1000-MWe LMFBR FOLLOW-ON STUDY

— Control Study —

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PREFACE

Babcock & Wilcox (B&W) is participating in the 1000-MWe Fast Breeder Reactor Follow-On Study Program of the Atomic Energy Commission under Argonne National Laboratory (ANL) Contract No. 31-109-38-1998. As stated by ANL,

"The overall objective of the current 1000-MWe LMFBR Follow-On Study Program is to provide the AEC with information needed to establish research and development programs that will lead to the achievement of economical and safe LMFBR power plants by a viable nuclear industry. This information is to be developed through studies of 1000-MWe LMFBR power plant reference conceptual designs favored by the nuclear industry for further development and eventual sale to electric utilities in the period 1975 to 1985."

The B&W Follow-On Study consists of the following four tasks:

Task I — The development of four basic plant concepts based on the established ground rules and the estimated state of technology in 1980, and the selection of a preliminary reference design that incorporates the best features of each concept.

Task II — Detailed engineering work on the preliminary reference design, and, in parallel, perform in-depth engineering trade-off studies.

Task III — Parametric studies to identify and evaluate the basic problem areas and to provide a basis for the selection of an optimized reference design.

Task IV — Preparation of a document outlining the research, development, and component testing required for the successful design and construction of the reference 1000-MWe LMFBR design.

This report describes the plant performance control studies carried out to verify and analyze the plant control arrangement. The studies were performed under Task II.

ABSTRACT

This report describes a thermal, hydraulic, and control analysis performed on a 1000-megawatt, sodium-cooled fast breeder reactor plant. The transient and steady-state analyses cover the reactor fuel, the reactor coolant system, the intermediate coolant system, the IHXs, the steam generators, and the reheaters. A digital computer was utilized for the whole plant analyses at steady state, while the transient and the control response analyses were performed on analog computers.

The dynamic study of the plant was accomplished by simulating the reactor and the intermediate systems on two analog computers. The neutron kinetics of the reactor are simulated by a point kinetics equation with one group of delayed neutrons. All heat transfer processes are described by conventional heat transfer equations. These model equations do account for variable values of the product UA . The overall plant model considers all significant time delays, including the delay effects of sodium mixing, sodium flow, valve actions, and sensor devices. The model delays are both constant and variable, depending on the particular application.

The control philosophy is that of reactor following turbine generator megawatt demand. All controls are of the proportional plus integral type and monitor either system temperatures, system flows, or neutron flux. Control action is taken through control rod insertion, reactor and intermediate pump speed changes, intermediate bypass valve stroke changes, and reheater valve stroke changes.

The results demonstrate that the chosen plant control arrangement responds adequately to typical changes in the turbine generator megawatt demand. The plant is limited to 2%/min load ramp and 5% step changes in load. The rates of change in the megawatt demand ranged from 1 to 2%/min load ramps and from 5 to 40% step changes. In all cases the plant responded well and showed control stability.

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1. INTRODUCTION

This report is to document the performance control analyses completed under the 1000-MWe LMFBR Follow-On Contract No. 31-109-38-1998 with Argonne National Laboratory. The plant control system design description which was evaluated in these analyses is given in BAW-1328.

The LMFBR plant is designed to produce power for an electric utility. The "plant" is the steam generation system which is connected to a turbine generator. The turbine generator is an output unit for the utility's grid system. This power plant, like conventional plants, can change load by moving from one power level to another in automatic control. The plant power rate of change depends on the kind of electrical grid system and its demands; the plants that generate the electrical power must be able to change the power to match these demand variations. Although the LMFBR plant is limited to a 2% per minute load ramp and 5% load step changes in the normal power maneuvering range of 20 to 100% of full load, this report contains other exemplary responses to more severe transients.

A designer must know the performance of a power plant during and following load-changing transients. The various operating parameters must be studied to ensure that the reactor, reactor coolant, intermediate coolant, and feedwater-steam systems operate well within their design conditions, and reactor plant safety must also be maintained during all operations. Because the operation of the entire plant must be understood during and following load transients, an analytical model was developed to describe the basic time response of the nuclear steam supply system. The simulation includes the reactor fuel, the reactor coolant system, the intermediate heat exchangers (IHXs), the intermediate coolant system, the steam generators-reheaters, the feedwater-steam system, and the control system. The simultaneous solution of models set

up for these parts of the plant will provide the thermal, hydraulic, nuclear, and control characteristics of the plant.

The individual systems were analyzed first in an open-loop fashion on general-purpose analog computers. The open-loop approach was used to simplify the power plant analysis. It also enhanced the understanding of the response of the individual systems that make up the plant. A final closed-loop solution for the two major heat generation and heat transport systems was also completed. This was the coupled solution of the reactor-reactor coolant and the intermediate coolant systems. This study did not include a closed-loop analysis of the entire plant. The results from the coupled solution of these two major systems confirmed the results obtained from the open-loop treatment.

Coupling of the reactor and intermediate coolant systems analyses represented a plateau in the complete plant analysis. Ideally, a total plant system representation would be most desirable, but this would require more analog equipment (and/or a hybrid arrangement) than was available for this study.

Partial load steady-state analyses were performed to establish the operating variables and the programmed variables to be maintained by the control system. The control arrangement is the combination of feedback-and-feedforward type, with some variables programmed as a function of plant load. It is commonly referred to as an integrated control system.

The studies indicated that the reactor and associated systems respond well to the ramp and step load changes required for an electrical generating station. The analysis shows that the requirements for the reactor control system allow the use of a simple, relatively slow, constant speed-regulating control rod system. The control loops in the reactor coolant and intermediate coolant systems are relatively straightforward, simple, control circuits. The analyses prove the feasibility of the control arrangement used in these systems.

This report discusses the reasons for the analyses, describes the methods (simulation) used, major input parameters, results, conclusions, and recommendations which result from the investigations.

2. CONCLUSIONS AND RECOMMENDATIONS

1. The studies demonstrated that the reactor, reactor coolant system, and intermediate coolant system control arrangement is workable. The simulated systems were subjected to load ramps and step changes that are typical of an electrical generating station. The systems responded well to these load changes, and all operating variables settled on their specified programs. No sustained diverging oscillations were evidenced, nor were any variables offset from their programmed values. The analyses prove the feasibility of the control system.

2. It is a characteristic of these systems that they respond slowly and sluggishly to the typical load transients, primarily because of the large amounts of sodium coolant in their hot and cold legs. In addition, some of the components contain rather large quantities of sodium (the steam generators, reheaters). This characteristic results in the requirement for rather typical, slow, control actions from the control circuits. Note that no derivative control actions were required in this analysis. The set of workable controller settings is given in Table 3-3.

3. Both open-loop and closed-loop analyses were performed on the reactor, reactor coolant, and intermediate coolant systems. No practical difference between these two methods of analysis was found.

4. The analyses should be expanded to include the feedwater system, steam system, the secondary side of the steam generators and reheaters, and the turbine generator; this would provide an entire coupled plant analysis. The plant contains many parallel components and loops in the sodium coolant and feedwater-steam systems. Therefore, methods should be developed for analyzing hydraulic and thermal unbalance in these parallel systems. The transients that result from the

failure or misoperation of components in these systems should be analyzed. These analyses should be combined with safety analysis and overall plant design efforts. A good description of these efforts is given in the "Dynamic Analysis and Control Study," Task 2-1.7 of WASH-1102,* where the general area of work described here is discussed specifically.

5. The major types of plant control systems, such as reactor-following, turbine-following, and other integrated control systems, should be compared, as should some other areas, including the reactor control system and other control loops.

6. The output from these studies should be used as input for detailed thermal stress analyses on pertinent piping and components in various parts of these systems.

* LMFBR Program Plan, Vol 2 - Plant Design, Task 2-1.7, "Dynamic Analysis and Control Study," Argonne National Laboratory, WASH-1102, August 1968, p 2 - 77.

3. ANALYTICAL METHODS

3.1. General

The methods described in this section were developed to analyze both steady-state partial-load and transient operation of the reactor and major heat transport systems. The plant operating conditions were stipulated for the normal maneuvering power range, 100 to 20% of full power. The plant control system maintains these process variables on their respective programs.* The partial-load analysis provides the programs used by the control system to regulate the various plant operating conditions.

The time-dependent model was devised to describe the response of the various process variables to the megawatt demands of the electrical grid system. The simulation model was programmed on general-purpose analog computers in two parts: the reactor-reactor coolant system and the intermediate coolant system. In the last phase of these analyses, both of these simulations were coupled together through the IHXs. The reactor-reactor coolant and the intermediate coolant systems were programmed for Electronics Associates, Inc. EAI 231-R and EAI 680 analog computers, respectively. The time response solution to each of these systems was solved first in an open-loop fashion and later in a coupled closed-loop fashion. The basic inputs to each of these model arrangements were the turbine-generator megawatt demand and the feedwater-steam system variables. This demand was fed into the models with the proper component and system time response effects. The control loops were also simulated and coupled to these process models. The system's transient response was illustrated from the variables of

*The plant control system is described in detail in BAW-1328, Volume 3, section 12.2.

megawatt demand, neutron power, flows, and temperatures recorded as a function of time.

The procedures used in applying these methods are described in section 3.2, and the equations of the simulation are discussed in section 3.3.

3.2. Procedures

The reactor-reactor coolant and the intermediate coolant systems were solved first in an open-loop fashion. Later these models were combined in a closed-loop analysis with respect to each other. No total plant closed-loop analysis was done. In each of the simulations completed, a balanced-single loop is assumed with no investigations made on any thermal or hydraulic unbalance in these systems. The open-loop, balanced-single-loop approach is a traditional procedure for studies of this kind. To completely simulate the plant would require a rather large analog or hybrid computer, neither of which was available. It is desirable to examine the "complete" system representation eventually.

The plant is required to operate at power levels lower than 100% of plant load. Partial-load steady-state plant conditions were stipulated in the normal power maneuvering range, 20 to 100% of full power. A partial-load analysis was the initial study made in the series of studies reported herein. From this analysis, restraints were placed on various system operating conditions, and consequently, the reactor neutron power, system temperatures, and system flows were established for power levels throughout this power range. These power levels, flows, and temperatures were used as basic input to the process models with selected system variables (functions of turbine megawatt demand) regulated by the plant control system. The way these variables are maintained leads one directly to the control system arrangement—what parameters must be controlled and how that control is accomplished. The plant control system is described in BAW-1328, section 12, and is illustrated schematically in Figure 3-2.

The simulation of the reactor-reactor coolant and intermediate coolant systems consists of basic energy, mass, and momentum balances which describe the nuclear, thermal, and hydraulic time responses of these systems. These characteristics are represented by numerous

algebraic and first-order, non-linear differential equations. Certain assumptions are made regarding the relations to facilitate their solution. The simulation model solved on the analog computers still remains as a set of non-linear equations. These relations describe the performance of the process components and interconnecting systems, including the simulation of the reactor fuel, core vessel, reactor coolant piping, reactor coolant pumps, IHXs, intermediate coolant piping, intermediate coolant pumps, reheaters, and steam generators. Proper time responses are included for the measuring instrument sensors and for the controlled devices (control rods, valves, pumps). The overall criterion for the simulation is for the model to give representative time responses for the individual components and systems, including the control actions for the transients analyzed.

The time response of the control devices and the measuring instrument sensors are simulated by first-order time constants.* Another important time response to the analysis is the speed of the regulating control rod. The control rod drive speed, controlled elements, and instrument sensor time responses that were incorporated for the final computer runs are listed in Table 3-1.

The reactor and intermediate coolant systems contain rather large quantities of sodium, which cause long time delays of the temperature variables throughout the process. These transport delays can be defined as the mass of sodium divided by the coolant flow rate, a pure transport delay. The variable delays (due to the variable flows) are simulated as a function of the flow in that particular region. These delays are listed in Table 3-2 at the steady-state operating conditions for both ends of the power maneuvering range, namely, 100 and 20% of plant loads.

The response of the system is affected by controller gains, reset rates, and derivative gains. The systems investigated required no derivative actions. The settings were varied, and a workable set for these systems was determined. Table 3-3 lists the workable set of controller settings determined in these analyses.

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* Considine, D. M. and Ross, S. D., Handbook of Applied Instrumentation, pp 1-14 and 1-15, McGraw Hill Book Company, New York, N. Y. (1964).

Table 3-1. Time Responses of Sensors and Controlled Elements

Parameter	Symbol	Time constant, sec
Regulating control rods	--	15 in. /min
Regulating control drive line	--	Two, 0.10 each
Reactor outlet temp sensor	T_1	5
Reactor inlet temp sensor	T_2^*	5
IHX intermediate outlet temp sensor	T_3	5
Steam generator intermediate outlet and feedwater inlet temp sensors	T_7, T_9	5, 10
Reheater steam outlet temp sensor (simulated by reheater sodium flow)	$w_{10}(T_{13})$	0
Reactor coolant pump eddy-current coupling	ω'_p	10
Intermediate coolant pump eddy-current coupling	ω'_i	10
Intermediate bypass control valve	v_1	2
Reheater steam outlet temp control valve	v_2	10

Table 3-2. Steady-State Pure Transport Delays

Variable	Delay, sec	Plant load, %
T_1	15	100
	37	20
T_2	75	100
	184	20
T_3	10	100
	38	20
T_7	3	100
	17	20
T_{11}	4	100
	22	20
T_4	13	100
	50	20

Table 3-3. Workable Controller Settings

<u>Controlled variable</u>	<u>Controlled device</u>	<u>Settings</u>
Reactor power level, N_1	Regulating control rods	$K_1 = 1.0$ Deadband = $\pm 1\%$
Reactor outlet temp, T_1	Regulating control rods	$K_2 = 0.3\%/^{\circ}\text{F}$ $R_2 = 0.1 \text{ repeats/min}$
Reactor inlet temp, T_2^*	Reactor coolant pumps	$K_3 = 1.0\%/^{\circ}\text{F}$ $R_3 = 1.0 \text{ repeats/min}$
IHX intermediate outlet temp, T_3	Intermediate coolant pumps	$K_4 = 0.5\%/^{\circ}\text{F}$ $R_4 = 0.3 \text{ repeats/min}$
Steam generator outlet temp, T_7	Intermediate bypass valve, v_1	$K_5 = 0.75\%/^{\circ}\text{F}$ $R_5 = 0.16 \text{ repeats/min}$
Reheater steam outlet temp (simulated by reheater sodium flow, w_{10})	Reheater steam temp control valve, v_2	$K_6 = 0.80\%/ \text{lb-sec}$ $R_6 = 3.75 \text{ repeats/min}$

3.3. Simulation

The analytical model describing the reactor-reactor coolant system and the intermediate coolant system consists of mass, energy, and momentum balances. These relationships define both the transient responses and the steady-state conditions for the systems. The process equations used in the partial load analysis performed on the digital computer are similar to those used in the transient analysis on the analog computer, with all time derivatives set to zero. The model describing the steam generators and reheaters is discussed in Appendix E.

The controls that were simulated for the reactor coolant and intermediate coolant systems are described in BAW-1328. The total plant model has these individual control loop relationships coupled with the process simulation equations. Thirteen locations in the main coolant systems are designated on Figure 3-1. The model variables in the equations are subscripted in accordance with these 13 points and the spaces in between. These and other subscripts and all symbols used in the simulation are defined in Appendix A.

The following paragraphs describe the simulation equations for (1) the steady-state analyses of the entire plant, (2) the transient analyses of the reactor-reactor coolant system, and (3) the transient analyses of the intermediate coolant system.

3.3.1. Steady-State Partial Load Analysis

The following paragraphs describe the simulation equations and the calculational procedure used to determine steady-state thermodynamic plant variables as a function of plant load. This description also approximates the PLS flow diagram.*

3.3.1.1. Steam Generator

The steam generator heat load is first calculated using the relationship

$$q_{sg} = w_9(h_8 - h_9) \quad (3-1)$$

where the values of w_9 , h_8 , and h_9 are input variables resulting from the turbine island characteristics. The value of the product UA for the steam generator is calculated from Table B-1. These two results are combined in the expression

$$q_{sg} = (UA)_{sg}(\Delta T)_{LM} \quad (3-2)$$

to arrive at a value for $(\Delta T)_{LM}$ for the steam generator. The steam-generator-inlet intermediate sodium temperature is then calculated using the expression

$$(\Delta T)_{LM} = \frac{(T_7 - T_9) - (T_6 - T_8)}{\ln \frac{T_7 - T_9}{T_6 - T_8}} \quad (3-3)$$

In this implicit expression for T_6 , $(T_7 - T_9)$ and T_8 are known as described in Appendix B. The steam generator sodium flow is subsequently determined, since T_7 , T_6 , and q_{sg} are now known. The pertinent relationship is

*See Appendix D.

$$w_6 = \frac{q_{sg}}{c_p(T_6 - T_7)} \quad (3-4)$$

This completes the steam generator analysis, since $w_7 = w_6$ and w_6 , T_6 , w_8 , T_8 , w_9 , T_9 , T_7 , and $(\Delta T)_{LM}$ are all known.

3.3.1.2. Reheater

A similar analysis is performed on the reheater. Again the first step is the evaluation of the reheater heat load, q_{rh} , by equation 3-5.

$$q_{rh} = w_{12}(h_{13} - h_{12}) \quad (3-5)$$

The value of h_{12} is given as $f(T_{12}, P_{12})$ where T_{12} and P_{12} are turbine island characteristics as shown in Appendix B (Figures B-7, B-8, and B-9). The value of w_{12} is equal to w_9 minus the drain flow to the feed-water heater "F" (see Figure B-10). The constant value of h_{13} is also reported in Appendix B. Using Table B-1, the value of UA for the reheater is calculated. The $(\Delta T)_{LM}$ for the reheater is now calculated analogously to the steam generator case. Knowing the values of T_{10} , T_{12} , and T_{13} (see Appendix B), the following expression is used to solve for the value of T_{11} :

$$(\Delta T)_{LM} = \frac{(T_{11} - T_{12}) - (T_{10} - T_{13})}{\ln \frac{T_{11} - T_{12}}{T_{10} - T_{13}}} \quad (3-6)$$

Knowing that

$$w_{10} = w_{11} = \frac{q_{rh}}{c_p(T_{10} - T_{11})}, \quad (3-7)$$

the values of w_{10} and w_{11} can be computed. This completes the reheater analysis.

3.3.1.3. Intermediate Heat Exchanger (IHX)

The IHX is considered next. Note that, since losses and pump effects are neglected,

$$q_i = q_{sg} + q_{rh} \quad (3-8)$$

Therefore, the intermediate sodium flow in the IHX is

$$w_4 = w_3 = \frac{q_i}{c_p (T_3 - T_4)} \quad (3-9)$$

where T_4 is a constant input variable and T_3 equals the previously calculated T_6 . In an effort to calculate the U value for the IHX, an approximate value for w_2 is calculated. This value, along with previously stated values of w_4 , c_p , T_4 , and T_2 are used to determine U for the particular plant load demand in question. The calculation of U is described in Appendix B and the PLS code has programmed in it the mechanical design of the IHX. These previous steps allow the evaluation of $(\Delta T)_{LM}$ for the IHX, since

$$(\Delta T)_{LM} = \frac{q_i}{UA_i} \quad (3-10)$$

The temperature T_1 can now be calculated with the knowledge of the previous section and the expression

$$(\Delta T)_{LM} = \frac{(T_1 - T_3) - (T_2 - T_4)}{\ln \frac{T_1 - T_3}{T_2 - T_4}} \quad (3-11)$$

Since $q_i = q_c$, reactor heat load, under the no-losses assumption, the value of w_2 can be determined by

$$w_2 = \frac{q_c}{c_p (T_1 - T_2)} \quad (3-12)$$

This completes the analysis of the IHX, as well as the reactor coolant system, since all of the values— w_4 , T_4 , w_3 , T_3 , $(\Delta T)_{LM}$, T_2 , w_2 and T_1 —are known.

3.3.2. Reactor-Reactor Coolant System Transient Analysis

3.3.2.1. Neutron Kinetics

The core neutron density and power level are derived from the widely used point neutron time-dependent relations. In this model a one-group delay equivalent was employed for the delayed neutrons. The power level and the concentration of the equivalent delayed neutron emitter are given by the following equations:

$$\ell^* \frac{dn}{dt} = n \delta k - \beta n + \ell^* \lambda C_i \quad (3-13)$$

$$\frac{\lambda_i \ell^*}{\beta_i} \frac{dC_i}{dt} = \lambda_i n - \frac{\lambda_i \ell^*}{\beta_i} \lambda_i C_i \quad (3-14)$$

where the total reactivity term is the sum of the Doppler reactivity effect, the sodium density reactivity term, and the control rod worth term.

$$\delta k = \delta k_d + \delta k_p + \delta k_{cr} \quad (3-15)$$

The Doppler term is a function of the average fuel temperature, the sodium density term a function of the average coolant temperature, and the control rod worth a function of the total worth and the control rod position. The reactivity inserted by the rods is the non-linear, familiar S-shaped curve shown in Figure B-1 (Appendix B). These relations are as follows:

$$\delta k_d = a_1 \Delta \bar{T}_f \quad (3-16)$$

$$\delta k_p = a_2 \Delta \bar{T}_p \quad (3-17)$$

$$\delta k_{cr} = a_3 W_{cr} \quad (3-18)$$

$$W_{cr} = f(S_{cr}) \quad (3-19)$$

3.3.2.2. Core Thermal Model

The core thermal model determines the thermal feedbacks to the total reactivity term for the neutron power level calculation. The two thermal feedbacks included in this simulation are the Doppler and the reactor coolant sodium density terms. This model is a series of single-node energy balances for the core. The energy balances are given below for the fuel,

$$\frac{d\bar{T}_f}{dt} = \frac{C_{1n}}{(Mc_p)_f} - \frac{(UA)_{f-g}}{(Mc_p)_f} (\bar{T}_f - \bar{T}_g) \quad (3-20)$$

assuming negligible thermal capacity (mass) for the gap (or bond),

$$(UA)_{f-g} (\bar{T}_f - \bar{T}_g) = (UA)_{g-c} (\bar{T}_g - \bar{T}_c) \quad (3-21)$$

the clad,

$$\frac{d\bar{T}_c}{dt} = \frac{(UA)_{g-c}}{(Mc_p)_c} (\bar{T}_g - \bar{T}_c) - \frac{(UA)_{c-p}}{(Mc_p)_c} (\bar{T}_c - \bar{T}_p) \quad (3-22)$$

and the reactor coolant:

$$\frac{d\bar{T}_p}{dt} = \frac{(UA)_{c-p}}{(Mc_p)_p} (\bar{T}_c - \bar{T}_p) + \frac{c_p}{(Mc_p)_p} (T_2^* - T_{po}) \quad (3-23)$$

3.3.2.3. Core Vessel

All of the reactor heat is assumed to be generated in the core and none in the blanket region. In the core vessel, the flow is divided into two parts: the flow passing through the core and the flow passing through the blanket region.

$$w_2 = w_c + w_b \quad (3-24)$$

The blanket flow is a linear function of the total flow.

$$w_b = \gamma_1 w_2 \quad (3-25)$$

The mixing relation is

$$c_p w_2 T_1 = c_p w_c T_{po} + c_p w_b T_2^* \quad (3-26)$$

The average reactor coolant temperature in the core is the arithmetic average of inlet and outlet temperatures, as follows:

$$\bar{T}_p = \frac{T_2^* + T_{po}}{2} \quad (3-27)$$

3.3.2.4. Reactor Coolant System and Pumps

The reactor coolant flow model contains the coolant flow-pressure drop relationships coupled with the variable-speed pump characteristics. The reactor coolant system pressure drops are determined from equation 3-28.

$$P_{pd} - P_1 = k_1 w_2^2 \quad (3-28)$$

$$P_1 - P_2 = k_2 w_1^2 \quad (3-29)$$

The pressure drop (ΔP) of the system must equal the pressure rise provided by the pumps. The sum of the equations above is the pressure rise across the pumps. Two of the pump similarity relations state that the flow is proportional to pump speed, and the pressure rise across the pump is proportional to the speed squared. These relations are used to incorporate the variable speed into the pump head-capacity performance curve. The pump curve is shown in Figure B-2 (Appendix B). The pump pressure rise is functionally described as follows:

$$P_{pd} - P_2 = f(w_1, \omega_p) \quad (3-30)$$

Since there are six coolant pumps, the flow through each pump is given by equation 3-31.

$$w_1 = \frac{w_2}{6} \quad (3-31)$$

The reactor and IHX outlet temperatures are delayed in time by the following perfect mixing equations:

$$\frac{dT_1^*}{dt} = \frac{c_p}{(Mc_p)_1} w_2 (T_1 - T_1^*) \quad (3-32)$$

$$\frac{dT_2^*}{dt} = \frac{c_p}{(Mc_p)_2} w_1 (T_2 - T_2^*) \quad (3-33)$$

These variable time delays provide an approximate time response for these outlet temperatures which feed back to the process model.

3.3.2.5. Intermediate Heat Exchanger (IHX)

The IHX is described by a single-model energy balance in two ways. The first is used in an open-looped study, and the second is for a closed-loop study between the reactor and intermediate coolant systems.

$$\frac{d\bar{T}_{ih}}{dt} = \frac{c_p w_1}{(Mc_p)_{ih}} (T_1^* - T_2) - \frac{C_2 q_i}{(Mc_p)_{ih}} \quad (3-34)$$

$$\frac{d\bar{T}_{ih}}{dt} = \frac{c_p w_1}{(Mc_p)_{ih}} (T_1^* - T_2) - \frac{(UA)_{eff}}{(Mc_p)_{ih}} (\bar{T}_{ih} - \bar{T}_{ic}) \quad (3-35)$$

The average coolant temperature on the hot side of the IHX is the arithmetic average of the inlet and outlet temperatures.

$$\bar{T}_{ih} = \frac{T_1^* + T_2}{2} \quad (3-36)$$

3.3.2.6. Reactor Inlet and Outlet Temperature Sensors

The reactor inlet and outlet thermocouple temperature measurements for control purposes are described by the first-order equations below.

$$\frac{dT_{1i}}{dt} = \frac{T_1 - T_{1i}}{\tau_{T_1}} \quad (3-37)$$

$$\frac{dT_{2i}^*}{dt} = \frac{T_2^* - T_{2i}^*}{\tau_{T_2}} \quad (3-38)$$

3.3.2.7. Control Rods and Drives

The time response for the control drives is simulated by two first-order equations to represent the servo motors in the control rod drive line. These and the control rod stroke position are described as follows:

$$\frac{dv'_{cr}}{dt} = \frac{v_{cr} - v'_{cr}}{\tau_1} \quad (3-39)$$

$$\frac{dv''_{cr}}{dt} = \frac{v'_{cr} - v''_{cr}}{\tau_2} \quad (3-40)$$

$$S_{cr} = (S_{cr})_{t=0} + \int v''_{cr} dt \quad (3-41)$$

The control rod drive speed is constant at 15 in./min. The controls that actuate the control rod movement are described in section 12.2.2.2 of BAW-1328.

3.3.2.8. Reactor Coolant Pumps

The time response of the reactor coolant pump eddy-current couplings is described by a first-order system. This and the pump speed are modeled by the following relations:

$$\frac{d\Delta\omega_p}{dt} = \frac{\Delta\omega_{pd} - \Delta\omega_p}{\tau_\omega} \quad (3-42)$$

$$\omega_p = (\omega_p)_{t=0} + \Delta\omega_p \quad (3-43)$$

The control that actuates the reactor coolant pump speed is described in section 12.2.2.2 of BAW-1328.

3.3.3. Intermediate Coolant System Transient Analysis

3.3.3.1. Process Equations

The process equations for the transient analysis of the intermediate coolant system heat and mass transfer are listed below, along with a note on the functional importance of particular terms.

Heat transfer on the cold side of the IHX is described by the equation

$$\frac{d\bar{T}_{ic}}{dt} = \frac{c_p}{(Mc_p)_{ic}} \left(\frac{w_4}{2} \right) T_4^* - T_3 + \frac{(UA)_{eff}}{(Mc_p)_{ic}} (\bar{T}_{ih} - \bar{T}_{ic}) \quad (3-44)$$

where

$$\bar{T}_{ic} = \frac{T_3 + T_4^*}{2}$$

Note that the model equation has the term $(w_4/2)$, which accounts for the fact that each intermediate loop has two IHXs, and w_4 is the flow through each pump and loop. The values of $\bar{T}_{ih}$ come from the PLS analysis.

The $(UA)_{eff}$ denotes the PLS value of $(UA)_i$ corrected to account for a discrepancy arising from the use of the log mean temperature difference in the PLS analysis while using a functionally simpler average temperature difference for the analog analysis. The overall effect is to give the analog model the accuracy of a log mean temperature analysis while minimizing computer equipment requirements. As it stands, the equation represents a transient heat balance of the cold side of the IHX. The transient energy balance on the reheater is expressed by equation 3-45.

$$\frac{d\bar{T}_{rh}}{dt} = \frac{c_p}{(Mc_p)_{rh}} w_{10}(T_{10}^* - T_{11}) - \frac{(UA)_{rh}}{(Mc_p)_{rh}} (\bar{T}_{rh} - \bar{T}_{rc}) \quad (3-45)$$

where

$$\bar{T}_{rh} = \frac{T_{10}^* + T_{11}}{2}$$

$$\bar{T}_{rc} = \frac{T_{12} + T_{13}}{2}$$

For the purpose of the analog model, the farthest-right term of equation 3-45 is written as

$$\frac{(UA)_{rh}}{(Mc_p)_{rh}} (\bar{T}_{rh} - \bar{T}_{rc}) = \frac{q_{rh}}{(Mc_p)_{rh}} \quad (3-46)$$

The analog model then uses equation 3-47, as follows:

$$\frac{d\bar{T}_{rh}}{dt} = \frac{c_p}{(Mc_p)_{rh}} w_{10}(T_{10}^* - T_{11}) - \frac{q_{sg}}{(Mc_p)_{rh}} \quad (3-47)$$

where q_{sg} is introduced as an input function of the plant load.

The analysis of the steam generator is handled similarly. The analog model equation for the transient thermal analysis is therefore:

$$\frac{d\bar{T}_{sg}}{dt} = \frac{c_p}{(Mc_p)_{sg}} w_6(T_3^* - T_7) - \frac{q_{sg}}{(Mc_p)_{sg}} \quad (3-48)$$

where

$$\bar{T}_{sg} = \frac{T_3^* + T_7}{2}$$

The sole mass transfer equation utilizing the model states the conservation of mass, i.e.,

$$w_4 = w_5 + w_6 + w_{10} \quad (3-49)$$

The process equations for a momentum balance are listed below. Constants evaluated in these pressure drop equations are the results of assumed pressure drop values across the main heat transfer units and maximum flow conditions predicted by partial load study. The estimated pressure drop breakdown over the intermediate system is listed in Table 3-4. These estimated values are based on past experience.

Table 3-4. Pressure Drop Breakdown, Intermediate System

<u>Pressure designation</u>	<u>Intermediate component</u>	<u>Pressure drop, psi</u>
$P_{id} - P_4$	Pump	75
$P_{id} - P_5$	IHX	50
$P_5 - P_4$	Steam generator	25
$P_5 - P_{10}^*$	Reheater valve	16
$P_{10}^* - P_{11}$	Reheater	9

The value of $P_{id} - P_5$ is given as

$$P_{id} - P_5 = k_5 w_{10}^2 \quad (3-50)$$

where $k_5 = 6.875 \times 10^{-5} \text{ psi}/(\text{lb}/\text{sec})^2$.

The pressure drop $P_5 - P_4$ is given in equation 3-51,

$$P_5 - P_4 = (P_{id} - P_4) - (P_{id} - P_5) \quad (3-51)$$

where $P_{id} - P_4$ is an input function of w_4 and the control variable ω_1 .

The pressure drop across the reheater, $P_{10}^* - P_{11}$, is expressed as

$$P_{10}^* - P_{11} = k_4 w_{10}^2 \quad (3-52)$$

where $k_4 = 1.678 \times 10^{-6} \text{ psi/(lb/sec)}^2$

The pressure drop across the steam generator,
 $P_5 - P_4$ is given as

$$P_5 - P_4 = k_3 w_6^2 \quad (3-53)$$

where $k_3 = 6.478 \times 10^{-6} \text{ psi/(lb/sec)}^2$

The pressure drop $P_{10} - P_{10}^*$ is equal to

$$P_{10} - P_{10}^* = (P_5 - P_4) - (P_{10}^* - P_{11}) \quad (3-54)$$

The only other equations related to the process model are those associated with the various temperature delays around the loop. These take the following forms:

$$T_3^* = f(T_3, w_4) \quad (3-55)$$

$$T_4^* = f(T_4, w_4) \quad (3-56)$$

$$T_{11}^* = f(T_{11}, w_{10}) \quad (3-57)$$

$$T_7^* = f(T_7, w_6) \quad (3-58)$$

These functions are explained in detail in Appendix F.

3.3.3.2. Control Associated Equations

The equations involving the control variables and control error values are discussed in detail in section 12.2.2.2 of BAW-1328. The equations listed below either relate control action to process variable definition or introduce required time delays in the control simulation.

The intermediate pump speed is defined as

$$\omega_i = (\omega_i)_{t=0} + \Delta\omega_i \quad (3-59)$$

where $\Delta\omega_{iwd}$ is defined by equation 12-7 in BAW-1328. Associated with the pump speed definition are time delays on the measurement of T_3 and the response of the pump. These delays are accounted for in the intermediate model by equations 3-60 and 3-61.

$$\frac{d\Delta\omega_i}{dt} = \frac{\Delta\omega_{id} - \Delta\omega_i}{\tau_{\omega i}} \quad (3-60)$$

$$\frac{d\Delta T_{3i}}{dt} = \frac{\Delta T_{3id} - \Delta T_{3i}}{\tau_{T_3}} \quad (3-61)$$

The delayed value of ω_i is then applied in equation 3-62 to define a pressure head for the pump.

$$P_{id} - P_4 = f(w_4, \omega_i) \quad (3-62)$$

The bypass valve stroke is modeled by equation 3-63. For this valve, as well as the reheater valve, the stroke is taken as equal to the valve coefficient. The valve stroke equation is as follows:

$$S_{v1} = (S_{v1})_{t=0} + \Delta S_{v1} \quad (3-63)$$

where ΔS_{v1d} is defined by equation 12-9 of BAW-1328. The value of S_{v1} is a function of the measured values of T_{7i} and T_{9i} . These delayed values are given by

$$\frac{d\Delta T_{7i}}{dt} = \frac{\Delta T_7 - \Delta T_{7i}}{\tau_{T_7}} \quad (3-64)$$

and

$$\frac{d\Delta T_{9i}}{dt} = \frac{\Delta T_9 - \Delta T_{9i}}{\tau_{T_9}} \quad (3-65)$$

in the intermediate model. Another delay in S_{v1} is due to the valve response. This delay is defined as

$$\frac{dS_{v1}}{dt} = \frac{S_{v1d} - S_{v1}}{\tau_{v1}} \quad (3-66)$$

The new value of S_{v1} affects the process via equation 3-67.

$$w_5 = k_{v1} S_{v1} \sqrt{P_5 - P_4} \quad (3-67)$$

where $k_{v1} = 1.133 \times 10^3$ (lb/sec)/gpm

The third intermediate system control action occurs through the reheater valve. The valve equation is

$$S_{v2} = (S_{v2})_{t=0} + \Delta S_{v2} \quad (3-68)$$

where ΔS_{v2d} is defined by equation 12-11 of BAW-1328. The only delay connected to this control is the response time delay of the valve. The delay is given by

$$\frac{dS_{v2}}{dt} = \frac{S_{v2d} - S_{v2}}{\tau_{v2}} \quad (3-69)$$

The value of S_{v2} is then used in equation 3-70 to regulate the reheater flow,

$$w_{10} = k_{v2} S_{v2} \sqrt{P_{10} - P_{10}^*} \quad (3-70)$$

where $k_{v2} = 7.237 \times 10^2$ (lb/sec)/gpm.

Figure 3-1. LMFBR Schematic Flow Diagram

Figure 3-2. LMFBR Overall Plant Control Schematic
Diagram (A31110E)

4. RESULTS

4.1. Summary

The reactor, reactor coolant, and intermediate coolant systems responded well to both the load ramp and the load step changes. The reactor and the sodium coolant systems moved deliberately from one steady-state condition to the final steady power level in the 20 to 100% power level. We found no evidence of adverse or unstable response of any of the plant variables. The performance was similar whether the power level went up or down.

The analyses demonstrated the feasibility of the control arrangement in the reactor, reactor coolant, and intermediate coolant systems. The plant control arrangement simulated is that described in BAW-1328. A major portion of the functional specifications for these control loops are determined. In addition, the general dynamic characteristics of these systems are better understood with respect to the typical megawatt load changes required of such a power plant.

The controller settings were varied in the analyses, and a workable set was determined to yield an acceptable response of the controlled variables to the step and ramp load changes studied. The reactor coolant and intermediate coolant systems contain considerable quantities of sodium coolant, which produce slow thermal response characteristics. Primarily because of this, the control actions required of the loops were standard-type actions. No derivative control actions were tried or required in these analyses. The workable control settings (proportional gains and reset rates) are given in Table 3-3. The requirements for the reactor control system allow a simple, relatively slow, constant-speed-regulating control rod drive system to be used. The control loops in the reactor coolant and intermediate coolant systems are typical simple controller circuits with standard sensor time response requirements.

Initially two open-loop control studies were done independently—one for the reactor-reactor coolant system and the other for the intermediate coolant system. After both systems had been analyzed separately, the systems were coupled together at the IHX. No practical difference was apparent between the open-loop and the coupled closed-loop analyses on the recordings from each of these studies. No complete closed-loop analysis was done with the feedwater-steam system and the turbine coupled to the reactor-intermediate coolant system simulation.

4.2. Partial-Load Study

This partial-load study established the steady-state operational characteristics of the 1000-MWe reference plant under certain controlled conditions. These results form the initial 100% power conditions for the transient studies performed on the analog computer, as well as final stable conditions for partial-load conditions.

The plant, as described by this partial-load study, is shown schematically in Figure 3-1. The calculational results of this effort were generated by the digital computer code PLS (Partial Load Study).^{*} This code uses basic heat transfer and thermodynamic relationships in addition to specific input describing the reference plant. The code generates plant parameters in the reactor coolant, intermediate coolant, and feedwater steam systems for 15, 20, 30, 40, 50, 60, 70, 80, 90, and 100% generator loads.

The following plots describe reactor coolant, intermediate coolant, and feedwater-steam systems for the 1000-MWe reference core. All variables are given as a function of plant load.

Figure 4-1 shows the flow rates of the reactor sodium coolant, intermediate sodium coolant, steam generator steam, and reheater steam as a function of plant load. Flow rates for full capacity are also shown.

Figure 4-2 shows the thermal duties of the reheater, steam generator, and IHX as a function of plant load. The thermal duties are given as a percentage of their respective full-capacity values, which are tabulated on the figure.

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^{*} See Appendix D.

Figure 4-3 is similar to 4-1, except that the flow rates of interest are reheater sodium, reheater steam, steam generator sodium, and steam generator steam. The figure shows clearly the relationship of the intermediate side flow to the secondary side flow for the reheater and steam generator. Again, the flow rates are plotted as a percentage of their full capacity values.

Figure 4-4 shows all of the fluid temperature variations as a function of plant load. These include all primary and intermediate sodium temperatures and feedwater-steam system temperatures.

Figure 4-5 shows the relationship between all the intermediate sodium flows as a function of plant load. IHX, reheater, and steam generator flow rates are given as a percentage of their full-capacity values. The bypass flow rate is given as a percentage of the value at 15% plant load flow rate. The bypass flow rate is read from the right-hand scale, and the other flow rate values are read from the left-hand scale.

4.3. Reactor-Reactor Coolant System (Open-Loop Study)

The load rate limit of 2% per minute was the input to the model to determine the response of the reactor-reactor coolant system to this load transient. The 5% (and greater) steps were also subjected to the simulation. The reactor and the reactor coolant system performed well to these transients.

The following discussion describes the time recordings of the system response to load ramp and step changes in the megawatt demand. The megawatt demand is recorded on channel 1 in each of the recordings. Table 4-1 identifies the variables that were recorded and indicates the figure in this section on which the variables are recorded.

Figures 4-6 and 4-7 illustrate the reactor-reactor coolant system response to the 2% per minute load ramp between 85 and 25% power level. Figure 4-6 shows the decreasing power ramp, and the increasing ramp is shown in Figure 4-7. The model was subjected to step changes of approximately 5% and greater between 100 and 20% power levels. The control variables respond well to these step changes, moving back toward their programs after the perturbation. Following these step changes, no variables responded with diverging oscillations or were offset from

programmed values. Figure 4-8 illustrates the response to step changes between 70 and 20% of plant load.

Table 4-1. Reactor System Recordings

<u>Variable</u>	<u>Symbol</u>	<u>Found in Figure</u>
Turbine generator megawatt demand, %	MW_d	All
Neutron power level, %	N_i	All
Reactor outlet temperature, F	T_1	All
Reactor outlet temperature minus program temperature, F	δT_1	4-6, 4-7
IHX reactor coolant outlet temperature, F	T_2	4-6, 4-7, 4-9
Reactor inlet temperature, F	T_2^*	4-8 through 4-12
Reactor coolant flow, %	w_2	All except 4-9
Regulating control rod stroke position, % full out	S_{cr}	4-8, 4-10, 4-11
IHX reactor inlet temperature, F	T_1^*	4-9
Height difference between the reactor coolant hot and cold legs, ft	H	4-12

Figure 4-9 illustrates the time difference (time delay) between the reactor outlet and IHX outlet temperatures and their respective delayed temperatures, namely, the IHX inlet and the reactor core inlet. These delays are a function of the variable flow and were simulated by a homogeneous mixing, first-order differential equation. The steady-state reactor coolant system loop time, neglecting core and IHX time delay, is 90 seconds at full flow and 220 seconds at 41% flow (at 20% of plant load).

The time responses for the temperature-measuring sensors were changed within the range of 2 to 20 seconds for the reactor outlet (T_1) and reactor inlet (T_2^*). The plant response was not affected adversely by this range of measurement time responses. The general system response could be stated as slow and sluggish, which does not put fast response requirements on the controlled variable instruments. Figure 4-10 shows the system's response to a load ramp of 2% per minute with a 20-second

first-order time constant for T_1 and T_2^* measurements. Likewise, the pump eddy-current coupling speed changer time response was varied between 5 and 20 seconds with no adverse plant response resulting.

Figure 4-11 shows the response when the regulating control rod worth was reduced by a factor of two. Rod movement between power level changes was consequently increased for a given power change. Compare the stroke of the control rod between the beginning power level and the 30% final level shown in Figures 4-10 and 4-11. The difference is a position approximately 12% lower for the case in which the rod worth is equal to half (Figure 4-11) the reference design rod worth case (Figure 4-10).

The sodium coolant height between the core outlet plenum and the reactor vessel is variable with reactor coolant flow. This height can be approximated as a function of the flow through the IHX. This variable, H on channel 4 of Figure 4-12, is shown as it would vary during and following (steady-state) a ramp load change of 2% per minute.

The control system arrangement was examined in a few areas in regard to different methods of control. The reactor coolant pumps were originally controlled by the reactor coolant flow program; later, the control was changed over to the IHX coolant outlet temperature. The final reference control loop for the pump speed was varied to maintain the reactor inlet temperature constant at all power levels. Each of these control arrangements performed well and accomplished the same thing. The final control scheme has some definite advantages—it requires neither a flow control measurement in any of its six inlet pipes, nor an IHX outlet temperature-control measurement on any of the six units where mixing effects and arrangement problems exist. Therefore, the reference design control loop (reactor inlet temperature) is a more straightforward and practical arrangement.

Other parameters in the simulation were changed to see their effect on plant performance. In general, these variations were changed one at a time (related parameters were changed together, e.g., the time responses of the reactor inlet and outlet temperature-measuring instruments were changed on the same run). Naturally, all combinations shown were not investigated. Each one was usually varied with other portions of the model in accordance with the reference plant design. The relatively

small response difference to these changes was evident, but no adverse or unexplainable response was found. The parameter variations are listed in Table 4-2.

Table 4-2. Parameter Variations

<u>Parameter</u>	<u>Variation</u>	<u>Reference design</u>	<u>Identifying symbol</u>
Reactor control dead-band, %	0.5, 1, 2	1	--
Regulating control rod worth, δk	0.0364, 0.005, 0.01, 0.012	0.01	a_3
Regulating control rod drive speed, in. /min	5, 10, 15	15	--
Reactor outlet temperature sensor time constant, sec	2, 5, 10, 20	5	τ_{T1}
Reactor inlet temperature sensor time constant, sec	2, 5, 10, 20	5	τ_{T2}
Reactor coolant pump eddy-current coupling time constant, sec	5, 10, 20	10	$\tau_{\omega p}$

4.4. Intermediate Coolant System Analysis (Open-Loop Study)

The following discussion describes the results obtained during independent analog analysis of the intermediate system.

4.4.1. Analog Results

The following section describes the dynamic reaction of the intermediate coolant system to various load changes in megawatt demand. Two types of demand changes are considered: a step change and a ramp change in plant power.

In general, all temperature recordings are in F, and all flow rates are expressed in units of lb/sec. Table 4-3 lists the available information on the chart recordings included in this section. Following

this table is a nomenclature discussion which identifies and briefly elaborates on the significance of each variable found in the table. The variables are discussed in alphabetical order.

Table 4-3. Analog Results for the Intermediate Coolant System Analysis

Input variation on MW _d	Variables plotted as a function of time
2%/min ramp change from 100% to 25%	$E_{v1}, S_{v1}, E_{v2}, S_{v2}, E_{\omega}, \omega, T_4$ $w_3, \omega, w_5, S_{v1}, w_6, w_{10}, S_{v2}$ $T_3, T_3^*, T_4, T_4^*, T_7, T_7^*, T_{11}, T_{11}^*$
Step change from 100% to 95%	$w_3, \omega, w_5, S_{v1}, w_6, w_{10}, S_{v2}$ $T_3, T_3^*, T_4, T_4^*, T_7, T_7^*, T_{11}, T_{11}^*$
Step change from 100% to 90%	$E_{v1}, S_{v1}, E_{v2}, S_{v2}, E_{\omega}, \omega, T_4$ $w_3, \omega, w_5, S_{v1}, w_6, w_{10}, S_{v2}$ $T_3, T_3^*, T_4, T_4^*, T_7, T_7^*, T_{11}, T_{11}^*$
Step change from 100% to 80%	$E_{v1}, S_{v1}, E_{v2}, S_{v2}, E_{\omega}, \omega, T_4$ $T_3, T_3^*, T_4, T_4^*, T_7, T_7^*, T_{11}, T_{11}^*$
Step change from 100% to 50%	$w_3, \omega, w_5, S_{v1}, w_6, w_1, S_{v2}$

The symbol S_{v1} denotes the bypass valve stroke; this valve regulates the flow w_5 . Initially, the bypass valve is closed for the intermediate system model. Analog results indicate that its greatest value occurs at 25% of maximum reactor power when it is about 95% open.

The reheater flow valve stroke is represented by S_{v2} ; it regulates the sodium flow through the reheater. Its initial value is 20% open, and its maximum value during the 2% ramp transient is shown as about 30%.

$E_{v1}, E_{v2}, E_{\omega i}$ are all indicated error variables. They are mathematically defined in BAW-1328. Physically, the value of E_{v1} reflects the control action on the system to bring the steam generator sodium outlet temperature to its proper value for a given steady-state

condition. Similarly, E_{v_2} reflects the control action required to establish the flow w_{10} needed for a given thermal duty imposed on the reheater. The remaining error indicator, E_{ω_i} , gives the instantaneous relationship between the transient value of the IHX sodium outlet temperature and the required value for steady-state operation. The approach, in time, of all these error variables to zero shows the effectiveness of their respective control actions. The dynamic responses of the error variables to the different power demand variations are shown in Figures 4-13, 4-18, and 4-21.

The megawatt demand of the entire plant is symbolized by MW_d ; its value corresponds to the power demanded by the controller. The initial value of MW_d for all of the chart recordings in this section is 100%. The 2% ramp from full power to 25% of full power adequately exemplifies the significance of MW_d .

The flow from the IHX is designated w_3 ; it varies directly with the intermediate system pump speed. As shown in Figure 4-14, it varies from a maximum of 8425 lb/sec to a minimum of 2700 lb/sec during the 2% ramp change. The w_3 transient settles out after approximately 58.3 minutes. For the 10% step change, the transient on w_3 disappears after 2 minutes; this is shown in Figure 4-19. Other time-dependent variations in w_3 are shown in Figures 4-16 and 4-23.

The bypass flow is w_5 . Its significance is self-explanatory. For the ramp decrease of 2% per minute it has a transient lasting 71.7 minutes after the ramp begins; this is shown in Figure 4-14. For the 10% step change in megawatt demand, the w_5 transient lasts only 11.7 minutes, as shown in Figure 4-19. Its reaction is directly related to the valve stroke S_{v_1} , as shown in these figures. Other figures showing the bypass flow behavior are 4-16 and 4-23.

The steam generator flow symbol is w_6 ; its value is complementary to the value of w_5 . In fact, the values of w_5 and w_6 for a given pump speed are interrelated, as shown by equation 3-49. The maximum value of w_6 during the ramp transient is 6200 lb/sec after zero seconds, and the minimum value is 1375 lb/sec after 53.3 minutes. These values are shown in Figure 4-14.

The w_6 response to a 10% step change in MW_d is shown in Figure 4-19. In this case, the slightly oscillatory transient disappears after 120 seconds. This result also appears in Figure 4-19.

The remaining flow not discussed is w_{10} . This, the reheater sodium flow, varies as shown in Figure 4-14 for the ramp change in MW_d . This change in MW_d yields a maximum value of w_{10} equal to 2330 lb/sec at about 5 minutes, while the minimum value equals 570 lb/sec and corresponds to 38.3 minutes after the ramp starts. The response of w_{10} to a 10% step change is shown in Figure 4-19. The transient in this case lasts 150 seconds.

The transient reaction of the IHX sodium outlet temperature is shown by the T_3 variable, which appears in Figures 4-15, 4-17, 4-20, and 4-23. Of equal interest is the sodium inlet temperature to the steam generator and the reheater. This variable is known as T_3^* and is related to T_3 by the function described in Appendix F.

The sodium temperature at the mixing point of the outlet flows from the bypass valve, the steam generator, and the reheater is T_4 . Its transient value reflects mass transport delays and mixing effects as well as the transient thermal duties of the intermediate heat transfer units. The inlet sodium temperature to the IHX is equal to a time-delayed value of T_4 . This delayed temperature is designated T_4^* . For easier instantaneous comparison, the value of T_4^* is recorded in a channel adjacent to the channel that records T_4 .

The steam generator outlet temperature is T_7 , and the time-delayed value of T_7 is T_7^* . In an analogous way, the reheater outlet temperature is T_{11} , while the time-delayed reheater outlet temperature is T_{11}^* . Again, the time-delayed temperatures are recorded in channels adjacent to their respective temperatures for direct comparison during transients.

All the temperature variations are shown in Figures 4-15, 4-17, and 4-20. These correspond to the ramp change, the 5% step, and the 10% step, respectively.

The final variable recorded during the analog study is ω_1 . This corresponds to the fraction of 100% power pump speed required to maintain the IHX outlet temperature at its proper value. The transient

on ω_i settles out after 58.3 minutes for the ramp, while it lasts for 2 minutes for the 10% step change. These responses are shown in Figures 4-14 and 4-19.

Other figures of interest for this report are described in Table 4-3. Of special interest is Figure 4-23, which shows the system's response to a step change from 100% to 50% power. The ability of the controls to handle this input illustrates the versatility of this control arrangement.

4.4.2. Analog Procedures

The intermediate analog model was built to operate independently of any simultaneous primary system analysis. Consequently, all necessary primary and turbine system thermodynamic parameters were put in the form of variable input on function generators. These input values are a result of a steady-state analysis of the entire reactor plant as performed by the PLS code at various partial load conditions. The input variables are T_{ih} , $(UA)_i$, T_3 , q_{sg} , T_7 , w_{10} , and q_r . The values of T_{ih} , $(UA)_i$, q_{sg} , and q_r were necessary for the process analysis of the system, while the values of T_3 , T_7 and w_{10} were used for control purposes. This approach also provided a dual steady-state analysis, since the analog model will duplicate the PLS results as the transient disappears if the two models are identical. This served as a check on all figures.

The analog simulation defines temperatures in terms of a constant reference temperature plus a variable temperature difference (ΔT). This technique was utilized to improve temperature accuracy.

4.5. Reactor-Intermediate Coolant Systems (Closed-Loop Study)

This section of the report describes the results of operating the reactor-intermediate systems as a single unit. These results were obtained by coupling the reactor coolant system analysis on the EAI 231-R to the intermediate system analysis on the EAI 680. The scope of the combined setup is reflected by the analog equipment requirements. The combined reactor-intermediate system analysis uses approximately 250 amplifiers and 11 variable-function generators. This effort culminated the total reactor-intermediate system analysis.

In general, everything already discussed regarding the independently operating systems applies to the coupled system. The only changes involved in connecting the two systems were (1) the transfer of MW_d and ΔT_{ih} from the reactor coolant analysis to the intermediate system analysis and (2) the transfer of $(UA)_i$ and ΔT_{ic} from the intermediate to the primary system analysis. Other than minor patching changes associated with this trunking of variables, the complete system has the same models as were discussed for the independent analyses of the reactor and intermediate coolant systems.

The following figures show the results of the coupled system for various types of MW_d variation. In all but the last two of these figures, the recorded variables in the reactor system are as follows: the megawatt demand, MW_d ; neutron power, N_i ; the difference between the actual temperature and the programmed reactor outlet temperature, δ_{T_1} ; the control rod stroke, S_{cr} ; the delayed reactor inlet temperature, T_2^* ; and the reactor coolant pump speed, ω_p . Similarly, the recorded values for the intermediate system are as follows: the IHX flow rate, w_3 ; the intermediate pump speed, ω_i ; the bypass flow rate, w_5 ; the bypass valve stroke, S_{v1} ; the steam generator flow rate, w_6 ; the reheater flow rate, w_{10} ; the reheater valve stroke, S_{v2} ; and the megawatt demand, MW_d . The last two figures record the values of the reactor outlet temperature, T_1 ; the delayed reactor outlet temperature, T_1^* ; the IHX outlet temperature, T_2 ; the average sodium temperature on the hot side of the IHX, T_{ih} ; and the average sodium temperature on the cold side of the IHX, T_{ic} .

The list below relates the MW_d variation to the figures in which the variable responses are shown.

<u>MW_d variation</u>	<u>Figures</u>
1%/min ramp decrease from 100 to 30% power	4-24, 4-25
5% step down from 40 to 35% power	4-26, 4-27
5% step up from 35 to 40% power	4-28, 4-29
40% step down from 100 to 60% power	4-30, 4-31
30% step up from 40 to 70% power	4-32, 4-33
Staggered 1%/min ramp increases from 25 to 50% and 50 to 90% power	4-34, 4-35
2%/min ramp decrease from 100 to 25% power	4-36, 4-37
Combination of 15% step down and step up between 100 and 85% power levels	4-38, 4-39
1%/min ramp increase from 25 to 60% power	4-40, 4-41

Figure 4-1. 1000-MWe LMFBR Reference Design - Plant Load Vs Flow (w_1 , w_3 , w_9 , w_{12})

Figure 4-2. 1000-MWe LMFBR Reference Design - Steam Generator, Reheater, and IHX Thermal Duty Vs Plant Load

Figure 4-3. 1000-MWe LMFBR Reference Design - Plant Load Vs Flow (w_6 , w_9 , w_{10} , w_{12})

Figure 4-4. 1000-MWe LMFBR Reference Design - Plant Load Vs Temperature

Figure 4-5. 1000-MWe LMFBR Reference Design - Plant Load Vs Flow (w_3 , w_6 , w_{10} , w_5)

Figure 4-6. Reactor-Reactor Coolant System Response
(85 to 25% Load Ramp - 2%/Minute)

Figure 4-7. Reactor-Reactor Coolant System Response
(25 to 85% Load Ramp - 2%/Minute)

Figure 4-8. Reactor-Reactor Coolant System Response
(20 to 70% Load Range - 5 and 15% Steps)

Figure 4-9. Reactor-Reactor Coolant System Response
(100 to 30% Load Ramp - 2%/Minute)

Figure 4-10. Reactor-Reactor Coolant System Response
(100 to 30% Load Ramp - 2%/Minute)

Figure 4-11. Reactor-Reactor Coolant System Response
(100 to 30%, 30 to 25%, and 25 to 75%
Load Ramps - 2%/Minute)

Figure 4-12. Reactor-Reactor Coolant System Response
(100 to 20% and 20 to 80% Load Ramps -
2%/Minute)

Figure 4-13. Intermediate Coolant System Response
(100 to 25% Load Ramp - 2%/Minute)

Figure 4-14. Intermediate Coolant System Response
(100 to 25% Load Ramp - 2%/Minute)

Figure 4-15. Intermediate Coolant System Response
(100 to 25% Load Ramp - 2%/Minute)

Figure 4-16. Intermediate Coolant System Response
(100 to 95% Load - 5% Step Decrease)

Figure 4-17. Intermediate Coolant System Response
(100 to 95% Load - 5% Step Decrease)

Figure 4-18. Intermediate Coolant System Response
(100 to 90% Load - 10% Step Decrease)

Figure 4-19. Intermediate Coolant System Response
(100 to 90% Load - 10% Step Decrease)

Figure 4-20. Intermediate Coolant System Response
(100 to 90% Load - 10% Step Decrease)

Figure 4-21. Intermediate Coolant System Response
(100 to 80% Load - 20% Step Decrease)

Figure 4-22. Intermediate Coolant System Response
(100 to 80% Load - 20% Step Decrease)

Figure 4-23. Intermediate Coolant System Response
(100 to 50% Load - 50% Step Decrease)

Figure 4-24. Reactor-Intermediate Coolant Systems
Response (100 to 30% Load Ramp -
1%/Minute)

Figure 4-25. Reactor-Intermediate Coolant Systems
Response (100 to 30% Load Ramp -
1%/Minute)

Figure 4-26. Reactor-Intermediate Coolant Systems Response (40 to 35% Load - 5% Step Decrease)

Figure 4-27. Reactor-Intermediate Coolant Systems
Response (40 to 35% Load - 5% Step
Decrease)

Figure 4-28. Reactor-Intermediate Coolant Systems Response (35 to 40% Load - 5% Step Increase)

Figure 4-29. Reactor-Intermediate Coolant Systems Response (35 to 40% Load - 5% Step Increase)

Figure 4-30. Reactor-Intermediate Coolant Systems
Response (90 to 50% Load - 40% Step
Decrease)

Figure 4-31. Reactor-Intermediate Coolant Systems Response (90 to 50% Load - 40% Step Decrease)

Figure 4-32. Reactor-Intermediate Coolant Systems Response (40 to 70% Load - 30% Step Increase)

Figure 4-33. Reactor-Intermediate Coolant Systems Response (40 to 70% Load - 30% Step Increase)

Figure 4-34. Reactor-Intermediate Coolant Systems
Response (25 to 50% and 50 to 90%
Load Ramp - 1%/Minute)

Figure 4-35. Reactor-Intermediate Coolant Systems
Response (25 to 50% and 50 to 90%
Load Ramp - 1%/Minute)

Figure 4-36. Reactor-Intermediate Coolant Systems
Response (100 to 25% Ramp - 2%/Minute)

Figure 4-37. Reactor-Intermediate Coolant Systems Response (100 to 25% Ramp - 2%/Minute)

Figure 4-38. Reactor-Intermediate Coolant Systems Response (100 to 85 to 100% Load - 15% Steps)

Figure 4-39. Reactor-Intermediate Coolant Systems Response (100 to 85 to 100% Load - 15% Steps)

Figure 4-40. Reactor-Intermediate Coolant Systems Response (25 to 60% Load Ramp - 1%/Minute)

Figure 4-41. Reactor-Intermediate Coolant Systems Response (25 to 60% Load Ramp - 1%/Minute)

APPENDIX A
Nomenclature

Symbol	Definition
c_p	specific heat of Na coolant at constant pressure, Btu/lb-°F
C_1	scale factor applied to n , (Btu/sec)(neut/cm ³)
C_2	scale factor applied to q_1 , (Btu/sec)/%
C_i	delayed neutron precursor concentration of i-th group, neut/cm ³
C_{v1}	valve coefficient for intermediate bypass valve, gpm/psi ^{1/2}
C_{v2}	valve coefficient for reheater steam temp control valve, gpm/psi ^{1/2}
d/dt	derivative with respect to time
H	height difference between reactor coolant hot and cold legs, ft
$k_1 - k_5$	flow coefficient, psi/(lb/sec) ²
k_{v1}	scale factor for intermediate bypass valve, (lb/sec)/gpm
k_{v2}	scale factor for reheater steam temp control valve, (lb/sec)/gpm
ℓ^*	effective neutron lifetime, sec
M	mass, lb (Subscripts are similar to those for T .)
n	neutron density, neut/cm ³
o	subscript designating time zero
P	pressure, psig
	Subscripts: 1 - 10 see Figure 3-1
	id intermediate pump discharge
	pd primary reactor coolant pump discharge
q	heat load, Btu/sec
	Subscripts: c reactor core
	i IHX
	r reheater
	sg steam generator
S_{cr}	control rod(s) stroke position, % full out
S_{v1}	intermediate bypass valve stroke position, % full open
S_{v2}	reheater steam temp control valve, % full open

Symbol	Defintion
T	temperature, F
Subscripts:	1 - 13 see Figure 3-1
	1i reactor outlet thermocouple-indicated
	2i reactor inlet thermocouple-indicated
	3i IHX intermediate outlet thermocouple-indicated
	7i steam generator intermediate outlet detector-indicated
	9i steam generator feedwater inlet detector-indicated
	c fuel cladding
	f fuel
	g gap or bond
	ic IHX cold side
	ih IHX hot side
	p primary reactor coolant Na in core
	po Na at core exit (out)
	rc reheater cold side avg
	rh reheater hot side avg
<p><u>Note:</u> $\bar{T}$ denotes an average T^* denotes a delayed temperature in time</p>	
U	overall heat transfer coefficient, Btu/ft ² -°F-sec
Subscripts:	i IHX
	r reheater
	sg steam generator
UA	overall heat transfer coefficient × heat transfer area, Btu/sec-°F
Subscripts:	c-p fuel cladding to Na (primary) coolant
	eff corrected (UA), to account for the difference between log-mean ΔT and avg ΔT
	f-g fuel to gap or bond
	g-c gap or bond to fuel cladding
	i IHX
	r reheater
	sg steam generator

Symbol	Defintion
v_{cr}	regulating control rod velocity, %/sec (or in. /min)
v'_{ci}, v''_{cr}	regulating control rod velocity delayed by time response, %/sec (or in. /min)
w	flow rate, lb/sec Subscripts: 1 - 13 see Figure 3-1 b core blanket region c core region
W	total control rod(s) worth, %
a_1	Doppler coefficient, $\delta k / \delta F$
a_2	Na temperature coefficient, $\delta k / \delta F$
a_3	regulating control rod group worth, δk
β	total delayed neutron fraction
β_i	delayed neutron fraction for i-th group
γ_1, γ_2	flow rate proportionality constant
γ_2	pressure-flow rate proportionality constant, psi/(lb/sec)
δk	reactivity Subscripts: none total d Doppler p primary Na coolant cr control rods
Δ	a change in a variable, e. g. , $\Delta F_{(T)} = F_{(t)} - F_{(t)}_{t=0}$
ΔT_m	log-mean temperature difference, F
λ_i	decay constant for i-th delayed neutron group, sec^{-1}
ρ	density of fluid, lb/ft ³
τ	time-response time constant, sec Subscripts: 1,2 regulating control rod drive system T1 reactor outlet temp thermocouple T2 reactor inlet temp thermocouple T3 IHX intermediate outlet temp sensor

SymbolDefintion

T7	steam generator intermediate outlet temp sensor
T9	steam generator feedwater temp sensor
v1	intermediate bypass valve
v2	intermediate reheater steam temp control valve
ω_i	intermediate coolant pump eddy-current coupling
ω_p	primary reactor coolant pump eddy-current coupling

ω pump speed, %

Subscripts: i intermediate coolant
p primary reactor coolant

APPENDIX B
Plant Characteristics

This appendix contains information on the various component characteristics of the plant. Included are input values used in both the analog and the digital computer analyses.

Figure B-1 shows the control rod worth (%) versus the regulating control rod stroke position, and Figure B-2 gives the reactor and intermediate coolant pump performance characteristics. Figures B-3 and B-4 are plots of h versus the flow for both the reactor and intermediate sides of the IHX. Accompanying these plots is a page of information on the IHX specifications. All of this information was used to evaluate the UA values as a function of reactor and intermediate coolant flow rates. Figures B-5 through B-13 are described in Table B-1.

Evaluation of the Heat Transfer Coefficient for the IHX

The evaluation of U is effected using the following information:

Shroud ID, in.	71.62
Shroud OD, in.	24.1
Pin pitch, in.	0.875
No. of tubes	4775
Tube OD, in.	0.625
Tube ID, in.	0.546

The overall coefficient is computed from the reactor coolant, tube metal, and intermediate coolant coefficients. The correlations used for the evaluation of h_{SHELL} and h_{TUBE} are given on the following pages.

The UA values for the steam generator, the reheater, and the IHX are collected in Table B-2, which also shows the ratio of UA at a particular load to UA at 100% load. The UA values for the steam generator and reheater are directly input. The UA for the IHX is calculated for each plant load factor. All of these calculations involve the evaluation of the inside film coefficient, the tube thermal resistance, and the outside film coefficient. These, in turn, depend on the IHX design specifications listed above.

The input data used to describe the partial-load operation of the steam generator, the reheater, the IHX, and the feedwater heaters are listed in Table B-1. The only thermodynamic input variable not mentioned in Table 3-1 is the reactor inlet sodium temperature, which is maintained at 800 F. This result, as well as the constant value for T_4 ,

will maintain a constant ΔT across the sodium-wetted tubesheet. This will restrict thermal stresses in the tubesheet.

Table B-1. Input Data for the Calculation of Partial-Load Conditions

Plant component	Input data used
Steam generator	<ol style="list-style-type: none"> 1. Feedwater flow (Figure B-6). 2. Feedwater enthalpy (Figure B-7). 3. Feedwater temperature (Figure B-5). 4. Superheat steam temperature $T_8 = 950$ F. 5. $T_7 - T_9 = 169.4$ F. 6. Constant steam outlet enthalpy = 1427.8 Btu/lb.
Reheater	<ol style="list-style-type: none"> 1. Feedwater flow (Figure B-6). 2. Feedwater temperature (Figure B-8). 3. Feedwater enthalpy (Figure B-7). 4. Constant outlet steam temperature = 950 F. 5. Constant outlet steam enthalpy = 1492 Btu/lb. 6. $T_{10} - T_{11} = 175$ F.
IHX	<ol style="list-style-type: none"> 1. Constant intermediate inlet temperature = 700 F.
Feedwater heaters	<p>"E"</p> <ol style="list-style-type: none"> 1. Shell-side pressure varies (Figure B-13). 2. FTD = 0 F <p>"F"</p> <ol style="list-style-type: none"> 1. Shell-side pressure varies (Figure B-12). 2. FTD = -3 F. 3. FDC = 10 F.

Table B-2. Values of UA for Various Partial Loads

Load factor, %	Steam generator UA/UA ₁₀₀	Reheater UA/UA ₁₀₀
20	0.348	0.308
40	0.585	0.521
60	0.808	0.692
80	0.928	0.858
100	1.000	1.000

Figure B-1. Control Rod Worth Vs Regulating Control Rod(s) Stroke Position

Figure B-2. Reactor and Intermediate Coolant Pump
Performance Curve

Figure B-3. Heat Transfer Coefficient Vs Flow, IHX
Primary Sodium

Figure B-4. Heat Transfer Coefficient Vs Flow, IHX
Intermediate Sodium

Figure B-5. Steam Generator Feedwater Temperature Vs Plant Load

Figure B-6. Feedwater Flows Vs Plant Load

Figure B-7. Feedwater Enthalpies Vs Plant Load

Figure B-8. Reheater Feedwater Temperature Vs
Plant Load

Figure B-9. Reheater Feedwater Pressure Vs Plant Load

Figure B-10. Turbine System Layout

Figure B-11. Feedwater Pressure/Turbine Exhaust Pressure Ratio Vs Plant Load

Figure B-12. High-Pressure Turbine Exhaust Pressure
Vs Plant Load

Figure B-13. Intermediate-Pressure Turbine Exhaust Pressure Vs Plant Load

APPENDIX C
Analog Model Input

The model input comprises the values that are directly required for the model solution; these values generally have an easily recognized physical significance. In terms of the model, they appear as either equation coefficients or initial conditions.

Listed below are the required initial conditions for the plant system. A product of the partial-load study analyses, they are applied as initial conditions (100% full load operating conditions) in the dynamic simulation of the plant.

<u>Variable</u>	<u>Value, F</u>	<u>Variable</u>	<u>Value, F</u>
T_1	1100	T_7	653
T_2	800	T_{11}	825
$\bar{T}_{ih}$	950	$\bar{T}_{fo}$	2201
$\bar{T}_{ic}$	850	$\bar{T}_{go}$	1157
T_3	1000	$\bar{T}_{co}$	994
T_4	700	$\bar{T}_p$	966

<u>Variable</u>	<u>Value, lb/sec</u>	<u>Variable</u>	<u>Value, Btu/sec</u>
w_1	4,290	q_i	3.876×10^5
w_2	25,738	q_{sg}	6.524×10^5
w_4	8,528	q_r	1.228×10^5
w_5	0.0	q_c	2.326×10^6
w_6	6,212		
w_{10}	2,315		
w_c	23,261		
w_b	2,477		

The following list comprises other relevant constants used mainly in coefficient terms of the model equations:

Constant	Value	Constant	Value
$(c_p)_{ih}$	0.3012 Btu/lb-°F	$(Mc_p)_{sg}$	67,872 Btu/°F
$(c_p)_{ic}$	0.3030 Btu/lb-°F	$(Mc_p)_{rh}$	16,875 Btu/°F
k_1	5.887×10^{-8} psi/(lb/sec) ²	$(Mc_p)_{sg}$	67,500 Btu/°F
k_2	2.717×10^{-7} psi/(lb/sec) ²	$(UA)_{f-g}$	2228 Btu/°F-sec
k_{v1}	1.133×10^3 (lb/sec)/gpm	$(UA)_{g-c}$	14,268 Btu/sec-°F
k_{v2}	7.237×10^2 (lb/sec)/gpm	$(UA)_{c-p}$	82,178 Btu/sec-°F
k_3	6.478×10^{-6} psi/(lb/sec) ²	$(UA)_i$	3876 Btu/sec-°F
k_4	1.678×10^{-6} psi/(lb/sec) ²	$(UA)_{rh}$	710 Btu/sec-°F
k_5	6.875×10^{-5} psi/(lb/sec) ²	$(UA)_{sg}$	4494 Btu/sec-°F
l^*	0.290×10^{-6} sec	α_1	-2.342×10^{-6} δ kd/°F
$(Mc_p)_f$	4185 Btu/°F	α_2	4.052×10^{-6} δ kp/°F
$(Mc_p)_c$	1220 Btu/°F	α_3	0.0100 δ k
$(Mc_p)_p$	1335 Btu/°F	β	0.00364
$(Mc_p)_{ih}$	2795 Btu/°F	λ_i	0.08940
$(Mc_p)_{ic}$	1670 Btu/°F	γ_1	0.09622
$(Mc_p)_{rh}$	46,965 Btu/°F		

The following are constants whose values were used to determine the variable transport delay times. The value of the quantity M_{i-j} represents the quantity of sodium in the pipework between locations i and j.

Constant	Value, lb/loop
M_{1-1}^*	390,830
M_{3-3}^*	84,106
M_{10-10}^*	3426
M_{3^*-6}	5824
M_{7-4}	17,781
M_{11-11}^*	9339
M_{4-4}^*	106,863
M_{2-2}^*	1.928×10^6

APPENDIX D

PLS — A Partial-Load Study Code for the
1000-MWe LMFBR Reference Concept

Since the PLS code was written expressly for use on the 1000-MWe LMFBR, it has inherent in it specific IHX design information. PLS performs a thermodynamic analysis of the steam generator, the reheater, the IHX, and the primary system. Calculated values of particular interest in this code are the primary system flows and temperatures and the intermediate system flows and temperatures.

The code flow during execution is as discussed previously. The only additional point of interest is that the values of T_6 , T_{11} , and T_1 are determined by iteration using Newton's method. The convergence criteria is that the log-mean temperature difference for an iterated temperature is within 0.1 F of what it should be when calculated by heat transfer relationships.

Since the general program flow is straightforward, a code edit is presented in lieu of a flow chart. This edit also shows calculational detail, and thus completes the PLS description.

```

0001      SUBROUTINE UIHX (GSEC,CP5,T5,TID,TOD,PFLOW,T6,CP6,HOVER )
0002      PFLOW =PFLOW/6.0
0003      SWRID = 71.62
0004      DROD = 24.1
0005      PITCH = .875
0006      TUBES = 4775.
0007      TIDFT=TID/12.0
0008      C      SECONDARY FILM COEFFICIENT
0009      GSEC = GSEC / (6.0 * TUBES * 3.1416 * TIDFT**2 )
0010      GI=GSFC**0.8
0011      REAL KM,KNA5 ,KNA1 ,IDI ,KNA6 ,NUT ,NU
0012      CPI=CP5**0.8
0013      KNA5=CONDNA(T5)
0014      KNA1=KNA5**0.2
0015      IDI=TIDFT**0.2
0016      HT=((5.0*KNA5)/TIDFT)+((0.025*GI*CPI*KNA1)/IDI)
0017      HSEC=(HT*TID)/TOD
0018      C      PRIMARY FILM COEFFICIENT
0019      SHAREA=(.7854*SWRID*SWRID)/144.0
0020      TUAREA=(.7854*TOD*TOD*TUBES)/144.0
0021      DRAREA=(.7854*DROD*DROD)/144.0
0022      APRIM=SHAREA-(TUAREA+DRAREA)
0023      GPRIM=PFLOW/APRIM
0024      TODFT=TOD/12.0
0025      KNA6=CONDNA(T6)
0026      PECLET=(TODFT*GPRIM*CP6)/KNA6
0027      NUT=7.0+(3.8*(PITCH/TOD)**1.52)+((0.027*(PITCH/TOD)**0.27)*
0028      4      PECLET**0.8)
0029      ALF =A/P(PECLET)
0030      NU=ALF *NUT
0031      WPRIM=(NU*KNA6)/TODFT
0032      C      TUBE METAL COEFFICIENT
0033      RPRIM=1./WPRIM
0034      RSEC=1./HSEC
0035      RMET=.001
0036      106      RT=RPRIM+RSEC+RMET
0037      TM=((T6+T5)/2.0)-((T6-T5)/2.0)+((RPRIM-RSEC)/RT)
0038      KM = 99.87279 + .057176 * TM
0039      TF=0.5*TOD*ALOG(TOD/TID)
0040      HM=KM/TF
0041      RMM = 1./HM
0042      TF (ABS(RMM+RMET)-.00005) 108, 108, 1-7
0043      107      RMET = RMM
0044      GO TO 106
0045      108      CONTINUE
0046      C      OVERALL COEFFICIENT
0047      ROVER=RT
0048      HOVER = 1. / ROVER
0049      PRINT 1
0050      1      FORMAT (1H1, 19H PRIMARY FILM COEF., 21H SECONDARY FILM COEF., 12H
0051      1      METAL COEF., 18H OVERALL THX.COEFF./)
0052      PRINT 2 , WPRIM , HSEC , HM , HOVER
0053      2      FORMAT ( E19.6 , E21.6 , E12.4 , E18.6 )
0054      RETURN
0055      END

```

FORTRAN 4 PROGRAM

APR. 4. 1968

D-4

```

0001      REAL FUNCTION ALP (PECLET)
0002      *
0003      P=PECLET-3256.25
0004      ALP=(((((((130237E-32*P-.214779E-28)*P+.113146E-24)*P
0005      1  -.117770E-21)*P+.718434E-18)*P+.160216E-14)*P+.44438E-11)*P
0006      2  -.112825E-07)*P+.129614E-04)*P+.85503
0007      *
0008      RETURN
0009      END

```

```
0001      REAL FUNCTION CONDNA (TEMP)
0002      *
0003      C      THERMAL CONDUCTIVITY OF LIQUID SODIUM (400-1500 DEG. F)
0004      *
0005      30 FORMAT (1H0/1H .52HSUBROUTINE CONDNA NOT ACCURATE FOR A TEMPERATU
0006      1RE OF .F7.1,15H.TEMP. RESET TO.F7.1/)
0007      C      *
0008      TEMP1=TEMP
0009      IF (TEMP - 400.0) 10,11,11
0010      10 TEMP1=400
0011      GO TO 13
0012      11 IF (TEMP - 1500.0) 14,14,12
0013      12 TEMP1=1500
0014      13 WRITE (4,30) TEMP,TEMP1
0015      14 TX=TEMP1
0016      C      *
0017      T=TX/100.0-9.05263
0018      CONDNA= ((-.244397E+02*T+.0254211)*1-1.36395)*T+38.9109
0019      RETURN
0020      END
```

```

0001      I      PLS
0002      DIMENSION PF(10), PFUS(10), PFUR(10), PW2(10)
0003      DATA (PW2(I),I=1,10) / 1.0 ,.990 ,.9674,.923 ,.8710,.794 ,.6788,
0004      1      .598,.3908,.415 /
0005      DATA (PFUS(I),I=1,10) / 1.0 ,.969 ,.9285, .877 ,.8080,.707 ,.5856,
0006      1      .469,.3481,.2820 /
0007      DATA (PFUR(I),I=1,10) / 1.0 ,.931 ,.8584, .780 ,.701 ,.615 ,.5219,
0008      1      .414,.3075,.250 /
0009      READ 3, PF
0010      3 FORMAT ( 10F5.0)
0011      READ 4 ,NPF,QSGT, UASGT, UARHT, W12T, W2T, UAT, UT ,D79
0012      4 FORMAT (T5.5E15.5/ 2E15.5, F10.5 )
0013      TOD = .85208 * 12.
0014      TID = .8455 * 12.
0015      K=0
0016      CP = .3030
0017      CPP = .3012
0018      200 CONTINUE
0019      K=K+1
0020      IF(K.GT. 10) GO TO 71
0021      IF( ABS(PF(K) - 1.0).LT.1.E-5 ) I=1
0022      IF( ABS(PF(K) - 0.9).LT.1.E-5 ) I=2
0023      IF( ABS(PF(K) - 0.8).LT.1.E-5 ) I=3
0024      IF( ABS(PF(K) - 0.7).LT.1.E-5 ) I=4
0025      IF( ABS(PF(K) - 0.6).LT.1.E-5 ) I=5
0026      IF( ABS(PF(K) - 0.5).LT.1.E-5 ) I=6
0027      IF( ABS(PF(K) - 0.4).LT.1.E-5 ) I=7
0028      IF( ABS(PF(K) - 0.3).LT.1.E-5 ) I=8
0029      IF( ABS(PF(K) - 0.2).LT.1.E-5 ) I=9
0030      IF( ABS(PF(K) - 0.15).LT.1.E-5 ) I=10
0031      IF(PF(K).EQ.0.0) GO TO 200
0032      READ 1,T1,T2,T3,T4,T5,T6,T7,T8,T9,T10,T11,T12,T13
0033      1 FORMAT (7F10.5 / 6F10.5 )
0034      READ 2,W1,W2,W3,W4,W5,W6,W7,W8,W9,W10,W11,W12,W13
0035      2 FORMAT (7E10.4 / 6E10.4 )
0036      READ 1,W1,W2,W3,W4,W5,W6,W7,W8,W9,W10,W11,W12,W13
0037      W13 = 1492.1
0038      W9 = W8
0039      C W8,W9 ARE READ IN , W8 IS A PROGRAM CONSTANT
0040      W8 = 1427.8
0041      QSG = W9 * (W8 - W9)
0042      UASG = PFUS(I) * UASGT
0043      TLMSG = QSG / UASG
0044      DFG68 = 40.0*PF(I)
0045      T6 = T8 + DFG68
0046      M = 0
0047      T7 = T9 + D79
0048      31 TLMSG1=((T7 -T9) * (T6 - T8)) / ALOG((T7 - T9)/ (T6 - T8))
0049      D68 = T6 -T8
0050      DD79 = T7 - T9
0051      FPRIME = ( ALOG(D68/DD79) - (1.0-DD79/D68)) / (ALOG(D68/DD79))**2
0052      DIF = TLMSG1 - TLMSG
0053      IF ( ABS( DIF ) - 0.1) 20,20,30
0054      30 T6 = T6 - DIF / FPRIME
0055      72 IF (T6.LE.T8) GO TO 70
0056      GO TO 31
0057      70 M=M+1

```

```

0058      DIF = DTF / 2.0
0059      T6 = T6 + DIF / FPRIME
0060      PRINT 106 , M , DIF , T6
0061 106 FORMAT (// 10X, I5, 2E20.7 )
0062      IF ( M.GT.100 ) GO TO 71
0063      GO TO 72
0064 20 W6 = QSG / (CP*(T6 - T7))
0065      W7 = W6
0066      T3=T6
0067      T5=T6
0068      T10=T6
0069 C W12, W12 ARE READ IN , W13 IS A PROGRAM CONSTANT
0070      W13 = W12
0071      ORH = W12 * (W13 + W12)
0072      UARM = PFUR(I)* UARM
0073      TLMRW = ORH / UARM
0074      DFG131 = 96.15 * PF(I) + 37.08
0075      T11 = T13 - DFG131
0076      M = 0
0077 43 TLMRW1=((T11 - T12) - (T10 - T13)) / (ALOG((T11 - T12)/(T10 - T13)))
0078      D1112 = T11 - T12
0079      D1013 = T10 - T13
0080      FPRIME = (ALOG(D1112 / D1013) - (1.0-D1013/D1112)) / (ALOG(D1112
0081      1/ D1013))**2
0082      DIF = TLMRW1 - TLMRW
0083      IF (ABS(DIF) - 0.1) 40,40.41
0084 41 T11 = T11 - DIF/FPRIME
0085 75 IF (T11.LE.T12) GO TO 76
0086      GO TO 43
0087 76 M = M + 1
0088      DIF = DTF / 2.0
0089      T11 = T11 + DIF / FPRIME
0090      PRINT 106 , M , DIF , T11
0091      IF ( M.GT.100 ) GO TO 71
0092      GO TO 75
0093 40 QIWX = QSG + ORH
0094      W4 = QIWX / (CP*(T3 - T4))
0095      W3 = W4
0096      W10 = ORH / (CP*(T10 - T11))
0097      W11 = W10
0098      W5 = W4 - W6 - W10
0099      W2 = W2T * PW2(T)
0100      DFG13 = 104.69 * PF(T)**2
0101      T1 = T3 + DFG13
0102      TAVSEC = (T3+T4)/2.0
0103      TAVPRM = (T2+1050.)/ 2.0
0104      CALL UIWX (W4,CP,TAVSEC,T10,TOD,W2,TAVPRM,CPP,U )
0105      W4 = W3
0106      A = UAT / UT
0107      TLMIWX = QIWX / (U * A)
0108      M = 0
0109 62 TLMIWI = ((T1 - T3) - (T2 - T4)) / LOG((T1-T3)/(T2-T4))
0110      DD24 = T2 - T4
0111      DD13 = T1 - T3
0112      FPRIME = (ALOG(DD13/DD24) - (1.0-DD24/DD13)) / (ALOG(DD13/DD24))**2
0113      DIF = TLMIWI - TLMIWX
0114      IF (ABS(DIF) - 0.1) 60,60.61

```

```

0115      61 T1 = T1 - DIF / FPRIME
0116      80 IF (T1.LE.T3) GO TO 81
0117          GO TO 62
0118      81 M = M + 1
0119          DIF = DTF/2.0
0120          T1 = T1 + DIF / FPRIME
0121          PRINT 110 , N, M, DIF, T1
0122      110 FORMAT(/10X, 2I5, 2E20.7 )
0123          IF( M.GT.100 ) GO TO 71
0124          GO TO 80
0125      60 QRE = QTHX
0126          W2 = QRF / (CPP*(T1 - T2))
0127          W1 = W2
0128          IF (PF(I).NE.1.0) GO TO 205
0129          W2A = W2
0130          W3A = W3
0131          W6A = W6
0132          W10A = W10
0133          W8A = W8
0134          W13A = W13
0135      205 CONTINUE
0136          IF (PF(T).EQ.1.0) GO TO 71
0137          W2FR = W2 / W2A
0138          W3FR = W3 / W3A
0139          W6FR = W6 / W6A
0140          W10FR = W10 / W10A
0141          W8FR = W8 / W8A
0142          W13FR = W13 / W13A
0143      71 CONTINUE
0144          PRINT 100 , PF(I)
0145      100 FORMAT (1H1,///40X, 32H *** OUTPUT FOR A PLANT LOAD OF , F5.2, 5H
0146          1 *** // )
0147          PRINT 105 , QSG,UASG,TLMSG,QRW,UARW,TIMRW,QTHX,U,TLMTWX
0148      105 FORMAT ( 7H QSG = ,E10.5,8X, 8H UASG = ,E10.5, 7X, 9H TLMSG = ,
0149          1E10.5, 4X/ 7H QRW = , E10.5, 8X, 8H UARW = ,E10.5,7X, 9H TLMRW = ,
0150          2E10.5,6X / 8H QTHX = ,E10.5,7X, 5H U = ,E10.5 ,10X,10H TLMTWX = ,
0151          3E10.5 )
0152          PRINT 101 ,T1,T2,T3,T4,T5,T6,T7,T8,T9,T10,T11,T12,T13
0153      101 FORMAT (1H0////////// 13F9.2 )
0154          PRINT 102 ,W1,W2,W3,W4,W5,W6,W7,W8,W9,W10,W11,W12,W13
0155      102 FORMAT(///6E15.6 ///7E15.6 )
0156          IF (PF(T).NE.1.0) PRINT 103
0157      103 FORMAT (////// 38H ** FRACTIONS OF 100 PERCENT FLOW ** / )
0158          IF (PF(T).NE.1.0) PRINT 104, W2FR,W3FR,W6FR,W10FR,W8FR,W13FR
0159      104 FORMAT ( 30H PRIMARY SYSTEM *****F6.3 / 30H THX,IN
0160          1INTERMEDIATE SODIUM ***F6.3 / 30H STEAM GEN.,SODIUM SIDE *****,
0161          2F6.3,/30H REHEATER ,SODIUM SIDE ***** F6.3,/30H STEAM GEN.,STEA
0162          3M SIDE *****F6.3 ,/30H REHEATER, STEAM SIDE ***** F6.3 )
0163          IF( K.LT.NPF ) GO TO 200
0164          STOP
0165          END

```


APPENDIX E
Steam Generator and Reheater Simulation

by
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1. Introduction

In a 1000-MWe LMFBR plant, liquid metal will be circulated through three parallel loops to generate steam in tubular steam generators and to reheat low-pressure steam in tubular steam reheaters. In examining the response of the various systems that make up the LMFBR, liquid-metal-heated steam generators and reheaters will be decidedly faster than their fossil-fuel-fired heat exchanging counterparts in the typical central station of today. This is a result of the heat transfer coefficients of liquid metals, which are higher than the coefficients of hot gases. The successful control of these systems, therefore, presents a new problem.

To begin solving this problem, we must devise a mathematical model of a sodium-heated steam generator and steam reheater. The model attempts to describe the dynamic characteristics of the steam generator and reheater proposed for the 1000-MWe LMFBR Follow-On contract. It should adequately describe the performance of the actual plant on a single-loop basis to permit the selection of variables and methods for control. At a later date, it should provide a satisfactory way to verify the control methods selected under the Follow-On Study.

2. Analytical Model and Assumptions

2.1. General

The system boundary of the steam generator and reheater loop that is simulated on the analog computer is that of the feedwater pump, turbine chest, and intermediate sodium inlets and outlets. For modeling purposes, the parallel flow circuits are lumped into a single flow path having average conditions.

The model is based on a two-dimensional (space and time) approach using lumped parameter techniques (spaced-lumped, continuous time). It has constant heat transfer coefficients and a constant inlet pressure at each operating point.

Since the steam generator and reheater tubes are continuous throughout their entire length, the heat transfer phenomena are modeled with respect to the moving regions that occur within the steam generator, and the reheater is naturally unaffected by virtue of the lack of fluid phase change occurring within it. This applies to both the intermediate and

secondary sides of the tubes. Thus, a constant flow cross section is seen by both the sodium and the water/steam.

In the steam generator the fixed boundaries are the ends of the tubes. The boundaries denoting the transition from subcooled water to a mixed or saturation region with two-phase flow and from a mixture to pure superheated vapor are both time-dependent.

The ability to obtain meaningful results from such an analog study depends on making certain arbitrary assumptions for problem simplification. Thus, the following assumptions have been made:

1. No axial heat conduction occurs along the tube walls in either the tubes, sodium, or water/steam.
2. The pressure on the sodium side is constant throughout.
3. The two-phase region will have no slip; therefore, a mean velocity based on a homogeneous mixture will be used in the steam generator.

2.2. Development of System Equations (see Figure E-1)

2.2.1. System Equation Assumptions

The equations are written on the basis of a single tube having the same properties as all of the steam generators and reheaters in the plant. The conservation of momentum will not be considered since this is an open-loop study.

2.2.2. Conversion of Mass

2.2.2.1. Steam Generator Economizer Region

Secondary Mass Balance

$$A_{sx} \rho_{se} \frac{dL_e}{dt} = w_9 - w_{bi} \quad (E-1)$$

Intermediate Mass Balance

$$A_{ix} \rho_{ie} \frac{dL_e}{dt} = w_{6b} - w_6 \quad (E-2)$$

2.2.2.2. Steam Generator Boiling Region

Secondary Mass Balance

$$A_{sx} \frac{d(\rho_{sb} L_b)}{dt} = w_{bi} - w_{bo} \quad (E-3)$$

Intermediate Mass Balance

$$A_{ix} \rho_{ib} \frac{dL_b}{dt} = w_{6a} - w_{6b} \quad (E-4)$$

2.2.2.3. Steam Generator Superheat Region

Secondary Mass Balance

$$A_{sx} \frac{d(\rho_{ssh} L_{sh})}{dt} = w_{bo} - w_8 \quad (E-5)$$

Intermediate Mass Balance

$$A_{ix} \rho_{ish} \frac{dL_{sh}}{dt} = w_6 - w_{6a} \quad (E-6)$$

2.2.3. Conservation of Energy

2.2.3.1. Steam Generator Economizer Region

Secondary Heat Balance

$$A_{sx} \rho_{se} \frac{d(L_e h_{se})}{dt} = h_9 w_9 - h_f w_{bi} + U_{se} A_o L_e (\bar{T}_{we} - \bar{T}_{se}) \quad (E-7)$$

Tube Wall Heat Balance

$$\begin{aligned} A_w \rho_w c_{pw} \frac{d(L_e \bar{T}_{we})}{dt} &= U_{ie} A_o L_e (\bar{T}_{ie} - \bar{T}_{we}) - U_{se} A_o L_e (\bar{T}_{we} - \bar{T}_{se}) \\ &+ A_w \rho_w c_{pw} \bar{T}_{we} \frac{dL_e}{dt} \end{aligned} \quad (E-8)$$

Intermediate Heat Balance

$$A_{ix} \rho_{ie} c_p \frac{d(L_e \bar{T}_{ie})}{dt} = c_p w_{6b} T_{6b} - c_p w_6 T_7 - U_{ie} A_o L_e (\bar{T}_{ie} - \bar{T}_{we}) \quad (E-9)$$

2.2.3.2. Steam Generator Boiling Region

Secondary Heat Balance

$$A_{sx} \frac{d(L_b \rho_{sb} h_{sb})}{dt} = h_f w_{bi} - h_g w_{bo} + U_{sb} A_o L_b (\bar{T}_{wb} - T_s) \quad (E-10)$$

Tube Wall Heat Balance

$$A_w \rho_w c_{pw} \frac{d(L_b \bar{T}_{wb})}{dt} = U_{ib} A_o L_b (\bar{T}_{ib} - \bar{T}_{wb}) - U_{sb} A_o L_b (\bar{T}_{wb} - \bar{T}_s) + A_w \rho_w c_{pw} \bar{T}_{we} \frac{dL_b}{dt} \quad (E-11)$$

Intermediate Heat Balance

$$A_{ix} \rho_{ib} c_p \frac{d(L_b \bar{T}_{ib})}{dt} = c_p w_{6a} T_{6a} - c_p w_{6b} T_{6b} - U_{ib} A_o L_b (\bar{T}_{ib} - \bar{T}_{wb}) \quad (E-12)$$

2.2.3.3. Steam Generator Superheat Region

Secondary Heat Balance

$$A_{sx} \frac{d(L_{sh} \rho_{ssh} h_{ssh})}{dt} = w_{bo} h_g - w_8 h_8 + U_{ssh} A_o L_{sh} (\bar{T}_{wsh} - \bar{T}_{ssh}) \quad (E-13)$$

Tube Wall Heat Balance

$$A_w \rho_w c_{pw} \frac{d(L_{ssh} \bar{T}_{wsh})}{dt} = U_{ish} A_o L_{sh} (\bar{T}_{ish} - \bar{T}_{wsh}) - U_{ssh} A_o L_{sh} (\bar{T}_{wsh} - \bar{T}_{ssh}) + A_w \rho_w c_{pw} \bar{T}_{wsh} \frac{dL_{ssh}}{dt} \quad (E-14)$$

Intermediate Heat Balance

$$A_{ix} \rho_{ish} c_p \frac{d(L_{sh} \bar{T}_{ish})}{dt} = c_p w_6 T_3^* - c_p w_{6a} T_{6a} - U_{ish} A_o L_{sh} (\bar{T}_{ish} - \bar{T}_{wsh}) \quad (E-15)$$

2.2.3.4. Reheater

Intermediate Heat Balance

$$\frac{d\bar{T}_{rh}}{dt} = \frac{c_p}{(Mc_p)_{rh}} w_{10} (T_{10}^* - T_{11}) - \frac{(UA)_r}{(Mc_p)_{rh}} (\bar{T}_{rh} - \bar{T}_{rc}) \quad (E-16)$$

Secondary Heat Balance

$$\frac{d\bar{T}_{rc}}{dt} = \frac{c_{ps}}{(Mc_p)_{rc}} w_{12} (T_{12} - T_{13}) + \frac{(UA)_r}{(Mc_p)_{rc}} (\bar{T}_{rh} - \bar{T}_{rc}) \quad (E-17)$$

2.2.4. Thermodynamic Properties

2.2.4.1. Steam Generator

$$\rho_{sb} = a_1 + m_1 T_s \quad (E-18)$$

$$\rho_{sb} h_{sb} = a_2 + m_2 T_s \quad (E-19)$$

$$h_f = a_3 + m_3 T_s \quad (E-20)$$

$$\rho_{ssh} = a_4 + m_4 \bar{T}_{ssh} \quad (E-21)$$

$$\rho_{ssh} h_{ssh} = a_5 + m_5 \bar{T}_{ssh} \quad (E-22)$$

$$P_s = a_6 + m_6 T_s \quad (E-23)$$

$$h_9 = a_7 + m_7 w_{st} \quad (E-24)$$

$$h_g = a_8 + m_8 T_s \quad (E-25)$$

$$h_8 = a_9 + m_9 T_8 \quad (E-26)$$

$$T_9 = a_{10} + m_{10} w_{st} \quad (E-27)$$

2.2.4.2. Reheater

$$T_{12} = a_{11} + m_{11} w_{st} \quad (E-28)$$

2.2.5. Feedwater-Steam System

$$w_9 = k_{v3} C_{v3} \sqrt{P_{fd} - P_{v3}} \quad (E-29)$$

$$C_{v3} = \frac{S_{v3}^2}{100} \quad (E-30)$$

$$P_{v3} - P_9 = k_6 w_9^2 \quad (E-31)$$

$$P_9 - P_s = k_7 w_{sg}^2 \quad (E-32)$$

$$P_{fd} - P_{fs} = f(w_9) \quad (E-33)$$

$$w_8 = w_{st} + w_{sd} \quad (E-34)$$

$$w_{st} = w_{12} + w_d \quad (E-35)$$

$$w_{12} = \gamma_2 w_{st} \quad (E-36)$$

$$w_{st} = k_{v4} C_{v4} \sqrt{P_s - P_c} \quad (E-37)$$

$$C_{v4} = \frac{S_{v4}^2}{100} \quad (E-38)$$

$$\frac{P_c}{P_s} \geq 0.56; P_s - P_c \quad (E-39)$$

$$\frac{P_c}{P_s} < 0.56; P_s - P_c = 0.44 P_s \quad (E-40)$$

$$P_c = \gamma_3 w_{st} \quad (E-41)$$

$$P_s - P_{sd} \geq 0; w_{sd} = w_D (1 - e^{-t/\tau_{sd}}) \quad (E-42)$$

$$P_s - P_{sd} < 0; w_{sd} = w_D (e^{-t/\tau_{sd}}) \quad (E-43)$$

2.2.6. Supplementary Relationships

2.2.6.1. Steam Generator

$$\bar{T}_{ie} = \frac{T_{6b} + T_7}{2} \quad (E-44)$$

$$\bar{T}_{se} = \frac{T_9 + T_s}{2} \quad (E-45)$$

$$\bar{T}_{ib} = \frac{T_{6a} + T_{6b}}{2} \quad (E-46)$$

$$\bar{T}_{ish} = \frac{T_6 + T_{6a}}{2} \quad (E-47)$$

$$\bar{T}_{ssh} = \frac{T_s + T_8}{2} \quad (E-48)$$

$$h_{se} = \frac{h_9 + h_f}{2} \quad (E-49)$$

2.2.6.2. Reheater

$$\bar{T}_{rc} = \frac{T_{12} + T_{13}}{2} \quad (E-50)$$

$$T_{rh} = \frac{T_{10}^* + T_{11}}{2} \quad (E-51)$$

2.2.6.3. Feedwater-Steam System

$$w_{sg} = \frac{w_9 + w_8}{2} \quad (E-52)$$

2.3. Nomenclature

2.3.1. Steam Generator

2.3.1.1. Constants

A_{ix}	intermediate flow cross-section area, ft ²
A_o	heat transfer area per unit length, ft ² /ft
A_{sx}	secondary flow cross-section area, ft ²
A_w	tube wall cross-section area, ft ²
$(c_p)_{ib}$	boiling region Na specific heat, Btu/lb-°F
$(c_p)_{ie}$	economizer region Na specific heat, Btu/lb-°F
$(c_p)_{ish}$	superheater region Na specific heat, Btu/lb-°F
$(c_p)_w$	tube specific heat, Btu/lb-°F
U_i	overall heat transfer coefficient (intermediate side), Btu/ft ² -°F-hr
U_{sb}	boiling region heat transfer coefficient (secondary side), Btu/ft ² -°F-hr
U_{se}	economizer region heat transfer coefficient (secondary side), Btu/ft ² -°F-hr
U_{ssh}	superheater region heat transfer coefficient (secondary side), Btu/ft ² -°F-hr

ρ_{ib}	boiling region intermediate Na density, lb/ft ³
ρ_{ie}	economizer region intermediate Na density, lb/ft ³
ρ_{ish}	superheater region intermediate Na density, lb/ft ³
ρ_{se}	economizer region water density, lb/ft ³
ρ_w	tube density, lb/ft ³

2.3.1.2. Variables

L_b	boiling region length, ft
L_e	economizer region length, ft
L_{sh}	superheater region length, ft
P_s	steam pressure, psi
q_b	boiling region heat load, Btu/hr
q_e	economizer region heat load, Btu/hr
q_{sh}	superheater region heat load, Btu/hr
T_s	saturated steam temp, F
T_3^*	intermediate Na inlet temp, F ^{**}
T_{6a}	superheater region inlet intermediate Na temp, F ^{**}
T_{6b}	boiling region inlet intermediate Na temp, F ^{**}
T_7	intermediate Na outlet temp, F ^{**}
T_8	superheater steam outlet temp, F ^{**}
T_9	feedwater temp, F ^{**}
w_d	portion of steam flow from H-P turbine going to feedwater heater "F", lb/hr
w_6	Na flow, lb/hr ^{**}
w_8	steam flow, lb/hr ^{**}

 ** Numbered subscripts are consistent with Figures 4-1 and E-1.

2.3.2. Reheater

2.3.2.1. Constants

c_{ps}	steam specific heat, Btu/lb-°F
$(Mc_p)_{rc}$	weight $\times$ specific heat (secondary side), Btu/°F
$(Mc_p)_{rh}$	weight $\times$ specific heat (intermediate side), Btu/°F
$(UA)_r$	overall heat transfer coefficient $\times$ heat transfer area, Btu/°F-hr

2.3.2.2. Variables

q_{rh}	reheater heat load, Btu/hr
T_{10}^*	intermediate Na inlet temp, F ^{**}
T_{11}	intermediate Na outlet temp, F ^{**}
T_{12}	reheater steam inlet temp, F ^{**}
T_{13}	reheat steam temp, F ^{**}
w_{10}	intermediate Na flow, lb/hr ^{**}
w_{12}	steam flow, lb/hr ^{**}

2.3.3. Feed-Steam System

2.3.3.1. Constants

k_{v3}	feedwater valve proportionality
k_{v4}	throttle valve proportionality
k_6	feedwater piping ΔP versus load squared
k_7	steam generator ΔP versus load squared
w_D	steam dump valve capacity, lb/hr
γ_2	steam extraction versus load
γ_3	turbine chest pressure versus load
τ_{sd}	steam dump valve time response time constant, sec

** Numbered subscripts are consistent with Figures 4-1 and E-1.

2.3.3.2. Variables

P_c	steam turbine chest pressure, psi
P_{fd}	feed pump discharge pressure, psi
P_g	feedwater pressure, psi
w_{ex}	steam turbine extraction flow, lb/hr
w_{sd}	steam dump flow, lb/hr
w_{st}	steam turbine entrance flow, lb/hr

3. Discussion and Results

3.1. General

A model has been run on the analog computer at full load for two steam cycles. The dynamic response of the model was obtained at 100% of load using actual design surface areas for each steam cycle. Step perturbations of the following variables were studied:

1. Steam generator steam and feedwater flow (Figures E-2, E-9).
2. Steam generator sodium flow (Figures E-3, E-10).
3. Steam generator sodium inlet temperature (Figures E-4, E-11).
4. Steam reheater steam inlet temperature (Figures E-5, E-12).
5. Steam reheater steam flow (Figures E-6, E-13).
6. Steam reheater sodium flow (Figures E-7, E-14).
7. Steam reheater sodium inlet temperature (Figure E-8, E-15).

As shown on the figures listed above, the responses of the following variables were recorded:

1. Steam generator economizer length.
2. Steam generator superheater length.
3. Main steam temperature.
4. Main steam pressure.
5. Steam generator outlet sodium temperature.
6. Reheat steam temperature.
7. Reheater outlet sodium temperature.

3.2. System Response

3.2.1. Steam and Feedwater Flow - Figures E-2, E-9

These figures show the responses of the steam generator to a simultaneous step increase in steam and feedwater flows. Because the responses to a step decrease are much the same as those for an increase (except that all variables behave in the opposite direction), only the increase is discussed and shown here.

As the secondary flow rate is increased with a constant heat input, lower temperatures occur at the main steam outlet, as expected. Steam properties provide the relationship between temperature and pressure; the pressure, directly proportional to temperature in an unrestrained model, also decreases as expected.

The length of the subcooled economizer region increases slightly, because, with higher flow, more heat must be absorbed in the subcooled region, and consequently a greater length is required. The greatest increase occurs in the length of the boiling region, where most of the heat is absorbed. This can be inferred from the decrease in length of the superheater. The introduction of more feedwater into the subcooled region causes an eventual decrease in the sodium outlet temperature as more heat is absorbed.

It should be noted that all variables have leveled out within one minute of the disturbance. This gives a very good indication that the steam generator is a rapidly responding system.

3.2.2. Steam Generator Sodium Flow - Figures E-3, E-10

As would be expected, a decrease in the steam generator sodium flow causes the opposite responses to those caused by a secondary-side flow increase. Steam temperature and pressure and sodium outlet temperature decrease along with the superheater region length as more heat is transferred.

3.2.3. Steam Generator Sodium Inlet Temperature - Figures E-4, E-11

The system responses to a step decrease in the steam generator sodium inlet temperature are decreased superheater

length, steam pressure, steam temperature, and sodium outlet temperature. The dips in steam pressure and sodium outlet temperature are due to the heat storage effects within the unit.

3.2.4. Steam Reheater Steam Inlet Temperature - Figures E-5, E-12

The simple heat balance model of the reheater responds to a step increase in steam inlet temperature with a slight rise in reheat steam temperature as less heat is removed from the unit. As would also be expected, the removal of less heat results in an increase in the sodium outlet temperature.

3.2.5. Steam Reheater Steam Flow - Figures E-6, E-13

The reheater responds to a step increase in steam flow by decreasing the sodium outlet temperature and reheat steam temperature as expected.

3.2.6. Steam Reheater Sodium Flow - Figures E-7, E-14

The reheater responds to a step increase in sodium flow in the same way as to an increase in steam inlet temperature: by increasing the reheat steam temperature and the sodium outlet temperature as expected.

3.2.7. Steam Reheater Sodium Inlet Temperature - Figures E-8, E-15

The reheater responds to the step increase in sodium inlet temperature by increasing the reheat steam temperature and the sodium outlet temperature. The sudden surge in the outlet sodium temperature is caused by the lack of an inertia term in the equations and should be neglected.

4. Recommendations

The following recommendations can be made:

1. The present wide-range model should be improved by employing the relationships between the flow rates of sodium and water (steam) and their respective heat transfer coefficients.

2. The control loops for the feedwater-steam system should be incorporated with this model to determine system response to plant load changes.

Figure E-1. Feedwater-Steam System and Once-Through Steam Generator Models

Feedwater-Steam System Model

Once-Through Steam Generator Model

Figure E-2. Responses to +5% Step in Steam Generator
Steam and Feedwater Flow (2400/1000/1000
Cycle)

Figure E-3. Responses to -5% Step in Steam Generator Sodium Flow (2400/1000/1000 Cycle)

Figure E-4. Responses to -4.65% Step in Steam Generator Sodium Inlet Temperature (2400/1000/1000 Cycle)

Figure E-5. Responses to +10% Step in Steam Reheater
Steam Inlet Temperature (2400/1000/1000
Cycle)

Figure E-6. Responses to +10% Step in Steam Reheater
Steam Flow (2400/1000/1000 Cycle)

Figure E-7. Responses to +10% Step in Steam Reheater
Sodium Flow (2400/1000/1000 Cycle)

Figure E-8. Responses to +4.65% Step in Steam Reheater
Sodium Inlet Temperature (2400/1000/1000
Cycle)

Figure E-9. Responses to +5% Step in Steam Generator
Steam and Feedwater Flow (2400/950/950
Cycle)

Figure E-10. Responses to -5% Step in Steam Generator Sodium Flow (2400/950/950 Cycle)

Figure E-11. Responses to -5% Step in Steam Generator Sodium Inlet Temperature (2400/950/950 Cycle)

Figure E-12. Responses to +10% Step in Steam Reheater
Steam Inlet Temperature (2400/950/950
Cycle)

Figure E-13. Responses to +10% Step in Steam Reheater
Steam Flow (2400/950/950 Cycle)

Figure E-14. Responses to +10% Step in Steam Reheater
Sodium Flow (2400/950/950 Cycle)

Figure E-15. Responses to +5% Step in Steam Reheater Sodium Inlet Temperature (2400/950/950 Cycle)

APPENDIX F
Analog Model Delay Functions

Incorporated in the analog models for the reactor and intermediate coolant systems are several types of parameter delays. These account for instrumentation delays, valve reaction delays, and transport delays associated with both the sodium coolant flow and the thermal inertia of the heat transfer units. The analog model effects these delays by using either a constant or variable time delay function.

Constant first-order time constant circuitry is used to represent the delay times of sensory devices, valve response, and thermal responses of the IHX, the reheater, and the steam generator. Sensory devices are considered to have constant time responses. The intermediate system bypass valve and the reheater flow valve are set to have response time constants of 2 and 10 seconds, respectively.

The thermal response times of the heat transfer units in the reactor and intermediate systems are functions of the sodium mass, the steel tube mass, and the UA product for the particular unit considered. For the model discussed here, the time constant for these units was calculated by the expression in equation F-1.

$$\tau = \frac{(Mc_p)_{Na} + (Mc_p)_{Fe}}{UA} \quad (F-1)$$

where the values $(Mc_p)_{Na}$, $(Mc_p)_{Fe}$, and UA refer to either the IHX, the steam generator, or the reheater. Since UA is a function of the flow through the unit, τ changes as the thermal demand on the unit changes. Values of UA for the IHX, the reheater, and the steam generator were calculated at different partial loads for the steady-state analysis. The analog model uses a thermal response time constant that is equal to the average of the 20 and 100% plant load time constants.

Table F-1 lists the values of $(Mc_p)_{Na}$, $(Mc_p)_{Fe}$, and UA for 100 and 20% plant loads on the IHX, the reheater, and the steam generator.

The table also lists the maximum, minimum, and average time constants. The average time constant, $\bar{\tau}$, is the value used in the analog model for all power levels.

All of these delays are constant; for delays of this type the delayed variable E_o is given as the solution of the differential equations following Table F-1.

Table F-1. Thermal Response Time Constants for the Reheater and Steam Generator

	MWd, %	(Mc _p) _{Na} , Btu/°F	(Mc _p) _{Fe} , Btu/°F	UA, Btu/°F-sec	τ, sec	$\bar{\tau}$, sec
Reheater	100	46,965	16,875	1086	59	125
	20	46,965	16,875	334	191	
Steam generator	100	67,872	67,500	667	20	39
	20	67,872	67,500	2321	58	
IHX	100	2,795	2,430	3876	1.4	1.5
	20	2,795	2,430	3159	1.7	

$$\frac{dE_o}{dt} + \frac{E_o}{\bar{\tau}} = \frac{E_i}{\bar{\tau}} \quad (F-2)$$

where E_i is the variable to be delayed and $\bar{\tau}$ is the time constant of the delay. In the time domain, E_o is given as

$$E_o = \frac{e^{t/\bar{\tau}}}{\bar{\tau}} \int E_i e^{-t/\bar{\tau}} dt + C e^{-t/\bar{\tau}} \quad (F-3)$$

where C is the initial value of E_o .

The variable time delay is used to reflect temperature lags caused by flow variation. In particular, the temperature θ is written as

$$\theta(t) = \theta[t - T(t)] \quad (F-4)$$

where $T(t)$ is the delay time, which is a function of the varying sodium flow. The temperatures where this type of delay is applied are T_1 , T_2 , T_3 , T_7 , T_{11} , and T_4 . The T_1 delay accounts for the lag between the reactor outlet and IHX inlet temperatures, and the T_2 delay accounts for the lag between the IHX outlet and the reactor inlet. The delay on T_3 accounts for the lag between the IHX outlet temperature and the inlet temperature to the steam generator and the reheater. The delays on T_7 and T_{11} represent the temperature lag between the steam generator outlet and reheater outlet, respectively, and the mixing point of these outlet

flows. The delay on T_4 reflects the lag between the mixing point temperature and the inlet temperature to the IHX. All of these variable delays have the form of equation F-4, where w is the flow rate between the points where the temperature lag exists.

The maximum delay times of the temperatures listed occur at 20% of full power, while minimum delay times occur at the full-power condition. Table F-2 is a list of the maximum, minimum, and ranges of delay times for the T_1 , T_2 , T_3 , T_7 , T_{11} , and T_4 .

Table F-2. Variable Time Delay Values

<u>Temperature</u>	<u>Max T(t), sec</u>	<u>Min T(t), sec</u>	<u>Range, sec</u>
T_1	37	15	22
T_2	184	75	109
T_3	38	10	28
T_7	17	3	14
T_{11}	22	4	18
T_4	49	13	36

The temperature delay circuitry corresponds to that of a variable first order Padé approximation. The delay time for this approximation is given as

$$T(t) = \frac{M}{w(t)} \quad (F-5)$$

where M is the sodium mass between the points of interest and $w(t)$ is the flow rate between these points. Note that in general the flow rate is a function of time.

In the time domain the delayed temperature is given as

$$\theta[t - T(t)] = \theta(t) - 2y(t) \quad (F-6)$$

where $y(t)$ is the solution of the differential equation

$$\frac{dy(t)}{dt} + \frac{2y(t)}{T(t)} = \frac{2x(t)}{T(t)} \quad (F-7)$$

This equation has the following general solution:

$$y(t) = \left[e^{-2 \int \frac{dt}{T(t)}} \int \frac{2x(t)}{T(t)} e^{2 \int \frac{dt}{T(t)}} dt + K e^{-2 \int \frac{dt}{T(t)}} \right] \quad (F-8)$$

For the particular test case where $x(t) = C$ and $w(t) = at$, the exact solution is

$$\theta[t - T(t)] = C - 2Ce^{\frac{-at^2}{M}} \quad (F-9)$$

Figure F-1 compares the calculated and analog results for this particular case. The results encompass the time interval $0 \leq t \leq 150$ seconds and verify the accuracy of the analog simulation.

The accuracy of the first-order Padé approximation itself is a function of the delay time and the radian frequency of the signal to be delayed. In fact, the error is related to the problem variables by

$$E \propto \omega T \quad (F-10)$$

The Padé first-order approximation is adequate as long as the product ωT is less than 0.6 radian. As shown in Table F-1, the maximum value of T is about 50 seconds. Consequently, the variable transport delays of this intermediate system will give adequate results for all periodic variations of MWd with periods greater than 83 seconds.

Figure F-1. Pade First-Order Response to Ramp Delay on a Constant Input