2.2.1 Energy Balance in the Recirculation Heater(s).

$$\frac{dh_{RC}}{dt} = \frac{1}{N_{LRC}} [W_{RCS}(h_{S62} - 168) - W_{S5S2}(h_{RC} - 168)] \quad (3-2.5)$$

where the number 168 is the water enthalpy at 200°F, which is the temperature of the water entering the recirculation heaters from the auxiliary feedwater pumps, assuming that it remains constant, and where

h_{RC} = subcooled water enthalpy in the recirculation heater(s).

N_L = number of recirculation heaters (or loops).

M_{RC} = mass of subcooled water in each recirculation heater
(lb_m/heater).

$h_{S62}(t)$ is determined from:

$$h_{S62}(t) = \text{PDELAY} (h_{S6}(t), \tau_{h62}(t), J, h_{S6}(o)) \quad (3-2.6)$$

(See Chapter 1 for the meaning of the PDELAY operator.)

where

h_{S6} = the subcooled water enthalpy in the steam drum
(see below).

τ_{h62} = variable time delay between the drum and the
recirculation heater in sec and is obtainable from:

$$\tau_{h62}(t) = M_{DRC} \frac{N_L}{\dot{W}_{RCS}(t)} \quad (3-2-7)$$

M_{DRC} = the mass of the subcooled water in the above
mentioned pipe line.

3-2.2.2 Energy Balance in the Steam Drum.

$$\begin{aligned} \frac{d(M_{S5} h_{S6} + M_{S4} h_{gS4})}{dt} = & \dot{W}_{S4S} h_{S4} + \dot{W}_{S5S} h_{S5} - \dot{W}_{S7S} h_{gS4} \\ & - (\dot{W}_{S1S} + \dot{W}_{RCS}) h_{S6} \end{aligned} \quad (3-2.8)$$

in which the flow rates are as defined in the mass balance and $h_{S4}(t)$, similar to $h_{S62}(t)$, is determined from

$$h_{S4}(t) = \text{PDELAY} (h_{S3}(t), \tau_{hS4}(t), J, h_{S3}(o)) \quad (3-2.9)$$

where τ_{hS4} and h_{S3} are defined by Eqs. (2-4.9, 2-3.18) of the previous chapter, respectively.

Also,

$$h_{S5} = (W_{S5S1} h_{S51} + W_{S5S2} h_{S52} + W_{S5S3} h_{S53}) / W_{S5S} \quad (3-2.10)$$

where

h_{S51} = enthalpy of the main feedwater entering the drum,
assumed to remain constant at its initial steady
state value (~ 434.7 BTU/lb_m).

h_{S52} = enthalpy of the auxiliary feedwater entering the
steam drum determined as follows:

$$h_{S52}(t) = \text{PDELAY} (h_{RC}(t), \tau_{h52}(t), J, h_{RC}(o)) \quad (3-2.11)$$

where

$$\tau_{h52}(t) = M_{RCD} \frac{N_L}{W_{S5S2}(t)} \quad (3-2.12)$$

M_{RCD} = mass of subcooled water in the pipe line connecting
the recirculation heater to the steam drum.

Also,

h_{S53} = enthalpy of saturated water (at $\bar{P}_{S4}$) returning
from the PACC to the steam drum, i.e.,

$$h_{S53} = h_{fS4} \quad (3-2.13)$$

3-2.3 Momentum Balance

As is well known, pump characteristics should be available if any adequate description of flow transients is to be sought. However, since these characteristics are not available at this time, it seems feasible to overcome this lack of information by deducing it in the following way:

The coast down flow of the primary pump is given in Figure 5-3.22 of reference [2]. Assume that coast-down may be predicted by treating heat transfer as isothermal (temperatures independent of time). This assumption eliminates the temperature feedback effects on the flow rates and thus breaks the coupling between the momentum balance equations in these loops. By substituting the values of the densities and other constants into the momentum balance equation in the primary loop, i.e., into Eq. (2-6.33), it was found that:

$$\frac{dW_{ps}}{dt} \approx 42.613 \text{ HOPP}(N_{pp}, Q_{pp}) + 37.4725 - 1.457 \times 10^{-4} W_{ps}^2 \quad (3-2.14)$$

During the pump coast down the pump speed is obtained from Eq. (2-7.7) in which TRQP is set to zero. Hence:

$$\frac{dN_{pp}}{dt} = - \left(\frac{60}{2\pi}\right)^2 \frac{g}{N_L I_{pp}} \left[\frac{HOPP W_{ps}}{\eta_{pp} N_{pp}} \right]$$

i.e., (3-2.15)

$$\frac{dN_{pp}}{dt} = - \frac{978.76}{I_{pp}} \left[\frac{HOPP W_{ps}}{\eta_{pp} N_{pp}} \right]$$

From Eqs. (3-2.14, 3-2.15, 2-7.5, 2-7.3) and Tables (2-7.1, 2-7.2), and by trial of different values of I_{pp} until the coast down flow agrees with that of Figure 5-3.22 of reference [2], I_{pp} was found to approximately be 1.6×10^4 ($lb_f - ft - Sec^2 / rad^2$). The time dependent primary pump head $HOPP(t)$ and the coast down flow $W_{ps}(t)$ were also obtained. To summarize:

$$\frac{dW_{ps}}{dt} = 42.613 HOPP(t) + 37.4725 - 1.457 \times 10^{-4} W_{ps}^2(t) \quad (3-2.16)$$

or

$W_{ps}(t)$ will be available in tabular form

and

$HOPP(t)$ will be available in tabular form

This information is used in deducing the coast down heads in the main and the auxiliary feedwater headers and the recirculation pump as follows:

3-2.3.1 Coast Down Head in the Main Feedwater Header. Substituting the constants, densities and the rated value of $\bar{P}_{S4}$ into Eq. (2-4.40), it is found that:

$$\frac{dW_{S5S1}}{dt} \approx 36.72[\text{PHFW1} - 1770.1559 - 2.6702 \times 10^{-4} W_{S5S1}^2] \quad (3-2.17)$$

However, if isothermal heat removal is to prevail the ratio of the flow rates in the different loops should remain constant, i.e.,

$$\left. \frac{W_{S5S1}}{W_{ps}} = \frac{W_{S5S1}}{W_{ps}} \right|_0 \approx 0.080586$$

In other words, during the coast down

$$W_{S5S1}(t) \approx 0.08058 W_{ps}(t) \quad (3-2.18)$$

Substituting this into Eq. (3-2.17) above it is found that:

$$\frac{dW_{ps}}{dt} = 455.668[\text{PHFW1} - 1770.1559 - 1.73409 \times 10^{-5} W_{ps}^2] \quad (3-2.19)$$

and from Eqs. (3-2.16, 19)

$$\text{PHFW1}(t) = 0.09352 \text{ HOPP}(t) + 1770.3243 + 1.41434 \times 10^{-5} W_{ps}^2(t)$$

Substitute for $W_{ps}(t)$ by

$$W_{ps}(t) = W_{ps}(0) \text{ WPFRT}(t) = 11512.77 \text{ WPFRT}(t) \quad (3-2.20)$$

Notice that Figure 5-3.22 of reference [2] gives WPFRT(t), not W_{ps} . It is concluded that:

$$\text{PHFW1}(t) = 0.09352 \text{ HOPP}(t) + 1770.2381 + 187.4622[\text{WPFRT}(t)]^2 \quad (3-2.21)$$

Knowing WPFRT(t) and HOPP(t) during the coast down PHFW1(t) is easily found (see Appendix B for numerical values).

3-2.3.2 Coast Down (and Start-Up) Head in the Auxiliary Feedwater Header. In deducing this pressure head, it was assumed that the characteristics of the auxiliary feedwater pump are similar to those of the main feedwater pump. Thus by normalizing the coast down pressure head in the main feedwater header (obtained above) it is easy to deduce it for the auxiliary feedwater header in the following way:

During coast down:

$$\text{PHFW2}(t) = (\text{PHFW2I}/\text{PHFW1I}) \text{ PHDMFW}(t-t_2) \quad t \geq t_2 \quad (3-2.22)$$

where PHFW1I and PHFW2I are the rated values of the pressure heads in the main and the auxiliary feedwater headers respectively, PHDMFW is the name of the table whose entries are the pressure heads in the main feedwater header (see the DCHT simulator listing in Appendix H), and where t_2 is the time at which the auxiliary pump coast down begins.

During the opening of the auxiliary feedwater isolation valves it is assumed that the pressure heads of the auxiliary feedwater pumps have been fully developed and that the pump flow rates are controlled by controlling the pump speeds such that the pressure head in the auxiliary feedwater header remains approximately equal to its rated value. Thus

$$\text{PHFW2}(t) = \text{PHFW2I} \quad t \leq t_2 \quad (3-2.23)$$

3-2.3.3 The Recirculation Pump Coast Down Head DPRC(t). Under the previously stated assumptions, and from the equations, the constants and the densities given in Sections (2-4.6) and (A-4.6) it is found that:

$$\frac{dW_{S1S}}{dt} \approx 74.555 \text{ DPRC}(t) - 4684.55 - 1.8442 \times 10^{-3} W_{S1S}^2 \quad (3-2.24)$$

but

$$W_{S1S}(t) \approx \frac{W_{S1S}}{W_{ps}} \bigg|_0 W_{ps}(t)$$

i.e.,

$$W_{S1S} \approx 0.16117 W_{ps}(t)$$

thus

$$\frac{dW_{ps}}{dt} = 462.576 \text{ DPRC}(t) - 29065.28 - 2.972 \times 10^{-4} W_{ps}^2 \quad (3-2.25)$$

Then from this and Eqs. (3-2.16, 20), DPRC(t) is found to satisfy the following equation:

$$\text{DPRC}(t) \approx 0.0921 \text{ HOPP}(t) + 62.9145 + 43.42 [\text{WPFRT}(t)]^2 \quad (3-2.26)$$

Knowing HOPP(t) and WPFRT(t) during the coast down DPRC(t) is obtained and is supplied to the simulator in tabular form under the table name DPRCP (see Appendix H).

In the following, the general momentum Eq. (2-4.17), in which the loss are assumed to be proportional to the square of the flow rates, is applied to both the main and auxiliary feedwater systems. The loss constants are obtained by assuming the operating point in the auxiliary system to be that corresponding to 10% of the rated power level. However, Eq. (2-4.17) in its present form causes practical and numerical difficulties, especially when applied to the auxiliary feedwater and the PACC flow rates. The reason for these difficulties is that the loss term is virtually zero¹ before and during the early stages in the start up of the auxiliary system where the flow is zero or very low. This will result in relatively large derivatives of the order of $10^3 \text{ lb}_m/\text{sec}$ of these flow rates during that period, which is practically unrealistic.

1. Even though it may be expected that the pressure drops across the valves are very large during that period, it should be noticed that setting the initial valve stroke exactly zero will cause a numerical overflow. By setting the initial valve stroke to some small value, say 10^{-4} , and specifying the initial flow to be zero or a small value, say $10^{-4} \text{ lb}_m/\text{sec}$, the problem will remain unsolved. Further increase in the initial flow will be unrealistic and will have some undesirable side effects on the energy balance equations.

At the same time, other variables' rates of change are much slower. This causes divergence with all the integration methods available on the DARE system. Thus even though the acceleration term (the derivative term) is more significant in the transients we are treating in this chapter compared to those discussed in the previous chapter, neglecting it will reduce the physical impracticality and the numerical difficulties without sacrifice of accuracy since it is practically small relative to other terms in the momentum balance equation at or near the operating point.

3-2.3.4 Main Feedwater Flow (W_{S5S1}). From Eq. (2-4.40) it is a simple matter to show that:

$$W_{S5S1} = (N_L C_{V51} S_{V51}) \{ [PHFW1(t) - \bar{P}_{S4} - 0.0868 \rho(T_{S5})] / [1 + f_{S51} (C_{V51} S_{V51})^2] \}^{0.5} \quad (3-2.27)$$

where ΔP_{V5} is replaced by

$$\left(\frac{W_{S5S1}}{N_L C_{V51} S_{V51}} \right)^2$$

and

$$PHFW1(t) = PHFW1I \quad t \leq t_{CD} \quad (3-2.28a)$$

$$PHFW1(t) = PHDMFW(t - t_{CD}) \quad t \geq t_{CD} \quad (3-2.28b)$$

where t_{CD} is time at the initiation of the pump coast down (~ 0.5 sec after initiation of the reactor scram).

3-2.3.5 Auxiliary Feedwater and Recirculation Flow Rates.

These are the feedwater flow (W_{S5S2}) from the recirculation heaters to the steam drums, and the recirculation flow (W_{RCS}) from the drums to the recirculation heaters.

Neglecting the acceleration term and applying the momentum balance Eq. (2-4.17) between the auxiliary feedwater header and the recirculation heater, we find that:

$$P_{RC} = PHFW2(t) - \frac{Y_{HDRC} \rho(200^\circ F)}{144} - f_{HDRC} \left(\frac{W_{APS}}{N_L} \right)^2 - \left(\frac{W_{APS}}{N_L C_{V52} S_{V52}} \right)^2 \quad (3-2.29)$$

where

P_{RC} = pressure at the inlet of the recirculation heater (psia)

$PHFW2$ = pressure in the auxiliary feedwater header (psia)

Y_{HDRC} = difference in level between the header and the recirculation heater (ft).

W_{APS} = auxiliary pumps' flow (lb_m/sec /three loops)

f_{HDRC} = friction constant $psi/(lb_m/sec)^2$

C_{V52} = AFW flow control valve constant

S_{V52} = normalized stroke of the AFW flow control valve

The 200°F in Eq. (3-2.29) is the feedwater temperature at the AFWPS.

Similarly, from the momentum balance between the drum and the recirculation heater:

$$P_{RC} = P_{S6} + \frac{Y_{DRC} \rho(T_{S6})}{144} - f_{DRC} \left(\frac{W_{RCS}}{N_L} \right)^2 - \left(\frac{W_{RCS}}{N_L C_{VRC} S_{VRC}} \right)^2 \quad (3-2.30)$$

and from the momentum balance between the recirculation heater and the drum it is found that:

$$P_{RC} = P_{S5} + \frac{Y_{RCD} \rho(T_{S5})}{144} + f_{RCD} \left(\frac{W_{S5S2}}{N_L} \right)^2 \quad (3-2.31a)$$

Subtracting Eq. (3-2.30) from Eq. (3-2.31a) and substituting

$$P_{S6} - P_{S5} = \frac{(Y_{RCD} - Y_{DRC})}{144}$$

one finds that:

$$\frac{Y_{RCD}(\rho(T_{S5}) - \rho(T_{S6}))}{144} = - f_{RCD} \left(\frac{W_{S5S2}}{N_L} \right)^2 - \left[f_{DRC} + \frac{1}{(C_{VRC} S_{VRC})^2} \right] \times \left(\frac{W_{RCS}}{N_L} \right)^2$$

However we know that $\rho(T_{S5}) > \rho(T_{S6})$. Thus, as could have been observed even without going through the above argument, dependence on natural circulation alone in the closed loop containing the recirculation heater and the steam drum is not possible as long as the heater is at a lower level than the drum. This suggests that the jet pump in the recirculation heater, whose function as stated in reference [1] is to promote mixing in the heater, should in addition be considered as providing a pressure head in the momentum balance equation. However, the value of this pressure head is not available and will therefore be assumed. In conclusion, Eq. (3-2.31a) should be modified to:

$$P_{RC} = P_{S5} + \frac{Y_{RCD} \rho(T_{S5})}{144} + f_{RCD} \left(\frac{W_{S5S2}}{N_L} \right)^2 - \frac{HOJTP \rho(T_{S5})}{144} \quad (3-2.31b)$$

where

HOJTP = head of the jet pump (ft. of water)

Finally noting that

$$W_{APS} = W_{S5S2} - W_{RCS} \quad (\text{see Eq. (3-2.1)})$$

it is straightforward to show that

$$W_{S5S2} = W_{RCS} + (N_L C_{V52} S_{V52}) \left\{ [PHFW2 - \bar{P}_{S4} + \frac{HOJTP \rho(T_{S5})}{144} - HDSH2 - f_{RCD} \left(\frac{W_{S5S2}}{N_L} \right)^2] / [1 + f_{HDRC} (C_{V52} S_{V52})^2] \right\}^{0.5} \quad (3-2.32)$$

where

$$HDSH2 = \frac{(Y_{S5}-1.5) \rho(T_{S6})}{144} + \frac{Y_{RCD} \rho(T_{S5})}{144} + \frac{Y_{HDRC} \rho(200^{\circ}F)}{144} \quad (3-2.33)$$

and

$$W_{RCS} = (N_L C_{VRC} S_{VRC}) \left\{ \left[\frac{HOJTP \rho(T_{S5})}{144} - HDSH1 \right. \right. \\ \left. \left. - f_{DRC} \left(\frac{W_{S5S2}}{N_L} \right)^2 \right] / [1 + f_{DRC} (C_{VRC} S_{VRC})^2] \right\}^{0.5} \quad (3-2.34)$$

where

$$HDSH1 = \frac{Y_{RCD} [\rho(T_{S5}) - \rho(T_{S6})]}{144} \quad (3-2.35)$$

However, when Eq. (3-2.34) was used in obtaining W_{RCS} it resulted in undesirable oscillations of this variable, it was therefore replaced by

$$W_{RCS} = N_L C_{VRC} S_{VRC} \sqrt{\Delta P_{VRC}} \quad (3-2.36)$$

Where ΔP_{VRC} is the pressure drop across the recirculation valve, which was assumed to remain constant at its normal operation value, i.e., W_{RCS} was assumed to be proportional to S_{VRC} . (See sections (B-2.1,3) for the normal operation values of W_{RCS} , S_{VRC} , and ΔP_{VRC}).

3-2.3.6 AFW Drive Turbine Flow (W_{APTS}). Applying the momentum balance between the steam drum and the inlet to the turbine, and neglecting the acceleration head,

$$P_{APT} = \bar{P}_{S4} + \frac{Y_{DAPT} \rho_{GS4}}{144} - f_{DAPT} \left(\frac{W_{APTS}}{N_L} \right)^2 - \left(\frac{W_{APTS}}{C_{VAPT} S_{VAPT}} \right)^2$$

(3-2.37)

where

P_{APT} = the pressure (psia) on the turbine side of the turbine pressure control valve, (i.e., at the inlet to the turbine).

S_{VAPT} = normalized stroke of the AFP drive turbines' pressure control valve.

Equation (3-2.37) is rearranged as follows:

$$W_{APTS} = (C_{VAPT} S_{VAPT}) \left\{ [\bar{P}_{S4} - P_{APT} + \frac{Y_{DAPT} \rho_{GS4}}{144.0}] / [1 + f_{DAPT} (C_{VAPT} S_{VAPT} / N_L)^2] \right\}^{0.5}$$

(3-2.38)

where

$$P_{APT} = A_{VAPT} W_{APTS}$$

(3-2.39)

in which A_{VAPT} is a constant determined knowing that [2]

$$P_{APT} = 1000 \text{ psig}$$

and

$$W_{\text{APTS}} = 13.34 \text{ lb}_m/\text{Sec} (\cong 4.8 \times 10^4 \text{ lb}_m/\text{hr})$$

at the auxiliary system rated conditions.

3-2.3.7 PACC Steam/Water Flow (W_{S7S3}). Applying the momentum balance along the closed loop containing the steam drum and the protected air cooled condenser, we find that:

$$\frac{Y_{\text{DPC}} (\rho_{fS4} - \rho_{gS4})}{144} = f_{\text{DPCD}} \left(\frac{W_{S7S3}}{N_L} \right)^2 + \left(\frac{W_{S7S3}}{N_L C_{\text{VPC}} S_{\text{VPC}}} \right)^2 \quad (3-2.40)$$

where

Y_{DPC} = the difference in levels between the drum outlet header and the PACC inlet (ft).

f_{DPCD} = friction constant of the path from the drum to the PACC and back to the drum.

S_{VPC} = normalized stroke of the PACC isolation valve.

Thus,

$$W_{S7S3} = (N_L C_{\text{VPC}} S_{\text{VPC}}) \left\{ \left[\frac{Y_{\text{DPC}} (\rho_{fS4} - \rho_{gS4})}{144} \right] / [1 + f_{\text{DPCD}} (C_{\text{VPC}} S_{\text{VPC}})^2] \right\}^{0.5} \quad (3-2.41)$$

and

$$\frac{dS_{VPC}}{dt} = \frac{S_{VPCD} - S_{VPC}}{\tau_{PC}} \quad (3-2.42)$$

where S_{VPCD} is the desired value of S_{VPC} and has two discrete values as follows: (a) from the start of the transient until the control system initiates the long term heat removal system, $S_{VPCD} = 0$, (b) during the period in which the long term heat removal subsystem is active, $S_{VPCD} = 1$, and τ_{PC} is the valve actuator time constant which is much larger (~ 700 Sec) than other valves' time constants (~ 0.5 to ~ 2 Sec).

3-3 After Shut Down Decay Heat

The main source of information for this section is Reference [14], in which the fission product shut down heating following an infinite irradiation period, $M(\infty, t)$ as a function of time, normalized with respect to the fission rate at the operating level in a typical thermal reactor, is presented in tabular form. "This infinite irradiation data can be corrected for any finite reactor irradiation time from the equation

$$M(I, t) = M(\infty, t) - M(\infty, I+t) \quad (3-3.1)$$

where $M(I, t)$ is the $\beta + \gamma$ energy release at time t sec, following an irradiation of I sec at unit fission rate." [14]

An estimate of I for the CRBR is obtained as follows: The capacity factor is 0.75 (see Table 2-3 of Reference [1]). Thus there

are $0.75 \times 365 = 274$ full-power days/year. The total irradiation time (the residence time) for three consecutive refueling cycles (the refueling cycle is one year period) is 822 days, and therefore

$$I \approx 7.1 \times 10^7 \text{ sec} \quad (3-3.2)$$

Using this value of I , and Eq. (3-3.1) above, with the $M(\infty, t)$ given in Table 2 of Reference [14], the table for $M(I, t)$ was constructed² (see Table B-3.1). However, it is suggested in the same reference that a 20% margin should be included to take into account the uncertainties in the cross sections. Taking this uncertainty factor into account, the normalized fission product decay heat table which is referred to as DCAYHT in the CRBRP DCHT simulator was obtained. The entries of this table still do not include the heating effect of the actinides. It is stated in Reference [14] that "for decay times $t \leq 10^8$ sec, the actinide shutdown heating is $< \sim 5\%$ of fission product shutdown heating." Thus the data from the DCAYHT table, multiplied by 1.05, will represent the normalized shutdown heating from both the fission products and the actinides.

The above data is for thermal reactors, whereas CRBR is a fast reactor. This is taken into account by multiplying the thermal reactor data by an assumed factor of 1.3.

2. This was done by Gorge Radda, a graduate student in the Nuclear Engineering Department.

Noting that the units of DCAYHT(t) are Mev/fission (see Table B-3.1), and taking the actinide and spectral factors into account, the estimated CRBR decay heat rate normalized relative to the total reactor power is given by:

$$\text{DCHT} = \left(\frac{1.05 \times 1.3}{180 \text{ Mev/ fission}} \right) \text{DCAYHT}(t) \quad t \geq t_{\text{scram}}$$

i.e.,

$$\text{DCHT} = 7.583 \times 10^{-3} N(0) \text{DCAYHT}(0) \quad t \leq t_{\text{scram}} \quad (3-3.3a)$$

and

$$\text{DCHT} = 7.583 \times 10^{-3} N(0) \text{DCAYHT}(t-t_{\text{scram}}) \quad t \geq t_{\text{scram}} \quad (3-3.3b)$$

where

$N(0)$ = the fission power at the normal operating level,
normalized relative to the total (fission and decay)
power at that level.

Consequently, the total power $N_T(t)$ is obtained from:

$$N_T(t) = N(t) + \text{DCHT}(t) \quad (3-3.4a)$$

with

$$N_T(0) = 1 \quad (3-3.4b)$$

3-4 The Outlet Plenum Model

Aside from its bearings on the prediction of the thermal stresses in the plenum and the hot leg pipe lines, the sodium temperatures in the outlet plenum directly influence the thermal transients in the IHX, and indirectly the transients in the rest of the plant, and should therefore be simulated as accurately as possible. Keeping this in mind, and anticipating large changes in reactor power and flow rate following the reactor scram, complete mixing in the outlet plenum is viewed as inadequate modeling of the actual temperature distribution in that plenum.

A more detailed model should therefore be considered. As a basis for such a model, it was assumed that the sodium temperature distribution in the reactor outlet plenum is mainly affected by the following two factors:

1. The magnitude of the fluid velocity at the subassembly exit nozzle (i.e., at the entrance of the plenum), which may be classified as a feed forward effect (except when natural circulation dominates in the primary loop(s)).
2. The axial distribution of the sodium density in the plenum, which is a feedback effect.

The first factor can be accounted for by calculating the penetration range that the incoming sodium can reach before it comes to a relative halt with respect to the surrounding sodium in the plenum, and then postulating that complete mixing will occur within this range, regardless of the value of the plenum inlet temperature

(which could have otherwise been an influencing factor). This penetration range is obtained in the following way: The reduction in the momentum force over the penetration range equals the gain in the potential force over that range, i.e.,

$$\frac{(FFC W_{ps})^2}{A_{SuB NOZ} N_{SuB} \rho_{NA}(T_{p3})} = \rho_{NA}(T_{p4}) g y_{KE} (A_{SuB NOZ} N_{SuB})$$

i.e.,

$$y_{KE} = \frac{1}{g \rho_{NA}(T_{p3}) \rho_{NA}(T_{p4})} \left(\frac{FFC W_{ps}}{A_{SuB NOZ} N_{SuB}} \right)^2 \quad (3-4.1)$$

where

y_{KE} = the (kinetic energy) penetration range, measured from the plenum entrance (ft).

$A_{SuB NOZ}$ = cross sectional area of the subassembly exit nozzle.

and where W_{ps} , FFC , T_{p3} and N_{SuB} have the same meanings stated in the previous chapter.

The role of the second factor, which is the sodium axial density distribution in the plenum, is easily described by postulating that the sodium in the plenum occupies three separate axial regions at most. (This number is chosen as a compromise between the simplicity of the model versus its accuracy, since the number of regions can be increased

toward approaching the distributed parameter model as a limit.) These regions from the bottom to the top are:

1. Complete mixing region within Y_{KE} .
2. Progressively lower density layers from Y_{KE} up to a certain level. (This region height will be referred to as Y_{p42} , and will be determined later).
3. Complete mixing region from $Y_{KE} + Y_{p42}$ to the sodium surface in the plenum, with region height Y_{p41} .

This configuration does not prevail all the time, of course, since the number of regions at any time depends on the relative values of the sodium density and its derivative at the boundaries between each pair of adjacent regions. It seemed preferable to compare $\rho_{NA}(Y_{KE} + Y_{p42}^-)$ with $\rho_{NA}(Y_{KE} + Y_{p42}^+)$ in order to determine whether mixing occurs or not between the middle and the upper regions, whereas the sign of $d\rho_{NA}(Y_{KE})/dt$ is the parameter selected for deciding whether mixing occurs between the lower and the middle regions or not. (The reason for this preference is clarified after the model presentation.)

Following this introduction, one can visualize one of the following configurations in the plenum:

$$1. \quad Y_{KE} \geq Y_{p4}$$

where Y_{p4} is the total sodium level in the plenum, assumed to remain constant at Y_{p4I} . In this case total mixing will take place in the plenum, and

$$\frac{dT_{p4M2}}{dt} = W_{ps} (T_{R3} - T_{p4M2}) / M_{p4M2} \quad (3-4.2)$$

where the subscript p4M2 refers to the lower mixing region (p4M1 is reserved for the upper mixing region).

Also

$$M_{p4M2} = Y_{KE} A_{p4} \rho_{NA} (T_{p4M2}) \quad (3-4.3)$$

where A_{p4} is an effective sodium cross sectional area in the outlet plenum (see Section A-6-4).

In this case we also have:

$$T_{p4} = T_{p4M2} \quad (3-4.4)$$

where T_{p4} is the sodium temperature at the reactor outlet nozzle(s).

In addition, from mass balance in the lower mixing region, we have:

$$W_{p4M2} = - \frac{dM_{p4M2}}{dt} \quad (3-4.5)$$

where W_{p4M2} is the flow rate across the boundary between the middle and the lower regions, and where

$$\frac{dM_{p4M2}}{dt} \approx A_{p4} \rho_{NA} (T_{p4M2}) \frac{dY_{KE}}{dt} \quad (3-4.6)$$

in this equation dY_{KE}/dt is obtained from:

$$\frac{dY_{KE}}{dt} = 10[Y_{KE}(t) - Y_{KE}(t - 0.1)] \quad (3-4.7)$$

(The 0.1 sec delay is arbitrarily chosen. Generally in the digital approximation of the time derivative, it is preferable to avoid dividing by the time step, since it can cause numerical divergence; therefore a suitable fixed time delay should be used instead.)

However, if $Y_{KE} \geq Y_{p4I}$, Y_{KE} is set equal to Y_{p4I} , such that M_{p4M2} will not be greater than the total mass of sodium in that plenum, which is $Y_{p4I} A_{p4} \rho_{NA}(T_{p4M2})$, i.e.,

$$\frac{dM_{p4M2}}{dt} = \frac{dY_{KE}}{dt} = 0 \quad \text{if } Y_{KE} \geq Y_{p4I}$$

Hence

$$W_{p4M2} = 0 \quad (3-4.8)$$

Also

$$Y_{p42} = 0 \quad (3-4.9)$$

where Y_{p42} is the height of the middle region, and

$$T_{p42} = T_{p4M2} \quad (3-4.10)$$

where T_{p42} is the temperature at the boundary between the middle and the upper region.

The temperature and mass of sodium in the upper mixing region are given by

$$T_{p4M1} = T_{p4M2} \quad (3-4.11)$$

$$M_{p4M1} = 0 \quad (3-4.12)$$

$$2. \quad Y_{PETON} \leq Y_{KE} \leq Y_{P4I} \quad \text{and} \quad \rho_{NA}(T_{p42}) \leq \rho_{NA}(T_{p4M1})$$

where Y_{PETON} is the difference in level from the plenum entrance to reactor outlet nozzle.

This case is referred to as an upper mixing case, since the middle and the upper regions will form one region, in which the temperature T_{p4M1} is given by:

$$\frac{dT_{p4M1}}{dt} = W_{p4M2} (T_{p4M2} - T_{p4M1}) / M_{p4MU} \quad (3-4.13)$$

where

$$M_{p4MU} = M_{p4M1} - M_{p4M2} \quad (3-4.14)$$

i.e.,

$$\frac{dM_{p4M1}}{dt} = - \frac{dM_{p4M2}}{dt} \quad (3-4.15)$$

However, in this case, as in the previous one:

$$W_{p4M2} = - \frac{dM_{p4M2}}{dt}$$

$$T_{p4} = T_{p4M2}$$

$$Y_{p42} = 0$$

$$T_{p42} = T_{p4M2}$$

and

$$\frac{dT_{p4M2}}{dt} = W_{ps} (T_{R3} - T_{p4M2}) / M_{p4M2}$$

$$3. \quad Y_{PETON} \leq Y_{KE} \leq Y_{p4I}, \quad \rho_{NA}(T_{p42}) > \rho_{NA}(T_{p4M1}) \quad \text{and} \quad \frac{d\rho(T_{p4M2})}{dt} \leq 0$$

This case is referred to as a lower mixing case, since the lower and the middle regions form one region (temperature wise), for which the mass M_{p4ML} is given by:

$$M_{p4ML} = M_{p4MI} - M_{p4M1} \quad (3-4.16)$$

where

$$\frac{dM_{p4M1}}{dt} = 0$$

(This is obtained from the mass balance in the upper region.)

The temperature in this lower mixed region is

$$\frac{dT_{p4M2}}{dt} = W_{ps} (T_{R3} - T_{p4M2}) / M_{p4ML} \quad (3-4.17)$$

We also have the following relations

$$W_{p4M2} = - \frac{dM_{p4M2}}{dt}$$

$$T_{p4} = T_{p4M2}$$

$$\frac{dT_{p4M1}}{dt} = 0$$

$$Y_{p42} = 0$$

and

$$T_{p42} = T_{p4M2}$$

The derivative $d\rho(T_{p4M2})/dt$ is obtained from the following equation (in which the 5° F is an arbitrary choice):

$$\frac{d\rho(T_{p4M2})}{dt} = \left[\frac{\rho_{NA}(T_{p4M2}+5) - \rho_{NA}(T_{p4M2}-5)}{10} \right] \frac{dT_{p4M2}}{dt} \quad (3-4.18)$$

$$4. \quad Y_{PETON} \leq Y_{KE} \leq Y_{p4I}, \quad \rho_{NA}(T_{p42}) > \rho_{NA}(T_{p4M1}) \quad \text{and} \quad \frac{d\rho(T_{p4M2})}{dt} > 0$$

In this case three separate regions exist in the plenum, for which we have the following relations:

$$\frac{dM_{p4M1}}{dt} = 0$$

$$W_{p4M2} = - \frac{dM_{p4M2}}{dt}$$

$$T_{p4} = T_{p4M2}$$

$$\frac{dT_{p4M1}}{dt} = 0$$

$$Y_{p42} = Y_{p4I} - Y_{p41} - Y_{KE} \quad (3-4.19)$$

where

$$\frac{dY_{p41}}{dt} = \frac{1}{A_{p4} \rho(T_{p4M1})} \frac{dM_{p4M1}}{dt} \quad (3-4.20)$$

we also have

$$\tau_{p42} = Y_{p42} A_{p4} [\rho(T_{p4M1}) + \rho(T_{p4M2})] / (2 W_{p4M2}) \quad (3-4.21)$$

and

$$T_{p42}(t) = \text{PDELAY}(T_{p4M2}(t), \tau_{p42}(t), J, T_{p4M2}(t_{p42})) \quad (3-4.22)$$

where t_{p42} is the time at which the three regions start to form. (Note that at $t = t_{p42}$ $\tau_{p42} = 0$ since $Y_{p42}(t_{p42}) = 0$)

Also

$$\frac{dT_{p4M2}}{dt} = W_{ps} (T_{R3} - T_{p4M2}) / M_{p4M2}$$

$$5. \quad Y_{KE} \leq Y_{PETON} \quad \text{and} \quad \rho_{NA}(T_{p42}) \leq \rho_{NA}(T_{p4M1})$$

This is an upper mixing case for which:

$$W_{p4M2} = W_{ps} - \frac{dM_{p4M2}}{dt}$$

$$T_{p4} = T_{p4M1}$$

$$\frac{dM_{p4M1}}{dt} = \frac{dM_{p4Mu}}{dt} = - \frac{dM_{p4M2}}{dt}$$

where

$$M_{p4Mu} = M_{p4I} - M_{p4M2} \quad (3-4.23)$$

$$\frac{dT_{p4M1}}{dt} = W_{p4M2} (T_{p4M2} - T_{p4M1}) / M_{p4Mu}$$

$$Y_{p42} = 0$$

$$\tau_{p42}(t) = 0$$

$$T_{p42} = T_{p4M2}$$

and

$$\frac{dT_{p4M2}}{dt} = W_{ps} (T_{R3} - T_{p4M2}) / M_{p4M2}$$

$$6. \quad Y_{KE} \leq Y_{PETON}, \quad \rho_{NA}(T_{p42}) > \rho_{NA}(T_{p4M1}) \quad \text{and} \quad \frac{d\rho(T_{p4M2})}{dt} \leq 0$$

$$6a. \quad Y_{p41} > (Y_{p4I} - Y_{PETON})$$

This is a lower mixing case for which:

$$\frac{dM_{p4M1}}{dt} = -W_{ps}$$

$$W_{p4M2} = W_{ps} - \frac{dM_{p4M2}}{dt}$$

$$T_{p4} = T_{p4M1}$$

$$\frac{dT_{p4M1}}{dt} = 0$$

$$Y_{p42} = 0$$

$$\tau_{p42} = 0$$

$$T_{p42} = T_{p4M2}$$

$$M_{p4ML} = M_{p4MI} - M_{p4M1} \quad (3-4.24)$$

and

$$\frac{dT_{p4M2}}{dt} = W_{ps} (T_{R3} - T_{p4M2}) / M_{p4ML}$$

$$6b. \quad Y_{p4I} \leq (Y_{p4I} - Y_{PETON})$$

This case is very similar to case (6a) above, except that:

$$\frac{dM_{p4M1}}{dt} = 0$$

and

$$T_{p4} = T_{p4M2}$$

$$7. \quad Y_{KE} \leq Y_{PETON}, \quad \rho_{NA}(T_{p42}) > \rho_{NA}(T_{p4M1}) \quad \text{and} \quad \frac{dp(T_{p4M2})}{dt} > 0$$

$$7a. \quad Y_{p4I} > (Y_{p4I} - Y_{PETON})$$

This case is similar to case (4) above, except that:

$$\frac{dM_{p4M1}}{dt} = -W_{ps}$$

$$T_{p4} = T_{p4M1}$$

and

$$W_{p4M2} = W_{ps} - \frac{dM_{p4M2}}{dt}$$

$$7b. \quad Y_{p4I} \leq (Y_{p4I} - Y_{PETON})$$

This case is similar to case (4) above, except that:

$$W_{p4M2} = W_{ps} - \frac{dM_{p4M2}}{dt}$$

and

$$T_{p4} = PDELAY (T_{p4M2}(t), \tau_{p4}(t), J, T_{p4M2}(t_{p4})) \quad (3-4.25)$$

where

$$\tau_{p4} = A_{p4} (Y_{PETON} - Y_{KE}) [\rho_{NA}(T_{p4M1}) + \rho_{NA}(T_{p4M2})] / (2 W_{p4M2}) \quad (3-4.26)$$

and where t_{p4} is the time at which the reactor outlet nozzles begin to fall within the middle region (t_{p4} can be a multivalued parameter depending on the number of repetitions of this case).

CHAPTER 4

PLANT CONTROLLERS

Actuating signals, set points, and transfer function block diagrams for the plant controllers are presented in this chapter.

4-1 Actuating Signals

4-1.1 Turbine Flow-Control Valve Position Regulator

Actuating signals are: (a) deviation of the generated power from its demand value, (b) deviation of the (feedback) rotary system speed from the synchronous value, and (c) deviation of the turbine high pressure from a set value, combined with the same for the exhaust pressure.

4-1.2 Dump-Flow Valve Actuator

The main purpose of this controller is to achieve a rapid regulation of the turbine high pressure whenever it exceeds a maximum value until it returns to its set point. Thus the only actuating signal in this case is the deviation of the turbine high pressure from its set point.

4-1.3 Steam Drum Water-Level Regulator

Actuating signals are generated from (a) drum water level deviation from its set point, and (b) superheated steam/feedwater flow mismatch.

4-1.4 Intermediate Flow/Pump Speed Regulator

Error signals are due to (a) deviation of the turbine high pressure from a set point, (b) deviation of the intermediate flow from its demand value, and (c) deviation of the intermediate pump speed from a set point.

4-1.5 Primary Flow/Pump Speed Regulator

Error signals are due to (a) deviation of the reactor inlet temperature from its demand value, (b) deviation of the primary flow from its demand value, and (c) deviation of the primary pump speed from a set point.

4-1.6 Control Rod Position Regulator (Reactivity Controller)

The error signals include those arising from (a) deviation of the superheated steam temperature at the turbine inlet from a desired value, (b) deviation of the reactor exit temperature from its demand value (actually the core exit temperature is measured, not the reactor exit temperature), and (c) deviation of the reactor power either from a set point (reactor follow mode of operation), or from a desired value corresponding to the load demand (i.e., load follow mode of operation).

4-2 Partial Load Characteristics of The Controlled Variables

The desired values (set points) of some of the controlled variables at partial load remain constant. These are:

$P_{S9D} = 1450$	Psig
$T_{S9D} = 900$	F°
$P_{EXH} = 2$	in.Hg (assumed)
$Y_{S5D} = 3$	ft (assumed)
$N_{PPD} = 1170$	rpm
$N_{IPD} = 1006$	rpm

The desired values for the other controlled variables are taken from Figure 4-1 of reference 1, where linear approximations over two power ranges ($40\% \leq \text{power} \leq 60\%$ of normal power and $60\% \leq \text{power} \leq 115\%$) are made:

a. $40\% \leq \text{power} \leq 60\%$:

$$W_{PSD} = 11512.777 \text{ N} \quad \text{lb}_m/\text{sec} \quad (4-2.1)$$

$$W_{ISD} = -1422.833 + 12072.833 \text{ N} \quad \text{lb}_m/\text{sec} \quad (4-2.2)$$

$$T_{P4D} = 898 + 96.73 \text{ N} \quad \text{F}^\circ \quad (4-2.3)$$

$$T_{R1D} = 644 + 86 \text{ N} \quad \text{F}^\circ \quad (4-2.4)$$

b. $60\% \leq \text{power} \leq 115\%$:

$$W_{PSD} = 11512.777 \text{ N} \quad \text{lb}_m/\text{sec} \quad (4-2.5)$$

$$W_{ISD} = 9701.4446 \text{ N} \quad \text{lb}_m/\text{sec} \quad (4-2.6)$$

$$T_{P4D} = 918.75 + 62.15 \text{ N} \quad \text{F}^\circ \quad (4-2.7)$$

$$T_{R1D} = 662.7 + 54.834 \text{ N} \quad \text{F}^\circ \quad (4-2.8)$$

Finally, TRQ_{ID} and TRQ_{PD} of the intermediate and primary pump speed regulators are obtained as follows:

$$TRQ_{ID} = \left(\frac{g}{2\pi/60}\right) W_{ISD} \quad HOIP_D / (N_L N_{IPD} \eta_{IPD}) \quad (4-2.9)$$

where

$$HOIP_D = HMM(N_{IPD}, Q_{IPD}) \quad (4-2.10)$$

in which HMM is the name given to Table 2-7.1 in the simulators (see appendices G and H), and where

$$Q_{IPD} = 0.44876 W_{ISD} / [N_L \rho_{NA}(T_{I9})] \quad (4-2.11)$$

and η_{IPD} is obtained from Eq. (2-7.4) in which Q_{IP} and N_{IP} are replaced by Q_{IPD} and N_{IPD} respectively.

Similarly,

$$TRQ_{PP} = \left(\frac{g}{2\pi/60}\right) W_{PSD} \quad HOPP_D / (N_L N_{PPD} \eta_{PPD}) \quad (4-2.12)$$

$$HOPP_D = HMM(N_{PPD}, Q_{PPD}) \quad (4-2.13)$$

$$Q_{PPD} = 0.44876 W_{PSD} / [N_L \rho_{NA}(T_{P4})] \quad (4-2.14)$$

and η_{PPD} is obtained from Eq. (2-7.3), with Q_{PP} and N_{PP} replaced by Q_{PPD} and N_{PPD} respectively.

4-3 Transfer Function Block Diagrams
for the ATWS Controllers.

In this section the transfer function block diagrams of the plant controllers during normal transients are presented in Figures 4-3.1 to 4-3.6.

Figure 4-3.1. Transfer Function Block Diagram of the Turbine Flow-Control Valve Position Regulator

Figure 4-3.2. Transfer Function Block Diagram of the Dump-Flow Valve Actuator

Figure 4-3.3. Transfer Function Block Diagram of the Steam Drum Water-Level Regulator

Figure 4-3.4. Transfer Function Block Diagram of the Intermediate Flow/Pump Speed Regulator

Figure 4-3.5. Transfer Function Block Diagram of the Primary Flow/Pump Speed Regulator

CHAPTER 5

AFTER-SCRAM PLANT CONTROLLERS

The controllers to be discussed in this chapter are:

1. The auxiliary feedwater pump drive turbine's high pressure controller.
2. The steam drum water level and AFW temperature controller.
3. The primary pony motor flow and pump speed controller.
4. The intermediate pony motor flow and pump speed controller.

In the following sections the controllers' actuating signals, the set points for the controlled variables and the controllers' transfer function block diagrams will be presented, respectively.

5-1 Actuating Signals

5-1.1 The AFWP Drive Turbine High Pressure Regulator

The actuating signal is the difference between unity and the measured value of the normalized high pressure of the AFWP drive turbine ($PAPTN = PAPT/PAPTD$; See Figure 5-3.1 below). The reason that the pressure signals are normalized is to reduce the wide range of the measured pressure signal from the time at which the measurements begin until the rated value is reached. This reduces the numerical divergence in the simulation.

5-1.2 The Steam Drum Water Level and AFW Temperature Regulator

The functions of this regulator are carried out by two flow control valves. One of these valves is located on the AFW pipe lines between the AFW header and the recirculation heater and is referred to as V52, and the second is placed on the recirculation line from the steam drum to the recirculation heater and is referred to as VRC. As is clear from the transfer function block diagram (Figure 5-3.2) the VRC valve does not play any role in regulating the water level in the drum since the flow across this valve goes directly and fully back to the drum (under the assumption that the mass of the subcooled water in the recirculation heater remains constant). However, the flow across this valve is adjusted simultaneously with that across V52 such that the temperature of the AFW to the drum remains close to its desired value. In addition to being a part of the AFW temperature controller, the V52 valve also regulates the AFW flow rate such that the drum water level remains as close as possible to its desired value.

5-1.3 The Primary Pony Motor Flow and Pump Speed Regulator

This is a two level regulator (i.e., composed of two nested regulators) in which the error signals of both the primary flow and the primary pump speed act to control the pump torque such that the set points of the flow and the pump speed are achieved (see Figure 5-3.3).

5-1.4 The Intermediate Pony Motor Flow and Pump Speed Regulator

As is clear from the transfer function block diagrams (see Figures 5-3.3,4) this regulator is identical with its primary loop counterpart.

5-2 The Set Points

$P_{\text{APTD}} = 1000 \text{ Psig}$, from Reference 2.

$S_{\text{VAPTD}} = 0.85$, assumed

$T_{\text{S5D}} = 454^\circ \text{ F}$, assumed to be the same as its normal operation value.

$Y_{\text{S5D}} = 3 \text{ ft}$, assumed to be equal to its normal operation value.

$S_{\text{VRCD}} = S_{\text{V52D}} = 0.7$, assumed as in all other water flow control valves.

$W_{\text{PSD}} = 1151.278 \text{ lb}_m/\text{sec}/\text{three loops}$, assumed to be $\sim 10\%$ of of the full power primary flow.

$EN_{\text{PPD}} = 107 \text{ rpm}$, assumed to be equal to the rated pony motor speed.

$TRQ_{\text{PD}} = 5128.9 \text{ lb}_f\text{-ft}/\text{rad}$, this is obtained from eq. (4-2.12) at

$(W_{\text{PSD}}, N_{\text{PPD}}) = (1151.278, 107)$

and

$$HOPP_D = HPM (N_{PPD}, Q_{PPD})$$

where HPM is the simulator name for Table 2-7.2 and Q_{PPD} is obtained from Eq. (4-2.14), whereas η_{PPD} is obtained from Eq. (2-7.3) in which Q_{pp} and N_{pp} are replaced by Q_{PPD} and N_{PPD} respectively (η_{PPD} appears in Eq. 4-2.12).

On the other hand $TRQ_{IP} \approx 3992.61 \text{ lb}_f\text{-ft/rad}$, which is obtained from Eq. (4-2.9) at

$$(W_{ISD}, N_{IPD}) = (1065, 92)$$

whereas

$$HOIP_D = HPM (EN_{IPD}, Q_{IPD})$$

and η_{IPD} is obtained from Eq. (2-7.4) in which Q_{IP} and N_{IP} are replaced by Q_{IPD} and N_{IPD} , respectively.

5-3 Transfer Function Block Diagrams
for the After Scram Controllers

The transfer function block diagrams of the plant controllers during the transients that follow reactor scram are presented in Figures 5-3.1, 2, 3, 4.

Figure 5-3.1. Transfer Function Block Diagram of the AFW Drive Turbine High Pressure Regulator

Figure 5-3.2. Transfer Function Block Diagram of the Steam Drum Water-Level-AFW Temperature Regulator

Figure 5-3.3. Transfer Function Block Diagram of the Primary Pony Motor Flow-Pump Speed Regulator

Figure 5-3.4. Transfer Function Block Diagram of the Intermediate Pony Motor Flow-Pump Speed Regulator

CHAPTER 6

RESULTS AND RECOMMENDATIONS

Results for selected perturbations are presented in graphs at the end of this Chapter. The first set of these graphical results is a comparison of the steam generator transients utilizing approximate linear thermodynamic state equations versus standard data tables. The Eposide integration rule was used in both transients. This is followed by a comparison of the steam generator transients utilizing the Episode, Gear's and Secker's integration rules. Standard data tables were used with each of the three rules. The transients for the total plant without controllers include those due to a step input reactivity and to two reactivity ramp rates. Controlled plant transients include those following two values of step reactivities and one ramp rate load change. An uncontrolled control rod withdrawal transient was simulated by the DCHT simulator and is presented following the controlled plant transients. The very expensive computer cost (especially when the controlled plant or the decay heat simulator is used) constituted a major factor in limiting the number of transients presented in this Chapter.

6.1 Discussion of Results

6.1.1 Steam Generator Transients

In obtaining the following results it was found that the value of the parameter EMAX (an integration error bound) is more significant for the numerical stability than the accuracy of an integration

rule. In other words, as long as there is no divergence, the variation in value of a variable for different values of specified EMAX is very much within the margin of expected errors due to the approximations made in constructing the model.

a. A Comparison of Approximate Linear Thermodynamic Equations Versus Standard Data-Tables. As was previously mentioned, the Episode integration rule was used with both models. Although it is not clear on the graphs, the initial values of some of the variables differ slightly in the two models (see Appendices I and J). This is because the constants of the linear thermodynamic equations are chosen such that the value of a thermodynamic property obtained from one of these equations closely approximates the value of that property as given by the standard data table over the expected range of the transient. From Figures 6-3.1, 2, and 3 the transients with both models following a 10% reduction in the superheated steam flow, a 10% reduction in the intermediate sodium flow, and a 20° F increase in the superheater inlet sodium temperature, respectively, are approximately identical. However, a 10% reduction in the feedwater flow rate results in a relatively larger difference between the two models (see Figure 6-3.4). The author believes that the larger sensitivity of the models to perturbations in the feedwater parameters as compared with perturbations in the sodium or superheated steam parameters is indicative of the inadequacy of using single slope linear approximations for the subcooled water thermodynamic properties over the whole range of a transient. In Figure 6-3.4, the superheater exit steam pressure (PSC) is larger and the temperature

(TSC) is lower when linear thermodynamic approximations are used than when tables are used because of the larger steam densities in the former model. The water level ELS1 is higher with linear thermodynamic approximations because of the higher subcooled water flow rate. The higher subcooled water and steam/water mixture flow rates (WS1 and WS3) are due to the larger pressure head in the steam/water loop resulting from the larger densities when linear thermodynamic approximations are used.

In Figure 6-3.1, which is the open loop steam generator transient following a 10% reduction in the superheated steam flow at constant inlet feedwater and intermediate sodium conditions, the initial sudden increase in the superheater exit steam pressure is due to the sudden reduction in the friction losses following the reduction in the steam flow rate (these losses are proportional to the square of the flow rate). The slower final increase of this pressure, even though the steam flow rate is constant, is due to the increase of the pressure in the steam drum resulting from the accumulation of steam and the increase in the water level in the drum. The initial rapid increase in the superheater exit steam temperature is due to the initial increase in the heat transferred to the steam compared with the heat transported out of it following the sudden reduction in the steam flow rate. This temperature will begin to decrease when the reduction in the inlet saturated steam enthalpy (due to the increase in the corresponding pressure) and the increase in the outlet superheated steam enthalpy offset the reduction in the steam flow rate to the point where the net heat transported out of the steam exceeds

the heat transferred into it. The increase in the superheater exit sodium temperature is due to the reduction in the heat transferred out of it. The rate of this increase in the superheater exit steam temperature is proportional to the temperature gradient between the sodium and the wall as can be easily seen from the superheater average temperature graphs. The reason that the average temperature of the superheated steam continues to increase slowly (following its initial faster increase) even when the exit steam temperature decreases is the continuous increase in the saturated steam temperature at the entrance of the superheater (not shown on the graphs) accompanying the increase in the pressure at that entrance. The increase in the length of the subcooled water region of the evaporator, even though the inlet sodium temperature to the evaporator and the subcooled water temperature are increasing, is due to the increase in the inlet subcooled water flow rate. The increase in the subcooled water temperature is attributed to the increase in the saturated water enthalpy and flow rate entering the steam drum. This increase in the subcooled water temperature may also be attributed to the partial condensation of the steam in the steam drum due to the increase of the pressure there. The initial rapid increase in the subcooled water flow and rapid reduction in the steam/water mixture flow rates are due to the faster response (increase) of the pressure in the steam drum relative to that in the evaporator following the reduction of the superheated steam flow. The final increase in the evaporator inlet and exit flow rates can be attributed to the negative change in the momentum pressure head $[W_{S3}^2/(gA_{S1}^2\rho_{S3}) - W_{S1}^2/(gA_{S1}^2\rho_{fS2})]$ following the

initial increase and decrease of the evaporator inlet and exit flow rates, respectively (see Equations 2-4.21 to 2-4.37). The average pressure on the steam/water side of the evaporator increases, even though the exit steam quality is decreasing, because the inlet flow to the evaporator is consistently higher than the exit flow during the transient. The increase in the water level of the drum is due to the increase in the relative fraction of water in an increasing steam/water mixture flow entering the drum, as well as due to the partial condensation of the steam in the drum because of the increase in the drum pressure.

Figure 6-3.2 is the open loop steam generator transient following a 10% reduction in the intermediate sodium flow rate for both approximate linear thermodynamic equations and standard data tables using the Episode integration rule. In this transient the superheater sodium inlet temperature, as well as the superheated steam flow rate and the feedwater temperature and flow rate, were kept constant at their corresponding initial values. In this figure the transient behavior of the graphed variables is readily understandable.

Figure 6-3.3 is the steam generator transient following a 20°F rise in the superheater inlet sodium temperature at constant intermediate sodium and superheated steam flow rates and constant feedwater temperature and flow rate. The undershoot in the superheater exit sodium temperature occurs because during that period the increase in the heat transferred out of the sodium region due to the increase in the temperature gradient between the sodium and the tube wall exceeds the increase in the

heat transported to the sodium due to the increase in its inlet temperature. The inlet and outlet evaporator flow rates coincide for each model (separately) because of the homogeneous effect of the sodium temperature perturbation on the pressures on the steam/water side. The evaporator flow rates in the approximate linear thermodynamic model are slightly higher than those for the standard data tables because of the larger densities of water and steam obtained from the first model relative to those from the second. The final decrease of the evaporator flow rates in each model is due to the reduction in the hydrostatic pressure head on the steam/water side following the increase in the temperatures on that side.

Figure 6-3.4 is the open loop steam generator transient following a 10% reduction in the feedwater flow at constant feedwater and superheater inlet sodium temperatures and constant intermediate sodium and superheated steam flow rates. The reason for the difference between the transients with the approximate linear thermodynamic equations and the standard data tables was explained earlier in this section. In this figure the decrease in the superheater exit steam pressure follows the decrease in the steam drum pressure which is due to the reduction of the water level in the drum. The transient behavior of the evaporator inlet and exit flow rates is opposite to their behavior in Figure 6-3.1 and a (reverse) correlation can be established between the causes of such behavior in the two cases (see above for the discussion of the transient of Figure 6-3.1).

Finally, in this comparison it should be mentioned that the computer cost of similar runs of the open loop steam generator tends to be 30 to 40% less with the linear approximate thermodynamic equations than with standard data tables.

b. A Comparison of Open Loop Steam Generator Transients

Using Three Different Integration Rules. The three rules utilized are Episode, Gear's, and Secker's. In all cases, standard data tables were used in evaluating the thermodynamic properties of steam, water and sodium. These transients are shown graphically in Figures 6-3.5, 6, 7, and 8. In all these figures, it is notable that there is no difference or very little difference between the transients when either the Episode or Gear's integration rule was used. However, when Secker's rule was used the transient tended to deviate from that in which either of the other two rules was used. In fact, some of the variables seemed to change in a way opposite to what was obtained when either the Episode or Gear's rule was used, as can be seen from region lengths, and inlet and outlet flow rates on the steam/water side of the evaporator shown in Figure 6-3.7. It should also be mentioned that in almost all transients the largest maximum error that can be specified with Secker's integration rule without numerical divergence is one tenth to one hundredth of its value when either the Episode or Gear's rule is used. This naturally increases the computer cost when Secker's rule is used in comparison to that when either of the other two rules is used. Generally, the cost of similar computer runs for the open loop steam generator ranges from 100 to 130% when the Episode rule is used relative to that when Gear's

rule is used; and from 200 to 350% when Secker's rule is used relative to that when Gear's rule is used.

6-1.2 Uncontrolled Plant Transients

Even though the uncontrolled plant transients following small load perturbations fall within the range of moderate transients, they are not presented here. This is because, in the absence of the feedback effect of the load changes on the turbine control valve position, the electric generator is virtually isolated from the rest of the plant, and all except the generator variables remain essentially unchanged following such load changes.

Three cases of reactivity transients were simulated. These are a 25¢ step, a 5¢/sec ramp for 5 seconds, and a 0.25¢/sec ramp for the whole transient period. In all cases the Episode integration rule was used. The maximum error in the first two cases was specified to be 10^{-7} , whereas in the third case it was 5×10^{-8} . The 25¢ step is the maximum anticipated step reactivity disturbance [2] without reactor scram, and the 5¢/sec is the maximum anticipated reactivity ramp rate disturbance [2].

Figure 6-3.9 is the uncontrolled plant transient following a 25¢ positive step reactivity. In this figure, the decrease in the total reactivity that follows its initial jump is, as expected, due to the increase in magnitude of the negative feedback reactivity. It should be noted that all reactivity coefficients, including the average sodium density coefficient, are negative for the CRBR. (No sodium void reactivity is considered since sodium boiling is not expected to take

place during such moderate transients). The normalized power level initial jump is, as expected, due to the use of the prompt jump approximation in evaluating the neutron density in the reactor. The reason that the coolant temperatures in the core initially increase at a rate not much slower than that of the fuel temperature is that the mass heat capacity (MC_p) of the fuel in the core is approximately two and one half times that of the coolant. (The volume fractions in a core fuel assembly are 32.8% fuel, 41.9% sodium, 1.9% gap, and 23.4% structure from Table 4-3.1 of Reference [2]). The continuing increase in the average and exit coolant temperatures of the core, even after the neutron density and the fuel temperature leveloff, is due to the continuing increase in the coolant inlet temperature to the core. The continuous increase in the IHX primary exit temperature even though the rate of heat transfer from the primary to the intermediate sodium of the IHX is increasing (see IHX regions average temperatures of this Figure), is due to the continuing increase in the IHX primary inlet temperature. The increase in the heat transfer from the primary to the intermediate sodium of the IHX is responsible for the large increase in its intermediate sodium exit temperature.

In the simulation, the maximum temperatures in the average and hot channels were assumed to be proportional to the power level, hence they have similar transient shapes to that of the power level. The initial values of these temperatures depend on the hot channel factors used. For more details about how these temperatures were obtained and about their initial values see "Maximum Temperatures in the Average and Hot Channels" in the reactor core section of Chapter 2, and Appendix G.

Figure 6-3.10 is the uncontrolled plant transient following a 5¢/sec ramp insertion for 5 seconds. Except for the value of the peak power and the initial rates of change of variables, this transient is approximately the same in shape and magnitude as that of the 25¢ step reactivity insertion discussed above.

Figure 6-3.11 displays the uncontrolled plant transient that follows the insertion of a 0.25¢/sec reactivity ramp for the whole period of the transient. In this Figure, the initial phase of the transient is much slower than in either of the previous two cases. This is because the slow rate of reactivity insertion allows enough time for the negative feedback reactivity to limit the net rate of reactivity increase to values much lower than the already slow control rod reactivity insertion rate.

6-1.3 Controlled Plant Transients

Two reactivity transients and one load perturbation transient were simulated, and the results are displayed in Figures 6-3.12, 13, and 14. The reactivity transients are due to sudden withdrawals of eccentric control rods causing the insertion of a 10¢ step and 25¢ step reactivity into the core. The Episode integration rule was used in the simulation of these reactivity transients, and the EMAX parameter was specified to be 7.5×10^{-7} and 10^{-6} , respectively. In the load perturbation transient, a ramp of -3% of nominal power per minute was simulated, and the results are presented in Figure 6-3.14. As in the reactivity transients, the Episode integration rule was utilized; however the maximum error in the load perturbation transient was specified as 10^{-5} .

In these controlled plant transients the author mistakenly simulated the stepwise center control rod movement by 0.25 inch increments rather than the correct value 0.025 inch. After uncovering this error, the author attempted to repeat the controlled plant transients with the correct value of the rod movement increment. The drastic increase in the computer run time and cost resulted in limiting this attempt to obtaining 50 sec of the 25¢ step reactivity transient in which the correct rod movement increment was used. This was then compared with the similar transient in which the rod movement increment was 0.25 inch. As expected, the difference between the two transients is minor. Therefore, in order to avoid the additional high computer cost, the author decided to present the controlled plant transient already available.

Figure 6-3.12 displays the transient for the controlled plant following a 10¢ step reactivity insertion. In this figure the rapid reduction of both the total reactivity and the normalized power level, following their initial jumps, is due to the reinforcement by the negative center (fine) control rod reactivity, resulting from its insertion into the core, of the large negative feedback reactivity. This rapid reduction is followed by relatively slower reduction of both the reactivity and the power due to the decrease in magnitude of the negative feedback reactivity once the core temperatures begin to decrease. The initial increase in the primary and the intermediate flow rates is due to the increase in their demand values following the initial jump of the power level (see Section 4-2). This is then followed by reduction of these flows at two different rates (rapid followed by slow)

which corresponds to the reduction of the power during that period (with small time delays between the power and the flow rates). The initial decrease in the evaporator inlet and exit flow rates on the steam/water side is caused by the reduction in the hydrostatic pressure head due to the initial decrease of the temperatures in the steam/water loop.

In Figure 6-3.13, the increase in the core exit and average sodium temperatures during the period 35 to 65 seconds of the transient, even though the reactor power is decreasing, is due to the decrease in the ratio of the primary flow to power during that period. The initial increase in the IHX primary exit temperature, even though the primary and the intermediate inlet temperatures are still constants because of the time delays, is due to the increase of the primary flow rate. The initial increase in the superheater exit steam and sodium temperatures, and the evaporator exit sodium temperature, even though the superheater and evaporator inlet sodium temperatures remain constant during that period because of the time delays, is due to the increase in the intermediate sodium flow rate during that period. The initial decrease of the IHX intermediate exit sodium temperature (T_{I3}) is due to the increase in the intermediate flow. The final increase of this temperature, even though the intermediate flow is leveling off and the intermediate inlet temperature is decreasing, is due to the increase in the heat transferred from the primary to the intermediate regions of the IHX during that period (see the IHX average temperatures in this figure).

Figure 6-3.14 is the controlled plant transient following a negative load ramp perturbation of 3% of full power per minute. In this figure the increase in the power angle is caused by the increase in the accelerating torque (or power) following the reduction in the load demand with respect to the driving torque (or power). The reduction of the generated power is less than the load reduction because of the increase in the power angle (see Equations 2-1.17, 18). Also in this figure, the reduction in the turbine flow is due to the partial closure of the turbine control valves in response to the reduction in the load demand. The decrease in the superheated steam temperatures is due to the reduction in the ratio of the intermediate flow to the superheated steam flow (the intermediate flow is not shown in this figure). The decreasing sodium temperatures in the superheater and evaporator are due to the decrease in the intermediate flow. The increase in the evaporator inlet and exit flow rates on the steam/water side is due to the increase in the hydrostatic pressure head in the steam/water loop. The decrease in the primary and intermediate flow rates is in response to the decrease in the reactor power level because of operating the reactor in a load follow mode.

6.1.4 Uncontrolled Control Rod Withdrawal Followed by Reactor Scram

This transient was simulated by the DCHT simulator described in Chapter 3. The uncontrolled control rod withdrawal was simulated by the insertion of a 25¢ step reactivity into the core. Following this reactivity insertion the control rod position remains constant until the power level reaches 115% of the normal operation level, at which time

a scram signal will be generated. However, the actual control rod motion initiating the reactor scram does not begin until 200 msec later [2]. In simulating the scram reactivity it was assumed that the scram period is 2 seconds and the total available scram reactivity is 7 dollars. This value [2] of available scram reactivity is based on the assumption that the control rod with maximum reactivity worth is stuck out of core. In simulating this transient it was also assumed that pump coast down is to be initiated 500 msec after reactor scram initiation.

The results of this transient indicate that reactor scram was initiated at 211 msec from the time the transient began. In Figure 6-3.15 the transient was terminated at 20 sec due to numerical instability of the integration rule that occurs shortly after 20 sec. In this Figure the initial jump in the net reactivity is followed by a slow reduction due to the increase in the magnitude of the feedback reactivity before the reactor scram. This is followed by a rapid rate of reactivity reduction for a very short period (during the reactor scram) during which the negative feedback reactivity is still increasing in magnitude, then a lesser rate of reactivity reduction takes place once the reactor temperatures start to decrease. The final slow increase of this reactivity after the completion of the reactor scram is due to the continuing decrease in the magnitude of the negative feedback reactivity accompanying the continuing decrease of the reactor temperatures. Also in Figure 6-3.15, the increase in the coolant temperature at the core exit (TP3) at about 8 seconds is due to the continuing

reduction in the primary flow at a faster rate than that in the net power because of the relative constancy of the decay heat during that period.

As mentioned in Chapter 3, the outlet plenum is occupied by three axial regions at most with different temperature distributions (for more details see Chapter 3 under "The Outlet Plenum Model"). Even though not clear on the graph, the length (YP41) of the upper region slightly decreases before the reactor scram due to the increase in the inlet temperature for the outlet plenum (TR3) which results in sodium mixing at the boundary between the top region and the slightly hotter temperature bottom region. During that period there is no sodium stratification in the outlet plenum. Thus the length (YP42) of the stratification (middle) region remains zero. Following reactor scram, the outlet plenum inlet temperature (TR3) starts to decrease in a steady manner. This causes the temperature in the lower mixing region (at the bottom of the plenum) to consistently be colder than that in the top region.

During the period after the reactor scram but before the primary pump coast down, a stratification middle region will start to form due to the continuing increase of the sodium density in the lower region. Thus during that period YP41 increases slightly, then remains constant, whereas YP42 and YKE will slowly increase and decrease, respectively.

After primary pump coast down the lower region length (YKE) decreases at a more rapid rate than before, and the length of the

(stratification) middle region will increase. During that period the length and temperature of the upper mixing region will remain constant since the temperature (TP42) at the top layer of the middle region continues to be lower than the (uniform) temperature of the upper region. It should also be noted that the sodium temperature at the reactor outlet nozzles (TP4) remains equal to that of the lower mixing region (TP4M2) until the length of the lower region (i.e., YKE) becomes less than the level of these nozzles above the plenum entrance. Henceforth, this temperature at the outlet nozzles (i.e., TP4) will follow the temperature in the lower mixing region (TP4M2) with a transport delay which is less than the transport delay between the temperature (TP42) at the top layer of the middle region and the temperature (TP4M2) of the lower mixing region. This explains why TP4 falls between TP42 and TP4M2.

In Figure 6-3.15 the reduction in the IHX primary exit temperature is caused by the reduction in the heat transported into the primary region ($C_{PP} W_P T_{P5}$) as a result of the reduction of the primary flow. The primary inlet temperature (TP5) remains initially constant due to the transport delay between the reactor exit and the IHX primary inlet (this delay increases from its initial value 15.2 sec due to the decrease in the primary flow rate). The increase in the IHX intermediate exit temperature (TI3) is due to the reduction in the intermediate flow such that the reduction in the heat transferred and transported into the intermediate sodium, $H_I(\bar{T}_{P5} - \bar{T}_{I1}) + C_{PI} \bar{T}_{I1} W_I$, is less than the reduction in the heat transported out of the intermediate region ($C_{PI} W_I T_{I3}$);

see Eq. (2-5.12). The IHX intermediate inlet temperature remains constant initially due to the transport delay between the IHX intermediate inlet and the evaporator sodium exit (the initial value of this delay is 21.2 sec).

The sensitivity of the exit temperature of a region in any component to the heat transport term at the hottest temperature in that region arises from the large difference between the inlet and exit temperature of that region. Therefore, this sensitivity could be reduced by increasing the number of axial regions in a component (and thus reduce the temperature difference between the inlet and exit of each region).

Returning to Figure 6-3.15, the superheated steam flow (WSA) remains constant before the reactor scram. After scram the isolation valves on the pipe lines extending from the exit of the superheater continue to close, resulting in a large rise of the superheater exit steam pressure (PSC). This pressure continues to rise until it reaches the set point for the pressure relief valves on the pipe lines between the superheater exit and the isolation valves. At this point the pressure relief valves open and the dump flow (WDMPS1) through them will increase. The rapid increase in the dump flow results in a rapid decrease in the pressure (PSC) and a rapid increase in the superheated steam flow (WSA). However, the continued closing of the isolation valves will then result in an increase of PSC because of reduced friction losses. The final decrease in PSC is due to the decrease of the steam pressure (PAS4) in the steam drum following the reduction in the water level in the drum.

The reduction in the drum water level is due to closing the main feed-water control valves.

The initial increase of the superheated steam temperature followed by its decrease and then increase, correspond to the changes in the superheated steam flow. The final decrease of this temperature is due to the reduction of the intermediate flow following the intermediate pump coast down. The slight increase in the superheater exit sodium temperature (TIC) is due to the decrease in the superheated steam flow relative to that of the intermediate sodium during that period. This temperature then continues to decrease due to the continuous decrease of the intermediate flow at a faster rate than the decrease in the superheated steam flow. The superheater inlet sodium temperature (TIA) is constant during that time, due to the transport delay which is about 34.5 sec initially.

Before the reactor scram, the evaporator inlet and exit flow rates remain constant at their initial values. This is followed by an increase in the subcooled water, and a decrease in the steam/water flow rates respectively. This behavior of the flow rates follows the increase in the steam drum pressure (PAS4), while the evaporator pressure is approximately constant, before the opening of the superheater relief valves. That slight increase in PAS4 is due to the closing of the superheated steam isolation valves. These evaporator flow rates then reverse their rates of change, i.e., WS1 starts to decrease, whereas WS3 increases once the steam drum pressure decreases. This occurs following the opening of the pressure relief valves because of the decrease in the ratio of feedwater to superheated steam flow rates. The steam/water

flow then starts to decrease and the subcooled water flow continues to decrease since the diversity of these flow rates results in the domination by the change in momentum pressure head $(W_{S3}^2/g\rho_{S3}A_{S1}^2 - W_{S1}^2/g\rho_{FS2}A_{S1}^2)$. See Eqs. (2-4.21) to (2-4.37) and the open loop steam generator transient following a 10% reduction in the feedwater flow. These flow rates then begin to increase. WS3 increases at a faster rate than that of WS1, due to the hindering effect of the increase in the hydrostatic pressure head on WS3. The increase in WS3 may be attributed to the decrease in the friction multiplier because of the reduction in the evaporator's exit steam quality and pressure. The increase in WS1 is mainly due to the increase in the hydrostatic pressure head. The final decrease in WS3 occurs when the increase in the hydrostatic head exceeds the reduction in the pressure loss.

The transient also indicated that the auxiliary system initiation was due to a superheated steam/feedwater flow mismatch. Before this initiation, the feedwater temperature (TS5) remains constant. Following the auxiliary system initiation, TS5 first increases then decreases depending on the fractions of the recirculation flow rate and the auxiliary feedwater pump flow rate in the auxiliary feedwater flow entering the steam drum (WS5S2).

The PACC flow rate increases linearly rather than exponentially because of the very slow opening of the isolation valves on the pipe lines between the PACC and the steam drum. The rapid decrease in the feedwater flow (WS5) following the reactor scram is due to the closing of the main feedwater control valves. The final slower increase of this flow is due

to the increase in the auxiliary feedwater flow (WS5S2). The saturated steam flow to the auxiliary feedwater turbine (WAPTS) increases following the initiation of the auxiliary system. The final slow decrease in this flow rate is due to the decrease in the steam drum pressure. The pressure relief valves on the steam drum outlet header remained closed since the pressure in the drum did not exceed the set point for these valves.

6.2 Recommendations

The following aspects should be considered in future modifications of the present versions of the simulators:

1. The maximum temperatures in the average and hot channels were treated in a rather crude way in the present simulators. However, since these temperatures are among the factors to be considered in analyzing the CRBRP safety, it is recommended that a more elaborate simulation of the temperature distribution in the core should have a high priority in any future modifications.

2. The radial distribution of the primary flow rate in the reactor channels was not treated. However, this distribution affects the hydrodynamic stability in these channels, and, consequently, the reactor safety. It is therefore recommended that this should be considered in any future improvements of the simulators.

3. From the results of the controlled plant and the after-scrum transients, it became evident that the temperature at the exit of a region is highly sensitive to any variations in the flow rate through that region. As was mentioned earlier, this is due to the large

difference between the inlet and exit temperatures of that region. This large difference is a result of the use of a very small number of regions (actually one or two) in each component. It is therefore recommended that a larger number of axial regions in each component should be used to reduce this sensitivity.

4. The sodium levels in the reactor outlet plenum and in the primary pump tank were assumed constant, in all except the two loop simulator (which has not been tested yet), due to the numerical problems encountered when these levels were treated as variables. It is therefore recommended for future modifications that the simulating equations for these levels be copied from the two-loop simulator to the other simulators (with slight modifications as necessary).

5. The number of axial regions on the steam/water side of the evaporator was restricted to a minimum (two). However, it is expected that, during transients, departure from nucleate boiling may occur. Although it was not pointed out before, it should be mentioned that a steam generator model in which the evaporator was simulated by three axial regions (subcooled water, nucleate boiling, and departure-from-nucleate-boiling regions on the steam/water side) was constructed by the author. (This simulator is available in the Nuclear Engineering department at the University of Arizona). However, this steam generator model was not incorporated into the total plant simulators because of the accompanying increase in the system stiffness and numerical instabilities. It is therefore recommended that this model should be incorporated into the total plant simulators, once these numerical problems are overcome.

6. The dynamics of the boundary layer between the subcooled water and the saturated steam regions in the steam drum was not considered. The effects of not dealing explicitly with this boundary layer are not clear at this point. However, these effects should be clarified by conducting further studies in which the dynamics of this boundary layer are explicitly simulated.

7. Most pump characteristics, especially feedwater pumps (main and auxiliary) were assumed or deduced. The accuracy of these characteristics is expected to affect the transient. Therefore, a review of the dynamic simulation of these pumps is recommended (especially in the DCHT simulator) once their characteristics are better known.

8. The CRBRP turbogenerator system was highly simplified in the present simulators. However, more accuracy could be achieved if the dynamics of the turbine, condenser, and the main feedwater heaters are explicitly simulated.

9. As was previously mentioned, the two loop simulator has not been tested because of the limit on the number of differential equations allowable in the simulator if either the Episode or Gear's integration rule was used. This simulator has the capability of simulating a primary cold leg leak, mechanical failure of one of the system pumps, and loss of electric power to one of the heat transport loops, in addition to those accidents which have similar effects on the three loops. However, it does not have the capability of simulating an evaporator tube leak. It should also be mentioned that, even though it is a straightforward matter to copy the control system of the controlled and

decay heat simulators into the two loop simulator, this was not done. This is because it is normally preferable to test a simulator before adding controllers to it, since the addition of controllers usually results in higher computer cost and more complications.

10. The primary control system of the CRBR consists of 15 control rods (one in the first row, two in the fourth, and twelve in the seventh row or ring). The control strategy is such that these rods are grouped into banks. The rods in one bank are stepped in or out successively in 0.025" increments. In a load follow operating mode, the rod pattern which minimizes the power peaking factors consists of the center rod grouped with the six seventh-row flat rods as the primary operating bank, which is withdrawn roughly one third of the way at the operating level, with the six seventh-row corner rods operating as a second bank which is fully withdrawn. However, in the controlled plant simulator, the center rod is the only control rod that can compensate for reactivity disturbances in the reactor. Therefore, more elaborate simulation of the actual control strategy should be considered in any future modifications of the control system simulation. It should also be added that some of the parameters (gains, time constants, etc.) of the system controllers were assumed or deduced, and should therefore be revised once they are better known.

11. A comparison or calibration of the system transients as predicted by these simulators with experimental data and/or other simulators should be performed as early as possible.

12. Parameter sensitivity studies were not performed. These studies should precede further model modifications.

13. Modifications of the present integration rules and/or incorporation of new ones into the DARE-P system is highly recommended, with the goals of reducing the high computer cost and of facilitating extensions and improvements of the simulators.

6-3 Graphical Presentation of the Results

This section is a graphical presentation of the results. Figures 6-3.1 to 6-3.8 pertain to the steam generator transients. Figures 6-3.9 to 6-3.11 are the transients of the uncontrolled plant following different reactivity perturbations. Figures 6-3.12 to 6-3.14 are the controlled plant transients, whereas Figure 6-3.15 is the after-scam plant transient caused by uncontrolled control rod withdrawal.

Figure 6-3.1. The Steam Generator Transients with Linear Thermodynamic Equations and with Tables, Following a 10% Step Reduction in the Superheated Steam Flow.

This figure presents a graphical comparison of the steam generator transients utilizing two models. In one of these models, approximate linear thermodynamic equations were used, whereas, in the other, standard data tables were used.

- Standard data tables
- . — Approximate linear thermodynamic equations
- + The corresponding transients with the two models coincide

Figure 6-3.1. The Steam Generator Transients with Linear Thermodynamic Equations and with Tables, Following a 10% Step Reduction in the Superheated Steam Flow.

EVAP. EXIT QUALITY AND VOID FRACTION

EVAP. INLET SURROUNDED WATER TEMP.

EVAP. AVG. PRESSURE ON THE STEAM/WATER SIDE

EVAP. INLET AND EXIT FLOW-RATES ON THE WATER/STEAM SIDE

EVAP. EXIT SODIUM TEMP.

EVAP. AVG. TEMPS. IN THE LOWER REGIONS

Figure 6-3.1. Continued.

EVAP. AVG. TEMPS. IN THE UPPER REGIONS

STEAM DRUM WATER LEVEL

STEAM DRUM PRESSURE

Figure 6-3.1. Continued.

Figure 6-3.2 The Steam Generator Transients with Linear Thermodynamic Equations and with Tables, Following a 10% Reduction in the Intermediate Sodium Flow.

This figure presents a graphical comparison of the steam generator transients utilizing two models. In one of these models, approximate linear thermodynamic equations were used, whereas, in the other, standard data tables were used

———— Standard data tables
— · — Approximate linear thermodynamic equations
+ The corresponding transients with the two models coincide

Figure 6-3.2. The Steam Generator Transients with Linear Thermodynamic Equations and with Tables, Following a 10% Reduction in the Intermediate Sodium Flow.

EVAP. EXIT SODIUM TEMP.

EVAP. AVG. TEMPS. IN THE LOWER REGIONS

EVAP. AVG. TEMPS. IN THE UPPER REGIONS

Figure 6-3.2. Continued.

Figure 6-3.3 The Steam Generator Transients with Linear Thermodynamic Equations and with Tables, Following a 20° F. Rise in the Superheater Inlet Sodium Temperature.

This figure presents a graphical comparison of the steam generator transients utilizing two models. In one of these models, approximate linear thermodynamic equations were used, whereas, in the other, standard data tables were used

———— Standard data tables
— . — Approximate linear thermodynamic equations
+ The corresponding transients with the two models coincide

Figure 6-3.3. The Steam Generator Transients with Linear Thermodynamic Equations and with Tables, Following a 20° F. Rise in the Superheater Inlet Sodium Temperature.

EVAP. INLET AND EXIT FLOW-RATES ON THE WATER/STEAM SIDE

EVAP. EXIT SODIUM TEMP.

EVAP. AVG. TEMPS. IN THE LOWER REGIONS

EVAP. AVG. TEMPS. IN THE UPPER REGIONS

Figure 6-3.3. Continued.

Figure 6-3.4 The Steam Generator Transients with Linear Thermodynamic Equations and with Tables, Following a 10% Step Reduction in the Feedwater Flow.

This figure presents a graphical comparison of the steam generator transients utilizing two models. In one of these models, approximate linear thermodynamic equations were used, whereas, in the other, standard data tables were used.

———— Standard data tables
— • — Approximate linear thermodynamic equations
+ The corresponding transients with the two models coincide

Figure 6-3.4. The Steam Generator Transients with Linear Thermodynamic Equations and with Tables, Following a 10% Step Reduction in the Feedwater Flow.

EVAP. INLET AND EXIT FLOW-RATES ON THE WATER/STEAM SIDE

EVAP. AVG. TEMPS. IN THE LOWER REGIONS

EVAP. AVG. TEMPS. IN THE UPPER REGIONS

STEAM DRUM PRESSURE

STEAM DRUM WATER LEVEL

Figure 6-3.4. Continued.

Figure 6-3.5. The Steam Generator Transients with the Episode, Gear's, and Secker's Integration Rules, Following a 10% Reduction in the Superheated Steam Flow.

This figure presents a graphical comparison of the steam generator transients utilizing three different integration rules. These are the Episode, Gear's and Secker's rule. Standard thermodynamic data tables were used with each rule. In this figure the following notations were used:

- Transient using the Episode rule
- • — Transient using Gear's rule
- .. — Transient using Secker's rule
- * The corresponding transient with Gear's rule coincides with that using the Episode rule
- Δ The corresponding transient with Secker's rule coincides with that using the Episode rule

Figure 6-3.5. The Steam Generator Transients with the Episode, Gear's, and Secker's Integration Rules, Following a 10% Reduction in the Superheated Steam Flow.

EVAP. EXIT QUALITY AND VOID FRACTION

EVAP. INLET SUBCOOLED WATER TEMP.

EVAP. AVG. PRESSURE ON THE STEAM/WATER SIDE

EVAP. INLET AND EXIT FLOW-RATES ON THE WATER/STEAM SIDE

EVAP. EXIT SODIUM TEMP.

EVAP. AVG. TEMPS. IN THE LOWER REGIONS

Figure 6-3.5. Continued.

EVAP. AVG. TEMPS. IN THE UPPER REGIONS

STEAM DRUM WATER LEVEL

STEAM DRUM PRESSURE

Figure 6-3.5. Continued.

Figure 6-3.6. The Steam Generator Transients with the Episode, Gear's and Secker's Integration Rules, Following a 10% Reduction in the Intermediate Sodium Flow.

This figure presents a graphical comparison of the steam generator transients utilizing three different integration rules. These are the Episode, Gear's and Secker's rule. Standard thermodynamic data tables were used with each rule. In this figure the following notations were used:

————— Transient using the Episode rule

— · — Transient using Gear's rule

— · · — Transient using Secker's rule

* The corresponding transient with Gear's rule coincides with that using the Episode rule

Figure 6-3.6. The Steam Generator Transients with the Episode, Gear's and Secker's Integration Rules, Following a 10% Reduction in the Intermediate Sodium Flow.

EVAP. INLET AND EXIT FLOW-RATES ON THE WATER/STEAM SIDE

EVAP. EXIT SODIUM TEMP.

EVAP. AVG. TEMPS. IN THE LOWER REGIONS

EVAP. AVG. TEMPS. IN THE UPPER REGIONS

Figure 6-3.6. Continued.

Figure 6-3.7. The Steam Generator Transients with the Episode, Gear's and Secker's Integration Rules, Following a 20° F Rise in the Superheater Inlet Sodium Temperature.

This figure presents a graphical comparison of the steam generator transients utilizing three different integration rules. These are the Episode, Gear's and Secker's rule. Standard thermodynamic data tables were used with each rule. In this figure the following notations were used:

- Transient using the Episode rule
- . — Transient using Gear's rule
- . . — Transient using Secker's rule
- * The corresponding transient with Gear's rule coincides with that using the Episode rule
- Δ The corresponding transient with Secker's rule coincides with that using the Episode rule

Figure 6-3.7. The Steam Generator Transients with the Episode, Gear's and Secker's Integration Rules, Following a 20°F Rise in the Superheater Inlet Sodium Temperature.

EVAP. EXIT QUALITY AND VOID FRACTION

EVAP. AVG. PRESSURE ON THE STEAM/WATER SIDE

EVAP. INLET AND EXIT FLOW-RATES ON THE WATER/STEAM SIDE

EVAP. EXIT SODIUM TEMP.

EVAP. AVG. TEMPS. IN THE LOWER REGIONS

EVAP. AVG. TEMPS. IN THE UPPER REGION

Figure 6-3.7. Continued.

Figure 6-3.7. Continued.

Figure 6-3.8. The Steam Generator Transients with the Episode, Gear's and Secker's Integration Rules, Following a 10% Reduction in the Feedwater Flow.

This figure presents a graphical comparison of the steam generator transients utilizing three different integration rules. These are the Episode, Gear's and Secker's rule. Standard thermodynamic data tables were used with each rule. In this figure the following notations were used:

———— Transient using the Episode rule

— — — Transient using Gear's rule

— — — Transient using Secker's rule

* The corresponding transient with Gear's rule coincides with that using the Episode rule

Δ The corresponding transient with Secker's rule coincides with that using the Episode rule

FEEDWATER FLOW

SUPERHEATER EXIT STEAM TEMP.

SUPERHEATER EXIT STEAM PRESSURE

SUPERHEATER AVG. TEMPS.

LENGTHS OF REGIONS IN THE EVAP.

EVAP. EXIT QUALITY AND VOID FRACTION

Figure 6-3.8. The Steam Generator Transients with the Episode, Gear's and Secker's Integration Rules, Following a 10% Reduction in the Feedwater Flow.

EVAP. INLET SURCOOLED WATER TEMP.

EVAP. AVG. PRESSURE ON THE STEAM/WATER SIDE

EVAP. INLET AND EXIT FLOW-RATES ON THE WATER/STEAM SIDE

EVAP. EXIT SODIM TEMP.

EVAP. AVG. TEMPS. IN THE LOWER REGIONS

EVAP. AVG. TEMPS. IN THE UPPER REGIONS

Figure 6-3.8. Continued.

Figure 6-3.8. Continued.

Figure 6-3.9. The Uncontrolled Plant Transient Following a 25¢ Step Reactivity Insertion.

MIN. PIN-CLAD TEMPS. IN THE AVG. AND HOT CHANNELS

MAX. FUEL-SURFACE TEMPS. IN THE AVG. AND HOT CHANNEL

OUTLET-PLENUM INLET AND EXIT TEMPS. AND IHX PRIMARY INLET TEMP. IHX PRIMARY EXIT TEMP. AND REACTOR INLET TEMP.

IHX REGIONS AVG. TEMPS.

IHX INTERMEDIATE EXIT AND SUPERHEATER INLET SODIUM TEMPS.

Figure 6-3.9. Continued, The Uncontrolled Plant Transient Following a 25¢ Step Reactivity Insertion

Figure 6-3.9. Continued, The Uncontrolled Plant Transient Following a 25c Step Reactivity Insertion.

EVAP. AVG. TEMPS. IN THE UPPER REGIONS

SUPERHEATED STEAM TEMP. AT THE TURBINE INLET

TURBINE AND GENERATOR POWERS

Figure 6-3.9. Continued, The Uncontrolled Plant Transient Following a 25¢ Step Reactivity Insertion.

Figure 6-3.10. The Uncontrolled Plant Transient Following a 5¢/Sec Terminated Ramp Reactivity Insertion For 5 Sec.

MAX. PIN-CLAD TEMPS. IN THE AVG. AND HOT CHANNELS

MAX. FUEL-SURFACE TEMPS. IN THE AVG. AND HOT CHANNEL

MAX. FUEL-CENTER-LINE TEMPS. IN THE AVG. AND HOT CHANNEL

OUTLET PLENUM INLET AND EXIT TEMPS.
AND IHX PRIMARY INLET TEMP

IHX PRIMARY EXIT TEMP. AND REACTOR INLET TEMP.

IHX REGIONS AVG. TEMPS.

Figure 6-3.10. Continued, The Uncontrolled Plant Transient Following a 5¢/Sec Terminated Ramp Reactivity Insertion for 5 Sec.

DIX INTERMEDIATE EXIT AND SUPERHEATER INLET SODIUM TEMPS.

SUPERHEATER EXIT STEAM TEMP.

SUPERHEATER AVG. TEMPS.

SUPERHEATER EXIT AND EVAP. INLET TEMPS. SODIUM SIDES

LENGTHS OF REGIONS IN THE EVAP.

EVAP. EXIT QUALITY AND VOID FRACTION

Figure 6-3.10. Continued, The Uncontrolled Plant Transient Following a 5¢/Sec Terminated Ramp Reactivity Insertion for 5 Sec.

Figure 6-3.10. Continued, The Uncontrolled Plant Transient Following a 5¢/Sec Terminated Ramp Reactivity Insertion for 5 Sec.

Figure 6-3.11. The Uncontrolled Plant Transient Following a 0.25¢/Sec Reactivity Ramp.

MAX. PIN-CLAD TEMPS. IN THE AVG. AND HOT CHANNELS

MAX. FUEL-SURFACE TEMPS. IN THE AVG. AND HOT CHANNEL

MAX. FUEL-CENTER-LINE TEMPS. IN THE AVG. AND HOT CHANNEL

OUTLET PLENUM INLET AND EXIT TEMPS.
AND IXH PRIMARY INLET TEMP.

IXH PRIMARY EXIT TEMP. AND REACTOR INLET TEMP.

IXH REGIONS AVG. TEMPS.

Figure 6-3.11. Continued.

Figure 6-3.11. Continued.

Figure 6-3.12. The Controlled Plant Transient Following a 10¢ Step Reactivity Insertion.

HX REGIONS AVO. TEMPS.

LENGTHS OF REGIONS OF THE EVAP.

EVAP. EXIT QUALITY AND VOID FRACTION

EVAP. INLET AND EXIT FLOW-RATES ON THE WATER/STEAM SIDE

EVAP. AVO. TEMPS. IN THE LOWER REGIONS

EVAP. AVO. TEMPS. IN THE UPPER REGIONS

Figure 6-3.12. Continued, The Controlled Plant Transient Following a 10¢ Step Reactivity Insertion.

Figure 6-3.12. Continued, The Controlled Plant Transient Following a 10¢ Reactivity Insertion.

Figure 6-3.13. The Controlled Plant Transient Following a 25¢ Step Reactivity Insertion.

Figure 6-3.13. Continued, The Controlled Plant Transient Following a 25¢ Step Reactivity Insertion.

EVAP. INLET AND EXIT FLOW-RATES ON THE WATER/STEAM SIDE

LENGTHS OF REGIONS OF THE EVAP.

EVAP. EXIT QUALITY AND VOID FRACTION

EVAP. AVG. TEMPS. IN THE LOWER REGIONS

EVAP. AVG. TEMPS. IN THE UPPER REGIONS

EVAP. EXIT SODIUM TEMP. AND INX INTERMEDIATE INLET TEMP.

Figure 6-3.13. Continued, The Controlled Plant Transient Following a 25¢ Step Reactivity Insertion.

Figure 6-3.13. Continued, The Controlled Plant Transient Following a 25¢ Step Reactivity Insertion.

Figure 6-3.14. The Controlled Plant Transient Following a Negative Load Ramp of 3% of Full Power Per Minute.

Figure 6-3.14. Continued, The Controlled Plant Transient Following a Negative Load Ramp of 3% of Full Power Per Minute.

EVAP. AVO. TEMPS. IN THE LOWER REGIONS

EVAP. AVO. TEMPS. IN THE UPPER REGIONS

EVAP. EXIT SODIUM TEMP. AND IXH INTERMEDIATE INLET TEMP.

IXH REGIONS AVO. TEMPS.

PRIMARY FLOW

IXH PRIMARY EXIT TEMP. AND REACTOR INLET TEMP.

Figure 6-3.14. Continued, The Controlled Plant Transient Following a Negative Load Ramp of 3% of Full Power Per Minute.

Figure 6-3.14. Continued, The Controlled Plant Transient Following a Negative Load Ramp of 3% of Full Power Per Minute.

MAX. FUEL-CENTER-LINE TEMPS. IN THE AVG. AND HOT CHANNEL

Figure 6-3.14. Continued, The Controlled Plant Transient Following a Negative Load Ramp of 3% of Full Power Per Minute.

Figure 6-3.15. The Transient For The Uncontrolled Control Rod Withdrawal Followed by Reactor Scram.

REGIONS: (TOP TO BOTTOM). IN AND OUT TEMPS. OF THE UPPER PLENUM

IXH PRIMARY EXIT AND REACTOR INLET TEMPS.

IXH EXIT INTERMEDIATE SODIUM TEMP.

PRIMARY AND INTERMEDIATE FLOW RATES

PRIMARY PUMP SPEED

INTERMEDIATE PUMP SPEED

Figure 6-3.15. Continued, The Transient For The Uncontrolled Control Rod Withdrawal Followed by Reactor Scram.

Figure 6-3.15. Continued, The Transient For The Uncontrolled Control Rod Withdrawal Followed by Reactor Scram.

AVG. PRESSURE IN THE EVAP.

AVG. TEMPS. IN THE LOWER REGIONS OF THE EVAP.

AVG. TEMPS. IN THE UPPER REGIONS OF THE EVAP.

MASS FLOW-RATES AT THE INLET AND EXIT OF THE EVAP.

LENGTHS OF REGIONS IN THE EVAPORATOR

EXIT QUALITY AND VOID FRACTION OF THE EVAP.

Figure 6-3.15. Continued, The Transient For The Uncontrolled Control Rod Withdrawal Followed by Reactor Scram.

Figure 6-3.15. Continued, The Transient For The Uncontrolled Control Rod Withdrawal Followed By Reactor Scram.

Figure 6-3.15. Continued, The Transient For The Uncontrolled Control Rod Withdrawal Followed by Reactor Scram.

APPENDIX A

DYNAMICS OF THE PLANT MAIN UNITS

This appendix includes detailed derivations of some of the system equations and criteria presented in Chapter 2, together with the values of the system constants and the initial conditions for the variables.

A-1 Turbogenerator

A-1.1 Turbine Efficiency

This is assumed to remain constant and is obtained from

$$\eta_T = \frac{STWBTU}{W_{S9} (h_{S9} - h_{EXH})} \Big|_0$$

but

$$STWBTU \Big|_0 = \frac{P_{G\theta} + P_{\omega}}{2.931 \times 10^{-7}} \Big|_0$$

$$P_{G\theta} = 380 \quad \text{Mw, (from Reference 1)}$$

$$P_{\omega} \approx 2\% \text{ of rated power (Assumed)}$$

i.e.,

$$P_{\omega} \approx 7.6 \quad \text{Mw}$$

thus

$$\text{STWBTU}|_o \approx 1.3224 \times 10^9 \text{ BTU/hr}$$

also

$$P_{S9} = 1450 \text{ Psig (from Reference 1)}$$

and

$$T_{S9} = 900 \text{ F}^\circ \text{ (from Reference 1)}$$

thus

$$h_{S9} \approx 1430.577 \text{ BTU/lb}_m$$

$$s_{S9} \approx 1.5605 \text{ BTU/F}^\circ$$

also

$$P_{\text{EXH}} = 2.0 \text{ in.Hg (Assumed)}$$

consequently

$$X_{\text{EXH}} \approx 0.773$$

$$h_{\text{EXH}} \approx 870.273 \quad \text{BTU/lb}_m$$

in addition

$$W_{\text{S9}} = 3.34 \times 10^6 \quad \text{lb}_m/\text{hr (from Reference 1)}$$

thus

$$\eta_T = 0.706639$$

A-1.2 Constants and Parameters Related to the Turbine Inlet Temperature

a. The temperature constant C_{TS9} :

$$C_{\text{TS9}} \sim \frac{T_{\text{S9}}}{T_{\text{SC}}}$$

The assumptions involved in this approximation are that the heat losses to the surroundings per unit flow rate from the pipe lines extending from the superheater exit to the turbine are proportional to the temperature T_{SC} at the entrance of these pipe lines, and that the slight change in the specific heat of the superheated steam (for which $\Delta h \sim C_p \times \Delta T$) between the two locations may be neglected, thus

$$T_{\text{SC}} - T_{\text{S9}} = \text{constant} \cdot T_{\text{SC}}$$

Since T_{S9} is not constant it must be proportional to T_{SC} , and if there had been no time delay between the two locations, one would have:

$$T_{S9} = C_{TS9} T_{SC}$$

i.e.,

$$C_{TS9} = \left. \frac{T_{S9}}{T_{SC}} \right|_0 = \frac{900}{905} = 0.99447$$

However, with time delay T_{S9} is related to T_{SC} by Eqs. (2-1.4a,b)

b. τ_{TS9} : The time delay between T_{S9} and T_{SC} is obtained from:

$$\tau_{TS9} = \sum_{i=1}^2 \frac{M_{SCi}}{W_{SCS}}$$

See Eq. (2-1.5) and the paragraph following it for the definition of M_{SC} . Also see Figure 2-1.2 for construction details.

$$M_{SCi} = \pi \frac{D_{SCi}^2}{4} L_{SCi} N_{SCi} \rho (T_{SC})$$

The values of L_{SC1} and L_{SC2} are not known (and therefore will be left as parameters input to the simulator), whereas D_{SC1} and D_{SC2} are known to have the following values [2]:

$$D_{SC1} = 17'' \quad \text{and} \quad D_{SC2} = 19''$$

By substituting these values τ_{TS9} is obtained from:

$$\tau_{TS9}(t) \approx (1.576 L_{SC1} N_L + 1.969 L_{SC2} N_{SC2}) (\rho (T_{SC})/W_{SCS})$$

A-1.3 Constants Related to the Turbine High Pressure

- a. A_{V9} : See Eq. (2-1.6). Assume that the initial pressure drop across the turbine control valve (V9) is ~ 150 psi, from which:

$$P_{V9} \big|_0 = P_{S9} \big|_0 - 150 = 1314.7 \text{ Psia}$$

Then from Eq. (2-1.6)

$$A_{V9} = \frac{1314.7 \times 4 \times 3600}{3.34 \times 10^6} = 5.66816 \text{ Psia}/(\text{lb}_m/\text{sec})$$

- b. C_{V9} : It is assumed that

$$S_{V9} \big|_0 = 0.85$$

in order that $S_{V9} \approx 1$ at maximum power (115% of rated power). Thus

$$C_{V9} = \left[\frac{W_{S9S}/N_{S94}}{S_{V9} \sqrt{P_{S9} - P_{V9}}} \right]_0 = 22.28 \text{ lb}_m/\text{sec}/\text{Psi}^{1/2}$$

- c. C_{S9} : To avoid discontinuity in P_{S9} or W_{S9} (even though their rates of change may be discontinuous) at the boundary between supercritical and critical flow, P_{S9SC} and P_{S9C} have to be equal on this boundary ($P_{V9} = 0.55 P_{S9}$). Consequently,

$$C_{S9} = \frac{W_{S9}}{N_{S94} S_{V9} P_{S9SC}} \quad \text{for } \frac{P_{V9}}{P_{S9SC}} \geq 0.55$$

and remains constant if

$$\frac{P_{V9}}{P_{S9SC}} \leq 0.55$$

(Notice that C_{S9} will have the correct value only when it is in use and provided that the flow is initially supercritical, which is our case.)

- d. C_{DMP} : There are four parallel dump valves (see Figure 2-1.2), whose total capacity (valves fully open) is 80% of the rated turbine flow at the normal operating conditions [2]. From Eq. (2-1.8b):

$$C_{DMP} = \frac{W_{DMPS}}{4 S_{VDMP} P_{S9}} \bigg|_0 = \frac{(3.34 \times 10^4 / 3600) \times 0.8}{4 \times 1 \times 1464.7}$$

$$= 0.126685 \quad \text{lb}_m/\text{sec}/\text{psia}$$

A-1.4 Turbogenerator Inertia I_{TG}

The turbogenerator inertia is estimated as follows:

The H-constant (also known as the per-unit inertia constant) is independent of the system size (typical values [5] are in the range 2 to 8 sec.), and is defined by [3]:

$$H \triangleq \frac{\text{rotating system kinetic energy at synchronous speed}}{\text{rated MVA}}$$

i.e.,

$$H = \frac{1/2 I_{TG} \omega_{GI}^2}{\alpha \text{ MVA}} \quad \text{sec.}$$

Thus,

$$I_{TG} = \frac{2 \alpha H \text{ MVA}}{\omega_{GI}^2} \quad \text{lb}_f\text{-ft-sec}^2/\text{rad}^2$$

But

$$\text{MVA} = 488 \quad \text{and} \quad \omega_{GI} = 377 \text{ rad/sec}$$

Assuming that

$$H=3 \quad \text{sec}$$

it is found that:

$$I_{TG} = 1.5196 \times 10^4 \quad \text{lb}_f\text{-ft-sec}^2/\text{rad}^2$$

A-1.5 The Friction Coefficient A_ω

The frictional losses are assumed to be ~ 2% of the rated power at the synchronous speed. From Eq. (2-1.14)

$$A_\omega \approx \frac{380 \times 0.02}{377} \approx 0.02 \quad \text{MW/(rad/sec)}$$

A-1.6 The Electrical Loss Constant A_{GE}

To determine this constant refer to Eq. (2-1.17), which for small perturbations in θ_G (such that v will remain constant) will take the following form:

$$P_{G\theta} = A_{G\theta} \sin \frac{\pi\theta}{18^\circ}$$

Noting that $\theta_G|_0 = 25.57^\circ$ (see next section), it is found that

$$A_{G\theta} = \frac{380}{\sin(25.57)} = 880.416 \text{ MW}$$

Substituting the values of I_{TG} , A_ω , $A_{G\theta}$, and Eqs. (2-1.14, 15, 21) into Eq. (2-1.1), one gets:

$$\ddot{\theta}_G + \frac{48.539}{\omega_G} A_{GE} \dot{\theta}_G + \frac{42734.59}{\omega_G} \sin \theta_G = 2773.66 \left(\frac{P_T}{\omega_G} - 0.02 \right)$$

(where θ_G is now in radians).

Then by assuming that $\sin \theta_G \approx \theta_G$, it is found that:

$$\ddot{\theta}_G + 0.1287 A_{GE} \dot{\theta}_G + 113.357 \theta_G = 2773.66 \left(\frac{P_T}{377} - 0.02 \right)$$

The natural frequency of this oscillations is

$$\omega_n = 10.647 \text{ rad/sec}$$

and if we put the coefficient of $\dot{\theta}_G$ in the standard form

$$2 \xi \omega_n = 0.1287 A_{GE}$$

we find that

$$A_{GE} = 165.38\xi$$

where ξ is regarded as a damping factor and is kept as a parameter.

Consequently:

$$P_{GE} = 165.38 \xi (\omega_G - \omega_{GI})$$

A-1.7 The Initial Steady State for the Generator Variables

a. Reactance: Assuming a round rotor, it is found that

$$X = X'$$

where [5]

$$X' \triangleq \frac{|V|^2}{MVA} = \frac{(22)^2}{488} = 0.9918 \text{ ohm}$$

b. Current: (see Figure A-1.1)

$$I_a \triangleq \frac{MVA}{V} = \frac{488}{22} = 22.1818 \text{ KA}$$

c. Generator Power Factor PF:

$$\cos \phi = \frac{P_{G\theta}}{MVA}$$

Thus

$$PF = \frac{380}{488} = 0.7787$$

from which

$$\phi = 38.859^\circ$$

d. Power Angle θ_G : From Figure A-1.1, we have

$$I_q = \frac{V \sin \theta_G}{X} = I_a \cos (\theta_G + \phi)$$

Figure A-1.1. A Phasor Diagram of the Generator Armature Voltage and Current

Thus

$$\frac{\cos(\theta_G + \phi)}{\sin \theta_G} = \frac{V}{I_a X}$$

whence

$$\theta_G = \tan^{-1} \left[\frac{\cos \phi}{V/(I_a X) + \sin \phi} \right] = 25.57^\circ$$

e. EMF: From the power equation

$$P_{G\theta} = \frac{|V| \cdot |E|}{X} \sin \theta_G$$

therefore

$$|E| = \frac{P_{G\theta} X}{V \sin \theta_G} = 39.69 \text{ kv}$$

A-2 Superheater

A-2.1 Sodium Heat Transfer Coefficient

Sodium specific heat and thermal conductivity are assumed to remain constant and have the following values [15];

$$k_{IA} = 39.187 \quad \text{BTU/hr/ft/F}^\circ$$

$$C_{PIA} = 0.3014 \quad \text{BTU/lb}_m/\text{F}^\circ$$

The following data are also available [1]:

$$D_{IS} = 0.407" , \quad D_{OS} = 0.625"$$

$$L_S = 46 \text{ ft.} , \quad N_S = 2271$$

The pitch between tubes (in a triangular cell [2]) $S = 1.22"$.
 Thus the sodium equivalent area per tube $A_{IS} = 6.2808 \times 10^{-3} \text{ ft.}^2$.
 Consequently

$$D_{EIS} = 0.1905 \text{ ft.}$$

where D_{EIS} is the sodium equivalent diameter.

The Peclet number and the sodium film heat transfer coefficient are therefore given by:

$$Pe_S = 0.188(W_I/N_S) \quad (A-2.1)$$

and

$$h_{NS} = 1222.078 + 1.92584(W_I/N_S)^{0.8} \text{ BTU/hr/ft}^2/\text{F}^\circ \quad (A-2.2)$$

where W_I is the intermediate sodium flow and

$$W_I|_O = 3.834 \times 10^7 \quad \text{lb}_m/\text{hr}$$

Consequently

$$h_{NS}|_O = 5862.6318 \quad \text{BTU/hr/ft}^2/\text{F}^\circ$$

In order to get H_{WA} , one has to know k_{wall} . Since the wall is made of 2-1/4 Cr - 1 Mo steel alloy, the thermal conductivity of this material is [16]:

$$k_{WA} = 22 \quad \text{BTU/hr/ft/F}^\circ$$

Also for the wall material we have the following data [6]:

$$\rho_{WA} = 496 \quad \text{lb}_m/\text{ft}^3 \quad \text{and} \quad C_{PWA} = 0.12 \text{ BTU/lb}_m/\text{F}^\circ$$

Substituting for L_S , D_{IS} , D_{OS} and k_{WA} into Eq. (2-2.18a), H_{WA} is found to be:

$$H_{WA} = 144.51 N_S / (0.004875 + \frac{19.2}{h_{NS}}) \text{ BTU/hr/F}^\circ \quad (\text{A-2.3})$$

consequently

$$H_{WA}|_O = 4.0267785 \times 10^7 \quad \text{BTU/hr/F}^\circ$$

A-2.2 Steam Fouling Resistance and Heat Transfer Coefficient

For superheated steam the following properties are available [7]:

$$k_{SA} = 0.0355 \quad \text{BTU/hr/ft/F}^\circ$$

$$\mu_{SA} \approx 0.07 \quad \text{lb}_m/\text{hr/ft}$$

The specific heat is calculated from:

$$C_{PS} \approx \frac{h_{SC} - h_{SA}}{T_{SC} - T_{SA}} = \frac{1430.71 - 1150.47}{905.00 - 615.21} \approx 0.967 \quad \text{BTU/lb}_m/\text{F}^\circ$$

substituting into Eq. (2-2.17b), we find that:

$$h_{SS} = 4.2454 (W_{SA}/N_S)^{0.8} \quad \text{BTU/hr/ft}^2/\text{F}^\circ \quad (\text{A-2.4})$$

But

$$W_{SA}|_O = 3.34 \times 10^6 \quad \text{lb}_m/\text{hr}$$

thus

$$h_{SS}|_O = 1451.938 \quad \text{BTU/hr/ft}^2/\text{F}^\circ$$

Referring to Eq. (2-2.17a), H_{SSA} is determined from

$$H_{SSA} = 144.513 N_S / (0.004875 + \frac{29.484}{h_{FS}} + \frac{29.484}{h_{SS}}) \quad (\text{A-2.5})$$

therefore

$$H_{SSA}|_O = 144.513 N_S / (0.02518 + \frac{29.484}{h_{FS}}) \quad (\text{A-2.6})$$

where h_{FS} is assumed constant.

The initial energy balance yields:

$$\begin{aligned} T_{IC} &= T_{IA} - \frac{W_{SA}(h_{SC} - h_{SA})}{C_{PA} W_I} = 936 - \frac{3.34 \times 10^4 (1430.71 - 1150.47)}{0.3014 \times 3.834 \times 10^7} \\ &= 855 \text{ F}^\circ \end{aligned}$$

Consequently

$$\bar{T}_{IA} = \frac{936 + 855}{2} = 895.5 \text{ F}^\circ$$

Also at the steady state we have:

$$\bar{T}_{WA} = \bar{T}_{IA} - \frac{W_I C_{PIA} (T_{IA} - T_{IC})}{H_{WA}} = 872.255 \text{ F}^\circ$$

but

$$T_{SA} = T_{sat} (1739.7 \text{ psia}) = 615.21 \text{ F}^\circ$$

therefore

$$\bar{T}_{SA} = \frac{615.21 + 905}{2} = 760.1 \text{ F}^\circ$$

However, we also have:

$$H_{SSA}|_o = \frac{W_{SA} (h_{SC} - h_{SA})}{(\bar{T}_{WA} - \bar{T}_{SA})}|_o$$

Thus

$$H_{SSA}|_o = 8.345576 \times 10^6 \text{ BTU/hr}$$

Comparison with Eq. (A-2.6) yields

$$h_{FS} = 2084.42 \text{ BTU/hr/F}^\circ/\text{ft}^2$$

The fouling resistance is

$$\frac{1}{\pi D_{IS} L_S h_{FS}} = 9.78796 \times 10^{-5} \text{ (BTU/hr/F}^\circ)^{-1} \quad (\text{A-2.7})$$

The total resistance at the initial steady state is 3.28515×10^{-3} (BTU/hr/F°)⁻¹. Thus the fouling resistance is 29.8% of the total at the initial steady state.

Substituting the value of h_{FS} into Eq. (A-2.5), we get

$$H_{SSA} = 144.513 N_S / [0.01902 + \frac{29.484}{h_{SS}}] \quad (A-2.8)$$

where h_{SS} is given by Eq. (A-2.4).

A-2.3 Time Delays

a. τ_{TIA} : (See Eq. 2-2.10)

$$\tau_{TIA} = \sum_{i=1} \frac{M_{I3i}}{W_{IS}}$$

From Table (5-1.3) of Reference [2], the volume of sodium in the pipe lines (one cross section) connecting the IHX to the superheater is 2354 ft^3 (Loop #3). Thus

$$\tau_{TIA} = 2354 \rho_{NA} (T_{I3}) N_L / (W_I / 3600)$$

i.e.,

$$\tau_{TIA} = 8474400 \rho_{NA} (T_{I3}) N_L / W_I \text{ sec} \quad (A-2.9)$$

b. τ_{hSA} : (See Eq. 2-2.14)

$$\tau_{hSA} = \frac{M_{S7}}{W_{SAS}} = \frac{\pi}{4} D_{S7}^2 L_{S7} \rho_{gS4} N_L / W_{SAS}$$

where $D_{S7} = 13''$ and L_{S7} is not known and is left as a parameter. An estimate of L_{S7} is 120 ft. Thus

$$\tau_{hSA} = 0.92175 L_{S7} N_L \rho_{gS4} / W_{SAS} \quad (A-2.10)$$

A-2.4 Constants in the Momentum Equations

A-2.4.1 Friction Constants.

a. f_{SAC} :

$$P_{SA}|_o = 1725 \text{ psig}, \quad P_{SC} = 1525 \text{ psig}$$

$$W_{SAS} = 927.777 \text{ lb}_m/\text{sec}$$

Substituting these values into Eq. (2-2.19), we find that:

$$f_{SAC} = 2.091 \times 10^{-3} \text{ psi}/(\text{lb}_m/\text{sec})^2$$

b. f_{SC1}, f_{SC2} : The initial value of the pressure drop between the superheater and the turbine is

$$P_{SC} - P_{S9}|_o = 75 \text{ psi}$$

The inner diameter of the pipe lines between the superheater and the header, and between the header and the turbine respectively are:

$$D_{SC1} = 17'', \quad D_{SC2} = 19''$$

But

$$\frac{\Delta P_{SC1}}{P_{SC} - P_{S9}} \Big|_o \approx \frac{L_{SC1}}{D_{SC1}^5 N_L^2} / \left[\frac{L_{SC1}}{D_{SC1}^5 N_L^2} + \frac{L_{SC2}}{D_{SC2}^2 N_{SC2}^2} \right]$$

(see Eq. 2-4.18) on the other hand

$$\Delta P_{SC1} \Big|_o = f_{SC1} \left(\frac{W_{SAS}}{N_L} \right)^2 \Big|_o$$

Thus

$$f_{SC1} = [(P_{SC} - P_{S9}) \left(\frac{N_L}{W_{SAS}} \right)^2 \Big|_o] \left[\frac{L_{SC1}}{D_{SC1}^5 N_L^2} / \left(\frac{L_{SC1}}{D_{SC1}^5 N_L^2} + \frac{L_{SC2}}{D_{SC2}^2 N_{SC2}^2} \right) \right]$$

Substituting for $P_{SC} \Big|_o$, $P_{S9} \Big|_o$, $(W_{SAS}/N_L) \Big|_o$, D_{SC1} and D_{SC2} , we find that:

$$f_{SC1} = 7.84177 \times 10^{-4} L_{SC1} / [L_{SC1} + 0.5734 \left(\frac{N_L}{N_{SC2}} \right)^2 L_{SC2}] \quad (A-2.11a)$$

Similarly

$$f_{SC2} = 3.48525 \times 10^{-4} L_{SC2} / [L_{SC2} + 1.7439 \left(\frac{N_{SC2}}{N_L} \right)^2 L_{SC1}] \quad (A-2.11b)$$

L_{SC1} and L_{SC2} are not given, and therefore are left as parameters, however it is assumed that

$$L_{SC1}/L_{SC2} \approx 2 \quad (\text{see Figure 2-1.2})$$

and that

$$L_{SC1} \approx 200 \text{ ft.}$$

c. f_{S7A} : we have

$$\bar{P}_{S4}|_o = 1751 \text{ psig} , \quad P_{SA}|_o = 1725.0 \text{ psig}$$

and

$$\rho_{gS4} \approx 4.36 \text{ lb}_m/\text{ft}^3$$

$$Y_{S7A} \approx 53.21 + Y_{S5} \quad (\text{see Figure A-4.2})$$

$$Y_{S7A}|_o = 56.21 \text{ ft.}$$

Thus from Eq. (2-2.21) we find that:

$$f_{S7A} \approx 2.8964 \times 10^{-4} \text{ psi}/(\text{lb}_m/\text{sec})^2$$

A-2.4.2 The Momentum Constants.

a. τ_{WSAC} :

$$\tau_{WSAC} = \frac{L_{SHT}}{144 \times 32.2 (757 N_L) (\pi D_{IS}^2/4)} \quad (\text{A-2.12a})$$

where L_{SHT} is the total length of the superheater tubes (not the effective tube length), given as 65.0 ft [1].

$$\text{Thus } \tau_{\text{WSAC}} = 3.153 \times 10^{-4} L_{\text{SHT}}/N_L \text{ ft}^{-1} \quad (\text{A-2.12b})$$

b. $\tau_{\text{WSC9}}:$

$$\tau_{\text{WSC9}} = \frac{1}{144 \text{ g}} \left[\frac{L_{\text{SC1}}}{1/4 N_L \pi D_{\text{SC1}}^2} + \frac{L_{\text{SC2}}}{1/4 N_{\text{SC2}} \pi D_{\text{SC2}}^2} \right] \quad (\text{A-2.13a})$$

$$\tau_{\text{WSC9}} = 1.3682 \times 10^{-4} \frac{L_{\text{SC1}}}{N_L} + 1.0953 \times 10^{-4} \frac{L_{\text{SC2}}}{N_{\text{SC2}}} \text{ ft}^{-1} \quad (\text{A-2.13b})$$

($L_{\text{SC1}}, L_{\text{SC2}}$ are in ft.).

c. $\tau_{\text{WS7A}}:$

$$\tau_{\text{WS7A}} = \frac{1}{144 \text{ g}} \frac{L_{\text{S7}}}{1/4 N_L \pi D_{\text{S7}}^2} \quad (\text{A-2.14a})$$

Since

$$D_{\text{S7}} = 13''$$

$$\tau_{\text{WS7A}} = 2.3397 \times 10^{-4} L_{\text{S7}}/N_L \text{ ft}^{-1} \quad (\text{A-2.14b})$$

d. $\tau_{\text{WSA}}:$

$$\tau_{\text{WSA}} = \tau_{\text{WS7A}} + \tau_{\text{WSAC}} + \tau_{\text{WSC9}} \quad (\text{A-2.15a})$$

$$\tau_{\text{WSA}} = (2.3397 \times 10^{-4} L_{\text{S7}} + 3.153 \times 10^{-4} L_{\text{SHT}}$$

$$+ 1.3682 \times 10^{-4} L_{\text{SC1}})/N_L + 1.0953 \times 10^{-4} L_{\text{SC2}}/N_{\text{SC2}} \text{ ft}^{-1}$$

(A-2.15b)

A-3 Evaporator

A-3.1 Steam/Water Mass and Energy Balance

In this section Eqs. (2-3.20a, b) will be deduced, and the mass and energy balance equations will be reduced to the forms used in the simulators.

From Eq. (2-3.1):

$$W_{S2} = W_{S1} - A_{S1} \bar{\rho}_{S1} \frac{dL_{S1}}{dt} \quad (A-3.1)$$

from this and Eqs. (2-3.2) to (2-3.5):

$$\frac{d\bar{\alpha}_{S2}}{dt} = \frac{1}{A_{S1} L_{S2} (\rho_{fS2} - \rho_{gS2})} [W_{S3} - W_{S1} + A_{S1} (\bar{\rho}_{S1} - \bar{\rho}_{S2}) \frac{dL_{S1}}{dt}] \quad (A-3.2)$$

Then from Eqs. (2-3.6), (2-3.13) and (A-3.1):

$$\begin{aligned} \frac{dL_{S1}}{dt} = 2 \left[- \frac{H'_{S1} L_{S1} (\bar{T}_{W1} - \bar{T}_{S1})}{A_{S1} \bar{\rho}_{S1} (h_{S2} - h_{S2})} + \frac{L_{S1}}{2(h_{S2} - h_{S1})} \left(\frac{dh_{S1}}{dt} \right. \right. \\ \left. \left. + \frac{\partial h_{fS2}}{\partial \bar{P}_{S2}} \frac{d\bar{P}_{S2}}{dt} \right) + \frac{W_{S1}}{A_{S1} \bar{\rho}_{S1}} \right] \quad (A-3.3) \end{aligned}$$

But from Eqs. (2-3.2, 16);

$$\begin{aligned} A_{S1} \frac{d(L_{S2} \bar{\rho}_{S2} h_{S2})}{dt} = h_{S2} A_{S1} \frac{d(\bar{\rho}_{S2} L_{S2})}{dt} + h_{S2} W_{S3} - h_{S3} W_{S3} \\ + H'_{S2} L_{S2} (\bar{T}_{W2} - \bar{T}_{SAT}) \quad (A-3.4a) \end{aligned}$$

This equation is expanded and then lumped into four terms in the following way:

$$I + II + III = IV \quad (A-3.4b)$$

where

$$I = L_{S2} A_{S1} [(1 - \bar{\alpha}_{S2}) \rho_{fS2} \frac{\partial h_{fS2}}{\partial \bar{P}_{S2}} + \bar{\alpha}_{S2} \rho_{gS2} \frac{\partial h_{gS2}}{\partial \bar{P}_{S2}}$$

$$+ \bar{\alpha}_{S2} (h_{gS2} - h_{fS2}) \frac{\partial \rho_{gS2}}{\partial \bar{P}_{S2}}] \frac{d\bar{P}_{S2}}{dt}$$

$$II = L_{S2} A_{S1} \rho_{gS2} (h_{gS2} - h_{fS2}) \left[\frac{d\bar{\alpha}_{S2}}{dt} + \frac{\bar{\alpha}_{S2}}{L_{S2}} \frac{dL_{S2}}{dt} \right]$$

$$III = W_{S3} X_{S3} (h_{gS2} - h_{fS2})$$

$$IV = L_{S2} H'_{S2} (\bar{T}_{W2} - T_{SAT})$$

Then substituting for $\frac{d\bar{\alpha}_{S2}}{dt}$ from Eq. (A-3.2) and noting that

$$\frac{dL_{S2}}{dt} = - \frac{dL_{S1}}{dt} \text{ the second term will be:}$$

$$II = A_{S1} \rho_{gS2} \left(\frac{h_{gS2} - h_{fS2}}{\rho_{fS2} - \rho_{gS2}} \right) [(\bar{\rho}_{S1} - \rho_{fS2}) \frac{dL_{S1}}{dt} + \frac{W_{S3} - W_{S1}}{A_{S1}}]$$

(A-3.5)

Comparing I with III, it is found that the former will be negligible relative to the latter if:

$$\left| \frac{d\bar{P}_{S2}}{dt} \right| < \left| \frac{W_{S3} X_{S3} (h_{gS2} - h_{fS2})}{A A_{S1}} \right| \quad (A-3.6)$$

where

$$A = L_{S2} \left\{ (1 - \bar{\alpha}_{S2}) \rho_{fS2} \frac{\partial h_{fS2}}{\partial \bar{P}_{S2}} + \bar{\alpha}_{S2} \left[\rho_{gS2} \frac{\partial h_{gS2}}{\partial \bar{P}_{S2}} + (h_{gS2} - h_{fS2}) \frac{\partial \rho_{gS2}}{\partial \bar{P}_{S2}} \right] \right\} \quad (A-3.7)$$

Typical values of A are in the range 40 to 60, so let $A \approx 50$.

Further,

$$\begin{aligned} W_{S3} &= 6.68 \times 10^6 && \text{lb}_m/\text{hr} \\ X_{S3} &= 0.5 \\ h_{gS2} &= 1146.2 && \text{BTU/lb}_m \quad (\text{at } \bar{P}_{S2} = 1830.7 \text{ psia}) \\ h_{fS2} &= 651.35 && \text{BTU/lb}_m \\ N_E &= 4542 && \text{tubes/6 evaporators} \\ A_{S1} &= 4.1 && \text{ft}^2/\text{6 evaporators} \end{aligned}$$

(Notice that all dimensional data for the evaporator are the same as those for the superheater given in Section A-2.)

Substituting these typical values into Eq. (A-3.6), it is found that I in Eq. (A-3.4b) can be neglected if

$$\left| \frac{d\bar{P}_{S2}}{dt} \right| \ll 8.06 \times 10^6 \quad \text{psi/hr}$$

i.e., if

$$\left| \frac{d\bar{P}_{S2}}{dt} \right| \ll 2238.7 \quad \text{psi/sec}$$

or more conveniently, if

$$\left| \frac{d\bar{P}_{S2}}{dt} \right| \ll 2000.0 \quad \text{psi/sec} \quad (\text{A-3.8})$$

Similarly comparing II and III in Eq. (A-3.5), it is found that II may be neglected relative to III if

$$\left| \frac{dL_{S1}}{dt} \right| \ll \left| \frac{1}{A_{S1} (\bar{\rho}_{S1} - \rho_{fS2})} [W_{S3} X_{S3} \frac{\rho_{fS2} - \rho_{gS2}}{\rho_{gS2}} + W_{S1} - W_{S3}] \right| \quad (\text{A-3.9})$$

Substituting typical values of the variables on the R.H.S. ($\rho_{gS2} \sim 4.6$, $\rho_{fS2} \sim 40$, $\bar{\rho}_{S1} \sim 43.78$), it is found that II may be neglected relative to III if

$$\left| \frac{dL_{S1}}{dt} \right| \ll 1.658 \times 10^6 \quad \text{ft/hr}$$

i.e., if

$$\left| \frac{dL_{S1}}{dt} \right| \ll 460.7 \quad \text{ft/sec}$$

or for convenience, if

$$\left| \frac{dL_{S1}}{dt} \right| \ll 400.0 \quad \text{ft/sec} \quad (\text{A-3.10})$$

It is possible to specify a maximum error limit that can be allowed if the two terms I and II are to be neglected relative to III. By selecting this limit to be $\pm 5\%$, criteria (A-3.8,10) will be replaced by

$$\left| \frac{d\bar{P}_{S2}}{dt} \right| \leq 100 \quad \text{psi/sec} \quad (\text{A-3.11})$$

and

$$\left| \frac{dL_{S1}}{dt} \right| \leq 20 \quad \text{ft/sec} \quad (\text{A-3.12})$$

Provided that these conditions are satisfied a maximum error in X_{S3} less than 5% (relative to its value had the two terms I and II of Eq.(A-3.4b) not been neglected) will result if X_{S3} is obtained from

$$X_{S3} = \frac{H'_{S2} L_{S2} (\bar{T}_{W2} - T_{SAT})}{W_{S3} (h_{gS2} - h_{fS2})} \quad (\text{A-3.13})$$

This equation is exact in steady state, as may be seen from Eqs. (2-3.18, A-3.4a). It is physically reasonable to expect that Eq. (A-3.13) will remain valid during slow transients. Then from Eq. (A-3.4a),

$$A_{S1} \frac{d(L_{S2} \bar{\rho} h_{S2})}{dt} - h_{S2} A_{S1} \frac{d(\bar{\rho}_{S2} L_{S2})}{dt} \approx 0.$$

which, in the terminology of Eq. (A-3.4b), means

$$I + II \approx 0. \quad (A-3.14a)$$

This yields

$$\frac{d\bar{P}_{S2}}{dt} = \frac{\rho_{gS2}(h_{gS2} - h_{fS2})}{A(\rho_{fS2} - \rho_{gS2})} [-(\bar{\rho}_{S1} - \rho_{fS2}) \frac{dL_{S1}}{dt} + \frac{W_{S1} - W_{S3}}{A_{S1}}] \quad (A-3.14b)$$

Substituting this into Eq. (A-3.3) it is found that:

$$\begin{aligned} \frac{dL_{S1}}{dt} = \left(\frac{2}{C}\right) [& - \frac{H'_{S1} L_{S1} (\bar{T}_{W1} - \bar{T}_{S1})}{A_{S1} \bar{\rho}_{S1} (h_{S2} - h_{S1})} + \frac{W_{S1}}{A_{S1} \bar{\rho}_{S1}} + \frac{L_{S1}}{2(h_{S2} - h_{S1})} \frac{dh_{S6}}{dt} \\ & + \frac{B(W_{S1} - W_{S3})}{A_{S1}(\rho_{fS2} - \rho_{gS2})}] \end{aligned} \quad (A-3.15)$$

in which $\frac{dh_{S1}}{dt}$ is replaced by $\frac{dh_{S6}}{dt}$ since they are approximately equal.

This was later decided on in order to avoid the use of delayed variables in obtaining this derivative.

$$B = \frac{L_{S1} \rho_{gS2} (h_{gS2} - h_{fS2})}{2 A (h_{S2} - h_{S1})} \frac{\partial h_{fS2}}{\partial \bar{P}_{S2}} \quad (A-3.16)$$

and

$$C = 1 + 2 B \left(\frac{\bar{\rho}_{S1} - \rho_{fS2}}{\rho_{fS2} - \rho_{gS2}} \right) \quad (A-3.17)$$

Finally, Eq. (2-3.26) is obtained from Eq. (2-3.25) as follows:
in Eq. (2-3.25), let $Z = -\alpha_{S3}(1-\psi)$

Thus

$$\bar{\alpha}_{S2} = \frac{1}{1-\psi} \left[1 - \frac{(1+Z)}{Z} \ln(1+Z) \right]$$

Then use the approximation [9]:

$$\ln(1+Z) = Z - \frac{Z^2}{2} + \frac{Z^3}{3} - \dots \quad |Z| \leq 1 \text{ and } Z \neq -1$$

A-3.2 Wall Energy Balance

In order to show how one can get either of Eqs. (2-3.28, 32), consider a small section of length Δz in the tube wall and write the energy balance for this section,

$$\begin{aligned} (A_W \rho_W \Delta z) C_{PW} \Delta T_W(z,t) &= H'_W \Delta z [T_I(z,t) - T_W(z,t)] \Delta t \\ &- H'_S \Delta z [T_W(z,t) - T_S(z,t)] \Delta t \end{aligned} \quad (A-3.18)$$

where axial conduction is neglected. Dividing both sides by Δt , taking the limit when $\Delta t \rightarrow 0$, and integrating with respect to z over the region length, it is found that

a. Region AW1:

$$\begin{aligned} \rho_{W1} A_{W1} C_{PW1} \int_0^{L_{S1}(t)} \frac{\partial T_W(z,t)}{\partial t} dz &= H'_{W1} L_{S1} [\bar{T}_{I8}(t) - \bar{T}_{W1}(t)] \\ &- H'_{S1} L_{S1} [\bar{T}_{W1}(t) - \bar{T}_{S1}(t)] \end{aligned} \quad (A-3.19)$$

where

$$\bar{T} = \frac{1}{L} \int_0^L T \, dz$$

But by Leibniz's theorem [9]:

$$\frac{d}{dt} \int_0^{L_{S1}(t)} T_{W1}(z,t) dz = \int_0^{L_{S1}(t)} \frac{\partial T_{W1}(z,t)}{\partial t} dz + T_{W1}(L_{S1},t) \frac{dL_{S1}}{dt}$$

Thus

$$\int_0^{L_{S1}(t)} \frac{\partial T_W(z,t)}{\partial t} dz = \frac{d(\bar{T}_{W1} L_{S1})}{dt} - T_{W2} \frac{dL_{S1}}{dt} \quad (A-3.20)$$

From Eqs. (A-3.19, 20) we get Eq. (2-3.28).

b. Region AW2: Similar to region AW1.

A-3.3 Initial Conditions, Heat Transfer Coefficients, and Fouling Resistance

Properties used in these computations are

a. Water [7]:

$$c_p = 1.41 \quad \text{BTU/(lb}_m \text{ F}^\circ)$$

$$k = 0.3064 \quad \text{BTU/(hr-ft-F}^\circ)$$

$$\mu = 0.217 \quad \text{lb}_m/(\text{hr-ft})$$

(These are for saturated water at 580°F.)

b. Wall: The wall properties are the same as those given in the superheater Section (A-2).

c. Sodium [15]:

$$c_p = 0.30566 \quad \text{BTU/(lb}_m \text{ F}^\circ)$$

$$k = 41.0866 \quad \text{BTU/(hr-ft-F}^\circ)$$

(These values are for sodium at 750°F.)

Substituting these properties into Eqs. (2-3.14,15,19,30,31) we get:

$$H'_{S1} = \pi N_E / (0.004875 + \frac{29.484}{h_{FE}} + \frac{29.484}{h_{WE}}) \quad (\text{A-3.21})$$

where

$$h_{WE} = 12.817 \left(\frac{W_{S1}}{N_E} \right)^{0.8} \quad (\text{A-3.22})$$

and

$$H'_{S2} = \pi N_E / (0.004875 + \frac{29.484}{h_{FE}}) \quad (\text{A-3.23})$$

$$H'_{W1} = \pi N_E / (0.004875 + \frac{19.2}{h_{NE}}) \quad (\text{A-3.24})$$

where

$$h_{NE} = 1281.3193 + 1.966 \left(\frac{W_I}{N_E} \right)^{0.8} \quad (\text{A-3.25})$$

In these equations H'_{S1} , H'_{S2} , H'_{W1} are in BTU/(hr-ft-F°), and h_{WE} , h_{FE} , h_{NE} are in BTU/(hr-ft²-F°).

Initially, we have:

$$W_{S1} = 6.68 \times 10^6 \quad \text{lb}_m/\text{hr}/\text{three loops}$$

$$W_I = 3.834 \times 10^7 \quad \text{lb}_m/\text{hr}/\text{three loops}$$

also

$$N_E = 4542$$

thus

$$h_{NE}|_0 = 4002.344$$

$$H'_{W1}|_0 = 1.47527 \times 10^6$$

and

$$H'_{S1}|_0 = 1.4269 \times 10^4 / [0.0116 + \frac{29.484}{h_{FE}}] \quad (\text{A-3.26})$$

But at the initial steady state

$$T_{I8}|_0 = [T_{I9} + \frac{W_{S1}(h_{fS2} - h_{S1})}{C_{PI} W_I}]_0$$

The initial two phase pressure $\bar{P}_{S2}|_0$ is assumed to be 1830.7 psia (see Section A-4). Therefore, initially

$$h_{fS2} = 651.32 \text{ BTU/lb}_m, \quad h_{gS2} = 1146.2 \text{ BTU/lb}_m$$

and

$$T_{SAT} = 622.4 \text{ F}^\circ$$

In addition:

$$x_{S3}|_o = 0.5$$

but

$$h_{S3} = h_{fS2} + x_{S3}(h_{gS2} - h_{fS2})$$

thus

$$h_{S3}|_o = 898.778 \text{ BTU/lb}_m$$

also

$$h_{S1}|_o = [h_{S3} - \frac{w_I C_{PIE}(T_{I7} - T_{I9})}{w_{S1}}]_o$$

and since

$$T_{I7} = 855.0 \text{ F}^\circ \text{ and } T_{I9} = 651.0 \text{ F}^\circ$$

it is found that

$$h_{S1}|_o = 540.89 \text{ BTU/lb}_m$$

from which

$$T_{S1} = 543.35 \text{ F}^\circ \quad (\text{from steam tables})$$

Therefore

$$\bar{T}_{S1} = \frac{1}{2} (T_{S1} + T_{SAT}) = 582.88 \text{ F}^\circ$$

$$T_{I8}|_o = 713.96 \text{ F}^\circ$$

$$\bar{T}_{I8}|_o = \frac{1}{2} (T_{I8} + T_{I9}) = 682.48 \text{ F}^\circ$$

and

$$\bar{T}_{I7}|_o = \frac{1}{2} (T_{I7} + T_{I8}) = 784.48 \text{ F}^\circ$$

However in the steady state, it can easily be proven that:

$$\frac{1}{L_{S1}} = \frac{H'_{W1} H'_{S1} (\bar{T}_{I8} - \bar{T}_{S1})}{C_{PI} W_I (T_{I8} - T_{I9}) (H'_{S1} + H'_{W1})} \quad (\text{A-3.27})$$

and

$$\frac{1}{L_{S2}} = \frac{H'_{W1} H'_{S2} (\bar{T}_{I7} - T_{SAT})}{C_{PI} W_I (T_{I7} - T_{I8}) (H'_{S2} + H'_{W1})} \quad (\text{A-3.28})$$

Thus, initially,

$$\frac{1}{L_{S1}} = \frac{0.199148 H'_{S1}}{1.47527 \times 10^6 + H'_{S1}} \quad (\text{A-3.29})$$

and

$$\frac{1}{46-L_{S1}} = \frac{0.144667 H'_{S2}}{1.47527 \times 10^6 + H'_{S2}} \quad (\text{A-3.30})$$

From Eqs. (A-3.26, 29), we get:

$$\frac{3048.35}{h_{FE}} = 0.199148 L_{S1} - 2.1993 \quad (\text{A-3.31})$$

and from Eqs. (A-3.23, 30)

$$\frac{3048.35}{h_{FE}} = 5.1506 - 0.144667 L_{S1} \quad (\text{A-3.32})$$

thus

$$L_{S1} = 21.3777 \text{ ft} , \quad L_{S2} = 24.6223 \text{ ft}$$

and

$$h_{FE} \approx 1481.22 \quad \text{BTU}/(\text{hr-ft}^2\text{-F}^\circ)$$

The fouling resistance is

$$\frac{1}{\pi D_{IE} L_E h_{FE}} = 1.3774 \times 10^{-4} \quad (\text{BTU/hr-F}^\circ)^{-1}$$

This represents 48.34% of the total heat transfer resistance in region AS1, and 57.77% in region AS2. Then, by assuming that h_{FE} remains constant, Eqs. (A-3.21, 23) will be:

$$H'_{S1} = \pi N_E / [0.02478 + \frac{29.484}{h_{WE}}] \quad (\text{A-3.33})$$

$$H'_{S2} = 126.7782 N_E \quad (\text{A-3.34})$$

From these the initial values of H'_{S1} and H'_{S2} are:

$$H'_{S1}|_0 = 4.52897 \times 10^5 \quad \text{BTU/(hr-ft-F}^\circ)$$

$$H'_{S2}|_0 = 5.75826 \times 10^5 \quad \text{BTU/(hr-ft-F}^\circ)$$

But initially:

$$\bar{T}_{W1} = \frac{H'_{W1} \bar{T}_{I8} + H'_{S1} \bar{T}_{S1}}{H'_{W1} + H'_{S1}} \quad (\text{A-3.35})$$

and

$$\bar{T}_{W2} = \frac{H'_{W1} \bar{T}_{I7} + H'_{S2} T_{SAT}}{H'_{W1} + H'_{S2}} \quad (\text{A-3.36})$$

Thus

$$\bar{T}_{W1}|_o = 659.085 \text{ F}^\circ \quad \text{and} \quad \bar{T}_{W2}|_o = 738.977 \text{ F}^\circ$$

A-3.4 Time Delays

- a. τ_{hS1} : From Table 5-5.7 of Ref. [2], the pipe lines in the downcomer are composed of four sections, in each of which the pipe cross sections are different, these are:

$$A_{S61} = \frac{\pi}{4} \left(\frac{9}{12}\right)^2 = 0.44178 \text{ ft}^2 \quad (4 \text{ lines/loop})$$

$$A_{S62} = \frac{\pi}{4} \left(\frac{17}{12}\right)^2 = 1.5762 \text{ ft}^2 \quad (\text{one line/loop})$$

$$A_{S63} = \frac{\pi}{4} \left(\frac{15}{12}\right)^2 = 1.227 \text{ ft}^2 \quad (\text{one line/loop})$$

$$A_{S64} = \frac{\pi}{4} \left(\frac{9}{12}\right)^2 = 0.44178 \text{ ft}^2 \quad (\text{one line/evaporator})$$

but

$$\begin{aligned} \tau_{hS1} = \sum_1 \frac{M_{S61}}{W_{S1S}} = & (4 A_{S61} L_{S61} + A_{S62} L_{S62} + A_{S63} L_{S63} \\ & + \frac{N_{EVAP}}{N_L} A_{S64} L_{S64}) (N_L \rho(T_{S6}) / W_{S1S}) \end{aligned}$$

Thus

$$\begin{aligned} \tau_{hS1} = & (1.7674 L_{S61} + 1.5762 L_{S62} + 1.227 L_{S63} \\ & + 0.44178 N_{EVAP}/N_L)(N_L \rho(T_{S6})/W_{S1S}) \end{aligned} \quad (A-3.37)$$

The pipe lengths L_{S6i} are not known and are therefore left as input parameters to the simulator. However, the following values are used in the simulations:

$$L_{S61} = 15 \text{ ft} , \quad L_{S62} = 100 \text{ ft}$$

$$L_{S63} = 75 \text{ ft} , \quad L_{S64} = 30 \text{ ft}$$

b. τ_{TI7} : From Table 5.1-3 of Ref. [2], the volume of sodium in the pipe lines connecting the superheater to the evaporators per loop (per two lines) is

$$V_{I7} = 391 \text{ ft}^3$$

from which

$$M_{I7} = (391/2) N_{EVAP} \rho(T_{IC})$$

but

$$\tau_{TI7} = \frac{M_{I7}}{W_{IS}} \quad (\text{see Eq. 2-3.41})$$

thus

$$\tau_{TI7} = 703800.0 \cdot \rho(T_{IC}) N_{EVAP}/W_I \quad (A-3.38)$$

(Noting that $W_{IS} = W_I/3600$)

A-4 Steam Drum

A-4.1 Water Level in the Drum

From Figure (A-4.1), the area of the sector enclosed by the radii OA and OC and the arc ABC is given by:

$$\text{Area} = 2 \int_0^{\theta_1} \int_0^R r dr d\theta = R^2 \theta_1$$

But the area of the triangle OAC = $R \sin \theta_1 R \cos \theta_1 = 1/2 R^2 \sin 2 \theta_1$.

Thus the cross-sectional area of the water region $A_{S5} = R^2 \theta_1 - \frac{1}{2} R^2 \sin 2 \theta_1$, from which

$$\theta_1 - \frac{1}{2} \sin 2 \theta_1 = A_{S5}/R^2 \quad (A-4.1)$$

But if the initial water level is at the central plane, we would have

$$A_{S5}/(\frac{1}{2} \pi R^2) = M_{S5}/M_{S5I} \quad (A-4.2)$$

where M_{S5} is the mass of water in the drum and M_{S5I} is its initial value. We also know that

Figure A-4.1. Steam Drum Cross Section

$$\theta_1 = \cos^{-1}\left(1 - \frac{Y_{S5}}{R}\right) \quad (\text{A-4.3})$$

Therefore from Eqs. (A-4.1, 2, 3) we find that:

$$\cos^{-1}\left(1 - \frac{Y_{S5}}{R}\right) - \frac{1}{2} \sin 2 \theta_1 = \frac{\pi}{2} \frac{M_{S5}}{M_{S5I}} \quad (\text{A-4.4})$$

Then by assuming that the change in the water level from its initial value is small, we can assume that θ_1 is approximately 90° and that $\sin 2 \theta_1$ is approximately zero. Consequently:

$$1 - \frac{Y_{S5}}{R} = \cos \left(\frac{\pi}{2} \frac{M_{S5}}{M_{S5I}} \right)$$

From which

$$Y_{S5} = R \left[1 - \cos \left(\frac{\pi}{2} \frac{M_{S5}}{M_{S5I}} \right) \right]$$

i.e.,

$$Y_{S5} = R \left[1 + \sin \frac{\pi}{2} \left(\frac{M_{S5}}{M_{S5I}} - 1 \right) \right] \quad (\text{A-4.5})$$

A-4.2 Initial Values of the Drum Variables

- a. Water and Steam Masses. The inner diameter of the drum is six feet (see Figure A-4.2), however, the drum length is not known, therefore the drum volume V_D was assumed to be 1000 ft^3 .

Figure A-4.2. Steam Generation System Hydraulic Profile

Under the assumption that the initial water volume is half the volume of the drum, and knowing that the initial pressure $\bar{P}_{S4}$ in the drum is 1751 psig, i.e., $\rho_{fS4} \approx 40.536$, M_{S5} is found to be

$$M_{S5} \Big|_o \approx \frac{V_D}{2} \rho_{fS4} = 20268.287 \quad \text{lb}_m/\text{drum} \quad (\text{A-4.6})$$

Similarly, knowing that $\rho_{gS4} = 4.36$, M_{S4} is found to be

$$M_{S4} \Big|_o = 2179.933 \quad \text{lb}_m/\text{drum}$$

b. h_{S6} :

$$h_{S6} \Big|_o = h_{S1} \Big|_o = 540.89 \quad \text{BTU/lb}_m \quad (\text{see Section A-3})$$

c. h_{S5} , T_{S5} : From either Eq. (2-4.13) or Eq. (2-4.14) at the steady state, we find that

$$h_{S5} \Big|_o = 434.6885 \quad \text{BTU/lb}_m$$

Thus

$$T_{S5} \Big|_o \approx 454.0 \quad \text{F}^\circ$$

A-4.3 Time Delays

a. τ_{hS4} : from Eq. (2-4.9)

$$\tau_{hS4} = \sum_i \frac{M_{S3i}}{W_{S3S}}$$

From Table (5-5.7) of Ref. [2], we find that the pipe lines in the riser are composed of two sections which have the following cross-sections:

$$A_{S31} = \frac{\pi}{4} \left(\frac{11}{12} \right)^2 = 0.66 \text{ ft}^2 \quad (\text{one line/evaporator})$$

$$A_{S32} = \frac{\pi}{4} \left(\frac{7}{12} \right)^2 = 0.2672 \text{ ft}^2 \quad (\text{eight lines/loop})$$

Thus

$$\begin{aligned} \tau_{hS4} &= (A_{S31} N_{EVAP} L_{S31} + A_{S32} 8N_L L_{S32}) (\rho_{S3}/W_{S3S}) \\ &= (0.66 N_{EVAP} L_{S31} + 2.138 N_L L_{S32}) (\rho_{S3}/W_{S3S}) \quad (A-4.7) \end{aligned}$$

where L_{S31} , L_{S32} are not known, and therefore they are left as input parameters to the simulator. The values used in the simulation are:

$$L_{S31} = 70 \text{ ft} \quad \text{and} \quad L_{S32} = 10 \text{ ft}$$

A-4.4 General Momentum Equation

Equation (2-4.16) is rewritten here for convenience:

$$\frac{\partial \vec{\rho v}}{\partial t} + \nabla \cdot (\vec{\rho v} \cdot \vec{v}) = - \nabla P + \vec{\rho g} - \nabla \tau \quad (2-4.16)$$

For each region we integrate this equation over that region length assuming that region boundaries are fixed, and then a coordinate transformation from fixed to movable boundaries is made where applicable.

For fixed boundary regions, integrating Eq. (2-4.16) leads to

$$\frac{L}{A} \frac{d\bar{W}}{dt} + \frac{W_{2a}^2}{\rho_2 A_2^2} - \frac{W_{1a}^2}{\rho_1 A_1^2} = P_1 - P_2 + Y_{12} \bar{\rho} g - \text{losses} \quad (2-4.17)$$

Since the only variable boundary regions we will be considering are those of the evaporator, the appropriate transformations are:

$$\begin{pmatrix} W_{S1a} \\ W_{S2a} \\ W_{S3a} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} W_{S1} \\ W_{S2} \\ W_{S3} \end{pmatrix} \quad (A-4.8)$$

As should be expected, the flow rates at the inlet and exit (fixed boundaries) are not affected by the coordinate representation. However,

$$W_{S2} = W_{S1} - \bar{\rho}_{S1} A_{S1} \frac{dL_{S1}}{dt}$$

(see Eq. (2-3.1)), whereas

$$W_{S2a} \stackrel{\Delta}{=} W_{S1} - 0$$

since $\frac{dL_{S1}}{dt} = 0$ for a fixed boundary. In other words $W_{S2a} = W_{S1}$ (not W_{S2}).

Thus, generally, the momentum equations in the two regions AS1 and AS2 of the evaporator are:

$$\frac{L_{S1}}{A_{S1}} \frac{d\bar{W}_{S1a}}{dt} = P'_{S1} - P_{S2} + L_{S1} \bar{\rho}_{S1} g - F_{S1t} W_{S1}^2 \quad (A-4.9)$$

and

$$\begin{aligned} \frac{L_{S2}}{A_{S1}} \frac{d\bar{W}_{S2a}}{dt} + \frac{W_{S3}^2}{\rho_{S3} A_{S1}^2} - \frac{W_{S1}^2}{\rho_{fS2} A_{S1}^2} = P_{S2} - P'_{S3} + L_{S2} \bar{\rho}_{S2} g \\ - F_{S2t} \bar{W}_{S2a}^2 \end{aligned} \quad (A-4.10)$$

where

$$\bar{W}_{S1a} = \frac{W_{S1a} + W_{S2a}}{2} = W_{S1} \quad (A-4.11a)$$

and

$$\bar{W}_{S2a} = \frac{W_{S2a} + W_{S3a}}{2} = \frac{W_{S1} + W_{S3}}{2} \quad (A-4.11b)$$

Notice that P'_{S1} , P_{S2} and P'_{S3} are the pressures at the beginning of the effective tube length, the boundary between the two regions, and the end of the effective tube length respectively. Notice also that P'_{S1} and P'_{S3} are not the P_{S1} and P_{S3} used below, where P_{S1} and P_{S3} are the pressures at the inlet and exit of the evaporator.

A-4.5 The Momentum Equations for the Evaporator/Steam Drum Loop

Most of the dimensional data used in this section is obtained from Figure (A-4.2), unless otherwise specified.

A-4.5.1 Evaporator. In the steady state, the total pressure drop [1] in the evaporator is 103 psi. However, neither the losses in each region nor the relative fractions of frictional to obstruction losses are known. Therefore the average pressure $\bar{P}_{S2}$ in the upper region was first assumed to be the arithmetic average of the known inlet and exit pressures (1879 psig and 1776 psig) [1], i.e., $\bar{P}_{S2}$ is assumed to be 1842.2 psia. This pressure was used to estimate the steady state densities, the region length, and the friction multiplier. These are then used to estimate the hydrostatic heads, the frictional losses, and the change in momentum pressure heads in both regions. It is found that the sum of the hydrostatic and frictional heads in the first region is about 20 psi (not including obstruction losses), and that the sum of the hydrostatic pressure head, the change in momentum pressure head, and the frictional losses in the second region is ~ 65 psi. Consequently, the following assumptions were made: (1) The total pressure drop in the subcooled water region = 23 psi, (2) the total pressure drop in the two phase region = 80 psi (note that the obstruction loss in the two phase region is larger because of the bends in that region).

Thus:

$$P_{S2} = 1870.7 \text{ psia}$$

and

$$\bar{P}_{S2} = \frac{P_{S2} + P_{S3}}{2} = 1830.7 \text{ psia} \quad (\text{A-4.12})$$

Using this value of $\bar{P}_{S2}$ in Section (A-3) we obtain the following initial steady state values:

$$L_{S1} = 21.3777 \text{ ft} , \quad L_{S2} = 24.623 \text{ ft}$$

$$\rho_{S1}(T_{S1}) = 46.3 \text{ lb}_m/\text{ft}^3 , \quad \rho_{fS2} = 40 \text{ lb}_m/\text{ft}^3$$

$$\rho_{gS2} = 4.59 \text{ lb}_m/\text{ft}^3 , \quad \alpha_{S3} = 0.897$$

Since

$$\rho_{S3} = \rho_{fS2} + \alpha_{S3} (\rho_{gS2} - \rho_{fS2}) \quad (\text{A-4.13})$$

one finds that

$$\rho_{S3}|_o = 8.237 \text{ lb}_m/\text{ft}^3$$

Also

$$\bar{\rho}_{S1} = \rho_f(\bar{T}_{S1})$$

hence

$$\bar{\rho}_{S1}|_o = 43.79 \text{ lb}_m/\text{ft}^3 \text{ (from subcooled water tables)}$$

In addition

$$\bar{\rho}_{S2} = \rho_{fS2} + \bar{\alpha}_{S2} (\rho_{gS2} - \rho_{fS2}) \quad (\text{A-4.14})$$

But

$$\bar{\alpha}_{S2} \Big|_o = 0.6145$$

Thus

$$\bar{\rho}_{S2} \Big|_o = 13 \quad \text{lb}_m/\text{ft}^3$$

The friction multiplier is (see Section 2-3):

$$R \Big|_o = RD(1830.7, 0.5) = 4.65$$

Also

$$\text{Re}_{S1} = 2.544 \times 10^5, \quad \text{Re}_{S2} = 2.76 \times 10^5$$

a. The subcooled water region: The momentum equation in this region is

$$\begin{aligned} P_{S1} - P_{S2} = & \frac{L_{S1}}{144 \, g A_{S1}} \frac{dW_{S1S}}{dt} + \frac{L_{S1} \bar{\rho}_{S1} + 16.79 \, \rho_{S1}}{144} \\ & + (F_{S1a} L_{S1} + f_{S2a}) \left(\frac{W_{S1S}}{N_E} \right)^2 \end{aligned} \quad (\text{A-4.15})$$

Where P_{S1} and P_{S2} are in psi, W_{S1S} is in lb_m/sec , L_{S1} is in ft, and A_{S1} is in ft^2 .

The friction head is:

$$\Delta P_{S1a} = f_{S1a} L_{S1} \left(\frac{W_{S1S}}{N_E} \right)^2 \quad (\text{A-4.16})$$

and the obstruction loss is:

$$\Delta P_{S1b} = f_{S1b} \left(\frac{W_{S1S}}{N_E} \right)^2 \quad (A-4.17)$$

Comparing Eqs. (A-4.16) and (2-4.18), we find that:

$$f_{S1a} = \frac{8 f_{S1}}{144 (2 g A_{S1}^2 \bar{\rho}_{S1} D_{IE})} \quad (A-4.18a)$$

Thus

$$\begin{aligned} f_{S1a} \Big|_o &= 711.58 f_{S1} \quad \text{psi/ft}/(1b_m/\text{sec})^2 \\ &= 102467.41 f_{S1} \quad 1b_f/\text{ft}^3/(1b_m/\text{sec})^2 \end{aligned} \quad (A-4.18b)$$

but from Eq. (2-4.19b) and the value of Re_{S1} given above:

$$f_{S1} \Big|_o \approx 2.749 \times 10^{-3}$$

Thus

$$f_{S1a} \Big|_o = 1.956 \quad \text{psi/ft}/(1b_m/\text{sec})^2$$

Substituting this and other steady state values into Eq. (A-4.15), we get

$$f_{S1b} = 24.685 \quad \text{psi}/(1b_m/\text{sec})^2$$

Hence,

$$\Delta P_{S1a} \approx 7.0 \quad \text{psi}$$

$$\Delta P_{S1b} \approx 4.1 \quad \text{psi}$$

b. The Two Phase Region: The momentum equation for this region is:

$$\begin{aligned} P_{S2} - P_{S3} = & \frac{1}{144 \text{ g } A_{S1}} \left[L_{S2} \frac{d\bar{W}_{S2aS}}{dt} + 9.67 \frac{dW_{S3aS}}{dt} \right] \\ & + \frac{L_{S2} \bar{\rho}_{S2} + 5.083 \rho_{S3}}{144} + \frac{1}{144 \text{ g } A_{S1}^2} \left(\frac{W_{S3aS}^2}{\rho_{S3}} - \frac{W_{S2aS}^2}{\rho_{fS2}} \right) \\ & + f_{S2a} R L_{S2} \left(\frac{\bar{W}_{S2aS}}{N_E} \right)^2 + (9.67 f_{S2a} R + f_{S2b}) \left(\frac{W_{S3aS}}{N_E} \right)^2 \end{aligned} \quad (\text{A-4.19})$$

where

$$\bar{W}_{S2aS} = \frac{W_{S1S} + W_{S3S}}{2} \quad \text{lb}_m / \text{sec} \quad (\text{A-4.20})$$

$$\Delta P_{S2a} = f_{S2a} R \left[L_{S2} \left(\frac{\bar{W}_{S2aS}}{N_E} \right)^2 + 9.67 \left(\frac{W_{S3aS}}{N_E} \right)^2 \right] \quad (\text{A-4.21})$$

$$\Delta P_{S2b} = f_{S2b} \left(\frac{W_{S3aS}}{N_E} \right)^2 \quad (\text{A-4.22})$$

Comparing Eqs. (A-4.21) and (2-4.18)

$$f_{S2a} = \frac{8 f_{S2}}{144 (2 g A_{S1}^2 \rho_{fS2} D_{IE})} \quad (A-4.23)$$

i.e.,

$$\begin{aligned} f_{S2a} \Big|_o &= 777.6 f_{S2} \quad \text{psi/ft/(lb}_m\text{/sec)}^2 \\ &= 111974.13 f_{S2} \quad \text{lb}_f\text{/ft}^3\text{/(lb}_m\text{/sec)}^2 \end{aligned}$$

But $Re_{S2} > 10^5$, thus

$$f_{S2} = 0.02117/Re_{S2}^{0.164} \quad (\text{see Eq. (2-4.19b)})$$

Substituting for Re_{S2} , we find that

$$f_{S2} \Big|_o = 2.71 \times 10^{-3}$$

Thus

$$f_{S2a} \Big|_o = 2.11 \quad \text{psi/ft/(lb}_m\text{/sec)}^2$$

Substituting this and other steady state values into Eq. (A-4.19), it is found that:

$$f_{S2b} = 102.26 \quad \text{psi/(lb}_m\text{/sec)}^2$$

Hence,

$$\Delta P_{S2a} \approx 56.125 \quad \text{psi}$$

and

$$\Delta P_{S2b} \approx 17.067 \quad \text{psi}$$

A-4.5.2 The Riser.

$$\begin{aligned} P_{S3} - \bar{P}_{S4} = & \frac{1}{144 \text{ g}} \left[\frac{L_{S31}}{N_{\text{EVAP}} L_{S31}} + \frac{L_{S32}}{8 N_L A_{S32}} \right] \frac{dW_{S3S}}{dt} \\ & + \frac{5.125 \rho_{S3}}{144} + f_{S34} \left(\frac{W_{S3S}}{N_{\text{EVAP}}} \right)^2 \end{aligned} \quad (\text{A-4.24})$$

(See Figures A-4.2 and A-4.3 for configuration and data, and Table 5-5.7 of Ref. 2 for data.) Values for A_{S31} , A_{S32} , L_{S31} , L_{S32} are given in Section (A-4.3).

Noting that $\bar{P}_{S4}$ is 1765.7 psia, and substituting this and other steady state values into Eq. (A-4.24), one finds that:

$$f_{S34} = 2.583 \times 10^{-4} \quad \text{psi}/(\text{lb}_m/\text{sec})^2$$

A-4.5.3 Steam Drum. Here only the hydrostatic pressure head is considered. The entrance and exit losses are lumped with those in the riser and downcomer, respectively. Thus,

$$\bar{P}_{S4} - P_{S6} = - \left(Y_{S5} + \frac{D_{\text{OD}} - D_{\text{ID}}}{2} \right) \rho_{S6}/144 \quad (\text{A-4.25})$$

Figure A-4.3. Steam Drum Schematic Flow Diagram

D_{OD} is assumed to be seven feet, whereas D_{ID} is given [1] as six feet, and initially

$$\rho_{S6} = \rho_{S1} = 46.3 \quad \text{lb}_m/\text{ft}^3$$

and

$$Y_{S5} \Big|_o = 3 \text{ ft.}$$

Hence

$$P_{S6} \Big|_o \approx 1766.825 \text{ psia}$$

A-4.5.4 Downcomer. The momentum equation in this region is:

$$P_{S6} - P_{S1} = \frac{1}{144 \text{ g } N_L} \left[\frac{L_{S61}}{4 A_{S61}} + \frac{L_{S62}}{A_{S62}} + \frac{L_{S63}}{A_{S63}} + \frac{N_L}{N_{EVAP}} \frac{L_{S64}}{A_{S64}} \right] \frac{dW_{S1S}}{dt} - \frac{69.50 \rho_{S6}}{144} - \Delta P_{RC} + f_{S6} \left(\frac{W_{S1S}}{N_L} \right)^2 \quad (\text{A-4.26})$$

(See Figures A-4.2 and A-4.3, and Table 5-5.7 of Reference [2].)

The A_{S61} and L_{S61} are given in Section (A-3.4). From page 5.5-22 of Ref. [2], the recirculation pump head ΔP_{RC} is 148 psi at $2.226 \times 10^6 \text{ lb}_m/\text{hr.}$ pump flow. If we then assume that the shut-off head ΔP_{RCSF} is 175 psi the pump friction coefficient f_{RC} is found from Eq. (2-4.34) to be

$$f_{RC} = 7.0576 \times 10^{-5} \quad \text{psi}/(\text{lb}_m/\text{sec})^2$$

and from Eq. (A-4.26) we find that:

$$\begin{aligned} f_{S6} &= 1.136318 \times 10^{-4} && \text{psi}/(\text{lb}_m/\text{sec})^2 \\ &= 1.6362977 \times 10^{-2} && \text{lb}_f/\text{ft}^2/(\text{lb}_m/\text{sec})^2 \end{aligned}$$

(Notice that f_{S6} depends on the values of D_{OD} and ΔP_{RC} , and will change if either is changed. Therefore f_{S6} is left as an input parameter.)

A-4.6 Overall Momentum Balance in the Evaporator/Steam Drum Loop

The goal in this section is to obtain the inlet and exit flow rates for the evaporator in terms of the other variables and parameters in the loop.

Adding Eqs. (A4.15, 19, 24, 25, 26), we get the following:

$$A_{11}(t) \frac{dW_{S1S}}{dt} + A_{12}(t) \frac{dW_{S3S}}{dt} = B_1(t) \quad (\text{A-4.27})$$

where

$$\begin{aligned} A_{11}(t) &= \frac{L_{S1}}{32.2 A_{S1}} + \frac{L_{S2}}{64.4 A_{S1}} + \frac{1}{N_L} \left(\frac{L_{S61}}{56.9} + \frac{L_{S62}}{50.755} + \frac{L_{S63}}{39.51} \right. \\ &\quad \left. + \frac{N_L}{N_{EVAP}} \frac{L_{S64}}{14.22} \right) \end{aligned} \quad (\text{A-4.28})$$

$$A_{12}(t) = \frac{L_{S2}}{64.4 A_{S1}} + \frac{0.3}{A_{S1}} + \frac{L_{S31}}{21.25 N_{EVAP}} + \frac{L_{S32}}{68.8445} \quad (\text{A-4.29})$$

Notice that $A_{S1} = \frac{\pi}{4} D_{IE}^2 N_E = 9.034 \times 10^{-4} N_E \text{ ft}^2$.

and

$$B_1(t) = - (HDSPH + CHMPH - \Delta P_{RC} + FRPH) \quad (A-4.3)$$

where

$$\begin{aligned} HDSPH = & L_{S1} \bar{\rho}_{S1} + L_{S2} \bar{\rho}_{S2} + 10.2 \rho_{S3} - 52.96 \rho_{S6} \\ & - (Y_{S5} + (D_{OD} - D_{ID})/2) \rho_{S6} \end{aligned} \quad (A-4.31)$$

$$CHMPH = \frac{1}{32.2 A_{S1}^2} \left(\frac{W_{S3S}^2}{\rho_{S3}} - \frac{W_{S1S}^2}{\rho_{fS2}} \right) \quad (A-4.32)$$

and

$$\begin{aligned} FRPH = & [f_{S1a} L_{S1} + 3554.657 + \left(\frac{N_E}{N_L} \right)^2 f_{S6}] (W'_{S1S})^2 \\ & + f_{S2a} R L_{S2} (\bar{W}'_{S2aS})^2 + (35304.868 + 9.67 f_{S2a} R) (W'_{S3S})^2 \end{aligned} \quad (A-4.33)$$

where

$$W'_{S1S} = W_{S1S}/N_E$$

$$\bar{W}'_{S2aS} = \bar{W}_{S2aS}/N_E$$

By substituting

$$P_{S2} = 2 \bar{P}_{S2} - P_{S3}$$

into Eq. (A-4.19), and dividing by two, and adding to Eq. (A-4.24), we get:

$$A_{21}(t) \frac{dW_{S1S}}{dt} + A_{22}(t) \frac{dW_{S3S}}{dt} = B_2(t) \quad (A-4.34)$$

where

$$A_{21}(t) = \frac{L_{S2}}{128.8 A_{S1}} \quad (A-4.35)$$

$$A_{22}(t) = \frac{L_{S2}}{128.8 A_{S1}} + \frac{0.15}{A_{S1}} + \frac{L_{S31}}{21.25 N_{EVAP}} + \frac{L_{S32}}{68.844 N_L} \quad (A-4.36)$$

and

$$B_2(t) = 144 (\bar{P}_{S2} - \bar{P}_{S4}) - HSPH34 - CHMPH/2 - FRPH34 \quad (A-4.37)$$

where

$$HSPH34 = L_{S2} \bar{\rho}_{S2}/2 + 7.67 \rho_{S3}$$

$$FRPH34 = F_{S2a} R L_{S2} (\bar{W}'_{S2aS})^2/2 + (4.834R f_{S2a} + 28309)$$

$$(\bar{W}'_{S3S})^2 \quad (A-4.38)$$

Thus from Eqs. (A-4.27, 34), we get

$$\frac{dW_{S1S}}{dt} = \frac{A_{22}(t) B_1(t) - A_{12}(t) B_2(t)}{\Delta} \quad (A-4.39)$$

and

$$\frac{dW_{S3S}}{dt} = \frac{A_{11}(t) B_2(t) - A_{21}(t) B_1(t)}{\Delta} \quad (A-4.40)$$

where

$$\Delta = A_{11}(t) A_{22}(t) - A_{12}(t) A_{21}(t) \quad (A-4.41)$$

Dividing both sides of Eqs. (A-4.39, 40) by N_E we get:

$$\frac{dW'_{S1S}}{dt} = \frac{A_{22}(t) B_1(t) - A_{12}(t) B_2(t)}{N_E \Delta}$$

and

$$\frac{dW'_{S3S}}{dt} = \frac{A_{11}(t) B_2(t) - A_{21}(t) B_1(t)}{N_E \Delta}$$

The reason for this division, as was mentioned in Section (2-4.3), is to scale down any initial error in the R.H.S. of either equation.

A-4.7 Momentum Conservation in the Feedwater Loop(s)

The suction pressure of the feedwater pump is assumed to remain constant at the value [1] $P_{SFWP} = 60$ psig. The pump head at normal operation [1] is $\Delta P_{FW} = 5000$ psi. At feedwater temperature 300°F , $\rho_{FW} = 55.58 \text{ lb}_m/\text{ft}^3$. Thus the discharge pressure is

$$P_{DFWP} = 60 + \frac{5000 \times 55.58}{144} + 14.7 = 2004.56 \text{ psia}$$

Therefore the pressure head in the main feedwater header may be assumed as $PHFW = 2000$ psia.

The vertical distance between the feedwater pump level and the central plane of the drum is [2] $Y'_{S5} = 12.5$ ft.

The outer diameter of the pipe lines extending from the feedwater header to the steam drum is [2] $D_{S5} = 12$ ". Thus the cross section $A_{S5} = \frac{\pi}{4} \left(\frac{11}{12}\right)^2 = 0.66$ ft².

However, neither the normal operation control valve stroke nor the pressure drop across this valve are known and are therefore assumed as follows:

$$\Delta P_{V5} \approx 15 \text{ psi}$$

$$S_{V5} \approx 0.7$$

Substituting these values into Eqs. (2-4.40, 41, 42), and noting that $\rho_{S5} \Big|_o = 51.33 \text{ lb}_m/\text{ft}^3$ is the water density at 454°F (which is $T_{S5} \Big|_o$, see Section (A-4.2)), we get the following:

$$f_{S5} = 0.32347 \quad \text{lb}_f/\text{ft}^2/(\text{lb}_m/\text{sec})^2$$

$$f_{V5} = 7.685 \times 10^{-5} \quad \text{psi}/(\text{lb}_m/\text{sec})^2$$

$$\tau_{WS5} = \frac{L_{S5}}{21.25 N_L} \quad \text{ft-l}$$

A-5 Intermediate Heat Exchanger

A-5.1 Heat Transfer Coefficients and Initial Values

Tube material is 316 stainless steel

Number of tubes = 2850/IHX

$N_I = 8550/\text{three loops}$, $D_{OI} = 7/8"$

Wall thickness = 0.045"

Triangular pitch = 21/16"

Effective tube length = 25' - 4-7/16"

Equivalent area of sodium per tube is $A_c = 6.184 \times 10^{-3} \text{ ft}^2$

Equivalent diameter $D_{EI} = 4 A_c / \pi D_{OI} = 0.10799 \text{ ft}$

Wall thermal conductivity $k_{WI} = 13.1 \text{ BTU}/(\text{hr ft } F^\circ)$ [6]

The thermal conductivities and specific heats at the corresponding average region temperatures are:

For Intermediate Sodium

$k_{NII} = 40.5$ $\text{BTU}/(\text{hr ft } F^\circ)$

$C_{PI} = 0.30445$ $\text{BTU}/(\text{lb}_m F^\circ)$

For Primary Sodium

$k_{NIP} = 39.6$ $\text{BTU}/(\text{hr ft } F^\circ)$

$C_{PP} = 0.3032$ $\text{BTU}/(\text{lb}_m F^\circ)$

Substituting these parameters into Eq. (2-5.1), we find that:

$$h_{NIP} = 1906.877 + 2.2875 (W_P/N_I)^{0.8} \quad (\text{A-5.1})$$

From Eq. (2-5.2) we find that:

$$h_{NII} = 2476.433 + 3.193 (W_I/N_I)^{0.8} \quad (A-5.2)$$

The initial steady state values are:

$$T_{p5} = T_{p4} = 994.73 \text{ F}^\circ$$

$$T_{p7} = 730 \text{ F}^\circ$$

$$T_{I1} = 651 \text{ F}^\circ$$

$$T_{I3} = 936 \text{ F}^\circ$$

Thus

$$\bar{T}_{I1} = \frac{T_{I1} + T_{I3}}{2} = 793.5 \text{ F}^\circ$$

$$\bar{T}_{p5} = \frac{T_{p5} + T_{p7}}{2} = 862.365 \text{ F}^\circ$$

and

$$H_I \Big|_o = \frac{W_I C_{pI} (T_{I3} - T_{I1})}{\bar{T}_{p5} - \bar{T}_{I1}} = 4.83075 \times 10^7$$

BTU/(hr F°)/three loops

Substituting this and other initial values into Eq. (2-5.3),
it is found that:

$$h_{FI} \approx 4358.576 \quad \text{BTU}/(\text{hr ft}^2 \text{ F}^\circ)$$

$$\text{The fouling resistance} = \frac{1}{\pi D_{II} \frac{L_I}{L_I} h_{FI}} = 4.4 \times 10^{-5} \quad (\text{BTU}/\text{hr}/\text{F}^\circ)^{-1}$$

This represents 24.86% of the total heat transfer resistance in the IHX. Assuming that this fouling resistance remains constant, and substituting for h_{FI} back into Eq. (2-5.3), it is found that:

$$H_I = 227149.4 N_L / (0.00765 + \frac{13.714}{h_{NIP}} + \frac{15.286}{h_{NII}}) \quad (\text{A-5.3})$$

A-5.2 Time Delays

a. τ_{TII} : (see Eq. (2-5.7))

$$\tau_{TII} = (V_{I11} + V_{I12}) \rho(T_{I9}) / (W_{IS} / N_L) \quad (\text{A-5.4})$$

where V_{I11} , V_{I12} are the sodium volumes in the pipe lines extending from the evaporator to the intermediate pump, and from the intermediate pump to the IHX, respectively. From Table 5.1-3 of Ref. [2], $V_{I11} = 330 \text{ ft}^3/\text{loop}$ and $V_{I12} = 1050 \text{ ft}^3/\text{loop}$.

Thus

$$\tau_{TII} = 1380 \rho(T_{I9}) N_L / W_{IS} = 4968000 \rho(T_{I9}) N_L / W_I \text{ sec} \quad (\text{A-5.5})$$

b. τ_{Tp5} : (see Eq. (2-5.6))

$$\tau_{Tp5} = (V_{p51} + V_{p52}) \rho (T_{p4}) / (W_{IS} / N_L)$$

where V_{p51} , V_{p52} are the sodium volumes in the pipe lines extending from the reactor vessel to the primary pump and from the primary pump to the IHX, respectively. From Table (5.1-2) of Ref. [2], $V_{p51} = 821 \text{ ft}^3/\text{loop}$ and $V_{p52} = 310 \text{ ft}^3/\text{loop}$.

Thus

$$\tau_{Tp5} = 4071600 \rho (T_{p4}) N_L / W_P \text{ sec} \quad (\text{A-5.6})$$

A-5.3 Momentum Conservation in the Intermediate Loop(s)

The main sources of data for this section are Table (5-1.3) of Ref. [2] and Figures (A-5.1,2,3). Other data are obtained from Ref. [1], unless they are assumed.

The intermediate sodium level above the discharge nozzle of the intermediate pump at normal operation = 20' - 11". The intermediate pump suction head $P_{SI} = 107.9 \text{ psig}$ (notice that the argon gas pressure above the sodium surface is 100 psig, and remains constant at this value).

Intermediate pump head at normal operation = 125.5 psi

Thus

Discharge pressure $P_{DI} \approx 233.4 \text{ psig}$

Figure A-5.1. The Hydraulic Profile of the Intermediate Heat Transport System

Figure A-5.2. Intermediate Sodium Pump

Figure A-5.3. IHX Design Layout

We also know that:

$$P_{I1} - P_{I3} = 14 \text{ psi}, \quad P_{IA} - P_{IC} = 40 \text{ psi}$$

$$P_{I7} - P_{I9} = 10 \text{ psi}$$

The following regions pressure drops, are assumed:

$$P_{I3} - P_{IA} = 20 \text{ psi}, \quad P_{IC} - P_{I7} = 15 \text{ psi}$$

$$P_{I9} - P_{SI} = 11 \text{ psi}, \text{ and } P_{DI} - P_{II} = 15.5 \text{ psi}$$

The acceleration terms on the shell sides of the superheater and the evaporator may be neglected because the flow is not unidirectional flow in these regions. The momentum Eq. (2-4.17) is applied to each region, assuming that frictional and nonfrictional losses are proportional to the square of the flow in that region. This yields the following set of momentum balance equations (see Table A-5.1 for pipe and tube lengths and diameters).

$$P_{I1} = P_{DI} - \frac{1}{144} \left[\frac{3.917}{N_L} \frac{dW_{IS}}{dt} + 12.857 \rho(T_{I1}) \right. \\ \left. + 1.2155 \times 10^{-4} \left(\frac{W_{IS}}{N_L} \right)^2 \right] \quad (A-5.7)$$

Table A-5.1. Intermediate Loop Piping Data.

Pipe or Tube Location	Length (ft)	Diameter (in)	No.	Initial Sodium ₃ Density (lb _m /ft ³)
Downcomer In the IHX	41.42	26.25	N _L	54.44
Tubes In the IHX	25.838	0.785	2850N _L	53.254
Pipe Lines (IHX to SH)	815.875	23.0	N _L	52.064
Pipe Lines (SH to EVAP.)	124.0	17.0	N _{EVAP}	52.74
Pipe Lines (Evap. to Inter. Pump)	114.375	23.0	N _L	54.44
Pipe Lines (Inter. pump to IHX)	363.92	23.0	N _L	54.44

$$\begin{aligned}
P_{I3} = P_{I1} - \frac{1}{144} \left[\frac{0.426}{N_L} \frac{dW_{IS}}{dt} - 41.42 \rho(T_{I1}) + 25.37 \rho(\bar{T}_{I1}) \right. \\
\left. + 12.54 \rho(T_{I3}) + 1.8 \times 10^{-4} \left(\frac{W_{IS}}{N_L} \right)^2 \right] \quad (A-5.8)
\end{aligned}$$

$$\begin{aligned}
P_{IA} = P_{I3} - \frac{1}{144} \left[\frac{8.78}{N_L} \frac{dW_{IS}}{dt} + 5.32 \rho(T_{I3}) \right. \\
\left. + 2.06 \times 10^{-4} \left(\frac{W_{IS}}{N_L} \right)^2 \right] \quad (A-5.9)
\end{aligned}$$

$$P_{IC} = P_{IA} - \frac{1}{144} \left[-35.416 \rho(\bar{T}_{IA}) + 6.04 \times 10^{-4} \left(\frac{W_{IS}}{N_L} \right)^2 \right] \quad (A-5.10)$$

$$\begin{aligned}
P_{I7} = P_{IC} - \frac{1}{144} \left[\frac{2.4431}{N_{EVAP}} \frac{dW_{IS}}{dt} + 35.41 \rho(T_{IC}) \right. \\
\left. + 9.27 \times 10^{-5} \left(\frac{W_{IS}}{N_{EVAP}} \right)^2 \right] \quad (A-5.11)
\end{aligned}$$

$$\begin{aligned}
P_{I9} = P_{I7} - \frac{1}{144} \left[-35.416 \rho(\bar{T}_{IE}) + 1.0594 \times 10^{-3} \right. \\
\left. \left(\frac{W_{IS}}{N_{EVAP}} \right)^2 \right] \quad (A-5.12)
\end{aligned}$$

where

$$\bar{T}_{IE} = \frac{1}{2} (T_{I7} + T_{I9})$$

$$\begin{aligned}
P_{SI} = P_{I9} - \frac{1}{144} \left[\frac{123}{N_L} \frac{dW_{IS}}{dt} + 20.75 \rho(T_{I1}) \right. \\
\left. + 3.605 \times 10^{-5} \left(\frac{W_{IS}}{N_L} \right)^2 \right] \quad (A-5.13)
\end{aligned}$$

and

$$P_{DI} = P_{SI} + \text{HOIP } \rho(T_{I1})/144 \quad (A-5.14)$$

where

HOIP = Head of Intermediate Pump (ft)

Adding Eqs. (A-5.7) to (A-5.14) and rearranging, we get the following overall momentum balance equation in the intermediate loop:

$$\begin{aligned}
\frac{dW_{IS}}{dt} = \frac{1}{\tau_{WI}} \{ (\text{HOIP} + 7.815) \rho(T_{I1}) - 25.37 \rho(\bar{T}_{I1}) \\
- 17.862 \rho(T_{I3}) + 35.416 [\rho(\bar{T}_{IA}) + \rho(\bar{T}_{IE}) - \rho(T_{IC})] \\
- [1.152 \times 10^{-3}/N_{\text{EVAP}}^2 + 1.1486 \times 10^{-3}/N_L^2] W_{IS}^2 \} \quad (A-5.15a)
\end{aligned}$$

where

$$\tau_{WI} = \frac{2.4431}{N_{\text{EVAP}}} + \frac{14.356}{N_L} \quad (A-5.15b)$$

A-6 Reactor

A-6.1 Reactor Kinetics Data

The following are the values of β_i and λ_i of Eqs. (2-6.5 ,6)

[2]:

$$\beta_1 = 0.8254 \times 10^{-4} , \quad \beta_2 = 7.756 \times 10^{-4}$$

$$\beta_3 = 6.660 \times 10^{-4} , \quad \beta_4 = 13.54 \times 10^{-4}$$

$$\beta_5 = 5.908 \times 10^{-4} , \quad \beta_6 = 1.810 \times 10^{-4}$$

$$\beta = \sum_{i=1}^6 \beta_i = 3.65 \times 10^{-3}$$

$$\lambda_1 = 0.0129 , \quad \lambda_2 = 0.0312$$

$$\lambda_3 = 0.1330 , \quad \lambda_4 = 0.3450$$

$$\lambda_5 = 1.4100 , \quad \lambda_6 = 3.7500$$

In Eq. (2-6.4) the feedback reactivity coefficients are [2]:

$$DC = - 0.0058 , \quad AXECC = - 0.023 \text{ } \$/F^\circ$$

$$SODDCC = - 0.006 \text{ } \$/F^\circ , \quad RECC = - 0.21 \text{ } \$/F^\circ$$

Thus

$$\rho_{FB} \Big|_0 \approx - 2.9444 \text{ } \$$$

(The Initial values of fuel and coolant temperatures are given in the next section.)

A-6.2 Gap Conductance, Heat Transfer Coefficients and Initial Values

As could be seen from Eqs. (2-6.15, 16), the gap conductance depends on the clad inner surface temperature, which in turn depends on the sodium film heat transfer coefficient. Therefore, this film coefficient h_c is evaluated first.

From Ref. [1], we have:

$$D_{OC} = 0.23'' \quad , \quad D_{IC} = 0.2'' \quad , \quad L_C = 3'$$

Triangular pitch to diameter ratio is 1.25, therefore the pitch is 0.2875" and the sodium equivalent area per fuel pin is $2.0857 \times 10^{-4} \text{ ft}^2$.

The equivalent (hydraulic) diameter D_{EP} is 0.013855 ft. We also have [15]:

$$k_{NP} = 39.6 \quad \text{BTU}/(\text{hr ft } F^\circ)$$

$$C_{PP} = 0.3032 \quad \text{BTU}/(\text{lb}_m F^\circ)$$

$$k_c \approx 13.4 \quad \text{BTU}/(\text{hr ft } F^\circ) \quad (\text{for SS-316 at } 900^\circ F)$$

thus

$$h_c = 14861.86 + 51.92(W'_p)^{0.8} \quad (\text{A-6.1})$$

where

$$W'_p = \text{FFC } W_p / N_p$$

$$N_p = \text{number of fuel pins in the core} = 42966 \text{ and } \text{FFC} = 0.8$$

Thus

$$h_C \Big|_o = 25461.75 \text{ BTU}/(\text{hr ft}^2 \text{ F}^\circ)$$

But the initial value of T_{R3} is:

$$T_{R3} \Big|_o = \frac{\epsilon N}{C_{pP} W_p} \Big|_o + T_{p1} \Big|_o$$

where

ϵ = rated thermal power

$$= 975 \times 3.412 \times 10^6 = 3.3267 \times 10^9 \text{ BTU/hr}$$

and

$$W_p = 41.446 \times 10^6 \text{ lb}_m/\text{hr}$$

Thus

$$T_{R3} \Big|_o \approx 994.73 \text{ F}^\circ$$

From the steady state versions of Eqs. (2-6.24, 25), we find that:

$$T_{p3} \Big|_o = [\text{FPGC } \epsilon / (\text{FFC } C_p W_p)] \Big|_o + T_{p1} \Big|_o \quad (\text{A-6.4})$$

But from Table (2-5) of Ref. [1]:

$$\text{FPGC} = 0.9239$$

Thus

$$T_{p3} \Big|_o \approx 1035.73 \text{ F}^\circ$$

and

$$\bar{T}_{p1} \Big|_o = \frac{T_{p1} + T_{p3}}{2} \Big|_o = 882.865 \text{ F}^\circ$$

However in the steady state:

$$T_{IC} - \bar{T}_{p1} = [\epsilon \text{ FPGC} / (N_p \pi L_c)] \left[\frac{1}{D_{OC} h_c} + \frac{\ln(D_{OC}/D_{IC})}{2 k_c} \right] \quad (\text{A-6.5})$$

Thus the initial value of the clad inner surface temperature is:

$$T_{IC} \Big|_o \approx 938 \text{ F}^\circ = 503.33 \text{ C}^\circ$$

But from Reference [1], $q' = 7 \text{ Kw/ft} = 229.67 \text{ watt/cm}$. In addition [2]:

fuel pellet diameter $D_p = 0.1935''$

diametral gap width $G = 6.5 \text{ mils}$

$G/D_p \% = 3.359\%$

Pellet density (% TD) = 91.3, thus

$D = 0.913$ (see Eq. (2-6.21))

Substituting into Eqs. (2-6.15, 16, 17), we find that:

$$B = 1.82 \times 10^{-9}$$

$$T_{\text{gap}} = 855.7 \text{ K}^\circ$$

Thus

$$h_{\text{gap}} = 0.445 \text{ W/(cm}^2 \text{ C}^\circ)$$

The fuel gap conductance h'_G is $784.4 \text{ BTU/(hr ft}^2 \text{ F}^\circ)$.

It should be mentioned, however, that during the early stage of this work, and while overly busy in shaping the model for all components of the plant, the author overlooked the fact that she misplaced¹ one of the factors on the R.H.S. of Eq. (A-6.5). This resulted in h'_G being equal to 756.82 BTU/(hr ft² F°) rather than the correct value given above, this corresponds to an error of $\sim 3.6\%$ in h'_G . However, it was found that its effect on other variables is $< 1\%$. Its main effect, however, is on the initial value of the average fuel temperature which should be 2195.54 °F rather than the 2217.18 F° computed below and used in the simulators.

From Eqs. (2-6.19, 20), the fuel thermal conductivity is determined from:

$$k'_F = \frac{36.1}{T + 129.2} + 5.7829 \times 10^{-13} T^3 \text{ W/(cm C°)} \quad (\text{A-6.6})$$

where

$$T = 273 + \frac{5}{9} (\bar{T}_F - 32) \quad \text{K°} \quad (\text{A-6.7})$$

But at steady state

$$\bar{T}_F = \frac{\epsilon \text{ FPGC}}{H_R} + \bar{T}_{p1} \quad \text{F°} \quad (\text{A-6.8})$$

where H_R is that of Eq. (2-6.22). Substituting known initial values and constants in this equation and noting that the value of h'_G used is 756.82 BTU/(hr ft² F°), we get

$$H_R \Big|_0 = \frac{4.0494 \times 10^5}{0.0865 + 0.125/K_F} \quad (\text{A-6.9})$$

1. This was uncovered after the results were obtained, by G. Kolb, a graduate student at the Nuclear Engineering Department.

where

$$k_F = 57.78 k'_F \quad \text{BTU}/(\text{hr ft } F^\circ) \quad (\text{A-6.10})$$

But from Eq. (A-6.8)

$$\bar{T}_F \Big|_0 = \frac{3.0735 \times 10^9}{H_R} + 882.866 \quad F^\circ \quad (\text{A-6.11})$$

Substituting from Eqs. (A-6.10, 6, 7, 9) into Eq. (A-6.11) leads to a fourth order equation in $\bar{T}_F \Big|_0$, which is not easy to solve analytically. Thus a trial and error approach was utilized in obtaining the initial values of $\bar{T}_F$ and K_F from the aforementioned equations. These values were found to be:

$$k_F \Big|_0 \approx 1.4 \text{ BTU}/(\text{hr ft } F^\circ) \text{ and } \bar{T}_F \Big|_0 = 2217.18 \text{ } F^\circ$$

In the simulator k_F is not substituted as constant but rather kept as a defined variable which is determined from Eqs. (A-6.8, 6, 10). However h'_G is regarded as parameter that must be input to the simulator.

Finally, substituting for D_{IC} , D_{OC} , L_C and K_C in Eq. (2-6.22), it is found that:

$$H_R = 9.42478 N_P / \left[\frac{0.125}{k_F} + \frac{0.00024}{h'_G} + \frac{52.1739}{h_C} + 0.005215 \right] \quad (\text{A-6.12})$$

A-6.3 Time Delays

a. τ_{TR1} : (See Eq. (2-6.12))

$$\tau_{TR1} = M_{R1} N_L / W_{PS}$$

where

$$M_{R1} = V_{R1} \rho(T_{P7})$$

But from Table (5.1-2) of Ref. [1],

$$V_{R1} = 499 \text{ ft}^3$$

Thus

$$\tau_{TR1} = 1796400 \rho(T_{P7}) N_L / W_P \text{ sec} \quad (\text{A-6.13})$$

A-6.4 Mass of Sodium in the Reactor Plena and Mass of Fuel in the Core

a. Lower Plenum:

The volume of sodium in this plenum is assumed to be:

$$V_{P1} = 3000 \text{ ft}^3$$

Thus

$$M_{P1} = 3000 \rho(T_{P1})$$

b. Upper Plenum:

The volum of sodium in the upper plenum (V_{P4}) is [1] 6325 ft^3 .

However, the sodium level above the outlet plenum entrance (Y_{P4}) is [1] 22 ft. Thus, the equivalent cross section of the sodium in this plenum (A_{P4}) is $V_{P4} / Y_{P4} = 287.5 \text{ ft}^2$.

Consequently:

$$M_{P4} = A_{P4} Y_{P4} \rho(T_{P4}) = 287.5 Y_{P4} \rho(T_{P4}) \quad (A-6.14)$$

Hence,

$$M_{P4} \Big|_0 \approx 3.26 \times 10^5 \text{ lb}_m$$

Notice that $\rho(T_{P4}) \approx 51.542$; see Table (A-6.2).

c. Fuel Mass M_F : From Table (1-3.3) of Ref. [2].

$$M_{U-238} = 5065 \text{ kg}, M_{U-235} = 35.5 \text{ kg in } UO_2.$$

Whereas the plutonium mass in PuO_2 is 1475.9 kg.

Thus the fuel mass in the core (M_F) is 6576.4 kg = 14498 lb_m.

A-6.5 Momentum Conservation in the Primary Loop(s)

Detailed information on the normal pressure losses in the CRBR is given in Table A-6.1 below. Other data to be used in this section are obtained from Figures (A-5.1, A-6.1) and from Table (5-1.2) of Ref. [2] unless otherwise specified.

Hydraulically, the reactor is divided into four axial regions having different flow rates. The pressure losses in these regions are:

Pressure losses in the inlet plenum $\Delta P_{l141} = 4.6 \text{ psi}$

Pressure losses in the core inlet module $\Delta P_{l142} = 9 \text{ psi}$

Table A-6.1. CRBRP Reactor Pressure Loss.

Component	Thermal and Hydraulic Nominal Pressure Loss (psi)
Core inlet module	9
Assembly inlet nozzle	15.3
Shield-orifice assembly	22.5
Rod bundle inlet	1
Rod bundle	44.2
Fuel assembly	3
Inlet plenum	4.6
Outlet plenum	4.8

Pressure losses in the inlet nozzle (of a fuel assembly), shield-orifice, rod bundle inlet, rod bundle and fuel assembly $\Delta P_{\ell 143} = 86 \text{ psi}$

Pressure losses in the outlet plenum $\Delta P_{\ell 144} = 4.8 \text{ psi}$

The sum amounts to a total pressure loss in the reactor at normal operation of 103.4 psi.

The sodium level in the outlet plenum in reference to that plenum entrance $Y_{p4} = 22 \text{ ft.}$

The outlet nozzle level above the outlet plenum entrance = 5.733 ft.

The pump suction nozzle is above the discharge nozzle by 8.334 ft.

However, the sodium level Y_{SPP} above the suction nozzle in the primary pump tank is assumed to be 8.5 ft.

The primary pump head at normal operation ($33.42 \times 10^3 \text{ gpm}$) is 452.24 ft. which corresponds to 161.873 psi.

The pressure of the argon gas cover above the sodium surfaces in the reactor outlet plenum and the primary pump tank is maintained at 10 inches of water above atmospheric pressure [1,2], i.e., the cover gas pressure is maintained at approximately 15 psia.

The pressure loss on the primary side of the IHX is 13 psi. The pressure loss coefficient (which is assumed to remain constant) in each region of the reactor is obtained as follows:

$$\Delta P_{l141} = f_{141} \left(\frac{W_{PS}}{N_L} \right)^2 / 144 = 4.6 \text{ psi}$$

from which

$$f_{141} = 3.1235 \times 10^{-7} \text{ lb}_f/\text{ft}^2 / (\text{lb}_m/\text{sec})^2$$

$$\Delta P_{l142} = f_{142} (W_{PS})^2 / 144 = 9 \text{ psi}$$

from which

$$f_{142} = 9.7776 \times 10^{-6} \text{ lb}_f/\text{ft}^2 / (\text{lb}_m/\text{sec})^2$$

$$\Delta P_{l143} = f_{143} \left(\frac{FFC W_{PS}}{N_{SUB}} \right)^2 / 144 = 86 \text{ psi}$$

from which

$$f_{143} = 5.72335 \text{ lb}_f/\text{ft}^2 / (\text{lb}_m/\text{sec})^2$$

and

$$\Delta P_{l144} = f_{144} \left(\frac{W_{PS}}{N_L} \right)^2 / 144 = 4.8 \text{ psi}$$

from which

$$f_{144} = 4.6934 \times 10^{-5} \text{ lb}_f/\text{ft}^2 / (\text{lb}_m/\text{sec})^2$$

Then by applying the general momentum Eq. (2-4.17) between the reactor inlet nozzle and the outlet plenum entrance, we get (see Table A-6.2):

$$\begin{aligned}
 144(P_1 - P_3) = & \frac{6.5527 \text{ FFC}}{N_{\text{SUB}}} \frac{dW_{\text{PS}}}{dt} + 11 \rho(T_{\text{P1}}) + 3\rho(\bar{T}_{\text{P1}}) \\
 & + 5.68 \rho(T_{\text{P3}}) + [5.72335 \left(\frac{\text{FFC}}{N_{\text{SUB}}}\right)^2 \\
 & + 4.497 \times 10^{-5}/N_L^2 + 9.7776 \times 10^{-6}] W_{\text{PS}}^2 \quad (\text{A-6.15})
 \end{aligned}$$

On the other hand

$$P_3 = P_{\text{ARGON}} + Y_{\text{P4}} \rho(T_{\text{P4}})/144 = 15 + 22 \rho(T_{\text{P4}})/144 \text{ psia} \quad (\text{A-6.16})$$

Thus

$$P_3 \Big|_o = 22.8745 \text{ psia}$$

Also

$$P_4 = P_3 - 5.733 \rho(T_{\text{P4}})/144 - \Delta P_{\ell 144}$$

whence

$$144(P_3 - P_4) = [5.733 \rho(T_{\text{P4}}) + 4.6934 \times 10^{-5} \left(\frac{W_{\text{PS}}}{N_L}\right)^2] \quad (\text{A-6.17})$$

Table A-6.2. Primary Loop Piping Data.

Pipe or Tube Location	Length (ft)	Diameter (in)	No.	Initial Density of Sodium (lb_m/ft^3)
Pipe Lines (R.V. to Primary Pump)	122.88	35.0	N_L	51.542
Pipe Lines (Primary Pump to IHX)	107.44	23.0	N_L	51.542
Pipe Lines (IHX to R.V.)	169.25	23.0	N_L	53.78
Core Fuel Subassemblies	9.55 (Fig. 2.9 of Ref. 1)	2.88 (For an equivalent circular cross section)	N_{SUB}	53.78 in the lower blanket region, 52.5 in the core and 51.17 in the upper blanket and fuel plenum regions.

Consequently

$$P_4 \Big|_0 = 20.126 \text{ psia}$$

The suction pressure of the primary pump P_{SPP} is obtained from

$$P_{SPP} = 15 + 16.833 \rho(T_{P4})/144$$

Thus

$$P_{SPP} \Big|_0 \approx 21.025 \text{ psia}$$

The pressure at the suction nozzle of the primary pump is

$$P_{SNPP} = 15 + 8.5 \rho(T_{P4})/144$$

thus

$$P_{SNPP} \Big|_0 = 18.043 \text{ psia}$$

and from the momentum balance between the reactor exit nozzle and the primary pump suction nozzle, we have:

$$144(P_4 - P_{SNPP}) = \frac{122.88}{32.2 \left[\frac{\pi}{4} (35/12)^2 \right] N_L} \frac{dW_{PS}}{dt} - 6 \rho(T_{P4}) \\ + f_{4PP} \left(\frac{W_{PS}}{N_L} \right)^2$$

Substituting initial steady state values we get:

$$f_{4PP} = 1.02836 \times 10^{-6} \quad \text{lb}_f/\text{ft}^2/(\text{lb}_m/\text{sec})^2$$

Consequently:

$$144(P_4 - P_{SNPP}) = \frac{0.57116}{N_L} \frac{dW_{PS}}{dt} - 6 \rho(T_{P4}) + 1.02836 \times 10^{-6} \left(\frac{W_{PS}}{N_L}\right)^2 \quad (\text{A-6.18})$$

and

$$144(P_{SNPP} - P_{SPP}) = - 8.333 \rho(T_{P4}) \quad (\text{A-6.19})$$

The discharge pressure of the primary pump is

$$P_{DPP} = P_{SPP} + \text{HOPP} \rho(T_{P4})/144$$

whence

$$144(P_{SPP} - P_{DPP}) = - \text{HOPP} \rho(T_{P4}) \quad (\text{A-6.20})$$

where

HOPP = Head of Primary Pump

Thus

$$P_{DPP} \Big|_0 = 21.025 + 161.873 = 182.898 \text{ psia}$$

Assume

$$P_5 = 152 \text{ psig} = 166.7 \text{ psia}$$

Thus

$$P_7 = 152 - 13 = 139 \text{ psig} = 153.7 \text{ psia}$$

Also by substituting the initial value of P_3 into Eq. (A-6.15) we find that:

$$P_1 \Big|_0 = 115 \text{ psig} = 129.7 \text{ psia}$$

Substituting these initial values into the momentum equations in the rest of the primary loop regions we find the following:

$$\begin{aligned} 144(P_{DPP} - P_5) = & \frac{1.1565}{N_L} \frac{dW_{PS}}{dt} + 20.667 \rho(T_{P4}) \\ & + 8.605 \times 10^{-5} \left(\frac{W_{PS}}{N_L}\right)^2 \end{aligned} \quad (\text{A-6.21})$$

and

$$\begin{aligned} 144(P_5 - P_7) = & 9.3255 \rho(T_{P4}) - 25.37 \rho(\bar{T}_{P5}) - 6.93 \rho(T_{P7}) \\ & + 2.1 \times 10^{-4} \left(\frac{W_{PS}}{N_L}\right)^2 \end{aligned} \quad (\text{A-6.22})$$

Notice that the acceleration term on the shell side of the IHX is neglected because the flow is not unidirectional.

Also

$$144(P_7 - P_1) = \frac{1.82175}{N_L} \frac{dW_{PS}}{dt} - 8.9 \rho(T_{P7}) + 2.6718 \times 10^{-4} \left(\frac{W_{PS}}{N_L}\right)^2 \quad (A-6.23)$$

Adding Eqs. (A-6.15, 17, 18, 19, 20, 21, 22, 23) and rearranging, we get the following overall momentum balance equation in the primary loop:

$$\begin{aligned} \frac{dW_{PS}}{dt} = \frac{1}{\tau_{WP}} \{ & 15.839 \rho(T_{P7}) - 11 \rho(T_{P1}) - 3 \rho(\bar{T}_{P1}) \\ & - 5.6833 \rho(T_{P3}) + (HOPP - 21.4) \rho(T_{P4}) + 25.37 \rho(\bar{T}_{P5}) \\ & - [6.5716 \times 10^{-4}/N_L^2 + 5.72335 \left(\frac{FFC}{N_{SUB}}\right)^2 \\ & + 9.7776 \times 10^{-6}] W_{PS}^2 \} \end{aligned} \quad (A-6.24a)$$

where

$$\tau_{WP} = \frac{3.5494}{N_L} + \frac{6.5527}{N_{SUB}} FFC \quad (A-6.24b)$$

APPENDIX B

DECAY HEAT REMOVAL

B-1 Superheater Isolation and Dump Valves

B-1.1 Isolation valve

a. Initial valve stroke. Since the valve is an isolation rather than a control valve, it is either fully open or fully closed, and logically it is fully open before the reactor scram. Thus the initial value of the normalized valve stroke is:

$$S_{IVSC}|_0 = 1$$

b. Valve actuator time constant (T_{SIVSC}). This time constant is assumed to be 0.5 sec.

c. Valve flow constant (A_{SIVSC}). The flow across the valve (W_{SAS1}/N_L) is assumed to be proportional to the valve stroke, and the constant of proportionality is obtained by substituting (W_{SAS1}/N_L)₀ and $S_{IVSC}|_0$ into Eq. (3-1.3) as follows:

$$(W_{SAS1}/N_L)_0 = 309.2592 \quad \text{lb}_m/\text{sec}$$

Thus

$$A_{SIVSC} \approx 309.26 \quad \text{lb}_m/\text{sec}$$

B-1.2 Dump valve

a. P_{SCMX} : From Table (5-5.8) of Reference [2], the superheater power relief valve, pressure set point is 1600 psig, thus

$$P_{SCMX} = 1600 \quad \text{psig}$$

b. Dump Flow Constant (C_{DMP1}): As indicated in Chapter 3, this constant is determined from the fact that the three parallel valves provide a relief capacity of 75% of the rated flow at P_{SCMX} . Thus

$$C_{DMP1} = \frac{0.75 \times 3.34 \times 10^5}{3600 \times 3 \times 1614.7} \approx 0.14365 \text{ lb}_m/\text{sec/psia}$$

B-2 The Auxiliary Heat Removal System (AHRS) and the Steam Drum

B-2.1 AHRS Initiating Parameters

The set points of this system's initiating signals, Y_{S5MN} and $FLOW_{MS}$, are given in Table 15-1.3.1 of Reference [2] as

$$Y_{S5MN} = 2'-4'', \quad FLOW_{MS} = -0.3$$

B-2.2 Mass Balance

B-2.2.1 Initial and Rated Values. The initial (rated) values of the variables associated with the main system, W_{S5S1} , W_{SAS} , M_{S4} , M_{S5} , W_{S4S} , and W_{S1S} are the same as those given in Appendix A. This section presents the initial and rated values of the auxiliary system variables, W_{APS} , W_{RCS} , W_{APTS} , W_{DMPS2} along with $\bar{P}_{S4MX}$ and W_{S7S3} .

a. W_{APS} : This flow remains at zero until the auxiliary feed-water flow control valve is actuated.

The rated value is not available, and it is assumed to be that corresponding to the pony motors flow rates in the primary and the intermediate loops, which correspond to $\sim 10\%$ of the rated power had the heat removal process been isothermal. However, if the heat removal process were isothermal, the saturation temperatures and consequently

the corresponding pressures (especially in the steam/water loops) would remain at (or near) their full power values. Then by neglecting the amount of heat transfer in the superheater relative to the total at these auxiliary system operating conditions ($\sim 10\%$ of the rated power), and assuming that the heat losses to the surroundings are approximately balanced by the pump heating effects, the rated auxiliary feedwater flow W_{APS} can be determined from the following energy balance (see Figure 3-2.1):

$$W_{S7S} h_{gS4} - W_{APS} h_{water} \equiv 10\% \text{ of the rated power}$$

where

$$h_{gS4} = h_g(1765.7 \text{ psia}) \approx 1150.7 \quad \text{BTU/lb}_m$$

$$h_{water} = h_{water}(200^\circ \text{ F}) \approx 168 \quad \text{BTU/lb}_m$$

(The 200° F is the water temperature in the protected water storage tank). But 10% of the rated power is

$$0.1 \times 975 \text{ MW} \times 3.412 \times 10^6 \text{ (BTU/hr)/MW} = 3.3267 \times 10^8 \text{ BTU/hr}$$

and since $W_{S7S} \approx W_{APS}$ (from the mass balance), we find that:

$$W_{APS} \approx 94 \text{ lb}_m/\text{sec}/\text{Three loops} \approx 700 \text{ gpm}$$

b. W_{RCS} : The initial value of this recirculation flow is zero.

As with W_{APS} the rated value of W_{RCS} is obtained by taking an energy balance (of the steam drum in this case) at 10% of the rated power.

From Eq. (3-2.8) at the steady state:

$$W_{S4S}h_{S4} + W_{S5S}h_{S5} - W_{S7S}h_{gS4} - (W_{S1S} + W_{RCS})h_{S6} = 0$$

but

$$h_{S5} = 434.688 \quad \text{BTU/lb}_m$$

$$h_{S6} = 540 \quad \text{BTU/lb}_m$$

$$h_{gS4} = 1150.47 \quad \text{BTU/lb}_m$$

and

$$W_{S7S} = W_{APS} = 94 \quad \text{lb}_m/\text{sec/three loops}$$

We also know that

$$\begin{aligned} W_{S4S}h_{S4} - W_{S1S}h_{S1} &\equiv 10 \% \text{ of full power} \\ &\equiv 9.2408 \times 10^4 \text{ BTU/sec} \end{aligned}$$

and

$$W_{S5S2} = W_{APS} + W_{RCS}$$

i.e.,

$$W_{S5S} \approx W_{S5S2} \approx W_{S7S} + W_{RCS}$$

consequently

$$W_{RCS} = \frac{9.2408 \times 10^4 - W_{S7S}(h_{gS4} - h_{S5})}{h_{S6} - h_{S5}}$$

Therefore

$$W_{RCS} \approx 236.2 \quad \text{lb}_m/\text{sec}/\text{three loops}$$

so let

$$W_{RCS} = 236 \quad \text{lb}_m/\text{sec}/\text{three loops}$$

and

$$W_{S5S2} = 330 \quad \text{lb}_m/\text{sec}/\text{three loops}$$

c. W_{APTS} : This is the saturated steam flow to the auxiliary pump turbine, which remains zero until that turbine's pressure control valve is actuated. The rated value of this flow is given in Table (5-6.1) of Reference [2] as:

$$W_{APT} = 48.0 \times 10^3 \quad \text{lb}_m/\text{hr}$$

whence

$$W_{APTS} = 13.333 \quad \text{lb}_m/\text{sec}$$

d. W_{DMPS2} , $\bar{P}_{S4MN}$ and C_{DMp2} : As indicated in Section (3-2.1), W_{DMPS2} represents 25% of the rated flow [2] or,

$$W_{DMPS2} \approx 231.944 \quad \text{lb}_m/\text{sec}/\text{three loops}$$

$\bar{P}_{S4MX}$ is the high pressure setting point of the power relief valves on the outlet headers of the steam drums and is given in Table (5-5.8) of Reference [2], as

$$\bar{P}_{S4MX} = 1840 \quad \text{psig}$$

and from Eq. (3-2.4b)

$$C_{DMP2} = \frac{231.944}{3 \times 1854.7} \approx 4.168 \times 10^{-2} \quad \text{lb}_m/\text{sec}/\text{psia}$$

e. W_{S7S3} : This flow is initially zero, and it remains so until the isolation valve on the line between the drum and the PACC is actuated. Its rated value is obtained by assuming that it corresponds to the long term heat removal subsystem full capacity conditions (45 MW(t) power). Then from the steady state energy balance, we find that

$$W_{S7S3} = \frac{45\text{MW(t)} \times 3.412 \times 10^6 \text{ (BTU/hr)}/\text{MW}}{3600 (h_{gS4} - h_{fS4})}$$

but

$$h_{gS4} \approx h_g (1765.7 \text{ Psia}) \approx 1150.47 \quad \text{BTU}/\text{lb}_m$$

$$h_{fS4} = h_f (1765.7 \text{ Psia}) \approx 643.537 \quad \text{BTU}/\text{lb}_m$$

therefore

$$W_{S7S3} \approx 84.133 \quad \text{lb}_m/\text{sec}/\text{three loops}$$

so let

$$W_{S7S3} = 84 \quad \text{lb}_m/\text{sec}/\text{three loops}$$

B-2.3 Energy Balance

B-2.3.1 The Recirculation Heater.

a. h_{RC} : Due to the mixing in the recirculation heaters, the heater exit and average water enthalpies are equal, and each equals the enthalpy of the feedwater

$$h_{RC} = h_{S5} = 434.6885 \quad \text{BTU/lb}_m$$

(h_{RC} can also be obtained from the energy balance equation of the recirculation heater Eq. (3-2.5), by substituting $h_{S6} = 540.89$, $W_{RCS} = 236$ and $W_{S5S2} = 330$).

b. M_{RC} : This mass is assumed to be 10000 lb_m/heater (this corresponds to a heater volume of $\sim 200 \text{ ft}^3$, or $\sim 1/5$ th of the drum volume).

c. τ_{h62} : See Eq. (3-2.7). In order to estimate this time delay we have to estimate M_{DRC} ,

$$M_{DRC} = \frac{\pi}{4} D_{DRCI}^2 L_{DRC} \rho (T_{S6})$$

where D_{DRCI} is the inner diameter of the pipe line from the drum to the recirculation heater (ft) and L_{DRC} is the pipe line length (ft).

Even though L_{DRC} is not available and is left as an input parameter to the simulator, the value used in the simulation is:

$$L_{DRC} = 30 \text{ ft} \quad (\text{Assumed})$$

However, D_{DRCI} is given in Reference [2] as

$$D_{\text{DRCI}} = 7 \text{ in}$$

Thus for $W_{\text{RCS}} > 0$, we have

$$\tau_{\text{h62}} = 0.267 L_{\text{DRC}} \rho (T_{\text{S6}}) N_{\text{L}}/W_{\text{RCS}} \quad (\text{B-2.1})$$

B-2.3.2 The Steam Drum.

a. τ_{h52} : See Eq. (3-2.12). This time delay is obtained from

$$\tau_{\text{h52}} = M_{\text{RCD}} N_{\text{L}}/W_{\text{S5S2}}$$

where

$$M_{\text{RCD}} = \frac{\pi}{4} D_{\text{RCDI}}^2 L_{\text{RCD}} \rho (T_{\text{S5}})$$

and

$$D_{\text{RCDI}} = 5 \text{ in} \quad (\text{From Reference [2]})$$

thus

$$\tau_{\text{h52}} = 0.1363 L_{\text{RCD}} \rho (T_{\text{S5}}) N_{\text{L}}/W_{\text{S5S2}} \quad (\text{B-2.2})$$

L_{RCD} is not available and is left as an input to the simulator, however the value used in the simulation is

$$L_{\text{RCD}} = 30 \text{ ft} \quad (\text{Assumed})$$

B-2.4 Momentum Balance

B-2.4.1 Primary Pump Coast Down Characteristics. The coast down normalized primary flow (relative to its full power value) and the primary pump head as functions of time are obtained from Eqs. (3-2.14, 3-2.15, 2-7.5, 2-7.3) and Tables (2-7.1, 2). The numerical values of these coast down variables are given in the second and third columns of Table (B-2.1) below.

B-2.4.2. Feedwater Headers and Recirculation Pump Coast Down Pressure Heads:

a. Coast Down Head in the Main Feedwater Header: From Eq. (3-2.21) and the first three columns of Table (B-2.1) the main feedwater header coast down head $PHFW1(t-t_{CD})$ for $t \geq t_{CD}$, where t_{CD} is the time at the beginning of the coast down, was found and is listed in Column Four of the same table.

b. The Recirculation Pump Coast Down Head $DPRC(t-t_{CD})$: From Eq. (3-2.26) and the first three columns of Table (B-2.1), the recirculation pump coast down head for $t \geq t_{CD}$ was found and is listed in the last column of that Table.

B-2.4.3. Rated Pressure Head in the AFW Header (PHFW2I).

The pressure head of the auxiliary feedwater pump is 4540 ft. of water at 200°F (water density $60.5 \text{ lb}_m/\text{ft}^3$) which is equivalent to 1907.43 psi. Then by assuming that the positive suction head of the pump is consumed as hydrostatic and frictional losses along the pipe lines from the pump discharge to the auxiliary feedwater header, one concludes that the pressure in the header is approximately equal to the pump head.

Table B-2.1. Pump Coast Down Characteristics.

$t - t_{CD}$ (sec)	WPFRT	HOPP (ft. of sodium)	PHFW1 (psia)	DPRC (psi)
0	1	452.3	2000	148
1	0.83386	269.511	1925.79	117.93
2	0.68596	175.955	1874.90	99.55
3	0.56429	114.048	1840.60	87.24
4	0.46877	77.540	1818.68	79.59
5	0.40867	61.594	1807.31	75.84
7	0.32754	38.128	1793.92	71.08
10	0.25577	23.88	1784.74	67.95
12	0.22355	18.07	1781.30	66.75
15	0.18965	12.81	1778.18	65.65
20	0.14961	7.48	1775.13	64.57
25	0.12551	5.288	1773.7	64.08
40	0.08702	2.1	1771.85	63.436
50	0.07387	1.318	1771.38	63.27
60	0.06535	0.86	1771.12	63.18
70	0.05937	0.617	1770.96	63.12
100	0.05215	0.297	1770.78	63.06
200	0.04605	0.0777	1770.64	63.01

Therefore

$$\text{PHFW2I} \approx 1900 \quad \text{psia}$$

B-2.4.4 Constants Related to Main Feedwater Flow (W_{S5S1}).

a. C_{V51} and f_{S51} : The pressure drop ΔP_{V51} across the main feedwater control valve is given by:

$$\Delta P_{V51} = \left(\frac{W_{S5S1}}{N_L C_{V51} S_{V51}} \right)^2 \quad (\text{B-2.3})$$

but from Section (A-4.7)

$$\Delta P_{V51}|_o = 15.0 \quad \text{psi}$$

$$S_{V51}|_o = 0.7$$

and

$$W_{S5S1}|_o = 927.777 \quad \text{lb}_m/\text{sec}$$

one finds

$$C_{V51} \approx 114.072$$

and (see Section A-4.7)

$$f_{S51} = f_{S5/144} = 2.2463 \times 10^{-3} \quad \text{psi}/(\text{lb}_m/\text{sec})^2$$

B-2.4.5 Constants Related to the Auxiliary Feedwater and Recirculation Flow Rates.

a. C_{V52} and C_{VRC} : These are the constant coefficients of the pressure losses across the flow control valves. These losses are given by:

$$\Delta P_{V52} = \left(\frac{W_{S5S2} - W_{RCS}}{N_L C_{V52} S_{V52}} \right)^2 \quad (B-2.4)$$

and

$$\Delta P_{VRC} = \left(\frac{W_{RCS}}{N_L C_{VRC} S_{VRC}} \right)^2 \quad (B-2.5)$$

Assuming that these pressure losses take the following values:

$$\Delta P_{V52} \approx 2 \quad \text{psi}$$

and

$$\Delta P_{VRC} \approx 3 \quad \text{psi}$$

and that the normalized valve strokes are:

$$S_{V52} = S_{VRC} = 0.7$$

together with the previously determined flow rates (see Section B-2.2):

$$W_{S5S2} = 330 \quad \text{lb}_m/\text{sec}/\text{three loops}$$

and

$$W_{RCS} = 236 \quad \text{lb}_m/\text{sec}/\text{three loops}$$

one finds that

$$C_{V52} \approx 31.65 \quad (1b_m/\text{sec})/(\text{Psi})^{1/2}$$

$$C_{VRC} \approx 64.88 \quad (1b_m/\text{sec})/(\text{Psi})^{1/2}$$

b. f_{DRC} , f_{RCD} and f_{HDRC} : These are coefficients of pressure losses in the pipe lines connecting the drum to the recirculation heater, the recirculation heater to the drum, and the auxiliary feedwater header to the recirculation heater, in that order.

Subtracting Eq. (3-2.31b) from Eq. (3-2.30), and noting that

$$P_{S6} - P_{S5} = (Y_{RCD} - Y_{DRC}) \rho (T_{S6}) / 144 \quad (B-2.6)$$

where

Y_{RCD} = Level difference from the recirculation heater exit to the drum feedwater inlet

Y_{DRC} = Level difference from the drum recirculation water exit to the recirculation heater inlet, yields

$$\begin{aligned} \frac{HOJTP \rho (T_{S5})}{144} - \frac{Y_{RCD} [\rho (T_{S5}) - \rho (T_{S6})]}{144} - f_{RCD} \frac{W_{S5S2}^2}{N_L^2} \\ - \left[f_{DRC} + \frac{1}{(C_{VRC} S_{VRC})^2} \right] \left(\frac{W_{RCS}}{N_L} \right)^2 = 0 \end{aligned} \quad (B-2.7)$$

To evaluate Y_{RCD} , we consult Figure A-4.2 for the drum feedwater inlet level (828.5 ft.) and Figure 5-1.1c of Reference [2] for the recirculation heater exit level (808.5 ft.). The difference is

$$Y_{RCD} = 20.5 \text{ ft.}$$

We also know that

$$\rho(T_{S5}) = \rho_{\text{water}}(454.^\circ\text{F}) \approx 51.33 \text{ lb}_m/\text{ft}^3$$

and

$$\rho(T_{S6}) = \rho_{\text{water}}(543.^\circ\text{F}) \approx 46.3 \text{ lb}_m/\text{ft}^3$$

Assuming that

$$\text{HOJTP} \approx 15.0 \text{ ft. of water at } 200^\circ\text{F}$$

and that

$$f_{\text{DRC}} \approx f_{\text{RCD}} \quad (\text{B-2.8})$$

together with the known values of C_{VRC} , S_{VRC} , W_{S5S2} and W_{RCS} obtained above, we find that

$$f_{\text{DRC}} = f_{\text{RCD}} = 4.9559 \times 10^{-4} \text{ psi}/(\text{lb}_m/\text{sec})^2$$

By subtracting Eq. (3-2.30) from Eq. (3-2.29), we find that:

$$\begin{aligned} \text{PHFW2} - \bar{P}_{S4} + \frac{\text{HCJTP} \rho(T_{S5})}{144} - \text{HDSH2} - f_{\text{RCD}} \left(\frac{W_{\text{S5S2}}}{N_L} \right)^2 \\ - \left[f_{\text{HDRC}} + \frac{1}{(C_{V52} S_{V52})^2} \right] \left(\frac{W_{\text{S5S2}} - W_{\text{RCS}}}{N_L} \right)^2 = 0 \end{aligned} \quad (\text{B-2.9})$$

where $\bar{P}_{S4}$ is the pressure in the steam drum, and

$$\begin{aligned} \text{HDSH2} = \frac{1}{144} \left[(Y_{S5} - 1.5) \rho(T_{S6}) + Y_{\text{RCD}} \rho(T_{S5}) \right. \\ \left. + Y_{\text{HDRC}} \rho_{\text{water}}(200^\circ\text{F}) \right] \end{aligned} \quad (\text{B-2.10})$$

in which

$Y_{\text{HDRC}} = 60.75 \text{ ft}$ (estimated from Figure 5-1.6 of Reference 2)
and $\rho_{\text{water}} (200^\circ\text{F}) \approx 60.5 \text{ lb}_m/\text{ft}^3$.

From these and the previously known values of the other variables and constants, f_{HDRC} is found to be:

$$f_{\text{HDRC}} \approx 0.1 \quad \text{psi}/(\text{lb}_m/\text{sec})^2$$

B-2.4.6 Constants Related to the AFW Drive Turbine

Flow and Pressure.

a. A_{VAPT} : This constant is defined by Eq. (3.2.39) as

$$A_{\text{VAPT}} = P_{\text{APT}}/W_{\text{APTS}}$$

where P_{APT} and W_{APTS} are defined in Section (3-2.3.6) and

$$P_{\text{APT}} = 1000 \quad \text{psig} \quad (\text{from Reference [2]})$$

$$W_{\text{APTS}} = 13.33 \quad \text{lb}_m/\text{sec} \quad (\text{from Section B-2.2.1})$$

thus

$$A_{\text{VAPT}} = 76.1 \quad \text{psia}/(\text{lb}_m/\text{sec})$$

b. f_{DAPT} : An estimate of pressure losses in pipe lines extending from the drum outlet header to the AFW drive turbine-pressure control valve manifold is obtained in reference to the pressure losses in the pipe lines connecting the drum to the superheater as follows:

Noting that the friction coefficient is approximately proportional to $\text{Re}^{-0.164}$, where Re is the Reynolds number, the ratio of the friction

coefficients in the two pipe lines is:

$$\begin{aligned} \frac{f_{DVAPT}}{f_{DSH}} &= \left(\frac{D_{DVAPT}}{D_{DSH}} \cdot \frac{W_{SA}}{W_{APT}} \right)^{0.164} \\ &= \left(\frac{2}{14} \cdot \frac{3.34 \times 10^6}{4.8 \times 10^4} \right)^{0.164} \end{aligned} \quad (B-2.11)$$

where D_{DVAPT} is the diameter of the pipe line between the drum and the auxiliary pump turbine pressure control valve, and D_{DSH} is the diameter of the pipe line between the drum and the superheater.

From Eq. (2-4.18)

$$\frac{\Delta P_{DVAPT}}{\Delta P_{DSH}} \approx \frac{f_{DVAPT}}{f_{DSH}} \cdot \frac{D_{DSH}}{D_{DVAPT}} \frac{L_{DVAPT}}{L_{DSH}} \left(\frac{W_{APT}}{A_{DVAPT}} \right)^2 \left(\frac{A_{DSH}}{W_{SA}} \right)^2 \quad (B-2.12)$$

we have

$$\Delta P_{DSH} = P_{S4} - P_{SA} \approx 26.0 \text{ psi (See Section A-2.4), at}$$

$$W_{SA} = 3.34 \times 10^6 \text{ lb}_m/\text{hr.}$$

By assuming that

$$\frac{L_{DVAPT}}{L_{DSH}} = \frac{2}{1}$$

we find that

$$\Delta P_{DVAPT} \approx 270 \text{ psi}$$

From this (noting that ΔP_{DVAPT} does not include either the hydrostatic or the valve pressure losses)

$$f_{DAPT} = 270 \left(\frac{3 \times 3600}{4.8 \times 10^4} \right)^2 \approx 13.66 \text{ psi}/(\text{lb}_m/\text{sec})^2$$

c. C_{VAPT} : By substituting

$$Y_{DAPT} = 94.667 \text{ ft. (from Figure 5-1.6 of Reference 2)}$$

$$S_{VAPT} = 0.85 \quad (\text{assumed})$$

and

$$\rho_{gS4} = \rho_g (1765.7 \text{ psia}) \approx 4.36 \text{ lb}_m/\text{ft}^3$$

into Eq. (3-2.38), C_{VAPT} is found to be

$$C_{VAPT} \approx 0.717 \quad (\text{lb}_m/\text{sec})/\text{psi}^{1/2}$$

B-2.4.7 Constants Related to the PACC Flow.

a. C_{VPC} : This is the valve pressure loss coefficient defined by the equation:

$$\Delta P_{VPC} = \left(\frac{W_{S7S3}}{N_L C_{VPC} S_{VPC}} \right)^2 \quad (\text{B-2.13})$$

An estimate of C_{VPC} is obtained by assuming that:

$$\Delta P_{VPC} \approx 3 \text{ psi}$$

and recalling that S_{VPC} is an isolation valve which is fully open at its normal operating conditions ($S_{VPC} = 1$), and that W_{S7S3} was found (see Section B-2.2) to be 84.0 lb_m/sec/three loops, and substituting these into Eq. (B-2.13) above, it is found that:

$$C_{VPC} = 16.1658 \quad (\text{lb}_m/\text{sec})/\text{Psi}^{1/2}$$

b. f_{DPCD} : This is the coefficient for the frictional losses along the pipe lines from the drum to the PACC and back to the drum. It is obtained from Eq. (3-2.40) by substituting:

$$Y_{DPC} \approx 46.5 \text{ ft.} \quad (\text{from Figure 5-1.6 of Reference [2]})$$

$$\rho_{fS4} = \rho_f(1765.7 \text{ Psia}) \approx 40.53 \text{ lb}_m/\text{ft}^3$$

$$\rho_{gS4} = \rho_g(1765.7 \text{ Psia}) \approx 4.36 \text{ lb}_m/\text{ft}^3$$

together with the previously known values of the other variables and constants, we find that:

$$f_{DPCD} \approx 0.011 \quad \text{psi}/(\text{lb}_m/\text{sec})^2$$

B-3 Decay Heat

B-3.1 Construction of the Fission Product Decay Heat Table

This is Table (B-3.1) whose first two columns are taken from Reference [14], and in which the column $M(I, \tau)$ is obtained from:

$$M(I, \tau) = M(\infty, \tau) - M(\infty, I + \tau) \quad (\text{B-3.1})$$

Table B-3.1. Typical Thermal Reactor Fission Product Decay Heat

Decay Time τ (sec)	$M(\infty, \tau)$ (Mev/Fission)	$M(\infty, I+\tau)$ (Mev/Fission)	$M(I, \tau)$ (Mev/Fission)	DCAYHT (Mev/Fission)
0.0	13.89	0.11988	13.77	16.524
1.0	12.6	0.119	12.48	14.976
2.0	11.75	0.119	11.63	13.956
5.0	10.5	0.119	10.38	12.456
10.0	9.47	0.119	9.35	11.22
20.0	8.44	0.119	8.32	9.984
50.0	7.1	0.119	6.98	8.376
100.0	6.13	0.119	6.01	7.212
200.0	5.27	0.119	5.15	6.18
500.0	4.29	0.119	4.17	5.004
1×10^3	3.61	0.119	3.49	4.188
5×10^3	2.35	0.119	2.23	2.676
1×10^4	1.91	0.119	1.79	2.148
5×10^4	1.18	0.119	1.06	1.272
1×10^5	0.957	0.119	0.838	1.0056
1×10^6	0.539	0.119	0.42	0.506
1×10^7	0.238	0.119	0.119	0.1428

with

$$I \approx 7.1 \times 10^7 \text{ sec.}$$

The last column of this Table is obtained by multiplying the $M(I, \tau)$ column by a factor 1.2 to account for the uncertainty in the cross sections: [14]

$$\text{DCAYHT} = 1.2 M(I, \tau) \quad \text{Mev/fission}$$

As indicated in Section (3-3), an estimate of the CRBR decay heat, normalized with respect to the total reactor power, is obtained from Eqs. (3-3.3a,b).

B-3.2 Initial Values of the Normalized Fission Power and Delayed Neutron Precursors

From Eqs. (3-3.3a, 4a, 4b) and Table (B-3.1) it is found that:

$$N(0) [1 + 7.583 \times 10^{-3} \times 16.524] = 1, \text{ from which } N(0) = 0.88865, \text{ and}$$

$$D_i(0) = 0.88865 \quad i = 1, \dots, 6$$

B-4 Outlet Plenum Model

B-4.1 Initial Values of Variables

a. Y_{KE} and Y_{P4I} : Y_{KE} is obtained from Eq. (3-4.1), knowing that

$$\text{at } t=0 \quad T_{P3} = 1035.7 \quad ^\circ\text{F (see Section A-6.2)}$$

$$\rho_{NA}(T_{P3}) = 51.178 \quad \text{lb}_m/\text{ft}^3$$

$$T_{P4} = T_{R3} = 994.73 \quad ^\circ\text{F (see Section A-6.2)}$$

$$\rho_{NA}(T_{P4}) = 51.54 \quad \text{lb}_m/\text{ft}^3$$

$$W_{PS} = 11512.77 \quad \text{lb}_m/\text{sec}$$

and that FFC, A_{SUB} , N_{SUB} , and g have the following values:

$$\text{FFC} = 0.8$$

$$A_{SUB} \approx 0.04523 \quad \text{ft}^2 \text{ (see Table A-6.2)}$$

$$N_{SUB} = 198$$

$$g = 32.2 \quad \text{ft/sec}^2$$

$$\text{the result is } Y_{KE}|_o \approx 12.4475 \quad \text{ft}$$

The sodium surface level Y_{P4I} above the plenum entrance is [1]
22 ft., thus

$$Y_{P4I}|_o = Y_{P4I} - Y_{P42}|_o - Y_{KE}|_o = 22 - 12.4475 \approx 9.55 \text{ ft}$$

b. T_{P41} and T_{P4M2} : These are the temperatures of sodium in the upper and lower regions, which are the only regions initially existing in the plenum. There is no middle region since the axial temperature distribution in the plenum is initially uniform.

$$T_{P41} \big|_0 = T_{P4M2} \big|_0 = T_{R3} \big|_0 = 994.73 \text{ } ^\circ\text{F}$$

APPENDIX C

PLANT CONTROLLERS

In this Appendix, measuring devices and compensator gains, time constants, and the upper and lower limits of the signals (and consequently the corresponding variables), as well as the dead zones, are approximately estimated or assumed as needed.

C-1 Turbine Control Valve Position Regulator

C-1.1 T_{PS9} , T_{PEXH}

On page 7.28 of Reference [2]. It is stated that the time constants for the pressure transducers is ~ 0.15 sec, thus

$$T_{PS9} = 0.15 \text{ sec and } T_{PEXH} \approx 0.15 \text{ sec}$$

C-1.2 A_{EPS91}

$$A_{EPS91} = \frac{\partial h_{S9}}{\partial P_{S9}}$$

From Table 2-2.1, we find that

$$\frac{\partial h_{S9}}{\partial P_{S9}} \approx -0.05$$

Thus

$$A_{EPS91} = -0.05 \quad \text{BTU/lb}_m/\text{psia}$$

$$C-1.3 \quad A_{EPEXH}: A_{EPEXH} = \frac{\partial h_{EXH}}{\partial P_{EXH}} = \left[\frac{\partial h_f}{\partial P} + X \frac{\partial h_{fg}}{\partial P} \right]_{P = P_{EXH}}$$

where

$$P_{EXH} = 2 \text{ in Hg} \equiv 0.98 \text{ psia}$$

$$X_{EXH} = 0.773 \quad (\text{See Section A-1.1})$$

and from steam tables at 0.98 psia, we find that:

$$\frac{\partial h_f}{\partial P} \approx 24.3 \quad \text{and} \quad \frac{\partial h_{fg}}{\partial P} \approx -14.1$$

thus

$$A_{EPEXH} \approx 13.5 \quad \text{BTU/lb}_m/\text{psia}$$

$$C.1.4 \quad A_{EXH}$$

A conversion factor from in Hg to psi, used to allow P_{EXH} to be expressed in in Hg which is a more convenient unit for this variable.

$$A_{EXH} = 0.4912 \quad \text{psi/(in Hg)}$$

$$C-1.5 \quad A_{EPT} \quad A_{EPT} = \eta_T \eta_G W_{S9}/CF$$

$$\eta_T = 0.7066 \quad (\text{See Section A-1.1})$$

$$\eta_G = \text{generator efficiency} = 0.98 \text{ (Assumed)}$$

$$W_{S9} = 3.34 \times 10^6 \quad \text{lb}_m/\text{hr}$$

$$CF = \text{Conversion Factor} = 3.412 \times 10^6 \text{ (BTU/hr)}/\text{Mw}$$

Thus,

$$A_{EPT} \approx 0.7 \quad \text{MW}/(\text{BTU}/\text{lb}_m)$$

$$C-1.6 \quad A_{E\omega G} \quad A_{E\omega G} = \frac{\Delta P_G}{\Delta \omega_G}$$

However, at or near steady state operating point, we have

$$MVA \approx \frac{1/2 I_{TG} \omega_{GI}^2}{\alpha H} \quad (\text{See Section A-1.4})$$

and noting that

$$MVA = \left(P_{G\theta}^2 + Q_{G\theta}^2 \right)^{1/2}$$

where $Q_{G\theta}$ is the reactive power, which is weakly dependent on ω_G , it is found that:

$$\Delta P_G \approx \frac{MVA}{P_{G0}} \frac{I_{TG} \omega_{GI}}{\alpha H} \Delta \omega_G$$

Thus

$$A_{E\omega G} = \frac{MVA}{P_{G0}} \frac{I_{TG} \omega_{GI}}{\alpha H} = 3.327$$

Therefore let

$$A_{E\omega G} = 3 \quad \text{MW/(rad/sec)}$$

C-1.7 T_{PG}

The time constant of the power meter

$$T_{PG} = 0.2 \text{ sec} \quad (\text{Assumed})$$

C-1.8 A_{EMW1}

$$A_{EMW1} = 1$$

C-1.9 T_{EEMW}

The time constants of all compensation networks are assumed to be 10 seconds, in order to force the zero of the $(1 + TS)/S$ compensator to be as close as possible to the pole at the origin, thus avoiding large changes in the original system transfer function while at the same time achieving zero error from any step perturbations due to the existence of the pole at the origin.

$$\text{Thus } T_{EEMW} = 10 \text{ sec}$$

C-1.10 T_{SV9}

The valve actuator time constant

$$T_{SV9} \approx 0.5 \text{ sec} \quad (\text{Assumed})$$

C-1.11 A_{SV9}

The gain of the TCV actuator, evaluated as follows:

$$A_{SV} \triangleq \frac{\Delta S_{V9}}{\Delta P_{G\theta}}$$

But

$$P_{G\theta} \propto \eta_T \eta_G W_{S9} (h_{S9} - h_{EXH})$$

and

$$W_{S9} \propto S_{V9}$$

thus

$$\frac{\Delta S_{V9}}{\Delta P_{G\theta}} = \frac{S_{V9}}{P_{G\theta}} = \frac{0.85}{380} = 2.2368 \times 10^{-3}$$

Therefore let

$$A_{SV9} = 2.25 \times 10^{-3} \text{ MW}^{-1}$$

C-2 Dump Flow Valve Actuator

C-2.1 A_{EVDMP}

$$A_{EVDMP} \triangleq \frac{\Delta S_{VDMP}}{\Delta P_{S9}}$$

But

$$W_{DMPS} \propto P_{S9} S_{VDMP}$$

To get a relation between ΔS_{VDMP} and ΔP_{S9} assume that W_{DMPS} remains constant, consequently,

$$S_{VDMP} = (S_{VDMP} P_{S9})_o / P_{S9}$$

$$\frac{\Delta S_{VDMP}}{\Delta P_{S9}} = - \left(\frac{S_{VDMP}}{P_{S9}} \right)_o = - \frac{1}{1464.7} = - 6.827 \times 10^{-4}$$

therefore let

$$A_{EVDMP} = - 0.0007 \quad (\text{psia})^{-1}$$

C-2.2 T_{EVDMP}

For the reason stated above concerning T_{EEMW} let $T_{EVDMP} = 10$ sec.

C-2.3 T_{SVDMP}

Assumed to be

$$T_{SVDMP} \approx 0.5 \quad \text{sec}$$

C-3 Steam Drum Water Level RegulatorC-3.1 A_{EYS5}

$$A_{EYS5} \approx \frac{W_{S5S} - W_{SCS}}{N_L \Delta Y_{S5}}$$

but

$$\frac{\Delta Y_{S5}}{Y_{S5}} = \frac{\Delta M_{S5}}{M_{S5}}$$

and

$$\frac{dM_{S5}}{dt} \approx (W_{S5S} - W_{SCS}) / N_L$$

i.e.,

$$\Delta M_{S5} \approx (W_{S5S} - W_{SCS}) \Delta t / N_L$$

Hence

$$A_{EYS5} \approx \frac{M_{S5}}{Y_{S5} \Delta t} = \frac{2.0268 \times 10^4}{3 \times 0.1} \approx 67560$$

Therefore let

$$A_{EYS5} \approx 6 \times 10^4 \quad (\text{lb}_m/\text{sec})/\text{ft}$$

C-3.2 T_{YS5}

The time constant of the level measuring device is ~ 0.5 sec
(see page 7-2.8 of Reference [2]).

C-3.3 A_{ESV5}

$$A_{ESV5} = \frac{\Delta S_{V5}}{\Delta(W_{SSS}/N_L)}$$

i.e.,

$$A_{ESV5} = \frac{S_{V5} N_L}{W_{SSS}} = \frac{0.7 \times 3 \times 3600}{3.34 \times 10^6} = 2.2634 \times 10^{-3}$$

Therefore let

$$A_{ESV5} = 2.25 \times 10^{-3} \quad (1b_m/sec)^{-1}$$

C-3.4 T_{EYS5} , T_{ESV5}

$$T_{EYS5} = T_{ESV5} = 10 \text{ sec} \quad (\text{Assumed})$$

C-3.5 T_{WS5S} , T_{WSCS}

On page 7-2.9 of Reference [2], it is stated that the time constants of the flow measuring devices are ~ 0.5 sec.

C-3.6 T_{SV5}

$$T_{SV5} \approx 0.5 \text{ sec} \quad (\text{Assumed})$$

C-4 Intermediate Flow/Pump Speed Regulator

C-4.1 Time Constants

$$T_{PS9} = 0.15 \text{ sec} \quad (\text{P. 7-2.8 of Reference 2})$$

$$T_{WIS} = 0.5 \text{ sec} \quad (\text{P. 7-2.9 of Reference 2})$$

$$T_{TRQI} \approx 0.01 \text{ sec} \quad (\text{Assumed})$$

and as indicated in section C-1.9, the time constants of the compensators are

$$T_{EPS9} = T_{EWIS} = T_{ENIP} = 10 \text{ sec}$$

C-4.2 A_{EPS92}

At or near a steady state

$$W_{IS} C_{PI} (T_{IA} - T_{I9}) \approx W_{SCS} (h_{S9} - h_{S5})$$

If we then make a small perturbation in P_{S9} and see what effect it has on W_{IS} , we have to retain all other variables at their steady state values (in accordance with the principle of transfer functions), thus:

$$C_{PI} (T_{IA} - T_{I9}) \Delta W_{IS} = W_{SCS} \frac{\partial h_{S9}}{\partial P_{S9}} \Delta P_{S9}$$

from which

$$\frac{\Delta W_{IS}}{\Delta P_{S9}} = \frac{W_{SCS}}{C_{PI} (T_{IA} - T_{I9})} \frac{\partial h_{S9}}{\partial P_{S9}}$$

But

$$\frac{\partial h_{S9}}{\partial P_{S9}} = -0.05 \quad (\text{See Table 2-2.1})$$

$$W_{SCS} = 927.77 \text{ lb}_m/\text{sec}, C_{PI} \approx 0.303 \text{ BTU}/(\text{lb}_m \text{ F}^\circ)$$

$$T_{IA} = 936 \text{ }^\circ\text{F}, T_{I9} = 651 \text{ F}^\circ$$

Thus

$$\frac{\Delta W_{IS}}{\Delta P_{S9}} = -0.537$$

Therefore let

$$A_{EPS92} = 0.5 \quad (\text{lb}_m/\text{sec})/\text{psi}$$

(The positive sign is necessary for system stability).

C-4.3 A_{EWIS}

From Eq. (2-7.2), near the steady state, the pump speed and flow rate are proportional. Consequently:

$$\Delta N_{IP} = \frac{N_{IP}}{W_{IS}} \bigg|_0 \Delta W_{IS}$$

$$A_{EWIS} \approx \frac{\Delta N_{IP}}{\Delta W_{IS}} = \frac{1006 \times 3600}{3.834 \times 10^6} = 0.09446$$

Therefore let

$$A_{EWIS} = 0.1 \quad \text{rpm/(lb}_m/\text{sec)}$$

C-4.4 A_{TRQ_I}

From Eq. (2-7.8) at or near a steady state,

$$TRQ_I \propto \frac{HOIP}{N_{IP}}$$

But from Eq. (2-7.1)

$$HOIP \propto N_{IP}^2$$

Thus

$$TRQ_I \propto N_{IP}$$

i.e.,

$$TRQ_I \approx \left(\frac{TRQ_I}{N_{IP}} \right) \circ N_{IP}$$

$$\Delta TRQ_I = \left(\frac{TRQ_I}{N_{IP}} \right) \circ \Delta N_{IP}$$

Thus

$$A_{TRQI} = \frac{\Delta TRQ_I}{\Delta N_{IP}} = \frac{TRQ_I}{N_{IP}} \Big|_0 = \frac{448790.3}{1006} \approx 446.11 \text{ (See Section 2-7)}$$

Therefore let

$$A_{TRQI} = 450 \quad (lb_f\text{-ft/rad})/\text{rpm}$$

C-4.5 N_{IPMX}

The maximum allowable speed of the intermediate pump is

$$N_{IPMX} = 1400 \text{ rpm [2].}$$

C-4.6 TRQ_{IMX}

Assumed to correspond to N_{IPMX} , had all other variables remained at their normal operation values, i.e., $TRQ_{MX} = \left(\frac{TRQ_I}{N_{IP}} \right) \circ N_{IPMX} = 6.2456 \times 10^5$.

Therefore let

$$TRQ_{MX} = 6 \times 10^5 \quad lb_f\text{-ft/rad}$$

C-5 Primary Flow/Pump Speed Regulator

C-5.1 Time Constants

$$T_{TR1} = 5 \quad \text{sec} \quad (\text{P. 7-5.7 of Reference [2]})$$

$$T_{WPS} = 0.5 \quad \text{sec} \quad (\text{P. 7-2.9 of Reference [2]})$$

$$T_{TRQP} \approx 0.01 \text{ sec} \quad (\text{Assumed})$$

and, similar to the intermediate loop, the time constants for the compensators are:

$$T_{ETR1} = T_{EWPS} = T_{ENPP} = 10 \text{ sec}$$

C-5.2 A_{ETR1}

$$A_{ETR1} = \frac{\Delta W_{PS}}{\Delta T_{R1}}$$

But at or near steady state

$$W_{PS} (T_{P4} - T_{R1}) = \text{constant}$$

i.e.,

$$\Delta W_{PS} = \frac{\text{constant}}{(T_{P4} - T_{R1})^2} \Delta T_{R1}$$

hence

$$\frac{\Delta W_{PS}}{\Delta T_{R1}} = \frac{W_{PS}}{(T_{P4} - T_{R1})} \Big|_o = \frac{41.446 \times 10^6}{3600 (994.73 - 730)} \approx 51.167$$

Therefore let

$$A_{ETR1} = 50 \quad (1b_m/\text{sec})/F^\circ$$

C-5.3 A_{EWPS}

$$A_{EWPS} = \frac{\Delta N_{PP}}{\Delta W_{PS}}$$

Similar to what was done in the intermediate loop

$$\frac{\Delta N_{PP}}{\Delta W_{PS}} = \frac{N_{PP}}{W_{PS}} \bigg|_o = \frac{1170 \times 3600}{41.446 \times 10^6} = 0.106$$

therefore let

$$A_{EWPS} = 0.1 \quad \text{rpm}/(\text{lb}_m/\text{sec})$$

C-5.4 A_{TRQP}

$$A_{TRQP} = \frac{\Delta TRQ_P}{\Delta N_{PP}} = \frac{TRQ_P}{N_{PP}} \bigg|_o = 491.82$$

Therefore let

$$A_{TRQP} = 500 \quad (\text{lb}_f \text{-ft/rad})/\text{rpm}$$

C-5.5 N_{PPMX}

The maximum allowable speed of the primary pump is [2]

$$N_{PPMX} = 1500 \text{ rpm.}$$

C-5.6 TRQ_{PMX}

$$TRQ_{PMX} = \frac{TRQ_P}{N_{PP}} \bigg|_o N_{PPMX} = \frac{575431.6}{1170} 1500 \approx 7.3773 \times 10^5$$

(see Section 2-7).

Therefore let

$$TRQ_{PMX} = 7 \times 10^5 \quad \text{lb}_f \text{ ft/rad}$$

C-6 Control Rod Position Regulator

C-6.1 Time Constants

$$T_{TS9} = T_{TP3} = 5 \quad \text{sec} \quad (\text{P. 7-5.7 of Reference 2})$$

$$T_{EN} = 0.1 \quad \text{sec} \quad (\text{P. 7-5.3 of Reference 2})$$

$$T_{ETS9} = T_{ETP4} = T_{EEN} = 10 \quad \text{sec}$$

$$T_{TP4}: \quad T_{TP4} \triangleq \frac{M_{P4}}{W_{PS}} = \frac{3.26 \times 10^5 \times 3600}{41.446 \times 10^6} = 28.3$$

Therefore let

$$T_{TP4} = 25 \quad \text{sec}$$

and

$$\alpha_{TP4} = 5 \quad (\text{Assumed})$$

C-6.2 A_{TP4}

$$A_{TP4} \triangleq \left. \frac{T_{P4}}{T_{P3}} \right|_0 = \frac{994.73}{1035.73} = 0.9604$$

We are restricted to use the exact value of A_{TP4} in order to avoid any initial error. Note that this is not the case in any of the aforementioned regulators, since in the previous cases the gains were always multiplied by error signals.

C-6.3 A_{ETS9}, A_{EEN}

$$A_{ETS9} = \left. \frac{T_{P4}}{T_{S9}} \right|_0 = \frac{994.73}{900} = 1.105$$

Therefore let

$$A_{ETS9} = 1$$

$$A_{EEN} = 1 \quad (\text{Assumed})$$

C.6.4 A_{ETP4}

$$A_{ETP4} = \frac{\Delta N}{\Delta T_{P4}} = \frac{N}{T_{P4}} \Big|_0 = \frac{1}{994.73}$$

Therefore let

$$A_{ETP4} = 0.001 \quad (F^\circ)^{-1}$$

C-6.5 N_{MX}

The maximum normalized power is $N_{MX} = 1.15$ (p. 5-7.4 of Reference [2]).

C-6.6 V_{CROUT}, V_{CRIN}

The maximum rod withdrawal and insertion speeds, given as [1] 9 in/min, i.e.,

$$V_{CROUT} = 0.15 \quad \text{in/sec}$$

$$V_{CRIN} = 0.15 \quad \text{in/sec}$$

C-6.7 $\rho(X_{CR})$

The central control rod reactivity worth as a function of its position above the bottom of the core (X_{CR}) is obtained as follows:

$$\rho(X_{CR}) = \rho(H) \rho_N(X_{CR})$$

where $\rho(H)$, the fully-inserted rod worth, is [2] \$2 and $\rho_N(X_{CR})$, the normalized worth of the partially inserted central control rod, is

supplied to the simulator in tabular form under table name FROCRX (see Appendix G). The entries of this table are obtained from Figure 4-3.29 of Reference [2].

The initial value of X_{CR} is [2] 12 in, therefore $\rho(X_{CR})|_0 = \$0.48$, and since the initial control rod reactivity (external reactivity) necessary to keep the reactor critical is $\$2.94$ (see Section A-6), a $\$2.46$ worth of reactivity has to come from eccentric control rods.

Finally it should be pointed out that the actual control rod motion is not continuous, but is in steps of 0.025 in. Thus assuming X to be the theoretical rod position, and X_{CR} the actual position, it is found that

$$\frac{dX}{dt} = V_{CR} \quad (\text{See Figure 4-3.6})$$

where V_{CR} is the control rod velocity, and X_{CR} is obtained from the following logic:

```
IF(T.EQ.0.0) XCR = X
DX = X - XCR
IF(DX.LE. - 0.025) XCR = XCR -0.025
IF(DX.GE. + 0.025) XCR = XCR +0.025
```

APPENDIX D

AFTER-SCRAM PLANT CONTROLLERS

All parameters associated with the control system including gains and time constants of the compensation networks, time constants of the measuring devices, initial values of the control valve strokes, and valve actuator time constants will be presented in this Appendix. Other parameters or variables that may appear in the transfer function block diagrams but which are related to the physical rather than the electronic system (such as W_{APTS} , T_{S5} , Y_{S5} , etc.) are given in Appendix B, and the set points for the controlled variables are given in Chapter 5.

D-1 AFWP Drive Turbine High Pressure Regulator

D-1.1 Pressure Compensator

a. Gain A_{EVAPT} : Defined by the following equation

$$A_{EVAPT} = \frac{\Delta S_{VAPT}}{\Delta P_{APTN}} \approx \frac{S_{VAPT}}{P_{APTN}} \bigg|_0 \quad (D-1.1)$$

where

S_{VAPT} = the AFWP drive turbine pressure control valve stroke

P_{APTN} = the normalized high pressure of the AFWP drive turbine

i.e.,

$$A_{EVAPT} \approx -\frac{0.85}{1}$$

therefore let

$$A_{EVAPT} = -1$$

- b. T_{VAPT} : Recalling the argument made in Appendix C (Section C-1.9) regarding compensation network's zero-pole locations, T_{EVAPT} is assumed to be 10 sec.

D-1.2 Valve Actuator

- a. Time Constant T_{SVAPT} : Based on the information given in Table (7-4.1) of Ref. [2], the valve will be in its operating position within two seconds of its initiation. However, it takes ~ 4 time constants for the valve stroke to reach 98% of its final value. Thus an estimate of T_{SVAPT} is:

$$T_{SVAPT} \approx 0.5 \text{ sec}$$

- b. Initial Valve Stroke: This valve is initially closed.

D-1.3 The Pressure Measuring Device

- a. Time Constant T_{PAPTM} : Similar to the main system pressure transducers time constants given in Appendix C,

$$T_{PAPTM} = 0.15 \text{ sec}$$

b. Initial Value of the Measured Normalized Pressure P_{ATNM} :

Assume that automatic control of the pressure becomes effective once the pressure rises to 85% or more of its desired value, consequently

$$P_{ATNM} \Big|_0 = 0.85$$

D-2 Steam Drum Water Level and AFW Temperature Regulator

D-2.1 AFW-Temperature Compensator

a. Recirculation Valve Stroke Gain A_{ETRC} : Defined as follows:

$$A_{ETRC} = \frac{\Delta S_{VRC}}{\Delta T_{S5}} \quad (D-2.1)$$

In order to evaluate this gain return to the recirculation heater energy balance given by Eq. (3-2.5). From this equation at the steady state

$$h_{S5} = (W_{RCS} h_{S6} + 168 W_{APS}) / W_{S5S2} \quad (D-2.2)$$

(Note that at steady state $h_{RC} = h_{S5}$, $h_{S62} = h_{S6}$ and $W_{APS} = W_{S5S2} - W_{RCS}$.) Thus

$$\frac{\Delta W_{RCS}}{\Delta h_{S5}} \approx \frac{W_{S5S2}}{h_{S6}} \quad (D-2.3)$$

i.e.,

$$\frac{\Delta S_{VRC}}{\Delta T_{S5}} \approx \frac{W_{S5S2}}{h_{S6}} \cdot \frac{S_{VRC}}{W_{RCS}} \quad (D-2.4)$$

Using the following rated values:

$$\begin{aligned} h_{S6} &= 540.89 && \text{BTU/lb}_m \\ W_{RCS} &= 236 && \text{lb}_m/\text{sec/three loops} \\ W_{S5S2} &= 330 && \text{lb}_m/\text{sec/three loops} \\ S_{VRC} &= 0.7 && (\text{Assumed}) \end{aligned}$$

we find that

$$A_{ETRC} \approx 1.809 \times 10^{-3}$$

Therefore let

$$A_{ETRC} = 0.002 \quad (F^\circ)^{-1}$$

b. AFW Valve Stroke Gain A_{ET52} : Defined by

$$A_{ET52} = \frac{\Delta S_{V52}}{\Delta T_{S5}} \quad (D-2.5)$$

Eq. (D-2.2) above can be rewritten as:

$$W_{APS} (h_{S5} - 168) = W_{RCS} (h_{S6} - h_{S5}) \quad (D-2.6)$$

Thus

$$\frac{\Delta W_{APS}}{\Delta h_{S5}} = -W_{RCS} \frac{h_{S6} - 168}{(h_{S5} - 168)^2} \quad (D-2.7)$$

Consequently

$$\begin{aligned} \frac{\Delta S_{V52}}{\Delta T_{S5}} &\approx - \frac{W_{RCS}}{W_{APS}} \frac{h_{S6} - 168}{(h_{S5} - 168)^2} \cdot S_{V52} \Big|_0 \quad (D-2.8) \\ &= - \frac{236}{94} \frac{540.89 - 168}{(434.6885 - 168)^2} \times 0.7 = -0.0092 \end{aligned}$$

Therefore let

$$A_{ET52} = -0.01 \quad (F^\circ)^{-1}$$

$$\text{c. } \underline{T_{ETS5}}: T_{ETS5} \sim 10 \text{ sec}$$

D-2.2 Recirculation Valve Actuator

a. Time Constant T_{SVRC} : Based on the assumption that the valve stroke will reach its desired value in ~ 8 sec and that it takes ~ 4 time constants to achieve 98% of the desired value, T_{SVRC} is assumed to be $T_{SVRC} \approx 2$ sec.

b. Initial Valve Stroke: This valve is initially closed.

D-2.3 Drum Water Level Compensator

a. Gain A_{EY55} : Defined as follows

$$A_{EYS5} = \frac{\Delta S_{V52}}{\Delta Y_{S5}} \quad (D-2.9)$$

But

$$\frac{\Delta S_{V52}}{\Delta Y_{S5}} \approx \frac{S_{V52}}{W_{APS}} \frac{\Delta W_{APS}}{\Delta Y_{S5}} = \left(\frac{S_{V52}}{W_{APS}/N_L} \right) \cdot \frac{\Delta M_{S5}/\Delta t}{\Delta Y_{S5}}$$

(Notice that M_{S5} is the mass/drum whereas W_{APS} is the flow/three loops.)

and

$$\frac{\Delta M_{S5}}{\Delta Y_{S5}} \approx \frac{M_{S5}}{Y_{S5}}$$

Thus

$$A_{EYS5} \approx \frac{S_{V52}}{W_{APS}/N_L} \frac{M_{S5}}{Y_{S5} \Delta t} \quad (D-2.10)$$

From Section (C-3.1)

$$\frac{M_{S5}}{Y_{S5} \Delta t} \approx 6 \times 10^4 \quad \text{lb}_m / (\text{ft} \cdot \text{sec})$$

with

$$S_{V52} = 0.7, \quad W_{APS}/N_L = \frac{94}{3}$$

we find that

$$A_{EYS5} = 1340.4$$

Thus let

$$A_{EYS5} = 1350 \quad (\text{ft})^{-1}$$

b. T_{EYS5} : $T_{EYS5} = 10 \text{ sec}$ (Assumed)

D-2.4 AFW Valve Actuator

a. T_{SV52} : Similar to T_{SVRC} above, T_{SV52} is assumed to be 2 sec.

b. Initial valve stroke: This valve is initially closed.

D-2.5 AFW Temperature Measuring Device

a. Time Constant T_{TS5} : Similar to other temperature measuring devices time constants mentioned in Appendix C,

$$T_{TS5} = 5 \quad \text{sec}$$

D-2.6 Drum Water Level Measuring Device

a. Time Constant T_{YS5} : As in Appendix C, $T_{YS5} = 0.5 \text{ sec}$.

D-3 Primary Pony Motor Flow and Pump Speed Regulator

D-3.1 Flow Compensator

a. Gain A_{EWPS} : This is the ratio of the change in the primary pump speed from the desired pony motor speed to the change in the primary flow from its desired value corresponding to this speed, i.e.,

$$A_{EWPS} = \frac{\Delta N_{PP}}{\Delta W_{PS}} \bigg|_{\text{Near the pony motor speed}} \approx \frac{N_{PP}}{W_{PS}} \bigg|_{\text{At the pony motor speed}} \quad (D-3.1)$$

Thus substituting for W_{PS} and N_{PP} (See Section 5-2 of Chapter 5) by the following values

$$W_{PS} = W_{PSD} = 1151.27 \quad \text{lb}_m/\text{sec}$$

and

$$N_{PP} = N_{PPD} = 107 \quad \text{rpm}$$

A_{EWPS} is found to be

$$A_{EWPS} \approx 0.0929$$

Therefore let

$$A_{EWPS} = 0.1 \quad \text{rpm}/(\text{lb}_m/\text{sec})$$

D-3.2 Primary Pump Pony Motor

$$\begin{aligned} \text{a. } A_{TRQP}: \\ \frac{A_{TRQP}}{A_{TRQP}} \triangleq \frac{\Delta TRQ_P}{\Delta N_{PP}} \approx \frac{TRQ_{PD}}{N_{PPD}} \quad (\text{see Section C-4.4}) \quad (D-3.2) \end{aligned}$$

But

$$N_{PPD} = 107 \quad \text{rpm}$$

$$TRQ_{PD} = 5128.9 \quad lb_f\text{-ft/rad} \quad (\text{see Section 5-2})$$

Thus

$$A_{TRQP} \approx 47.93$$

Therefore let

$$A_{TRQP} = 50 \quad lb_f\text{-ft/rad/rpm}$$

b. T_{TRQP} : This time constant is the ratio of the motor field inductance to resistance, and is assumed to be

$$T_{TRQP} \approx 0.01 \quad \text{sec}$$

D-3.3 Primary Flow Meter

a. Flow Detector Time Constant T_{WPS} : As given in Section (C-5.1),

$$T_{WPS} \approx 0.5 \quad \text{sec}$$

D-4 Intermediate Pony Motor Flow and Pump Speed Regulator

D-4.1 Flow Compensator

a. Gain A_{EWIS} :

$$A_{EWIS} \triangleq \left. \frac{\Delta N_{IP}}{\Delta W_{IS}} \right|_{\text{Near the pony motor speed}} \approx \left. \frac{N_{IP}}{W_{IS}} \right|_{\text{At the pony motor speed}} \quad (D-4.1)$$

But from section (5-2)

$$W_{IP} = W_{IPD} = 1065.0 \quad \text{lb}_m/\text{sec}$$

$$N_{IP} = N_{IPD} \approx 92.0 \quad \text{rpm}$$

Thus

$$A_{EWIS} \approx 0.08638$$

Therefore let

$$A_{EWIS} = 0.1 \quad \text{rpm}/(\text{lb}_m/\text{sec})$$

D-4.2 Intermediate Pump Pony Motor

a. A_{TRQI} :

$$A_{TRQI} \triangleq \frac{\Delta TRQ_I}{\Delta N_{IP}} \approx \frac{TRQ_{ID}}{N_{IPD}} \quad (\text{D-4.2})$$

but from section (5-2) it is known that

$$TRQ_{ID} = 3992.6 \quad \text{lb}_f\text{-ft}/\text{rad}$$

and

$$N_{IPD} = 92 \quad \text{rpm}$$

Thus

$$A_{\text{TRQI}} = 43.397$$

Therefore let

$$A_{\text{TRQI}} = 45 \quad (\text{lb}_f\text{-ft/rad})/\text{rpm}$$

b. T_{TRQI} : $T_{\text{TRQI}} = 0.01 \text{ sec}$ (Assumed)

D-4.3 Intermediate Flow Meter

a. Flow Detector Time Constant T_{WIS} : Similar to T_{WPS} ,

$$T_{\text{WIS}} \approx 0.5 \quad \text{sec}$$

APPENDIX E

USER MANUAL FOR THE CRBRP-ATWS SIMULATOR

This simulator is prepared for the Clinch River Breeder Reactor Plant (CRBRP), and is most suitable for studying the Anticipated Transients Without Reactor Scram (ATWS), (i.e., moderate transients), due to the limited range of the data tables incorporated.

It offers the options of including or excluding the plant electronic controllers, such that one may get the so-called controlled plant transients or the uncontrolled plant transients respectively, as well as the transients with one or more of the controllers inoperative. It can also be used in studying the transients of the plant subsystems (e.g., the steam generator as a unit), or the transients of the plant individual components (e.g., Reactor, Evaporator, etc., see Figure 1-1.1 of Chapter 1).

The user should know about what is called the SWITCH PARAMETERS (S.P.'s). These parameters are used to facilitate the choice of particular perturbations in the input variables of the system components as well as the choice of connecting or isolating two consecutive components, and whether or not one wants to include or exclude any of the controllers. In the following few sections, the question "How to use these S.P.'s" will be answered. (The order in which these S.P.'s

are presented is consistent with that of their appearance in the simulator). Each of these S.P.'s has either one of the two following formats:

1. ENVAR
2. SWVAR

where VAR is one to four letters which identify the corresponding variable.

In the last section, some examples of different combinations of these switch parameters will be presented.

E-1 Turbogenerator--S.P.'s

E-1.1 The Load S.P. (ENLD)

This may have one of the values; zero (the default value), one or two according to the following:

ENLD = 0. In this case the electric load (EMW) is specified as a function of time in tabular form. A table (ELD) is included in the simulator, whose entries are those of a typical [5] utility load demand during the period from 6 a.m. to 6 p.m., normalized to 380 MW at 6 a.m. The user can use his or her own set of data provided that the table dimensions are respecified according to the number of its entries.

ENLD = 1. In this case the user has two options depending on the value of DLTLTD, which is the percentage (%) change in load and which may be positive or negative.

ENLD = 1 and DLTLD = 0. The EMW will remain constant at its initial value (EMWI).

ENLD = 1 and DLTLD $\neq$ 0. The EMW will have a step change from its initial value EMWI at $t = 0$ to its final value EMWI $(1 + \text{DLTLD}/100)$ at $\Delta t(0)$, etc.

ENLD = 2. One has three options depending on the value of DLTLD, which is the percentage load change per second, and on the value of SLD, which is the (terminated) ramp period in seconds.

ENLD = 2 and DLTLD = 0. The EMW will remain constant.

ENLD = 2, DLTLD $\neq$ 0 and $0 < \text{SLD} < \text{TMAX}$ where TMAX is the problem run time to be specified by the user. In this case there will be a terminated ramp perturbation in the EMW.

ENLD = 2, DLTLD $\neq$ 0 and $\text{SLD} \geq \text{TMAX}$. In this case there will be a continuous linear change in the EMW.

E-1.2 Turbine control valve S.P. (ENV9)

By specifying this S.P. the turbine control valves' normalized strokes (stroke = 1 for fully open valve) are adjusted in the following manner:

ENV9 = 0. The normalized valves' strokes are automatically controlled such that the generated power, the turbine inlet and exhaust pressures, as well as the load frequency each approaches its set point.

ENV9 = 1. Here as in the load perturbations we have the following options:

ENV9 = 1 and DLTV9 = 0. No changes in the valve position.

ENV9 = 1 and DLTV9 $\neq$ 0. Step change in the valve stroke.

It should be noted that DLTV9 is the fractional change in the normalized valve stroke relative to its maximum value (=1), not to its initial value (which is less than unity for practical reasons).

ENV9 = 2. Three options similar to those of load changes are available, with the exception that DLTV9 is the fractional (of the maximum value) perturbation per second. It should also be noted that the ramp period in this case is denoted SSV9 (not SV9 which is the valve stroke itself) and is in seconds.

E-1.3 Steam Dump Valve S.P. (ENDMP)

The dump valves (four in parallel) are normally closed, i.e., initial valves' strokes are zero and the following cases are obtainable:

ENDMP = 0. All dump valves remain closed unless the turbine high pressure (PS9) exceeds a set point (PS9MX), at which point all dump valves will automatically open and their positions are automatically regulated such that a quick (quicker than if we were to depend on positioning V9 alone) return of PS9 to its desired value (PS9D) is achieved. Once this occurs the valves will be and will remain closed.

When ENDMP = 1 or ENDMP = 2 only one dump valve is allowed to open accidentally, in a step or gradually in a ramp fashion depending on whether ENDMP = 1 or 2 respectively. The associated parameters to ENDMP are DLTDMP and SSVDMP.

E-1.4 The Short Circuit S.P. (ENSSC)

A complete short circuiting of the transmission lines for a specified period, that is referred to in the simulator as the time

for recovery (TFR), is simulated by specifying ENSSC as follows
 (Note that the parameter TFR can either be assigned one value to be specified in the input block, or multi-values each of which for one run to be specified in the logic block such that we may be able to determine the runaway value of TFR):

ENSSC = 0. No fault in the transmission lines, i.e., the power generated equals the power transmitted.

ENSSC $\neq$ 0. Power transmitted = 0 for $t \leq \text{TFR}$.

Power transmitted = power generated for $t > \text{TFR}$.

E-2 Superheater--S.P.'s

E-2.1 Steam Flow Rate S.P. (ENWSA)

This parameter differs according to whether the superheater is connected to the turbine or not, and to the kind of perturbations in the flow whenever the superheater is isolated from the turbine (as in the open loop steam generator transients) or from the turbine and the steam drum (as in the open loop superheater transients). Similar to those mentioned above this S.P. may be assigned one of three values as follows:

ENWSA = 0. The superheater is assumed to be connected to both the turbine and the steam drum, and the flow rate (WSAS) is determined from the momentum balance differential equation applied between the steam drum and the turbine.

ENWSA = 1. As in the load perturbations, we have two options according to whether DLTWSA = 0 or not. DLTWSA is the percentage (%) change in WSA.

ENWSA = 2. As expected, three options are available according to whether DLTWSA is zero or not and whether SWSA is less or greater than TMAX. Notice that DLTWSA is the percentage (%) change in WSA per second (even though WSA is in lb_m/hr).

E-2.2 Inlet (Saturated) Steam Pressure S.P. (ENPSA)

Similar to other switch parameters. However, ENPSA can have a non-zero value only if the superheater is isolated from the steam drum. Also notice that PSA (and consequently PSAI which is an input parameter) is in psia not in psig.

E-2.3 Sodium Flow Rate S.P. (ENWI)

Very similar to ENSWA. However, when ENWI = 0, the intermediate loop is assumed to be closed and the flow is determined from the momentum balance along this loop. DLTWI and WII are the forced perturbation associated parameters. Don't forget to input the initial value of WIS (lb_m/sec) whenever ENWI = 0 ($\text{WIS} = \text{WI}/3600$).

E-2.4 Sodium Inlet Temperature S.P. (ENTIA)

As other S.P.'s this parameter may be assigned one of three values:

ENTIA = 0. The superheater is connected to the IHX, and $\text{TIA} = \text{FDELAY}(\text{TI3}, \text{TAUTIA}, \text{J}, \text{TI3I})$ or $\text{TIA} = \text{PDELAY}(\text{TI3}, \text{TAUTIA}, \text{J}, \text{TI3I})$. (See Chapter 1 for the meanings of the FDELAY and the PDELAY operators).

ENTIA = 1. The superheater is disconnected from the IHX, and this case is similar to its counterpart in other S.P.'s with the exception that DLTTIA is in °F, not a percentage (%) change in TIA.

ENTIA = 2. Similar to the corresponding cases of the other S.P.'s. However, the forced perturbation parameters in this case are TIAI (°F), DLTTIA (°F/sec) and STIA (sec).

E-3 Evaporator--S.P.'s

E-3.1 Inlet (Subcooled) Water Enthalpy S.P. (ENHS1)

We have the following cases:

ENHS1 = 0. The evaporator is connected to the steam drum and HS1 = FDELAY (HS6, TAUHS1, J, HS6I) or HS1 = PDELAY (HS6, TAUHS1, J, HS6I).

ENHS1 = 1. In this case DLTHS1 is the percentage change in HS1 and as expected we have two cases depending on whether DLTHS1 is zero or not.

ENHS1 = 2. Similar to its counterpart of other enthalpy switch parameters.

E-3.2 Inlet Water Flow S.P. (ENWS1)

Same as in other flow rate S.P.'s except that when ENWS1 = 0 the evaporator/steam drum loop is assumed to be closed and the initial conditions for the flow in this case is that of WS1D which is in lb_m/sec/evaporator tube. The reason for such a choice of units is to enhance the numerical stability (see Section 2-4.3 of Chapter 2 for more details).

E-3.3 Inlet Sodium Temperature S.P. (ENTI7)

Similar to other temperatures. However, $ENTI7 = 0$ implies that the evaporator is connected to the superheater and that $TI7 = FDELAY (TIC, TAUTI7, J, TICI)$ or $TI7 = PDELAY (TIC, TAUTI7, J, TICI)$. (See Chapter 1 for the meanings of the FDELAY and the PDELAY operators).

E-4 Feedwater/Steam Drum--S.P.'s

E-4.1 Feedwater Control Valve S.P. (ENV5)

As in ENV9 except that when $ENV5 = 0$ this valve is automatically controlled such that the water level in the steam drum remains at its set point $YS5D$, and that any flow mismatch (i.e., the difference between the feedwater flow $WS5$ and the superheated steam flow WSC) is to be eliminated.

E-4.2 Feedwater Flow S.P. (ENWS5)

Similar to other flow rates, except that when $ENWS5 = 0$ the existence of the feedwater control valve (V5) in the feedwater loop is taken into account (for the purpose of the feedwater flow control), in contrast to the other cases in which $ENWS5 \neq 0$ (e.g., $ENWS5 = 1$ or 2) where the feedwater flow changes (or perturbations) are arbitrary with no consideration of the feedwater valves. It should also be noticed that only when both $ENWS5$ and $ENV5$ are zero the feedwater flow is automatically controlled, since even if $ENWS5 = 0$ but $ENV5 \neq 0$, the arbitrary perturbations in $ENV5$ are transmitted into arbitrary perturbations in $WS5$.

E-4.3 Steam Drum Feedwater Enthalpy S.P. (ENHS5)

As with ENHS1, except that when ENHS5 = 0, HS5 is not a delayed function of any other enthalpy but is rather determined from an overall energy balance of the plant.

E-4.4 Steam Drum Two Phase Mixture Flow S.P. (ENWS4)

Setting this parameter to zero results in equating this flow to the evaporator exit flow. Otherwise similar to other flow rates.

E-4.5 Steam Drum Two Phase Mixture Enthalpy S.P. (ENHS4)

Direct correspondence with other enthalpy S.P.'s. However, when ENHS4 = 0, HS4 is obtained from either $HS4 = FDELAY(HS3, TAUHS4, J, HS3I)$ or $HS4 = PDELAY(HS3, TAUHS4, J, HS3I)$.

E-5 Intermediate Heat Exchanger-- S.P.'s

E-5.1 Primary Flow S.P. (ENWP)

Similar to ENWI

E-5.2 Primary Inlet Temperature S.P. (ENTP5)

Direct correspondence with ENTIA. However, when ENTP5 = 0, the IHX primary inlet is connected to the reactor vessel outlet plenum; consequently $TP5 = FDELAY(TP4, TAUTP5, J, TP4I)$ or $TP5 = PDELAY(TP4, TAUTP5, J, TP4I)$.

E-5.3 Intermediate Inlet Temperature S.P. (ENTII)

As with other temperatures. However, when ENTII = 0, the IHX intermediate inlet (tube side) is connected to the evaporator sodium exit; hence $TII = FDELAY(TI9, TAUII, J, TI9I)$ or $TII = PDELAY$

(TI9, TAUT11, J, TI9I). (See Chapter 1 for the meanings of the FDELAY and the PDELAY operators).

E-6 Reactor --S.P.'s

E-6.1 Reactor Outlet Temperature S.P. (SWTP4)

This S.P. enables us to choose between automatically controlled reactor exit temperature, such that it will follow a partial load characteristic profile by setting or defaulting SWTP4 to zero, versus manually specifying a set point (TP4MC), in which case SWTP4 must be assigned a non-zero value.

E-6.2 Reactor Power Level S.P. (SWEN)

Either we adopt the load follow mode (in which the reactor power level is automatically controlled) by setting $SWEN = 0$ or adopt the reactor follow mode (in which the reactor power is led to approach a certain level ENMC to be specified by the user) by giving SWEN any non zero value.

The error signals from the automatic control subsystems of TP4 and EN are fed to the control rod drive mechanism to adjust the rod position (by withdrawing or inserting it at fixed size steps of 0.025" each, to be accomplished by specifying the rod speeds VCROUT and VCRIN) such that the reactor power level approaches a value corresponding to the load demand EMWD, TS9 remains at or near its set point TS9D, and TP4 follows a certain partial load profile. (This profile has two segments in each of which TP4 is a linear function of the reactor power). In addition to this profile, others for WPS, WIS and TR1 are also

incorporated into the simulator. All profiles cover the automatic control range which extends from 40% of the nominal power level to ENMX, which is 115% of the normal operation level of the CRBR, unless otherwise specified. For more details see Section 4-2 of Chapter 4.

E-6.3 Control Rod Reactivity S.P. (ENROC)

This can be assigned one of three values 0, 1 and 2. If ENROC = 0 the rod position is automatically controlled, as has just been mentioned above. The other two values ENROC = 1 and ENROC = 2 are similar to all other forced perturbations discussed previously. However, it should be noted that even though RHOCDI (the initial rod reactivity) is in \$, DLTRC is either in ¢ or in ¢/sec depending on whether ENROC is 1 or 2, respectively.

E-6.4 Reactor Inlet Temperature S.P. (ENTRI)

Similar to all other temperature S.P.'s, and, as is to be expected when ENTRI = 0, TRI is obtained from $TRI = FDELAY (TP7, TAUTRI, J, TP7I)$ or $TRI = PDELAY (TP7, TAUTRI, J, TP7I)$. (See Chapter 1 for the meanings of the FDELAY and the PDELAY operators.)

E-7 Pumps--S.P.'s

E-7.1 Primary Pump Flow S.P. (SWWPS)

This parameter effectiveness is confined to those cases in which we have a closed primary loop. It can be assigned one of the following values:

SWWPS = 0. In this case the primary pump flow is automatically controlled such that the reactor flow and inlet temperature follow their respective desired profiles.

SWWPS $\neq$ 0. In this case the primary flow WPS (lb_m/sec) is led to approach a set point WPSMC.

E-7.2 Primary Pump Speed S.P. (SWENPP)

Facilitates the choice between automatically controlling the pump speed by setting $\text{SWENPP} = 0$, such that the primary flow follows its desired profile, or manually forcing the pump speed to approach a set point ENPPMC by setting $\text{SWENPP} \neq 0$. It should be noted that a maximum limit on the pump speed ENPPMX has to be specified when $\text{SWENPP} = 0$.

E-7.3 Primary Pump Torque S.P. (SWTRQP)

This parameter is included to permit either an automatic control of the driving torque exerted on the pump via the feedback signals to the driving motor such that the pump speed will remain at its desired value while the primary flow (or the pump flow) is closely following its desired profile, a choice which can be achieved by setting $\text{SWTRQP} = 0$, or otherwise to manipulate this torque (without the aid of any feedback signals) to different set points TRQPMC and consequently manipulate the pump speed and flow rate accordingly. It should be noted that an upper limit on TRQP (i.e., TRQPMX which usually corresponds to ENPPMX) in the case of automatic control will have to be specified.

The intermediate pump S.P.'s, SWWIS, SWENIP AND SWTRQI have complete similiarity with their counterparts for the primary pump,

except that while the primary flow is automatically controlled such that TR1 follows its desired profile, the intermediate flow is automatically controlled such that the turbine high pressure PS9 remains at its set point PS9D.

In the next section some examples of different combinations of these S.P.'s will be presented.

E-8 Examples

E-8.1 How to Get an Open Loop Transient of the Steam Generator

Open loop means isolated from adjacent subsystems, i.e., from the turbogenerator and the feedwater subsystems, as well as from the IHX.

In reviewing the S.P.'s discussed above, only those which must have non zero values will be specified (since by default unspecified S.P.s will have zero values). Consequently, for the present purpose the following combination is preferable:

ENLD = 1.

ENV9 = 1.

ENDMP = 1.

ENWSA = 1 or 2, and depending on whether you want to make any perturbations in WSC (which is equal to WSA), you have to specify DLTWSA and SWSA accordingly.

ENWI = 1 or 2. DLTWI and SWI are to be specified or defaulted to zeros.

ENTIA = 1 or 2. DLTIA and STIA are to be chosen.

ENV5 = 1.

ENWS5 = 1 or 2. DLTWS5 and SWS5 as you want them to be.

ENHS5 = 1 or 2. DLTHS5 and SHS5 may or may not be specified.

ENWP = 1.

ENTP5 = 1.

ENT11 = 1.

ENROC = 1.

ENTR1 = 1.

SWTRQP ≠ 0. Specify TRQPMC (to be the steady state value of the main motor primary pump torque in order to avoid undesirable transients in the primary pump speed).

SWTRQI ≠ 0. Specify TRQIMC as mentioned with TRQPMC above.

E-8.2 How to Get Transients of the Closed Uncontrolled Plant

As mentioned in the previous example the S.P.'s not stated below will automatically be defaulted to zeros.

ENLD = 0, 1 or 2, and accordingly you either specify DLTL D and SLD or default them to zeros. In case you let ENLD = 0, you may also specify the entries of the ELD table (§ T14) and modify the table dimension according to the number of its entries.

ENV9 = 1 or 2. You may specify DLTV9 and SSV9 or default them.

ENDMP = 0, 1 or 2. DLTDMP and SSVDMP are to be specified according to the kind of transient to be studied.

ENSSC = 0 or not, and if it is not zero, remember to specify the TFR parameter (see Section E-1.4).

ENV5 = 1 or 2.

ENROC = 1 or 2.

SWTRQP and SWTRQI. Similar to the open loop steam generator example above.

E-8.3 How to Get the Transients of "Reactor Follow Mode" Auto-Manually Controlled Plant

In this case we have to deal with two S.P.'s only. These are:

ENLD = 0, 1 or 2.

SWEN $\neq$ 0; specify ENMC to be the desired power level normalized relative to the initial steady state operating level.

E-8.4 How to Get the Transients of "Load Follow Mode" Automatically Controlled Plant

The only S.P. to be considered in this case is:

ENLD = 0, 1 or 2. (See the uncontrolled plant example for this parameter.)

E-8.5 Accidental (Sudden) Withdrawal of the Control Rod in an Automatically Controlled Plant

This can be simulated by adopting either of the following procedures (keep ENLD = 1 in either case)

Sudden Withdrawal of the Central Rod. This rod is considered as a fine control rod, due to its high reactivity worth and effectiveness, because of its central location in the core.

Sudden withdrawal of this control rod can be simulated by changing the initial value of its position XCR (via X which is the theoretical axial location of the rod; see Appendix G) from the present 12" (the 12" corresponds [2] to initially critical reactor at full power) to a value that will result in the desired reactivity insertion, and defaulting all other S.P.'s to zeros, except ENLD which should preferably be 1. One drawback in the results of this case is that, even though the initial value of the rod location will be that in the withdrawn position, the initial value of the power level is forced to be that before the reactivity insertion in order to preserve the initial steady state of the system physical variables. This is not consistent with the prompt jump approximation used in evaluating EN. However, it is physically more acceptable and would have resulted if we had not used the prompt jump approximation.

Eccentric Rod Withdrawal. In this case the initial value of X is to remain at 12", whereas the eccentric rods' reactivity is to be changed according to the following procedural section:

```

PRØCED RØEXCD = T
IF (T.EQ.0) RØEXCD = its initial value
IF (T.GT.0) RØEXCD = its initial value + the desired
                    amount of reactivity insertion.

ENDPRØ

```

E-8.6 Sudden Opening of One of the (Four Parallel) Dump Valves

In this case let ENDMP = 1 and specify DLTDMP. All other S.P.'s except ENLD are to be defaulted to zeros.

E-8.7 Transmission Line Short-Circuiting

ENSSC should have a non zero value; specify TFR.

Finally it should be noted that if you have to use this simulator in obtaining the so-called "open loop" transient of one of the system components (even though this is highly unfavorable on cost basis) be cautious especially in specifying the S.P.'s of those variables at the inputs to that component. It is recommended that they should all be set to one at first, then the S.P. corresponding to the desired perturbation may be modified and its associated DLT and terminated ramp period specified accordingly.

APPENDIX F

USER MANUAL FOR THE CRBRP DCHT SIMULATOR

An obvious difference between this and the CRBRP ATWS simulator is the absence of the switch parameters (S.P.'s) related to the variables at the inputs of the various plant components. All except six (see below) of the S.P.'s used in this simulator are automatically adjusted, therefore only these six S.P.'s need to be specified (or defaulted to zeros). However, a "PROCED" section or a "LOGIC" block, in which the reactivity parameters are adjusted, and the scram initiator is simulated, will have to be included in this simulator.

In the following sections the S.P.'s that need to be set will be presented; this is followed by a presentation of the procedural sections describing a number of credible accidents followed by reactor scram.

F-1 Switch Parameters to be Set

F-1.1 Loss of Normal Feedwater to All Loops S.P. (ENV5)

Allows the user to specify whether the closure of the main feedwater control valves is due to the loss of the main feedwater to all the heat transport loops or due to a signal following the reactor scram, as follows:

ENV5 = 0. The closure of the main feedwater control valves is due to a signal following reactor scram.

ENV5 $\neq$ 0. The closure of the valves is due to the loss of the main feedwater to all heat transport loops.

F-1.2 Turbine Trip S.P. (ENTRBN)

Enables the user to specify whether the closure of the isolation valves on the pipe lines between the superheaters and the high pressure turbine follows or initiates the reactor scram according to the following:

ENTRBN = 0. Closure of the isolation valve IVSC is due to reactor scram.

ENTRBN $\neq$ 0. Closure of the IVSC valves is due to a turbine trip.

F-1.3 AFW-Drive Turbine Pressure Control Valve S.P. (ENVAPT)

The main role of this S.P. is to make possible the choice between operating the turbine driven AFW-pump or not in the following way:

ENVAPT = 0. This will cause the activation of the valve actuator, i.e., the turbine driven pump is in an operating mode.

ENVAPT $\neq$ 0. The valve remains closed; i.e., the AFW turbine driven pump is shut off.

F-1.4 Natural Convection in the Steam/Water Recirculation Loop S.P. (ENNCSW)

As the title implies, this S.P. facilitates the choice of natural versus forced convection of the flow in the steam/water recirculation loop as follows:

ENNCSW = 0. The recirculation pump is not shut off after the reactor scram.

ENNCSW $\neq$ 0. The recirculation pump is allowed to coast down after the reactor scram, and natural circulation takes place in the loop.

The time at which pump coast down begins (TPMPCD) is given by $TPMPCD = TSCRAM + TCDASC$, where TSCRAM is the time at which reactor scram is initiated and TCDASC is the time delay between reactor scram initiation and pump coast down (~ 0.5 sec from Reference [2]).

F-1.5 Natural Convection in the Intermediate Loop S.P. (ENNCI)

After reactor scram and main motor shut off in the intermediate loop, a pressure driving head is maintained in the loop by operating the pump at the pony motor speed (i.e., forced convection); otherwise the pump will be allowed to coast down until shut off, leaving the hydrostatic head as the only driving head in the loop (i.e., natural circulation). This is done by specifying (or defaulting) ENNCI as follows:

ENNCI = 0. Forced convection.

ENNCI $\neq$ 0. Natural convection.

F-1.6 Natural Convection in the Primary Loop S.P. (ENNCP)

Identical to ENNCI described above.

F-2 Examples of Scram Initiating Accidents Procedural Sections

F-2.1 Uncontrolled Control Rod Withdrawal at Full Power

a. Positive Step Reactivity Insertion:

```

      PRØCED ENRØC, DLTRØC, SRØC, TSCRAM, TPMPCD,
      $ENRØCD, EN2, EN2D = ENT, RHØCDI, DLTRØI, ASCRØD,
      $DTSCRM, TSCISC, TCDASC

      IF(T.EQ.0.0) GØ TØ 840

      IF(ENT.LT.1.15) GØ TØ 850

      EN2 = 2.0

      DEN2 = EN2 - EN2D

      IF(DEN2.GT.1.0) T1 = T

      IF(T.LT.(T1+TSCISC)) GØ TØ 830

      ENRØC = 2.0

      DENRØC = ENRØC - ENRØCD

      IF(DENROC.GT.1.0) GØ TØ 800

      GØ TØ 820

800 TSCRAM = T

      TPMPCD = TSCRAM + TCDASC

      PRINT 810, TSCRAM, TPMPCD

810 FØRMAT(1H-/*0 TIME AT WHICH REACTØR SCRAM
      $IS. INITIATED FØLLØWED BY TIME AT WHICH PUMPS'
      $COAST-DOWN IS INITIATED *//20X, * TSCRAM = *,
      $F7.3, 10X, * TPMPCD = *, F7.3)

820 DLTRØC = -100.0 (RHØCDI+ASCRØD+DLTROI/100.0)/DTSCRM

      SRØC = DTSCRM

      ENRØCD = ENRØC

830 EN2D = EN2

      GØ TØ 850

```

```

840 ENRØC = 1.0

      DLTRØC = DLTRØI

      TSCRAM = 9999.0

      TPMPCD = 9999.0

      EN2D = 0.0

      ENRØCD = 0.0

850 CØNTINUE

      ENDPRØ

```

In this procedural section

ENT is the total normalized reactor power (i.e., fission plus decay heat).

RHØCDI is the control rod reactivity of the critical reactor at full power in dollars.

DLTRØI is the amount in cents of the positive reactivity insertion due to the uncontrolled rod withdrawal.

ASCRØD is the minimum available scram reactivity in dollars.

DTSCRM is the scram period in seconds.

TSCISC is the time delay of reactor scram initiation after scram signal (~ 0.2 sec. from Reference 2).

TSCRAM, TCDASC and TPMPCD are as defined above.

b. Positive ramp:

Similar to above except that the following lines should replace their counterparts:

```

820 DLTRØC = -100.0*(RHØCDI+ASCRØD+DLTRØI*
    $TSCRAM/100.0)/DTSCRM

```

```

:
```

```

840 ENRØC = 2.0

```

where DLTRØI is in ¢/sec.

F-2.2 Total Loss of Off-site Power

a. Without Loss of On-site Power:

```

PRØCED ENRØC, DLTRØC, SRØC, TSCRAM, TPMPCD =

```

```

    RHØCDI, ASCRØD, DTSCRM, TSCALP

```

```

IF (T.EQ.0.0) GO TO 800

```

```

IF (T.LT.TSCALP) GØ TØ 810

```

```

TSCRAM = TSCALP

```

```

ENRØC = 2.0

```

```

DLTRØC = 100.0*(RHØCDI+ASCRØD)/DTSCRM

```

```

SRØC = DTSCRM

```

```

GØ TØ 810

```

```

800 ENRØC = 0.0

```

```

DLTRØC = 0.0

```

```

TSCRAM = 9999.0

```

```

TPMPCD = 0.0

```

```

810 CØNTINUE

```

```

ENDPRØ

```

where TSCALP is the time delay between loss of power and reactor scram initiation in seconds (~ 0.5 sec. from Reference [2]).

b. Accompanied by Loss of On-Site Power:

Same procedural section as above, and in addition the S.P.'s ENNCSW, ENNCI AND ENNCP should be assigned non-zero values.

F-2.3 Loss of Normal Feedwater to All Loops

Similar to the uncontrolled control rod withdrawal at full power described above. However, DLTRØI should be zero, ENV5 should be assigned a non zero value, and the statement IF(ENT.LT.1.15) GØ TØ 850 should be replaced by: IF(EFLØW.LT.FLØWMS.OR.YS5.LE.YS5MN) GØ TØ 850 where EFLØW, FLØWMS, YS5 and YS5MN are as defined in Section (3-2) of Chapter 3.

F-2.4 Turbine Trip Followed by Reactor Trip

Similar to loss of normal feedwater to all loops except that ENTRBN should replace ENV5.

APPENDIX G

LISTING OF THE CRBRP-ATWS SIMULATOR

```

00010  MERVAT,BN4101273P,CM115000,T10000,ST0,P0.      PLANT.C
00020  CALL OUTPUT,*NDEPT,ID=PLC,RP=5.
00030  ~Z
00040  SD1
00050  *
00060  *          CONTROLLED PLANT
00070  *
00080  *          I.  TURBOGENERATOR
00090  *
00100  *
00110  PROCED  EMW=ENLD,DLTLD,EMWI,SLD,T
00120  IF (ENLD.EQ.0.0)  EMW=ELD(T)
00130  IF (ENLD.EQ.1..AND.T.EQ.0.0)  EMW=EMWI
00140  IF (ENLD.EQ.1..AND.T.GT.0.0)  EMW=EMWI*(1.+DLTLD/100.0)
00150  IF (ENLD.EQ.2..AND.T.LE.SLD)  EMW=EMWI*(1.+DLTLD*T/100.0)
00160  ENDPRO
00170  *
00180  *
00190  *          TURBINE CONTROL VALVE CONTROLLER
00200  *
00210  OMGGD=OMGGI
00220  EPS9=PS9D-PS9M
00230  EPEXH=0.4912*(PEXHD-PEXHM)
00240  *
00250  EEMW=EMW-PGM
00260  EOMGG=OMGGD-OMGG
00270  EEMW1=AEPT*(AEPS91*EPS9+AEPEXH*EPEXH)+AEOMGG*EOMGG+EEMW
00280  EMW1I.=EEMW1
00290  EEMW2=AEEMW1*(EEMW1+EMW1I/TEEMW)
00300  DESV9=(1./TSV9)*(ASV9+EEMW2-ESV9)
00310  ESV9.=DESV9
00320  *
00330  PROCED  SV9C=ESV9,SV9I
00340  SV9AC=SV9I+ESV9
00350  IF (SV9AC.LE.0.0)  SV9C=0.0001
00360  IF (SV9AC.GT.0.0.AND.SV9AC.LE.1.0)  SV9C=SV9AC
00370  IF (SV9AC.GT.1.0)  SV9C=1.0
00380  ENDPRO
00390  *
00400  *
00410  *
00420  PROCED  SV9=ENV9,DLTV9,SV9I,SSV9,T,SV9C
00430  IF (ENV9.EQ.0.0)  SV9=SV9C
00440  IF (ENV9.EQ.1..AND.T.EQ.0.0)  SV9=SV9I
00450  IF (ENV9.EQ.1..AND.T.NE.0.0)  SV9=SV9I+DLTV9
00460  IF (ENV9.EQ.2..AND.T.LE.SSV9)  SV9=SV9I+DLTV9*T
00470  ENDPRO
00480  *
00490  *
00500  *          DUMP VALVE CONTROLLER
00510  *
00520  ESDM=AEVDMP*EPS9
00530  ESDMI.=ESDM
00540  ESDMP=ESDM+ESDMI/TEVDMP
00550  *
00560  PROCED  ENVDM=PS9,PS9D,PS9MX
00570  IF (PS9.GE.PS9MX)  ENVDM=1.0
00580  IF (PS9.LE.PS9D)  ENVDM=0.0
00590  ENDPRO
00600  *

```

```

00610      PROCED  SVDMPD=ENVDMF,ESDMP
00620      IF(ENVDMF.EQ.1.0)  SVDMPD=ESDMP
00630      IF(ENVDMF.EQ.0.0)  SVDMPD=0.0
00640      ENDPRO
00650      *
00660      SVDMC.=(SVDMPD-SVDMC)/0.5
00670      *
00680      PROCED  SVDMP=SVDMC
00690      IF(SVDMC.LE.0.0)  SVDMP=0.0
00700      IF(SVDMC.GT.0.0.AND.SVDMC.LE.1.0)  SVDMP=SVDMC
00710      IF(SVDMC.GT.1.0)  SVDMP=1.0
00720      ENDPRO
00730      *
00740      *
00750      PROCED  SVDMP=ENDMP,DLTDMF,SSVDMF,SVDMP
00760      IF(ENDMP.EQ.0.0)  SVDMP=SVDMC
00770      IF(ENDMP.EQ.1..AND.T.EQ.0.0)  SVDMP=0.0
00780      IF(ENDMP.EQ.1..AND.T.NE.0.0)  SVDMP=DLTDMF
00790      IF(ENDMP.EQ.2.0.AND.T.LE.SSVDMF)  SVDMP=DLTDMF*T
00800      ENDPRO
00810      *
00820      PROCED  WDMPS=PS9I,CDMP,SVDMP
00830      IF(T.EQ.0.0.AND.ENDMP.NE.0.0)  WDMPS=CDMP*PS9I*SVDMP
00840      IF(T.EQ.0.0.AND.ENDMP.EQ.0.0)  WDMPS=4.0*CDMP*PS9I*SVDMP
00850      IF(T.GT.0.0.AND.ENDMP.NE.0.0)  WDMPS=CDMP*PS9*SVDMP
00860      IF(T.GT.0.0.AND.ENDMP.EQ.0.0)  WDMPS=4.0*CDMP*PS9*SVDMP
00870      ENDPRO
00880      *
00890      WDMF=3600.0*WDMPS
00900      *
00910      *
00920      *
00930      WSC=WSA
00940      WSCS=WSC/3600.0
00950      *
00960      WS9S=WSCS-WDMPS
00970      WS9=3600.0*WS9S
00980      *
00990      *
01000      PROCED  CS9=PRV91,PS9SC,WS9,SV9,ENS94
01010      IF(PRV91.GT..55)  CS9=WS9/(ENS94*SV9*PS9SC)
01020      ENDPRO
01030      *
01040      PV9=AV9*WS9S/ENS94
01050      PS9SC=PV9*(WS9S/(CV9*ENS94*SV9))**2.0
01060      PS9C=WS9/(ENS94*CS9*SV9)
01070      *
01080      PRV91=PV9/PS9SC
01090      *
01100      PROCED  PRV9=PS9I,PV9
01110      IF(T.EQ.0.0)  PRV9=PV9/PS9I
01120      IF(T.GT.0.0)  PRV9=PV9/PS9
01130      ENDPRO
01140      *
01150      PROCED  PS9=PS9SC,PS9C,PRV9
01160      IF(PRV9.GT.0.55)  PS9=PS9SC
01170      IF(PRV9.LE.0.55)  PS9=PS9C
01180      ENDPRO
01190      *
01200      PS9M.=(1./TPS9)*(PS9-PS9M)

```



```

01210      PEXH=APEXH*WS9S
01220      PEXHM.= (1./TPEXH) * (PEXH-PEXHM)
01230      *
01240      TSA=TSATF (PSA)
01250      TASA=(TSA+TSC)/2.
01260      *
01270      RHOSC=1./VSC
01280      TAU9S9=(1.57625*ELSC1*ENL+1.96895*ELSC2*ENSC2) * (RHOSC/WSCS)
01290      *
01300      TS9=0.994475*PDELAY (TSC,TAUTS9,6,TSCI)
01310      *
01320      *
01330      HS9=HSH (PS9,TS9)
01340      *
01350      SS9=S9 (PS9,TS9)
01360      SEXH=SS9
01370      XEXH=(SEXH-0.1313)/1.8487
01380      HEXH=68.997+1036.5*XEXH
01390      *
01400      STWBTU=0.706639*(HS9-HEXH)*WS9
01410      STWMW=2.931E-7*STWBTU
01420      PT.=(STWMW-PF)/0.5
01430      *
01440      *
01450      V=22.0*EMW/EMWI
01460      *
01470      XD=0.9918032
01480      *
01490      Z=19.845232+20.009242*XD
01500      *
01510      PROCED AI=V,E,XD,FETAG
01520      IF (ENLD.NE.2.0) AI=((0.431618*V/XD)**2.0
01530      $   +((E-0.902056*V)/XD)**2.0)**0.5
01540      IF (ENLD.EQ.2.0) AI=((V*SIN(0.017453292*FETAG)/XD)**2.0
01550      $   +((E-V*COS(0.017453292*FETAG))/XD)**2.0)**0.5
01560      ENDPRO
01570      *
01580      PGFETD=(V*E/XD)*SIN(0.017453292*FETAG)
01590      *
01600      PROCED PGFETA=ENSSC,PGFETD,T,TFR
01610      IF (ENSSC.NE.0.0) GO TO 30
01620      PGFETA=PGFETD
01630      GO TO 40
01640      30 IF (T.GT.0.0.AND.T.LE.TFR) PGFETA=0.0
01650      IF (T.EQ.0.0.OR.T.GT.TFR) PGFETA=PGFETD
01660      40 CONTINUE
01670      ENDPRO
01680      *
01690      PGM.= (1./TPG) * (PGFETA-PGM)
01700      *
01710      PF=PGFETA/(AI*V)
01720      *
01730      *
01740      POMG=0.020159685*OMGG
01750      PGE=165.38356*EXAI*(OMGG-376.99)
01760      PGA=PT-(POMG+PGE+PGFETA)
01770      *
01780      FETAG.=(OMGG-OMGGI)/0.017453292
01790      OMGG.=48.539*PGA/OMGG
01800      *

```

```

01810 *
01820 *
01830 *      II.  SUPERHEATER
01840 *
01850      PROCED  WSA=ENWSA,DLTWSA,WSAI,WSAS,T,SWSA
01860      IF(ENWSA.EQ.0.0)  WSA=3600.0*WSAS
01870      IF(ENWSA.EQ.1.AND.T.EQ.0.)  WSA=WSAI
01880      IF(ENWSA.EQ.1.AND.T.NE.0.)  WSA=WSAI*(1.+DLTWSA/100.0)
01890      IF(ENWSA.EQ.2.0.AND.T.LE.SWSA)  WSA=WSAI*(1.+DLTWSA*T/100.0)
01900      ENDPRO
01910 *
01920 *
01930      PSC1=7.841775E-4*ELSC1/(ELSC1+0.573425*ELSC2*(ENL/ENSC2)**2.0)
01940      PSC2=3.48525E-4*ELSC2/(ELSC2+1.74391*ELSC1*(ENSC2/ENL)**2.0)
01950 *
01960      TAUWSA=2.339742E-4*ELS7/ENL+3.1533E-4*ELSHT/ENL
01970      S +1.3682E-4*ELSC1/ENL+1.095337E-4*ELSC2/ENSC2
01980 *
01990      DWSASD=(1./TAUWSA)*(PAS4-PS9+(53.21+YSS)*PHOGS4/144.0
02000      S -(2.3807823E-3+PSC1)*(WSAS/ENL)**2.0-PSC2*(WSAS/ENSC2)**2.0)
02010 *
02020      PROCED  DWSAS=DWSASD
02030      IF(ENWSA.EQ.0.0)  DWSAS=DWSASD
02040      IF(ENWSA.EQ.2.0.AND.T.LE.SWSA)  DWSAS=WSAI*DLTWSA/360000.0
02050      IF((ENWSA.EQ.2.0.AND.T.GT.SWSA).OR.ENWSA.EQ.1.)  DWSAS=0.0
02060      ENDPRO
02070 *
02080      WSAS.=DWSAS
02090      VGS4=VG(PAS4)
02100      RHOGS4=1./VGS4
02110 *
02120      PSAD=PAS4+(1./144.)*(-0.03369228*ELS7*DWSAS/ENL+(53.21+YSS)*RHOGS4
02130      S -0.0417085*(WSAS/ENL)**2.0)
02140 *
02150      PROCED  PSA=ENPSA,DLTPSA,PSAI,T,SPSA,PSAD
02160      IF(ENPSA.EQ.0.0)  PSA=PSAD
02170      IF(ENPSA.EQ.1..AND.T.EQ.0.)  PSA=PSAI
02180      IF(ENPSA.EQ.1..AND.T.NE.0.)  PSA=PSAI*(1.+DLTPSA/100.0)
02190      IF(ENPSA.EQ.2..AND.T.LE.SPSA)  PSA=PSAI*(1.+DLTPSA*T/100.0)
02200      ENDPRO
02210 *
02220      PSC=PSA-2.09114E-3*(WSAS/ENL)**2.0-3.1533E-4*ELSHT*DWSAS/ENL
02230 *
02240      PROCED  WI=ENWI,DLTWI,WII,T,SWI
02250      IF(ENWI.EQ.0.)  WI=3600.0*WIS
02260      IF(ENWI.EQ.1.AND.T.EQ.0.)  WI=WII
02270      IF(ENWI.EQ.1.AND.T.NE.0.)  WI=WII*(1.+DLTWI/100.0)
02280      IF(ENWI.EQ.2.0.AND.T.LE.SWI)  WI=WII*(1.+DLTWI*T/100.0)
02290      ENDPRO
02300 *
02310 *
02320      TAI1=(TI1+TI3)/2.0
02330 *
02340      RHOTI3=RHONA(TI3)
02350 *
02360      TAUTIA=8474400.0*RHOTI3*ENL/WI
02370 *
02380      PROCED  DTIA,TIA=ENTIA,DLTTIA,TIAI,T,STIA,TAUTIA,TI3I
02390      IF(ENTIA.EQ.0.)  TIA=PDDELAY(TI3,TAUTIA,3,TI3I)
02400      IF(ENTIA.EQ.0.)  DTIA=(TI3-TIA)/TAUTIA

```

```

02410      IF (ENTIA.EQ.1.OR.(ENTIA.EQ.2.0.AND.T.GT.STIA)) DTIA=0.0
02420      IF (ENTIA.EQ.1.AND.T.EQ.0.) TIA=TIAI
02430      IF (ENTIA.EQ.1.AND.T.NE.0.) TIA=TIAI+DLTTIA
02440      IF (ENTIA.EQ.2.0.AND.T.LE.STIA) TIA=TIAI+DLTTIA*T
02450      IF (ENTIA.EQ.2.0.AND.T.LE.STIA) DTIA=DLTTIA
02460      ENDPRO
02470      *
02480      *
02490      HGS4I=HG(PAS4I)
02500      HGS4=HG(PAS4)
02510      *
02520      TAUHSA=0.92175*ELS7*ENL*RHOGS4/WSAS
02530      HSA=PDELAY(HGS4,TAUHSA,7,HGS4I)
02540      *
02550      HSC=HSH(PSC,TSC)
02560      *
02570      *
02580      CPS=(HSC-HSA)/(TSC-TSA)
02590      *
02600      HASA=(HSA+HSC)/2.0
02610      PSS=(PSA+PSC)/2.0
02620      *
02630      VGSA=VG(PSA)
02640      VSC=VSH(PSC,TSC)
02650      RHOASA=(1./VGSA+1./VSC)/2.0
02660      *
02670      TAIA=(TIA+TIC)/2.0
02680      ROTAIA=RHONA(TAIA)
02690      *
02700      *      HEAT TRANSFER COEFFICIENTS IN THE SUPERHEATER
02710      *
02720      PES=0.18802368*(WI/ENS)
02730      HNS=1222.0787+1.9258444*(WI/ENS)**0.8
02740      HWA=144.51325*ENS/(0.0048751818+19.2/HNS)
02750      *
02760      RES=536.299*(WSA/ENS)
02770      HSS=4.2454582*(WSA/ENS)**0.8
02780      HSSA=144.51325*ENS/(0.01901711+29.484029/HSS)
02790      *
02800      *
02810      *      II-1. SUPERHEATED STEAM
02820      *
02830      DTSC=(0.0066838/(CPS*RHOASA*ENS))*(HSSA*(TAWA-TASA)
02840      S      -WSA*(HSC-HSA))
02850      TSC.=DTSC
02860      *
02870      *
02880      *      II-2. WALL
02890      *
02900      DTAWA=(8.2682436E- 5/ENS)*(HWA*(TAIA-TAWA)-HSSA*(TAWA-TASA))
02910      TAWA.=DTAWA
02920      *
02930      *      II-3. INTERMEDIATE SODIUM
02940      *
02950      DTIC=(2.93739E- 3/(ROTAIA*ENS))*(0.3014*WI*(TIA-TIC)
02960      S      -HWA*(TAIA-TAWA))
02970      TIC.=DTIC
02980      *
02990      *
03000      *

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03010 *
03020 *      III.  EVAPORATOR
03030 *
03040 RHOTS6=RHOW(TS1)
03050 TAUHS1=(1.76744*ELS61+1.576246*ELS62+1.22718*ELS63
03060 S   +0.441796*ENEVAP*ELS64/ENL)*(ENL*RHOTS6/WS1S)
03070 *
03080 PROCED DHS1=HS1,HS6,TAUHS1,HS1I
03090 IF(ENHS1.EQ.0.0) DHS1=3600.0*(HS6-HS1)/TAUHS1
03100 IF(ENHS1.EQ.1.0.OR.(ENHS1.EQ.2.0.AND.T.GT.SHS1)) DHS1=0.0
03110 IF(ENHS1.EQ.2.0.AND.T.LE.SHS1) DHS1=36.0*DLTHS1*HS1I
03120 ENDPRO
03130 *
03140 PROCED HS1=ENHS1,DLTHS1,HS1I,T,SHS1
03150 IF(ENHS1.EQ.0.0) HS1=PODELAY(HS6,TAUHS1,8,HS1I)
03160 IF(ENHS1.EQ.1.AND.T.EQ.0.0) HS1=HS1I
03170 IF(ENHS1.EQ.1.AND.T.NE.0.0) HS1=HS1I*(1.+DLTHS1/100.0)
03180 IF(ENHS1.EQ.2.AND.T.LE.SHS1) HS1=HS1I*(1.+DLTHS1*T/100.0)
03190 ENDPRO
03200 *
03210 HS2=HP(PAS2)
03220 HAS1=(HS1+HS2)/2.0
03230 TS1=TS1P(HS1)
03240 TSAT=TSATP(PAS2)
03250 TAS1=(TS1+TSAT)/2.0
03260 HFS2=HS2
03270 HGS2=HG(PAS2)
03280 VFS2=VF(PAS2)
03290 RHOF2=1./VFS2
03300 VGS2=VG(PAS2)
03310 RHOG2=1./VGS2
03320 *
03330 PROCED WS1=ENWS1,DLTWS1,WS1I,T,WS1,WS1D,ENE
03340 IF(ENWS1.EQ.0.0) WS1=3600.0*ENE*WS1D
03350 IF(ENWS1.EQ.1..AND.T.EQ.0.0) WS1=WS1I
03360 IF(ENWS1.EQ.1..AND.T.NE.0.0) WS1=WS1I*(1.+DLTWS1/100.0)
03370 IF(ENWS1.EQ.2..AND.T.LE.SWS1) WS1=WS1I*(1.+DLTWS1*T/100.0)
03380 ENDPRO
03390 *
03400 PROCED WS3=WS1,WS3D
03410 IF(ENWS1.EQ.0.0) WS3=3600.0*ENF*WS3D
03420 IF(ENWS1.NE.0.0) WS3=WS1
03430 ENDPRO
03440 *
03450 *
03460 WS1S=ENE*WS1D
03470 WS3S=ENE*WS3D
03480 WS2AD=(WS1D+WS3D)/2.0
03490 *
03500 *      HEAT TRANSFER COEFFICIENTS IN THE EVAPORATOR
03510 *
03520 RES1=172.99645*(WS1/ENE)
03530 RES2=187.70115*(WS1/ENE)
03540 HWE=12.817068*(WS1/ENE)**0.8
03550 HDS1=3.1415926*ENE/(0.02478+29.484029/HWE)
03560 HDS2=126.77825*ENE
03570 *
03580 PEE=0.18186595*(WI/ENE)
03590 HNE=1281.3193+1.9661152*(WI/ENE)**0.8
03600 HDW1=3.1415926*ENE/(0.0048751818+19.2/HNE)

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03610      HDW2=HDW1
03620      *
03630      AS1=0.00090347512*ENE
03640      *
03650      ELS2=46.0-ELS1
03660      *
03670      SAI=RHOGS2/RHOPS2
03680      *
03690      *
03700      XS3=HDS2*ELS2*(TAW2-TSAT)/(7S3*(HGS2-HS2))
03710      ALF3=XS3/(SAI+(1.-SAI)*XS3)
03720      ALFSI=ALF3*(1.-SAI)
03730      ALFA2=ALF3*(0.5+ALFSI/6.0+ALFSI*ALFSI/12.)
03740      *
03750      RHOAS1=RHOW(TAS1)
03760      RHOAS2=ALFA2*RHOGS2+(1.-ALFA2)*RHOPS2
03770      RHOS2=ALFA2*RHOGS2*HGS2+(1.-ALFA2)*RHOPS2*HFS2
03780      *
03790      HS3=HGS2*XS3+HFS2*(1.-XS3)
03800      RHOS3=ALF3*RHOGS2+(1.-ALF3)*RHOPS2
03810      *
03820      DRFP2=(1./VFS2**2.0)*DVP(PAS2)
03830      DRGP2=(1./VGS2**2.0)*DVG(PAS2)
03840      DHFP2=DHP(PAS2)
03850      DHGP2=DHG(PAS2)
03860      DRHFP2=RHOPS2*DHFP2+HFS2*DRFP2
03870      DRHGP2=RHOGS2*DHGP2+HGS2*DRGP2
03880      *
03890      A=ELS2*(ALFA2*(DRHGP2-DRGP2*HFS2)+(1.-ALFA2)*(DRHFP2-DRFP2*HFS2))
03900      B=ELS1*RHOGS2*DHFP2*(HGS2-HFS2)/(2.0*A*(HS2-HS1))
03910      C=1.0+2.*B*(RHOAS1-RHOPS2)/(RHOPS2-RHOGS2)
03920      *
03930      III-1.  WATER / STEAM
03940      *
03950      DLS1=(2./C)*(-HDS1*ELS1*(TAW1-TAS1)/(AS1*RHOAS1*(HS2-HS1))
03960      S      +WS1/(AS1*RHOAS1)+(ELS1/2.0)*DHS6/(HS2-HS1)
03970      S      +B*(WS1-WS3)/(AS1*(RHOPS2-RHOGS2)))
03980      ELS1.=DLS1/3600.0
03990      *
04000      WS2=WS1-AS1*RHOAS1*DLS1
04010      *
04020      DPAS2=(RHOGS2*(HGS2-HFS2)/(A*(RHOPS2-RHOGS2)))*(-(RHOAS1-RHOPS2)
04030      S      *DLS1+(WS1-WS3)/AS1)
04040      PAS2.=DPAS2/3600.0
04050      *
04060      III-2.  WALL
04070      *
04080      WMHCD=0.073034229*ENE
04090      TW2=(TAW1*ELS1+TAW2*ELS2)/46.0
04100      *
04110      DTAW1=(1./WMHCD)*(-(HDW1+HDS1+WMHCD*DLS1/ELS1)*TAW1
04120      S      +HDS1*TAS1+HDW1*TAI8)+TW2*DLS1/ELS1
04130      TAW1.=DTAW1/3600.0
04140      *
04150      DTAW2=(1./WMHCD)*(-(HDW2+HDS2+WMHCD*DLS1/ELS2)*TAW2
04160      S      +HDS2*TSAT+HDW2*TAI7)-TW2*DLS1/ELS2
04170      TAW2.=DTAW2/3600.0
04180      *
04190      III-3.  INTERMEDIATE SODIUM
04200      *

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04210 *
04220 RHOTIC=RHONA (TIC)
04230 TANTI7=703800.0*RHOTIC*ENEVAP/WI
04240 *
04250 PROCED TI7=ENTI7,DLTTI7,TIC, TI7I,STI7,TAUTI7,TICI
04260 IF (ENTI7.EQ.0.) TI7=PDELAY (TIC,TAUTI7,14,TICI)
04270 IF (ENTI7.EQ.1..AND.T.EQ.0.) TI7=TI7I
04280 IF (ENTI7.EQ.1..AND.T.NE.0.) TI7=TI7I+DLTTI7
04290 IF (ENTI7.EQ.2..AND.T.LE.STI7) TI7=TI7I+DLTTI7*T
04300 ENDPRO
04310 *
04320 *
04330 TAI7= (TI7+TI8)/2.0
04340 TAI8= (TI8+TI9)/2.0
04350 *
04360 TIE= (TI7+TI9)/2
04370 RHOIE=RHONA (TIE)
04380 SMHCD=0.0020848433*RHOIE*ENE
04390 WI8=WI+0.00682079*ENE*RHOIE*DLS1
04400 *
04410 DTI8= (1./ (SMHCD*ELS2)) * (- (HDW2*ELS2-SMHCD*DLS1) *TAI7
04420 $ +HDW2*ELS2*TAI7+0.30566168*(WI*TI7-WI8*TI8))
04430 TI8=DTI8/3600.0
04440 *
04450 DTI9= (1./ (SMHCD*ELS1)) * (- (HDW1*ELS1+SMHCD*DLS1) *TAI8
04460 $ +HDW1*ELS1*TAI7+0.30566168*(WI8*TI8-WI*TI9))
04470 TI9=DTI9/3600.0
04480 *
04490 *
04500 * WATER / STEAM LOOP MOMENTUM EQUATIONS
04510 *
04520 *
04530 R=RD (PAS2,XS3)
04540 *
04550 TAUWS3=ELS31/ (21.25048*ENEVAP)+ELS32/ (68.844553*ENL)
04560 TAUWS1=ELS61/ (56.9*ENL) +ELS62/ (50.755*ENL)
04570 $ +ELS63/ (39.515*ENL) +ELS64/ (14.22555*ENEVAP)
04580 *
04590 A11T=ELS1/ (32.2*AS1) +ELS2/ (64.4*AS1) +TAUWS1
04600 A12T=ELS2/ (64.4*AS1) +0.30020714/AS1+TAUWS3
04610 A21T=ELS2/ (128.8*AS1)
04620 A22T=ELS2/ (128.8*AS1) +0.15010357/AS1+TAUWS3
04630 *
04640 DETERM=A11T*A22T-A12T*A21T
04650 *
04660 * FRICTION COEFFICINTS
04670 *
04680 PROCED FS1=RES1
04690 IF (RES1.LT.1000.0) FS1=8.0/RES1
04700 IF (RES1.GE.1000.0.AND.RES1.LT.100000.0) FS1=0.05256/ (RES1**0.243)
04710 IF (RES1.GE.100000.0) FS1=0.02117/ (RES1**0.164)
04720 ENDPRO
04730 FS1A=102467.41*FS1
04740 *
04750 PROCED FS2=RES2
04760 IF (RES2.LT.1000.0) FS2=8.0/RES2
04770 IF (RES2.GE.1000.0.AND.RES2.LT.100000.0) FS2=0.05256/ (RES2**0.243)
04780 IF (RES2.GE.100000.0) FS2=0.02117/ (RES2**0.164)
04790 ENDPRO
04800 FS2A=111974.13*FS2

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04810 *
04820 DPRC=DPRCSF-FRC*(WS1S/ENL)**2
04830 *
04840 HDSPH=ELS1*RHOAS1+ELS2*RHOAS2+10.208333*RHOS3-52.708333*RHOTS6
04850 * -(YS5+(DOD-6.0)/2.0)*RHOTS6
04860 CHMPH=(1./((32.2*AS1*AS1)))*(WS3S**2/RHOS3-WS1S**2/RHOF52)
04870 FRPH=(FS1A*ELS1+3554.6572*(ENE/FNL)**2.0*FS6)*(WS1D**2.0)
04880 * +(PS2A*R*ELS2)*(WS2AD**2)+(35304.868+9.66667*FS2A*R)*(WS3D**2)
04890 *
04900 HSPH34=ELS2*RHOAS2/2.0+7.6666665*RHOS3
04910 FRPH34=PS2A*R*ELS2*(WS2AD**2)/2.0+(4.833335*FS2A*R
04920 * +28309.)* (WS3D**2)
04930 B1T=-(HDSPH+CHMPH-144.0*DPRC+FRPH)
04940 B2T=144.0*(PAS2-PAS4)-HSPH34-CHMPH/2.0-FRPH34
04950 *
04960 WS1DD=(A22T*B1T-A12T*B2T)/(ENE*DETERM)
04970 WS3DD=(A11T*B2T-A21T*B1T)/(ENE*DETERM)
04980 *
04990 PROCD DWS1D=WS1DD
05000 IF(ENWS1.EQ.0.0) DWS1D=WS1DD
05010 IF(ENWS1.NE.0.0) DWS1D=0.0
05020 ENDPRO
05030 *
05040 PROCD DWS3D=WS3DD
05050 IF(ENWS1.EQ.0.0) DWS3D=WS3DD
05060 IF(ENWS1.NE.0.0) DWS3D=0.0
05070 ENDPRO
05080 *
05090 WS1D.=DWS1D
05100 WS3D.=DWS3D
05110 *
05120 *
05130 * IV. STEAM DRUM
05140 *
05150 *
05160 * DRUM WATER LEVEL CONTROLLER
05170 *
05180 YS5=3.0*(1.0+SIN(1.5707963*(EMS5/EMS5I-1.0)))
05190 *
05200 YS5M.=(1./TYS5)*(YS5-YS5M)
05210 EYS5=YSSD-YSSM
05220 EYS5I.=EYS5
05230 EWS5=WSCSM-WS5SM+AEYS5*(EYS5+EYS5I/TEYS5)
05240 EWS5I.=EWS5
05250 ESV5A=AEVS5*(EWS5+EWS5I/TEVS5)
05260 *
05270 ESV5.=(ESV5A-ESV5)/TSV5
05280 *
05290 PROCD SV5C=ESV5,SV5I
05300 SV5AC=SV5I+ESV5
05310 IF(SV5AC.LE.0.0) SV5C=0.0001
05320 IF(SV5AC.GT.0.0.AND.SV5AC.LE.1.0) SV5C=SV5AC
05330 IF(SV5AC.GT.1.0) SV5C=1.0
05340 ENDPRO
05350 *
05360 *
05370 WSCSM.=(WSCS-WSCSM)/TWSCS
05380 WS5SM.=(WS5S-WS5SM)/TWS5S
05390 *
05400 PROCD SV5=ENV5,DLTV5,SV5I,SSV5,T,SV5C

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05410      IF(ENV5.EQ.0.0)  SV5=SV5C
05420      IF(ENV5.EQ.1..AND.T.EQ.0.0)  SV5=SV5I
05430      IF(ENV5.EQ.1..AND.T.NE.0.0)  SV5=SV5I+DLTV5
05440      IF(ENV5.EQ.2..AND.T.LE.SSV5)  SV5=SV5I+DLTV5*T
05450      ENDPRO
05460      *
05470      TSS=TS1F(HS5)
05480      TAUWS5=ELSS/(21.25*ENL)
05490      *
05500      *      FEED WATER VALVE'S PRESSURE CONTROLLER
05510      *
05520      *      EDPV5=DPV5D-DPV5M
05530      *      EDP5I.=EDPV5
05540      *      EENFP=ADPV5*(EDPV5+EDPSI/TEDPV5)
05550      *      ETRQF.=(1./TTRQF)*(ATRQF*EENFP-ETRQF)
05560      *      WS5SD=ENL*SV5*SQRT(DPV5D/FV5)
05570      *      TRQFD=307.476*WS5SD*HOPP/(ENL*ENFPD*ETAFP)
05580      *      TRQFDD=TRQFD+ETRQF
05590      **
05600      *      PROCED  TRQFAC=TRQFDD,TRQFMX
05610      *      IF(TRQFDD.LE.0.0)  TRQFAC=0.0
05620      *      IF(TRQFDD.GT.0.0.AND.TRQFDD.LE.TRQFMX)  TRQFAC=TRQFDD
05630      *      IF(TRQFDD.GT.TRQFMX)  TRQFAC=TRQFMX
05640      *      ENDPRO
05650      **
05660      *      PROCED  TRQFP=SWTRQF,TRQFAC,TRQFMC
05670      *      IF(SWTRQF.EQ.0.0)  TRQFP=TRQFAC
05680      *      IF(SWTRQF.NE.0.0)  TRQFP=TRQFMC
05690      *      ENDPRO
05700      **
05710      *      PAS4M.=(1./TPAS4)*(PAS4-PAS4M)
05720      *      PHFWM.=(1./TPHFW)*(PHFW-PHFWM)
05730      **
05740      *      DPV5M=AV5*(PAS4M-PHFW)
05750      *
05760      *      DPV5=FV5*(WS5S/(ENL*SV5))**2.0
05770      *
05780      *      DRWS5S=(1./TAUWS5)*(144.0*(PHFW-PAS4)-12.5*RHOW(TSS)
05790      *      S      -PS5*(WS5S/ENL)**2.-144.*DPV5)
05800      *
05810      *      PROCED  DWS5S=ENWS5,DRWS5S
05820      *      IF(ENWS5.EQ.0.0)  DWS5S=DRWS5S
05830      *      IF(ENWS5.NE.0.0)  DWS5S=0.0
05840      *      ENDPRO
05850      *
05860      *      WS5S.=DWS5S
05870      *
05880      *      PROCED  WS5=DLTWS5,SWSS,WS5I
05890      *      IF(ENWS5.EQ.0.0)  WS5=3600.0*WS5S
05900      *      IF(ENWS5.EQ.1..AND.T.EQ.0.0)  WS5=WS5I
05910      *      IF(ENWS5.EQ.1..AND.T.NE.0.0)  WS5=WS5I*(1.+DLTWS5/100.0)
05920      *      IF(ENWS5.EQ.2..AND.T.LE.SWS5)  WS5=WS5I*(1.+DLTWS5*T/100.0)
05930      *      ENDPRO
05940      *
05950      *      HSSD=(WSC*HSC-3.412E6*PT/0.39754)/WS5
05960      *
05970      *      PROCED  HS5=FNHS5,DLTHS5,T,SHS5,HS5I,HSSD
05980      *      IF(ENHS5.EQ.0.0)  HS5=HS5D
05990      *      IF(ENHS5.EQ.1..AND.T.EQ.0.0)  HS5=HS5I
06000      *      IF(ENHS5.EQ.1..AND.T.NE.0.0)  HS5=HS5I*(1.+DLTHS5/100.0)

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06010      IF (ENHS5.EQ.2..AND.T.LE.SHS5)  HS5=HS5I*(1.+DLTHS5*T/100.0)
06020      ENDPRO
06030      *
06040      PROCED  WS4=ENWS4,DLTHS4,T,SWS4,WS4I,WS3
06050      IF (ENWS4.EQ.0.0)  WS4=WS3
06060      IF (ENWS4.EQ.1..AND.T.EQ.0.0)  WS4=WS4I
06070      IF (ENWS4.EQ.1..AND.T.NE.0.0)  WS4=WS4I*(1.+DLTHS4/100.0)
06080      IF (ENWS4.EQ.2..AND.T.LE.SWS4)  WS4=WS4I*(1.+DLTHS4*T/100.0)
06090      ENDPRO
06100      *
06110      TAUHS4=(0.66*ENEVAP*ELS31/ENL+2.1380*ELS32)*(ENL*RHOS3/WS3S)
06120      *
06130      PROCED  HS4=ENHS4,DLTHS4,T,SHS4,HS4I,HS3
06140      IF (ENHS4.EQ.0.0)  HS4=PDELAY(HS3,TAUHS4,9,HS4I)
06150      IF (ENHS4.EQ.1..AND.T.EQ.0.0)  HS4=HS4I
06160      IF (ENHS4.EQ.1..AND.T.NE.0.0)  HS4=HS4I*(1.+DLTHS4/100.0)
06170      IF (ENHS4.EQ.2..AND.T.LE.SHS4)  HS4=HS4I*(1.+DLTHS4*T/100.0)
06180      ENDPRO
06190      *
06200      PROCED  WS6=ENWS6,WS6I,WS1
06210      IF (ENWS6.EQ.0.0)  WS6=WS1
06220      IF (ENWS6.NE.0.0)  WS6=WS6I
06230      ENDPRO
06240      *
06250      PROCED  WS7=ENWS7,WS7I,WSA
06260      IF (ENWS7.EQ.0.0)  WS7=WSA
06270      IF (ENWS7.NE.0.0)  WS7=WS7I
06280      ENDPRO
06290      *
06300      VFS4=VF(PAS4)
06310      RHOPS4=1./VFS4
06320      *
06330      EMS4=RHOGS4*(DV-EMS5/RHOPS4)
06340      *
06350      EMS4D=DELAY(EMS4,0.2,5,EMS4I)
06360      DEMS4=18000.0*(EMS4-EMS4D)
06370      *
06380      DEMS5=(WS4+WS5-WS6-WS7)/ENL-DEMS4
06390      EMS5.=DEMS5/3600.0
06400      *
06410      D=EMS4*DVG(PAS4)+EMS5*DVP(PAS4)
06420      DPAS4=(-1./D)*(VGS4*DEMS4+VFS4*DEMS5)
06430      PAS4.=DPAS4/3600.0
06440      *
06450      DHS6=(1./(ENL*EMS5))*(WS4*HS4+WS5*HS5-WS6*HS6-WS7*HGS4
06460      -ENL*(HGS4*DEMS4+HS6*DEMS5+EMS4*DHG(PAS4)*DPAS4))
06470      HS6.=DHS6/3600.0
06480      *
06490      *
06500      *
06510      *
06520      *
06530      PROCED  WP=ENWP,DLTWP,WPI,T,SWP
06540      IF (ENWP.EQ.0.)  WP=3600.0*WPS
06550      IF (ENWP.EQ.1..AND.T.EQ.0.0)  WP=WPI
06560      IF (ENWP.EQ.1..AND.T.NE.0.0)  WP=WPI*(1.+DLTWP/100.0)
06570      IF (ENWP.EQ.2.0..AND.T.LE.SWP)  WP=WPI*(1.+DLTWP*T/100.0)
06580      ENDPRO
06590      *
06600      *

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06610      RHOTP4=RHONA(TP4)
06620      TAUTP5=4071600.0*RHOTP4*ENL/WP
06630      *
06640      PROCED DTP5,TP5=ENTP5,DLTTP5,TAUTP5,TP4I,TP4,TP5I,T,STP5
06650      IF(ENTP5.EQ.0.) TP5=PDELAY(TP4,TAUTP5,2,TP4I)
06660      IF(ENTP5.EQ.0.) DTP5=(TP4-TP5)/TAUTP5
06670      IF(ENTP5.EQ.1.OR.(ENTP5.EQ.2.AND.T.GT.STP5)) DTP5=0.0
06680      IF(ENTP5.EQ.1.AND.T.EQ.0.) TP5=TP5I
06690      IF(ENTP5.EQ.1.AND.T.NE.0.) TP5=TP5I+DLTTP5
06700      IF(ENTP5.EQ.2.0.AND.T.LE.STP5) TP5=TP5I+DLTTP5*T
06710      IF(ENTP5.EQ.2.0.AND.T.LE.STP5) DTP5=DLTTP5
06720      ENDPRO
06730      *
06740      TAP5=(TP5+TP7)/2.0
06750      *
06760      *
06770      *      HEAT TRANSFER COEFFICIENTS IN THE IHX
06780      *
06790      HNIP=1906.8776+2.2875323*(WP/ENI)**0.8
06800      HNII=2476.4331+3.1930386*(WI/ENI)**0.8
06810      HI=227149.4/(0.007650483+15.286624/HNII+13.714285/HNIP)
06820      *
06830      ROTAP5=RHONA(TAP5)
06840      *
06850      TP7.=(2.0488692E-6/ROTAP5)*(-HI*(TAP5-TAI1)
06860      $ +0.3032*WP*(TP5-TP7)/ENL)
06870      *
06880      RHOTI1=RHONA(TI9)
06890      TAUTI1=4968000.0*RHOTI1*ENL/WI
06900      *
06910      PROCED DTI1,TI1=ENTI1,DLTTI1,TAUTI1,TI9I,TI9,TI1I,T,STI1
06920      IF(ENTI1.EQ.0.) TI1=PDELAY(TI9,TAUTI1,4,TI9I)
06930      IF(ENTI1.EQ.0.0) DTI1=(TI9-TI1)/TAUTI1
06940      IF(ENTI1.EQ.1.OR.(ENTI1.EQ.2.AND.STI1.GT.STI1)) DTI1=0.0
06950      IF(ENTI1.EQ.1.AND.T.EQ.0.) TI1=TI1I
06960      IF(ENTI1.EQ.1.AND.T.NE.0.) TI1=TI1I+DLTTI1
06970      IF(ENTI1.EQ.2.0.AND.T.LE.STI1) TI1=TI1I+DLTTI1*T
06980      IF(ENTI1.EQ.2.0.AND.T.LE.STI1) DTI1=DLTTI1
06990      ENDPRO
07000      *
07010      *
07020      ROTAI1=RHONA(TAI1)
07030      TI3.=(3.7545E-6/ROTAI1)*(HI*(TAP5-TAI1)
07040      $ +0.30445*WI*(TI1-TI3)/ENL)
07050      *
07060      *
07070      *      VI. REACTOR
07080      *
07090      *      VI-1. POINT KINETIC EQUATIONS
07100      *      WITH FEEDBACK
07110      BETA=3.65E- 3
07120      BD=(0.8254*D1+7.756*D2+6.66*D3+13.54*D4
07130      $ +5.908*D5+1.81*D6)*1.0E- 4
07140      BDOB=BD/BETA
07150      RHOFBC=(100.0*DC/BETA)*ALOG((460.0+TAP)/(460.0+TAPI))
07160      $ +AXECC*TAP+SODDCC*TAPI+RECC*TP1+ROFBCI
07170      RHOFBD=RHOFBC/100.0
07180      *
07190      *      LINEAR APPROXIMATIONS OF THE DESIRED PRIMARY AND INTERMEDIATE
07200      *      FLOW RATES AS WELL AS REACTOR INLET AND EXIT TEMPERATURES

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06610      RHOTP4=RHONA(TP4)
06620      TAUTP5=4071600.0*RHOTP4*ENL/WP
06630      *
06640      *      PROCED DTP5,TP5=ENTP5,DLTTP5,TAUTP5,TP4I,TP4,TP5I,T,STP5
06650      IF(ENTP5.EQ.0.) TP5=PDELAY(TP4,TAUTP5,2,TP4I)
06660      IF(ENTP5.EQ.0.) DTP5=(TP4-TP5)/TAUTP5
06670      IF(ENTP5.EQ.1.OR.(ENTP5.EQ.2.AND.T.GT.STP5)) DTP5=0.0
06680      IF(ENTP5.EQ.1.AND.T.EQ.0.) TP5=TP5I
06690      IF(ENTP5.EQ.1.AND.T.NE.0.) TP5=TP5I+DLTTP5
06700      IF(ENTP5.EQ.2.0.AND.T.LE.STP5) TP5=TP5I+DLTTP5*T
06710      IF(ENTP5.EQ.2.0.AND.T.LE.STP5) DTP5=DLTTP5
06720      ENDPRO
06730      *
06740      *      TAP5=(TP5+TP7)/2.0
06750      *
06760      *
06770      *      HEAT TRANSFER COEFFICIENTS IN THE IHX
06780      *
06790      HNIP=1906.8776+2.2875323*(WP/ENI)**0.8
06800      HNII=2476.4331+3.1930386*(WI/ENI)**0.8
06810      HI=227149.4/(0.007650483+15.286624/HNII+13.714285/HNIP)
06820      *
06830      *      ROTAP5=RHONA(TAP5)
06840      *
06850      *      TP7.=(2.0488692E-6/ROTAP5)*(-HI*(TAP5-TAI1)
06860      *      S +0.3032*WP*(TP5-TP7)/ENL)
06870      *
06880      *      RHOTI1=RHONA(TI9)
06890      *      TAUTI1=4968000.0*RHOTI1*ENL/WI
06900      *
06910      *      PROCED DTI1,TI1=ENTI1,DLTTI1,TAUTI1,TI9I,TI9,TI1I,T,STI1
06920      IF(ENTI1.EQ.0.) TI1=PDELAY(TI9,TAUTI1,4,TI9I)
06930      IF(ENTI1.EQ.0.0) DTI1=(TI9-TI1)/TAUTI1
06940      IF(ENTI1.EQ.1.OR.(ENTI1.EQ.2.AND.STI1.GT.STI1)) DTI1=0.0
06950      IF(ENTI1.EQ.1.AND.T.EQ.0.) TI1=TI1I
06960      IF(ENTI1.EQ.1.AND.T.NE.0.) TI1=TI1I+DLTTI1
06970      IF(ENTI1.EQ.2.0.AND.T.LE.STI1) TI1=TI1I+DLTTI1*T
06980      IF(ENTI1.EQ.2.0.AND.T.LE.STI1) DTI1=DLTTI1
06990      *      ENDPRO
07000      *
07010      *
07020      *      ROTAI1=RHONA(TAI1)
07030      *      TI3.=(3.7545E-6/ROTAI1)*(HI*(TAP5-TAI1)
07040      *      S +0.30445*WI*(TI1-TI3)/ENL)
07050      *
07060      *
07070      *      VI. REACTOR
07080      *
07090      *      VI-1. POINT KINETIC EQUATIONS
07100      *      WITH FEEDBACK
07110      *      BETA=3.65E- 3
07120      *      BD=(0.8254*D1+7.756*D2+6.66*D3+13.54*D4
07130      *      S +5.908*D5+1.81*D6)*1.0E- 4
07140      *      BDOB=BD/BETA
07150      *      RHOFBC=(100.0*DC/BETA)*ALOG((460.0+TAP)/(460.0+TAI1))
07160      *      S +AXECC*TAP+SODDCC*TAI1+RECC*TP1+ROFBCI
07170      *      RHOFBD=RHOFBC/100.0
07180      *
07190      *      LINEAR APPROXIMATIONS OF THE DESIRED PRIMARY AND INTERMEDIATE
07200      *      FLOW RATES AS WELL AS REACTOR INLET AND EXIT TEMPERATURES

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07810      IF (ENAC1.LE.0.0)  ENAC2=0.0
07820      IF (ENAC1.GT.0.0.AND.ENAC1.LE.ENMX)  ENAC2=ENAC1
07830      IF (ENAC1.GT.ENMX)  ENAC2=ENMX
07840      ENDPRO
07850      *
07860      ENM.= (1./TEN) * (EN-ENM)
07870      *
07880      EEN=ENAC2-ENM
07890      EENI.=EEN
07900      ECR=A EEN* (EEN+EENI/TEEN)
07910      *
07920      PROCED  VCR=VCROUT,VCRIN
07930      DTVCR1=0.001
07940      DTVCR2=-0.001
07950      IF (ECR.GT.DTVCR2.AND.ECR.LT.DTVCR1)  VCR=0.0
07960      IF (ECR.GT.DTVCR1)  VCR=VCROUT
07970      IF (ECR.LT.DTVCR2)  VCR=-VCRIN
07980      ENDPRO
07990      *
08000      X.=VCR
08010      *
08020      PROCED  XCR=X
08030      IF (T.EQ.0.0)  XCR=X
08040      DX=X-XCR
08050      IF (DX.LE.-0.025)  XCR=XCR-0.025
08060      IF (DX.GE.+0.025)  XCR=XCR+0.025
08070      ENDPRO
08080      *
08090      ROCRXD=ROCRHD*FROCRX(XCR)
08100      *
08110      ROCDAC=ROCRXD+ROEXCD
08120      *
08130      PROCED  RHOD=ENROC,DLTROC,RHOCDI,SROC,ROCDAC
08140      IF (ENROC.EQ.0.0)  RHOD=ROCDAC
08150      IF (ENROC.EQ.1.0.AND.T.EQ.0.0)  RHOD=RHOCDI
08160      IF (ENROC.EQ.1.0.AND.T.NE.0.0)  RHOD=RHOCDI+DLTROC/100.0
08170      IF (ENROC.EQ.2.0.AND.T.LE.SROC)  RHOD=RHOCDI+DLTROC*T/100.0
08180      ENDPRO
08190      *
08200      *
08210      RHOD=RHOD+RHOFBD
08220      *
08230      PROCED  EN=BDOB,RHOD
08240      EN=BDOB/(1.0 - RHOD)
08250      IF (T.EQ.0.0)  EN=1.0
08260      ENDPRO
08270      *
08280      D1.=0.0129*(EN-D1)
08290      D2.=0.0312*(EN-D2)
08300      D3.=0.1330*(EN-D3)
08310      D4.=0.3450*(EN-D4)
08320      D5.=1.4100*(EN-D5)
08330      D6.=3.7500*(EN-D6)
08340      *
08350      *
08360      *
08370      *
08380      TFC= (5./9.) * (TAF-32.0)
08390      TFK=TFC+273.0
08400      AKFW=36.100867/(TFK+129.2) +5.782936E-13*TFK**3.0

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VI-2. REACTOR THERMODYNAMIC EQUATIONS

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08410      AKF=57.78*AKFW
08420      WPD=PFC*WP/ENP
08430      HC=14861.86+51.921027*WPD**0.8
08440      HR=9.4247778*ENP/(0.125/AKF+60.00024/HDG+52.173914/HC
08450      $    +0.0052151492)
08460      *
08470      *
08480      TAP.=2.520883E- 7*(EPS*PPGC*EN-HR*(TAP-TAP1))
08490      *
08500      RHOTR1=RHONA(TP7)
08510      RHOTP1=RHONA(TP1)
08520      TAU1=1796400.0*RHOTR1*ENL/WP
08530      *
08540      PROCD TR1=ENTR1,DLTTR1,TAUTR1,TP7I,TP7,TR1I,T,STR1
08550      IF(ENTR1.EQ.0.) TR1=PDELAY(TP7,TAUTR1,1,TP7I)
08560      IF(ENTR1.EQ.1.AND.T.EQ.0.) TR1=TR1I
08570      IF(ENTR1.EQ.1.AND.T.NE.0.) TR1=TR1I+DLTTR1
08580      IF(ENTR1.EQ.2.0.AND.T.LE.STR1) TR1=TR1I+DLTTR1*T
08590      ENDPRO
08600      *
08610      DTP1=(WP/(3600.0*VP1*RHOTP1))*(TR1-TP1)
08620      TP1.=DTP1
08630      *
08640      ROTAP1=RHONA(TAP1)
08650      TAP1=(TP1+TP3)/2.0
08660      RHOTP3=RHONA(TP3)
08670      RHOTR3=RHONA(TR3)
08680      *
08690      TP3.= (3.4093E-5/ROTAP1)*(HR*(TAP-TAP1)+0.3032*PFC*WP*(TP1-TP3))
08700      *
08710      TR3.= (3.71815E-7/(RHOTP1+RHOTR3))*(EPS*EN-0.3032*WP*(TR3-TP1))
08720      TP4.= (WP/(3600.0*VP4*RHOTP4))*(TR3-TP4)
08730      *
08740      *
08750      *
08760      *
08770      *
08780      *
08790      *
08800      QPP=1.2465E-4*WP/(ENL*RHOTP4)
08810      *
08820      QPPD=0.4487625*WPSD/(ENL*RHOTP4)
08830      HOPP=HMM(ENPP,QPP)
08840      QPONP=QPP/ENPP
08850      ETAPP=0.019275+69.86*QPONP-1970.0*QPONP**2.0+16531.46*QPONP**3.0
08860      *
08870      QPONPD=QPPD/ENPPD
08880      ETAPPD=0.019275+69.86*QPONPD-1970.0*QPONPD**2.0+16531.46*QPONPD**3.0
08890      *
08900      *
08910      *
08920      *
08930      TR1N.= (1./TTR1)*(TR1-TR1N)
08940      ETR1=TR1D-TR1N
08950      ETR1I.=ETR1
08960      *
08970      WPSAC=WPSD+AETR1*(ETR1+ETR1I/TETR1)
08980      *
08990      *
09000      *
09000      PROCD EWPS=SWWPS,WPSAC,WPSMC,WPSM
09000      IF(SWWPS.EQ.0.0) EWPS=WPSAC-WPSM

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09010      IF (SWWPS.NE.0.0)  EWPS=WPSMC-WPSM
09020      ENDPRO
09030      *
09040      EWPSI.=EWPS
09050      ENPPDD=ENPPD+AEWPS*(EWPS+EWPSI/TEWPS)
09060      *
09070      PROCED  ENPPAC=ENPPDD,ENPPMX
09080      IF (ENPPDD.LE.0.0)  ENPPAC=0.0
09090      IF (ENPPDD.GT.0.0.AND. ENPPDD.LE.ENPPMX)  ENPPAC=ENPPDD
09100      IF (ENPPDD.GT.ENPPMX)  ENPPAC=ENPPMX
09110      ENDPRO
09120      *
09130      *
09140      PROCED  EENPP=SWENPP,ENPPMC,ENPPAC,ENPP
09150      IF (SWENPP.EQ.0.0)  EENPP=ENPPAC-ENPP
09160      IF (SWENPP.NE.0.0)  EENPP=ENPPMC-ENPP
09170      ENDPRO
09180      *
09190      ENPPI.=EENPP
09200      EENPPC=EENPP+ENPPI/TEENPP
09210      *
09220      ETRQP.=(1./TTRQP)*(ATRQP*EENPPC-ETRQP)
09230      *
09240      TRQPD=307.476*WPSD*HOPPD/(ENL*ENPPD*ETAPPD)
09250      TRQDD=TRQPD+ETRQP
09260      *
09270      PROCED  TRQPAC=TRQDD,TRQPMX
09280      IF (TRQDD.LE.0.0)  TRQPAC=0.0
09290      IF (TRQDD.GT.0.0.AND. TRQDD.LE.TRQPMX)  TRQPAC=TRQDD
09300      IF (TRQDD.GT.TRQPMX)  TRQPAC=TRQPMX
09310      ENDPRO
09320      *
09330      PROCED  TRQPP=SWTRQP,TRQPAC,TRQPMC
09340      IF (SWTRQP.EQ.0.0)  TRQPP=TRQPAC
09350      IF (SWTRQP.NE.0.0)  TRQPP=TRQPMC
09360      ENDPRO
09370      *
09380      WPSM.=(1./TWPS)*(WPS-WPSM)
09390      *
09400      DRENPP=(9.5493/AIPP)*(TRQPP-0.02847*WP*HOPP/(ENPP*ETAPP))
09410      *
09420      TAUWP=3.5491816/ENL+1421.9498*FFC/ENP
09430      DWPST=15.3392*RHOTR1-11.0*RHOT1-3.0*ROTAP1-5.68333*RHOT2
09440      $  + (HOPP-21.403855)*RHOT4+25.369791*ROTAP5
09450      $  - (6.5714464E-4/ENL**2+F143*(FFC/ENSUB)**2.+9.7776E-6)
09460      $  *(WPS**2.)
09470      *
09480      PROCED  DWPS,DENPP=ENWP,TAUWP,DWPST,DRENPP
09490      IF (ENWP.EQ.0.0)  DWPS=DWPST/TAUWP
09500      IF (ENWP.EQ.0.0)  DENPP=DRENPP
09510      IF (ENWP.NE.0.0)  DWPS=0.0
09520      IF (ENWP.NE.0.0)  DENPP=0.0
09530      ENDPRO
09540      *
09550      WPS.=DWPS
09560      ENPP.=DENPP
09570      *
09580      QIP=1.24657E-4*WI/(ENL*RHOT11)
09590      *
09600      QIPD=0.4487625*WISD/(ENL*RHOT11)

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09610      HOIPD=HMM (ENIPD,QIPD)
09620      HOIP=HMM (ENIP,QIP)
09630      QIONI=QIP/ENIP
09640      ETAIP=0.006337+72.0258*QIONI-2049.*QIONI**2+17671.51*QIONI**3
09650      *
09660      *
09670      QIONID=QIPD/ENIPD
09680      ETAIPD=0.006337+72.0258*QIONID-2049.*QIONID**2+17671.51*QIONID**3
09690      *
09700      *
09710      *      INTERMEDIATE PUMP SPEED CONTROLLER
09720      *
09730      *
09740      EPS9I.=EPS9
09750      WISAC=WISD+AEP92*(EPS9+EPS9I/TEPS9)
09760      *
09770      PROCED  EWIS=SWWIS,WISMC,WISAC
09780      IF (SWWIS.EQ.0.0)  EWIS=WISAC-WISM
09790      IF (SWWIS.NE.0.0)  EWIS=WISMC-WISM
09800      ENDPRO
09810      *
09820      EWISI.=EWIS
09830      ENIPDD=ENIPD+AEWIS*(EWIS+EWISI/TEWIS)
09840      *
09850      PROCED  ENIPAC=ENIPDD,ENIPMX
09860      IF (ENIPDD.LE.0.0)  ENIPAC=0.0
09870      IF (ENIPDD.GT.0.0.AND.ENIPDD.LE.ENIPMX)  ENIPAC=ENIPDD
09880      IF (ENIPDD.GT.ENIPMX)  ENIPAC=ENIPMX
09890      ENDPRO
09900      *
09910      *
09920      PROCED  EENIP=SWENIP,ENIPMC,ENIPAC,ENIP
09930      IF (SWENIP.EQ.0.0)  EENIP=ENIPAC-ENIP
09940      IF (SWENIP.NE.0.0)  EENIP=ENIPMC-ENIP
09950      ENDPRO
09960      *
09970      ENIPI.=EENIP
09980      EENIPC=EENIP+ENIPI/TEENIP
09990      *
10000      ETRQI.=(1./TTRQI)*(ATRQI+EENIPC-ETRQI)
10010      *
10020      TRQID=307.476*WISD*HOIPD/(ENL*ENIPD*ETAIPD)
10030      TRQIDD=TRQID+ETRQI
10040      *
10050      PROCED  TRQIAC=TRQIDD,TRQIMX
10060      IF (TRQIDD.LE.0.0)  TRQIAC=0.0
10070      IF (TRQIDD.GT.0.0.AND.TRQIDD.LE.TRQIMX)  TRQIAC=TRQIDD
10080      IF (TRQIDD.GT.TRQIMX)  TRQIAC=TRQIMX
10090      ENDPRO
10100      *
10110      PROCED  TRQIP=SWTRQI,TRQIAC,TRQIMC
10120      IF (SWTRQI.EQ.0.0)  TRQIP=TRQIAC
10130      IF (SWTRQI.NE.0.0)  TRQIP=TRQIMC
10140      ENDPRO
10150      *
10160      WISM.=(1./TWIS)*(WIS-WISM)
10170      *
10180      DRENIP=(9.5493/AIIP)*(TRQIP-0.02847*WI*HOIP/(ENIP*ETAIP))
10190      *
10200      TAUWI=2.4431/ENEVAP+14.356/ENL

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10210 *
10220 DWIST=(HOIP+7.315098)*RHOTI1-25.36979*ROTAI1
10230 $ -17.86197*RHOTI3+35.416666*(ROTAIA+RHOIE-RHOTIC)
10240 $ -(1.1521861E- 3/ENEVAP**2.+1.148583E- 3/ENL**2.)*(WIS**2.)
10250 *
10260 PROCED DWIS,DENIP=ENWI,TAUWI,DWIST,DRENIP
10270 IF(ENWI.EQ.0.0) DWIS=DWIST/TAUWI
10280 IF(ENWI.EQ.0.0) DENIP=DRENIP
10290 IF(ENWI.NE.0.0) DWIS=0.0
10300 IF(ENWI.NE.0.0) DENIP=0.0
10310 ENDPRO
10320 *
10330 WIS.=DWIS
10340 ENIP.=DENIP
10350 *
10360 *
10370 * MAX. AVERAGE AND HOT CHANNEL TEMPERATURES
10380 * AND THEIR LOCATIONS RELATIVE TO CORE CENTRAL PLANE
10390 *
10400 HRM= 1. / (0.25 /AKF+60.00024/HDG+52.173914/HC +0.0052151492)
10410 HRS=1./ (60.00024/HDG+52.173914/HC+0.0052151492)
10420 *
10430 *
10440 * THE THEORITICAL LOCATIONS OF THE MAX. TEMPS. AT THE PIN-CLAD
10450 * OUTER SURFACE,PIN SURFACE,AND FUEL PIN CENTER LINE IN THE AVG. CHANNEL
10460 *
10470 YCMXTH=1.5078339*ATAN(0.29944753*HC/WPD)
10480 YSMXTH=1.5078339*ATAN(15.62335*HRS/WPD)
10490 YFMXTH=1.5078339*ATAN(15.62335*HRM/WPD)
10500 *
10510 *
10520 *THE ACTUAL LOCATION OF THE PIN-CLAD OUTER SURFACE MAX. TEMP. IN THE AVG.CHANNEL
10530 *
10540 PROCED YCMAX=YCMXTH
10550 IF(YCMXTH.LT.1.5) YCMAX=YCMXTH
10560 IF(YCMXTH.GE.1.5) YCMAX=1.5
10570 ENDPRO
10580 *
10590 *THE ACTUAL LOCATION OF THE FUEL PIN MAX. SURFACE TEMP. IN THE AVG CHANNEL
10600 *
10610 PROCED YSMAX=YSMXTH
10620 IF(YSMXTH.LT.1.5) YSMAX=YSMXTH
10630 IF(YSMXTH.GE.1.5) YSMAX=1.5
10640 ENDPRO
10650 *
10660 *THE ACTUAL LOCATION OF THE FUEL PIN MAX. CENTER LINE TEMP. IN THE AVG. CHANNEL
10670 *
10680 PROCED YFMAX=YFMXTH
10690 IF(YFMXTH.LT.1.5) YFMAX=YFMXTH
10700 IF(YFMXTH.GE.1.5) YFMAX=1.5
10710 ENDPRO
10720 *
10730 * THE THEORITICAL LOCATIONS OF THE MAX. TEMPS. AT THE PIN-CLAD
10740 * OUTER SURFACE,PIN SURFACE,AND FUEL PIN CENTER LINE IN THE HOT CHANNEL
10750 *
10760 YCMTH=1.5078339*ATAN(0.17787267*HC/WPD)
10770 YSMTH=1.5078339*ATAN(0.001401791/(WPD*(0.0078808679/HC
10780 $ +4.4692799E- 7+0.0063842402/HDG)))
10790 YFMTH=1.5078339*ATAN(0.001401791/(WPD*(0.0078808679/HC
10800 $ +4.4692799E- 7+0.0063842402/HDG+1.9770937E- 5/AKF)))

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10810 *
10820 *THE ACTUAL LOCATION OF THE PIN-CLAD OUTER SURFACE MAX. TEMP. IN THE HOT CHANNEL
10830 *
10840   PROCED YCMM=YCMTN
10850   IF(YCMTN.LT.1.5) YCMM=YCMTN
10860   IF(YCMTN.GE.1.5) YCMM=1.5
10870   ENDPRO
10880 *
10890 *THE ACTUAL LOCATION OF THE FUEL PIN MAX. SURFACE TEMP. IN THE HOT CHANNEL
10900 *
10910   PROCED YSMM=YSMTN
10920   IF(YSMTN.LT.1.5) YSMM=YSMTN
10930   IF(YSMTN.GE.1.5) YSMM=1.5
10940   ENDPRO
10950 *
10960 *THE ACTUAL LOCATION OF THE FUEL PIN MAX. CENTER LINE TEMP. IN THE HOT CHANNEL
10970 *
10980   PROCED YFMM=YFMTN
10990   IF(YFMTN.LT.1.5) YFMM=YFMTN
11000   IF(YFMTN.GE.1.5) YFMM=1.5
11010   ENDPRO
11020 *
11030 *
11040 *
11050 *VOLUMETRIC HEAT GENERATION AT THE CENTER OF THE FUEL PIN IN THE AVG. CHANNEL
11060 *
11070   QC=0.045077766*EPS*PPGC*EN
11080 *
11090 *COOLANT MAX. TEMP. AT THE EXIT OF THE AVG. CHANNEL
11100 *
11110   TPMAX=TP1+7.6761921E- 5*EPS*PPGC*EN/WPD
11120 *
11130 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
11140 *OF THE MAX. TEMP. AT THE PIN-CLAD OUTER SURFACE IN THE AVG. CHANNEL
11150 *
11160   DTP1CX=(4.5780019E- 5*EPS*PPGC*EN/WPD)
11170   S *(0.838378+SIN(0.66320299*YCMAX))
11180 *
11190 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
11200 *OF THE MAX. TEMP. AT THE PIN-CLAD OUTER SURFACE IN THE HOT CHANNEL
11210 *
11220   DTP1CM=(5.06327E- 5*EPS*PPGC*EN/WPD)
11230   S *(0.838378+SIN(0.66320299*YCMH))
11240 *
11250 *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
11260 *PIN-CLAD OUTER SURFACE IN THE AVG. CHANNEL
11270 *
11280   TPYCNX=TP1+DTP1CX
11290 *
11300 *THE DIFFERENCE BETWEEN THE PIN-CLAD OUTER SURFACE TEMP. AND THE
11310 *SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE CLAD
11320 *OUTER SURFACE IN THE AVG. CHANNEL
11330 *
11340   DTPCNX=0.0033915082*QC*COS(0.66320299*YCMAX)/HC
11350 *
11360 *THE DIFFERENCE BETWEEN THE PIN-CLAD OUTER SURFACE TEMP. AND THE
11370 *SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE CLAD
11380 *OUTER SURFACE IN THE HOT CHANNEL
11390 *
11400   DTPCH=0.0033915082*QC*COS(0.66320299*YCMH)/HC

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11410 *
11420 *MAX. PIN-CLAD OUTER SURFACE TEMP. IN THE AVG. CHANNEL
11430 *
11440 TCMAX=TPYCMX+DTPCMX
11450 *
11460 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
11470 *OF THE MAX. TEMP. AT THE FUEL PIN SURFACE IN THE AVG. CHANNEL
11480 *
11490 DTP1SX=(4.5780019E- 5*EPS*FPGC*EN/WPD)
11500 S *(0.838378+SIN(0.66320299*YSMAX))
11510 *
11520 *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
11530 *FUEL PIN SURFACE IN THE HOT CHANNEL
11540 *
11550 DTP1SM=(5.06327E- 5*EPS*FPGC*EN/WPD)
11560 S *(0.838378+SIN(0.66320299*YSMM))
11570 *
11580 *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
11590 *FUEL PIN SURFACE IN THE AVG. CHANNEL
11600 *
11610 TPYSMX=TP1+DTP1SX
11620 *
11630 * MAX. FUEL PIN SURFACE TEMP. IN THE AVG. CHANNEL
11640 *
11650 TSMAX=TPYSMX+6.5003905E- 5*QC*COS(0.66320299*YSMAX)/HRS
11660 *
11670 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
11680 *OF THE MAX. TEMP. AT THE FUEL PIN CENTER LINE IN THE AVG. CHANNEL
11690 *
11700 DTP1FX=(4.5780019E- 5*EPS*FPGC*EN/WPD)
11710 S *(0.838378+SIN(0.66320299*YFMAX))
11720 *
11730 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
11740 *OF THE MAX. TEMP. AT THE FUEL PIN CENTER LINE IN THE HOT CHANNEL
11750 *
11760 DTP1FM=(5.06327E- 5*EPS*FPGC*EN/WPD)
11770 S *(0.838378+SIN(0.66320299*YFMM))
11780 *
11790 *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
11800 *FUEL PIN AT ITS CENTER LINE IN THE AVG. CHANNEL
11810 *
11820 *
11830 TPYFMX=TP1+DTP1FX
11840 *MAX. FUEL PIN TEMP. AT ITS CENTER LINE IN THE AVG. CHANNEL
11850 *
11860 TFMAX=TPYFMX+6.5003905E- 5*QC*COS(0.66320299*YFMAX)/HRM
11870 *
11880 *COOLANT MAX. TEMP. IN THE HOT CHANNEL
11890 *
11900 TPMH=1.248*(TP1+8.4898684E-5*EPS*FPGC*EN/WPD)
11910 *
11920 *PIN-CLAD MAX. OUTER SURFACE TEMP. IN THE HOT CHANNEL
11930 *
11940 TCMM=1.248*(TP1+DTP1CM)+2.323706*DTPCM
11950 *
11960 *FUEL PIN MAX. SURFACE TEMP. IN THE HOT CHANNEL
11970 *
11980 TSMH=1.248*(TP1+DTP1SM) +(0.0078808679/HC+4.4692799E- 7
11990 S +0.0063842402/HDG)*QC*COS(0.66320299*YSMM)
12000 *

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12010 *FUEL PIN MAX. CENTER LINE TEMP. IN THE HOT CHANNEL
12020 *
12030 TFM=1.248*(TP1+DTP1FM) +(0.0078808679/HC+4.4692799E- 7
12040 $ +0.0063842402/HDG+1.9770937E- 5/AKF)*QC*COS(0.66320299*YFM)
12050 *
12060 STORE , WS9,PS9,TS9,HS9,SS9,XEXH,HEXH,STWBTU,PT,PGFETA,POMG,PGE,
12070 $ EMW,PGA,PETAG,OMGG,AL,E,PF,XD,WSA,WSC,RHOASA,CPS,PSA,PSC,TSA,
12080 $ TSC,HSA,HSC,TIC,TASA,TAWA,TAIA,ELS1,ELS2,WS1,WS3,XS3,ALF3,HS3,
12090 $ TAW1,TAW2,TAI7,TAI8,TAI9,PAS2,ALFA2,HS1,TS1,TAS1,TSAT,B1T,B2T,
12100 $ DETERM,EMS4,EMS5,YSS,PAS4,HS6,RHOD,EN,TAF,TAP1,TAP5,TAI1,TAI3,
12110 $ TAUTR1,TP7,TP1,TAUTP5,TP3,TP4,TP5,WP,WI,TPMAX,TPMM,YCMAX,YCMM,
12120 $ TCMAX,TCMM,YSMAX,TS MAX,YSMM,TSMM,YFMAX,TFMAX,YFMM,TFMM,
12130 $ DWPS,DWIS,TAUWP,TAUWI,WS5,TSS,QPP,HOPP,QIP,HOIP,TR1,DWSAS,ROEXCD
12140 $ ,X,XCR,TAUTI1,TAUTIA,TAUTI7,TAUHS1,TAUHS4,TAUHS5,WDMP
12150 $ ,TI7,TI8,TIA,TI1,TR3,ENPP,ETAPP,ENIP,ETAIP
12160 *
12170 *
12180 PROCD ROEXCD=T
12190 IP(T.EQ.0.0) ROEXCD=2.4644232
12200 IP(T.GT.0.0) ROEXCD=2.7144232
12210 ENDPRO
12220 *
12230 *
12240 $T1*
12250 RHONA , 6
12260 * NEXT IS THE INDEPENDENT VARIABLE FOLLOWED BY THE DEPENDENT
12270 392.0 ,36.4
12280 572.0 ,55.1
12290 752.0 ,53.6
12300 932.0 ,52.1
12310 1112.0 ,50.5
12320 1292.0 ,48.9
12330 $T2
12340 TS1F , 12
12350 374.97 ,400.0
12360 396.77 ,420.0
12370 418.9 ,440.0
12380 430.1 ,450.0
12390 441.4 ,460.0
12400 464.4 ,480.0
12410 487.8 ,500.0
12420 511.9 ,520.0
12430 536.6 ,540.0
12440 562.2 ,560.0
12450 588.9 ,580.0
12460 610.0 ,600.0
12470 $T3
12480 RHOW , 12
12490 400.0 ,53.648
12500 420.0 ,52.798
12510 440.0 ,51.921
12520 450.0 ,51.546
12530 460.0 ,51.02
12540 480.0 ,50.0
12550 500.0 ,49.02
12560 520.0 ,47.847
12570 540.0 ,46.512
12580 560.0 ,45.249
12590 580.0 ,43.860
12600 600.0 ,43.373

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12610	ST4							
12620	VF , 6							
12630		1200.0	,0.0223					
12640		1300.0	,0.0227					
12650		1400.0	,0.0231					
12660		1500.0	,0.0235					
12670		2000.0	,0.0257					
12680		2500.0	,0.0287					
12690	ST5							
12700	HF , 6							
12710		1200.0	,571.7					
12720		1300.0	,585.4					
12730		1400.0	,598.7					
12740		1500.0	,611.6					
12750		2000.0	,671.7					
12760		2500.0	,730.6					
12770	ST6							
12780	TSATF , 6							
12790		1200.0	,567.22					
12800		1300.0	,577.46					
12810		1400.0	,587.1					
12820		1500.0	,596.23					
12830		2000.0	,635.82					
12840		2500.0	,668.13					
12850	ST7							
12860	VG , 6							
12870		1200.0	,0.3619					
12880		1300.0	,0.3293					
12890		1400.0	,0.3012					
12900		1500.0	,0.2765					
12910		2000.0	,0.1878					
12920		2500.0	,0.1307					
12930	ST8							
12940	HG , 6							
12950		1200.0	,1183.4					
12960		1300.0	,1178.6					
12970		1400.0	,1173.4					
12980		1500.0	,1167.9					
12990		2000.0	,1135.1					
13000		2500.0	,1091.1					
13010	ST9							
13020	RD , 3 , 5							
13030	*							
13040	* THE FOLLOWING IS A DEFINITION OF THE SECOND							
13050	* INDEPENDENT VARIABLE.							
13060	*							
13070		0.2	,0.4	,0.6	,0.8	,1.0		
13080	*							
13090	* NEXT COMES THE FIRST INDEPENDENT VARIABLE							
13100	* FOLLOWED BY THE DEPENDENT VARIABLE							
13110	*							
13120		1000.0	,4.81801	,7.43707	,10.6082	,12.915	,14.4123	
13130		2000.0	,2.48938	,3.21363	,4.30274	,4.97874	,5.35559	
13140		2500.0	,1.72844	,2.23131	,2.6778	,2.98751	,2.98751	
13150	ST10							
13160	VSH , 6,5							
13170		700.0	,800.0	,900.0	,1000.0	,1200.0		
13180		1200.0	,0.4909	,0.5617	,0.6250	,0.6843	,0.7967	
13190		1400.0	,0.4062	,0.4714	,0.5281	,0.5805	,0.6789	
13200		1600.0	,0.3417	,0.4034	,0.4553	,0.5027	,0.5906	

13210		1800.0	,0.2907	,0.3502	,0.3986	,0.4421	,0.5218
13220		2000.0	,0.2489	,0.3074	,0.3532	,0.3935	,0.4668
13230		2500.0	,0.1686	,0.2294	,0.2710	,0.3061	,0.3678
13240	ST11						
13250	HSN ,6,5						
13260		700.0		,800.0	,900.0	,1000.0	,1200.0
13270		,1311.0		,1379.3	,1440.7	,1499.2	,1613.1
13280		1200.0	,1295.5	,1369.1	,1433.1	,1493.2	,1608.9
13290		1400.0	,1278.7	,1358.4	,1425.3	,1487.0	,1604.6
13300		1600.0	,1260.3	,1347.2	,1417.4	,1480.8	,1600.4
13310		1800.0	,1240.0	,1335.5	,1409.2	,1474.5	,1596.1
13320		2000.0	,1176.8	,1303.6	,1387.8	,1458.4	,1585.3
13330	ST12						
13340	S9 ,6,5						
13350		700.0		,800.0	,900.0	,1000.0	,1200.0
13360		,1.4843		,1.5409	,1.5859	,1.6293	,1.7025
13370		1200.0	,1.4567	,1.5177	,1.5666	,1.6093	,1.6386
13380		1400.0	,1.4304	,1.4964	,1.5476	,1.5914	,1.6669
13390		1600.0	,1.4044	,1.4765	,1.5301	,1.5752	,1.6520
13400		1800.0	,1.3783	,1.4576	,1.5139	,1.5603	,1.6384
13410		2000.0	,1.3073	,1.4127	,1.4772	,1.5273	,1.6088
13420	ST13						
13430	HMM,9,12						
13440		0.0		,4.0	,8.0	,12.0	,16.0
13450	\$	,20.0	,24.0	,28.0	,32.0	,36.0	,40.0
13460	\$	,44.0					
13470		500.0	,98.8	,97.8	,94.9	,89.2	,79.5
13480	\$	,65.7	,50.0	,32.0	,22.0	,10.0	,5.0
13490	\$	,2.0					
13500		980.0	,380.0	,378.0	,376.0	,370.0	,363.0
13510	\$	,353.0	,340.0	,322.0	,302.0	,277.0	,244.0
13520	\$	,210.0					
13530		1006.0	,400.0	,398.5	,396.0	,391.0	,384.0
13540	\$	,374.0	,361.0	,342.647	,308.92	,300.0	,266.0
13550	\$	,230.0					
13560		1030.0	,419.0	,418.0	,415.0	,410.0	,404.0
13570	\$	,393.0	,380.0	,364.0	,343.0	,319.0	,288.0
13580	\$	,253.0					
13590		1150.0	,514.0	,512.0	,510.0	,504.0	,496.0
13600	\$	,486.0	,470.0	,454.0	,440.0	,420.0	,390.0
13610	\$	,355.0					
13620		1170.0	,532.0	,531.0	,528.0	,522.0	,514.0
13630	\$	,504.0	,489.0	,472.0	,463.6156	,431.5789	,410.0
13640	\$	,375.0					
13650		1200.0	,560.0	,558.0	,555.0	,549.0	,541.5
13660	\$	,531.0	,516.0	,500.0	,485.0	,466.0	,439.0
13670	\$	,404.0					
13680		1400.0	,775.0	,773.0	,770.0	,765.0	,758.0
13690	\$	,749.0	,738.0	,723.0	,705.0	,684.0	,658.0
13700	\$	,634.0					
13710		1500.0	,874.0	,872.0	,870.0	,865.0	,856.0
13720	\$	,846.0	,833.0	,817.0	,797.0	,776.0	,758.0
13730	\$	,736.0					
13740	ST14						
13750	ELD,13						
13760		0.0	,380.0				
13770		3600.0	,381.5				
13780		7200.0	,382.3				
13790		10800.0	,383.5				
13800		14400.0	,384.7				

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13810          18000.0      ,388.0
13820          21600.0      ,391.0
13830          25200.0      ,392.0
13840          28800.0      ,392.2
13850          32400.0      ,392.1
13860          36000.0      ,391.9
13870          39600.0      ,391.0
13880          43200.0      ,390.0
13890      *
13900      ST15
13910          PROCRX , 13
13920          0.0          ,0.0
13930          2.4          ,0.01
13940          4.8          ,0.04
13950          7.2          ,0.09334
13960          12.0         ,0.24
13970          14.4         ,0.32667
13980          18.0         ,0.47334
13990          21.6         ,0.62667
14000          26.4         ,0.82667
14010          28.8         ,0.92
14020          31.2         ,0.97334
14030          33.6         ,0.99334
14040          36.0         ,1.0
14050      *
14060      SF
14070      FUNCTION DRP(PAS)
14080      PAS21=PAS-50.0
14090      PAS22=PAS+50.0
14100      HP1=HP(PAS21)
14110      HP2=HP(PAS22)
14120      DRP=(HP2-HP1)/100.0
14130      RETURN
14140      END
14150      FUNCTION DVP(PAS)
14160      PAS21=PAS-50.0
14170      PAS22=PAS+50.0
14180      VP1=VP(PAS21)
14190      VP2=VP(PAS22)
14200      DVP=(VP2-VP1)/100.0
14210      RETURN
14220      END
14230      FUNCTION DVG(PAS)
14240      PAS21=PAS-50.0
14250      PAS22=PAS+50.0
14260      VG1=VG(PAS21)
14270      VG2=VG(PAS22)
14280      DVG=(VG2-VG1)/100.0
14290      RETURN
14300      END
14310      FUNCTION DHG(PAS)
14320      PAS21=PAS-50.0
14330      PAS22=PAS+50.0
14340      HG1=HG(PAS21)
14350      HG2=HG(PAS22)
14360      DHG=(HG2-HG1)/100.0
14370      RETURN
14380      END
14390      *
14400      SF

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14410      FUNCTION PDELAY(XC,TAU,I,XCI)
14420      C
14430      C PIPE DELAY PUNCTION FOR THE DARE P RUNTIME SYSTEM
14440      C
14450      C XC = VARIABLE TO BE DELAYED
14460      C
14470      C TAU = AMOUNT OF DELAY BEFORE PRESENT VALUE OF XC IS VALID.
14480      C      (VARIABLE, ANY VALUE .GE. ZERO)
14490      C
14500      C I = INTEGER CONSTANT BETWEEN 1 AND IMAX IDENTIFYING
14510      C      INDEPENDENT PDELAY OPERATORS
14520      C
14530      C XCI = INITIAL VALUE OF XC (VALUE RETURNED UNTIL T .GT. TAU(0) )
14540      C
14550      C PDELAY MODELS AN INCOMPRESSIBLE FLUID FLOWING THROUGH A UNIT
14560      C LENGTH PIPE AT A VELOCITY OF 1./TAU
14570      C
14580      LOGICAL WRAP
14590      LOGICAL EXIT,RLDONE
14600      COMMON /SYSVAR/ EXIT,RLDONE,IOUT,IFILE,IRUNNO,T,TMAX,TNEXT
14610      COMMON /SYSVAR/ DT,DTMAX,DTMIN,EMAX,EMIN,SY(35)
14620      COMMON DELAY(8101)
14630      COMMON TNS(20),NP(20),WRAP(20),TSAV(100,20),XSAV(100,20),TAUL(20)
14640      1,XCL(20)
14650      DATA NPA/100/,IMAX/20/
14660      C
14670      PDELAY=XCI
14680      DUMMY=XC
14690      IF(EXIT) RETURN
14700      IF(I.GT.0.AND.I.LE.IMAX) GO TO 4
14710      WRITE(IOUT,3) I
14720      3      FORMAT(36H FATAL ERROR - INVALID PDELAY NUMBER,I3)
14730      CALL ABORT
14740      4      IF(TAU.GE.0.) GO TO 7
14750      WRITE(IOUT,6) I,IRUNNO,T
14760      6      FORMAT(15H ERROR - PDELAY,I3,9H NEGATIVE/
14770      2      7H - RUN,I4,19H TERMINATED AT T =,1PE12.5)
14780      EXIT=.TRUE.
14790      RETURN
14800      C
14810      C IF T.EQ.0, INITIALIZE
14820      C
14830      7      IF(T.GT.0.) GO TO 8
14840      NP(I)=1
14850      TNS(I)=AMAX1(DT,TAU*2./FLOAT(NPA))
14860      WRAP(I)=.FALSE.
14870      TSAV(1,I)=TAU
14880      XSAV(1,I)=XC
14890      TSAV(NPA,I)=0.
14900      TAUL(I)=TAU
14910      XCL(I)=XC
14920      GO TO 12
14930      C
14940      C IF T.GE.TNS, SAVE X AND T, CALCULATE TNS
14950      C
14960      8      IF(T.LT.TNS(I).OR..NOT.RLDONE) GO TO 12
14970      C
14980      C IF TAU DIFFERS FROM LAST CALL, ADJUST TSAV ARRAY TO MATCH NEW
14990      C PIPE VELOCITY
15000      C

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15010      IF(TAU.EQ.TAUL(I)) GO TO 10
15020      N=NP(I)
15030      IF(T.GE.TSAV(N,I)) GO TO 10
15040      TSAV(N,I) = (TSAV(N,I)-T)*TAU/TAUL(I)+T
15050      N=MOD(N-2+NPA,NPA)+1
15060      GO TO 9
15070      10  IF(TAUL(I)-TAU.LT.0.0) GO TO 43
15080      DUMMY=(DT*XC + TAU*XCL(I))/(TAU + DT)
15090      C
15100      C CHECK FOR BUFFER OVERFLOW (YES, IT CAN OCCUR)
15110      C BUFFER OVERFLOW IS STORING NEW DATA INTO A CELL BEFORE
15120      C FINISHED WITH OLD DATA
15130      C
15140      43  N=NP(I)
15150      TAUL(I)=TAU
15160      XCL(I)=DUMMY
15170      N2=MOD(N+1,NPA)+1
15180      IF(.NOT.WRAP(I).AND.N2.GT.2) GO TO 11
15190      IF(T.GE.TSAV(N2,I)) GO TO 11
15200      TNS(I)=TSAV(N2,I)
15210      WRITE(IOUT,105) I,T,TNS(I)
15220      105  FORMAT(17H WARNING - PDELAY,I3,22H BUFFER OVERFLOW AT T=,
15230      2    1PE12.5,6H, TNS=,E12.5)
15240      GO TO 12
15250      11  IF(N.EQ.NPA) WRAP(I)=.TRUE.
15260      N=MOD(N,NPA)+1
15270      NP(I)=N
15280      TSAV(N,I)=T+TAU
15290      XSAV(N,I)=DUMMY
15300      TNS(I)=T+AMAX1(DT,TAU*2./FLOAT(NPA))
15310      C
15320      C IF T .LT. FIRST-T-STORED, RETURN XCI
15330      C
15340      12  IF(.NOT.WRAP(I).AND.T.LT.TSAV(1,I)) RETURN
15350      C
15360      C CHECK FOR T .GT. LAST-T-STORED (WILL BE IF TAU.LT.DT)
15370      C
15380      NBIG=NP(I)
15390      IF(T.LE.TSAV(NBIG,I)) GO TO 13
15400      NSM=NBIG
15410      NBIG=MOD(NBIG,NPA)+1
15420      IF(NBIG.EQ.1) WRAP(I)=.TRUE.
15430      TSAV(NBIG,I)=T+TAU
15440      XSAV(NBIG,I)=DUMMY
15450      GO TO 33
15460      C
15470      C CHECK WHICH HALF OF CIRCULAR BUFFER T IS IN
15480      C
15490      13  NSM=1
15500      IF(.NOT.WRAP(I).OR.T.GE.TSAV(1,I)) GO TO 15
15510      NSM=NBIG+1
15520      NBIG=NPA
15530      C
15540      C CHECK FOR T IN THE CRACK BETWEEN TSAV(NPA) AND TSAV(1)
15550      C
15560      IF(T.LE.TSAV(NPA,I)) GO TO 15
15570      NSM=NPA
15580      NBIG=1
15590      GO TO 33
15600      C

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15610 C PERFORM BINARY SEARCH TO LOCATE INDEX OF T
15620 C
15630 15 IF(NBIG.LT.NSM) GO TO 33
15640 NTRY=(NBIG+NSM)/2
15650 IF(T-TSAV(NTRY,I)) 17,19,21
15660 17 NBIG=NTRY-1
15670 GO TO 15
15680 19 PDELAY=XSAV(NTRY,I)
15690 RETURN
15700 21 NSM=NTRY+1
15710 GO TO 15
15720 C
15730 C INTERPOLATE BETWEEN TWO CLOSEST POINTS
15740 C
15750 33 PDELAY = XSAV(NSM,I) + (XSAV(NBIG,I) - XSAV(NSM,I)) *
15760 2 ( (T-TSAV(NSM,I)) / (TSAV(NBIG,I) - TSAV(NSM,I)) )
15770 RETURN
15780 END
15790 *
15800 *
15810 SM11
15820 END
15830 TMAX=100.0 , DT=1.0E-5 , DTMIN=1.0E-6
15840 NPOINT=201
15850 EMAX=1.0E-6
15860 SY(8)=3.0
15870 PETAG=25.5703, OMGG=376.99
15880 WSAS=927.7778, PT=387.6
15890 TSC=905.0, TAWA=372.25542, TIC=855.0
15900 ELS1=21.377693
15910 PAS2=1830.7, PAS4=1765.7
15920 WS1D=0.4085327, WS3D=0.4085327, WS5S=927.7778
15930 TAW1=659.08545, TAW2=738.97753
15940 TI8=713.96, TI9=651.0
15950 EMS5=20268.287, HS6=540.89027
15960 D1=1.0, D2=1.0, D3=1.0
15970 D4=1.0, D5=1.0, D6=1.0
15980 WPS=11512.777, WIS=10650.0
15990 TAF=2217.1839, TP3=1035.729
16000 TP1=730.0, TP4=994.73, TR3=994.73
16010 TP7=730.0, TI3=936.0
16020 ENPP=1170.0, ENIP=1006.0
16030 ENS=2271, ENSC2=2.0
16040 ENL=3.0, ENZVAP=6.0
16050 ENI=8550.0, ENZ=4542.0
16060 ENP=42966.0
16070 EMWI=380.0
16080 EXAI=0.2
16090 SV9I=0.85
16100 PS9I=1464.7
16110 CV9=22.28, ENS94=4.0
16120 AV9=5.66816
16130 CDM9=0.126685
16140 OMGGI=376.99
16150 TIAI=936.0, PSAI=1739.7
16160 WSAI=3.34E 6
16170 HS1I=540.89027, WS1I=6.68E6, TI7I=855.0
16180 WII=3.834E 7, TICI=855.0
16190 DPRCSF=175.0, FRC=7.057624E-5, PS6=1.6362977E-2
16200 DOD=7.0

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16210 DV=1000.0 , EMS4I=2179.9332, EMS5I=20268.287
16220 PSS=0.32347367 , PV5=7.685E-5 , SV5I=0.7
16230 WS4I=6.68E 6 , WS6I=6.68E 6
16240 WS5I=3.34E 6 , WS7I=3.34E 6
16250 HS4I=898.781 , HSSI=434.6885
16260 RHOCDI=2.9444232 , ROFBCI=95.6 , DC=-0.0058
16270 SODDCC=-0.006 , RECC=-0.21 , AXECC=-0.023
16280 VP1=3000.0 , VP4=6325.0
16290 EPS=3.3267E 9 , FPGC=0.9239
16300 HDG=756.81825
16310 AIPP=16000.0 , AIIP=16000.0
16320 WPI=41.446E 6 , PFC=0.8
16330 TAPI=400.0 , TRII=730.0 , TP7I=730.0
16340 TP4I=994.73135 , TP5I=994.73135
16350 TI1I=651.0 , TI3I=936.0 , TI9I=651.0
16360 TSCI=905.0 , PAS4I=1765.7
16370 P143=5.72335 , ENSUB=198.0
16380 ELSC1=200.0 , ELSC2=100.0
16390 ELSHT=65.0 , ELS7=120.0
16400 ELS31=70.0 , ELS32=10.0
16410 ELS61=15.0 , ELS62=100.0
16420 ELS63=75.0 , ELS64=30.0
16430 ELS5=250.0
16440 TS9D=900.0
16450 PS9D=1464.7 , PEXHD=2.0 , PS9MX=1500.0
16460 YS5D=3.0 , YS5M=3.0
16470 * DPV5D=15.0
16480 ENPPD=1170.0 , ENIPD=1006.0
16490 PS9M=1464.7 , PEXHM=2.0 , PGM=380.0
16500 TS9M=900.0 , ENM=1.0
16510 WSCSM=927.7778 , WSSSM=927.7778
16520 * PAS4M=1765.7 , PHPWM=2000.0
16530 WPSM=11512.777 , WISM=10650.0
16540 TP3M=1035.73 , TP4M=994.727
16550 TRI1M=730.0
16560 AEPT=0.7 , AEPS91=-0.05 , AEPEXH=13.5
16570 AEOMGG=3.0 , AEMW1=1.0 , ASV9=2.25E-3
16580 AEYSS=6.0E4 , AESV5=2.25E-3 , APEXH=2.1556E-3
16590 * ADPV5=0.0 , ATRQP=0.0 , AV5=0.06402486
16600 ARPS92=0.5 , AETR1=50.0 , AEVDMP=-0.0007
16610 AEWPS=0.1 , AEWIS=0.1
16620 ATRQP=500.0 , ATRQI=450.0
16630 AETS9=1.1 , AETP4=0.001
16640 AEEN=1.0 , VCROUT=0.15 , VCRIN=0.15
16650 ATP4=0.9604
16660 TERMW=10.0 , TSV9=0.5 , TSV5=0.5
16670 TEYSS=10.0 , TSV5=10.0
16680 TPS9=0.15 , TPEXH=0.15 , TYS5=0.5
16690 TWSCS=0.5 , TWSSS=0.5 , TPG=0.2
16700 * TEDPV5=10.0 , TTRQP=0.1
16710 * TRQPMX=152387.23
16720 * TPAS4=0.15 , TPHFW=0.15
16730 TTR1=5.0
16740 TEPS9=10.0 , TETR1=10.0 , TEVDMP=10.0
16750 TEENPP=10.0 , TEENIP=10.0
16760 TTRQP=0.01 , TTRQI=0.01
16770 TWPS=0.5 , TWIS=0.5
16780 TEWPS=10.0 , TEWIS=10.0
16790 TTS9=5.0 , TEN=0.1
16800 TEEN=10.0

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16810      TTP3=5.0
16820      ALFTP4=5.0      ,      TTP4=25.0
16830      *      HOFB=5000.0      ,      ETAFP=0.8      ,      ENFPD=5000.0
16840      PHFW=2000.0
16850      ENPPMX=1500.0      ,      ENIPMX=1400.0
16860      TRQPMX=7.0E5      ,      TRQIMX=6.0E5
16870      TETS9=10.0      ,      TETP4=10.0
16880      ENMX=1.5
16890      X=12.0      ,      ROCRHD=2.0
16900      ENLD=1.0
16910      END
16920      *      CRBRP ATWS SIMULATOR WITH CONTROLLERS
16930      *      TURBO-GENERATOR
16940      LIST,FETAG,OMGG,PGFFTA,POMG,PGE,PT
16950      LIST,WS9,PS9,TS9,HS9
16960      *      FREQUENCY
16970      FACTOR(,0.8,1.0,0.2)
16980      GRAPH,OMGG
16990      *      POWER ANGLE
17000      GRAPH,FETAG
17010      *      THE ELECTRIC LOAD DEMAND
17020      GRAPH,EMW
17030      *      TURBINE AND GENERATOR POWERS
17040      GRAPH,PT,PGFETA
17050      *      TURBINE FLOW
17060      GRAPH,WS9
17070      *      TURBINE HIGH PRESSURE
17080      GRAPH,PS9
17090      *      SUPERHEATED STEAM TEMP. AT THE TURBINE INLET
17100      GRAPH,TS9
17110      *      STEAM-GENERATOR
17120      *      SUPERHEATER
17130      LIST,WSC,TASA,TAWA,TAIA
17140      LIST,PSA,PSC,TSA,TSC,HSC,TIA,TIC
17150      *      SUPERHEATED STEAM FLOW
17160      GRAPH,WSC
17170      *      SUPERHEATER EXIT STEAM PRESSURE
17180      GRAPH,PSC
17190      *      SUPERHEATER AVG. TEMPS.
17200      GRAPH,TASA,TAWA,TAIA
17210      *      SUPERHEATER EXIT STEAM TEMP.
17220      GRAPH,TSC
17230      *      SUPERHEATER EXIT AND EVAP. INLET SODIUM TEMPS.
17240      GRAPH,TIC,TI7
17250      *      IHX INTERMEDIATE EXIT TEMP. AND SUPERHEATER INLET SODIUM TEMP.
17260      GRAPH,TI3,TIA
17270      *      EVAPORATOR
17280      LIST,ELS1,ELS2,XS3,ALF3,HS3
17290      LIST,TI8,TI9,TAW1,TAW2,TS1,TSAT
17300      LIST,WS1,WS3,PAS2,ALFA2
17310      *      LENGTHS OF REGIONS OF THE EVAP.
17320      GRAPH,ELS1,ELS2
17330      *      EVAP. EXIT QUALITY AND VOID FRACTION
17340      GRAPH,XS3,ALF3
17350      *      EVAP. AVG. TEMPS. IN THE LOWER REGIONS
17360      GRAPH,TAS1,TAW1,TAI8
17370      *      EVAP. AVG. TEMPS. IN THE UPPER REGIONS
17380      GRAPH,TSAT,TAW2,TAI7
17390      *      EVAP. INLET SUBCOOLED WATER TEMP.
17400      GRAPH,TS1

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17410 *      EVAP. EXIT SODIUM TEMP. AND IHX INTERMEDIATE INLET TEMP.
17420 GRAPH,TI9,TI1
17430 *      EVAP. AVG. PRESSURE ON THE STEAM/WATER SIDE
17440 GRAPH,PAS2
17450 *      EVAP. INLET AND EXIT FLOW-RATES ON THE WATER/STEAM SIDE
17460 GRAPH,WS1,WS3
17470 *      STEAM DRUM
17480 LIST,WS5,TS5,YS5,PAS4,HS6,ENS4,EMS5
17490 *      STEAM DRUM WATER LEVEL
17500 GRAPH,YS5
17510 *      STEAM DRUM PRESSURE
17520 GRAPH,PAS4
17530 *      STEAM DRUM FEEDWATER TEMP.
17540 GRAPH,TS5
17550 *      REACTOR AND IHX
17560 *      IHX
17570 LIST,TP7,TI3,TP5,TI1,TAP5,TAI1
17580 *      IHX REGIONS AVG. TEMPS.
17590 GRAPH,TAP5,TAI1
17600 *      IHX PRIMARY EXIT TEMP. AND REACTOR INLET TEMP.
17610 GRAPH,TP7,TR1
17620 *      INTERMEDIATE FLOW
17630 GRAPH,WI
17640 *      PRIMARY FLOW
17650 GRAPH,WP
17660 *      REACTOR
17670 LIST,WP,WI,X,XCR,RHOD,EN,TAP
17680 LIST,TR1,TP1,TAP1,TP3,TR3,TP4
17690 LIST,ENPP,ETAPP,HOPP,ENIP,ETAIP,HOIP
17700 *      CENTER CONTROL-ROD POSITION
17710 GRAPH,X,XCR
17720 *      ECCENTRAL ROD REACTIVITY ($)
17730 GRAPH,ROEXCD
17740 *      TOTAL REACTIVITY ($)
17750 GRAPH,RHOD
17760 *      REACTOR NORMALIZED POWER LEVEL
17770 GRAPH,EN
17780 *      FUEL AVG. TEMP. IN THE CORE
17790 GRAPH,TAP
17800 *      COOLANT AVG. TEMP. IN THE CORE
17810 GRAPH,TAP1
17820 *      CORE EXIT TEMP.
17830 GRAPH,TP3
17840 *      OUTLET PLZNUM INLET AND EXIT TEMPS. AND IHX PRIMARY INLET TEMP.
17850 GRAPH,TR3,TP4,TP5
17860 *      DELAYS
17870 LIST,TAUTS9,TAUHS4,TAUHS1,TAUTI7,TAUTIA
17880 LIST,TAUTI1,TAUTP5,TAUTR1
17890 *      MAX. TEMPS. IN THE AVG. AND HOT CHANNELS AND THEIR AXIAL LOCATIONS
17900 LIST,TPMAX,TPMN,YCMAX,TCMAX,YCMN,TCMN
17910 LIST,TSMAX,YSMN,TSNM,YFMAX,TFMAX,YFMN,TFMN
17920 *      MAX. PIN-CLAD TEMPS. IN THE AVG. AND HOT CHANNELS
17930 GRAPH,TCMAX,TCMN
17940 *      MAX. FUEL-SURFACE TEMPS. IN THE AVG. AND HOT CHANNEL
17950 GRAPH,TSMAX,TSNM
17960 *      MAX. FUEL-CENTER-LINE TEMPS. IN THE AVG. AND HOT CHANNEL
17970 GRAPH,TFMAX,TFMN
17980 END

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APPENDIX H

LISTING OF THE CRBRP-DCHT SIMULATOR

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00010  MERVAT, BN4101273P, CM120000, T8000, ST0, P0.      DCHT.C
00020  CALL DAREP, *NEDEPT, ID=CDCHT, RP=5.
00030  ~Z
00040  SD1
00050  *
00060  *          CONTROLLED DECAYHEAT REMOVAL
00070  *
00080  *
00090  *P
00100  *
00110  PPROCED  ENPSC, ENPAS4=PSC, PSCMX, PAS4, PAS4MX, TSCRAM
00120  IF (T.GE.TSCRAM.AND.PSC.GE.PSCMX)  ENPSC=1.0
00130  IF (T.GE.TSCRAM.AND.PAS4.GE.PAS4MX)  ENPAS4=1.0
00140  ENDPRO
00150  *
00160  POWER=EPS*ENT/3.412E6
00170  *
00180  PPROCED  WDNPS1, WDNPS2=PSC, PAS4, CDM1, CDM2, ENL, POWER, ZNPSC, ENPAS4
00190  IF (ENPSC.EQ.1.0)  WDNPS1=ENL*CDM1*PSC
00200  IF (ENPAS4.EQ.1.0)  WDNPS2=ENL*CDM2*PAS4
00210  IF (POWER.LE.45.0)  WDNPS1=0.0
00220  IF (POWER.LE.45.0)  WDNPS2=0.0
00230  ENDPRO
00240  *
00250  PPROCED  SIVSCD=SIVSC, TSCRAM, ENTRBN, ENV5
00260  IF (T.EQ.0.0)  SIVSCI=SIVSC
00270  IF (T.LT.TSCRAM)  SIVSCD=SIVSCI
00280  IF (T.GE.TSCRAM.OR.ENTRBN.NE.0.0.OR.ENV5.NE.0.0)  SIVSCD=0.0
00290  ENDPRO
00300  *
00310  SIVSC.= (SIVSCD-SIVSC)/0.5
00320  *
00330  *
00340  *          I.  SUPERHEATER
00350  *
00360  PPROCED  WSAS1=ASIVSC, SIVSC, ENL
00370  IF (SIVSC.GT.0.0)  WSAS1=ENL*ASIVSC*SIVSC
00380  IF (SIVSC.LE.0.0)  WSAS1=0.0001
00390  ENDPRO
00400  *
00410  PPROCED  WSAS=WSAS1
00420  WSAS=WSAS1*WDNPS1
00430  ENDPRO
00440  *
00450  WSA=3600.0*WSAS
00460  *
00470  WSCS=WSAS
00480  WSC=WSA
00490  *
00500  PSA=PAS4+ (53.21+YS5) *RHOGS4/144.0-2.8964236E-4* (WSAS/ENL) **2
00510  *
00520  PSC=PAS4+ (53.21+YS5) *RHOGS4/144.0-2.3807823E-3* (WSAS/ENL) **2
00530  *
00540  TAUHSA=0.92175*ELS7*ENL*RHOGS4/WSAS
00550  HSA=PDELAY (HGS4, TAUHSA, 7, HGS4I)
00560  *
00570  HSC=HSH (PSC, TSC)
00580  *
00590  *
00600  CPS=(HSC-HSA)/(TSC-TSA)

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00610 *
00620 HASA=(HSA+HSC)/2.0
00630 PSS=(PSA+PSC)/2.0
00640 *
00650 VGSA=VG(PSA)
00660 VSC=VSH(PSC,TSC)
00670 RHOASA=(1./VGSA+1./VSC)/2.0
00680 *
00690 TSA=TSATP(PSA)
00700 TASA=(TSA+TSC)/2.
00710 *
00720 *
00730 WI=3600.0*WIS
00740 *
00750 RHOTI3=RHONA(TI3)
00760 *
00770 TAUTIA=9474400.0*RHOTI3*ENL/WI
00780 *
00790 TIA=PDELAY(TI3,TAUTIA,3,TI3I)
00800 *
00810 TAIA=(TIA+TIC)/2.0
00820 ROTAIA=RHONA(TAIA)
00830 *
00840 * HEAT TRANSFER COEFFICIENTS IN THE SUPERHEATER
00850 *
00860 PES=0.18802368*(WI/ENS)
00870 ENS=1222.0787+1.925844*(WI/ENS)**0.8
00880 HWA=144.51325*ENS/(0.0048751818+19.2/HNS)
00890 *
00900 RES=536.289*(WSA/ENS)
00910 HSS=4.2454582*(WSA/ENS)**0.8
00920 HSSA=144.51325*ENS/(0.01901711+29.484029/HSS)
00930 *
00940 *
00950 * I-1. SUPERHEATED STEAM
00960 *
00970 DTSC=(0.0066838/(CPS*RHOASA*ENS))*(HSSA*(TAWA-TASA)
00980 S -WSA*(HSC-HSA))
00990 *
01000 *
01010 * I-2. WALL
01020 *
01030 DTAWA=(8.2682436E- 5/ENS)*(HWA*(TAIA-TAWA)-HSSA*(TAWA-TASA))
01040 *
01050 * I-3. INTERMEDIATE SODIUM
01060 *
01070 DTIC=(2.93739E- 3/(ROTAIA*ENS))*(0.3014*WI*(TIA-TIC)
01080 S -HWA*(TAIA-TAWA))
01090 *
01100 *
01110 TSC=DTSC
01120 TAWA=DTAWA
01130 TIC=DTIC
01140 *
01150 *
01160 * II. EVAPORATOR
01170 *
01180 *
01190 RHOTS6=RHOW(TS1)
01200 TAUHS1=(1.76744*ELS61+1.576246*ELS62+1.22718*ELS63

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01210      5      +0.441786*ENEVAP*ELS64/ENL) *(ENL*RHOTS6/WS1S)
01220      *
01230      PROCED HS1,HS6I=HS6
01240      IF (T.EQ.0.0) HS6I=HS6
01250      HS1=PDELAY(HS6,TAUHS1,8,HS6I)
01260      ENDPRO
01270      *
01280      DHS1=3600.0*(HS6-HS1)/TAUHS1
01290      *
01300      HS2=HF(PAS2)
01310      HAS1=(HS1+HS2)/2.0
01320      TS1=TS1P(HS1)
01330      TSAT=TSATP(PAS2)
01340      TAS1=(TS1+TSAT)/2.0
01350      HFS2=HS2
01360      HGS2=HG(PAS2)
01370      VFS2=VF(PAS2)
01380      RHOF2=1./VFS2
01390      VGS2=VG(PAS2)
01400      RHOGS2=1./VGS2
01410      *
01420      *
01430      WS1S=ENE*WS1D
01440      WS3S=ENE*WS3D
01450      WS2AD=(WS1D+WS3D)/2.0
01460      *
01470      WS1=3600.0*WS1S
01480      WS3=3600.0*WS3S
01490      *
01500      *      HEAT TRANSFER COEFFICIENTS IN THE EVAPORATOR
01510      *
01520      RES1=172.99645*(WS1/ENE)
01530      RES2=187.70115*(WS1/ENE)
01540      HWE=12.817068*(WS1/ENE)**0.8
01550      HDS1=3.1415926*ENE/(0.02478+29.484029/HWE)
01560      HDS2=126.77825*ENE
01570      *
01580      DEE=0.18186595*(WI/ENE)
01590      HNE=1281.3193+1.9661152*(WI/ENE)**0.8
01600      HDW1=3.1415926*ENE/(0.0048751818+19.2/HNE)
01610      HDW2=HDW1
01620      *
01630      AS1=0.00090347512*ENE
01640      *
01650      ELS2=46.0-ELS1
01660      *
01670      SAI=RHOGS2/RHOF2
01680      *
01690      *
01700      XS3=HDS2*ELS2*(TAW2-TSAT)/(WS3*(HGS2-HS2))
01710      ALF3=XS3/(SAI+(1.-SAI)*XS3)
01720      ALFSI=ALF3*(1.-SAI)
01730      ALFA2=ALF3*(0.5+ALFSI/6.0+ALFSI*ALFSI/12.)
01740      *
01750      RHOAS1=RHOF(TAS1)
01760      RHOAS2=ALFA2*RHOGS2+(1.-ALFA2)*RHOF2
01770      RHOHS2=ALFA2*RHOGS2+HGS2+(1.-ALFA2)*RHOF2*HFS2
01780      *
01790      HS3=HGS2*XS3+HFS2*(1.-XS3)
01800      RHOS3=ALF3*RHOGS2+(1.-ALF3)*RHOF2

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01810 *
01820 DRFP2=- (1./VFS2**2.0) *DVF(PAS2)
01830 DRGP2=- (1./VGS2**2.0) *DVG(PAS2)
01840 DHFP2=DHF(PAS2)
01850 DHGP2=DHG(PAS2)
01860 DRHFP2=RHOPS2*DHFP2+HFS2*DRFP2
01870 DRHGP2=RHOGS2*DHGP2+HGS2*DRGP2
01880 *
01890 A=ELS2*(ALFA2*(DRHGP2-DRGP2*HFS2) + (1.-ALFA2) *(DRHFP2-DRFP2*HFS2))
01900 B=ELS1*RHOGS2*DHFP2*(HGS2-HFS2)/(2.0*A*(HS2-HS1))
01910 C=1.0+2.*B*(RHOAS1-RHOPS2)/(RHOPS2-RHOGS2)
01920 *
01930 *      II-1.  WATER / STEAM
01940 *
01950 DLS1= (2./C) * (-HDS1*ELS1*(TAW1-TAS1)/(AS1*RHOAS1*(HS2-HS1))
01960 $      +WS1/(AS1*RHOAS1) + (ELS1/2.0) *DHS6/(HS2-HS1)
01970 $      +B*(WS1-WS3)/(AS1*(RHOPS2-RHOGS2)))
01980 ELS1.=DLS1/3600.0
01990 *
02000 WS2=WS1-AS1*RHOAS1*DLS1
02010 *
02020 DPAS2=(RHOGS2*(HGS2-HFS2)/(A*(RHOPS2-RHOGS2))) * (- (RHOAS1-RHOPS2)
02030 $      *DLS1+ (WS1-WS3)/AS1)
02040 PAS2.=DPAS2/3600.0
02050 *
02060 *      II-2.  WALL
02070 *
02080 WMHCD=0.073034229*ENE
02090 TW2=(TAW1*ELS1+TAW2*ELS2)/46.0
02100 *
02110 DTAW1=(1./WMHCD) * (- (HDW1+HDS1*WMHCD*DLS1/ELS1) *TAW1
02120 $      +HDS1*TAS1+HDW1*TAI8) +TW2*DLS1/ELS1
02130 TAW1.=DTAW1/3600.0
02140 *
02150 DTAW2=(1./WMHCD) * (- (HDW2+HDS2*WMHCD*DLS1/ELS2) *TAW2
02160 $      +HDS2*TSAT+HDW2*TAI7) -TW2*DLS1/ELS2
02170 TAW2.=DTAW2/3600.0
02180 *
02190 *      II-3.  INTERMEDIATE SODIUM
02200 *
02210 RHOTIC=RHONA(TIC)
02220 TAUT17=703800.0*RHOTIC*ZNEVAP/WI
02230 TI7=PDELAY(TIC,TAUT17,14,TICI)
02240 *
02250 TAI7=(TI7+TI8)/2.0
02260 TAI8=(TI8+TI9)/2.0
02270 *
02280 TIE=(TI7+TI9)/2
02290 RHOIE=RHONA(TIE)
02300 SMHCD=0.0020848433*RHOIE*ENE
02310 WI8=WI+0.00682079*ENE*RHOIE*DLS1
02320 *
02330 DTI7=3600.0*(TIC-TI7)/TAUT17
02340 DTI8=(1./(SMHCD*ELS2)) * (- (HDW2*ELS2-SMHCD*DLS1) *TAI7
02350 $      +HDW2*ELS2*TAW2+0.30566168*(WI*TI7-WI8*TI8))
02360 TI8.=DTI8/3600.0
02370 *
02380 DTI9=(1./(SMHCD*ELS1)) * (- (HDW1*ELS1+SMHCD*DLS1) *TAI8
02390 $      +HDW1*ELS1*TAW1+0.30566168*(WI8*TI8-WI*TI9))
02400 TI9.=DTI9/3600.0

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02410 *
02420 *
02430 *      WATER / STEAM LOOP MOMENTUM EQUATIONS
02440 *
02450 *
02460 *      R=RD(PAS2,XS3)
02470 *
02480 *      TAUWS3=ELS31/(21.25048*ENEVAP)+ELS32/(68.844553*ENL)
02490 *      TAUWS1=ELS61/(56.9*ENL)+ELS62/(50.755*ENL)
02500 *      $ +ELS63/(39.515*ENL)+ELS64/(14.22555*ENEVAP)
02510 *
02520 *      A11T=ELS1/(32.2*AS1)+ELS2/(64.4*AS1)+TAUWS1
02530 *      A12T=ELS2/(64.4*AS1)+0.30020714/AS1+TAUWS3
02540 *      A21T=ELS2/(128.8*AS1)
02550 *      A22T=ELS2/(128.8*AS1)+0.15010357/AS1+TAUWS3
02560 *
02570 *      DETERM=A11T*A22T-A12T*A21T
02580 *
02590 *      FRICTION COEFFICINTS
02600 *
02610 *      PROCED FS1=RES1
02620 *      IF (RES1.LT.1000.0) FS1=8.0/RES1
02630 *      IF (RES1.GE.1000.0.AND.RES1.LT.100000.0) FS1=0.05256/(RES1**0.243)
02640 *      IF (RES1.GE.100000.0) FS1=0.02117/(RES1**0.164)
02650 *      ENDPRO
02660 *      FS1A=102467.41*FS1
02670 *
02680 *      PROCED FS2=RES2
02690 *      IF (RES2.LT.1000.0) FS2=8.0/RES2
02700 *      IF (RES2.GE.1000.0.AND.RES2.LT.100000.0) FS2=0.05256/(RES2**0.243)
02710 *      IF (RES2.GE.100000.0) FS2=0.02117/(RES2**0.164)
02720 *      ENDPRO
02730 *      FS2A=111974.13*FS2
02740 *
02750 *      DPRC1=DPRCSF-FRC*(WS1S/ENL)**2
02760 *
02770 *      HDSPH=ELS1*RHOAS1+ELS2*RHOAS2+10.208333*RHOS3-52.708333*RHOTS6
02780 *      $ -(YS5+(DOD-6.0)/2.0)*RHOTS6
02790 *      CHMPH=(1./(32.2*AS1*AS1))*(WS3S**2/RHOS3-WS1S**2/RHOF52)
02800 *      FRPH=(FS1A*ELS1+3554.6572*(ENE/ENL)**2.0*FS6)*(WS1D**2.0)
02810 *      $ +(FS2A*R*ELS2)*(WS2AD**2)+(35304.868+9.66667*FS2A*R)*(WS3D**2)
02820 *
02830 *      HSPH34=ELS2*RHOAS2/2.0+7.6666665*RHOS3
02840 *      FRPH34=FS2A*R*ELS2*(WS2AD**2)/2.0+(4.833335*FS2A*R
02850 *      $ +28309.0)*(WS3D**2)
02860 *
02870 *      PROCED DPRC=DPRC1,DPRC1,ENNC5W,TPMPCD
02880 *      DPRC=DPRC1
02890 *      IF (ENNC5W.NE.0.0.AND.T.LT.TPMPCD) DPRC=DPRC1
02900 *      IF (ENNC5W.NE.0.0.AND.T.GE.TPMPCD) DPRC=DPRCP(T-TPMPCD)
02910 *      ENDPRO
02920 *
02930 *      B1T=-(HDSPH+CHMPH-144.0*DPRC+FRPH)
02940 *      B2T=144.0*(PAS2-PAS4)-HSPH34-CHMPH/2.0-FRPH34
02950 *
02960 *      DWS1D=(A22T*B1T-A12T*B2T)/(ENE*DETERM)
02970 *      DWS3D=(A11T*B2T-A21T*B1T)/(ENE*DETERM)
02980 *
02990 *      WS1D.=DWS1D
03000 *      WS3D.=DWS3D

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```

03010 *
03020 *
03030 *      III.  STEAM  DRUM
03040 *
03050 *
03060 *      YS5=3.0*(1.0+SIN(1.5708*(EMS5/EMS5I-1.0)))
03070 *
03080 *      PROCED  TS5=HS5I
03090 *      IF (T.EQ.0.0)  TS5=TS1F(HS5I)
03100 *      IF (T.GT.0.0)  TS5=TS1F(HS5)
03110 *      ENDPRO
03120 *
03130 *      RHOTS5=RHOW(TS5)
03140 *
03150 *      PROCED  PHFW1=PHFW1I,TPMPCD
03160 *      IF (T.LT.TPMPCD)  PHFW1=PHFW1I
03170 *      IF (T.GE.TPMPCD)  PHFW1=PHDMFW(T-TPMPCD)
03180 *      ENDPRO
03190 *
03200 *      PROCED  SV51D=ENV5,SV51,TSCRAM,ENTRBN
03210 *      IF (T.EQ.0.0)  SV51I=SV51
03220 *      IF (T.LT.TSCRAM)  SV51D=SV51I
03230 *      IF (T.GE.TSCRAM.OR.ENV5.NE.0.0.OR.ENTRBN.NE.0.0)  SV51D=0.0
03240 *      ENDPRO
03250 *
03260 *      SV51.=(SV51D-SV51)/0.5
03270 *
03280 *      WS51SQ=(ENL*CV51*SV51)**2*(PHFW1-PAS4-0.08680555*RHOTS5)
03290 *      S  /((1.0+PS51*(CV51*SV51)**2)
03300 *
03310 *      PROCED  WS5S1=WS51SQ
03320 *      IF (WS51SQ.GT.0.0)  WS5S1=SQRT(WS51SQ)
03330 *      IF (WS51SQ.LE.0.0)  WS5S1=0.0
03340 *      ENDPRO
03350 *
03360 *
03370 *      WS5S3=WS7S3
03380 *      WS5S=WS5S1+WS5S2+WS5S3
03390 *
03400 *      WS51=3600.0*WS5S1
03410 *      WS52=3600.0*WS5S2
03420 *      WS53=3600.0*WS5S3
03430 *
03440 *      WS5=3600.0*WS5S
03450 *
03460 *      WS7S=WSAS+WDMPS2+WAPTS+WS7S3
03470 *      WS7=3600.0*WS7S
03480 *
03490 *      HS51=HS5I
03500 *      HS53=HF(PAS4)
03510 *
03520 *      HS5=(HS51*WS51+HS52*WS52+HS53*WS53)/WS5
03530 *
03540 *      WS4=WS3
03550 *
03560 *      TAUHS4=(0.66*ENEVAP*ELS31/ENL+2.1380*ELS32)*(ENL*RHOS3/WS3S)
03570 *
03580 *      PROCED  HS4,HS3I=HS3
03590 *      IF (T.EQ.0.0)  HS3I=HS3
03600 *      HS4=PDELAY(HS3,TAUHS4,9,HS3I)

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03610      ENDPRO
03620      *
03630      *
03640      WS6=WS1
03650      *
03660      HGS4I=HG(PAS4I)
03670      HGS4=HG(PAS4)
03680      *
03690      VGS4=VG(PAS4)
03700      RHOGS4=1./VGS4
03710      VFS4=VF(PAS4)
03720      RHOPS4=1./VFS4
03730      *
03740      EMS4=RHOGS4*(DV-EMS5/RHOPS4)
03750      *
03760      EMS4D=DELAY(EMS4,0.2,5,EMS4I)
03770      DEMS4=13000.0*(EMS4-EMS4D)
03780      *
03790      WRC=3600.0*WRCS
03800      *
03810      DEMS5=(WS4+WS5-WS6-WRC-WS7)/ENL-DEMS4
03820      EMS5.=DEMS5/3600.0
03830      *
03840      D=EMS4*DVG(PAS4)+EMS5*DVF(PAS4)
03850      DPAS4=(-1./D)*(VGS4*DEMS4+VFS4*DEMS5)
03860      PAS4.=DPAS4/3600.0
03870      *
03880      DHS6=(1./(ENL*EMS5))*(WS4*HS4+WS5*HS5-(WS6+WRC)*HS6-WS7*HGS4
03890      S    -ENL*(HGS4*DEMS4+HS6*DEMS5+EMS4*DHG(PAS4)*DPAS4))
03900      HS6.=DHS6/3600.0
03910      *
03920      *
03930      *      IV.  INTERMEDIATE  HEAT  EXCHANGER
03940      *
03950      *
03960      WP=3600.0*WPS
03970      *
03980      PROCD  TP4I=TP4
03990      IF(T.EQ.0.0)  TP4I=TP4
04000      ENDPRO
04010      *
04020      RHOTP4=RHONA(TP4)
04030      TAUTP5=4071600.0*RHOTP4*ENL/WP
04040      *
04050      TP5=PDELAY(TP4,TAUTP5,2,TP4I)
04060      *
04070      TAP5=(TP5+TP7)/2.0
04080      TAI1=(TI1+TI3)/2.0
04090      *
04100      *      HEAT  TRANSFER  COEFFICIENTS  IN  THE  IHX
04110      *
04120      HNIP=1906.8776+2.2875323*(WP/ENI)**0.9
04130      HNII=2476.4331+3.1930386*(WI/ENI)**0.8
04140      HI=227149.4/(0.007650483+15.286624/HNII+13.714285/HNIP)
04150      *
04160      ROTAP5=RHONA(TAP5)
04170      *
04180      TP7.=(2.0488692E-6/ROTAP5)*(-HI*(TAP5-TAI1)
04190      S    +0.3032*WP*(TP5-TP7)/ENL)
04200      *

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04210      RHOTI1=RHONA(TI9)
04220      TAUTI1=4968000.0*RHOTI1*ENL/WI
04230      TI1=PDELAY(TI9,TAUTI1,4,TI9I)
04240      *
04250      *
04260      ROTAI1=RHONA(TAI1)
04270      TI3.=(3.7545E-6/ROTAI1)*(HI*(TAP5-TAI1)
04280      $      +0.30445*WI*(TI1-TI3)/ENL)
04290      *
04300      *
04310      *      V. REACTOR
04320      *
04330      *      V-1. POINT KINETIC EQUATIONS
04340      *      WITH FEEDBACK
04350      *
04360      *
04370      BETA=3.65E- 3
04380      BD=(0.8254*D1+7.756*D2+6.66*D3+13.54*D4
04390      $      +5.908*D5+1.81*D6)*1.0E- 4
04400      BDOB=BD/BETA
04410      RHOFBC=(100.0*DC/BETA)*ALOG((460.0+TAF)/(460.0+TAFI))
04420      $      +AXECC*TAF+SODDCC*TAP1+RECC*TP1+ROFBCI
04430      RHOFBD=RHOFBC/100.0
04440      *
04450      PROCED RHOD=ENROC,DLTROC,RHOCDI,T,SROC
04460      IF(ENROC.EQ.0.) RHOD=RHOCDI
04470      IF(ENROC.EQ.1.AND.T.EQ.0.) RHOD=RHOCDI
04480      IF(ENROC.EQ.1.AND.T.NE.0.) RHOD=RHOCDI+DLTROC/100.0
04490      IF(ENROC.EQ.2.0.AND.T.LE.SROC) RHOD=RHOCDI+DLTROC*T/100.0
04500      IF(T.LE.TSCRAM) RHOD1=RHOD
04510      IF(ENROC.EQ.2.0.AND.T.GT.TSCRAM.AND.T.LE.(TSCRAM+SROC))
04520      $      RHOD=RHOD1+DLTROC*(T-TSCRAM)/100.0
04530      ENDPRO
04540      *
04550      RHOD=RHOD+RHOFBD
04560      *
04570      EN=BDOB/(1.0 - RHOD)
04580      *
04590      D1.=0.0129*(EN-D1)
04600      D2.=0.0312*(EN-D2)
04610      D3.=0.1330*(EN-D3)
04620      D4.=0.3450*(EN-D4)
04630      D5.=1.4100*(EN-D5)
04640      D6.=3.7500*(EN-D6)
04650      *
04660      *
04670      *      V-2. REACTOR THERMODYNAMIC EQUATIONS
04680      *
04690      TFC=(5./9.)*(TAF-32.0)
04700      TFK=TFC+273.0
04710      AKFW=36.100867/(TFK+129.2)+5.782936E-13*TFK**3.0
04720      AKF=57.78*AKFW
04730      WPD=FPC*WP/ENP
04740      HC=14861.86+51.921027*WPD**0.8
04750      HR=9.4247778*ENP/(0.125/AKF+60.00024/HDG+52.173914/HC
04760      $      +0.0052151492)
04770      *
04780      *
04790      *
04800      PROCED DCYHT=TSCRAM

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04810      IF (T.LT.TSCRAM) DCYHT=0.0075834*DCAYHT(0.0)
04820      IF (T.GZ.TSCRAM) DCYHT=0.0075834*DCAYHT(T-TSCRAM)
04830      ENDPRO
04840      *
04850      *
04860      PROCED ENINI=EN
04870      IF (T.EQ.0.0) ENINI=EN
04880      ENDPRO
04890      *
04900      DCHT=DCYHT*ENINI
04910      *
04920      PROCED ENT=EN,DCHT
04930      ENT=EN+DCHT
04940      ENDPRO
04950      *
04960      *
04970      TAP.=2.520883E- 7*(EPS*FPGC*ENT-HR*(TAP-TAP1))
04980      *
04990      RHOTR1=RHONA(TP7)
05000      RHOTP1=RHONA(TP1)
05010      TAUTR1=1796400.0*RHOTR1*ENL/WP
05020      *
05030      TR1=PDELAY(TP7,TAUTR1,1,TP7I)
05040      *
05050      DTP1=(WP/(VP1*RHOTP1*3600.0))*(TR1-TP1)
05060      TP1.=DTP1
05070      *
05080      TAP1=(TP1+TP3)/2.0
05090      ROTAP1=RHONA(TAP1)
05100      *
05110      *
05120      P3=15.0+EMP4MI/(144.*AP4)
05130      PSPP=15.0+YSPP*RHOTP4/144.0
05140      PSNPP=15.0+(YSPP-8.333)*RHOTP4/144.0
05150      *
05160      TSATP3=TSATNA(P3)
05170      *
05180      PROCED =P3,TPMM,TSATP3
05190      IF (TPMM.LT.TSATP3) GO TO 80
05200      PRINT 70,T,P3,TSATP3,TPMM
05210      70 FORMAT(1H-/*0 BOILING OCCURS AT CORE EXIT*/
05220      $ 10X,* T=*,E15.5,10X,* P3=*,E15.5,10X,* TSATP3=*,E15.5,
05230      $ 10X,* TPMM=*,E15.5)
05240      STOP
05250      80 CONTINUE
05260      ENDPRO
05270      *
05280      RHOTP3=RHONA(TP3)
05290      *
05300      TP3.=(3.4093E-5/ROTAP1)*(HR*(TAP-TAP1)+0.3032*FPC*WP*(TP1-TP3))
05310      *
05320      $P
05330      *
05340      *
05350      *
05360      TR3.=(3.71815E-7/(RHOTP1+RHOTR3))*(EPS*EN-0.3032*WP*(TR3-TP1))
05370      RHOTR3=RHONA(TR3)
05380      ROP4M1=RHONA(TP4M1)
05390      ROP4M2=RHONA(TP4M2)
05400      *

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THE REACTOR OUTLET PLENUM MODEL

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05410      YK=15.17468*(FFC*WPS/ENSUB)**2/(RHOTP3*ROP4M2)
05420      *
05430      PROCED YKE=YK,YP4I
05440      IF(YK.GE.YP4I) YKE=YP4I
05450      IF(YK.LT.YP4I) YKE=YK
05460      ENDPRO
05470      *
05480      EMP4M2=YKE*AP4*ROP4M2
05490      *
05500      YKED=DELAY(YKE,0.1,6,YKEI)
05510      DMP4M2=10.0*(YKE-YKED)*AP4*ROP4M2
05520      *
05530      EMP4M1=YP4I*AP4*ROP4M1
05540      *
05550      PROCED YKEI,EMP4MI,DRP4M2=YKE,YP4I,AP4,ROP4M2
05560      IF(T.EQ.0.0) GO TO 400
05570      DRP4M2=(RHONA(TP4M2+5.0)-RHONA(TP4M2-5.0))*DTP4M2/10.0
05580      GO TO 410
05590      400 YKEI=YKE
05600      EMP4MI=YP4I*AP4*ROP4M2
05610      DRP4M2=0.0
05620      410 CONTINUE
05630      ENDPRO
05640      *
05650      PROCED TP4,TP42,YP42,DMP4M1,DTP4M1,DTP4M2,WP4M2,TAUP42,TP42I,TAUP4
05660      5      =YP4I,YONTSS,YKE,AP4,EMP4M2,ROP4M1,ROP4M2,DRP4M2
05670      *
05680      YPETON=YP4I-YONTSS
05690      IF(T.EQ.0.0) TP42I=TP4M2
05700      IF(T.EQ.0.0) TP42=PDELAY(TP4M2,0.0,6,TP42I)
05710      IF(T.EQ.0.0) TP4=PDELAY(TP4M2,0.0,15,TP42I)
05720      ROP42=RHONA(TP42)
05730      *
05740      IF(YKE.LE.YPETON) GO TO 500
05750      IF(YKE.EQ.YP4I.OR.ROP42.LE.ROP4M1) GO TO 210
05760      IF(ROP42.GT.ROP4M1) GO TO 200
05770      500 IF(ROP42.LE.ROP4M1) GO TO 310
05780      IF(DRP4M2.LE.0.0) GO TO 510
05790      IF(YP41.GT.YONTSS) GO TO 300
05800      IF(YP41.LE.YONTSS) GO TO 305
05810      510 IF(YP41.GT.YONTSS) GO TO 320
05820      IF(YP41.LE.YONTSS) GO TO 330
05830      *
05840      *
05850      200 IF(DRP4M2.LE.0.0) GO TO 328
05860      DMP4M1=0.0
05870      WP4M2=-DMP4M2
05880      TP4=TP4M2
05890      GO TO 307
05900      300 DMP4M1=-WPS
05910      TP4=TP4M1
05920      GO TO 306
05930      305 DMP4M1=0.0
05940      TAUP4=0.0
05950      IF(WP4M2.GT.0.0) TAUP4=AP4*(YPETON-YKE)
05960      5      *(ROP4M1+ROP4M2)/(2.*WP4M2)
05970      TP4=PDELAY(TP4M2,TAUP4,15,TP4)
05980      306 WP4M2=WPS-DMP4M2
05990      307 DTP4M1=0.0
06000      *

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06010      YP42=YP4I-YP41-YKE
06020      TAUP42=0.0
06030      IF (WP4M2.GT.0.0.AND.YP42.GT.0.1)  TAUP42=YP42*AP4*(ROP4M1+
06040      $      ROP4M2)/(2.0*WP4M2)
06050      TP42=PDELAY(TP4M2,TAUP42,6,TP42I)
06060      *
06070      DTP4M2=WPS*(TR3-TP4M2)/EMP4M2
06080      *
06090      GO TO 600
06100      *
06110      *
06120      210 WP4M2=-DMP4M2
06130      TP4=TP4M2
06140      IF (YKE.EQ.YP4I) GO TO 312
06150      GO TO 311
06160      310 WP4M2=WPS-DMP4M2
06170      TP4=TP4M1
06180      311 EMP4MU=EMP4MI-EMP4M2
06190      DTP4M1=WP4M2*(TP4M2-TP4M1)/EMP4MU
06200      312 DMP4M1=-DMP4M2
06210      *
06220      YP42=0.0
06230      TAUP42=0.0
06240      TP42=TP4M2
06250      TP42I=TP42
06260      *
06270      DTP4M2=WPS*(TR3-TP4M2)/EMP4M2
06280      *
06290      GO TO 600
06300      *
06310      *
06320      320 DMP4M1=-WPS
06330      WP4M2=WPS-DMP4M2
06340      TP4=TP4M1
06350      GO TO 331
06360      330 WP4M2=WPS-DMP4M2
06370      GO TO 329
06380      328 WP4M2=-DMP4M2
06390      329 DMP4M1=0.0
06400      TP4=TP4M2
06410      331 DTP4M1=0.0
06420      *
06430      YP42=0.0
06440      TAUP42=0.0
06450      TP42=TP4M2
06460      TP42I=TP42
06470      *
06480      EMP4MI=EMP4MI-EMP4M1
06490      DTP4M2=WPS*(TR3-TP4M2)/EMP4MI
06500      *
06510      GO TO 600
06520      *
06530      600 CONTINUE
06540      *
06550      ENDPRO
06560      *
06570      *
06580      PROCED TP4M1=TP41,TP4M2,YKE,YP4I
06590      TP4M1=TP41
06600      IF (YKE.EQ.YP4I) TP4M1=TP4M2

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06610      ENDPRO
06620      *
06630      YP41.=DMP4M1/(AP4*ROP4M1)
06640      TP41.=DTP4M1
06650      *
06660      TP4M2.=DTP4M2
06670      *
06680      *
06690      SP
06700      RHOTP5=RHOTP4
06710      *
06720      *      PRIMARY AND INTERMEDIATE LOOPS MOMENTUM EQUATIONS
06730      *
06740      WPP=WPD/ENL
06750      QPP=1.24657E-4*WPP/RHOTP4
06760      *
06770      QPPD=0.4487625*WPSD/(ENL*RHOTP4)
06780      HOPP=HPM(ENPP,QPP)
06790      *
06800      *
06810      HOPP1=HPM(ENPP,QPP)
06820      HOPP2=HPM(ENPP,QPP)
06830      PROCED HOPP=ENPP,HOPP1,HOPP2
06840      IF(ENPP.GT.110.0) HOPP=HOPP1
06850      IF(ENPP.LE.110.0) HOPP=HOPP2
06860      ENDPRO
06870      *
06880      QPONP=QPP/ENPP
06890      ETAPP=0.019275+69.86*QPONP-1970.0*QPONP**2+16531.46*QPONP**3
06900      *
06910      QPONPD=QPPD/ENPPD
06920      ETAPPD=0.019275+69.86*QPONPD-1970.0*QPONPD**2+16531.46*QPONPD**3
06930      *
06940      *      PRIMARY PUMP SPEED CONTROL
06950      *
06960      PROCED ENENPP=ENPP
06970      IF(T.EQ.0.0) ENENPP=0.0
06980      IF(ENPP.LE.107.0) ENENPP=1.0
06990      ENDPRO
07000      *
07010      DWPSMD=(1./TWPS)*(WPS-WPSM)
07020      *
07030      PROCED DWPSM=DWPSMD,ENENPP
07040      IF(ENENPP.NE.1.0) DWPSM=0.0
07050      IF(ENENPP.EQ.1.0) DWPSM=DWPSMD
07060      ENDPRO
07070      *
07080      WPSM.=DWPSM
07090      *
07100      EWPS=WPSD-WPSM
07110      EWPSI.=EWPS
07120      ENPPDD=ENPPD+AEWPS*(EWPS+EWPSI/TWPS)
07130      *
07140      *
07150      PROCED ENPPM=ENPPD,ENPP,ENENPP
07160      IF(ENENPP.NE.1.0) ENPPM=ENPPD
07170      IF(ENENPP.EQ.1.0) ENPPM=ENPP
07180      ENDPRO
07190      *
07200      EENPP=ENPPDD-ENPPM

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07210 *
07220      ENPPI.=EENPP
07230      EENPPC=EENPP+ENPPI/TEENPP
07240 *
07250      ETRQP.= (1./TTRQP) * (ATEQP+EENPPC-ETRQP)
07260 *
07270      TRQPD=307.476*WPSD*HOPPD/(ENL*ENPPD*ETAPPD)
07280      TRQPD=TRQPD+ETRQP
07290 *
07300      PROCED TOPPM=TRQPD
07310      IF (TRQPD.LE.0.0) TOPPM=0.0
07320      IF (TRQPD.GT.0.0) TOPPM=TRQPD
07330      ENDPRO
07340 *
07350 *
07360      PROCED TRQPPM=TOPPM,POWER
07370      IF (POWER.LE.45.0) TRQPPM=0.0
07380      IF (POWER.GT.45.0) TRQPPM=TOPPM
07390      ENDPRO
07400 *
07410 *
07420      PROCED CDTRQP=TPMPCD,TRQPM
07430      IF (T.LE.TPMPCD) CDTRQP=TRQPM
07440      IF (T.GT.TPMPCD.AND.T.LE.(TPMPCD+50.)) GO TO 20
07450      IF (T.GT.(TPMPCD+50.)) CDTRQP=0.0
07460      GO TO 21
07470      20 CDTRQP=TRQPM*EXP(-2.0*(T-TPMPCD))
07480      21 CONTINUE
07490      ENDPRO
07500 *
07510      PROCED TRQPP=CDTRQP,TRQPM,EENPP,ENNCP
07520      IF (EENPP.NE.1.0.OR.ENNCP.NE.0.0) TRQPP=CDTRQP
07530      IF (EENPP.EQ.1.0.AND.ENNCP.EQ.0.0) TRQPP=TRQPM
07540      ENDPRO
07550 *
07560      DENPP=(9.5493/APP) * (TRQPP-0.08541*WP*HOPP/(ENPP*ETAPP*ENL))
07570      ENPP.=DENPP
07580 *
07590      TAWP=3.5491816/ENL+1421.9498*PFC/ENP
07600 *
07610      DWPS=(1./TAWP) * (15.8392*RHOTR1-11.0*RHOTR1-3.0*ROTAP1
07620      $ -5.68333*RHOTR3+(HOPP-21.403855)*RHOTR4+25.37*ROTAP5
07630      $ - (6.5714464E-4/ENL**2+P143*(PFC/ENSUB)**2.+9.7776E-6)
07640      $ *WPS**2.)
07650 *
07660      WPS.=DWPS
07670 *
07680      WPFRT=W9/41.446E6
07690 *
07700      WIP=W1/ENL
07710      QIP=1.24657E-4*WIP/RHOT11
07720 *
07730      QIPD=0.4487625*WISD/(ENL*RHOT11)
07740      HOIPD=HPM (ENIPD,QIPD)
07750 *
07760      HOIP1=HNM (ENIP,QIP)
07770      HOIP2=HPM (ENIP,QIP)
07780 *
07790      PROCED HOIP=ENIP,HOIP1,HOIP2
07800      IF (ENIP.GT.110.0) HOIP=HOIP1

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07810      IF(ENIP.LE.110.0)  HOIP=HOIP2
07820      ENDPRO
07830      *
07840      QIONI=QIP/ENIP
07850      ETAIP=0.006337+72.0258*QIONI-2049.0*QIONI**2.0
07860      $    +17671.51*QIONI**3.0
07870      *
07880      QIONID=QIPD/ENIPD
07890      ETAIPD=0.006337+72.0258*QIONID-2049.0*QIONID**2.0
07900      $    +17671.51*QIONID**3.0
07910      *
07920      *      INTERMEDIATE PUMP SPEED CONTROL
07930      *
07940      *
07950      PROCED  ENENIP=ENIP
07960      IF(T.EQ.0.0)  ENENIP=0.0
07970      IF(ENIP.LE.92.0)  ENENIP=1.0
07980      ENDPRO
07990      *
08000      DWISMD=(1./TWIS)*(WIS-WISM)
08010      *
08020      PROCED  DWISM=DWISMD,ENENIP
08030      IF(ENENIP.NE.1.0)  DWISM=0.0
08040      IF(ENENIP.EQ.1.0)  DWISM=DWISMD
08050      ENDPRO
08060      *
08070      WISM.=DWISM
08080      *
08090      EWIS=WISD-WISM
08100      EWISI.=EWIS
08110      ENIPDD=ENIPD+AEWIS*(EWIS+EWISI/TEWIS)
08120      *
08130      *
08140      PROCED  ENIPM=ENIPD,ENIP,ENENIP
08150      IF(ENENIP.NE.1.0)  ENIPM=ENIPD
08160      IF(ENENIP.EQ.1.0)  ENIPM=ENIP
08170      ENDPRO
08180      *
08190      EENIP=ENIPDD-ENIPM
08200      *
08210      ENIPI.=EENIP
08220      EENIPC=EENIP+ENIPI/TEENIP
08230      *
08240      ETRQI.= (1./TTRQI)*(ATRQI*EENIPC-ETRQI)
08250      *
08260      TRQID=307.476*WISD*HOIPD/(ENL*ETAIPD*ENIPD)
08270      TRQIDD=TRQID+ETRQI
08280      *
08290      PROCED  TQIPM=TRQIDD
08300      IF(TRQIDD.LE.0.0)  TQIPM=0.0
08310      IF(TRQIDD.GT.0.0)  TQIPM=TRQIDD
08320      ENDPRO
08330      *
08340      PROCED  TRQIPM=TQIPM,POWER
08350      IF(POWER.LE.45.0)  TRQIPM=0.0
08360      IF(POWER.GT.45.0)  TRQIPM=TQIPM
08370      ENDPRO
08380      *
08390      *
08400      *

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08410      PROCED CDTRQI=TPMPCD,TRQIMM
08420      IF(T.LE.TPMPCD) CDTRQI=TRQIMM
08430      IF(T.GT.TPMPCD.AND.T.LE.(TPMPCD+50.)) GO TO 25
08440      IF(T.GT.(TPMPCD+50.)) CDTRQI=0.0
08450      30 TO 26
08460      25 CDTRQI=TRQIMM*EXP(-2.0*(T-TPMPCD))
08470      26 CONTINUE
08480      ENDPRO
08490      *
08500      PROCED TRQIP=CDTRQI,TRQIPM,ENENIP,ENNCI
08510      IF(ENENIP.NE.1.0.OR.ENNCI.NE.0.0) TRQIP=CDTRQI
08520      IF(ENENIP.EQ.1.0.AND.ENNCI.EQ.0.0) TRQIP=TRQIPM
08530      ENDPRO
08540      *
08550      DENIP=(9.5493/ATIP)*(TRQIP-0.08541*WI*HOIP/(ENIP*ETAIP*ENL))
08560      ENIP.=DENIP
08570      *
08580      TAUWI=2.4431/ENEVAP+14.356/ENL
08590      DWIST=(HOIP+7.815098)*RHOTI1-25.36979*ROTAI1
08600      $ -17.86197*RHOTI3+35.416666*(ROTAI+RHOIE-RHOTIC)
08610      $ -(1.1521861E- 3/ENEVAP**2.+1.148583E- 3/ENL**2.)*(WIS**2.)
08620      *
08630      DWIS=DWIST/TAUWI
08640      WIS.=DWIS
08650      *
08660      WIFRT=WI/38.3426
08670      *
08680      *
08690      *      MAX. AVERAGE AND HOT CHANNEL TEMPERATURES
08700      *      AND THEIR LOCATIONS RELATIVE TO CORE CENTRAL PLANE
08710      *
08720      HRM=      1. / (0.25 /AKF+60.00024/HDG+52.173914/HC +0.0052151492)
08730      HRS=1./(60.00024/HDG+52.173914/HC+0.0052151492)
08740      *
08750      *
08760      *      THE THEORETICAL LOCATIONS OF THE MAX. TEMPS. AT THE PIN-CLAD
08770      *      OUTER SURFACE,PIN SURFACE,AND FUEL PIN CENTER LINE IN THE AVG. CHANNEL
08780      *
08790      YCMXTH=1.5078339*ATAN(0.29944753*HC/WPD)
08800      YSMXTH=1.5078339*ATAN(15.62335*HRS/WPD)
08810      YPMXTH=1.5078339*ATAN(15.62335*HRM/WPD)
08820      *
08830      *
08840      *THE ACTUAL LOCATION OF THE PIN-CLAD OUTER SURFACE MAX. TEMP. IN THE AVG.CHANNEL
08850      *
08860      PROCED YCMAX=YCMXTH
08870      IF(YCMXTH.LT.1.5) YCMAX=YCMXTH
08880      IF(YCMXTH.GE.1.5) YCMAX=1.5
08890      ENDPRO
08900      *
08910      *THE ACTUAL LOCATION OF THE FUEL PIN MAX. SURFACE TEMP. IN THE AVG CHANNEL
08920      *
08930      PROCED YSMAX=YSMXTH
08940      IF(YSMXTH.LT.1.5) YSMAX=YSMXTH
08950      IF(YSMXTH.GE.1.5) YSMAX=1.5
08960      ENDPRO
08970      *
08980      *THE ACTUAL LOCATION OF THE FUEL PIN MAX. CENTER LINE TEMP. IN THE AVG. CHANNEL
08990      *
09000      PROCED YPMAX=YPMXTH

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09010      IF(YPMXTH.LT.1.5)  YFMAX=YPMXTH
09020      IF(YPMXTH.GE.1.5)  YFMAX=1.5
09030      ENDPRO
09040      *
09050      *      THE THEORITICAL LOCATIONS OF THE MAX. TEMPS. AT THE PIN-CLAD
09060      *      OUTER SURFACE,PIN SURFACE,AND FUEL PIN CENTER LINE IN THE HOT CHANNEL
09070      *
09080      YCMTH=1.5078339*ATAN(0.17787267*HC/WPD)
09090      YSMTH=1.5078339*ATAN(0.001401791/(WPD*(0.0078808679/HC
09100      $      +4.4692799E- 7+0.0063842402/HDG)))
09110      YPMTH=1.5078339*ATAN(0.001401791/(WPD*(0.0078808679/HC
09120      $      +4.4692799E- 7+0.0063842402/HDG+1.9770937E- 5/AKF)))
09130      *
09140      *THE ACTUAL LOCATION OF THE PIN-CLAD OUTER SURFACE MAX. TEMP. IN THE HOT CHANNEL
09150      *
09160      PROCED YCMM=YCMTH
09170      IF(YCMM.LT.1.5)  YCMM=YCMMTH
09180      IF(YCMM.GE.1.5)  YCMM=1.5
09190      ENDPRO
09200      *
09210      *THE ACTUAL LOCATION OF THE FUEL PIN MAX. SURFACE TEMP. IN THE HOT CHANNEL
09220      *
09230      PROCED YSMM=YSMTH
09240      IF(YSMM.LT.1.5)  YSMM=YSMMTH
09250      IF(YSMM.GE.1.5)  YSMM=1.5
09260      ENDPRO
09270      *
09280      *THE ACTUAL LOCATION OF THE FUEL PIN MAX. CENTER LINE TEMP. IN THE HOT CHANNEL
09290      *
09300      PROCED YFMM=YFMTTH
09310      IF(YFMM.LT.1.5)  YFMM=YFMTTH
09320      IF(YFMM.GE.1.5)  YFMM=1.5
09330      ENDPRO
09340      *
09350      *
09360      *
09370      *VOLUMETRIC HEAT GENERATION AT THE CENTER OF THE FUEL PIN IN THE AVG. CHANNEL
09380      *
09390      QC=0.045077766*EPS*PPGC*EN
09400      *
09410      *COOLANT MAX. TEMP. AT THE EXIT OF THE AVG. CHANNEL
09420      *
09430      TPMAX=TP1+7.6761921E- 5*EPS*PPGC*EN/WPD
09440      *
09450      *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
09460      *OF THE MAX. TEMP. AT THE PIN-CLAD OUTER SURFACE IN THE AVG. CHANNEL
09470      *
09480      DTP1CX=(4.5780019E- 5*EPS*PPGC*EN/WPD)
09490      $      *(0.838378+SIN(0.66320299*YCMAX))
09500      *
09510      *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
09520      *OF THE MAX. TEMP. AT THE PIN-CLAD OUTER SURFACE IN THE HOT CHANNEL
09530      *
09540      DTP1CM=(5.06327E- 5*EPS*PPGC*EN/WPD)
09550      $      *(0.838378+SIN(0.66320299*YCMM))
09560      *
09570      *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
09580      *PIN-CLAD OUTER SURFACE IN THE AVG. CHANNEL
09590      *
09600      TPYCMX=TP1+DTP1CX

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09610 *
09620 *THE DIFFERENCE BETWEEN THE PIN-CLAD OUTER SURFACE TEMP. AND THE
09630 *SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE CLAD
09640 *OUTER SURFACE IN THE AVG. CHANNEL
09650 *
09660 DTPCMX=0.0033915082*QC*COS(0.66320299*YCMAX)/HC
09670 *
09680 *THE DIFFERENCE BETWEEN THE PIN-CLAD OUTER SURFACE TEMP. AND THE
09690 *SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE CLAD
09700 *OUTER SURFACE IN THE HOT CHANNEL
09710 *
09720 DTPCH=0.0033915082*QC*COS(0.66320299*YCHM)/HC
09730 *
09740 *MAX. PIN-CLAD OUTER SURFACE TEMP. IN THE AVG. CHANNEL
09750 *
09760 TCMAX=TPYCMX+DTPCMX
09770 *
09780 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
09790 *OF THE MAX. TEMP. AT THE FUEL PIN SURFACE IN THE AVG. CHANNEL
09800 *
09810 DTP1SX=(4.5780019E- 5*EPS*PPGC*EN/WPD)
09820 $ *(0.938378+SIN(0.66320299*YSMAX))
09830 *
09840 *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
09850 *FUEL PIN SURFACE IN THE HOT CHANNEL
09860 *
09870 DTP1SH=(5.06327E- 5*EPS*PPGC*EN/WPD)
09880 $ *(0.938378+SIN(0.66320299*YSMH))
09890 *
09900 *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
09910 *FUEL PIN SURFACE IN THE AVG. CHANNEL
09920 *
09930 TPYSMX=TP1+DTP1SX
09940 *
09950 * MAX. FUEL PIN SURFACE TEMP. IN THE AVG. CHANNEL
09960 *
09970 TSMAX=TPYSMX+6.5003905E- 5*QC*COS(0.66320299*YSMAX)/HRS
09980 *
09990 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
10000 *OF THE MAX. TEMP. AT THE FUEL PIN CENTER LINE IN THE AVG. CHANNEL
10010 *
10020 DTP1FX=(4.5780019E- 5*EPS*PPGC*EN/WPD)
10030 $ *(0.938378+SIN(0.66320299*YFMAX))
10040 *
10050 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
10060 *OF THE MAX. TEMP. AT THE FUEL PIN CENTER LINE IN THE HOT CHANNEL
10070 *
10080 DTP1FH=(5.06327E- 5*EPS*PPGC*EN/WPD)
10090 $ *(0.938378+SIN(0.66320299*YFHM))
10100 *
10110 *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
10120 *FUEL PIN AT ITS CENTER LINE IN THE AVG. CHANNEL
10130 *
10140 *
10150 TPYFMX=TP1+DTP1FX
10160 *MAX. FUEL PIN TEMP. AT ITS CENTER LINE IN THE AVG. CHANNEL
10170 *
10180 TFMAX=TPYFMX+6.5003905E- 5*QC*COS(0.66320299*YFMAX)/HRS
10190 *
10200 *COOLANT MAX. TEMP. IN THE HOT CHANNEL

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10210 *
10220 *      TFMN=1.248*(TP1+8.4898684E-5*EPS*FPGC*EN/WPD)
10230 *
10240 *PIN-CLAD MAX. OUTER SURFACE TEMP. IN THE HOT CHANNEL
10250 *
10260 *      TCMN=1.248*(TP1+DTP1CM)+2.323706*DTPCM
10270 *
10280 *FUEL PIN MAX. SURFACE TEMP. IN THE HOT CHANNEL
10290 *
10300 *      TSMN=1.248*(TP1+DTP1SM) +(0.0078808679/HC+4.4692799E- 7
10310 *      +0.0063842402/HDG)*QC*COS(0.66320299*YSMN)
10320 *
10330 *FUEL PIN MAX. CENTER LINE TEMP. IN THE HOT CHANNEL
10340 *
10350 *      TFMN=1.248*(TP1+DTP1FM) +(0.0078808679/HC+4.4692799E- 7
10360 *      +0.0063842402/HDG+1.9770937E- 5/AKF)*QC*COS(0.66320299*YFMN)
10370 *
10380 *
10390 *
10400 *      INITIATION OF THE AUXILIARY HEAT REMOVAL SYSTEM
10410 *
10420 *
10430 *      EFLOW=(WS5S-WSAS)/WS5SI
10440 *
10450 *      PROCD ENSTHR,ENLTHR=EFLOW,FLOWMS,YS5,YS5MN,POWER,TSAT
10460 *      ,TPMPCD
10470 *      IF((YS5.LT.YS5MN.OR.EFLOW.LT.FLOWMS.OR.POWER.LE.120.0)
10480 *      .AND.T.GE.TPMPCD) ENSTHR=1.0
10490 *      IF((YS5.LT.YS5MN.OR.EFLOW.LT.FLOWMS.OR.POWER.LE.45.0)
10500 *      .AND.T.GE.TPMPCD) ENLTHR=1.0
10510 *      IF(POWER.LE.45.0) ENSTHR=0.0
10520 *      IF(TSAT.LE.400.0) ENLTHR=0.0
10530 *      ENDPRO
10540 *
10550 *
10560 *      SHORT-TERM HEAT REMOVAL
10570 *
10580 *
10590 *      THE APW DERIVE-TURBINE PRESSURE CONTROL
10600 *
10610 *      PAPT=PATNM*PAPTD
10620 *      PROCD SVATAC,DPATNM,EPAPT,PAPT=ENSTHR,ENVAPT,TSACRAN
10630 *      ,AVAPT,WAPTS,PATNM,PAPTD,SVAPTD,AEVAPT,TEVAPT,TPAPT
10640 *      IF(ENSTHR.EQ.0.0.OR.ENVAPT.NE.0.0.OR.T.LE.TSACRAN) GO TO 110
10650 *      PAPT=AVAPT*WAPTS
10660 *      PAPT=PAPT/PAPTD
10670 *      IF(PAPT.NE.PATNM) GO TO 100
10680 *      EPAPT=1.0-PATNM
10690 *      ESVAPT=AEVAPT*(EPAPT+EPATI/TEVAPT)
10700 *      DPATNM=(PAPT-PATNM)/TPAPT
10710 *      100 SVATAC=SVAPTD+ESVAPT
10720 *      GO TO 120
10730 *      110 SVATAC=0.0
10740 *      ESVAPT=0.0
10750 *      DPATNM=0.0
10760 *      120 CONTINUE
10770 *      ENDPRO
10780 *
10790 *      PROCD SVAPT=SVATC
10800 *      IF(SVATC.LE.0.0) SVAPT=0.0

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10810      IF (SVATC.GT.0.0.AND.SVATC.LE.1.0)  SVAPT=SVATC
10820      IF (SVATC.GT.1.0)  SVAPT=1.0
10830      ENDPRO
10840      *
10850      SVATC.=(SVATAC-SVATC)/0.5
10860      *
10870      PATNM.=DPATNM
10880      EPATI.=EPAPT
10890      *
10900      WAPTSQ=(CVAPT*SVAPT)**2*(PAS4-PAPT+C.6574*RHOGS4)
10910      S  /(1.+PDAPT*(CVAPT*SVAPT/ENL)**2)
10920      *
10930      PROCED  WAPTS=T
10940      WAPTS=0.0
10950      IF (WAPTSQ.GT.0.0)  WAPTS=SQRT (WAPTSQ)
10960      ENDPRO
10970      *
10980      *
10990      *      STEAM DRUM WATER LEVEL AND APW TEMP. CONTROL
11000      *
11010      YSSM.=(1./TYS5)*(YS5-YSSM)
11020      EYSS=YSSD-YSSM
11030      EYSSI.=EYSS
11040      *
11050      TSSM.=(1./TTS5)*(TS5-TSSM)
11060      ETS5=TSSD-TSSM
11070      ETS5I.=ETS5
11080      *
11090      ETS52=ETS5+ETS5I/TETS5
11100      *
11110      ESV52=AEYSS*(EYSS+EYSSI/TEYSS)+AETS2*ETS52
11120      *
11130      *
11140      PROCED  SV52AC=SV52D,ESV52
11150      IF (ENSTHR.EQ.0.0)  SV52AC=0.0
11160      IF (ENSTHR.EQ.1.0)  SV52AC=SV52D+ESV52
11170      ENDPRO
11180      *
11190      DSV52C=(SV52AC-SV52C)/2.0
11200      SV52C.=DSV52C
11210      *
11220      PROCED  SV52=SV52C
11230      IF (SV52C.LE.0.0)  SV52=0.0
11240      IF (SV52C.GT.0.0.AND.SV52C.LE.1.0)  SV52=SV52C
11250      IF (SV52C.GT.1.0)  SV52=1.0
11260      ENDPRO
11270      *
11280      ESVRC=AETRC*ETS52
11290      *
11300      *
11310      PROCED  SVRCAC=SVRCD,ESVRC
11320      IF (ENSTHR.EQ.0.0)  SVRCAC=0.0
11330      IF (ENSTHR.EQ.1.0)  SVRCAC=SVRCD+ESVRC
11340      ENDPRO
11350      *
11360      DSVRC=(SVRCAC-SVRCC)/2.0
11370      SVRC.=DSVRC
11380      *
11390      PROCED  SVRC=SVRC
11400      IF (SVRC.LE.0.0)  SVRC=0.0

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11410      IF (SVRCC.GT.0.0.AND.SVRCC.LE.1.0)  SVRC=SVRCC
11420      IF (SVRCC.GT.1.0)  SVRC=1.0
11430      ENDPRO
11440      *
11450      *
11460      *
11470      PROCED  HS62,HS62I,TAUH62=WRCS,HS6,ELDRC
11480      IF (T.EQ.0.0)  HS62I=HS6
11490      IF (WRCS.LT.0.01)  TAUH62=0.0
11500      IF (WRCS.GE.0.01)  TAUH62=0.2672537*ELDRC*ENL*RHOTS6/WRCS
11510      HS62=PDZLAY (HS6,TAUH62,10,HS62I)
11520      ENDPRO
11530      *
11540      *
11550      HRC=(1./((ENL*EMRC)))*((HS62-168.0)*WRCS-(HRC-168.0)*WS5S2)
11560      *
11570      *
11580      HD5H1=0.142361*(RHOTS5-RHOTS6)
11590      HD5H2=(YS5-1.5)*RHOTS6/144.+0.142361*RHOTS5+25.528
11600      *
11610      WRCSQ=(ENL*CVRC*SVRC)**2*(HOJTP*RHOTS5/144.-HD5H1-PRCD*
11620      5      (WS5S2/ENL)**2)/(1.+PDRC*(CVRC*SVRC)**2)
11630      *
11640      *      PROCED  WRCS=SVRC
11650      *      IF (WRCSQ.GT.0.0)  WRCS=SQRT (WRCSQ)
11660      *      IF (WRCSQ.LE.0.0)  WRCS=0.0
11670      *      ENDPRO
11680      WRCS=ENL*CVRC*SVRC
11690      PROCED  T2=ENSTHR,POWER
11700      IF (POWER.GE.45.0)  ENST=1.0
11710      DN=ENSTHR-ENST
11720      IF (DN.EQ.-1.0.AND.POWER.LE.45.0)  GO TO 960
11730      30 TO 980
11740      960 T2=T
11750      ENST=ENSTHR
11760      PRINT 970 , T2
11770      970 FORMAT (1H-/'0 AUX. SYSTEM SHUT-OFF TIME */20X,* T2= *,P7.3)
11780      980 CONTINUE
11790      ENDPRO
11800      *
11810      PROCED  PHFW2=PHFW2I,PHFW1I,T2,POWER
11820      PHFW2=PHFW2I
11830      IF (POWER.LE.45.0)  PHFW2=(PHFW2I/PHFW1I)*PHDNFW(T-T2)
11840      ENDPRO
11850      *
11860      *
11870      WAPSSQ=(ENL*CV52*SV52)**2*(PHFW2-PAS4+HOJTP*RHOTS5/144.
11880      5      -HD5H2-PRCD*(WS5S2/ENL)**2)/(1.+PHDRC*(CV52*SV52)**2)
11890      *
11900      PROCED  WS5S2=SV52
11910      IF (WAPSSQ.GT.0.0)  WS5S2=SQRT (WAPSSQ)*WRCS
11920      IF (WAPSSQ.LE.0.0)  WS5S2=WRCS
11930      ENDPRO
11940      *
11950      PROCED  HS52,HRCI,TAUH52=HRC,WS5S2,ELRCD,RHOTS5
11960      IF (T.EQ.0.0)  HRCI=HRC
11970      IF (WS5S2.LT.0.01)  TAUH52=0.0
11980      IF (WS5S2.GE.0.01)  TAUH52=0.13635375*ELRCD*ENL*RHOTS5/WS5S2
11990      HS52=PDZLAY (HRC,TAUH52,11,HRCI)
12000      ENDPRO

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12010 *
12020 *
12030 *
12040 *      LONG-TERM HEAT REMOVAL
12050 *
12060 *
12070 *
12080 *
12090      PROCED SVPCAC=SVPCD
12100      IF (ENLTHR.EQ.0.0) SVPCAC=0.0
12110      IF (ENLTHR.EQ.1.0) SVPCAC=SVPCD
12120      ENDPRO
12130 *
12140      SVPC.=(SVPCAC-SVPC)/700.0
12150 *
12160      HDSDCD=0.32291666*(RHOP54-RHOGS4)
12170 *
12180      WS73SQ=HDSDCD*(ENL*CVPC*SVPC)**2/(1.+PDPCD*(CVPC*SVPC)**2)
12190 *
12200      PROCED WS7S3=WS73SQ
12210      IF (WS73SQ.GT.0.0) WS7S3=SQRT (WS73SQ)
12220      IF (WS73SQ.LE.0.0) WS7S3=0.0
12230      ENDPRO
12240 *
12250 *
12260      STORE , TSA,WSC,RHOASA,CPS,PSA,PSC,TSA,WDMP51,WDMP52,
12270 *      TSC,HSA,HSC,TIC,TASA,TAWA,TAIA,ELS1,ELS2,WS1,WS3,XS3,ALP3,HS3,
12280 *      TAW1,TAW2,TAI7,TAI8,TAI7,TI9,TI9,PAS2,ALPA2,HS1,TS1,TSAT,
12290 *      EMS4,EMS5,YS5,PAS4,HS6,RHOD,EN,ENT,TR3,
12300 *      TAP,TAP1,TAP5,TAI1,TI1,TI3,TP4M1,TP42,TP4M2,
12310 *      TAUTR1,TR1,TP7,TP1,TAUTP5,TP3,TP4,TP5,WP,WI,TPMAX,TPMH,YCMAX,
12320 *      YCNH,TCHMAX,TCMH,YSMAX,YSMH,TSMH,YPHAX,TPMAX,YPMH,TPMH,
12330 *      BIT,R2T,DWPS,DWIS,TAUWP,TAUWI,WS5,TS5,QPP,HOPP,QIP,HOIP,
12340 *      ENPP,ENIP,WPPRT,WIPRT,ETAPP,ETAIP,DCHT,WAPTS,YP41,YP42,YKE,
12350 *      WRCS,WS5S2,WS7S3,ENSTHR,ENLTHR,DMP4M2,WP4M2
12360 *      ,HS62,HRC,HS4,SVBC,SV52,SVPC,TAUTIA,TAUTII,TAUP42,TAUP4,TAUHS4
12370 *      ,TAUTI7,TAUHS1,TAUHS4,TAUH52,TAUH62,TSCRAN,TPMPCD,HS52,TIA
12380 *      ,DTP4M1,DTP4M2,DMP4M1
12390 *
12400 *P
12410 *
12420      PROCED ENROC,DLTROC,SROC,TSCRAN,TPMPCD,ENROCD,EN2,EN2D=T
12430      IF (T.EQ.0.0) GO TO 800
12440      IF (ENT.LT.1.15) GO TO 310
12450      EN2=2.0
12460      DEN2=EN2-EN2D
12470      IF (DEN2.GT.1.0) T1=T
12480      IF (T.LT.(T1+0.2)) GO TO 880
12490      ENROC=2.0
12500      DNRO=ENROC-ENROCD
12510      IF (DNRO.GT.1.0) GO TO 850
12520      GO TO 870
12530      850 TSCRAN=T
12540      TPMPCD=TSCRAN*0.5
12550      PRINT 860 , TSCRAN,TPMPCD
12560      860 FORMAT (1X,/*0 TIME AT WHICH REACTOR SCRAM IS INITIATED FOLLOWED
12570 *      BY TIME AT WHICH PUMPS' COAST-DOWN IS INITIATED */
12580 *      10X,* TSCRAN=*,P7.3,10X,* TPMPCD=*,P7.3)
12590      870 DLTROC=-509.72115
12600      SROC=2.0

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12610      ENROCD=ENROC
12620      880 EN2D=EN2
12630      30 TO 810
12640      800 ENROC=1.0
12650      DLTROC=25.0
12660      TSCRAM=9999.0
12670      TPNPCD=9999.0
12680      EN2D=0.0
12690      ENROCD=0.0
12700      810 CONTINUE
12710      ENDPRO
12720      *
12730      5P
12740      *
12750      $T1
12760      RHONA , 6
12770      *      NEXT IS THE INDEPENDENT VARIABLE FOLLOWED BY THE DEPENDENT
12780      392.0      ,56.4
12790      572.0      ,55.1
12800      752.0      ,53.6
12810      932.0      ,52.1
12820      1112.0     ,50.5
12830      1292.0     ,48.9
12840      $T2
12850      TSATNA,11
12860      1.176      ,1214.6
12870      2.205      ,1304.6
12880      4.557      ,1412.0
12890      11.76      ,1574.6
12900      21.756     ,1700.6
12910      37.926     ,1826.6
12920      50.568     ,1898.6
12930      66.15      ,2024.6
12940      102.312    ,2096.6
12950      121.569    ,2150.6
12960      226.968    ,2366.6
12970      $T3
12980      TS1P , 12
12990      374.97      ,400.0
13000      396.77      ,420.0
13010      418.9       ,440.0
13020      430.1       ,450.0
13030      441.4       ,460.0
13040      464.4       ,480.0
13050      487.8       ,500.0
13060      511.9       ,520.0
13070      536.6       ,540.0
13080      562.2       ,560.0
13090      588.9       ,580.0
13100      610.0       ,600.0
13110      $T4
13120      RHOW , 12
13130      400.0       ,53.648
13140      420.0       ,52.798
13150      440.0       ,51.921
13160      450.0       ,51.546
13170      460.0       ,51.02
13180      480.0       ,50.0
13190      500.0       ,49.02
13200      520.0       ,47.847

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13210		540.0		,46.512				
13220		560.0		,45.249				
13230		580.0		,43.860				
13240		600.0		,43.373				
13250	ST5							
13260		VF , 6						
13270		1200.0		,0.0223				
13280		1300.0		,0.0227				
13290		1400.0		,0.0231				
13300		1500.0		,0.0235				
13310		2000.0		,0.0257				
13320		2500.0		,0.0287				
13330	ST6							
13340		HF , 6						
13350		1200.0		,571.7				
13360		1300.0		,585.4				
13370		1400.0		,598.7				
13380		1500.0		,611.6				
13390		2000.0		,671.7				
13400		2500.0		,730.6				
13410	ST7							
13420		TSATF , 6						
13430		1200.0		,567.22				
13440		1300.0		,577.46				
13450		1400.0		,587.1				
13460		1500.0		,596.23				
13470		2000.0		,635.82				
13480		2500.0		,668.13				
13490	ST8							
13500		VG , 6						
13510		1200.0		,0.3619				
13520		1300.0		,0.3293				
13530		1400.0		,0.3012				
13540		1500.0		,0.2765				
13550		2000.0		,0.1878				
13560		2500.0		,0.1307				
13570	ST9							
13580		HG , 6						
13590		1200.0		,1183.4				
13600		1300.0		,1178.6				
13610		1400.0		,1173.4				
13620		1500.0		,1167.9				
13630		2000.0		,1135.1				
13640		2500.0		,1091.1				
13650	ST10							
13660		RD , 3 , 5						
13670	*							
13680	*	* THE FOLLOWING IS A DEFINITION OF THE SECOND						
13690	*	* INDEPENDENT VARIABLE.						
13700	*							
13710			0.2	,0.4	,0.6	,0.8	,1.0	
13720	*							
13730	*	* NEXT COMES THE FIRST INDEPENDENT VARIABLE						
13740	*	* FOLLOWED BY THE DEPENDENT VARIABLE						
13750	*							
13760		1000.0	,4.81801	,7.43707	,10.6082	,12.915	,14.4123	
13770		2000.0	,2.48938	,3.21363	,4.30274	,4.97874	,5.35559	
13780		2500.0	,1.72844	,2.23131	,2.6778	,2.98751	,2.98751	
13790	ST11							
13800		VSH , 6,5						

13810		700.0	,800.0	,900.0	,1000.0	,1200.0
13820	1200.0	,0.4909	,0.5617	,0.6250	,0.6843	,0.7967
13830	1400.0	,0.4062	,0.4714	,0.5281	,0.5805	,0.6789
13840	1600.0	,0.3417	,0.4034	,0.4553	,0.5027	,0.5906
13850	1800.0	,0.2907	,0.3502	,0.3986	,0.4421	,0.5218
13860	2000.0	,0.2489	,0.3074	,0.3532	,0.3935	,0.4668
13870	2500.0	,0.1686	,0.2294	,0.2710	,0.3061	,0.3678
13880	ST12					
13890	RSR ,6,5					
13900		700.0	,800.0	,900.0	,1000.0	,1200.0
13910	1200.0	,1311.0	,1379.3	,1440.7	,1499.2	,1613.1
13920	1400.0	,1295.5	,1369.1	,1433.1	,1493.2	,1608.9
13930	1600.0	,1278.7	,1358.4	,1425.3	,1487.0	,1604.6
13940	1800.0	,1260.3	,1347.2	,1417.4	,1480.8	,1600.4
13950	2000.0	,1240.0	,1335.5	,1409.2	,1474.5	,1596.1
13960	2500.0	,1176.8	,1303.6	,1387.8	,1458.4	,1585.3
13970	ST13					
13980	HMM,13,12					
13990		0.0	,4.0	,8.0	,12.0	,16.0
14000	\$	,20.0	,24.0	,28.0	,32.0	,40.0
14010	\$	,44.0				
14020		,110.0	,4.77	,3.43	,0.0	,0.0
14030	\$	,0.0	,0.0	,0.0	,0.0	,0.0
14040	\$	,0.0				
14050		,150.0	,8.86	,7.616	,2.95	,0.0
14060	\$	,0.0	,0.0	,0.0	,0.0	,0.0
14070	\$	,0.0				
14080		,250.0	,24.5	,23.0	,19.55	,11.7
14090	\$	,0.0	,0.0	,0.0	,0.0	,0.0
14100	\$	,0.0				
14110		,350.0	,47.8	,46.25	,42.65	,36.65
14120	\$	,13.425	,1.1	,0.0	,0.0	,0.0
14130	\$	,0.0				
14140		,500.0	,98.8	,97.8	,94.9	,89.2
14150	\$	,65.7	,50.0	,32.0	,22.0	,10.0
14160	\$	,2.0				
14170		,980.0	,380.0	,378.0	,376.0	,370.0
14180	\$	,353.0	,340.0	,322.0	,302.0	,277.0
14190	\$	,210.0				
14200		,1006.0	,409.0	,398.5	,396.0	,391.0
14210	\$	,374.0	,361.0	,342.647	,308.92	,300.0
14220	\$	,230.0				
14230		,1030.0	,419.0	,418.0	,415.0	,410.0
14240	\$	,393.0	,380.0	,364.0	,343.0	,319.0
14250	\$	,253.0				
14260		,1150.0	,514.0	,512.0	,510.0	,504.0
14270	\$	,486.0	,470.0	,454.0	,440.0	,420.0
14280	\$	,355.0				
14290		,1170.0	,532.0	,531.0	,528.0	,522.0
14300	\$	,504.0	,489.0	,472.0	,463.6156	,431.5789
14310	\$	,375.0				
14320		,1200.0	,560.0	,558.0	,555.0	,549.0
14330	\$	,531.0	,516.0	,500.0	,485.0	,466.0
14340	\$	,404.0				
14350		,1400.0	,775.0	,773.0	,770.0	,765.0
14360	\$	,749.0	,738.0	,723.0	,705.0	,684.0
14370	\$	,634.0				
14380		,1500.0	,874.0	,872.0	,870.0	,865.0
14390	\$	,846.0	,833.0	,817.0	,797.0	,776.0
14400	\$	,736.0				

14410	ST14						
14420	HBM,9,9						
14430		0.0	,0.5	,1.0	,1.5	,2.0	
14440	F	,2.5	,3.0	,3.5	,4.0		
14450		10.0	,0.03939	,0.0156	,0.0	,0.0	,0.0
14460	S	,0.0	,0.0	,0.0	,0.0		
14470		50.0	,0.98	,0.95	,0.9	,0.81	,0.65
14480	F	,0.406	,0.08	,0.0	,0.0		
14490		70.0	,1.93	,1.88	,1.82	,1.75	,1.63
14500	S	,1.43	,1.2	,0.8	,0.5		
14510		80.0	,2.52	,2.47	,2.4	,2.31	,2.2
14520	S	,2.03	,1.77	,1.4	,1.0		
14530		90.0	,3.19	,3.14	,3.06	,2.97	,2.87
14540	S	,2.71	,2.48	,2.17	,1.8		
14550		100.0	,3.94	,3.88	,3.8	,3.71	,3.6
14560	S	,3.44	,3.26	,2.98	,2.61		
14570		105.0	,4.34	,4.274	,4.195	,4.095	,3.977
14580	S	,3.844	,3.65	,3.376	,3.033		
14590		107.0	,4.51	,4.44	,4.36	,4.26	,4.14
14600	S	,4.01	,3.92	,3.56	,3.16		
14610		110.0	,4.77	,4.694	,4.61	,4.51	,4.4
14620	S	,4.27	,4.08	,3.83	,3.43		
14630	ST15						
14640	DCAYHT , 17						
14650		0.0	,16.524				
14660		1.0	,14.976				
14670		2.0	,13.956				
14680		5.0	,12.456				
14690		10.0	,11.22				
14700		20.0	,9.984				
14710		50.0	,8.376				
14720		100.0	,7.212				
14730		200.0	,6.18				
14740		500.0	,5.004				
14750		1.023	,4.188				
14760		5.023	,2.676				
14770		1.024	,2.148				
14780		5.024	,1.272				
14790		1.025	,1.0056				
14800		1.026	,0.504				
14810		1.027	,0.1428				
14820	ST16						
14830	PHDNFW,17						
14840		0.0	,2000.0				
14850		1.0	,1925.79				
14860		2.0	,1874.90				
14870		3.0	,1840.60				
14880		4.0	,1818.68				
14890		5.0	,1807.31				
14900		7.0	,1793.92				
14910		10.0	,1784.74				
14920		15.0	,1778.18				
14930		20.0	,1775.13				
14940		25.0	,1773.69				
14950		40.0	,1771.85				
14960		50.0	,1771.38				
14970		60.0	,1771.12				
14980		70.0	,1770.96				
14990		100.0	,1770.78				
15000		200.0	,1770.64				

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15010 *
15020 ST 17
15030 DPRCP, 17
15040 0.0 ,148.0
15050 1.0 ,117.933
15060 2.0 ,99.5545
15070 3.0 ,87.2468
15080 4.0 ,79.5988
15090 5.0 ,75.8402
15100 7.0 ,71.0851
15110 10.0 ,67.9549
15120 12.0 ,66.7490
15130 15.0 ,65.6562
15140 20.0 ,64.5757
15150 25.0 ,64.0857
15160 40.0 ,63.4367
15170 50.0 ,63.2729
15180 60.0 ,63.1792
15190 100.0 ,63.0600
15200 200.0 ,63.0137
15210 *
15220 SP
15230 FUNCTION DHF(PAS)
15240 PAS21=PAS-50.0
15250 PAS22=PAS+50.0
15260 HF1=HF(PAS21)
15270 HF2=HF(PAS22)
15280 DHF=(HF2-HF1)/100.0
15290 RETURN
15300 END
15310 FUNCTION DVF(PAS)
15320 PAS21=PAS-50.0
15330 PAS22=PAS+50.0
15340 VF1=VF(PAS21)
15350 VF2=VF(PAS22)
15360 DVF=(VF2-VF1)/100.0
15370 RETURN
15380 END
15390 FUNCTION DVG(PAS)
15400 PAS21=PAS-50.0
15410 PAS22=PAS+50.0
15420 VG1=VG(PAS21)
15430 VG2=VG(PAS22)
15440 DVG=(VG2-VG1)/100.0
15450 RETURN
15460 END
15470 FUNCTION DHG(PAS)
15480 PAS21=PAS-50.0
15490 PAS22=PAS+50.0
15500 HG1=HG(PAS21)
15510 HG2=HG(PAS22)
15520 DHG=(HG2-HG1)/100.0
15530 RETURN
15540 END
15550 *
15560 SP
15570 FUNCTION PDELAY(XC,TAU,I,XCI)
15580 C
15590 C PIPE DELAY FUNCTION FOR THE DABE P RUNTIME SYSTEM
15600 C

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15610 C XC = VARIABLE TO BE DELAYED
15620 C
15630 C TAU = AMOUNT OF DELAY BEFORE PRESENT VALUE OF XC IS VALID.
15640 C (VARIABLE, ANY VALUE .GE. ZERO)
15650 C
15660 C I = INTEGER CONSTANT BETWEEN 1 AND IMAX IDENTIFYING
15670 C INDEPENDENT PDELAY OPERATORS
15680 C
15690 C XCI = INITIAL VALUE OF XC (VALUE RETURNED UNTIL T .GT. TAU(0) )
15700 C
15710 C PDELAY MODELS AN INCOMPRESSIBLE FLUID FLOWING THROUGH A UNIT
15720 C LENGTH PIPE AT A VELOCITY OF 1./TAU
15730 C
15740 LOGICAL WRAP
15750 LOGICAL EXIT,RLDONE
15760 COMMON /SYSVAR/ EXIT,RLDONE,IOUT,IFILE,IRUNNO,T,TMAX,TNEXT
15770 COMMON /SYSVAR/ DT,DTMAX,DTMIN,EMAX,EMIN,SY(35)
15780 COMMON DELAY(8101)
15790 COMMON TNS(20),NP(20),WRAP(20),TSAV(100,20),XSAV(100,20),TAUL(20)
15800 1,XCL(20)
15810 DATA NPA/100/,IMAX/20/
15820 C
15830 PDELAY=XC1
15840 DUMMY=XC
15850 IF(EXIT) RETURN
15860 IF(I.GT.0.AND.I.LE.IMAX) GO TO 4
15870 WRITE(IOUT,3) I
15880 3 FORMAT(16H FATAL ERROR - INVALID PDELAY NUMBER,I3)
15890 CALL ABORT
15900 4 IF(TAU.GE.0.) GO TO 7
15910 WRITE(IOUT,6) I,IRUNNO,T
15920 6 FORMAT(15H ERROR - PDELAY,I3,9H NEGATIVE/
15930 2 7H - RUN,I4,19H TERMINATED AT T =,1PE12.5)
15940 EXIT=.TRUE.
15950 RETURN
15960 C
15970 C IF T.EQ.0, INITIALIZE
15980 C
15990 7 IF(T.GT.0.) GO TO 8
16000 NP(I)=1
16010 TNS(I)=AMAX1(DT,TAU*2./FLOAT(NPA))
16020 WRAP(I)=.FALSE.
16030 TSAV(1,I)=TAU
16040 XSAV(1,I)=XC
16050 TSAV(NPA,I)=0.
16060 TAUL(I)=TAU
16070 XCL(I)=XC
16080 GO TO 12
16090 C
16100 C IF T.GE.TNS, SAVE X AND T, CALCULATE TNS
16110 C
16120 8 IF(T.LT.TNS(I).OR..NOT.RLDONE) GO TO 12
16130 C
16140 C IF TAU DIFFERS FROM LAST CALL, ADJUST TSAV ARRAY TO MATCH NEW
16150 C PIPE VELOCITY
16160 C
16170 IF(TAU.EQ.TAUL(I)) GO TO 10
16180 N=NP(I)
16190 9 IF(T.GE.TSAV(N,I)) GO TO 10
16200 TSAV(N,I)=(TSAV(N,I)-T)*TAU/TAUL(I)+T

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16210      N=MOD (N-2+NPA,NPA)+1
16220      GO TO 9
16230      10 IF (TAUL(I)-TAU.LT.0.0) GO TO 43
16240      DUMMY=(DT*KC + TAU*XCL(I.)/(TAU + DT)
16250      C
16260      C CHECK FOR BUFFER OVERFLOW (YES, IT CAN OCCUR)
16270      C BUFFER OVERFLOW IS STORING NEW DATA INTO A CELL BEFORE
16280      C FINISHED WITH OLD DATA
16290      C
16300      43 N=NP(I)
16310      TAUL(I)=TAU
16320      XCL(I)=DUMMY
16330      N2=MOD (N+1,NPA)+1
16340      IF (.NOT.WRAP(I).AND.N2.GT.2) GO TO 11
16350      IF (T.GE.TSAV(N2,I)) GO TO 11
16360      TNS(I)=TSAV(N2,I)
16370      WRITE (IOBT,105) I,T,TNS(I)
16380      105 FORMAT(17H WARNING - PDELAY,I3,22H BUFFER OVERFLOW AT T=,
16390      2      1PE12.5,6H, TNS=,E12.5)
16400      GO TO 12
16410      11 IF (N.EQ.NPA) WRAP(I)=.TRUE.
16420      N=MOD (N,NPA)+1
16430      NP(I)=N
16440      TSAV(N,I)=T+TAU
16450      XSAV(N,I)=DUMMY
16460      TNS(I)=T+AMAX1(DT,TAU*2./FLOAT(NPA))
16470      C
16480      C IF T .LT. FIRST-T-STORED, RETURN XCI
16490      C
16500      12 IF (.NOT.WRAP(I).AND.T.LT.TSAV(1,I)) RETURN
16510      C
16520      C CHECK FOR T .GT. LAST-T-STORED (WILL BE IF TAU.LT.DT)
16530      C
16540      NBIG=NP(I)
16550      IF (T.LE.TSAV(NBIG,I)) GO TO 13
16560      NSM=NBIG
16570      NBIG=MOD (NBIG,NPA)+1
16580      IF (NBIG.EQ.1) WRAP(I)=.TRUE.
16590      TSAV(NBIG,I)=T+TAU
16600      XSAV(NBIG,I)=DUMMY
16610      GO TO 33
16620      C
16630      C CHECK WHICH HALF OF CIRCULAR BUFFER T IS IN
16640      C
16650      13 NSM=1
16660      IF (.NOT.WRAP(I).OR.T.GE.TSAV(1,I)) GO TO 15
16670      NSM=NBIG+1
16680      NBIG=NPA
16690      C
16700      C CHECK FOR T IN THE CRACK BETWEEN TSAV(NPA) AND TSAV(1)
16710      C
16720      IF (T.LE.TSAV(NPA,I)) GO TO 15
16730      NSM=NPA
16740      NBIG=1
16750      GO TO 33
16760      C
16770      C PERFORM BINARY SEARCH TO LOCATE INDEX OF T
16780      C
16790      15 IF (NBIG.LT.NSM) GO TO 33
16800      NTRY=(NBIG+NSM)/2

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16810      IF (T-TSAV(NTRY,I)) 17,19,21
16820 17      NBIG=NTRY-1
16830      GO TO 15
16840 19      PDELAY=XSAV(NTRY,I)
16850      RETURN
16860 21      NSM=NTRY+1
16870      GO TO 15
16880      C
16890      C INTERPOLATE BETWEEN TWO CLOSEST POINTS
16900      C
16910 33      PDELAY = XSAV(NSM,I) + (XSAV(NBIG,I) - XSAV(NSM,I)) *
16920 2          ( (T-TSAV(NSM,I)) / (TSAV(NBIG,I) - TSAV(NSM,I)) )
16930      RETURN
16940      END
16950      *
16960      SP
16970      *
16980      SN11
16990      *
17000      END
17010      TMAX=20.0      ,      DT=1.0E-5      ,      DTMIN=1.0E-6
17020      EMAX=1.0E-6      ,      NPOINT=201
17030      SZ(8)=3.0
17040      ASIVSC=309.25925      ,      SIVSC=1.0
17050      ISC=905.0      ,      TAWA=872.25542      ,      TIC=855.0
17060      ELS1=21.377693
17070      PAS2=1830.7      ,      PAS4=1765.7
17080      WS1D=0.4085327      ,      WS3D=0.4085327
17090      HRC=434.6885
17100      TAW1=659.08545      ,      TAW2=738.97753
17110      TI8=713.96      ,      TI9=651.0
17120      EMS5=20268.287      ,      HS6=540.89027
17130      SV51=0.7
17140      SV52C=0.0      ,SVRCC=0.0      ,      SVPC=0.0
17150      D1=0.88865      ,      D2=0.88865      ,      D3=0.88865
17160      D4=0.88865      ,      D5=0.88865      ,      D6=0.88865
17170      WPS=11512.777      ,      WTS=10650.0
17180      TAP=2217.1839      ,      TP3=1035.729
17190      TP1=730.0      ,      TR3=994.873
17200      YP41=9.5525
17210      TP41=994.878      ,      TP4M2=994.878
17220      YSP=20.4225
17230      TP7=730.0      ,      TI3=936.0
17240      SNPP=1170.0      ,      ENIP=1006.0
17250      PSCMX=1614.7      ,      PAS4MX=1854.7
17260      YS5MH=2.334
17270      CDMP1=0.14364553      ,      CDMP2=0.041685883
17280      ENS=2271
17290      ENL=3.0      ,      ENZVAP=6.0
17300      ENI=4550.0      ,      ENE=4542.0
17310      ENP=42966.0
17320      PS6=1.6362977E-2
17330      DOD=7.0
17340      DY=1000.0      ,      ENS4I=2179.9332      ,      EMS5I=20268.287
17350      PAS4I=1765.7
17360      PS51=2.2463449E-3      ,      CV51=114.07199
17370      SV52D=0.7      ,      SVRCD=0.7
17380      CV52=31.651447      ,      CVRC=112.38095      ,      CVPC=16.1658
17390      ENRC=1.0E4
17400      PHDRC=0.100157

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17410 PHF42I=1900.0 , ROJTP=15.0
17420 PDRC=4.955898E-4 , PRCD=4.955898E-4
17430 PDPCD=0.011074
17440 RHOCDI=2.9444232 , ROFBCI=95.6 , DC=-0.0058
17450 SODDCC=-0.006 , RECC=-0.21 , AX ECC=-0.023
17460 VP1=3000.0 , AP4=287.5
17470 EPS=3.3267E 9 , PPGC=0.9239
17480 HDG=756.81825
17490 AIIP=16000.0 , AIIP=16000.0
17500 TRQPMN=575431.61 , TRQIMN=448790.3
17510 PFC=0.8
17520 TAPI=400.0 , TP7I=730.0
17530 YP4I=22.0 , YONTSS=16.2667
17540 TI3I=936.0 , TI9I=651.0 , TICI=855.0
17550 HSSI=434.6885 , WSSI=927.7778
17560 F143=5.72335 , ENSUB=198.0
17570 ELS7=120.0
17580 ELS31=70.0 , ELS32=10.0
17590 ELS61=15.0 , ELS62=100.0
17600 ELS63=75.0 , ELS64=30.0
17610 ELRCD=30.0 , ELORC=30.0
17620 WPSM=1151.2777 , WISM=1065.0
17630 ENPPD=107.0 , ENIPD=92.0 , YSSD=3.0
17640 WPSD=1151.2777 , WISD=1065.0 , TSSD=454.0
17650 FLOWMS=-0.3 , PAPT=1014.7
17660 SVATC=0.0 , CVAPT=0.71737307 , AVAPT=76.1025
17670 SVAPT=0.85 , SVPCD=1.0 , PDAPT=13.66875
17680 TEYS5=10.0 , TEVAPT=10.0 , AEVAPT=-1.0
17690 AEYS5=1350.0 , TETSS=10.0
17700 AETS2=-0.01 , AETRC=0.002
17710 AEWPS=0.1 , AEWIS=0.1
17720 TYSS=0.5 , YSSM=3.0 , PATNM=0.85
17730 TTSS=5.0 , TSSM=454.0 , TPAPTM=0.15
17740 TWPS=0.5 , TWIS=0.5
17750 TEENPP=10.0 , TTRQP=0.01 , ATRQP=50.0
17760 TEENIP=10.0 , TTRQI=0.01 , ATRQI=45.0
17770 TEWPS=10.0 , TEWIS=10.0
17780 PHF41I=2000.0 , DPRCI=148.0
17790 DPRCSF=175.0 , FRC=7.057624E-5
17800 END
17810 *
17820 * SHORT AND LONG TERM HEAT REMOVAL S.P.'S
17830 LIST,ENSTHR,ENLTHR
17840 * DCAY-HEAT SUPERHEATER
17850 LIST,WP,WI,WSA,TASA,TAWA,TAUTIA,TIA
17860 LIST,PSA,PSC,TSA,TSC,HSA,HSC,TIC
17870 * PRIMARY AND INTERMEDIATE FLOW RATES
17880 FACTOR(,0.8,1.0,0.2)
17890 GRAPH,WP,WI
17900 * SUPERHEATED STEAM FLOW
17910 GRAPH,WSA
17920 * AVG. TEMP.S IN THE SUPERHEATER
17930 GRAPH,TASA,TAWA,TAIA
17940 * SUPERHEATER EXIT TEMP. ON THE STEAM SIDE
17950 GRAPH,TSC
17960 * SUPERHEATER EXIT AND EVAP. INLET TEMPS. ON THE SODIUM SIDE
17970 GRAPH,TIC,TI7
17980 * SUPERHEATER EXIT PRESSURE ON THE STEAM SIDE
17990 GRAPH,PSC
18000 * DCAY-HEAT EVAPORATOR

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18010 LIST,ELS1,ELS2,WS1,WS3,XS3,ALF3,HS3
18020 LIST,TAW1,TAW2,TAUT17,TI7,TI8,TI9
18030 LIST,PAS2,ALPA2,TAUHS1,HS1,TS1,TSAT
18040 * LENGTHS OF REGIONS IN THE EVAPORATOR
18050 GRAPH,ELS1,ELS2
18060 * MASS FLOW-RATES AT THE INLET AND EXIT OF THE EVAP.
18070 GRAPH,WS1,WS3
18080 * EXIT QUALITY AND VOID FRACTION OF THE EVAP.
18090 GRAPH,XS3,ALF3
18100 * INLET WATER TEMP. TO THE EVAP.
18110 GRAPH,TS1
18120 * EVAP. EXIT AND IHX INLET INTERMEDIATE SODIUM TEMPS.
18130 GRAPH,TI9,TI1
18140 * AVG. TEMPS. IN THE UPPER REGIONS OF THE EVAP.
18150 GRAPH,TSAT,TAW2,TAI7
18160 * AVG. TEMPS. IN THE LOWER REGIONS OF THE EVAP.
18170 GRAPH,TAS1,TAW1,TAI8
18180 * AVG. PRESSURE IN THE EVAP.
18190 GRAPH,PAS2
18200 * STEAM-DRUM AND MAIN FEED-WATER & AUX. HEAT REMOVAL SYSTEMS
18210 LIST,WSS,EMS4,EMSS,YSS,PAS4,TS5
18220 LIST,SVRC,WRC5,SV52,WS5S2,SVPC,WS7S3
18230 LIST,TAUHS4,HS4,WDMPS2,WAPTS,WDMPS1
18240 LIST,TAUH62,HS6,HS62,TAUH52,HRC,HS52
18250 * FEEDWATER FLOW (TOTAL)
18260 GRAPH,WS5
18270 * FEEDWATER TEMP. (AVG. OVERALL)
18280 GRAPH,TS5
18290 * AVG. PRESSURE IN THE STEAM DRUM
18300 GRAPH,PAS4
18310 * WATER LEVEL IN THE DRUM
18320 GRAPH,YSS
18330 * AUX. FEEDWATER AND RECIRCULATION FLOW-RATES (IBM/SEC)
18340 GRAPH,WS5S2,WRC5
18350 * SUPERHEATER DUMP FLOW (IBM/SEC)
18360 GRAPH,WDMPS1
18370 * STEAM-DRUM DUMP AND APWP-TURBINE FLOW-RATES (IBM/SEC)
18380 GRAPH,WDMPS2,WAPTS
18390 * PACC FLOW RATE (IBM/SEC)
18400 GRAPH,WS7S3
18410 * REACTOR AND IHX
18420 LIST,RHOD,EN,DCHT,ENT,TAF,TAP1
18430 LIST,TAUTR1,TP7,TR1,TAUTP5,TP4,TP5
18440 LIST,TP1,TP3,TR3,TAUT11,TI1,TI3
18450 LIST,TP4M1,TAUP42,TP4M2,TP42,TAUP4
18460 LIST,DMP4M2,WP4M2,YP41,YP42,YKE
18470 LIST,WFPRT,QPP,ENPP,ETAPP,HOPP
18480 LIST,WIPRT,QIP,ENIP,ETAIP,HOIP
18490 * REACTIVITY
18500 GRAPH,RHOD
18510 * FISSION, DECAY AND TOTAL NORMALIZED POWERS
18520 GRAPH,EN,DCHT,ENT
18530 * AVG. FUEL TEMP. IN THE CORE
18540 GRAPH,TAF
18550 * INLET TEMP. TO THE CORE
18560 GRAPH,TP1
18570 * EXIT TEMP. OF THE CORE
18580 GRAPH,TP3
18590 * REGIONS' (TOP TO BOTTOM), IN AND OUT TEMPS. OF THE UPPER PLENUM
18600 GRAPH,TP4M1,TP42,TP4M2,TR3,TP4

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18610 * REGIONS LENGTHS IN THE UPPER PLENUM
18620 GRAPH,YP41,YP42,YKE
18630 * IHX PRIMARY INLET TEMP.
18640 GRAPH,TP5
18650 * IHX PRIMARY EXIT AND REACTOR INLET TEMPS.
18660 GRAPH,TP7,TR1
18670 * IHX EXIT INTERMEDIATE SODIUM TEMP.
18680 GRAPH,TI3
18690 * PRIMARY PUMP SPEED
18700 GRAPH,ENPP
18710 * INTERMEDIATE PUMP SPEED
18720 GRAPH,ENIP
18730 END
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APPENDIX I

LISTING OF THE OPEN-LOOP STEAM GENERATOR SIMULATOR WITH APPROXIMATE LINEAR THERMODYNAMIC EQUATIONS

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00010  NERVAT,BN4101273P,CM104000,T400,ST0,P0.    SG.LNR
00020  CALL DAREP,*NEDEPT,ID=SGLNR,RP=5.
00030  -Z
00040  $D1
00050  *
00060  *          STEAM-GENERATOR WITH LINEAR THERMODYNAMIC-EQ.'S
00070  *
00080  $P
00090  *          I.  SUPERHEATER
00100  *
00110  *
00120  PROCED WSA=ENWSA,DLTWSA,WSAI,T,SWSA
00130  IF(ENWSA.EQ.0.0) WSA=WSAI
00140  IF(ENWSA.EQ.1.AND.T.EQ.0.) WSA=WSAI
00150  IF(ENWSA.EQ.1.AND.T.NE.0.) WSA=WSAI*(1.+DLTWSA/100.0)
00160  IF(ENWSA.EQ.2.0.AND.T.LE.SWSA) WSA=WSAI*(1.+DLTWSA*T/100.0)
00170  ENDPRO
00180  *
00190  WSAS=WSA/3600.0
00200  *
00210  PROCED DWSAS=T
00220  IF(ENWSA.EQ.2.0.AND.T.LE.SWSA) DWSAS=WSAI*DLTWSA/360000.0
00230  IF(ENWSA.EQ.2.0.AND.T.GT.SWSA) DWSAS=0.0
00240  IF(ENWSA.NE.2.0) DWSAS=0.0
00250  ENDPRO
00260  *
00270  YS5=3.0*(1.0+SIN(1.5707963*(EMS5/EMS5I-1.0)))
00280  RHOGS4=-2.18+0.0037649*PAS4
00290  WSC=WSA
00300  WSCS=WSC/3600.0
00310  *
00320  PSAD=PAS4*(1./144.)*(-0.03369228*ELS7*DWSAS/ENL+(53.21+YS5)*RHOGS4
00330  $ -0.0417718*(WSAS/ENL)**2.0)
00340  *
00350  PROCED PSA=ENPSA,DLTPSA,PSAI,T,SPSA,PSAD
00360  IF(ENPSA.EQ.0.0) PSA=PSAD
00370  IF(ENPSA.EQ.1..AND.T.EQ.0.) PSA=PSAI
00380  IF(ENPSA.EQ.1..AND.T.NE.0.) PSA=PSAI*(1.+DLTPSA/100.0)
00390  IF(ENPSA.EQ.2..AND.T.LE.SPSA) PSA=PSAI*(1.+DLTPSA*T/100.0)
00400  ENDPRO
00410  *
00420  PSC=PSA-2.09114E-3*(WSAS/ENL)**2.0-3.1533E-4*ELSHT*DWSAS/ENL
00430  TSA=488.+0.07346*PSA
00440  TASA=(TSA+TSC)/2.
00450  *
00460  PROCED WI=ENWI,DLTWI,WII,T,SWI
00470  IF(ENWI.EQ.0.) WI=WII
00480  IF(ENWI.EQ.1.AND.T.EQ.0.) WI=WII
00490  IF(ENWI.EQ.1.AND.T.NE.0.) WI=WII*(1.+DLTWI/100.0)
00500  IF(ENWI.EQ.2.0.AND.T.LE.SWI) WI=WII*(1.+DLTWI*T/100.0)
00510  ENDPRO
00520  *
00530  *
00540  PROCED DTIA,TIA=ENTIA,DLTTIA,TIAI,T,STIA
00550  IF(ENTIA.EQ.0.0) TIA=TIAI
00560  IF(ENTIA.EQ.0.0) DTIA=0.0
00570  IF(ENTIA.EQ.1.OR.(ENTIA.EQ.2.0.AND.T.GT.STIA)) DTIA=0.0
00580  IF(ENTIA.EQ.1.AND.T.EQ.0.) TIA=TIAI
00590  IF(ENTIA.EQ.1.AND.T.NE.0.) TIA=TIAI+DLTTIA
00600  IF(ENTIA.EQ.2.0.AND.T.LE.STIA) TIA=TIAI+DLTTIA*T

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00610      IF (ENTIA.EQ.2.0.AND.T.LE.STIA)  DTIA=DLTTIA
00620      ENDPPO
00630      *
00640      *
00650      *
00660      HGS4I=1278.7-0.072323*PAS4I
00670      HGS4=1278.7-0.072323*PAS4
00680      *
00690      TAUHSA=0.92175*ELS7*ENL*RHOHGS4/WSAS
00700      HSA=PODELAY(HGS4,TAUHSA,7,HGS4I)
00710      *
00720      HSC=872.5-0.05066*PSC+0.703*TSC
00730      *
00740      *
00750      CPS=(HSC-HSA)/(TSC-TSA)
00760      *
00770      HASA=(HSA+HSC)/2.0
00780      PSS=(PSA+PSC)/2.0
00790      *
00800      RHOSA=-2.18+0.0037649*PSA
00810      RHOSC=3.92+0.001625*PSC-0.0046*TSC
00820      RHOASA=(RHOSA+RHOSC)/2.0
00830      *
00840      TAIA=(TIA+TIC)/2.0
00850      ROTAI=59.533-0.008333*TAIA
00860      *
00870      *      HEAT TRANSFER COEFFICIENTS IN THE SUPERHEATER
00880      *
00890      PES=0.18802368*(WI/ENS)
00900      HNS=1222.0787+1.9258444*(WI/ENS)**0.8
00910      HWA=144.51325*ENS/(0.0048751818+19.2/ENS)
00920      *
00930      RES=536.289*(WSA/ENS)
00940      HSS=4.2454582*(WSA/ENS)**0.8
00950      HSSA=144.51325*ENS/(0.019031+29.484029/HSS)
00960      *
00970      *
00980      *      II-1. SUPERHEATED STEAM
00990      *
01000      DTSC=(0.0066838/(CPS*RHOASA*ENS))*(HSSA*(TAWA-TASA)
01010      *      -WSA*(HSC-HSA))
01020      TSC=DTSC
01030      *
01040      *
01050      *      II-2. WALL
01060      *
01070      DTAWA=(9.2682436E-5/ENS)*(HWA*(TAIA-TAWA)-HSSA*(TAWA-TASA))
01080      TAWA=DTAWA
01090      *
01100      *      II-3. INTERMEDIATE SODIUM
01110      *
01120      DTIC=(2.93739E-3/(ROTAIA*ENS))*(0.3014*WI*(TIA-TIC)
01130      *      -HWA*(TAIA-TAWA))
01140      TIC=DTIC
01150      *
01160      *
01170      *      II. EVAPORATOR
01180      *
01190      *
01200      RHOTS6=74.046-0.05*TS1

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01210      TAUHS1=(1.76744*ELS61+1.576246*ELS62+1.22718*ELS63
01220      $ +0.441786*ENEVAP*ELS64/ENL)*(ENL*RHOTS6/WS1S)
01230      *
01240      PROCED DHS1=HS1,HS6,TAUHS1,HS1I,DLTHS1
01250      IF(ENHS1.EQ.0.0) DHS1=3600.0*(HS6-HS1)/TAUHS1
01260      IF(ENHS1.EQ.1.0.OR.(ENHS1.EQ.2.0.AND.T.GT.SHS1)) DHS1=0.0
01270      IF(ENHS1.EQ.2.0.AND.T.LE.SHS1) DHS1=36.0*DLTHS1*HS1I
01280      ENDPRO
01290      *
01300      PROCED HS1=ENHS1,DLTHS1,HS1I,T,SHS1
01310      IF(ENHS1.EQ.0.0) HS1=PDELAY(HS6,TAUHS1,8,HS1I)
01320      IF(ENHS1.EQ.1.AND.T.EQ.0.0) HS1=HS1I
01330      IF(ENHS1.EQ.1.AND.T.NE.0.0) HS1=HS1I*(1.+DLTHS1/100.0)
01340      IF(ENHS1.EQ.2.AND.T.LE.SHS1) HS1=HS1I*(1.+DLTHS1*T/100.0)
01350      ENDPRO
01360      *
01370      HS2=437.35+0.11674*PAS2
01380      HAS1=(HS1+HS2)/2.0
01390      TS1=68.5+0.9788*HS1
01400      TSAT=488.+0.07346*PAS2
01410      TAS1=(TS1+TSAT)/2.0
01420      HPS2=HS2
01430      HGS2=1278.7-0.072323*PAS2
01440      RHOPS2=56.6-0.009*PAS2
01450      RHOGS2=-2.18+0.0037649*PAS2
01460      *
01470      PROCED WS1=ENWS1,DLTWS1,WS1I,T,SWS1,WS1D,ENE
01480      IF(ENWS1.EQ.0.0) WS1=3600.0*ENE*WS1D
01490      IF(ENWS1.EQ.1.AND.T.EQ.0.0) WS1=WS1I
01500      IF(ENWS1.EQ.1.AND.T.NE.0.0) WS1=WS1I*(1.+DLTWS1/100.0)
01510      IF(ENWS1.EQ.2.AND.T.LE.SWS1) WS1=WS1I*(1.+DLTWS1*T/100.0)
01520      ENDPRO
01530      *
01540      PROCED WS3=WS1,WS3D
01550      IF(ENWS1.EQ.0.0) WS3=3600.0*ENE*WS3D
01560      IF(ENWS1.NE.0.0) WS3=WS1
01570      ENDPRO
01580      *
01590      WS1S=ENE*WS1D
01600      WS3S=ENE*WS3D
01610      WS2AD=(WS1D+WS3D)/2.0
01620      *
01630      *      HEAT TRANSFER COEFFICIENTS IN THE EVAPORATOR
01640      *
01650      RES1=172.99645*(WS1/ENE)
01660      RES2=187.70115*(WS1/ENE)
01670      HWE=12.817068*(WS1/ENE)**0.8
01680      HDS1=3.1415926*ENE/(0.0247376+29.484029/HWE)
01690      HDS2=126.99652*ENE
01700      *
01710      PEE=0.18186595*(WI/ENE)
01720      HYE=1291.3193+1.9661152*(WI/ENE)**0.8
01730      HDW1=3.1415926*ENE/(0.0048751818+19.2/HYE)
01740      HDW2=HDW1
01750      *
01760      AS1=0.00090347512*ENE
01770      *
01780      ELS2=46.0-ELS1
01790      *
01800      SAI=RHOGS2/RHOPS2

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01910 *
01920 *
01830 XS3=HDS2*ELS2*(TAW2-TSAT)/(WS3*(HGS2-HS2))
01840 ALP3=XS3/(SAI+(1.-SAI)*XS3)
01850 ALPSI=ALP3*(1.-SAI)
01860 ALPA2=ALP3*(0.5+ALPSI/6.0+ALPSI*ALPSI/12.)
01870 *
01880 RHOAS1=74.046-0.05*TAS1
01890 RHOAS2=ALPA2*RHOGS2+(1.-ALPA2)*RHOPS2
01900 RHOHS2=ALPA2*RHOGS2*HGS2+(1.-ALPA2)*RHOPS2*HPS2
01910 *
01920 HS3=HGS2*XS3+HPS2*(1.-XS3)
01930 RHOS3=ALP3*RHOGS2+(1.-ALP3)*RHOPS2
01940 *
01950 DRFP2=-0.009
01960 DRGP2=0.0037649
01970 DRFP2=0.11674
01980 DRGP2=-0.072323
01990 DRHFP2=RHOFS2*DHFP2+HPS2*DRFP2
02000 DRHGP2=RHOFS2*DRGP2+HGS2*DRGP2
02010 *
02020 A=ELS2*(ALPA2*(DRHGP2-DRGP2*HPS2)+(1.-ALPA2)*(DRHFP2-DRFP2*HPS2))
02030 B=ELS1*RHOFS2*DHFP2*(HGS2-HPS2)/(2.0*A*(HS2-HS1))
02040 C=1.0+2.*B*(RHOAS1-RHOPS2)/(RHOPS2-RHOFS2)
02050 *
02060 *      III-1.  WATER / STEAM
02070 *
02080 DLS1=(2./C)*(-HDS1*ELS1*(TAW1-TAS1)/(AS1*RHOAS1*(HS2-HS1))
02090 $ +WS1/(AS1*RHOAS1)+(ELS1/2.0)*DRS6/(HS2-HS1)
02100 $ +B*(WS1-WS3)/(AS1*(RHOPS2-RHOFS2)))
02110 ELS1=DLS1/3600.0
02120 *
02130 WS2=WS1-AS1*RHOAS1*DLS1
02140 *
02150 DPAS2=(RHOFS2*(HGS2-HPS2)/(A*(RHOPS2-RHOFS2)))*(-(RHOAS1-RHOPS2)
02160 $ *DLS1+(WS1-WS3)/AS1)
02170 PAS2=DPAS2/3600.0
02180 *
02190 *      III-2.  WALL
02200 *
02210 WMHCD=0.073034229*ENE
02220 TW2=(TAW1*ELS1+TAW2*ELS2)/46.0
02230 *
02240 DTAW1=(1./WMHCD)*(-(HDW1+HDS1+WMHCD*DLS1/ELS1)*TAW1
02250 $ +HDS1*TAS1+HDW1*TAI8)+TW2*DLS1/ELS1
02260 TAW1=DTAW1/3600.0
02270 *
02280 DTAW2=(1./WMHCD)*(-(HDW2+HDS2+WMHCD*DLS1/ELS2)*TAW2
02290 $ +HDS2*TSAT+HDW2*TAI7)-TW2*DLS1/ELS2
02300 TAW2=DTAW2/3600.0
02310 *
02320 *      III-3.  INTERMEDIATE SODIUM
02330 *
02340 RHOTIC=59.533-0.008333*TIC
02350 TAUT17=703800.0*RHOTIC*ENEVAP/WI
02360 *
02370 PROCED TI7=ENTI7,DLTTI7,TIC,TI7I,STI7,TAUTI7,TICI
02380 IF(ENTI7.EQ.0.) TI7=PDELAY(TIC,TAUTI7,14,TICI)
02390 IF(ENTI7.EQ.1..AND.T.EQ.0.) TI7=TI7I
02400 IF(ENTI7.EQ.1..AND.T.NE.0.) TI7=TI7I+DLTTI7

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02410      IF (ENT17.EQ.2.AND.T.LE.STI7)  TI7=TI7I+DLTTI7*T
02420      ENDPRO
02430      *
02440      *
02450      TAI7=(TI7+TI9)/2.0
02460      FAI8=(TI8+TI9)/2.0
02470      *
02480      TIE=(TI7+TI9)/2
02490      RHOIE=59.533-0.008333*TIE
02500      SMHCD=0.0020848433*RHOIE*ENE
02510      WI8=WI+0.00682079*ENE*RHOIE*DLS1
02520      *
02530      DTI8=(1./(SMHCD*ELS2))*(-(HDW2*ELS2-SMHCD*DLS1)*TAI7
02540      $      +HDW2*ELS2*TAW2+0.30566168*(WI*TI7-WI8*TI8))
02550      TI8.=DTI8/3600.0
02560      *
02570      DTI9=(1./(SMHCD*ELS1))*(-(HDW1*ELS1+SMHCD*DLS1)*TAI3
02580      $      +HDW1*ELS1*TAW1+0.30566168*(WI8*TI8-WI*TI9))
02590      TI9.=DTI9/3600.0
02600      *
02610      *
02620      *      WATER / STEAM LOOP MOMENTUM EQUATIONS
02630      *
02640      *
02650      R=RD(PAS2,XS3)
02660      *
02670      TAUWS3=ELS31/(21.25048*ENEVAP)+ELS32/(68.844553*ENL)
02680      TAUWS1=ELS61/(56.9*ENL)+ELS62/(50.755*ENL)
02690      $      +ELS63/(39.515*ENL)+ELS64/(14.22555*ENEVAP)
02700      *
02710      A11T=ELS1/(32.2*AS1)+ELS2/(64.4*AS1)+TAUWS1
02720      A12T=ELS2/(64.4*AS1)+0.30020714/AS1+TAUWS3
02730      A21T=ELS2/(128.8*AS1)
02740      A22T=ELS2/(128.8*AS1)+0.15010357/AS1+TAUWS3
02750      *
02760      DETERM=A11T*A22T-A12T*A21T
02770      *
02780      *      FRICTION COEFFICIENTS
02790      *
02800      PROCED FS1=RES1
02810      IF (RES1.LT.1000.0)  FS1=8.0/RES1
02820      IF (RES1.GE.1000.0.AND.RES1.LT.100000.0)  FS1=0.05256/(RES1**0.243)
02830      IF (RES1.GE.100000.0)  FS1=0.02117/(RES1**0.164)
02840      ENDPRO
02850      FS1A=99943.154*FS1
02860      *
02870      PROCED FS2=RES2
02880      IF (RES2.LT.1000.0)  FS2=8.0/RES2
02890      IF (RES2.GE.1000.0.AND.RES2.LT.100000.0)  FS2=0.05256/(RES2**0.243)
02900      IF (RES2.GE.100000.0)  FS2=0.02117/(RES2**0.164)
02910      ENDPRO
02920      FS2A=111628.91*FS2
02930      *
02940      DPRC=DPRCSF*PRC*(WS1S/ENL)**2
02950      *
02960      HDSPH=ELS1*RHOAS1+ELS2*RHOAS2+10.268333*RHOS3-52.708333*RHOTS6
02970      $      -(YS5*(DOD-6.0)/2.0)*RHOTS6
02980      CHMRH=(1./((32.2*AS1*AS1)))*((WS3S**2/RHOS3-WS1S**2/RHOPS2)
02990      PRPRH=(FS1A*ELS1+3054.5503*(ENE/ENL)**2.0*FS6)*(WS1D**2.0)
03000      $      +(FS2A*R*ELS2)*(WS2AD**2)+ (35979.643+9.66667*FS2A*R)*(WS3D**2)

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03010 *
03020 HSPH34=ELS2*RHOAS2/2.0+7.6666665*RHOS3
03030 PRPH34=PS2A*R*ELS2*(WS2AD**2)/2.0+(4.833335*PS2A*R
03040 $ +28424.507)*(WS3D**2)
03050 B1T=- (HDS PH+CHMPH-144.0*DPFC+PRPH)
03060 B2T=144.0*(PAS2-PAS4)-HSPH34-CHMPH/2.0-PRPH34
03070 *
03080 WS1DD=(122T*B1T-A12T*B2T)/(ENE*DETERM)
03090 WS3DD=(A11T*B2T-A21T*B1T)/(ENE*DETERM)
03100 *
03110 PROCED DWS1D=WS1DD
03120 IF(ENWS1.EQ.0.0) DWS1D=WS1DD
03130 IF(ENWS1.NE.0.0) DWS1D=0.0
03140 ENDPRO
03150 *
03160 PROCED DWS3D=WS3DD
03170 IF(ENWS1.EQ.0.0) DWS3D=WS3DD
03180 IF(ENWS1.NE.0.0) DWS3D=0.0
03190 ENDPRO
03200 *
03210 WS1D.=DWS1D
03220 WS3D.=DWS3D
03230 *
03240 *
03250 * III. STEAM DRUM
03260 *
03270 PROCED WS5=ENWS5,DLTWS5,T,SHS5,WS5I
03280 IF(ENWS5.EQ.0.0) WS5=WS5I
03290 IF(ENWS5.EQ.1..AND.T.EQ.0.0) WS5=WS5I
03300 IF(ENWS5.EQ.1..AND.T.NE.0.0) WS5=WS5I*(1.+DLTWS5/100.0)
03310 IF(ENWS5.EQ.2..AND.T.LE.SHS5) WS5=WS5I*(1.+DLTWS5*T/100.0)
03320 ENDPRO
03330 *
03340 *
03350 PROCED HS5=ENHS5,DLTHS5,T,SHS5,HS5I
03360 IF(ENHS5.EQ.0.0) HS5=HS5I
03370 IF(ENHS5.EQ.1..AND.T.EQ.0.0) HS5=HS5I
03380 IF(ENHS5.EQ.1..AND.T.NE.0.0) HS5=HS5I*(1.+DLTHS5/100.0)
03390 IF(ENHS5.EQ.2..AND.T.LE.SHS5) HS5=HS5I*(1.+DLTHS5*T/100.0)
03400 ENDPRO
03410 *
03420 TS5=68.5+0.8788*HS5
03430 *
03440 PROCED WS4=ENWS4,DLTWS4,T,SHS4,WS4I,WS3
03450 IF(ENWS4.EQ.0.0) WS4=WS3
03460 IF(ENWS4.EQ.1..AND.T.EQ.0.0) WS4=WS4I
03470 IF(ENWS4.EQ.1..AND.T.NE.0.0) WS4=WS4I*(1.+DLTWS4/100.0)
03480 IF(ENWS4.EQ.2..AND.T.LE.SHS4) WS4=WS4I*(1.+DLTWS4*T/100.0)
03490 ENDPRO
03500 *
03510 TAUHS4=(0.66*ENPVAP*ELS31/ENL+2.1380*ELS32)*(ENL*RHOS3/WS3S)
03520 *
03530 PROCED HS4=ENHS4,DLTHS4,T,SHS4,HS4I,HS3
03540 IF(ENHS4.EQ.0.0) HS4=PDDELAY(HS3,TAUHS4,9,HS4I)
03550 IF(ENHS4.EQ.1..AND.T.EQ.0.0) HS4=HS4I
03560 IF(ENHS4.EQ.1..AND.T.NE.0.0) HS4=HS4I*(1.+DLTHS4/100.0)
03570 IF(ENHS4.EQ.2..AND.T.LE.SHS4) HS4=HS4I*(1.+DLTHS4*T/100.0)
03580 ENDPRO
03590 *
03600 PROCED WS6=ENWS6,WS6I,WS1

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03610      IF (ENWS6.EQ.0.0)  WS6=WS1
03620      IF (ENWS6.NE.0.0)  WS6=WS6I
03630      ENDPRO
03640      *
03650      PROCED  WS7=ENWS7,WS7I,WSA
03660      IF (ENWS7.EQ.0.0)  WS7=WSA
03670      IF (ENWS7.NE.0.0)  WS7=WS7I
03680      ENDPRO
03690      *
03700      RHOPFS4=56.6-0.009*PAS4
03710      *
03720      EMS4=RHOGS4*(DV-EMS5/RHOPFS4)
03730      *
03740      EMS4D=DELAY(EMS4,0.2,5,EMS4I)
03750      OEMS4=18000.0*(EMS4-EMS4D)
03760      *
03770      OEMS5=(WS4+WS5-WS6-WS7)/ENL-OEMS4
03780      EMS5.=OEMS5/3600.0
03790      *
03800      D=0.009*EMS5/RHOPFS4**2-0.0037649*EMS4/RHOGS4**2
03810      DPAS4=(-1./D)*(OEMS5/RHOPFS4+OEMS4/RHOGS4)
03820      PAS4.=DPAS4/3600.0
03830      *
03840      DRS6=(1./(ENL*OEMS5))*(WS4*HS4+WS5*HS5-WS6*HS6-WS7*HGS4
03850      $ -ENL*(HGS4*OEMS4+HS6*OEMS5-0.072323*EMS4*DPAS4))
03860      HS6.=DRS6/3600.0
03870      *
03880      *
03890      STORE , WSA,WSC,RHOASA,CPS,RHOIA,PSA,PSC,TSA,TSC,HSA,HSC,TIA,TIC,
03900      $  TASA,TAWA,TAIA,ELS1,ELS2,WS1,WS3,XS3,ALP3,HS3,TAW1,TAW2,TAI7,
03910      $  TAI9,TI7,TI8,TI9,PAS2,ALPA2,HS1,HS2,TAS1,TSAT,BIT,B2T,DETERM,
03920      $  TS1,EMS4,EMS5,YS5,PAS4,HS6,TSS,HS5,WS5,TAUHS4,TAUHS4,
03930      $  TAUHS1,TAUTI7,WI
03940      $T1
03950      RD , 3 , 5
03960      *
03970      * THE FOLLOWING IS A DEFINITION OF THE SECOND
03980      * INDEPENDENT VARIABLE.
03990      *
04000      0.2      ,0.4      ,0.6      ,0.8      ,1.0
04010      *
04020      * NEXT COMES THE FIRST INDEPENDENT VARIABLE
04030      *FOLLOWED BY THE DEPENDENT VARIABLE
04040      *
04050      1000.0      ,4.81801      ,7.43707      ,10.6082      ,12.915      ,14.4123
04060      2000.0      ,2.48938      ,3.21363      ,4.30274      ,4.97874      ,5.35559
04070      2500.0      ,1.72844      ,2.21131      ,2.6778      ,2.98751      ,2.98751
04080      *
04090      $F
04100      FUNCTION PDELAY(XC,TAU,I,XCI)
04110      C
04120      C PIPE DELAY FUNCTION FOR THE DARE P RUNTIME SYSTEM
04130      C
04140      C XC = VARIABLE TO BE DELAYED
04150      C
04160      C TAU = AMOUNT OF DELAY BEFORE PRESENT VALUE OF XC IS VALID.
04170      C (VARIABLE, ANY VALUE .GE. ZERO)
04180      C
04190      C I = INTEGER CONSTANT BETWEEN 1 AND IMAX IDENTIFYING
04200      C INDEPENDENT PDELAY OPERATORS

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04210 C
04220 C XCI = INITIAL VALUE OF XC (VALUE RETURNED UNTIL T .GT. TAU(0) )
04230 C
04240 C PDELAY MODELS AN INCOMPRESSIBLE FLUID FLOWING THROUGH A UNIT
04250 C LENGTH PIPE AT A VELOCITY OF 1./TAU
04260 C
04270 LOGICAL WRAP
04280 LOGICAL EXIT,RLDONE
04290 COMMON /SYSVAR/ EXIT,RLDONE,IOUT,IFILE,IRUNNO,T,TMAX,TNEXT
04300 COMMON /SYSVAR/ DT,DTMAX,DTMIN,EMAX,EMIN,SY(35)
04310 COMMON DELAY(8101)
04320 COMMON TNS(20),NP(20),WRAP(20),TSAV(100,20),XSAV(100,20),TAUL(20)
04330 1,XCL(20)
04340 DATA NPA/100/,IMAX/20/
04350 C
04360 PDELAY=XCI
04370 DUMMY=XC
04380 IF(EXIT) RETURN
04390 IF(I.GT.0.AND.I.LE.IMAX) GO TO 4
04400 WRITE(IOUT,3) I
04410 3 FORMAT(36H FATAL ERROR - INVALID PDELAY NUMBER,I3)
04420 CALL ABORT
04430 4 IF(TAU.GE.0.) GO TO 7
04440 WRITE(IOUT,6) I,IRUNNO,T
04450 6 FORMAT(15H ERROR - PDELAY,I3,9H NEGATIVE/
04460 2 7H - RUN,I4,19H TERMINATED AT T =,1PE12.5)
04470 EXIT=.TRUE.
04480 RETURN
04490 C
04500 C IF T.EQ.0, INITIALIZE
04510 C
04520 7 IF(T.GT.0.) GO TO 8
04530 NP(I)=1
04540 TNS(I)=AMAX1(DT,TAU*2./FLOAT(NPA))
04550 WRAP(I)=.FALSE.
04560 TSAV(1,I)=TAU
04570 XSAV(1,I)=XC
04580 TSAV(NPA,I)=0.
04590 TAUL(I)=TAU
04600 XCL(I)=XC
04610 GO TO 12
04620 C
04630 C IF T.GE.TNS, SAVE X AND T, CALCULATE TNS
04640 C
04650 8 IF(T.LT.TNS(I).OR..NOT.RLDONE) GO TO 12
04660 C
04670 C IF TAU DIFFERS FROM LAST CALL, ADJUST TSAV ARRAY TO MATCH NEW
04680 C PIPE VELOCITY
04690 C
04700 IF(TAU.EQ.TAUL(I)) GO TO 10
04710 N=NP(I)
04720 9 IF(T.GE.TSAV(N,I)) GO TO 10
04730 TSAV(N,I)=(TSAV(N,I)-T)*TAU/TAUL(I)+T
04740 N=MOD(N-2*NPA,NPA)+1
04750 GO TO 9
04760 10 IF(TAUL(I)-TAU.LT.0.0) GO TO 43
04770 DUMMY=(DT*XC + TAU*XCL(I))/(TAU + DT)
04780 C
04790 C CHECK FOR BUFFER OVERFLOW (YES, IT CAN OCCUR)
04800 C BUFFER OVERFLOW IS STORING NEW DATA INTO A CELL BEFORE

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04810 C FINISHED WITH OLD DATA
04820 C
04830 43 N=NP(I)
04840 TAU(I)=TAU
04850 XCL(I)=DUMMY
04860 N2=MOD(N+1,NPA)+1
04870 IF(.NOT.WRAP(I).AND.N2.GT.2) GO TO 11
04880 IF(T.GE.TSAV(N2,I)) GO TO 11
04890 TNS(I)=TSAV(N2,I)
04900 WRITE(IOUT,105) I,T,TNS(I)
04910 105 FORMAT(17H WARNING - PDELAY,I3,22H BUFFER OVERFLOW AT T=,
04920 2 1P12.5,6H, TNS=,E12.5)
04930 GO TO 12
04940 11 IF(N.EQ.NPA) WRAP(I)=.TRUE.
04950 N=MOD(N,NPA)+1
04960 NP(I)=N
04970 TSAV(N,I)=T+TAU
04980 XSAV(N,I)=DUMMY
04990 TNS(I)=T+AMAX1(DT,TAU*2./FLOAT(NPA))
05000 C
05010 C IF T .LT. FIRST-T-STORED, RETURN XCI
05020 C
05030 12 IF(.NOT.WRAP(I).AND.T.LT.TSAV(1,I)) RETURN
05040 C
05050 C CHECK FOR T .GT. LAST-T-STORED (WILL BE IF TAU.LT.DT)
05060 C
05070 NBIG=NP(I)
05080 IF(T.LE.TSAV(NBIG,I)) GO TO 13
05090 NSM=NBIG
05100 NBIG=MOD(NBIG,NPA)+1
05110 IF(NBIG.EQ.1) WRAP(I)=.TRUE.
05120 TSAV(NBIG,I)=T+TAU
05130 XSAV(NBIG,I)=DUMMY
05140 GO TO 33
05150 C
05160 C CHECK WHICH HALF OF CIRCULAR BUFFER T IS IN
05170 C
05180 13 NSM=1
05190 IF(.NOT.WRAP(I).OR.T.GE.TSAV(1,I)) GO TO 15
05200 NSN=NBIG+1
05210 NBIG=NPA
05220 C
05230 C CHECK FOR T IN THE CRACK BETWEEN TSAV(NPA) AND TSAV(1)
05240 C
05250 IF(T.LE.TSAV(NPA,I)) GO TO 15
05260 NSN=NPA
05270 NBIG=1
05280 GO TO 33
05290 C
05300 C PERFORM BINARY SEARCH TO LOCATE INDEX OF T
05310 C
05320 15 IF(NBIG.LT.NSM) GO TO 33
05330 NTRY=(NBIG+NSM)/2
05340 IF(T-TSAV(NTRY,I)) 17,19,21
05350 17 NBIG=NTRY-1
05360 GO TO 15
05370 19 PDELAY=XSAV(NTRY,I)
05380 RETURN
05390 21 NSM=NTRY+1
05400 GO TO 15

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05410 C
05420 C INTERPOLATE BETWEEN TWO CLOSEST POINTS
05430 C
05440 33 PDELAY = XSAV(NSM,I) + (XSAV(NBIG,I) - XSAV(NSM,I)) *
05450 2 ( (I-TSAV(NSM,I)) / (TSAV(NBIG,I) - TSAV(NSM,I)) )
05460 RETURN
05470 END
05480 *
05490 *P
05500 *
05510 3M11
05520 END
05530 TMAX=50.0 , EMAX=1.0E-6 , DT=1.0E-5
05540 SY(8)=3.0 , DTMIN=1.0E-6
05550 TSC=905.0 , TAWA=872.37566 , TIC=855.1528
05560 ELS1=21.392533
05570 PAS2=1830.7 , PAS4=1765.7
05580 WS1D=0.4085327 , WS3D=0.4085327
05590 TAW1=659.10738 , TAW2=739.0171
05600 TI8=714.0088 , TI9=651.0
05610 EMS5=20354.350 , HS6=540.52634
05620 ENL=3.0 , ENS=2271.0 , ENE=4542.0
05630 ENEVAP=6.0
05640 TIAI=936.0 , PSAI=1739.7
05650 PAS4I=1765.7
05660 WSAI=3.34E 6
05670 WS1I=540.52634 , WS1I=6.68E6
05680 TI7I=855.1528 , TICI=855.1528
05690 WII=3.934E 7
05700 DPCSC=175.0 , PSC=7.057624E-5 , PS6=1.6362977E-2
05710 DOD=7.0
05720 DV=1000.0 , EMS4I=2233.8419 , EMS5I=20354.35
05730 WS4I=6.68E 6 , WS6I=6.68E 6
05740 WS5I=3.34E 6 , WS7I=3.34E 6
05750 HS4I=898.68211 , HS5I=434.6885
05760 ELSHT=65.0 , ELS7=120.0
05770 ELS31=70.0 , ELS32=10.0
05780 ELS61=15.0 , ELS62=100.0
05790 ELS63=75.0 , ELS64=30.0
05800 DLTTIA=20.0 , DLTWI=-10.0 , DLTWSA=-10.0
05810 DLTWSS=-10.0 , DLTWSS=10.0
05820 ENWSA=1.0
05830 END
05840 * STEAM GENERATOR WITH LINEAR THERMODYNAMIC STATE-EQS.
05850 * SUPERHEATER
05860 LIST,WSA,WI,WSA,TASA,TAWA,TAIA
05870 LIST,PSA,PSC,TSA,TSC,HSC,TIA,TIC
05880 * SUPERHEATED STEAM FLOW (LINEAR THERMODYNAMIC EQS.)
05890 FACTOR(.08,1.0,0.2)
05900 GRAPH,WSC
05910 * INTERMEDIATE SODIUM FLOW (LINEAR THERMODYNAMIC EQS.)
05920 GRAPH,WI
05930 * SUPERHEATER INLET SODIUM TEMP. (LINEAR THERMODYNAMIC EQS.)
05940 GRAPH,TIA
05950 * SUPERHEATER EXIT STEAM PRESSURE
05960 GRAPH,PSC
05970 * SUPERHEATER AVG. TEMPS.
05980 GRAPH,TASA,TAWA,TAIA
05990 * SUPERHEATER EXIT STEAM TEMP.
06000 GRAPH,TSC

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06010 *      SUPERHEATER EXIT AND EVAP. INLET TEMPS. SODIUM SIDE
06020 GRAPH,TIC,TI7
06030 *      EVAPORATOR
06040 LIST,ELS1,ELS2,XS3,ALF3,HS3
06050 LIST,TI3,TI9,TAW1,TAW2,TS1,TSAT
06060 LIST,WS1,WS3,PAS2,ALFA2
06070 *      LENGTHS OF REGIONS IN THE EVAP.
06080 GRAPH,ELS1,ELS2
06090 *      EVAP. EXIT QUALITY AND VOID FRACTION
06100 GRAPH,XS3,ALF3
06110 *      EVAP. AVG. TEMPS. IN THE LOWER REGIONS
06120 GRAPH,TAS1,TAW1,TAI8
06130 *      EVAP. AVG. TEMPS. IN THE UPPER REGIONS
06140 GRAPH,TSAT,TAW2,TAI7
06150 *      EVAP. INLET SUBCOOLED WATER TEMP.
06160 GRAPH,TS1
06170 *      EVAP. EXIT SODIUM TEMP.
06180 GRAPH,TI9
06190 *      EVAP. AVG. PRESSURE ON THE STEAM/WATER SIDE
06200 GRAPH,PAS2
06210 *      EVAP. INLET AND EXIT FLOW-RATES ON THE WATER/STEAM SIDE
06220 GRAPH,WS1,WS3
06230 *      STEAM DRUM
06240 LIST,WS5,TS5,YSS,PAS4,HS6,EMS4,ZMS5
06250 *      STEAM DRUM WATER LEVEL
06260 GRAPH,YSS
06270 *      STEAM DRUM PRESSURE
06280 GRAPH,PAS4
06290 *      FEEDWATER FLOW (LINEAR THERMODYNAMIC EQS.)
06300 GRAPH,YS5
06310 *      STEAM DRUM FEEDWATER ENTHALPY (LINEAR THERMODYNAMIC EQS.)
06320 GRAPH,HS5
06330 *      DELAYS
06340 LIST,TAHSA,TAHSA4,TAHSA1,TAUTI7
06350 END

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APPENDIX J

LISTING OF THE CRBRP-ATWS SIMULATOR WITHOUT PLANT CONTROLLERS

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00010  MERVAT,BN4101273P,CM110000,T7000,ST0,PO.    PLANT.UC
00020  CALL DAREP,*NEDREP,TD=PLUC,RP=5.
00030  ^Z
00040  SD1
00050  *
00060  *      UNCONTROLLED PLANT
00070  SP
00080  *      I. TURBOGENERATOR
00090  *
00100  *
00110  *
00120  PROCED ENWD=ENLD,DLTLD,ENWI,SLD
00130  IF(ENLD.EQ.0.0) ENWD=ENW(T)
00140  IF(ENLD.EQ.1.0.AND.T.EQ.0.0) ENWD=ENWI
00150  IF(ENLD.EQ.1.0.AND.T.GT.0.0) ENWD=ENWI*(1.+DLTLD/100.0)
00160  IF(ENLD.EQ.2.0.AND.T.LE.SLD) ENWD=ENWI*(1.+DLTLD*T/100.0)
00170  ENDPRO
00180  *
00190  PROCED ENWM=ENHWM,ENWD
00200  IF(ENHWM.EQ.0.0) ENWM=ENWI
00210  IF(ENHWM.NE.0.0) ENWM=ENWD
00220  ENDPRO
00230  *
00240  SV9=(0.00223694*ENWM-SV9)/0.1
00250  *
00260  *
00270  PROCED SVOMP,DSVDMP=ENDMP,DLTOMP,SSVDMP
00280  IF(ENDMP.EQ.0.0) SVOMP=0.0
00290  IF(ENDMP.EQ.1.0.AND.T.EQ.0.0) SVOMP=0.0
00300  IF(ENDMP.EQ.1.0.AND.T.NE.0.0) SVOMP=DLTOMP
00310  IF(ENDMP.EQ.2.0.AND.T.LE.SSVDMP) SVOMP=DLTOMP*T
00320  IF(ENDMP.EQ.2.0.AND.T.LE.SSVDMP) DSVDMP=DLTOMP
00330  IF(ENDMP.EQ.2.0.AND.T.GT.SSVDMP) DSVDMP=0.0
00340  IF(ENDMP.NE.2.0) DSVDMP=0.0
00350  ENDPRO
00360  *
00370  PROCED WDMPS,DWDMP=PS9I,CDMP,SVOMP,DSVDMP
00380  IF(T.EQ.0.0) WDMPS=CDMP*PS9I*SVOMP
00390  IF(T.EQ.0.0) DWDMP=CDMP*PS9I*DSVDMP
00400  IF(T.GT.0.0) WDMPS=CDMP*PS9*SVOMP
00410  IF(T.GT.0.0) DWDMP=CDMP*PS9*DSVDMP
00420  ENDPRO
00430  *
00440  WOMP=3600.0*WDMPS
00450  *
00460  PROCED WSA=ENWSA,DLTWSA,WSAI,WSAS,T,SWSA
00470  IF(ENWSA.EQ.0.0) WSA=3600.0*WSAS
00480  IF(ENWSA.EQ.1.0.AND.T.EQ.0.0) WSA=WSAI
00490  IF(ENWSA.EQ.1.0.AND.T.NE.0.0) WSA=WSAI*(1.+DLTWSA/100.0)
00500  IF(ENWSA.EQ.2.0.AND.T.LE.SWSA) WSA=WSAI*(1.+DLTWSA*T/100.0)
00510  ENDPRO
00520  *
00530  *
00540  WSC=WSA
00550  WSCS=WSC/3600.0
00560  *
00570  WS9S=WSCS-WDMPS
00580  WS9=3600.0*WS9S
00590  *
00600  PROCED CS9=PRV91,PS9SC,SV9,ENS94

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00610      IF (PRV91.GE..55)   CS9=WS9/(ENS94*SV9*PS9SC)
00620      ENDPRO
00630      *
00640      PV9=1V9*WS9S/ENS94
00650      PS9SC=PV9*(WS9S/(CV9*ENS94*SV9)) **2.
00660      PS9C=WS9S/(CS9*ENS94*SV9)
00670      *
00680      PRV91=PV9/PS9SC
00690      *
00700      PROCD  PRV9=PS9I,PV9
00710      IF (T.EQ.0.0)   PRV9=PV9/PS9I
00720      IF (T.GT.0.0)   PRV9=PV9/PS9
00730      ENDPRO
00740      *
00750      PROCD  PS9=PS9SC,PS9C,PRV9
00760      IF (PRV9.GT.0.55)   PS9=PS9SC
00770      IF (PRV9.LE.0.55)   PS9=PS9C
00780      ENDPRO
00790      *
00800      *
00810      FSC1=7.841775E-4*ELSC1/(ELSC1+0.573425*ELSC2*(ENL/ENSC2)**2.0)
00820      FSC2=3.48525E-4*ELSC2/(ELSC2+1.74391*ELSC1*(ENSC2/ENL)**2.0)
00830      *
00840      TAUWSA=2.339742E-4*ELS7/ENL+3.1533E-4*ELSHT/ENL
00850      $ +1.3682E-4*ELSC1/ENL+1.095337E-4*ELSC2/ENSC2
00860      *
00870      DWSASD=(1./TAUWSA)*(PAS4-PS9*(53.21+Y55)*RHOGS4/144.0
00880      $ -(2.3807823E-3+FSC1)*(WSAS/ENL)**2.0-FSC2*(WSAS/ENSC2)**2.0)
00890      *
00900      PROCD  DWSAS=DWSASD
00910      IF (ENWSA.EQ.0.0)   DWSAS=DWSASD
00920      IF (ENWSA.EQ.2.0.AND.T.LE.SWSA)   DWSAS=WSAI*DLTWSA/360000.0
00930      IF ((ENWSA.EQ.2.0.AND.T.GT.SWSA).OR.ENWSA.EQ.1.)   DWSAS=0.0
00940      ENDPRO
00950      *
00960      WSAS.=DWSAS
00970      *
00980      Y55=3.0*(1.0+SIN(1.5707963*(ENSS/ENSSI-1.0)))
00990      VGS4=VG(PAS4)
01000      RHOGS4=1./VGS4
01010      *
01020      PSAD=PAS4*(1./144.)*( -0.03369228*ELS7*DWSAS/ENL+(53.21+Y55)*RHOGS4
01030      $ -0.0417085*(WSAS/ENL)**2.0)
01040      *
01050      PROCD  PSA=ENPSA,DLTPSA,PSAI,T,SPSA,PSAD
01060      IF (ENPSA.EQ.0.0)   PSA=PSAD
01070      IF (ENPSA.EQ.1..AND.T.EQ.0.)   PSA=PSAI
01080      IF (ENPSA.EQ.1..AND.T.NE.0.)   PSA=PSAI*(1.+DLTPSA/100.0)
01090      IF (ENPSA.EQ.2..AND.T.LE.SPSA)   PSA=PSAI*(1.+DLTPSA*T/100.0)
01100      ENDPRO
01110      *
01120      PSC=PSA-2.09114E-3*(WSAS/ENL)**2.0-3.1533E-4*ELSHT*DWSAS/ENL
01130      *
01140      TSA=TSATP(PSA)
01150      TASA=(TSA+TSC)/2.
01160      *
01170      RHOSC=1./VSC
01180      TAUTS9=(1.57625*ELSC1*ENL+1.96895*ELSC2*ENSC2)*(RHOSC/WSCS)
01190      *
01200      TS9=0.994475*PDELAY(TSC,TAUTS9,6,TSCI)

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01210 *
01220 *
01230 HS9=HSH (PS9,TS9)
01240 *
01250 SS9=SS9 (PS9,TS9)
01260 SEXR=SS9
01270 XEXH=(SEXH-0.1313)/1.8487
01280 HEXH=68.997+1036.5*XEXH
01290 *
01300 *
01310 STWBTU=0.706639*(HS9-HEXH)*WS9
01320 STWNV=2.931E-7*STWBTU
01330 PT.=(STWNV-PT)/0.5
01340 *
01350 *
01360 V=22.0*ENWD/ENWI
01370 *
01380 XD=0.9918032
01390 *
01400 E=19.845232+20.009242*XD
01410 *
01420 PROCED AI=V,E,XD,FETAG
01430 IF(ENLD.NE.2.0) AI=((0.431619*V/XD)**2.0
01440 * +((E-0.902056*V)/XD)**2.0)**0.5
01450 IF(ENLD.EQ.2.0) AI=((V*SIN(0.017453292*FETAG)/XD)**2.0
01460 * +((E-V*COS(0.017453292*FETAG)/XD)**2.0)**0.5
01470 3 ENDP
01480 *
01490 PGFETD=(V*E/XD)*SIN(0.017453292*FETAG)
01500 *
01510 PROCED PGFETA=ENSSC,PGFETD,T,TFR
01520 IF(ENSSC.NE.0.0) GO TO 30
01530 PGFETA=PGFETD
01540 GO TO 40
01550 30 IF(T.GT.0.0.AND.T.LE.TFR) PGFETA=0.0
01560 IF(T.EQ.0.0.OR.T.GT.TFR) PGFETA=PGFETD
01570 40 CONTINUE
01580 ENDP
01590 *
01600 PF=PGFETA/(AI*V)
01610 *
01620 *
01630 PONG=0.020159685*OMGG
01640 PGE=165.38356*EXAI*(OMGG-376.99)
01650 PGA=PT-(PONG+PGE+PGFETA)
01660 *
01670 FETAG.=(OMGG-376.99)/0.017453292
01680 OMGG.=48.539*PGA/OMGG
01690 *
01700 *
01710 *
01720 *
01730 *
01740 *
01750 II. SUPERHEATER
01760 PROCED WI=ENWI,DLTWI,WII,T,SWI
01770 IF(ENWI.EQ.0.) WI=3600.0*WIS
01770 IF(ENWI.EQ.1.AND.T.EQ.0.) WI=WII
01780 IF(ENWI.EQ.1.AND.T.NE.0.) WI=WII*(1.+DLTWI/100.0)
01790 IF(ENWI.EQ.2.0.AND.T.LE.SWI) WI=WII*(1.+DLTWI*T/100.0)
01800 ENDP

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01810 *
01820 *
01830 *
01840 RHOTI3=RHONA(TI3)
01850 *
01860 TAUTIA=8474400.0*RHOTI3*ENL/WI
01870 *
01880 PROCED TIA=ENTIA,DLTTIA,TIAI,T,STIA,TAUTIA,TI3I
01890 IF(ENTIA.EQ.0.) TIA=PDELAY(TI3,TAUTIA,3,TI3I)
01900 IF(ENTIA.EQ.1.AND.T.EQ.0.) TIA=TIAI
01910 IF(ENTIA.EQ.1.AND.T.NE.0.) TIA=TIAI+DLTTIA
01920 IF(ENTIA.EQ.2.0.AND.T.LE.STIA) TIA=TIAI+DLTTIA*T
01930 ENDPRO
01940 *
01950 *
01960 HGS4I=HG(PAS4I)
01970 HGS4=HG(PAS4)
01980 *
01990 TAUHSA=0.92175*ELS7*ENL*RHOGS4/WSAS
02000 HSA=PDELAY(HGS4,TAUHSA,7,HGS4I)
02010 *
02020 HSC=HSH(PSC,TSC)
02030 *
02040 *
02050 CPS=(HSC-HSA)/(TSC-TSA)
02060 *
02070 HASA=(HSA+HSC)/2.0
02080 PSS=(PSA+PSC)/2.0
02090 *
02100 VGS4=VG(PSA)
02110 VSC=VSH(PSC,TSC)
02120 RHOASA=(1./VGS4+1./VSC)/2.0
02130 *
02140 TAI4=(TIA+TIC)/2.0
02150 ROTAI4=RHONA(TAI4)
02160 *
02170 * HEAT TRANSFER COEFFICIENTS IN THE SUPERHEATER
02180 *
02190 PES=0.18802368*(WI/ENS)
02200 HNS=1222.0787+1.9258444*(WI/ENS)**0.8
02210 HWA=144.51325*ENS/(0.0048751818+19.2/HNS)
02220 *
02230 RES=536.289*(WSA/ENS)
02240 HSS=4.2454582*(WSA/ENS)**0.8
02250 HSSA=144.51325*ENS/(0.01901711+29.484029/HSS)
02260 *
02270 *
02280 * II-1. SUPERHEATED STEAM
02290 *
02300 DTSC=(0.0066838/(CPS*RHOASA*ENS))*(HSSA*(TAWA-TASA)
02310 5 -WSA*(HSC-HSA))
02320 TSC.=DTSC
02330 *
02340 *
02350 * II-2. WALL
02360 *
02370 DTAWA=(8.2682436E-5/ENS)*(HWA*(TAIA-TAWA)-HSSA*(TAWA-TASA))
02380 TAWA.=DTAWA
02390 *
02400 * II-3. INTERMEDIATE SODIUM

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02410 *
02420 DTIC=(2.93739E- 3/(ROTAIA*ENS))*(0.3014*HI*(TIA-TIC)
02430 S -HWA*(TAIA-TAWA))
02440 TIC.=DTIC
02450 *
02460 *
02470 * III. EVAPORATOR
02480 *
02490 *
02500 RHOTS6=RHOW(TS1)
02510 TAUHS1=(1.76744*ELS61+1.576246*ELS62+1.22718*ELS63
02520 S +0.441786*ENEVAP*ELS64/ENL)*(ENL*RHOTS6/WS1S)
02530 *
02540 PROCED DHS1=HS1,HS6,TAUHS1,HS1I
02550 IF(ENHS1.EQ.0.0) DHS1=3600.0*(HS6-HS1)/TAUHS1
02560 IF(ENHS1.EQ.1.0.OR.(ENHS1.EQ.2.0.AND.T.GT.SHS1)) DHS1=0.0
02570 IF(ENHS1.EQ.2.0.AND.T.LE.SHS1) DHS1=36.0*DLTHS1*HS1I
02580 ENDPRO
02590 *
02600 PROCED HS1=ENHS1,DLTHS1,HS1I,T,SHS1
02610 IF(ENHS1.EQ.0.0) HS1=PDELAY(HS6,TAUHS1,8,HS1I)
02620 IF(ENHS1.EQ.1.AND.T.EQ.0.0) HS1=HS1I
02630 IF(ENHS1.EQ.1.AND.T.NE.0.0) HS1=HS1I*(1.+DLTHS1/100.0)
02640 IF(ENHS1.EQ.2.AND.T.LE.SHS1) HS1=HS1I*(1.+DLTHS1*T/100.0)
02650 ENDPRO
02660 *
02670 HS2=HF(PAS2)
02680 HAS1=(HS1+HS2)/2.0
02690 TS1=TS1F(HS1)
02700 TSAT=TSATF(PAS2)
02710 TAS1=(TS1+TSAT)/2.0
02720 HFS2=HS2
02730 HGS2=HG(PAS2)
02740 VFS2=VF(PAS2)
02750 RHOF2=1./VFS2
02760 VGS2=VG(PAS2)
02770 RHOGS2=1./VGS2
02780 *
02790 PROCED WS1=ENWS1,DLTWS1,WS1I,T,SWS1,WS1D,ENE
02800 IF(ENWS1.EQ.0.0) WS1=3600.0*ENE*WS1D
02810 IF(ENWS1.EQ.1..AND.T.EQ.0.0) WS1=WS1I
02820 IF(ENWS1.EQ.1..AND.T.NE.0.0) WS1=WS1I*(1.+DLTWS1/100.0)
02830 IF(ENWS1.EQ.2..AND.T.LE.SWS1) WS1=WS1I*(1.+DLTWS1*T/100.0)
02840 ENDPRO
02850 *
02860 PROCED WS3=WS1,WS3D
02870 IF(ENWS1.EQ.0.0) WS3=3600.0*ENE*WS3D
02880 IF(ENWS1.NE.0.0) WS3=WS1
02890 ENDPRO
02900 *
02910 WS1S=ENE*WS1D
02920 WS3S=ENE*WS3D
02930 WS2AD=(WS1D+WS3D)/2.0
02940 *
02950 * HEAT TRANSFER COEFFICIENTS IN THE EVAPORATOR
02960 *
02970 RES1=172.99645*(WS1/ENE)
02980 RES2=187.70115*(WS1/ENE)
02990 HWE=12.817068*(WS1/ENE)**0.8
03000 HDS1=3.1415926*ENE/(0.02478+29.484029/HWE)

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03010      HDS2=126.77825*ENE
03020      *
03030      PEE=0.18186595*(WI/ENE)
03040      HNE=1281.3193+1.9661152*(WI/ENE)**0.8
03050      HDW1=3.1415926*ENE/(0.0048751818+19.2/HNE)
03060      HDW2=HDW1
03070      *
03080      AS1=0.00090347512*ENE
03090      *
03100      ELS2=46.0-ELS1
03110      *
03120      SAI=RHOGS2/RHOPS2
03130      *
03140      *
03150      XS3=HDS2*ELS2*(TAW2-TSAT)/(WS3*(HGS2-HS2))
03160      ALP3=XS3/(SAI+(1.-SAI)*XS3)
03170      ALPSI=ALP3*(1.-SAI)
03180      ALPA2=ALP3*(0.5+ALPSI/6.0+ALPSI*ALPSI/12.)
03190      *
03200      RHOAS1=RHOW(TAS1)
03210      RHOAS2=ALPA2*RHOGS2+(1.-ALPA2)*RHOPS2
03220      RHOS2=ALPA2*RHOGS2*HGS2+(1.-ALPA2)*RHOPS2*HPS2
03230      *
03240      HS3=HGS2*XS3*HPS2*(1.-XS3)
03250      RHOS3=ALP3*RHOGS2+(1.-ALP3)*RHOPS2
03260      *
03270      DRFP2=-(1./VPS2**2.0)*DVP(PAS2)
03280      DRGP2=-(1./VGS2**2.0)*DVG(PAS2)
03290      DRFP2=DHP(PAS2)
03300      DHGP2=DHG(PAS2)
03310      DRHFP2=RHOPS2*DRFP2+HPS2*DRFP2
03320      DRHGP2=RHOGS2*DHGP2+HGS2*DRGP2
03330      *
03340      A=ELS2*(ALPA2*(DRHGP2-DRGP2*HPS2)+(1.-ALPA2)*(DRHFP2-DRFP2*HPS2))
03350      B=ELS1*RHOGS2*DRFP2*(HGS2-HPS2)/(2.0*A*(HS2-HS1))
03360      C=1.0+2.*B*(RHOAS1-RHOPS2)/(RHOPS2-RHOGS2)
03370      *
03380      III-1.  WATER / STEAM
03390      *
03400      DLS1=(2./C)*(-HDS1*ELS1*(TAW1-TAS1)/(AS1*RHOAS1*(HS2-HS1))
03410      +WS1/(AS1*RHOAS1)+(ELS1/2.0)*DHS6/(HS2-HS1)
03420      +B*(WS1-WS3)/(AS1*(RHOPS2-RHOGS2)))
03430      ELS1.=DLS1/3600.0
03440      *
03450      WS2=WS1-AS1*RHOAS1*DLS1
03460      *
03470      DPAS2=(RHOGS2*(HGS2-HPS2)/(A*(RHOPS2-RHOGS2)))*(-(RHOAS1-RHOPS2)
03480      +DLS1*(WS1-WS3)/AS1)
03490      PAS2.=DPAS2/3600.0
03500      *
03510      III-2.  WALL
03520      *
03530      WMHCD=0.073038229*ENE
03540      TW2=(TAW1*ELS1+TAW2*ELS2)/46.0
03550      *
03560      DTAW1=(1./WMHCD)*(-(HDW1+HDS1+WMHCD*DLS1/ELS1)*TAW1
03570      +HDS1*TAS1+HDW1*TAT9)+TW2*DLS1/ELS1
03580      TAW1.=DTAW1/3600.0
03590      *
03600      DTAW2=(1./WMHCD)*(-(HDW2+HDS2+WMHCD*DLS1/ELS2)*TAW2

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03610      $      +HDS2*TSAT+HDW2*TAI7) -TW2*DLS1/ELS2
03620      TAW2.=DTAW2/3600.0
03630      *
03640      *      III-3.  INTERMEDIATE  SODIUM
03650      *
03660      RHOTIC=RHONA(TIC)
03670      TAUT17=703800.0*RHOTIC*ENEVAP/WI
03680      *
03690      PROCED  TI7=ENTI7,DLTTI7,TIC,TI7I,STI7,TAUT17,TICI
03700      IF(ENTI7.EQ.0.)  TI7=PDELAY(TIC,TAUT17,14,TICI)
03710      IF(ENTI7.EQ.1..AND.T.EQ.0.)  TI7=TI7I
03720      IF(ENTI7.EQ.1..AND.T.NE.0.)  TI7=TI7I+DLTTI7
03730      IF(ENTI7.EQ.2..AND.T.LE.STI7)  TI7=TI7I+DLTTI7*T
03740      ENDPRO
03750      *
03760      *
03770      TAI7=(TI7+TI8)/2.0
03780      TAI8=(TI8+TI9)/2.0
03790      *
03800      TIE=(TI7+TI9)/2
03810      RHOIE=RHONA(TIE)
03820      SMHCD=0.0020848433*RHOIE*ENE
03830      WI8=WI+0.00682079*ENE*RHOIE*DLS1
03840      *
03850      DTI8=(1./(SMHCD*ELS2))*(-(HDW2*ELS2-SMHCD*DLS1)*TAI7
03860      $      +HDW2*ELS2*TAW2+0.30566168*(WI*TI7-WI8*TI8))
03870      TI9.=DTI8/3600.0
03880      *
03890      DTI9=(1./(SMHCD*ELS1))*(-(HDW1*ELS1+SMHCD*DLS1)*TAI8
03900      $      +HDW1*ELS1*TAW1+0.30566168*(WI8*TI8-WI*TI9))
03910      TI9.=DTI9/3600.0
03920      *
03930      *
03940      *      WATER / STEAM  LOOP  MOMENTUM  EQUATIONS
03950      *
03960      *
03970      R=RD(PAS2,XS3)
03980      *
03990      TAUWS3=ELS31/(21.25048*ENEVAP)+ELS32/(68.844553*ENL)
04000      TAUWS1=ELS61/(56.9*ENL)+ELS62/(50.755*ENL)
04010      $      +ELS63/(39.515*ENL)+ELS64/(14.22555*ENEVAP)
04020      *
04030      A11T=ELS1/(32.2*AS1)+ELS2/(64.4*AS1)+TAUWS1
04040      A12T=ELS2/(64.4*AS1)+0.30020714/AS1+TAUWS3
04050      A21T=ELS2/(128.8*AS1)
04060      A22T=ELS2/(128.8*AS1)+0.15010357/AS1+TAUWS3
04070      *
04080      DETERM=A11T*A22T-A12T*A21T
04090      *
04100      *      FRICTION  COEFFICINTS
04110      *
04120      PROCED  FS1=RES1
04130      IF(RES1.LT.1000.0)  FS1=8.0/RES1
04140      IF(RES1.GE.1000.0..AND.RES1.LT.100000.0)  FS1=0.05256/(RES1**0.243)
04150      IF(RES1.GE.100000.0)  FS1=0.02117/(RES1**0.164)
04160      ENDPRO
04170      FS1A=102467.41*FS1
04180      *
04190      PROCED  FS2=RES2
04200      IF(RES2.LT.1000.0)  FS2=8.0/RES2

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04210      IF (RES2.GE.1000.0.AND.RES2.LT.100000.0) PS2=0.05256/(RES2**0.243)
04220      IF (RES2.GE.100000.0) PS2=0.02117/(RES2**0.164)
04230      ENDPRO
04240      PS2A=111974.13*PS2
04250      *
04260      DPRC=DPRCSF-FRC*(WS1S/ENL)**2
04270      *
04280      HDSPH=ELS1*RHOAS1+ELS2*RHOAS2+10.208333*RHOS3-52.708333*RHOTS6
04290      $      -(YS5+(DOD-6.0)/2.0)*RHOTS6
04300      CHMPH=(1./(32.2*AS1*AS1))*(WS3S**2/RHOS3-WS1S**2/RHOS2)
04310      PRPH=(PS1A*ELS1+3554.6572*(ENE/ENL)**2.0*PS6)*(WS1D**2.0)
04320      $      +(PS2A*R*ELS2)*(WS2AD**2)+(35304.868+9.66667*PS2A*R)*(WS3D**2)
04330      *
04340      HSPH34=ELS2*RHOAS2/2.0+7.6666665*RHOS3
04350      PRPH34=PS2A*R*ELS2*(WS2AD**2)/2.0+(4.833335*PS2A*R
04360      $      +28309.001)*(WS3D**2)
04370      B1T=(HDSPH+CHMPH-144.0*DPRC+PRPH)
04380      B2T=144.0*(PAS2-PAS4)-HSPH34-CHMPH/2.0-PRPH34
04390      *
04400      WS1DD=(A22T*B1T-A12T*B2T)/(ENE*DETERM)
04410      WS3DD=(A11T*B2T-A21T*B1T)/(ENE*DETERM)
04420      *
04430      PROCD DWS1D=WS1DD
04440      IF (ENWS1.EQ.0.0) DWS1D=WS1DD
04450      IF (ENWS1.NE.0.0) DWS1D=0.0
04460      ENDPRO
04470      *
04480      PROCD DWS3D=WS3DD
04490      IF (ENWS1.EQ.0.0) DWS3D=WS3DD
04500      IF (ENWS1.NE.0.0) DWS3D=0.0
04510      ENDPRO
04520      *
04530      WS1D.=DWS1D
04540      WS3D.=DWS3D
04550      *
04560      *
04570      IV. STEAM DRUM
04580      *
04590      PROCD SV5=ENV5,DLTV5,SV5I,SSV5,T
04600      IF (ENV5.EQ.0.0) SV5=SV5I
04610      IF (ENV5.EQ.1..AND.T.EQ.0.0) SV5=SV5I
04620      IF (ENV5.EQ.1..AND.T.NE.0.0) SV5=SV5I+DLTV5
04630      IF (ENV5.EQ.2..AND.T.LE.SSV5) SV5=SV5I+DLTV5*T
04640      ENDPRO
04650      *
04660      *
04670      TS5=TS1F(HS5)
04680      TAUWS5=ELS5/(21.25*ENL)
04690      DPV5=PV5*(WS5S/(ENL*SV5))**2.0
04700      *
04710      WSSSD=(1./TAUWS5)*(144.0*(PRPH-PAS4)-12.5*RHOW(TS5)
04720      $      -PS5*(WSSS/ENL)**2.-144.*DPV5)
04730      *
04740      PROCD DWS5S=ENWS5,WSSSD
04750      IF (ENWS5.EQ.0.0) DWS5S=WSSSD
04760      IF (ENWS5.NE.0.0) DWS5S=0.0
04770      ENDPRO
04780      *
04790      WSSS.=DWS5S
04800      *

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04810      PROCD  WS5=DLTWS5,SWSS,WS5I
04820      IF (ENWS5.EQ.0.0)  WS5=3600.0*WS5S
04830      IF (ENWS5.EQ.1..AND.T.EQ.0.0)  WS5=WS5I
04840      IF (ENWS5.EQ.1..AND.T.NE.0.0)  WS5=WS5I*(1.+DLTWS5/100.0)
04850      IF (ENWS5.EQ.2..AND.T.LE.SWS5)  WS5=WS5I*(1.+DLTWS5*T/100.0)
04860      ENDPRO
04870      *
04880      HS5D=(WSC*HSC-3.412E6*PT/0.39754)/WS5
04890      *
04900      PROCD  HS5=ENHS5,DLTHS5,T,SHS5,HS5I,HS5D
04910      IF (ENHS5.EQ.0.0)  HS5=HS5D
04920      IF (ENHS5.EQ.1..AND.T.EQ.0.0)  HS5=HS5I
04930      IF (ENHS5.EQ.1..AND.T.NE.0.0)  HS5=HS5I*(1.+DLTHS5/100.0)
04940      IF (ENHS5.EQ.2..AND.T.LE.SHS5)  HS5=HS5I*(1.+DLTHS5*T/100.0)
04950      ENDPRO
04960      *
04970      PROCD  WS4=ENWS4,DLTWS4,T,SWS4,WS4I,WS3
04980      IF (ENWS4.EQ.0.0)  WS4=WS3
04990      IF (ENWS4.EQ.1..AND.T.EQ.0.0)  WS4=WS4I
05000      IF (ENWS4.EQ.1..AND.T.NE.0.0)  WS4=WS4I*(1.+DLTWS4/100.0)
05010      IF (ENWS4.EQ.2..AND.T.LE.SWS4)  WS4=WS4I*(1.+DLTWS4*T/100.0)
05020      ENDPRO
05030      *
05040      TAUHS4=(0.66*ENEVAP*ELSG1/ENL+2.1380*ELSG2)*(ENL*RHOS3/WS3S)
05050      *
05060      PROCD  HS4=ENHS4,DLTHS4,T,SHS4,HS4I,HS3
05070      IF (ENHS4.EQ.0.0)  HS4=DELAY(HS3,TAUHS4,9,HS4I)
05080      IF (ENHS4.EQ.1..AND.T.EQ.0.0)  HS4=HS4I
05090      IF (ENHS4.EQ.1..AND.T.NE.0.0)  HS4=HS4I*(1.+DLTHS4/100.0)
05100      IF (ENHS4.EQ.2..AND.T.LE.SHS4)  HS4=HS4I*(1.+DLTHS4*T/100.0)
05110      ENDPRO
05120      *
05130      PROCD  WS6=ENWS6,WS6I,WS1
05140      IF (ENWS6.EQ.0.0)  WS6=WS1
05150      IF (ENWS6.NE.0.0)  WS6=WS6I
05160      ENDPRO
05170      *
05180      PROCD  WS7=ENWS7,WS7I,WSA
05190      IF (ENWS7.EQ.0.0)  WS7=WSA
05200      IF (ENWS7.NE.0.0)  WS7=WS7I
05210      ENDPRO
05220      *
05230      VFS4=VF(PAS4)
05240      RHOPFS4=1./VFS4
05250      *
05260      EMS4=RHOGS4*(DV-EMS5/RHOPFS4)
05270      *
05280      EMS4D=DELAY(EMS4,0.2,5,EMS4I)
05290      DEMS4=18000.0*(EMS4-EMS4D)
05300      *
05310      DEMS5=(WS4+WS5-WS6-WS7)/ENL-DEMS4
05320      EMS5.=DEMS5/3600.0
05330      *
05340      D=EMS4*DVG(PAS4)+EMS5*DVF(PAS4)
05350      DPAS4=(-1./D)*(VGS4*DEMS4+VFS4*DEMS5)
05360      PAS4.=DPAS4/3600.0
05370      *
05380      DHS6=(1./(ENL*EMS5))*(WS4*HS4+WS5*HS5-WS6*HS6-WS7*HGS4
05390      $      -ENL*(HGS4*DEMS4+HS6*DEMS5+EMS4*DHG(PAS4)+DPAS4))
05400      HS6.=DHS6/3600.0

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V. INTERMEDIATE HEAT EXCHANGER

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PROCED WP=ENWP,DLTWP,WPI,T,SWP
IF(ENWP.EQ.0.) WP=3600.0*WPS
IF(ENWP.EQ.1.AND.T.EQ.0.) WP=WPI
IF(ENWP.EQ.1.AND.T.NE.0.) WP=WPI*(1.+DLTWP/100.0)
IF(ENWP.EQ.2.0.AND.T.LE.SWP) WP=WPI*(1.+DLTWP*T/100.0)
ENDPROC

RHOTP4=RHONA(TP4)
TAUTP5=4071600.0*RHOTP4*ENL/WP

PROCED TP5=ENTP5,DLTTP5,TAUTP5,TP4I,TP4,TP5I,T,STP5
IF(ENTP5.EQ.0.) TP5=PDELAY(TP4,TAUTP5,2,TP4I)
IF(ENTP5.EQ.1.AND.T.EQ.0.) TP5=TP5I
IF(ENTP5.EQ.1.AND.T.NE.0.) TP5=TP5I+DLTTP5
IF(ENTP5.EQ.2.0.AND.T.LE.STP5) TP5=TP5I+DLTTP5*T
ENDPROC

TAP5=(TP5+TP7)/2.0
TAI1=(TI1+TI3)/2.0

HEAT TRANSFER COEFFICIENTS IN THE IHX

HNIP=1906.8776+2.2875323*(WP/ENI)**0.8
HNII=2476.4331+3.1930386*(WI/ENI)**0.8
HI=227149.4/(0.007650483+15.286624/HNII+13.714285/HNIP)

ROTAP5=RHONA(TAP5)

TP7.= (2.0488692E-6/ROTAP5)*(-HI*(TAP5-TAI1)
+0.3032*WP*(TP5-TP7)/ENL)

RHOTI1=RHONA(TI9)
TAUTI1=4968000.0*RHOTI1*ENL/WI

PROCED TI1=ENTI1,DLTTI1,TAUTI1,TI9I,TI9,TI1I,T,STI1
IF(ENTI1.EQ.0.) TI1=PDELAY(TI9,TAUTI1,4,TI9I)
IF(ENTI1.EQ.1.AND.T.EQ.0.) TI1=TI1I
IF(ENTI1.EQ.1.AND.T.NE.0.) TI1=TI1I+DLTTI1
IF(ENTI1.EQ.2.0.AND.T.LE.STI1) TI1=TI1I+DLTTI1*T
ENDPROC

ROTAI1=RHONA(TAI1)
TI3.= (3.7545E-6/ROTAI1)*(HI*(TAP5-TAI1)
+0.30445*WI*(TI1-TI3)/ENL)

VI. REACTOR

VI-1. POINT KINETIC EQUATIONS
WITH FEEDBACK

BETA=3.65E-3
BD= (0.8254*D1+7.756*D2+6.66*D3+13.54*D4
+5.908*D5+1.81*D6)*1.0E-4

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06010      BDOB=BD/BETA
06020      RHOFBC=(100.0*DC/BETA)*ALOG((460.0+TAP)/(460.0+TAPI))
06030      S  +AXECC*TAP+SODDCC*TAP1+RECC*TP1+ROFBCI
06040      RHOFBD=RHOFBC/100.0
06050      *
06060      PROCD RHOD=ENROC,DLTROC,RHOCDI,T,SROC
06070      IF(ENROC.EQ.0.) RHOD=RHOCDI
06080      IF(ENROC.EQ.1.AND.T.EQ.0.) RHOD=RHOCDI
06090      IF(ENROC.EQ.1.AND.T.NE.0.) RHOD=RHOCDI+DLTROC/100.0
06100      IF(ENROC.EQ.2.0.AND.T.LE.SROC) RHOD=RHOCDI+DLTROC*T/100.0
06110      ENDPRO
06120      *
06130      RHOD=RHOD+RHOFBD
06140      *
06150      EN=BDOB/(1.0 - RHOD)
06160      *
06170      D1.=0.0129*(EN-D1)
06180      D2.=0.0312*(EN-D2)
06190      D3.=0.1330*(EN-D3)
06200      D4.=0.3450*(EN-D4)
06210      D5.=1.4100*(EN-D5)
06220      D6.=3.7500*(EN-D6)
06230      *
06240      *      VI-2. REACTOR THERMODYNAMIC EQUATIONS
06250      *
06260      *
06270      TFC=(5./9.)*(TAP-32.0)
06280      TFK=TFC+273.0
06290      AKF=36.100867/(TFK+129.2)+5.782936E-13*TFK**3.0
06300      AKF=57.78*AKF
06310      WPD=PPC*WB/ENP
06320      HC=14861.86+51.921027*WPD**0.8
06330      HR=9.4247778*ENP/(0.125/AKF+60.00024/HDG+52.173914/HC
06340      S  +0.0052151492)
06350      *
06360      *
06370      TAP.=2.5208831E- 7*(EPS*PPGC*EN-HR*(TAP-TAP1))
06380      *
06390      RHOTR1=RHONA(TP7)
06400      RHOTP1=RHONA(TP1)
06410      TAUTR1=1796400.0*RHOTR1*ENL/WP
06420      *
06430      PROCD TR1=ENTR1,DLTTR1,TAUTR1,TP7I,TP7,TR1I,T,STR1
06440      IF(ENTR1.EQ.0.) TR1=PDLAY(TP7,TAUTR1,1,TP7I)
06450      IF(ENTR1.EQ.1.AND.T.EQ.0.) TR1=TR1I
06460      IF(ENTR1.EQ.1.AND.T.NE.0.) TR1=TR1I+DLTTR1
06470      IF(ENTR1.EQ.2.0.AND.T.LE.STR1) TR1=TR1I+DLTTR1*T
06480      ENDPRO
06490      *
06500      DTP1=(WP/(3600.0*VP1*RHOTP1))*(TR1-TP1)
06510      TP1.=DTP1
06520      *
06530      TAP1=(TP1+TP3)/2.0
06540      ROTAP1=RHONA(TAP1)
06550      RHOTP3=RHONA(TP3)
06560      RHOTR3=RHONA(TR3)
06570      *
06580      TP3.= (3.4093E-5/ROTAP1)*(HR*(TAP-TAP1)
06590      S  +0.3032*PPC*WP*(TP1-TP3))
06600      TR3.= (3.71815E-7/(RHOTP1+RHOTR3))*(EPS*EN-0.3032*WP*(TR3-TP1))

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06610      TP4.= (WP/ (3600.0*VP4*RHOTP4)) * (TR3-TP4)
06620      *
06630      *      PRIMARY AND INTERMEDIATE LOOPS MOMENTUM EQUATIONS
06640      *
06650      QPP=1.24657E-4*WP/ (ENL*RHOTP4)
06660      HOPP=HMM (ENPP,QPP)
06670      QPONP=QPP/ENPP
06680      ETAPP=0.019275+69.86*QPONP-1970.0*QPONP**2.0+16531.46*QPONP**3.0
06690      ENPP.= (9.5493/AIPP) * (TRQPP-0.02847*WP*HOPP/ (ENPP*ETAPP))
06700      *
06710      TAUWP=3.5491816/ENL+1421.9498*PFC/ENP
06720      DWPST=15.9392*RHOTR1-11.0*RHOTP1-3.0*ROTAP1-5.68333*RHOTP3
06730      $      + (HOPP-21.403855)*RHOTP4+25.369791*ROTAP5
06740      $      - (6.5714464E-4/ENL**2+P143* (PFC/ENSUB)**2.+9.7776E-6)
06750      $      * (WPS**2.)
06760      PROCED DWPS=ENWP,TAUWP,DWPST
06770      IF (ENWP.EQ.0.0) DWPS=DWPST/TAUWP
06780      IF (ENWP.NE.0.0) DWPS=0.0
06790      ENDPRO
06800      *
06810      WPS.=DWPS
06820      *
06830      *
06840      QIP=1.24657E-4*WI/ (ENL*RHOTI1)
06850      HOIP=HMM (ENIP,QIP)
06860      QIONI=QIP/ENIP
06870      ETAIP=0.006337+72.0258*QIONI-2049.*QIONI**2+17671.51*QIONI**3
06880      ENIP.= (9.5493/AIIP) * (TRQIP-0.02847*WI*HOIP/ (ENIP*ETAIP))
06890      *
06900      TAUWI=2.4431/ENEVAP+14.356/ENL
06910      DWIST= (HOIP+7.815098)*RHOTI1-25.36979*ROTAI1
06920      $      -17.86197*RHOTI3+35.416666* (ROTAIA+RHOIE-RHOTIC)
06930      $      - (1.1521861E-3/ENEVAP**2.+1.148583E-3/ENL**2.) * (WIS**2.)
06940      PROCED DWIS=ENWI,TAUWI,DWIST
06950      IF (ENWI.EQ.0.0) DWIS=DWIST/TAUWI
06960      IF (ENWI.NE.0.0) DWIS=0.0
06970      ENDPRO
06980      *
06990      WIS.=DWIS
07000      *
07010      *
07020      *      MAX. AVERAGE AND HOT CHANNEL TEMPERATURES
07030      *      AND THEIR LOCATIONS RELATIVE TO CORE CENTRAL PLANE
07040      *
07050      HRM=      1. / (0.25 /AKF+60.00024/HDG+52.173914/HC +0.0052151492)
07060      HRS=1./ (60.00024/HDG+52.173914/HC+0.0052151492)
07070      *
07080      *
07090      *      THE THEORITICAL LOCATIONS OF THE MAX. TEMPS. AT THE PIN-CLAD
07100      *      OUTER SURFACE,PIN SURFACE,AND FUEL PIN CENTER LINE IN THE AVG. CHANNEL
07110      *
07120      YCNXTH=1.5078339*ATAN (0.29944753*HC/WPD)
07130      YSNXTH=1.5078339*ATAN (15.62335*HRS/WPD)
07140      YFNXTH=1.5078339*ATAN (15.62335*HRM/WPD)
07150      *
07160      *
07170      *THE ACTUAL LOCATION OF THE PIN-CLAD OUTER SURFACE MAX. TEMP. IN THE AVG.CHANNEL
07180      *
07190      PROCED YCNAX=YCNXTH
07200      IF (YCNXTH.LT.1.5) YCNAX=YCNXTH

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07210      IF (YCNXTH.GE.1.5)  YCMAX=1.5
07220      ENDPRO
07230      *
07240      *THE ACTUAL LOCATION OF THE FUEL PIN MAX. SURFACE TEMP. IN THE AVG CHANNEL
07250      *
07260      PROCED  YSMAX=YSNXTH
07270      IF (YSNXTH.LT.1.5)  YSMAX=YSNXTH
07280      IF (YSNXTH.GE.1.5)  YSMAX=1.5
07290      ENDPRO
07300      *
07310      *THE ACTUAL LOCATION OF THE FUEL PIN MAX. CENTER LINE TEMP. IN THE AVG. CHANNEL
07320      *
07330      PROCED  YPMAX=YPMXTH
07340      IF (YPMXTH.LT.1.5)  YPMAX=YPMXTH
07350      IF (YPMXTH.GE.1.5)  YPMAX=1.5
07360      ENDPRO
07370      *
07380      *   THE THEORETICAL LOCATIONS OF THE MAX. TEMPS. AT THE PIN-CLAD
07390      *   OUTER SURFACE, PIN SURFACE, AND FUEL PIN CENTER LINE IN THE HOT CHANNEL
07400      *
07410      YCNTH=1.5078339*ATAN(0.17787267*HC/WPD)
07420      YSMTH=1.5078339*ATAN(0.001401791/(WPD*(0.0078808679/HC
07430      5   +4.4692799E- 7+0.0063842402/HDG)))
07440      YPMTH=1.5078339*ATAN(0.001401791/(WPD*(0.0078808679/HC
07450      3   +4.4692799E- 7+0.0063842402/HDG+1.9770937E- 5/ARF)))
07460      *
07470      *THE ACTUAL LOCATION OF THE PIN-CLAD OUTER SURFACE MAX. TEMP. IN THE HOT CHANNEL
07480      *
07490      PROCED  YCNH=YCNTH
07500      IF (YCNTH.LT.1.5)  YCNH=YCNTH
07510      IF (YCNTH.GE.1.5)  YCNH=1.5
07520      ENDPRO
07530      *
07540      *THE ACTUAL LOCATION OF THE FUEL PIN MAX. SURFACE TEMP. IN THE HOT CHANNEL
07550      *
07560      PROCED  YSMH=YSMTH
07570      IF (YSMTH.LT.1.5)  YSMH=YSMTH
07580      IF (YSMTH.GE.1.5)  YSMH=1.5
07590      ENDPRO
07600      *
07610      *THE ACTUAL LOCATION OF THE FUEL PIN MAX. CENTER LINE TEMP. IN THE HOT CHANNEL
07620      *
07630      PROCED  YPMH=YPMTH
07640      IF (YPMTH.LT.1.5)  YPMH=YPMTH
07650      IF (YPMTH.GE.1.5)  YPMH=1.5
07660      ENDPRO
07670      *
07680      *
07690      *
07700      *VOLUMETRIC HEAT GENERATION AT THE CENTER OF THE FUEL PIN IN THE AVG. CHANNEL
07710      *
07720      QC=0.045077766*EPS*PPGC*EN
07730      *
07740      *COOLANT MAX. TEMP. AT THE EXIT OF THE AVG. CHANNEL
07750      *
07760      TPNAX=TP1+7.6761921E- 5*EPS*PPGC*EN/WPD
07770      *
07780      *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
07790      *OF THE MAX. TEMP. AT THE PIN-CLAD OUTER SURFACE IN THE AVG. CHANNEL
07800      *

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07810      DTP1CX=(4.5780019E- 5*EPS*PPGC*EN/WPD)
07820      $      *(0.838378+SIN(0.66320299*YCMAX))
07830      *
07840      *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
07850      *OF THE MAX. TEMP. AT THE PIN-CLAD OUTER SURFACE IN THE HOT CHANNEL
07860      *
07870      DTP1CH=(5.06327E- 5*EPS*PPGC*EN/WPD)
07880      $      *(0.838378+SIN(0.66320299*YCHM))
07890      *
07900      *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
07910      *PIN-CLAD OUTER SURFACE IN THE AVG. CHANNEL
07920      *
07930      TPYCNX=TP1+DTP1CX
07940      *
07950      *THE DIFFERENCE BETWEEN THE PIN-CLAD OUTER SURFACE TEMP. AND THE
07960      *SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE CLAD
07970      *OUTER SURFACE IN THE AVG. CHANNEL
07980      *
07990      DTPCNX=0.0033915082*QC*COS(0.66320299*YCMAX)/HC
08000      *
08010      *THE DIFFERENCE BETWEEN THE PIN-CLAD OUTER SURFACE TEMP. AND THE
08020      *SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE CLAD
08030      *OUTER SURFACE IN THE HOT CHANNEL
08040      *
08050      DTPCH=0.0033915082*QC*COS(0.66320299*YCHM)/HC
08060      *
08070      *MAX. PIN-CLAD OUTER SURFACE TEMP. IN THE AVG. CHANNEL
08080      *
08090      TCMAX=TPYCNX+DTPCNX
08100      *
08110      *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
08120      *OF THE MAX. TEMP. AT THE FUEL PIN SURFACE IN THE AVG. CHANNEL
08130      *
08140      DTP1SX=(4.5780019E- 5*EPS*PPGC*EN/WPD)
08150      $      *(0.838378+SIN(0.66320299*YSMAX))
08160      *
08170      *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
08180      *FUEL PIN SURFACE IN THE HOT CHANNEL
08190      *
08200      DTP1SH=(5.06327E- 5*EPS*PPGC*EN/WPD)
08210      $      *(0.838378+SIN(0.66320299*YSHM))
08220      *
08230      *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
08240      *FUEL PIN SURFACE IN THE AVG. CHANNEL
08250      *
08260      TPYSNX=TP1+DTP1SX
08270      *
08280      *MAX. FUEL PIN SURFACE TEMP. IN THE AVG. CHANNEL
08290      *
08300      TSMAX=TPYSNX+6.5003905E- 5*QC*COS(0.66320299*YSMAX)/HRS
08310      *
08320      *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
08330      *OF THE MAX. TEMP. AT THE FUEL PIN CENTER LINE IN THE AVG. CHANNEL
08340      *
08350      DTP1FX=(4.5780019E- 5*EPS*PPGC*EN/WPD)
08360      $      *(0.838378+SIN(0.66320299*YFMAX))
08370      *
08380      *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
08390      *OF THE MAX. TEMP. AT THE FUEL PIN CENTER LINE IN THE HOT CHANNEL
08400      *

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08410      DTP1FM=(5.06327E- 5*EPS*PPGC*EN/WPD)
08420      $      *(0.338378+SIN(0.66320299*YFMM))
08430      *
08440      *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
08450      *FUEL PIN AT ITS CENTER LINE IN THE AVG. CHANNEL
08460      *
08470      *
08480      TPIYFMX=TP1+DTP1FX
08490      *MAX. FUEL PIN TEMP. AT ITS CENTER LINE IN THE AVG. CHANNEL
08500      *
08510      TFMX=TPIYFMX+6.5003905E- 5*QC*COS(0.66320299*YFMX)/HPM
08520      *
08530      *COOLANT MAX. TEMP. IN THE HOT CHANNEL
08540      *
08550      TFM=1.248*(TP1+8.4898684E-5*EPS*PPGC*EN/WPD)
08560      *
08570      *PIN-CLAD MAX. OUTER SURFACE TEMP. IN THE HOT CHANNEL
08580      *
08590      TCM=1.248*(TP1+DTP1CM)+2.323706*DTPCM
08600      *
08610      *FUEL PIN MAX. SURFACE TEMP. IN THE HOT CHANNEL
08620      *
08630      TSM=1.248*(TP1+DTP1SM) +(0.0078808679/HC+4.4692799E- 7
08640      $      +0.0063842402/HDG)*QC*COS(0.66320299*YSM)
08650      *
08660      *FUEL PIN MAX. CENTER LINE TEMP. IN THE HOT CHANNEL
08670      *
08680      TFM=1.248*(TP1+DTP1FM) +(0.0078808679/HC+4.4692799E- 7
08690      $      +0.0063842402/HDG+1.9770937E- 5/AKF)*QC*COS(0.66320299*YFM)
08700      *
08710      *
08720      STORE , WS9,PS9,TS9,HS9,SS9,XEXH,HEXH,STWBTU,PT,PGFETA,PONG,PGE,
08730      $      PGA,PETAG,ONGG,AI,E,PF,XD,WSA,WSC,RHOASA,CPS,PSA,PSC,TSA,
08740      $      TSC,RSA,HSC,TIC,TASA,TAWA,TAIA,ELS1,ELS2,WS1,WS3,XS3,ALP3,HS3,
08750      $      TAW1,TAW2,TAI7,TAI8,TAI9,PAS2,ALPA2,HS1,TS1,TSAT,B1T,B2T,
08760      $      DETERM,EMS4,EMS5,YS5,PAS4,HS6,RHOD,EN,TAF,TAP1,TAP5,TAI1,TAI3,
08770      $      TAUTR1,TP7,TP1,TAUTP5,TP3,TP4,TP5,WP,WI,TPMAX,TPMH,YCMAX,YCMH,
08780      $      TCMAX,TCMH,YSMAX,TSMAX,YSMH,TSNH,YPMAX,TFMAX,YFMH,TFMH,
08790      $      DWPST,DWIST,TAUWP,TAUWI,WS5,TS5,QPP,HOPP,QIP,HOIP,TR1
08800      $      ,TIA,TAI7,TAI8,TAI1,TAS1,TR3,TAUTS9,TAUHS9,TAUHS4,TAUTI1,
08810      $      TAUHS1,TAUTI7,TAUTIA,ENPP,ETAPP,ENIP,ETAIP
08820      $      ,HDW1,HDS1,RHOIE,HSSA,HWA,ROTAIA
08830      ST1
08840      RHONA , 6
08850      *      NEXT IS THE INDEPENDENT VARIABLE FOLLOWED BY THE DEPENDENT
08860      392.0      ,56.4
08870      572.0      ,55.1
08880      752.0      ,53.6
08890      932.0      ,52.1
08900      1112.0     ,50.5
08910      1292.0     ,48.9
08920      ST2
08930      TS1F , 12
08940      374.97      ,400.0
08950      396.77      ,420.0
08960      418.9       ,440.0
08970      430.1       ,450.0
08980      441.4       ,460.0
08990      464.4       ,480.0
09000      487.8       ,500.0

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09010		511.9	,520.0
09020		536.6	,540.0
09030		562.2	,560.0
09040		588.9	,580.0
09050		610.0	,600.0
09060	ST3		
09070	RHOW , 12		
09080		400.0	,53.648
09090		420.0	,52.798
09100		440.0	,51.921
09110		450.0	,51.546
09120		460.0	,51.02
09130		480.0	,50.0
09140		500.0	,49.02
09150		520.0	,47.847
09160		540.0	,46.512
09170		560.0	,45.249
09180		580.0	,43.860
09190		600.0	,43.373
09200	ST4		
09210	VF , 6		
09220		1200.0	,0.0223
09230		1300.0	,0.0227
09240		1400.0	,0.0231
09250		1500.0	,0.0235
09260		2000.0	,0.0257
09270		2500.0	,0.0287
09280	ST5		
09290	HF , 6		
09300		1200.0	,571.7
09310		1300.0	,585.4
09320		1400.0	,598.7
09330		1500.0	,611.6
09340		2000.0	,671.7
09350		2500.0	,730.6
09360	ST6		
09370	TSATP , 6		
09380		1200.0	,567.22
09390		1300.0	,577.46
09400		1400.0	,587.1
09410		1500.0	,596.23
09420		2000.0	,635.82
09430		2500.0	,668.13
09440	ST7		
09450	VG , 6		
09460		1200.0	,0.3619
09470		1300.0	,0.3293
09480		1400.0	,0.3012
09490		1500.0	,0.2765
09500		2000.0	,0.1878
09510		2500.0	,0.1307
09520	ST8		
09530	RG , 6		
09540		1200.0	,1183.4
09550		1300.0	,1178.6
09560		1400.0	,1173.4
09570		1500.0	,1167.9
09580		2000.0	,1135.1
09590		2500.0	,1091.1
09600	ST9		

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09610      RD , 3 , 5
09620      *
09630      * THE FOLLOWING IS A DEFINITION OF THE SECOND
09640      * INDEPENDENT VARIABLE.
09650      *
09660              0.2      ,0.4      ,0.6      ,0.8      ,1.0
09670      *
09680      * NEXT COMES THE FIRST INDEPENDENT VARIABLE
09690      * FOLLOWED BY THE DEPENDENT VARIABLE
09700      *
09710              1000.0      ,4.81801      ,7.43707      ,10.6082      ,12.915      ,14.4123
09720              2000.0      ,2.48938      ,3.21363      ,4.30274      ,4.97874      ,5.35559
09730              2500.0      ,1.72844      ,2.23131      ,2.6778      ,2.98751      ,2.98751
09740      ST10
09750      VSH , 6,5
09760              700.0      ,800.0      ,900.0      ,1000.0      ,1200.0
09770              1200.0      ,0.4909      ,0.5617      ,0.6250      ,0.6843      ,0.7967
09780              1400.0      ,0.4062      ,0.4714      ,0.5281      ,0.5805      ,0.6789
09790              1600.0      ,0.3417      ,0.4034      ,0.4553      ,0.5027      ,0.5906
09800              1800.0      ,0.2907      ,0.3502      ,0.3986      ,0.4421      ,0.5218
09810              2000.0      ,0.2489      ,0.3074      ,0.3532      ,0.3935      ,0.4668
09820              2500.0      ,0.1686      ,0.2294      ,0.2710      ,0.3061      ,0.3678
09830      ST11
09840      HSH , 6,5
09850              700.0      ,800.0      ,900.0      ,1000.0      ,1200.0
09860              1200.0      ,1311.0      ,1379.3      ,1440.7      ,1499.2      ,1613.1
09870              1400.0      ,1295.5      ,1369.1      ,1433.1      ,1493.2      ,1609.9
09880              1600.0      ,1278.7      ,1358.4      ,1425.3      ,1487.0      ,1604.6
09890              1800.0      ,1260.3      ,1347.2      ,1417.4      ,1480.8      ,1600.4
09900              2000.0      ,1240.0      ,1335.5      ,1409.2      ,1474.5      ,1596.1
09910              2500.0      ,1176.8      ,1303.6      ,1387.8      ,1458.4      ,1585.3
09920      ST12
09930      S9 , 6,5
09940              700.0      ,800.0      ,900.0      ,1000.0      ,1200.0
09950              1200.0      ,1.4843      ,1.5409      ,1.5859      ,1.6293      ,1.7025
09960              1400.0      ,1.4567      ,1.5177      ,1.5666      ,1.6093      ,1.6386
09970              1600.0      ,1.4304      ,1.4964      ,1.5476      ,1.5914      ,1.6669
09980              1800.0      ,1.4044      ,1.4765      ,1.5301      ,1.5752      ,1.6520
09990              2000.0      ,1.3783      ,1.4576      ,1.5139      ,1.5603      ,1.6394
10000              2500.0      ,1.3073      ,1.4127      ,1.4772      ,1.5273      ,1.6088
10010      ST13
10020      HMM , 9,12
10030              0.0      ,4.0      ,8.0      ,12.0      ,16.0
10040      $      ,20.0      ,24.0      ,28.0      ,32.0      ,36.0      ,40.0
10050      $      ,44.0
10060      $      ,500.0      ,98.8      ,97.8      ,94.9      ,89.2      ,79.5
10070      $      ,65.7      ,50.0      ,32.0      ,22.0      ,10.0      ,5.0
10080      $      ,2.0
10090      $      ,980.0      ,380.0      ,378.0      ,376.0      ,370.0      ,363.0
10100      $      ,353.0      ,340.0      ,322.0      ,302.0      ,277.0      ,244.0
10110      $      ,210.0
10120      $      ,1006.0      ,400.0      ,398.5      ,396.0      ,391.0      ,384.0
10130      $      ,374.0      ,361.0      ,342.647      ,308.92      ,300.0      ,266.0
10140      $      ,230.0
10150      $      ,1030.0      ,419.0      ,418.0      ,415.0      ,410.0      ,404.0
10160      $      ,393.0      ,380.0      ,364.0      ,343.0      ,319.0      ,288.0
10170      $      ,253.0
10180      $      ,1150.0      ,514.0      ,512.0      ,510.0      ,504.0      ,496.0
10190      $      ,486.0      ,470.0      ,454.0      ,440.0      ,420.0      ,390.0
10200      $      ,355.0

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10210		1170.0	,532.0	,531.0	,528.0	,522.0	,514.0
10220	\$	,504.0	,489.0	,472.0	,463.6156	,431.5789	,410.0
10230	\$	,375.0					
10240		1200.0	,560.0	,558.0	,555.0	,549.0	,541.5
10250	\$	,531.0	,516.0	,500.0	,485.0	,466.0	,439.0
10260	\$	,404.0					
10270		1400.0	,775.0	,773.0	,770.0	,765.0	,758.0
10280	\$	,749.0	,738.0	,723.0	,705.0	,684.0	,658.0
10290	\$	,634.0					
10300		1500.0	,874.0	,872.0	,870.0	,865.0	,856.0
10310	\$	,846.0	,833.0	,817.0	,797.0	,776.0	,758.0
10320	\$	,736.0					
10330	*						
10340	ST14						
10350	END	13					
10360		0.0	,380.0				
10370		3600.0	,381.5				
10380		7200.0	,382.3				
10390		10800.0	,383.5				
10400		14400.0	,384.7				
10410		18000.0	,388.0				
10420		21600.0	,391.0				
10430		25200.0	,392.0				
10440		28800.0	,392.2				
10450		32400.0	,392.1				
10460		36000.0	,391.9				
10470		39600.0	,391.0				
10480		43200.0	,390.0				
10490	ST						
10500	FUNCTION DHF(PAS)						
10510	PAS21=PAS-50.0						
10520	PAS22=PAS+50.0						
10530	HF1=HF(PAS21)						
10540	HF2=HF(PAS22)						
10550	DHF=(HF2-HF1)/100.0						
10560	RETURN						
10570	END						
10580	FUNCTION DVF(PAS)						
10590	PAS21=PAS-50.0						
10600	PAS22=PAS+50.0						
10610	VF1=VF(PAS21)						
10620	VF2=VF(PAS22)						
10630	DVF=(VF2-VF1)/100.0						
10640	RETURN						
10650	END						
10660	FUNCTION DVG(PAS)						
10670	PAS21=PAS-50.0						
10680	PAS22=PAS+50.0						
10690	VG1=VG(PAS21)						
10700	VG2=VG(PAS22)						
10710	DVG=(VG2-VG1)/100.0						
10720	RETURN						
10730	END						
10740	FUNCTION DHG(PAS)						
10750	PAS21=PAS-50.0						
10760	PAS22=PAS+50.0						
10770	HG1=HG(PAS21)						
10780	HG2=HG(PAS22)						
10790	DHG=(HG2-HG1)/100.0						
10800	RETURN						

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10810      END
10820      *
10830      $F
10840      FUNCTION PDELAY(XC,TAU,I,XCI)
10850      C
10860      C PIPE DELAY FUNCTION FOR THE DARE P RUNTIME SYSTEM
10870      C
10880      C XC = VARIABLE TO BE DELAYED
10890      C
10900      C TAU = AMOUNT OF DELAY BEFORE PRESENT VALUE OF XC IS VALID.
10910      C      (VARIABLE, ANY VALUE .GE. ZERO)
10920      C
10930      C I = INTEGER CONSTANT BETWEEN 1 AND IMAX IDENTIFYING
10940      C      INDEPENDENT PDELAY OPERATORS
10950      C
10960      C XCI = INITIAL VALUE OF XC (VALUE RETURNED UNTIL T .GT. TAU(0) )
10970      C
10980      C PDELAY MODELS AN INCOMPRESSIBLE FLUID FLOWING THROUGH A UNIT
10990      C LENGTH PIPE AT A VELOCITY OF 1./TAU
11000      C
11010      LOGICAL WRAP
11020      LOGICAL EXIT,RLDONE
11030      COMMON /SYSVAR/ EXIT,RLDONE,IOUT,IFILE,IRUNNO,T,TMAX,TNEXT
11040      COMMON /SYSVAR/ DT,DTMAX,DTMIN,ENAX,EMIN,ST(35)
11050      COMMON DELAY(8101)
11060      COMMON TNS(20),NP(20),WRAP(20),TSAV(100,20),XSAV(100,20),TAUL(20)
11070      1,XCL(20)
11080      DATA NPA/100/,IMAX/20/
11090      C
11100      PDELAY=XCI
11110      DUMMY=XC
11120      IF(EXIT) RETURN
11130      IF(I.GT.0.AND.I.LE.IMAX) GO TO 4
11140      WRITE(IOUT,3) I
11150      3      FORMAT(36H FATAL ERROR - INVALID PDELAY NUMBER,I3)
11160      CALL ABORT
11170      4      IF(TAU.GE.0.) GO TO 7
11180      WRITE(IOUT,6) I,IRUNNO,T
11190      6      FORMAT(15H ERROR - PDELAY,I3,9H NEGATIVE/
11200      2      7H - RUN,I4,19H TERMINATED AT T =,1PE12.5)
11210      EXIT=.TRUE.
11220      RETURN
11230      C
11240      C IF T.EQ.0, INITIALIZE
11250      C
11260      7      IF(T.GT.0.) GO TO 8
11270      NP(I)=1
11280      TNS(I)=AMAX1(DT,TAU*2./FLOAT(NPA))
11290      WRAP(I)=.FALSE.
11300      TSAV(1,I)=TAU
11310      XSAV(1,I)=XC
11320      TSAV(NPA,I)=0.
11330      TAUL(I)=TAU
11340      XCL(I)=XC
11350      GO TO 12
11360      C
11370      C IF T.GE.TNS, SAVE X AND T, CALCULATE TNS
11380      C
11390      8      IF(T.LT.TNS(I).OR..NOT.RLDONE) GO TO 12
11400      C

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11410 C IF TAU DIFFERS FROM LAST CALL, ADJUST TSAV ARRAY TO MATCH NEW
11420 C PIPE VELOCITY
11430 C
11440 IF (TAU.EQ.TAUL(I)) GO TO 10
11450 N=NP(I)
11460 9 IF (T.GE.TSAV(N,I)) GO TO 10
11470 TSAV(N,I) = (TSAV(N,I)-T)*TAU/TAUL(I)+T
11480 N=MOD(N-2+NPA,NPA)+1
11490 GO TO 9
11500 10 IF (TAUL(I)-TAU.LT.0.0) GO TO 43
11510 DUMMY = (DT*XC + TAU*XCL(I))/(TAU + DT)
11520 C
11530 C CHECK FOR BUFFER OVERFLOW (YES, IT CAN OCCUR)
11540 C BUFFER OVERFLOW IS STORING NEW DATA INTO A CELL BEFORE
11550 C FINISHED WITH OLD DATA
11560 C
11570 43 N=NP(I)
11580 TAUL(I)=TAU
11590 XCL(I)=DUMMY
11600 N2=MOD(N+1,NPA)+1
11610 IF (.NOT.WRAP(I).AND.N2.GT.2) GO TO 11
11620 IF (T.GE.TSAV(N2,I)) GO TO 11
11630 TNS(I)=TSAV(N2,I)
11640 WRITE(IOUT,105) I,T,TNS(I)
11650 105 FORMAT(17H WARNING - PDELAY,I3,22H BUFFER OVERFLOW AT T=,
11660 2 1P212.5,6H, TNS=,E12.5)
11670 GO TO 12
11680 11 IF (N.EQ.NPA) WRAP(I)=.TRUE.
11690 N=MOD(N,NPA)+1
11700 NP(I)=N
11710 TSAV(N,I)=T+TAU
11720 XSAV(N,I)=DUMMY
11730 TNS(I)=T+ANAX1(DT,TAU*2./FLOAT(NPA))
11740 C
11750 C IF T .LT. FIRST-T-STORED, RETURN XCI
11760 C
11770 12 IF (.NOT.WRAP(I).AND.T.LT.TSAV(1,I)) RETURN
11780 C
11790 C CHECK FOR T .GT. LAST-T-STORED (WILL BE IF TAU.LT.DT)
11800 C
11810 NBIG=NP(I)
11820 IF (T.LE.TSAV(NBIG,I)) GO TO 13
11830 NSM=NBIG
11840 NBIG=MOD(NBIG,NPA)+1
11850 IF (NBIG.EQ.1) WRAP(I)=.TRUE.
11860 TSAV(NBIG,I)=T+TAU
11870 XSAV(NBIG,I)=DUMMY
11880 GO TO 33
11890 C
11900 C CHECK WHICH HALF OF CIRCULAR BUFFER T IS IN
11910 C
11920 13 NSM=1
11930 IF (.NOT.WRAP(I).OR.T.GE.TSAV(1,I)) GO TO 15
11940 NSM=NBIG+1
11950 NBIG=NPA
11960 C
11970 C CHECK FOR T IN THE CRACK BETWEEN TSAV(NPA) AND TSAV(1)
11980 C
11990 IF (T.LE.TSAV(NPA,I)) GO TO 15
12000 NSM=NPA

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12010          NBIG=1
12020          GO TO 33
12030      C
12040      C PERFORM BINARY SEARCH TO LOCATE INDEX OF T
12050      C
12060      15      IF (NBIG.LT.NSM) GO TO 33
12070          NTRY=(NBIG+NSM)/2
12080          IF (T-TSAV(NTRY,I)) 17,19,21
12090      17      NBIG=NTRY-1
12100          GO TO 15
12110      19      PDELAY=XSAV(NTRY,I)
12120          RETURN
12130      21      NSM=NTRY+1
12140          GO TO 15
12150      C
12160      C INTERPOLATE BETWEEN TWO CLOSEST POINTS
12170      C
12180      33      PDELAY = XSAV(NSM,I) + (XSAV(NBIG,I) - XSAV(NSM,I)) *
12190          2      ( (T-TSAV(NSM,I)) / (TSAV(NBIG,I) - TSAV(NSM,I)) )
12200          RETURN
12210          END
12220      *
12230      *P
12240      *
12250      *SN11
12260      *
12270      END
12280          IMAX=150.0 ,      DT=1.0E-6 ,      DTMIN=1.0E-6
12290          NPOINT=201
12300          SY(8)=3.0
12310          ENAX=1.0E-7
12320          FETAG=25.5703,      OMGG=376.99
12330          SV9=0.85 ,      PT=387.6
12340          WSAS=927.7778
12350          TSC=905.0 ,      TAWA=872.25542 ,      TIC=855.0
12360          ELS1=21.377693
12370          PAS2=1830.7 ,      PAS4=1765.7
12380          WS1D=0.4085327,      WS3D=0.4085327 ,      WSSS=927.7778
12390          TAW1=659.98545 ,      TAW2=738.97753
12400          TI8=713.96 ,      TI9=651.0
12410          EMS5=20268.287,      HS6=540.89027
12420          D1=1.0 ,      D2=1.0 ,      D3=1.0
12430          D4=1.0 ,      D5=1.0 ,      D6=1.0
12440          WPS=11512.777,      WIS=10650.0
12450          TAP=2217.1839,      TP3=1035.729
12460          TP1=730.0 ,      TP4=994.73 ,      TR3=994.73
12470          TP7=730.0 ,      TI3=936.0
12480          ENPP=1170.0 ,      ENIP=1006.0
12490          ENS=2271 ,      ENSC2=2.0
12500          ENL=3.0 ,      ENEVAP=6.0
12510          ENI=8550.0 ,      ENZ=4542.0
12520          ENP=42966.0
12530          EXWI=380.0
12540          EXAI=0.2
12550          PS9I=1464.7
12560          CV9=22.28 ,      ENS94=4.0
12570          AV9=5.66816
12580          CDMP=0.3726
12590          TSCI=905.0 ,      PAS4I=1765.7
12600          TIAI=936.0 ,      PSAI=1739.7

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12610      WSAI=3.34E 6 ,      TICI=855.0
12620      HSI=540.89027 ,      WSI=6.68E6 ,      TI7I=855.0
12630      WII=3.834E 7
12640      DPRCSF=175.0 ,      PRC=7.057624E-5 ,      PS6=1.6362977E-2
12650      DOD=7.0
12660      DV=1000.0 ,      EMS4I=2179.9332 ,      EMS5I=20268.287
12670      PSS=0.32347367 ,      PV5=7.685E-5 ,      SV5I=0.7
12680      WS4I=6.68E 6 ,      WS6I=6.68E 6
12690      WSSI=3.34E 6 ,      WS7I=3.34E 6
12700      HS4I=898.781 ,      HSSI=434.6885
12710      RHODCI=2.9444232 ,      ROPBCI=95.6 ,      DC=-0.0058
12720      SODDCC=-0.006 ,      RECC=-0.21 ,      AXECC=-0.023
12730      VPI=3000.0 ,      VP4=6325.0
12740      EPS=3.3267E 9 ,      PPGC=0.9239
12750      HDG=756.81825
12760      AIIP=16000.0 ,      AIIP=16000.0
12770      TRQPP=575431.61 ,      TRQIP=448790.3
12780      WPI=41.446E 6 ,      FFC=0.8
12790      TAPI=400.0 ,      TRII=730.0 ,      TP7I=730.0
12800      TP4I=994.73135 ,      TP5I=994.73135
12810      TII=651.0 ,      TI3I=936.0 ,      TI9I=651.0
12820      FI43=5.72335 ,      ENSUB=198.0
12830      ELS1=200.0 ,      ELS2=100.0
12840      ELSHT=65.0 ,      ELS7=120.0
12850      ELS31=70.0 ,      ELS32=10.0
12860      ELS61=15.0 ,      ELS62=100.0
12870      ELS63=75.0 ,      ELS64=30.0
12880      ELS5=250.0 ,      PHFW=2000.0
12890      ENLD=1.0
12900      ENROC=2.0 ,      DLTROC=5.0 ,      SROC=5.0
12910      END
12920      *      CRBRP ATWS SIMULATOR WITHOUT CONTROLLERS
12930      *      TURBO-GENERATOR
12940      LIST,PETAG,OMGG,PGFETA,POMG,PGE,PT
12950      LIST,WS9,PS9,TS9,HS9
12960      *      FREQUENCY
12970      FACTOR(,0.8,1.0,0.2)
12980      GRAPH,OMGG
12990      *      POWER ANGLE
13000      GRAPH,PETAG
13010      *      TURBINE AND GENERATOR POWERS
13020      GRAPH,PT,PGFETA
13030      *      TURBINE FLOW
13040      GRAPH,WS9
13050      *      TURBINE HIGH PRESSURE
13060      GRAPH,PS9
13070      *      SUPERHEATED STEAM TEMP. AT THE TURBINE INLET
13080      GRAPH,TS9
13090      *      STEAM-GENERATOR
13100      *      SUPERHEATER
13110      LIST,WSC,TASA,TAWA,TAIA
13120      LIST,PSA,PSC,TSA,TSC,HSC,TIA,TIC
13130      *      SUPERHEATED STEAM FLOW
13140      GRAPH,WSC
13150      *      SUPERHEATER EXIT-STEAM PRESSURE
13160      GRAPH,PSC
13170      *      SUPERHEATER AVG. TEMPS.
13180      GRAPH,TASA,TAWA,TAIA
13190      *      SUPERHEATER EXIT STEAM TEMP.
13200      GRAPH,ISC

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13210 *      SUPERHEATER EXIT AND EVAP. INLET TEMPS. SODIUM SIDES
13220 GRAPH,TIC,TI7
13230 *      IHX INTERMEDIATE EXIT AND SUPERHEATER INLET SODIUM TEMPS.
13240 GRAPH,TI3,TIA
13250 *      EVAPORATOR
13260 LIST,ELS1,ELS2,XS3,ALF3,RS3
13270 LIST,TI9,TI9,TAW1,PAW2,TS1,TSAT
13280 LIST,WS1,WS3,PAS2,ALFA2
13290 *      LENGTHS OF REGIONS IN THE EVAP.
13300 GRAPH,ELS1,ELS2
13310 *      EVAP. EXIT QUALITY AND VOID FRACTION
13320 GRAPH,XS3,ALF3
13330 *      EVAP. AVG. TEMPS. IN THE LOWER REGIONS
13340 GRAPH,TAS1,TAW1,TAI8
13350 *      EVAP. AVG. TEMPS. IN THE UPPER REGIONS
13360 GRAPH,TSAT,TAW2,TAI7
13370 *      EVAP. INLET SUBCOOLED WATER TEMP.
13380 GRAPH,TS1
13390 *      EVAP. EXIT SODIUM TEMP. AND IHX INTERMEDIATE INLET TEMP.
13400 GRAPH,TI9,TI1
13410 *      EVAP. AVG. PRESSURE ON THE STEAM/WATER SIDE
13420 GRAPH,PAS2
13430 *      EVAP. INLET AND EXIT FLOW-RATES ON THE STEAM/WATER SIDE
13440 GRAPH,WS1,WS3
13450 *      STEAM DRUM
13460 LIST,WS5,TSS,YSS,PAS4,HSG,ENS4,ENS5
13470 *      STEAM DRUM WATER LEVEL
13480 GRAPH,YSS
13490 *      STEAM DRUM PRESSURE
13500 GRAPH,PAS4
13510 *      STEAM DRUM FEEDWATER TEMP.
13520 GRAPH,TS5
13530 *      REACTOR AND IHX
13540 *      IHX
13550 LIST,TP7,TI3,TP5,TI1,TAP5,TAI1
13560 *      IHX REGIONS AVG. TEMPS.
13570 GRAPH,TAP5,TAI1
13580 *      IHX PRIMARY EXIT TEMP. AND REACTOR INLET TEMP.
13590 GRAPH,TP7,TR1
13600 *      INTERMEDIATE FLOW
13610 GRAPH,WI
13620 *      PRIMARY FLOW
13630 GRAPH,WP
13640 *      REACTOR
13650 LIST,WP,WI,RHOD,EN,TAF,TAP1
13660 LIST,TR1,TP1,TP3,TR3,TP4
13670 LIST,ENPP,ETAPP,HOPP,ZNIP,ETAIP,HOIP
13680 *      REACTIVITY
13690 GRAPH,RHOD
13700 *      REACTOR NORMALIZED POWER LEVEL
13710 GRAPH,EN
13720 *      FUEL AVG. FPMP. IN THE CORE
13730 GRAPH,TAF
13740 *      COOLANT AVG. TEMP. IN THE CORE
13750 GRAPH,TAP1
13760 *      CORE EXIT TEMP.
13770 GRAPH,TP3
13780 *      OUTLET PLENUM INLET AND EXIT TEMPS. AND IHX PRIMARY INLET TEMP.
13790 GRAPH,TR3,TP4,TP5
13800 *      DELAYS

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```
13810 LIST,TAUTS9,TAUHS4,TAUHS1,TAUT17,TAUT1A
13820 LIST,TAUT11,TAUTP5,TAUTR1
13830 * MAX. TEMPS. IN THE AVG. AND HOT CHANNELS AND THEIR AXIAL LOCATIONS
13840 LIST,TPMAX,TPMM,YCMAX,TCHMAX,YCMM,TCMM
13850 LIST,TSMAX,YSMM,TSMM,YPMAX,TPMAX,YPM,TPMM
13860 * MAX. PIN-CLAD TEMPS. IN THE AVG. AND HOT CHANNELS
13870 GRAPH,TCHMAX,TCMM
13880 * MAX. FUEL-SURFACE TEMPS. IN THE AVG. AND HOT CHANNEL
13890 GRAPH,TSMAX,TSMM
13900 * MAX. FUEL-CENTER-LINE TEMPS. IN THE AVG. AND HOT CHANNEL
13910 GRAPH,TPMAX,TPMM
13920 END
```

APPENDIX K

LISTING OF THE TWO-LOOP SIMULATOR

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00010  MERVAT,EN4101273P,CM120000,T2000,ST0,P0.      LOOP.2
00020  CALL DAREP,*NEDEPT,ID=LOOP2,RP=2.
00030  -Z
00040  SD1
00050  *
00060  *
00070  *      TWO-LOOP PLANT
00080  *
00090  *
00100  *      I.  TURBOGENERATOR
00110  *
00120  *
00130  PROCED ENWD=ENLD,DLTLD,ENWI,SLD
00140  IF(ENLD.EQ.0.0) ENWD=ENW(T)
00150  IF(ENLD.EQ.1..AND.T.EQ.0.0) ENWD=ENWI
00160  IF(ENLD.EQ.1..AND.T.GT.0.0) ENWD=ENWI*(1.+DLTLD/100.0)
00170  IF(ENLD.EQ.2..AND.T.LE.SLD) ENWD=ENWI*(1.+DLTLD*T/100.0)
00180  ENDPRO
00190  *
00200  PROCED ENWM=ENMMN,ENW
00210  IF(ENMMN.EQ.0.0) ENWM=ENWI
00220  IF(ENMMN.NE.0.0) ENWM=ENW
00230  ENDPRO
00240  *
00250  SV9.=(0.00223684*ENWM-SV9)/0.1
00260  *
00270  *
00280  PROCED SVDMP,DSVDMP=ENDMP,DLTDM,SSVDMP
00290  IF(ENDMP.EQ.0.0) SVDMP=0.0
00300  IF(ENDMP.EQ.1..AND.T.EQ.0.0) SVDMP=0.0
00310  IF(ENDMP.EQ.1..AND.T.NE.0.0) SVDMP=DLTDM
00320  IF(ENDMP.EQ.2.0.AND.T.LE.SSVMP) SVDMP=DLTDM*T
00330  IF(ENDMP.EQ.2.0.AND.T.LE.SSVMP) DSVDMP=DLTDM
00340  IF(ENDMP.EQ.2.0.AND.T.GT.SSVMP) DSVDMP=0.0
00350  IF(ENDMP.NE.2.0) DSVDMP=0.0
00360  ENDPRO
00370  *
00380  PROCED WDMPS,DWDMP=PS9I,CDMP,SVDMP,DSVDMP
00390  IF(T.EQ.0.0) WDMPS=CDMP*PS9I*SVDMP
00400  IF(T.EQ.0.0) DWDMP=CDMP*PS9I*DSVDMP
00410  IF(T.GT.0.0) WDMPS=CDMP*PS9*SVDMP
00420  IF(T.GT.0.0) DWDMP=CDMP*PS9*DSVDMP
00430  ENDPRO
00440  *
00450  WDMPS=3600.0*WDMPS
00460  *
00470  WSAS=WSAS1+2.0*WSAS2
00480  WSA=3600.0*WSAS
00490  WSC=WSA
00500  WSCS=WSC/3600.0
00510  *
00520  WS9S=WSCS-WDMPS
00530  WS9=3600.0*WS9S
00540  *
00550  PROCED CS9=PRV91,PS9SC,SV9,ENS94
00560  IF(PRV91.GE..55) CS9=WS9/(ENS94*SV9*PS9SC)
00570  ENDPRO
00580  *
00590  PV9=AV9*WS9S/ENS94
00600  PS9SC=PV9*(WS9S/(CV9*ENS94*SV9))**2.

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```

00610      PS9C=WS9S/(CS9*ENS94*SY9)
00620      *
00630      PRV91=PV9/PS9SC
00640      *
00650      PROCED  PRV9=PS9I,PV9
00660      IF (T.EQ.0.0)  PRV9=PV9/PS9I
00670      IF (T.GT.0.0)  PRV9=PV9/PS9
00680      ENDPRO
00690      *
00700      PROCED  PS9=PS9SC,PS9C,PRV9
00710      IF (PRV9.GT.0.55)  PS9=PS9SC
00720      IF (PRV9.LE.0.55)  PS9=PS9C
00730      ENDPRO
00740      *
00750      YS51=3.0*(1.0+SIN(1.57*(ENS51/ENS5I-1.0)))
00760      YS52=3.0*(1.0+SIN(1.57*(ENS52/ENS5I-1.0)))
00770      VGS41=VG(PAS41)
00780      VGS42=VG(PAS42)
00790      ROGS41=1./VGS41
00800      ROGS42=1./VGS42
00810      *
00820      FSC1=7.841775E-4*ELSC1/(ELSC1+0.573425*ELSC2*(ENL/ENSC2)**2.0)
00830      FSC2=3.48525E-4*ELSC2/(ELSC2+1.74391*ELSC1*(ENSC2/ENL)**2.0)
00840      *
00850      TWSAS2=2.33974E-4*ELS7+3.1533E-4*ELSHT+1.3682E-4*ELSC1
00860      TWSAS=TWSAS2/3.0+1.0953E-4*ELSC2/ENSC2
00870      *
00880      PS4HD=PSA+FSH+FSC1
00890      *
00900      DWSAS=(1./(3.*TWSAS))*(2.0*PAS42+PAS41-3.0*PS9+(53.21+YS52)
00910      S      *ROGS42/72.0+(53.21+YS51)*ROGS41/144.-FS4HD*(2.0*WASAS2**2.+
00920      S      WASAS1**2.)-3.*FSC2*(WASAS/ENSC2)**2.0)
00930      *
00940      DWSAS2=(1./(3.*TWSAS2))*(PAS42-PAS41+53.21*(ROGS42-ROGS41)/144.0
00950      S      +(YS52*ROGS42-YS51*ROGS41)/144.-PS4HD*(WASAS2**2.-WASAS1**2.)
00960      S      +TWSAS2*DWSAS)
00970      *
00980      DWSAS1=DWSAS-2.*DWSAS2
00990      *
01000      WASAS1=DWSAS1
01010      WASAS2=DWSAS2
01020      *
01030      WSA1=3600.0*WASAS1
01040      WSA2=3600.0*WASAS2
01050      WSC1=WSA1
01060      WSC2=WSA2
01070      *
01080      *
01090      PSA1=PAS41-2.33974E-4*ELS7*DWSAS1+(53.21+YS51)*ROGS41/144.
01100      S      -PSA*WASAS1**2.0
01110      PSA2=PAS42-2.33974E-4*ELS7*DWSAS2+(53.21+YS52)*ROGS42/144.
01120      S      -PSA*WASAS2**2.0
01130      PSC1=PSA1-3.1533E-4*ELSHT*DWSAS1-FSH*WASAS1**2.0
01140      PSC2=PSA2-3.1533E-4*ELSHT*DWSAS2-FSH*WASAS2**2.0
01150      PSCHD=PAS42+(53.21+YS52)*ROGS42/144.-TWSAS2*DWSAS2-FS4HD*WASAS2**2
01160      *
01170      TSA1=TSATF(PSA1)
01180      TSA2=TSATF(PSA2)
01190      TASA1=(TSA1+TSC1)/2.
01200      TASA2=(TSA2+TSC2)/2.

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01210      TSCHD=(WSAS1*TSC1+2.0*WSAS2*TSC2)/WSAS
01220      *
01230      RHOSC=(1./VSC1+1./VSC2)/2.
01240      TAUTS9=1.96895*ELSC2*ENSC2*RHOSC/WSCS
01250      *
01260      PROCED TSCHDI=TSCHD
01270      IF(T.EQ.0.0) TSCHDI=TSCHD
01280      ENDPRO
01290      *
01300      TS9=0.994475*PDELAY(TSCHD,TAUTS9,6,TSCHDI)
01310      *
01320      *
01330      HS9=HSH(PS9,TS9)
01340      SS9=S9(PS9,TS9)
01350      *
01360      SEXH=SS9
01370      XEXH=(SEXH-0.1313)/1.8487
01380      HEXH=69.997+1036.5*XEXH
01390      *
01400      *
01410      STWBTU=0.706639*(HS9-HEXH)*WS9
01420      STWNV=2.931E-7*STWBTU
01430      PT=(STWNV-PT)/0.5
01440      *
01450      *
01460      V=22.0*ENVD/ENVI
01470      *
01480      XD=0.9919032
01490      *
01500      E=19.845232+20.009242*XD
01510      *
01520      PROCED AI=V,E,XD,PETAG
01530      IF(ENLD.NE.2.0) AI=((0.431618*V/XD)**2.0
01540      $      *((E-0.902056*V)/XD)**2.0)**0.5
01550      IF(ENLD.EQ.2.0) AI=((V*SIN(0.017453292*PETAG)/XD)**2.0
01560      $      *((E-V*COS(0.017453292*PETAG)/XD)**2.0)**0.5
01570      ENDPRO
01580      *
01590      PGFETD=(V*E/XD)*SIN(0.017453292*PETAG)
01600      *
01610      PROCED PGFETA=ENSSC,PGFETD,T,TFR
01620      IF(ENSSC.NE.0.0) GO TO 30
01630      PGFETA=PGFETD
01640      GO TO 40
01650      30 IF(T.GT.0.0.AND.T.LE.TFR) PGFETA=0.0
01660      IF(T.EQ.0.0.OR.T.GT.TFR) PGFETA=PGFETD
01670      40 CONTINUE
01680      ENDPRO
01690      *
01700      PF=PGFETA/(AI*V)
01710      *
01720      *
01730      POMG=0.020159685*OMGG
01740      PGE=165.38356*EXAI*(OMGG-376.99)
01750      PGA=PT-(POMG+PGE+PGFETA)
01760      *
01770      PETAG=(OMGG-376.99)/0.017453292
01780      OMGG.=49.539*PGA/OMGG
01790      *
01800      *

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01810 *           II.  SUPERHEATER
01820 *
01830 *
01840 *           WI1=3600.*WTS1
01850 *           WI2=3600.*WTS2
01860 *           WI =WI1+2.0*WI2
01870 *
01880 *           ROTI31=RHONA (TI31)
01890 *           ROTI32=RHONA (TI32)
01900 *
01910 *           TUTIA1=8474400.0*ROTI31/WI1
01920 *           TUTIA2=8474400.0*ROTI32/WI2
01930 *
01940 *           TIA1=PDELAY (TI31,TUTIA1,3,TI31)
01950 *           TIA2=PDELAY (TI32,TUTIA2,10,TI31)
01960 *
01970 *           HGS41=HG (PAS41)
01980 *           HGS42=HG (PAS42)
01990 *
02000 *           PROCEED HGS4I=HGS41
02010 *           IF (T.EQ.0.0) HGS4I=HGS41
02020 *           ENDPRO
02030 *
02040 *           TUHSA1=0.92175*ELS7*ROGS41/WSAS1
02050 *           TUHSA2=0.92175*ELS7*ROGS42/WSAS2
02060 *
02070 *           HSA1=PDELAY (HGS41,TUHSA1,7,HGS41)
02080 *           HSA2=PDELAY (HGS42,TUHSA2,14,HGS41)
02090 *
02100 *
02110 *           HSC1=HSH (PSC1,TSC1)
02120 *           HSC2=HSH (PSC2,TSC2)
02130 *
02140 *           CPS1= (HSC1-HSA1) / (TSC1-TSA1)
02150 *           CPS2= (HSC2-HSA2) / (TSC2-TSA2)
02160 *
02170 *           VGSA1=VG (PSA1)
02180 *           VGSA2=VG (PSA2)
02190 *           VSC1=VSH (PSC1,TSC1)
02200 *           VSC2=VSH (PSC2,TSC2)
02210 *           ROASA1= (1./VGSA1+1./VSC1) /2.0
02220 *           ROASA2= (1./VGSA2+1./VSC2) /2.0
02230 *
02240 *           ROAIA1=RHONA (TAIA1)
02250 *           ROAIA2=RHONA (TAIA2)
02260 *
02270 *           TAIA1= (TIA1+TIC1) /2.
02280 *           TAIA2= (TIA2+TIC2) /2.
02290 *
02300 *
02310 *
02320 *           HEAT TRANSFER COEFFICIENTS IN THE SUPERHEATER
02330 *
02340 *
02350 *           PESH1=2.4838E-4*WI1
02360 *           PESH2=2.4838E-4*WI2
02370 *           HNS1=1222.0787+9.579552E-3*WI1**0.8
02380 *           HNS2=1222.0787+9.579552E-3*WI2**0.8
02390 *           HWA1=109396.53/(0.0048751818+19.2/HNS1)
02400 *           HWA2=109396.53/(0.0048751818+19.2/HNS2)

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02410 *
02420 RESH1=0.70844*WSA1
02430 RESH2=0.70844*WSA2
02440 HSS1=0.0211*WSA1**0.8
02450 HSS2=0.0211*WSA2**0.8
02460 HSSA1=109396.53/(0.01901711+29.484/HSS1)
02470 HSSA2=109396.53/(0.01901711+29.484/HSS2)
02480 *
02490 *      II-1.  SUPERHEATED  STEAM
02500 *
02510 DTSC1=(3.829326E-6/(CPS1*ROASA1))*(HSSA1*(TAWA1-TASA1)
02520 $ -WSA1*(HSC1-HSA1))
02530 *
02540 DTSC2=(3.829326E-6/(CPS2*ROASA2))*(HSSA2*(TAWA2-TASA2)
02550 $ -WSA2*(HSC2-HSA2))
02560 *
02570 TSC1.=DTSC1
02580 *
02590 TSC2.=DTSC2
02600 *
02610 *
02620 *      II-2.  WALL
02630 *
02640 DTAWA1=1.092238E-7*(HWA1*(TAIA1-TAWA1)-HSSA1*(TAWA1-TASA1))
02650 *
02660 DTAWA2=1.9092238E-7*(HWA2*(TAIA2-TAWA2)-HSSA2*(TAWA2-TASA2))
02670 *
02680 TAWA1.=DTAWA1
02690 *
02700 TAWA2.=DTAWA2
02710 *
02720 *
02730 *      II-3.  INTERMEDIATE SODIUM
02740 *
02750 DTIC1=(3.8804E-6/ROAIA1)*(0.3014*WI1*(TIA1-TIC1)
02760 $ -HWA1*(TAIA1-TAWA1))
02770 *
02780 DTIC2=(3.8804E-6/ROAIA2)*(0.3014*WI2*(TIA2-TIC2)
02790 $ -HWA2*(TAIA2-TAWA2))
02800 *
02810 TIC1.=DTIC1
02820 TIC2.=DTIC2
02830 *
02840 *
02850 *
02860 *      III.  EVAPORATOR
02870 *
02880 *
02890 ROTS61=RHOW(TS11)
02900 ROTS62=RHOW(TS12)
02910 *
02920 TUHS11=(1.76744*ELS61+1.576246*ELS62+1.22718*ELS63
02930 $ +0.441786*ENEVP1*ELS64)*(ROTS61/WS1S1)
02940 TUHS12=(1.76744*ELS61+1.576246*ELS62+1.22718*ELS63
02950 $ +0.441786*ENEVP1*ELS64)*(ROTS62/WS1S2)
02960 *
02970 PROCD HS1I=HS6
02980 IF(T.2Q.0.0) HS1I=HS6
02990 ENDPRO
03000 *

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03010      HS11=PDELAY(HS61,TURS11,8,HS1I)
03020      HS12=PDELAY(HS62,TURS12,15,HS1I)
03030      *
03040      HS21=HF(PAS21)
03050      HS22=HF(PAS22)
03060      TS11=TS1F(HS11)
03070      TS12=TS1F(HS12)
03080      TSAT1=TSATF(PAS21)
03090      TSAT2=TSATF(PAS22)
03100      TAS11=(TS11+TSAT1)/2.0
03110      TAS12=(TS12+TSAT2)/2.0
03120      HFS21=HS21
03130      HFS22=HS22
03140      HGS21=HG(PAS21)
03150      HGS22=HG(PAS22)
03160      VFS21=VF(PAS21)
03170      ROPS21=1./VFS21
03180      VFS22=VF(PAS22)
03190      ROPS22=1./VFS22
03200      VGS21=VG(PAS21)
03210      ROGS21=1./VGS21
03220      VGS22=VG(PAS22)
03230      ROGS22=1./VGS22
03240      *
03250      WS1S1=757.0*ENEVP1*WS1D1
03260      WS1S2=1514.0*WS1D2
03270      WS3S1=757.0*ENEVP1*WS3D1
03280      WS3S2=1514.0*WS3D2
03290      WS2AD1=(WS1D1+WS3D1)/2.0
03300      WS2AD2=(WS1D2+WS3D2)/2.0
03310      *
03320      WS11=3600.0*WS1S1
03330      WS12=3600.0*WS1S2
03340      WS31=3600.0*WS3S1
03350      WS32=3600.0*WS3S2
03360      *
03370      *      HEAT TRANSFER COEFFICIENTS IN THE EVAPORATOR
03380      *
03390      *
03400      RES11=0.228529*(WS11/ENEVP1)
03410      RES12=0.1142645*WS12
03420      RES21=0.2479540*(WS11/ENEVP1)
03430      RES22=0.1239770*WS12
03440      HWE1=0.06375477*(WS11/ENEVP1)**0.8
03450      HWE2=0.336617523*WS12**0.8
03460      HDS11=2378.1855*ENEVP1/(0.02478+29.484/HWE1)
03470      HDS12=4756.3711/(0.02478+29.484/HWE2)
03480      HDS21=95971.135*ENEVP1
03490      HDS22=191942.27
03500      *
03510      PEE1=2.402456E-4*WI1/ENEVP1
03520      PEE2=1.20123E-4*WI2
03530      HNE1=1281.3193+9.779867E-3*(WI1/ENEVP1)**0.8
03540      HNE2=1281.3193+5.617062E-3*WI2**0.8
03550      HDW11=2378.1855*ENEVP1/(0.00487521818+19.2/HNE1)
03560      HDW12=4756.3711/(0.00487521818+19.2/HNE2)
03570      HDW21=HDW11
03580      HDW22=HDW12
03590      *
03600      AS11=0.68393*ENEVP1

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03610      AS12=1.36786
03620      *
03630      ELS21=46.0-ELS11
03640      ELS22=46.0-ELS12
03650      *
03660      SAI1=ROGS21/ROFS21
03670      SAI2=ROGS22/ROFS22
03680      *
03690      XS31=HDS21*ELS21*(TAW21-TSAT1)/(WS31*(HGS21-HS21))
03700      XS32=HDS22*ELS22*(TAW22-TSAT2)/(WS32*(HGS22-HS22))
03710      ALP31=XS31/(SAI1+(1.-SAI1)*XS31)
03720      ALP32=XS32/(SAI2+(1.-SAI2)*XS32)
03730      ALPSI1=ALP31*(1.-SAI1)
03740      ALPSI2=ALP32*(1.-SAI2)
03750      ALPA21=ALP31*(0.5+ALPSI1/6.0+ALPSI1*ALPSI1/12.0)
03760      ALPA22=ALP32*(0.5+ALPSI2/6.0+ALPSI2*ALPSI2/12.0)
03770      *
03780      ROAS11=RHOF(TAS11)
03790      ROAS12=RHOF(TAS12)
03800      ROAS21=ALPA21*ROGS21+(1.-ALPA21)*ROFS21
03810      ROAS22=ALPA22*ROGS22+(1.-ALPA22)*ROFS22
03820      ROHS21=ALPA21*ROGS21*HGS21+(1.-ALPA21)*ROFS21*HFS21
03830      ROHS22=ALPA22*ROGS22*HGS22+(1.-ALPA22)*ROFS22*HFS22
03840      *
03850      HS31=HGS21*XS31+HFS21*(1.-XS31)
03860      HS32=HGS22*XS32+HFS22*(1.-XS32)
03870      SOS31=ALP31*ROGS21+(1.-ALP31)*ROFS21
03880      SOS32=ALP32*ROGS22+(1.-ALP32)*ROFS22
03890      *
03900      DRFP21=-(1./VFS21**2.0)*DVF(PAS21)
03910      DRFP22=-(1./VFS22**2.0)*DVF(PAS22)
03920      DRGP21=-(1./VGS21**2.0)*DVG(PAS21)
03930      DRGP22=-(1./VGS22**2.0)*DVG(PAS22)
03940      DHFP21=DHF(PAS21)
03950      DHFP22=DHF(PAS22)
03960      DHGP21=DHG(PAS21)
03970      DHGP22=DHG(PAS22)
03980      DRHP21=ROFS21*DHF21+HFS21*DRFP21
03990      DRHP22=ROFS22*DHF22+HFS22*DRFP22
04000      DRHG21=ROGS21*DHGP21+HGS21*DRGP21
04010      DRHG22=ROGS22*DHGP22+HGS22*DRGP22
04020      *
04030      A1=ELS21*(ALPA21*(DRHG21-DRGP21*HFS21)+(1.-ALPA21)
04040      $      *(DRHP21-DRFP21*HFS21))
04050      A2=ELS22*(ALPA22*(DRHG22-DRGP22*HFS22)+(1.-ALPA22)
04060      $      *(DRHP22-DRFP22*HFS22))
04070      B1=ELS11*ROGS21*DHFP21*(HGS21-HFS21)/(2.0*A1*(HS21-HS11))
04080      B2=ELS12*ROGS22*DHFP22*(HGS22-HFS22)/(2.0*A2*(HS22-HS12))
04090      C1=1.0+2.0*B1*(ROAS11-ROFS21)/ROFS21-ROGS21
04100      C2=1.0+2.0*B2*(ROAS12-ROFS22)/ROFS22-ROGS22
04110      *****
04120      *      III-1.  WATER / STEAM
04130      *****
04140      DLS11=(2./C1)*(-HDS11*ELS11*(TAW11-TAS11)/(AS11*ROAS11*(HS21-HS11)
04150      $      )+WS11/(AS11*ROAS11)+(ELS11/2.)*DHS61/(HS21-HS11)
04160      $      +B1*(WS11-WS31)/(AS11*(ROFS21-ROGS21)))
04170      DLS12=(2./C2)*(-HDS12*ELS12*(TAW12-TAS12)/(AS12*ROAS12*(HS22-HS12)
04180      $      )+WS12/(AS12*ROAS12)+(ELS12/2.)*DHS62/(HS22-HS12)
04190      $      +B2*(WS12-WS32)/(AS12*(ROFS22-ROGS22)))
04200      ELS11.=DLS11/3600.0

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04240      ZLS12.=DLS12/3600.0
04250      *
04260      WS21=WS11-AS11*ROAS11*DLS11
04270      WS22=WS12-AS12*ROAS12*DLS12
04280      *
04290      DPAS21=(ROGS21*(HGS21-HFS21)/(A1*(ROFS21-ROGS21)))
04300      $      *(- (ROAS11-ROFS21)*DLS11+(WS11-WS31)/AS11)
04310      DPAS22=(ROGS22*(HGS22-HFS22)/(A2*(ROFS22-ROGS22)))
04320      $      *(- (ROAS12-ROFS22)*DLS12+(WS12-WS32)/AS12)
04330      PAS21.=DPAS21/3600.0
04340      PAS22.=DPAS22/3600.0
04350      *****
04360      *      III-2.  WALL
04370      *****
04380      WMHCD1=55.28691*ENEVP1
04390      WMHCD2=110.57382
04400      TW21=(TAW11*ELS11+TAW21*ZLS21)/46.0
04410      TW22=(TAW12*ELS12+TAW22*ZLS22)/46.0
04420      *
04430      DTAW11=(1./WMHCD1)*(-(HDW11+HDS11+WMHCD1*DLS11/ELS11)*TAW11
04440      $      +HDS11*TSAT1+HDW11*TAI81)+TW21*DLS11/ELS11
04450      DTAW12=(1./WMHCD2)*(-(HDW12+HDS12+WMHCD2*DLS12/ELS12)*TAW12
04460      $      +HDS12*TSAT12+HDW12*TAI82)+TW22*DLS12/ELS12
04470      TAW11.=DTAW11/3600.0
04480      TAW12.=DTAW12/3600.0
04490      DTAW21=(1./WMHCD1)*(-(HDW21+HDS21+WMHCD1*DLS11/ELS21)*TAW21
04500      $      +HDS21*TSAT1+HDW21*TAI71)-TW21*DLS11/ELS21
04510      DTAW22=(1./WMHCD2)*(-(HDW22+HDS22+WMHCD2*DLS12/ELS22)*TAW22
04520      $      +HDS22*TSAT2+HDW22*TAI72)-TW22*DLS12/ELS22
04530      TAW21.=DTAW21/3600.0
04540      TAW22.=DTAW22/3600.0
04550      *****
04560      *      III-3.  INTERMEDIATE  SODIUM
04570      *****
04580      *
04590      ROTIC1=RHONA(TIC1)
04600      ROTIC2=RHONA(TIC2)
04610      *
04620      TUTI71=703800.0*ROTI1*ENEVP1/WI1
04630      TUTI72=1407600.0*ROTI2/WI2
04640      *
04650      PROCD  TIC1=TIC
04660      IF(T.EQ.0.0)  TIC1=TIC
04670      ENDPRO
04680      *
04690      TI71=PDELAY(TIC1,TUTI71,14,TICI)
04700      TI72=PDELAY(TIC2,TUTI72,21,TICI)
04710      *
04720      TAI71=(TI71+TI81)/2.0
04730      TAI72=(TI72+TI92)/2.0
04740      TAI81=(TI81+TI91)/2.0
04750      TAI82=(TI82+TI92)/2.0
04760      TIE1=(TI71+TI91)/2.0
04770      TIE2=(TI72+TI92)/2.0
04780      ROIE1=RHONA(TIE1)
04790      ROIE2=RHONA(TIE2)
04800      SMHCD1=1.57822638*ENEVP1*ROIE1
04810      SMHCD2=3.15645266*ROIE2
04820      WI81=WI1*5.163339*ENEVP1*ROIE1*DLS11
04830      WI82=WI2*10.326676*ROIE2*DLS12

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04810 *
04820 DTI81=(1./(SMHCD1*ELS21))*(- (HDW21*ELS21-SMHCD1*DLS11)*TAI71
04830 $ +HDW21*ELS21*TAW21+0.30566*(WI1*TI71-WI81*TI81))
04840 DTI82=(1./(SMHCD2*ELS22))*(- (HDW22*ELS22-SMHCD2*DLS12)*TAI72
04850 $ +HDW22*ELS22*TAW22+0.30566*(WI2*TI72-WI82*TI82))
04860 TI81.=DTI81/3600.0
04870 TI82.=DTI82/3600.0
04880 *
04890 DTI91=(1./(SMHCD1*ELS11))*(- (HDW11*ELS11+SMHCD1*DLS11)*TAI81
04900 $ +HDW11*ELS11*TAW11+0.30566*(WI81*TI81-WI1*TI91))
04910 DTI92=(1./(SMHCD2*ELS12))*(- (HDW12*ELS12+SMHCD2*DLS12)*TAI82
04920 $ +HDW12*ELS12*TAW12+0.30566*(WI82*TI82-WI2*TI92))
04930 TI91.=DTI91/3600.0
04940 TI92.=DTI92/3600.0
04950 *****
04960 * WATER / STEAM MOMENTUM EQUATIONS
04970 *****
04980 *
04990 R1=RD (PAS21,XS31)
05000 R2=RD (PAS22,XS32)
05010 *
05020 TUWS31=ELS31/(21.25048*ENEVP1)+ELS32/68.844553
05030 TUWS32=ELS31/42.5+ELS32/68.844553
05040 TUWS11=ELS61/56.9+ELS62/50.755+ELS63/39.515
05050 $ +ELS64/(14.22555*ENEVP1)
05060 TUWS12=ELS61/56.9+ELS62/50.755+ELS63/39.515+ELS64/28.4511
05070 *
05080 A11T1=ELS11/(32.2*AS11)+ELS21/(64.4*AS11)+TUWS11
05090 A11T2=ELS12/(32.2*AS12)+ELS22/(64.4*AS12)+TUWS12
05100 A12T1=ELS21/(64.4*AS11)+0.3/AS11+TUWS31
05110 A12T2=ELS22/(64.4*AS12)+0.3/AS12+TUWS32
05120 A21T1=ELS21/(128.8*AS11)
05130 A21T2=ELS22/(128.8*AS12)
05140 A22T1=ELS21/(128.8*AS11)+0.15/AS11+TUWS31
05150 A22T2=ELS22/(128.8*AS12)+0.15/AS12+TUWS32
05160 *
05170 DTERN1=A11T1*A22T1-A12T1*A21T1
05180 DTERN2=A11T2*A22T2-A12T2*A21T2
05190 *
05200 * FRICTION COEFFICIENTS
05210 *
05220 PROCED FS11,FS12,FS21,FS22=RES11,RES12,RES21,RES22
05230 IF (RES11.LT.1000.0) FS11=8.0/RES11
05240 IF (RES12.LT.1000.0) FS12=8.0/RES12
05250 IF (RES21.LT.1000.0) FS21=8.0/RES21
05260 IF (RES22.LT.1000.0) FS22=8.0/RES22
05270 IF (RES11.GE.1000.0.AND.RES11.LT.100000.0) FS11=0.5256/
05280 $ (RES11**0.243)
05290 IF (RES12.GE.1000.0.AND.RES12.LT.100000.0) FS12=0.5256/
05300 $ (RES12**0.243)
05310 IF (RES21.GE.1000.0.AND.RES21.LT.100000.0) FS21=0.5256/
05320 $ (RES21**0.243)
05330 IF (RES22.GE.1000.0.AND.RES22.LT.100000.0) FS22=0.5256/
05340 $ (RES22**0.243)
05350 IF (RES11.GE.100000.0) FS11=0.02117/(RES11**0.164)
05360 IF (RES12.GE.100000.0) FS12=0.02117/(RES12**0.164)
05370 IF (RES21.GE.100000.0) FS21=0.02117/(RES21**0.164)
05380 IF (RES22.GE.100000.0) FS22=0.02117/(RES22**0.164)
05390 ENDPRO
05400 PS1A1=102467.41*FS11

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05410      PS1A2=102467.41*PS12
05420      PS2A1=111974.13*PS21
05430      PS2A2=111974.13*PS22
05440      *
05450      DPRC1=DPRCSF-FRC*WS1S1**2
05460      DPRC2=DPRCSF-FRC*WS1S2**2
05470      *
05480      HDSPH1=ELS11*ROAS11+ELS21*ROAS21+10.208333*ROS31-52.70833*ROS61
05490      $      -(YS51+(DOD-6.0)/2.0)*ROS61
05500      HDSPH2=ELS12*ROAS12+ELS22*ROAS22+10.208333*ROS32-52.70833*ROS62
05510      $      -(YS52+(DOD-6.0)/2.0)*ROS62
05520      CHMPH1=(1./((32.2*AS11*AS11)))*(WS3S1**2/ROS31-WS1S1**2/ROPS21)
05530      CHMPH2=(1./((32.2*AS12*AS12)))*(WS3S2**2/ROS32-WS1S2**2/ROPS22)
05540      FRPH1=(PS1A1*ELS11+3554.6572+573049.0*(ENEVP1**2)*PS6)*WS1D1**2
05550      $      +(PS2A1*R1*ELS21)*WS2AD1**2+(35304.868+9.67*PS2A1*R1)*WS3D1**2
05560      FRPH2=(PS1A2*ELS12+3554.6572+2292200.0*PS6)*WS1D2**2
05570      $      +(PS2A2*R2*ELS22)*WS2AD2**2+(35304.868+9.67*PS2A2*R2)*WS3D2**2
05580      *
05590      HDH341=ELS21*ROAS21/2.+7.67*ROS31
05600      HDH342=ELS22*ROAS22/2.+7.67*ROS32
05610      FRH341=PS2A1*R1*ELS21*WS2AD1**2/2.+(4.83*PS2A1*R1+28309.)*WS3D1**2
05620      FRH342=PS2A2*R2*ELS22*WS2AD2**2/2.+(4.83*PS2A2*R2+28309.)*WS3D2**2
05630      B1T1=-(HDSPH1+CHMPH1-144.0*DPRC1+FRPH1)
05640      B1T2=-(HDSPH2+CHMPH2-144.0*DPRC2+FRPH2)
05650      B2T1=144.0*(PAS21-PAS41)-HDH341-CHMPH1/2.-FRH341
05660      B2T2=144.0*(PAS22-PAS42)-HDH342-CHMPH2/2.-FRH342
05670      *
05680      WS1D1.=(A22T1*B1T1-A12T1*B2T1)/(757*ENEVP1*DTERM1)
05690      WS1D2.=(A22T1*B1T2-A12T2*B2T2)/(1514.0*DTERM2)
05700      WS3D1.=(A11T1*B2T1-A21T1*B1T1)/(757*ENEVP1*DTERM1)
05710      WS3D2.=(A11T2*B2T2-A21T2*B1T2)/(1514.0*DTERM2)
05720      *
05730      *****
05740      *      IV. STEAM DRUM
05750      *****
05760      *
05770      WS51=3600.*WS5S1
05780      WS52=3600.*WS5S2
05790      WS5=WS51+2.*WS52
05800      *
05810      SV51.=(SV51D-SV51)/0.5
05820      SV52.=(SV52D-SV52)/0.5
05830      *
05840      DPV51=PV5*(WS5S1/SV51)**2
05850      DPV52=PV5*(WS5S2/SV52)**2
05860      *
05870      TSS=TS1F(HS5)
05880      TAUWS5=ZLS5/21.25
05890      WS5S1.=(1./TAUWS5)*(144.0*(PHFW-PAS41)-12.5*RHOW(TS5)
05900      $      -PS5*WS5S1**2-144.0*DPV51)
05910      WS5S2.=(1./TAUWS5)*(144.0*(PHFW-PAS42)-12.5*RHOW(TS5)
05920      $      -PS5*WS5S2**2-144.0*DPV52)
05930      *
05940      HS5=(WSC1*HSC1+2.0*WSC2*HSC2-3.412E6*PT/0.39754)/WS5
05950      *
05960      TOWS41=(0.66*ENEVP1*ELS31+2.138*ELS32)*(ROS31/WS3S1)
05970      TOWS42=(1.32*ELS31+2.138*ELS32)*(ROS32/WS3S2)
05980      *
05990      PROCD HS4I=HS3
06000      IF(T.EQ.0.0) HS4I=HS3

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06010      ENDPRO
06020      *
06030      HS41=PDELAY (HS31,TUHS41,9,HS4I)
06040      HS42=PDELAY (HS32,TUHS42,16,HS4I)
06050      *
06060      VFS41=VF (PAS41)
06070      VFS42=VF (PAS42)
06080      ROPS41=1./VFS41
06090      ROPS42=1./VFS42
06100      *
06110      EMS41=ROGS41*(DV-EMS51/ROPS41)
06120      EMS42=ROGS42*(DV-EMS52/ROPS42)
06130      *
06140      EMS4D1=PDELAY (EMS41,0.2,5,EMS4I)
06150      EMS4D2=PDELAY (EMS42,0.2,12,EMS4I)
06160      *
06170      DMS41=18000.*(EMS41-EMS4D1)
06180      DMS42=18000.*(EMS42-EMS4D2)
06190      *
06200      DMS51=WS31+WS51-WS11-WSA1-DMS41
06210      DMS52=WS32+WS52-WS12-WSA2-DMS42
06220      EMS51.=DMS51/3600.0
06230      EMS52.=DMS52/3600.0
06240      *
06250      E1=EMS41*OVG (PAS41)+EMS51*DVF (PAS41)
06260      E2=EMS42*OVG (PAS42)+EMS52*DVF (PAS42)
06270      DPAS41=(-1./E1)*(VGS41*DMS41+VFS41*DMS51)
06280      DPAS42=(-1./E2)*(VGS42*DMS42+VFS42*DMS52)
06290      PAS41.=DPAS41/3600.0
06300      PAS42.=DPAS42/3600.0
06310      *
06320      DHS61=(1./EMS51)*(WS31*HS41+WS51*HS5-WS11*HS61-WSA1*HGS41
06330      $ -HGS41*DMS41-HS61*DMS51-EMS41*DHG (PAS41)*DPAS41)
06340      DHS62=(1./EMS52)*(WS32*HS42+WS52*HS5-WS12*HS62-WSA2*HGS42
06350      $ -HGS42*DMS42-HS62*DMS52-EMS42*DHG (PAS42)*DPAS42)
06360      HS61.=DHS61/3600.0
06370      HS62.=DHS62/3600.0
06380      *
06390      *****
06400      *      V. INTERMEDIATE HEAT EXCHANGER
06410      *****
06420      TP11=3600.0*WP1S1
06430      WP12=3600.0*WP1S2
06440      WP21=3600.0*WP2S1
06450      TP22=3600.0*WP2S2
06460      WP31=3600.0*WP3S1
06470      WP32=3600.0*WP3S2
06480      WPS=WP1S1+2.*WP1S2
06490      WP2=WP21+2.*WP22
06500      WP3=WP31+2.*WP32
06510      *
06520      WP=3600.0*WPS
06530      *
06540      ROTP4=BHONA (TP4)
06550      TOTP51=3600.0*ROTP4*(821.0/WP21+310.0/WP31)
06560      TUTP52=3600.0*ROTP4*(821.0/WP22+310.0/WP32)
06570      TP51=PDELAY (TP4,TOTP51,2,TP4I)
06580      TP52=PDELAY (TP4,TOTP52,9,TP4I)
06590      *
06600      TAP51=(TP51+TP71)/2.0

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06610      TAP52=(TP52+TP72)/2.0
06620      *
06630      TAI11=(TI11+TI31)/2.0
06640      TAI12=(TI12+TI32)/2.0
06650      *
06660      *
06670      *      HEAT TRANSFER COEFFICIENTS IN THE IHX
06680      *
06690      HNIP1=1906.8776+0.00394*WP31**0.8
06700      HNIP2=1906.878+0.00394*WP32**0.8
06710      HNII1=2476.433+0.0055*WI1**0.8
06720      HNII2=2476.433+0.0055*WI2**0.8
06730      HI1=227149.4/(0.00765+15.287/HNII1+13.71/HNIP1)
06740      HI2=227149.4/(0.00765+15.287/HNII2+13.71/HNIP2)
06750      *
06760      ROAP51=RHONA(TAP51)
06770      ROAP52=RHONA(TAP52)
06780      *
06790      TP71.=(2.05E-6/ROAP51)*(-HI1*(TAP51-TAI11)
06800      $      +0.3032*WP31*(TP51-TP71))
06810      TP72.=(2.05E-6/ROAP52)*(-HI2*(TAP52-TAI11)
06820      $      +0.3032*WP32*(TP52-TP72))
06830      *
06840      ROTI91=RHONA(TI91)
06850      ROTI92=RHONA(TI92)
06860      TUTI11=4968000.0*ROTI91/WI1
06870      TUTI12=4968000.0*ROTI92/WI2
06880      TI11=PDDELAY(TI91,TUTI11,4,TI9I)
06890      TI12=PDDELAY(TI92,TUTI12,11,TI9I)
06900      *
06910      ROAI11=RHONA(TAI11)
06920      ROAI12=RHONA(TAI12)
06930      *
06940      TI31.=(3.755E-6/ROAI11)*(HI1*(TAP51-TAI11)
06950      $      +0.30445*WI1*(TI11-TI31))
06960      TI32.=(3.755E-6/ROAI12)*(HI2*(TAP52-TAI12)
06970      $      +0.30445*WI2*(TI12-TI32))
06980      *
06990      *
07000      *****
07010      *      VI. REACTOR
07020      *
07030      *      VI-1. POINT KINETIC EQUATIONS
07040      *      WITH FEEDBACK
07050      *      *****
07060      *
07070      BETA=3.65E-3
07080      BD=(0.8254*D1+7.756*D2+6.66*D3+13.54*D4
07090      $      +5.908*D5+1.81*D6)*1.0E-4
07100      BDOB=BD/BETA
07110      RHOFBC=(100.0*DC/BETA)*ALOG((460.0+TAP)/(460.0+TAI))
07120      $      +AXECC*TAP+SODDCC*TAI+BECC*TP1+ROFBCI
07130      RHOFBD=RHOFBC/100.0
07140      *
07150      PROCD RHOC=ENROC,DLTROC,RHOCDI,T,SROC
07160      IF(ENROC.EQ.0.) RHOC=RHOCDI
07170      IF(ENROC.EQ.1.AND.T.EQ.0.) RHOC=RHOCDI
07180      IF(ENROC.EQ.1.AND.T.NE.0.) RHOC=RHOCDI+DLTROC/100.0
07190      IF(ENROC.EQ.2.0.AND.T.LE.SROC) RHOC=RHOCDI+DLTROC*T/100.0
07200      ENDPRO

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07210 *
07220 RHOD=RHODC+RHOFBD
07230 *
07240 EN=BDDB/(1.0 - RHOD)
07250 *
07260 D1.=0.0129*(EN-D1)
07270 D2.=0.0312*(EN-D2)
07280 D3.=0.1330*(EN-D3)
07290 D4.=0.3450*(EN-D4)
07300 D5.=1.4100*(EN-D5)
07310 D6.=3.7500*(EN-D6)
07320 *
07330 *
07340 * VI-2. REACTOR THERMODYNAMIC EQUATIONS
07350 *
07360 *
07370 TFC=(5./9.)*(TAF-32.0)
07380 TFK=TFC+273.0
07390 AKFW=36.100867/(TFK+129.2)+5.782936E-13*TFK**3.0
07400 AKF=57.78*AKFW
07410 WPD=FFC*WP/ENP
07420 HC=14861.86+51.921027*WPD**0.8
07430 HR=9.4247778*ENP/(0.125/AKF+60.00024/HDG+52.173914/HC
07440 S +0.0052151492)
07450 *
07460 *
07470 TAF.=2.5208831E- 7*(EPS*PPGC*EN-HR*(TAF-TAP1))
07480 *
07490 ROTR11=RHONA(TP71)
07500 ROTR12=RHONA(TP72)
07510 TUTR11=1796400.0*ROTR11/WP31
07520 TUTR12=1796400.0*ROTR12/WP32
07530 TR11=PDELAY(TP71,TUTR11,1,TP71)
07540 TR12=PDELAY(TP72,TUTR12,8,TP71)
07550 *
07560 ROTP1=RHONA(TP1)
07570 TR1=(WP11*TR11+2.0*WP12*TR12)/WP
07580 ROTR1=RHONA(TR1)
07590 TP1.=(WP/(3600.*VP1*ROTP1))*(TR1-TP1)
07600 *
07610 TSATP3=TSATNA(P3)
07620 PROCED =P3,TPHM,TSATP3
07630 IF(TPHM.LT.TSATP3) GO TO 60
07640 PRINT 50,T,P3,TSATP3,TPHM
07650 50 FORMAT(1H1/1H~/1H0,10X,31HBOILING OCCURS AT CORE EXIT,/,10X,
07660 S* TSATP3= *,E15.5,10X,* TPHM= *,E15.5)
07670 STOP
07680 60 CONTINUE
07690 ENDPRO
07700 *
07710 TAP1=(TP1+TP3)/2.0
07720 *
07730 ROTAP1=RHONA(TAP1)
07740 ROTP3=RHONA(TP3)
07750 RHOTE3=RHONA(TR3)
07760 *
07770 TP3.=(3.4093E-5/ROTAP1)*(HR*(TAF-TAP1)+0.3032*FFC*WP*(TP1-TP3))
07780 *
07790 PROCED YP4=Y4,Y4MIN
07800 IF(Y4.LE.Y4MIN) YP4=Y4MIN

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07810      IF (Y4.GT.Y4MIN)  YP4=Y4
07820      ENDPRO
07830      *
07840      ENP4=AP4*YP4*ROTP4
07850      *
07860      TR3.=(3.71815E-7/(RHOTP1+RHOTR3))*(EPS*EN-0.3032*WP*(TR3-TP1))
07870      TP4.=(WP/(3600.*ENP4))*(TR3-TP4)
07880      *
07890      *      PRIMARY LOOP PUMP AND MOMENTUM EQUATIONS
07900      *
07910      WPP1=(WP21+WP31)/2.0
07920      WPP2=(WP22+WP32)/2.0
07930      QPP1=1.24657E-4*WPP1/ROTP4
07940      QPP2=1.24657E-4*WPP2/ROTP4
07950      HOPP1=HMM(ENPP1,QPP1)
07960      HOPP21=HPM(ENPP1,QPP1)
07970      HOPP2=HMM(ENPP2,QPP2)
07980      *
07990      *      PROCED HOPP1=ENPP1,HOPP11,HOPP21
08000      IF(ENPP1.GT.110.0)  HOPP1=HOPP11
08010      IF(ENPP1.LE.110.0)  HOPP1=HOPP21
08020      ENDPRO
08030      *
08040      QPONP1=QPP1/ENPP1
08050      QPONP2=QPP2/ENPP2
08060      *
08070      ETAPP1=0.019275+69.68*QPONP1-1970.*QPONP1**2+16531.461*QPONP1**3
08080      ETAPP2=0.019275+69.68*QPONP2-1970.*QPONP2**2+16531.461*QPONP2**3
08090      *
08100      *      PROCED CDTROP=TRQPM
08110      IF(T.LE.50.)  CDTROP=TRQPM*EXP(-2.0*T)
08120      IF(T.GT.50.)  CDTROP=0.0
08130      ENDPRO
08140      *
08150      *      PROCED TRQP1=ENPCD,CDTRQP
08160      IF(ENPCD.EQ.0.0)  TRQP1=TRQPM
08170      IF(ENPCD.NE.0.0)  TRQP1=CDTRQP
08180      ENDPRO
08190      *
08200      TRQP2=TRQPM
08210      *
08220      ENPP1.=(9.5493/AIPP)*(TRQP1-0.0854*WPP1*HOPP1/(ENPP1*ETAPP1))
08230      ENPP2.=(9.5493/AIPP)*(TRQP2-0.0854*WPP2*HOPP2/(ENPP2*ETAPP2))
08240      *
08250      PSPP1=15.0+YSPP1*ROTP4/144.0
08260      PSPP2=15.0+YSPP2*ROTP4/144.0
08270      PSNPP1=PSPP1-0.057868*ROTP4
08280      PSNPP2=PSPP2-0.057868*ROTP4
08290      PDPP1=PSPP1+HOPP1*ROTP4/144.0
08300      PDPP2=PSPP2+HOPP2*ROTP4/144.0
08310      P41=15.+(YP4-5.733)*ROTP4/144.0-3.2593E-7*WP2S1**2.0
08320      P42=15.+(YP4-5.733)*ROTP4/144.0-3.2593E-7*WP2S2**2.0
08330      P3=15.+YP4*ROTP4/144.0
08340      *
08350      *      Y4.=(WP-WP2)/(3600.*AP4*ROTP4)
08360      *      YSPP1.=(WP2S1-WP3S1)/(42.6*ROTP4)
08370      *      YSPP2.=(WP2S2-WP3S2)/(42.6*ROTP4)
08380      *
08390      *      PROCED WOPF=ENORF,AORF,ROTR11
08400      IF(T.EQ.0.0.OR.ENORF.EQ.0.0.OR.(P11-24.7).LE.0.0)  WOPF=0.0

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08410      IF (T.NE.0.0.AND.ENORF.NE.0.0.AND.(P11-24.7).GT.0.0)
08420      $   WOPF=4.995*AORF*SQRT (ROTR11*(P11-24.7))
08430      ENDPRO
08440      *
08450      WP1S1=WP3S1-WOPF
08460      WP1S2=WP3S2
08470      *
08480      WP1S1D=DELAY (WP1S1,0.2,6,WP1S1I)
08490      DWP1S1=5.0*(WP1S1-WP1S1D)
08500      *
08510      DWP2S1=1.75*(144.*(P41-PSNPP1)+6.0*ROTP4-1.02836E-6*WP2S1**2.)
08520      DWP2S2=1.75*(144.*(P42-PSNPP2)+6.0*ROTP4-1.02836E-6*WP2S2**2.)
08530      WP2S1.=DWP2S1
08540      WP2S2.=DWP2S2
08550      *
08560      DWP3S1=0.33576*(144.*(PDPP1-P11)-30.*ROTP4+25.37*ROAP51
08570      $   +15.8392*ROTR11-5.6323E-4*WP3S1**2.)
08580      DWP3S2=0.33576*(144.*(PDPP2-P12)-30.*ROTP4+25.37*ROAP52
08590      $   +15.8392*ROTR12-5.6323E-4*WP3S2**2.)
08600      *
08610      WP3S1.=DWP3S1
08620      WP3S2.=DWP3S2
08630      *
08640      DWPS=DWP1S1+2.0*DWP3S2
08650      PROCD P1D=WP3,P143,ENSUB
08660      IF (T.EQ.0.0) DWPS=0.0
08670      P1D=P3+(1./144.0)*(11.0*ROTP1+3.0*ROTP1+5.6834*ROTP3
08680      $   +1421.95*PFC*DWPS/ENP)+(P143*(PFC/ENSUB)**2+6.79E-8)*WPS**2
08690      ENDPRO
08700      *
08710      P11=P1D+3.1235E-7*WP1S1**2.0
08720      P12=P1D+3.1235E-7*WP1S2**2.0
08730      P51=PDPP1-(1./144.0)*(20.667*ROTP4+8.605E-5*WP3S1**2+1.156*DWP3S1)
08740      P52=PDPP2-(1./144.0)*(20.667*ROTP4+8.605E-5*WP3S2**2+1.156*DWP3S2)
08750      P71=P51-(1./144.0)*(9.3255*ROTP4-25.37*ROAP51-6.93*ROTR11
08760      $   +2.1E-4*WP3S1**2.0)
08770      P72=P52-(1./144.0)*(9.3255*ROTP4-25.37*ROAP52-6.93*ROTR12
08780      $   +2.1E-4*WP3S2**2.0)
08790      *
08800      *
08810      *
08820      *
08830      *
08840      QIP1=1.2466E-4*WI1/ROTI91
08850      QIP2=1.2466E-4*WI2/ROTI92
08860      HOIP11=HMM(ENIP1,QIP1)
08870      HOIP21=HMM(ENIP1,QIP1)
08880      HOIP2=HMM(ENIP2,QIP2)
08890      *
08900      PROCD ROIP1=ENIP1,HOIP11,HOIP21
08910      IF (ENIP1.GT.110.) HOIP1=HOIP11
08920      IF (ENIP1.LE.110.) HOIP1=HOIP21
08930      ENDPRO
08940      *
08950      QIONI1=QIP1/ENIP1
08960      QIONI2=QIP2/ENIP2
08970      *
08980      ETAIP1=0.006337+72.0*QIONI1-2049.*QIONI1**2+17671.51*QIONI1**3
08990      ETAIP2=0.006337+72.0*QIONI2-2049.*QIONI2**2+17671.51*QIONI2**3
09000      *

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09010      PROCD COTRQI=TRQIM
09020      IF (T.LE.50.) COTRQI=TRQIM*EXP(-2.0*T)
09030      IF (T.LE.50.) COTRQI=0.0
09040      ENDPRO
09050      *
09060      PROCD TRQI1=ENICD,COTRQI
09070      IF (ENICD.EQ.0.0) TRQI1=TRQIM
09080      IF (ENICD.NE.0.0) TRQI1=COTRQI
09090      ENDPRO
09100      *
09110      TRQI2=TRQIM
09120      *
09130      ENIP1.=(9.5493/AIIP)*(TRQI1-0.0854*WI1*HOIP1/(ENIP1*ETAIP1))
09140      ENIP2.=(9.5493/AIIP)*(TRQI2-0.0854*WI2*HOIP2/(ENIP2*ETAIP2))
09150      *
09160      PSIP1=114.7+0.145255*ROTI91
09170      PSIP2=114.7+0.145255*ROTI92
09180      PSNIP1=PSIP1-0.0729167*ROTI91
09190      PSNIP2=PSIP2-0.0729167*ROTI92
09200      PDIP1=PSIP1+HOIP1*ROTI91/144.0
09210      PDIP2=PSIP2+HOIP2*ROTI92/144.0
09220      *
09230      TAUWI1=2.4431/ENEVP1+14.356
09240      TAUWI2=15.57755
09250      *
09260      ROTIC1=RHONA (TIC1)
09270      ROTIC2=RHONA (TIC2)
09280      *
09290      DWIS1=(1/TAUWI1)*((HOIP1+7.8151)*ROTI91-25.37*ROAI11-17.862*ROTI31
09300      * +35.417*(ROAI11+ROIE1-ROTI1)-(1.1522E-3/ENEVP1**2+1.148583E-3)
09310      * *WIS1**2.)
09320      DWIS2=(1/TAUWI2)*((HOIP2+7.8151)*ROTI92-25.37*ROAI12-17.862*ROTI32
09330      * +35.417*(ROAI12+ROIE2-ROTI2)-1.436633E-3*WIS2**2)
09340      WIS1.=DWIS1
09350      WIS2.=DWIS2
09360      *
09370      PI11=PDIP1-(1./144.)* (3.917*DWIS1+12.857*ROTI91+1.2155E-4*WIS1**2.)
09380      PI12=PDIP2-(1./144.)* (3.917*DWIS2+12.857*ROTI92+1.2155E-4*WIS2**2.)
09390      PI31=PI11-(1./144.0)* (0.426*DWIS1-41.422*ROTI91+25.37*ROAI11
09400      * +12.54*ROTI31+1.8E-4*WIS1**2)
09410      PI32=PI12-(1./144.0)* (0.426*DWIS2-41.422*ROTI92+25.37*ROAI12
09420      * +12.54*ROTI32+1.8E-4*WIS2**2)
09430      PIA1=PI31-(1./144.0)* (8.782*DWIS1+5.32*ROTI31+2.065E-4*WIS1**2.0)
09440      PIA2=PI32-(1./144.0)* (8.782*DWIS2+5.32*ROTI32+2.065E-4*WIS2**2.0)
09450      PIC1=PIA1-(1./144.0)* (-35.417*ROAI11+6.043E-4*WIS1**2.0)
09460      PIC2=PIA2-(1./144.0)* (-35.417*ROAI12+6.043E-4*WIS2**2.0)
09470      PI71=PIC1-(1./144.0)* (2.4435*DWIS1/ENEVP1+35.417*ROTI1
09480      * +9.27E-5*(WIS1/ENEVP1)**2.)
09490      PI72=PIC2-(1./144.0)* (2.22*DWIS2+35.417*ROTI2-2.3175E-5*WIS2**2)
09500      PI91=PI71-(1./144.0)* (-35.417*ROIE1+1.0595E-3*(WIS1/ENEVP1)**2.0)
09510      PI92=PI72-(1./144.0)* (-35.417*ROIE2+2.639E-4*WIS2**2.0)
09520      *
09530      *
09540      *
09550      *      MAX. AVERAGE AND HOT CHANNEL TEMPERATURES
09560      *      AND THEIR LOCATIONS RELATIVE TO CORE CENTRAL PLANE
09570      *
09580      HRM=      1. / (0.25 /AKP+60.00024/HDG+52.173914/HC +0.0052151492)
09590      HRS=1./ (60.00024/HDG+52.173914/HC+0.0052151492)
09600      *

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09610 *      THE THEORITICAL LOCATIONS OF THE MAX. TEMPS. AT THE PIN-CLAD
09620 *      OUTER SURFACE, PIN SURFACE, AND FUEL PIN CENTER LINE IN THE AVG. CHANNEL
09630 *
09640      YCNXTH=1.5078339*ATAN(0.29944753*HC/WPD)
09650      YSNXTH=1.5078339*ATAN(15.62335*HRS/WPD)
09660      YFNXTH=1.5078339*ATAN(15.62335*HRS/WPD)
09670 *
09680 *
09690 *THE ACTUAL LOCATION OF THE PIN-CLAD OUTER SURFACE MAX. TEMP. IN THE AVG.CHANNEL
09700 *
09710      PROCED YCNAX=YCNXTH
09720      IF(YCNXTH.LT.1.5) YCNAX=YCNXTH
09730      IF(YCNXTH.GE.1.5) YCNAX=1.5
09740      ENDPRO
09750 *
09760 *THE ACTUAL LOCATION OF THE FUEL PIN MAX. SURFACE TEMP. IN THE AVG CHANNEL
09770 *
09780      PROCED YSNAX=YSNXTH
09790      IF(YSNXTH.LT.1.5) YSNAX=YSNXTH
09800      IF(YSNXTH.GE.1.5) YSNAX=1.5
09810      ENDPRO
09820 *
09830 *THE ACTUAL LOCATION OF THE FUEL PIN MAX. CENTER LINE TEMP. IN THE AVG. CHANNEL
09840 *
09850      PROCED YFNAX=YFNXTH
09860      IF(YFNXTH.LT.1.5) YFNAX=YFNXTH
09870      IF(YFNXTH.GE.1.5) YFNAX=1.5
09880      ENDPRO
09890 *
09900 *      THE THEORITICAL LOCATIONS OF THE MAX. TEMPS. AT THE PIN-CLAD
09910 *      OUTER SURFACE, PIN SURFACE, AND FUEL PIN CENTER LINE IN THE HOT CHANNEL
09920 *
09930      YCNTH=1.5078339*ATAN(0.17787267*HC/WPD)
09940      YSMTH=1.5078339*ATAN(0.001401791/(WPD*(0.0078808679/HC
09950      $ +4.4692799E- 7+0.0063842402/HDG)))
09960      YFNTH=1.5078339*ATAN(0.001401791/(WPD*(0.0078808679/HC
09970      $ +4.4692799E- 7+0.0063842402/HDG+1.9770937E- 5/AKZ)))
09980 *
09990 *THE ACTUAL LOCATION OF THE PIN-CLAD OUTER SURFACE MAX. TEMP. IN THE HOT CHANNEL
10000 *
10010      PROCED YCNH=YCNTH
10020      IF(YCNTH.LT.1.5) YCNH=YCNTH
10030      IF(YCNTH.GE.1.5) YCNH=1.5
10040      ENDPRO
10050 *
10060 *THE ACTUAL LOCATION OF THE FUEL PIN MAX. SURFACE TEMP. IN THE HOT CHANNEL
10070 *
10080      PROCED YSMH=YSMTH
10090      IF(YSMTH.LT.1.5) YSMH=YSMTH
10100      IF(YSMTH.GE.1.5) YSMH=1.5
10110      ENDPRO
10120 *
10130 *THE ACTUAL LOCATION OF THE FUEL PIN MAX. CENTER LINE TEMP. IN THE HOT CHANNEL
10140 *
10150      PROCED YFNH=YFNTH
10160      IF(YFNTH.LT.1.5) YFNH=YFNTH
10170      IF(YFNTH.GE.1.5) YFNH=1.5
10180      ENDPRO
10190 *
10200 *

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10210 *
10220 *VOLUMETRIC HEAT GENERATION AT THE CENTER OF THE FUEL PIN IN THE AVG. CHANNEL
10230 *
10240   QC=0.045077766*EPS*PPGC*EN
10250 *
10260 *COOLANT MAX. TEMP. AT THE EXIT OF THE AVG. CHANNEL
10270 *
10280   TPNAX=TP1+7.6761921E- 5*EPS*PPGC*EN/WPD
10290 *
10300 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
10310 *OF THE MAX. TEMP. AT THE PIN-CLAD OUTER SURFACE IN THE AVG. CHANNEL
10320 *
10330   DTP1CX=(4.5780019E- 5*EPS*PPGC*EN/WPD)
10340   $   *(0.838378+SIN(0.66320299*YCMAX))
10350 *
10360 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
10370 *OF THE MAX. TEMP. AT THE PIN-CLAD OUTER SURFACE IN THE HOT CHANNEL
10380 *
10390   DTP1CH=(5.06327E- 5*EPS*PPGC*EN/WPD)
10400   $   *(0.838378+SIN(0.66320299*YCHMAX))
10410 *
10420 *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
10430 *PIN-CLAD OUTER SURFACE IN THE AVG. CHANNEL
10440 *
10450   TPYCNX=TP1+DTP1CX
10460 *
10470 *THE DIFFERENCE BETWEEN THE PIN-CLAD OUTER SURFACE TEMP. AND THE
10480 *SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE CLAD
10490 *OUTER SURFACE IN THE AVG. CHANNEL
10500 *
10510   DTPCNX=0.0033915082*QC*COS(0.66320299*YCMAX)/HC
10520 *
10530 *THE DIFFERENCE BETWEEN THE PIN-CLAD OUTER SURFACE TEMP. AND THE
10540 *SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE CLAD
10550 *OUTER SURFACE IN THE HOT CHANNEL
10560 *
10570   DTPCH=0.0033915082*QC*COS(0.66320299*YCHMAX)/HC
10580 *
10590 *MAX. PIN-CLAD OUTER SURFACE TEMP. IN THE AVG. CHANNEL
10600 *
10610   TCNAX=TPYCNX+DTPCNX
10620 *
10630 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
10640 *OF THE MAX. TEMP. AT THE FUEL PIN SURFACE IN THE AVG. CHANNEL
10650 *
10660   DTP1SX=(4.5780019E- 5*EPS*PPGC*EN/WPD)
10670   $   *(0.838378+SIN(0.66320299*YSMAX))
10680 *
10690 *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
10700 *FUEL PIN SURFACE IN THE HOT CHANNEL
10710 *
10720   DTP1SH=(5.06327E- 5*EPS*PPGC*EN/WPD)
10730   $   *(0.838378+SIN(0.66320299*YSHMAX))
10740 *
10750 *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
10760 *FUEL PIN SURFACE IN THE AVG. CHANNEL
10770 *
10780   TPYSNX=TP1+DTP1SX
10790 *
10800 * MAX. FUEL PIN SURFACE TEMP. IN THE AVG. CHANNEL

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10810 *
10820 TSNA=TPYSMX*6.5003905E- 5*QC*CS(0.66320299*YSNA)/HRS
10830 *
10840 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
10850 *OF THE MAX. TEMP. AT THE FUEL PIN CENTER LINE IN THE AVG. CHANNEL
10860 *
10870 DTP1FX=(4.5780019E- 5*EPS*PPGC*EN/WPD)
10880 $ *(0.838378+SIN(0.66320299*YFNA))
10890 *
10900 *THE TEMP. RISE OF THE SODIUM COOLANT FROM THE CORE INLET TO THE LEVEL
10910 *OF THE MAX. TEMP. AT THE FUEL PIN CENTER LINE IN THE HOT CHANNEL
10920 *
10930 DTP1FN=(5.06327E- 5*EPS*PPGC*EN/WPD)
10940 $ *(0.838378+SIN(0.66320299*YFHN))
10950 *
10960 *THE SODIUM COOLANT TEMP. AT THE LEVEL OF THE MAX. TEMP. OF THE
10970 *FUEL PIN AT ITS CENTER LINE IN THE AVG. CHANNEL
10980 *
10990 *
11000 TYPFHX=TP1+DTP1FX
11010 *MAX. FUEL PIN TEMP. AT ITS CENTER LINE IN THE AVG. CHANNEL
11020 *
11030 TFMX=TPYFHX*6.5003905E- 5*QC*CS(0.66320299*YFHN)/HRM
11040 *
11050 *COOLANT MAX. TEMP. IN THE HOT CHANNEL
11060 *
11070 TFMH=1.248*(TP1+8.4898684E-5*EPS*PPGC*EN/WPD)
11080 *
11090 *PIN-CLAD MAX. OUTER SURFACE TEMP. IN THE HOT CHANNEL
11100 *
11110 TCMH=1.248*(TP1+DTP1CH)+2.323706*DTPCH
11120 *
11130 *FUEL PIN MAX. SURFACE TEMP. IN THE HOT CHANNEL
11140 *
11150 TSMH=1.248*(TP1+DTP1SH) +(0.0078808679/HC+4.4692799E- 7
11160 $ +0.0063842402/HDG)*QC*CS(0.66320299*YSMH)
11170 *
11180 *FUEL PIN MAX. CENTER LINE TEMP. IN THE HOT CHANNEL
11190 *
11200 TFMH=1.248*(TP1+DTP1FN) +(0.0078808679/HC+4.4692799E- 7
11210 $ +0.0063842402/HDG+1.9770937E- 5/ANP)*QC*CS(0.66320299*YFMH)
11220 *
11230 *
11240 *
11250 STORE , WS9,PS9,TS9,HS9
11260 $,PT,PGFETA,PONG,PGE,PGA
11270 $,PETAG,OMGS,PF
11280 $,WP11,WP12,WP21,WP22,WP31,WP32,WP
11290 $,WI1,WI2,WSC1,WSC2
11300 $,TASA1,TASA2,TAWA1,TAWA2,TAIA1,TAIA2
11310 $,PSA1,PSA2,PSC1,PSC2
11320 $,TSA1,TSA2,TSC1,TSC2
11330 $,HSA1,HSA2,HSC1,HSC2
11340 $,TIA1,TIA2,TIC1,TIC2
11350 $,ELS11,ELS12,ELS21,ELS22
11360 $,WS11,WS12,WS31,WS32
11370 $,XS31,XS32,ALF31,ALF32,HS31,HS32
11380 $,TAW11,TAW12,TAW21,TAW22
11390 $,TAI71,TAI72,TAI81,TAI82,TAI91,TAI92
11400 $,PAS21,PAS22,ALPA21,ALPA22

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11410 $,TS11,TS12,HS11,HS12
11420 $,WS51,WS52,TS51,TS52,PAS41,PAS42
11430 $,EMS41,EMS42,EMS51,EMS52,YS51,YS52
11440 $,RHOD,EN,TAP,TP1,TAP1,TP3
11450 $,TUTP51,TUTP52,TP4,TP51,TP52
11460 $,TAP51,TAP52,TAI11,TAI12,TI31,TI32
11470 $,TUTR11,TP71,TR11,TUTR12,TP72,TR12
11480 $,TPMAX,TPMH,TCMAX,YCHH,TCMH
11490 $,TSMAX,TSMH
11500 $,TFMAX,YFMH,TFMH
11510 $,YP4,YSPP1,YSPP2,HOPP1,HOPP2,HOIP1,HOIP2
11520 $,P11,P12,P3,P41,P42
11530 $,P51,P52,P71,P72
11540 $,PI11,PI12,PI31,PI32,PIA1,PIA2
11550 $,PIC1,PIC2,PI72,PI72,PI91,PI92
11560 *
11570 ST1
11580 RHONA , 6
11590 * NEXT IS THE INDEPENDENT VARIABLE FOLLOWED BY THE DEPENDENT
11600 392.0 ,56.4
11610 572.0 ,55.1
11620 752.0 ,53.6
11630 932.0 ,52.1
11640 1112.0 ,50.5
11650 1292.0 ,48.9
11660 ST2
11670 TSATNA,11
11680 1.176 ,1214.6
11690 2.205 ,1304.6
11700 4.557 ,1412.0
11710 11.76 ,1574.6
11720 21.756 ,1700.6
11730 37.926 ,1826.6
11740 50.568 ,1898.6
11750 66.15 ,2024.6
11760 102.312 ,2096.6
11770 121.569 ,2150.6
11780 226.968 ,2366.6
11790 ST3
11800 TS1P , 12
11810 374.97 ,400.0
11820 396.77 ,420.0
11830 418.9 ,440.0
11840 430.1 ,450.0
11850 441.4 ,460.0
11860 464.4 ,480.0
11870 487.8 ,500.0
11880 511.9 ,520.0
11890 536.6 ,540.0
11900 562.2 ,560.0
11910 588.9 ,580.0
11920 610.0 ,600.0
11930 ST4
11940 RHOW , 12
11950 400.0 ,53.648
11960 420.0 ,52.798
11970 440.0 ,51.921
11980 450.0 ,51.546
11990 460.0 ,51.02
12000 480.0 ,50.0

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12010	500.0	,49.02			
12020	520.0	,47.847			
12030	540.0	,46.512			
12040	560.0	,45.249			
12050	580.0	,43.860			
12060	600.0	,43.373			
12070	ST5				
12080	VF , 6				
12090	1200.0	,0.0223			
12100	1300.0	,0.0227			
12110	1400.0	,0.0231			
12120	1500.0	,0.0235			
12130	2000.0	,0.0257			
12140	2500.0	,0.0287			
12150	ST6				
12160	HP , 6				
12170	1200.0	,571.7			
12180	1300.0	,585.4			
12190	1400.0	,598.7			
12200	1500.0	,611.6			
12210	2000.0	,671.7			
12220	2500.0	,730.6			
12230	ST7				
12240	TSATF , 6				
12250	1200.0	,567.22			
12260	1300.0	,577.46			
12270	1400.0	,587.1			
12280	1500.0	,596.23			
12290	2000.0	,635.82			
12300	2500.0	,668.13			
12310	ST8				
12320	VG , 6				
12330	1200.0	,0.3619			
12340	1300.0	,0.3293			
12350	1400.0	,0.3012			
12360	1500.0	,0.2765			
12370	2000.0	,0.1878			
12380	2500.0	,0.1307			
12390	ST9				
12400	HG , 6				
12410	1200.0	,1183.4			
12420	1300.0	,1178.6			
12430	1400.0	,1173.4			
12440	1500.0	,1167.9			
12450	2000.0	,1135.1			
12460	2500.0	,1091.1			
12470	ST10				
12480	RD , 3 , 5				
12490	*				
12500	* THE FOLLOWING IS A DEFINITION OF THE SECOND				
12510	* INDEPENDENT VARIABLE.				
12520	*				
12530		0.2	,0.4	,0.6	,0.8 ,1.0
12540	*				
12550	* NEXT COMES THE FIRST INDEPENDENT VARIABLE				
12560	*FOLLOWED BY THE DEPENDENT VARIABLE				
12570	*				
12580	1000.0	,4.81801	,7.43707	,10.6082	,12.915 ,14.4123
12590	2000.0	,2.48938	,3.21363	,4.30274	,4.97874 ,5.35559
12600	2500.0	,1.72844	,2.23131	,2.6778	,2.98751 ,2.98751

12610	ST11					
12620	VSH , 6,5					
12630		700.0	,800.0	,900.0	,1000.0	,1200.0
12640	1200.0	,0.4909	,0.5617	,0.6250	,0.6843	,0.7967
12650	1400.0	,0.4062	,0.4714	,0.5281	,0.5805	,0.6789
12660	1600.0	,0.3417	,0.4034	,0.4553	,0.5027	,0.5906
12670	1800.0	,0.2907	,0.3502	,0.3986	,0.4421	,0.5218
12680	2000.0	,0.2489	,0.3074	,0.3532	,0.3935	,0.4668
12690	2500.0	,0.1686	,0.2294	,0.2710	,0.3061	,0.3678
12700	ST12					
12710	HSH , 6,5					
12720		700.0	,800.0	,900.0	,1000.0	,1200.0
12730	1200.0	,1311.0	,1379.3	,1440.7	,1499.2	,1613.1
12740	1400.0	,1295.5	,1369.1	,1433.1	,1493.2	,1608.9
12750	1600.0	,1278.7	,1358.4	,1425.3	,1487.0	,1604.6
12760	1800.0	,1260.3	,1347.2	,1417.4	,1480.8	,1600.4
12770	2000.0	,1240.0	,1335.5	,1409.2	,1474.5	,1596.1
12780	2500.0	,1176.3	,1303.6	,1387.8	,1458.4	,1585.3
12790	ST13					
12800	S9 , 6,5					
12810		700.0	,800.0	,900.0	,1000.0	,1200.0
12820	1200.0	,1.4843	,1.5409	,1.5859	,1.6293	,1.7025
12830	1400.0	,1.4567	,1.5177	,1.5666	,1.6093	,1.6386
12840	1600.0	,1.4304	,1.4964	,1.5476	,1.5914	,1.6669
12850	1800.0	,1.4044	,1.4765	,1.5301	,1.5752	,1.6520
12860	2000.0	,1.3783	,1.4576	,1.5139	,1.5603	,1.6384
12870	2500.0	,1.3073	,1.4127	,1.4772	,1.5273	,1.6088
12880	ST14					
12890	HSH , 13, 12					
12900		0.0	,4.0	,8.0	,12.0	,16.0
12910	\$,20.0	,24.0	,28.0	,32.0	,36.0	,40.0
12920	\$,44.0					
12930	\$,110.0	,4.77	,3.43	,0.0	,0.0	,0.0
12940	\$,0.0	,0.0	,0.0	,0.0	,0.0	,0.0
12950	\$,0.0					
12960	\$,150.0	,8.86	,7.616	,2.95	,0.0	,0.0
12970	\$,0.0	,0.0	,0.0	,0.0	,0.0	,0.0
12980	\$,0.0					
12990	\$,250.0	,24.5	,23.0	,19.55	,11.7	,2.2
13000	\$,0.0	,0.0	,0.0	,0.0	,0.0	,0.0
13010	\$,0.0					
13020	\$,350.0	,47.8	,46.25	,42.65	,36.65	,26.1
13030	\$,13.425	,1.1	,0.0	,0.0	,0.0	,0.0
13040	\$,0.0					
13050	\$,500.0	,98.8	,97.8	,94.9	,89.2	,79.5
13060	\$,65.7	,50.0	,32.0	,22.0	,10.0	,5.0
13070	\$,2.0					
13080	\$,980.0	,380.0	,378.0	,376.0	,370.0	,363.0
13090	\$,353.0	,340.0	,322.0	,302.0	,277.0	,244.0
13100	\$,210.0					
13110	\$,1006.0	,400.0	,398.5	,396.0	,391.0	,384.0
13120	\$,374.0	,361.0	,342.647	,308.92	,300.0	,266.0
13130	\$,230.0					
13140	\$,1030.0	,419.0	,418.0	,415.0	,410.0	,404.0
13150	\$,393.0	,380.0	,364.0	,343.0	,319.0	,288.0
13160	\$,253.0					
13170	\$,1150.0	,514.0	,512.0	,510.0	,504.0	,496.0
13180	\$,486.0	,470.0	,454.0	,440.0	,420.0	,390.0
13190	\$,355.0					
13200	\$,1170.0	,532.0	,531.0	,528.0	,522.0	,514.0

13210	\$	,504.0	,489.0	,472.0	,463.6156	,431.5789	,410.0
13220	\$	,375.0					
13230		1200.0	,560.0	,558.0	,555.0	,549.0	,541.5
13240	\$	,531.0	,516.0	,500.0	,485.0	,466.0	,439.0
13250	\$	,404.0					
13260		1400.0	,775.0	,773.0	,770.0	,765.0	,758.0
13270	\$	,749.0	,738.0	,723.0	,705.0	,684.0	,658.0
13280	\$	,634.0					
13290		1500.0	,874.0	,872.0	,870.0	,865.0	,856.0
13300	\$	,846.0	,833.0	,817.0	,797.0	,776.0	,758.0
13310	\$	,736.0					
13320	ST15						
13330	RPM,9,9						
13340			0.0	,0.5	,1.0	,1.5	,2.0
13350	\$	,2.5	,3.0	,3.5	,4.0		
13360		10.0	,0.03939	,0.0156	,0.0	,0.0	,0.0
13370	\$	,0.0	,0.0	,0.0	,0.0		
13380		50.0	,0.98	,0.95	,0.9	,0.81	,0.65
13390	\$	,0.406	,0.08	,0.0	,0.0		
13400		70.0	,1.93	,1.88	,1.82	,1.75	,1.63
13410	\$	,1.43	,1.2	,0.8	,0.5		
13420		80.0	,2.52	,2.47	,2.4	,2.31	,2.2
13430	\$	,2.03	,1.77	,1.4	,1.0		
13440		90.0	,3.19	,3.14	,3.06	,2.97	,2.87
13450	\$	,2.71	,2.48	,2.17	,1.8		
13460		100.0	,3.94	,3.88	,3.8	,3.71	,3.6
13470	\$	,3.44	,3.26	,2.98	,2.61		
13480		105.0	,4.34	,4.274	,4.195	,4.095	,3.977
13490	\$	,3.944	,3.65	,3.376	,3.033		
13500		107.0	,4.51	,4.44	,4.36	,4.26	,4.14
13510	\$	,4.01	,3.82	,3.56	,3.16		
13520		110.0	,4.77	,4.694	,4.61	,4.51	,4.4
13530	\$	,4.27	,4.08	,3.83	,3.43		
13540	ST16						
13550	EMW,13						
13560		0.0	,380.0				
13570		3600.0	,381.5				
13580		7200.0	,382.3				
13590		10800.0	,383.5				
13600		14400.0	,384.7				
13610		18000.0	,388.0				
13620		21600.0	,391.0				
13630		25200.0	,392.0				
13640		28800.0	,392.2				
13650		32400.0	,392.1				
13660		36000.0	,391.9				
13670		39600.0	,391.0				
13680		43200.0	,390.0				
13690	SP						
13700	FUNCTION DHP(PAS)						
13710	PAS21=PAS-50.0						
13720	PAS22=PAS+50.0						
13730	HP1=HP(PAS21)						
13740	HP2=HP(PAS22)						
13750	DHP=(HP2-HP1)/100.0						
13760	RETURN						
13770	END						
13780	FUNCTION DVP(PAS)						
13790	PAS21=PAS-50.0						
13800	PAS22=PAS+50.0						

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13810      VF1=VF(PAS21)
13820      VP2=VF(PAS22)
13830      DVP=(VP2-VF1)/100.0
13840      RETURN
13850      END
13860      FUNCTION DVG(PAS)
13870      PAS21=PAS-50.0
13880      PAS22=PAS+50.0
13890      VG1=VG(PAS21)
13900      VG2=VG(PAS22)
13910      DVG=(VG2-VG1)/100.0
13920      RETURN
13930      END
13940      FUNCTION DHG(PAS)
13950      PAS21=PAS-50.0
13960      PAS22=PAS+50.0
13970      HG1=HG(PAS21)
13980      HG2=HG(PAS22)
13990      DHG=(HG2-HG1)/100.0
14000      RETURN
14010      END
14020      *
14030      *
14040      SP      FUNCTION PDELAY(XC,TAU,I,XCI)
14050      C      FUNCTION PDELAY(XC,TAU,I,XCI)
14060      C
14070      C PIPE DELAY FUNCTION FOR THE DARE P RUNTIME SYSTEM
14080      C
14090      C XC = VARIABLE TO BE DELAYED
14100      C
14110      C TAU = AMOUNT OF DELAY BEFORE PRESENT VALUE OF XC IS VALID.
14120      C      (VARIABLE, ANY VALUE .GE. ZERO)
14130      C
14140      C I = INTEGER CONSTANT BETWEEN 1 AND IMAX IDENTIFYING
14150      C      INDEPENDENT PDELAY OPERATORS
14160      C
14170      C XCI = INITIAL VALUE OF XC (VALUE RETURNED UNTIL T .GT. TAU(0) )
14180      C
14190      C PDELAY MODELS AN INCOMPRESSIBLE FLUID FLOWING THROUGH A UNIT
14200      C LENGTH PIPE AT A VELOCITY OF 1./TAU
14210      C
14220      LOGICAL ZBAP
14230      LOGICAL EXIT,RLDONE
14240      COMMON /SYSVAR/ EXIT,RLDONE,IOUT,IFILE,IRUNNO,T,TMAX,TNEXT
14250      COMMON /SYSVAR/ DT,DTMAX,DTMIN,EMAX,EMIN,SY(35)
14260      COMMON DELAY(8101)
14270      COMMON TMS(20),NP(20),WRAP(20),TSAV(100,20),XSAV(100,20),TAUL(20)
14280      1,XCL(20)
14290      DATA NPA/100/,IMAX/20/
14300      C
14310      PDELAY=XCI
14320      DUMMY=XC
14330      IF(EXIT) RETURN
14340      IF(I.GT.0.AND.I.LE.IMAX) GO TO 4
14350      WRITE(IOUT,3) I
14360      3      FORMAT(36H FATAL ERROR - INVALID PDELAY NUMBER,I3)
14370      CALL ABORT
14380      4      IF(TAU.GT.0.) GO TO 7
14390      WRITE(IOUT,6) I,IRUNNO,T
14400      6      FORMAT(15H ERROR - PDELAY,I3,9H NEGATIVE/

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14410      2 7H - RUN,I4,19H TERMINATED AT T =,1PE12.5)
14420      EXIT=.TRUE.
14430      RETURN
14440      C
14450      C IF T.EQ.0, INITIALIZE
14460      C
14470      7 IF(T.GT.0.) GO TO 8
14480      NP(I)=1
14490      TNS(I)=AMAX1(DT,TAU*2./FLOAT(NPA))
14500      WRAP(I)=.FALSE.
14510      TSAV(1,I)=TAU
14520      XSAV(1,I)=XC
14530      TSAV(NPA,I)=0.
14540      TAU(I)=TAU
14550      XCL(I)=XC
14560      GO TO 12
14570      C
14580      C IF T.GE.TNS, SAVE X AND T, CALCULATE TNS
14590      C
14600      8 IF(T.LT.TNS(I).OR..NOT.RLDONE) GO TO 12
14610      C
14620      C IF TAU DIFFERS FROM LAST CALL, ADJUST TSAV ARRAY TO MATCH NEW
14630      C PIPE VELOCITY
14640      C
14650      IF(TAU.EQ.TAU(I)) GO TO 10
14660      N=NP(I)
14670      9 IF(T.GE.TSAV(N,I)) GO TO 10
14680      TSAV(N,I)=(TSAV(N,I)-T)*TAU/TAUL(I)+T
14690      N=MOD(N-2+NPA,NPA)+1
14700      GO TO 9
14710      10 IF(TAU(I)-TAU.LT.0.0) GO TO 43
14720      DUMMY=(DT*XC + TAU*XCL(I))/(TAU + DT)
14730      C
14740      C CHECK FOR BUFFER OVERFLOW (YES, IT CAN OCCUR)
14750      C BUFFER OVERFLOW IS STORING NEW DATA INTO A CELL BEFORE
14760      C FINISHED WITH OLD DATA
14770      C
14780      43 N=NP(I)
14790      TAU(I)=TAU
14800      XCL(I)=DUMMY
14810      N2=MOD(N+1,NPA)+1
14820      IF(.NOT.WRAP(I).AND.N2.GT.2) GO TO 11
14830      IF(T.GE.TSAV(N2,I)) GO TO 11
14840      TNS(I)=TSAV(N2,I)
14850      WRITE(10UT,105) I,T,TNS(I)
14860      105 FORMAT(17H WARNING - PDELAY,I3,22H BUFFER OVERFLOW AT T=,
14870      2 1PE12.5,6H, TNS=,E12.5)
14880      GO TO 12
14890      11 IF(N.EQ.NPA) WRAP(I)=.TRUE.
14900      N=MOD(N,NPA)+1
14910      NP(I)=N
14920      TSAV(N,I)=T+TAU
14930      XSAV(N,I)=DUMMY
14940      TNS(I)=T+AMAX1(DT,TAU*2./FLOAT(NPA))
14950      C
14960      C IF T .LT. FIRST-T-STORED, RETURN XCI
14970      C
14980      12 IF(.NOT.WRAP(I).AND.T.LT.TSAV(1,I)) RETURN
14990      C
15000      C CHECK FOR T .GT. LAST-T-STORED (WILL BE IF TAU.LT.DT)

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15010 C
15020 NBIG=NP(I)
15030 IF(T.LE.TSAV(NBIG,I)) GO TO 13
15040 NSM=NBIG
15050 NBIG=MOD(NBIG,NPA)+1
15060 IF(NBIG.EQ.1) WRAP(I)=.TRUE.
15070 TSAV(NBIG,I)=T+TAU
15080 XSAV(NBIG,I)=DUMMY
15090 GO TO 33
15100 C
15110 C CHECK WHICH HALF OF CIRCULAR BUFFER T IS IN
15120 C
15130 13 NSM=1
15140 IF(.NOT.WRAP(I).OR.T.GE.TSAV(1,I)) GO TO 15
15150 NSM=NBIG+1
15160 NBIG=NPA
15170 C
15180 C CHECK FOR T IN THE CRACK BETWEEN TSAV(NPA) AND TSAV(1)
15190 C
15200 IF(T.LE.TSAV(NPA,I)) GO TO 15
15210 NSM=NPA
15220 NBIG=1
15230 GO TO 33
15240 C
15250 C PERFORM BINARY SEARCH TO LOCATE INDEX OF T
15260 C
15270 15 IF(NBIG.LT.NSM) GO TO 33
15280 NTRY=(NBIG+NSM)/2
15290 IF(T-TSAV(NTRY,I)) 17,19,21
15300 17 NBIG=NTRY-1
15310 GO TO 15
15320 19 PDELAY=XSAV(NTRY,I)
15330 RETURN
15340 21 NSM=NTRY+1
15350 GO TO 15
15360 C
15370 C INTERPOLATE BETWEEN TWO CLOSEST POINTS
15380 C
15390 33 PDELAY = XSAV(NSM,I) + (XSAV(NBIG,I) - XSAV(NSM,I)) *
15400 2 (T-TSAV(NSM,I)) / (TSAV(NBIG,I) - TSAV(NSM,I))
15410 RETURN
15420 END
15430 *
15440 $M11
15450 END
15460 TMAX=100.0 , DT=1.0E-5 , DTHIN=1.0E-6
15470 SY(8)=3.0 , ENAX=0.00001
15480 SY(3)=0.01
15490 PETAG=25.5703 , OMGG=376.99
15500 WSAS1=309.259 , WSAS2=309.259
15510 SV9=0.95 , PT=387.6
15520 TSC1=905.0 , TAWA1=872.25542 , TIC1=885.0
15530 TSC2=905.0 , TAWA2=872.25542 , TIC2=885.0
15540 ELS11=21.377693 , ELS12=21.377693
15550 PAS21=1830.7 , PAS41=1765.7
15560 PAS22=1830.7 , PAS42=1765.7
15570 WS1D1=0.408533 , WS3D1=0.408533 , WSSS1=309.2593
15580 WS1D2=0.408533 , WS3D2=0.408533 , WSSS2=309.2593
15590 TAW11=659.08545 , TAW21=738.97753
15600 TAW12=659.08545 , TAW22=738.97753

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15610      TI81=713.96,      TI91=651.0
15620      TI82=713.96,      TI92=651.0
15630      EMS51=20268.29,   HS61=540.89
15640      EMS52=20268.29,   HS62=540.89
15650      D1=1.0,          D2=1.0,          D3=1.0
15660      D4=1.0,          D5=1.0,          D6=1.0
15670      WP2S1=3837.592,   WP3S1=3837.592,   WIS1=3550.0
15680      WP2S2=3837.592,   WP3S2=3837.592,   WIS2=3550.0
15690      ENPP1=1170.0,     ENPP2=1170.0
15700      ENIP1=1006.0,     ENIP2=1006.0
15710      TAP=2217.184,     TP3=1035.729
15720      TP1=730.0,        TP4=994.73,        TR3=994.73
15730      TP71=730.0,       TI31=936.0
15740      TP72=730.0,       TI32=936.0
15750      ENSC2=2.0,        ENS94=4.0,        ENEVP1=2.0
15760      ENL=3,           ENP=42966.0,     ENSUB=198.0
15770      EXWI=380.0,       EXAI=0.2
15780      CDMP=0.7089
15790      PSA=2.89642E-4,    PSH=2.09114E-3
15800      PHPW=2000.0
15810      PSS=0.32347367,    PVS=7.685E-5
15820      SV51=0.7,          SV52=0.7
15830      SV51D=0.7,         SV52D=0.7,        TAUSV5=0.5
15840      Y4=22.0,          YSPR1=16.833,     YSPR2=16.833
15850      DPRCSF=175.0,     FRC=7.057624E-5, PS6=1.6362977E-2
15860      DOD=7.0,          DV=1000.0
15870      PS9I=1464.7
15880      AV9=5.66816,      CV9=22.28
15890      ZMS4I=2179.93,    EMS51=20268.287
15900      RHODCI=2.9444232, ROFBCI=95.6,    DC=-0.0058
15910      SODDCC=-0.006,    RECC=-0.21,      AXECC=-0.023
15920      EPS=3.3267E9,     PPGC=0.9239,     TAFI=400.0
15930      HOG=756.8182
15940      VP1=3000.0,        Y4MIN=9.15,      AP4=287.5
15950      TRQPT=575431.61,  TRQIN=448790.3
15960      AIP=16000.0,       AIIP=16000.0
15970      WP1S1I=3837.592,   FFC=0.8
15980      TP4I=994.7313,    TP7I=730.0
15990      TI3I=936.0,       TI9I=651.0
16000      F143=0.039745
16010      ELS1=200.0,       ELS2=100.0
16020      ELSHT=65.0,       ELS7=120.0
16030      ELS31=70.0,      ELS32=10.0
16040      ELS61=15.0,       ELS62=100.0
16050      ELS63=75.0,      ELS64=30.0
16060      ELS5=250.0
16070      ENLD=1.0
16080      *
16090      END
16100      LIST,WS9,PS9,TS9,HS9,SS9,XEXH,HEXH
16110      LIST,STZBTU,PT,PGFETA,PONG,PGE,PGA
16120      LIST,PETAG,OMGG,AI,E,PF,XD
16130      LIST,WP11,WP12,WP21,WP22,WP31,WP32,WP
16140      LIST,WI1,WI2,WSC1,WSC2
16150      LIST,TASA1,TASA2,TAWA1,TAWA2,TAIA1,TAIA2
16160      LIST,PSA1,PSA2,PSC1,PSC2
16170      LIST,TS1,TS2,TSC1,TSC2
16180      LIST,WSA1,WSA2,HSC1,HSC2
16190      LIST,TIA1,TIA2,TIC1,TIC2
16200      LIST,ELS11,ELS12,ELS21,ELS22

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16210 LIST,WS11,WS12,WS31,WS32
16220 LIST,XS31,XS32,ALP31,ALP32,HS31,HS32
16230 LIST,TAW11,TAW12,TAW21,TAW22
16240 LIST,TAI71,TAI72,TAI81,TAI82,TAI91,TAI92
16250 LIST,PAS21,PAS22,ALFA21,ALFA22
16260 LIST,TS11,TS12,HS11,HS12
16270 LIST,WS51,WS52,TS51,TS52,PAS41,PAS42
16280 LIST,EMS41,EMS42,EMS51,EMS52,YS51,YS52
16290 LIST,RHOD,EN,TAP,TP1,TAP1,TP3
16300 LIST,TUTP51,TUTP52,TP4,TP51,TP52
16310 LIST,TAP51,TAP52,TAI11,TAI12,TAI31,TAI32
16320 LIST,TUTR11,TP71,TR11,TUTR12,TP72,TR12
16330 LIST,TFMAX,TFMN,YCMAX,TCMAX,YCMN,TCMN
16340 LIST,YSMAX,YSMAZ,YSMN,YSMM
16350 LIST,YFMAX,TFMAX,YFMN,TFMN
16360 LIST,YP4,YSP1,YSP2,HOPP1,HOPP2,HOIP1,HOIP2
16370 LIST,P11,P12,P3,P41,P42
16380 LIST,P51,P52,P71,P72
16390 LIST,PI11,PI12,PI31,PI32,PIA1,PIA2
16400 LIST,PIC1,PIC2,PI72,PI72,PI91,PI92
16410 END

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