A PARAMETER SENSITIVITY STUDY IN THE DYNAMIC SIMULATION OF A SODIUM COOLED BREEDER REACTOR POWER PLANT

by

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APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

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14 December 1977
Date

To my Mom, Dad, and wife Laura

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I would like to thank Dr. David L. Hetrick for the invaluable assistance he gave me during the course of this study.

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ABSTRACT

The time domain sensitivity measure, peak sensitivity, was employed in studying the dynamics of a Clinch River Breeder Reactor Power Plant (CRBRP) digital simulator. With its use the most "safety sensitive" parameters in the plant model were identified for particular anticipated transients. Examples of such parameters include the Doppler feedback coefficient, fraction of power generated in the core, and the two phase flow friction multiplier. A method of putting first order bounds on a particular power plant transient due to parameter estimate error is also presented. This information is valuable since the CRBRP simulator was constructed with the intent of studying the safety of the system.

CHAPTER 1

INTRODUCTION

In a nuclear power plant model, parameters needed to describe the physical system may be lumped into various categories. Nuclear parameters include Doppler coefficients, delayed neutron fractions, and decay constants. Thermohydraulic parameters include heat transfer coefficients, friction factors, pump efficiencies and the like. Mechanical parameters, such as turbine time constants and inertia are also needed.

A parameter sensitivity study of a model of a dynamic system yields information as to how the characteristics of the model change when a parameter is varied. Model changes might be characterized by a difference in step response, frequency response (Bode analysis), or the location of system roots in the complex s-plane (root locus). After a sensitivity measure has been made the numerical analyst can then make judgments as to which are the most important parameters in the system model. This information is especially valuable in its application to a nuclear power plant dynamic simulator and has the following aims:

1. If a parameter is highly sensitive, then an accurate determination of it is necessary to yield good numerical results.
2. Bounding tolerances on a particular simulated power plant transient due to parameter estimate errors can be sought. (This aim is of prime importance when judging reactor safety.)

3. In system identification work the most highly sensitive parameters are adjusted to match the model with the physical system. Other, less sensitive, parameters are usually not considered.

The goal of this thesis is the achievement of aims 1 and 2. Since the Clinch River Breeder Reactor Power Plant (CRBRP) has not yet been constructed, the achievement of aim 3 must be postponed to a later date.

The CRBRP simulator to be considered consists of a set of coupled algebraic and ordinary differential equations (Shinaishin 1976) and are solved on a digital computer by the DARE software package (Lucas and Wait 1975). These equations describe the conservation laws of physics as applied to the various components in the CRBRP (i.e., reactor, evaporator, etc.). The space dependence has been handled by sectionalizing the system into several lumps (or nodes). The algebraic equations may be eliminated by substitution yielding the following simplified vector description of the system:

$$\frac{d\bar{x}}{dt} = A\,\bar{x} + \bar{f}\,(\bar{x},\, t) + B\,\bar{u}(t);\; X\,(0) = X_o \qquad (1\text{-}1)$$

where

$\bar{x}$ $\equiv$ the state vector

A $\equiv$ a matrix of constant coefficients of the linear terms

$\bar{f}\,(\bar{x},t)$ $\equiv$ the vector of nonlinear and variable coefficient terms

B $\equiv$ a matrix of constant coefficients

$\bar{u}(t)$ $\equiv$ forcing function vector

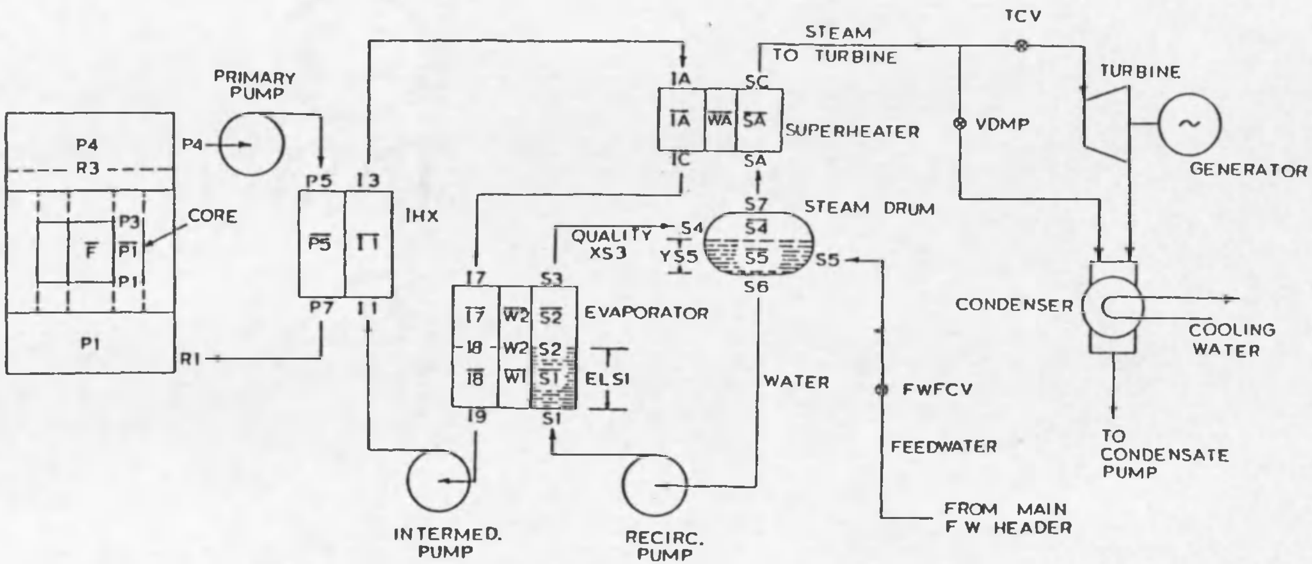
X_o $\equiv$ vector of initial conditions

Parameters of interest are found within the A and B matrices and within the nonlinear $\bar{f}$ vector.

A diagram of the CRBRP simulator with the appropriate state variable locations may be found in Figure 1-1. Also in this figure is a list of the nominal steady state initial conditions which must be met to match the plant design operating point at 100% power level (Clinch River Breeder Reactor Project, Preliminary Safety Analysis Report [PSAR] 1975).

It should be understood that the CRBRP simulator considered does not contain plant controllers. These controllers (i.e., reactivity, pump speed, etc.) were not included so that the effects of intrinsic parameter variations (i.e., inherent to the natural system) on the system response would not be masked by feedback effects from the automatic controllers. In this way a better understanding of these intrinsic parameters can be achieved. Another reason is that this is also a more conservative approach when sensitivity measures are used in judging reactor safety since the loss of system controllers might possibly occur.

The sensitivity measure employed in this thesis is suited for time domain analysis. Other sensitivity measures, namely root locus and Bode analysis, were not used. The reason for this decision, along with a discussion of the sensitivity measure employed, can be found in Chapter 2.



Temperature

$\overline{T}_{AF}$
T_{IC}(855°F)
T_{I3}(936°F)
T_{I8}
T_{I9}(651°F)
T_{P1}(730°F)
T_{P3}
T_{P4}(995°F)
T_{P7}(730°F)

Temperature (cont.)

T_{R3}
T_{SC}(905°F)
$\overline{T}_{WA}$
$\overline{T}_{W1}$
$\overline{T}_{W2}$

Flow

Primary(11518 lbm/sec)
Intermed(10650 lbm/sec)
Riser(1856 lbm/sec)

Flow (cont.)

Downcomer(1856 lbm/sec)
S.H.-Turbine(928 lbm/sec)
Feedwater(928 lbm/sec)

Pressure

$\overline{P}_{S4}$(1765 psi)
$\overline{P}_{S2}$(1830 psi)

Pump Speed

Primary(1170 RPM)
Intermed.(1006 RPM)

Mass

M_{S4}
M_{S5}

Water Height

L_{S1}

Water Enthalpy

H_{S6} (@ 544°F)

Turbine Variables

Power Angle
Turbine Speed(60 RPS)
Turbine Power(380 MW)

Delayed Neutrons

Six Groups

Figure 1-1 -- Schematic Diagram of the CRBRP.

Chapter 3 gives the results of the parameter sensitivity study with a discussion on its application to reactor safety. Chapter 4 is devoted to conclusions and recommendations and this will be followed by appendices containing sample calculations.

The CRBRP digital simulator to be tested for parameter sensitivity is actually one of three separate simulators developed by Shinaishin. These simulators were intended to study the safety of the CRBRP through a wide range of transients and power plant operating conditions. The second simulator is the same as the one tested in this thesis except for the plant automatic control system. These two simulators were intended to study moderate transients of the type referred to as Anticipated Transient Without Scram (ATWS). The third simulator was constructed for studying transients due to unexpected accidents followed by reactor scram. In this simulator emphasis was placed on simulating the auxiliary heat removal system, in order to determine its capability to remove the after-shut down fission and decay heat. Together, the three simulators are known as BRENDA (Breeder Reactor Nuclear Dynamic Analysis).

CHAPTER 2

SENSITIVITY MEASURES

Sensitivity measures generally relate the change in some system measure to the change in one or more plant parameters. A sensitivity measure should incorporate two features:

1. It should be mathematically tractable so that its utilization is not encumbered by great amounts of labor.
2. It must be physically meaningful in relation to the performance of the system.

Feature number 1 is essential when testing this simulator because of its complexity and large number of parameters. Number 2 must also be met if this study is going to have anything to say about reactor safety.

2.1 Root or Eigenvalue Sensitivity

This sensitivity measure has been used frequently in the analysis of control systems in several fields of engineering (Van Ness, Boyle and Imad 1965).

The roots of a system of non-linear ordinary differential equations can be found in the following way. The equations should first be linearized about an operating point and then Laplace transforms applied. (The linearization is done by looking at small perturbations about the operating point and is equivalent to removing the non-linear term in equation (1-1).) The roots of the system are then the solutions of the characteristic equation [1]:

$$P(s) = \det [sI - A] = 0 \tag{2-1}$$

Root sensitivity measures the change in position of a system root in the complex s - plane (root locus).

In the early phase of this work, root sensitivity was investigated because it had the advantage of not being dependent on the type of initiating transient, (i.e., step, ramp, frequency response of temperature, flow rate, or power). It was found, however, even for a small open loop system of equations, such as those that represent the superheater of the simulator, that the root sensitivity measure was difficult to interpret.

For example, Table 2-1 contains the numerical values of the roots for the 3rd order superheater model. To calculate the parameter sensitivity a 1% error was first assumed in the estimate of the parameter of interest and then other operating conditions were adjusted, if necessary, to meet the design operating conditions specified in the PSAR (see Figure 1-1 and Appendix A for details). The roots of the modified system were then found by applying equation (2-1). It can be seen from Table 2-1 that the percentage change in root position from the nominal is greater for the first 2 roots in the sodium to wall heat transfer coefficient, while the percentage change for the 3rd root is greater for the superheater wall specific heat. It is therefore difficult to judge which

1. It should be noted that the linearization procedure is generally done manually, while the roots for a high order system are found by computer. There are programs which do both but the analyst loses valuable information in the process.

Table 2-1 -- Root Sensitivity of the 3^{rd} Order Superheater Model.

Value of Root

Parameter \ Root Number	1	2	3
Nominal	-6.23348	-2.03931	-0.23244
Superheater Wall Specific Heat	-6.22975	-2.02620	-0.23177
Sodium to Wall Heat Transfer Coefficient	-6.22573	-2.05783	-0.23246

Percentage Change in Root from Nominal

Parameter \ Root Number	1	2	3
Superheater Wall Specific Heat	-0.0598	-0.6430	-0.0670
Sodium to Wall Heat Transfer Coefficient	-0.1243	0.9080	0.0086

is the more sensitive parameter. Since roots are the inverse time constants of the system, a great deal of intuition must be used to correlate how the change in system roots affects the transient response. For the large system of equations present in this simulator this interpretation would become hopelessly complicated.

There are also other problems that the analyst must accept if root sensitivity is to be used. One of these problems is the great amount of labor involved in the linearization of the equations. This would be especially tedious if several operating points must be investigated for sensitivity. Probably the most serious drawback of the method, however, is that it can be shown that the system roots can change by several hundred percent with an essentially unchanged step response (Truxal 1955, p. 295). This drawback cannot be tolerated in this sensitivity study because important information as to the safety oriented time behavior of the CRBRP is lost.

2.2 Frequency Domain Sensitivity--Bode Analysis

Probably the best known sensitivity measure is classical, or Bode, sensitivity. This is defined as the percent variation of a system transfer function, T, with respect to the percent variation of a parameter λ, and is defined as follows:

$$S_{\lambda}^{T}(s) = \frac{dT/T}{d\lambda/\lambda} = \frac{d(\ln T)}{d(\ln\lambda)} \qquad (2\text{-}2)$$

If the test input is a sinusoid, then $s = j\omega$, and Bode plots of equation (2-2) can be made showing the sensivitity as a function of frequency.

Unlike root sensitivity, this sensitivity measure depends on the type of test input (i.e., flow rate and temperature transients).

Because S_{λ}^{T} is a function of the complex variable s, a physical interpretation of S_{λ}^{T} is difficult. As an example of where such a difficulty may occur, White (1967) conducted a sensitivity study on a class of low order linear control systems and produced the asymptotic Bode gain sensitivity curves shown in Figure 2-1. It can be noted from the figure that the parameter sensitivity is a complicated function of frequency (i.e., k_1 is the most sensitive parameter at low frequency and the least sensitive at a higher frequency). Though the results of the model tested by White have little relevance to the model tested in this thesis, it is instructive in showing a problem which may occur if this approach is taken. For this reason, and the fact that the system of equations would have to be linearized about an operating point, as in root sensitivity, this approach was abandoned.

There are, however, important applications of Bode analysis in the closely related field of system identification (Chang and Kerlin 1976). The basic idea of system identification is to adjust the important (most sensitive) parameters of a model to minimize differences between experimental results obtained from the physical system and model predictions. The usual procedure is to impress a periodic test input signal ($s = j\omega$) on a linearized set of equations, and minimize the difference between Bode plots by least squares techniques. In this discipline, working in the frequency rather than in the time domain has several important advantages. One main advantage is that by looking at

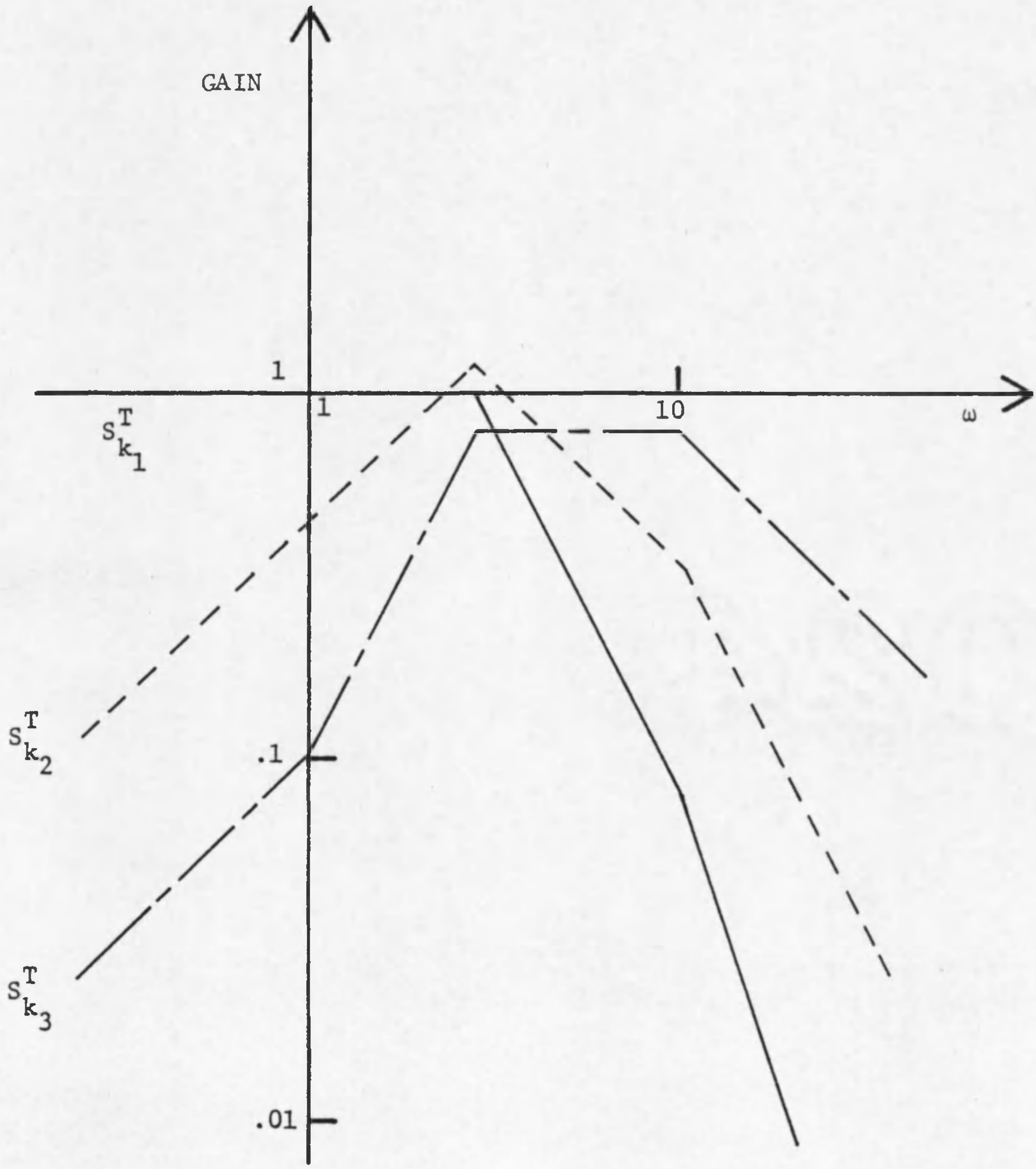


Figure 2-1 -- Bode Sensitivity of a Low Order Control System. (White 1967) the frequency response, low level signals can be used on the physical system because they permit averaging of multiple estimates of the results and the background noise effect is reduced in the averaging. If a non-periodic signal (i.e., step) is used it must be large enough in magnitude to overwhelm the background noise. However, the magnitude of such a signal is limited such that nonlinear effects do not appear and normal system operation is not disturbed.

2.3 Time Domain Sensitivity

The sensitivity measure used to obtain the results of this thesis was first introduced by Tomovic (1964). Let λ be a system parameter with a nominal value λ_o. If $x(t,\lambda)$ is the response of a system state variable to a step input, then for a change in the parameter λ, the step response may be expanded in a Taylor series

$$x(t,\lambda_o + \Delta\lambda) = x(t,\lambda_o) + \left.\frac{dx(t,\lambda)}{d\lambda}\right|_{\lambda_o} \Delta\lambda + \left.\frac{d^2x(t,\lambda)}{d\lambda^2}\right|_{\lambda_o} \Delta\lambda^2 + \ldots \tag{2-3}$$

(It should be noted that the step function is one of the standard signals used in testing systems of differential equations.) The first order effect is given by the time dependent first order sensitivity function

$$\left.\frac{dx(t,\lambda)}{d\lambda}\right|_{\lambda_o} .$$

It is desirable to have an estimate of the change in $x(t,\lambda)$ for a percentage change in λ. Therefore, the sensitivity of the system state variables with respect to the parameter λ is defined as:

$$u_{\lambda_i}(t) = \frac{dx_i(t,\lambda)}{\frac{d\lambda}{\lambda}} \qquad i = 1,n \tag{2-4}$$

This sensitivity measure is known as the <u>sensitivity function</u> (White 1967; Haberman 1977), and like Bode sensitivity, depends on the type of test input. A more concrete illustration of its physical meaning is shown in Figure 2-2. If a step input is applied simultaneously to both systems the differences between the outputs will be:

$$\Delta x = x(t, \lambda + \Delta\lambda) - x(t,\lambda) \quad .$$

Dividing by the percentage change in the parameter and letting $\Delta\lambda \rightarrow 0$, equation (2-4) is obtained.

As might be expected there exists a relationship between Bode sensitivity and the sensitivity function. This was shown by White (1967) to be

$$U_{\lambda}(s) = \frac{1}{s} T(s) S_{\lambda}^{T}(s) \tag{2-5}$$

where

$T(s) \equiv$ transfer function relating input to output

$\frac{1}{s} \equiv$ Laplace transform of step input

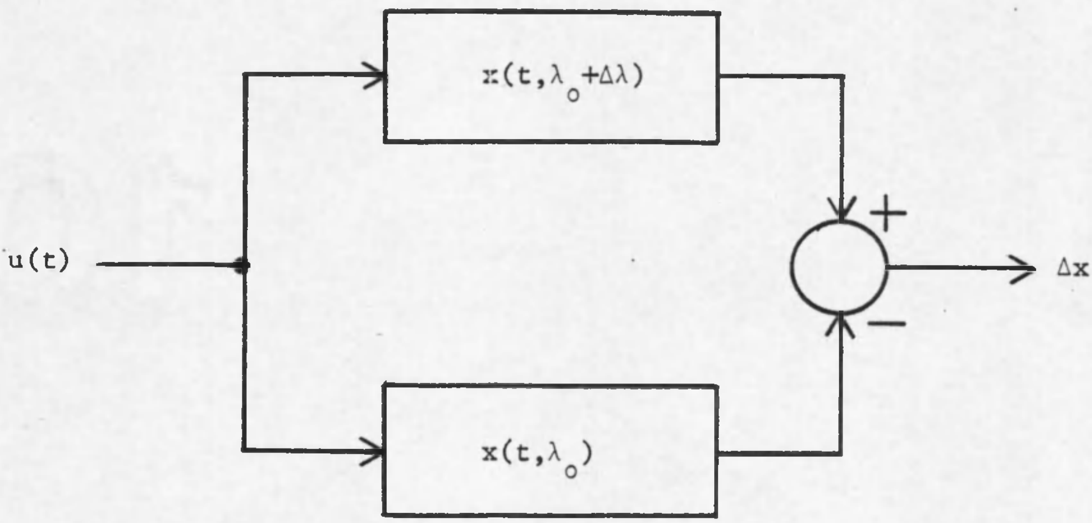


Figure 2-2 -- An Illustration of the Definition of the Sensitivity Function .

As an example of how the sensitivity function was used in the CRBRP simulator, consider the open loop superheater model mentioned earlier. To utilize equation 2-4 on a digital computer the following finite difference approximation was used

$$u_{\lambda_i}(t) \approx \frac{x_i(t, \lambda_o + \Delta\lambda) - x_i(t, \lambda_o)}{\Delta\lambda\ (\%)} \ ; \ i = 1,n \ . \qquad (2\text{-}6)$$

The state variables in this model are the outlet sodium temperature, the tube wall temperature and the outlet superheated steam temperature. A 1% error from nominal was assumed in the sodium to tube wall heat transfer coefficient (HWA). The new tube wall to steam fouling resistance and tube wall temperature initial condition were then recalculated. These changes to the modified system were necessary to meet the design inlet and outlet superheater temperatures as outlined in the PSAR (see Section A-1 for details). A 20°F step in the sodium inlet temperature was then applied to both systems and the differences between both systems were noted. A similar procedure was then applied to the wall specific heat (C_{PWA}). The sensitivity functions for the three state variables are plotted in Figure 2-3. From the figures it can be seen that a change in H_{WA} has a smaller effect than C_{PWA} for the state variables T_{SC} and T_{IC}. However, H_{WA} has a much greater effect on $\bar{T}_{WA}$ because of the change in the initial condition for $\bar{T}_{WA}$.

The sensitivity function plots have the desirable feature mentioned at the beginning of this chapter in that they are physically meaningful to the performance of the system. These plots are directly

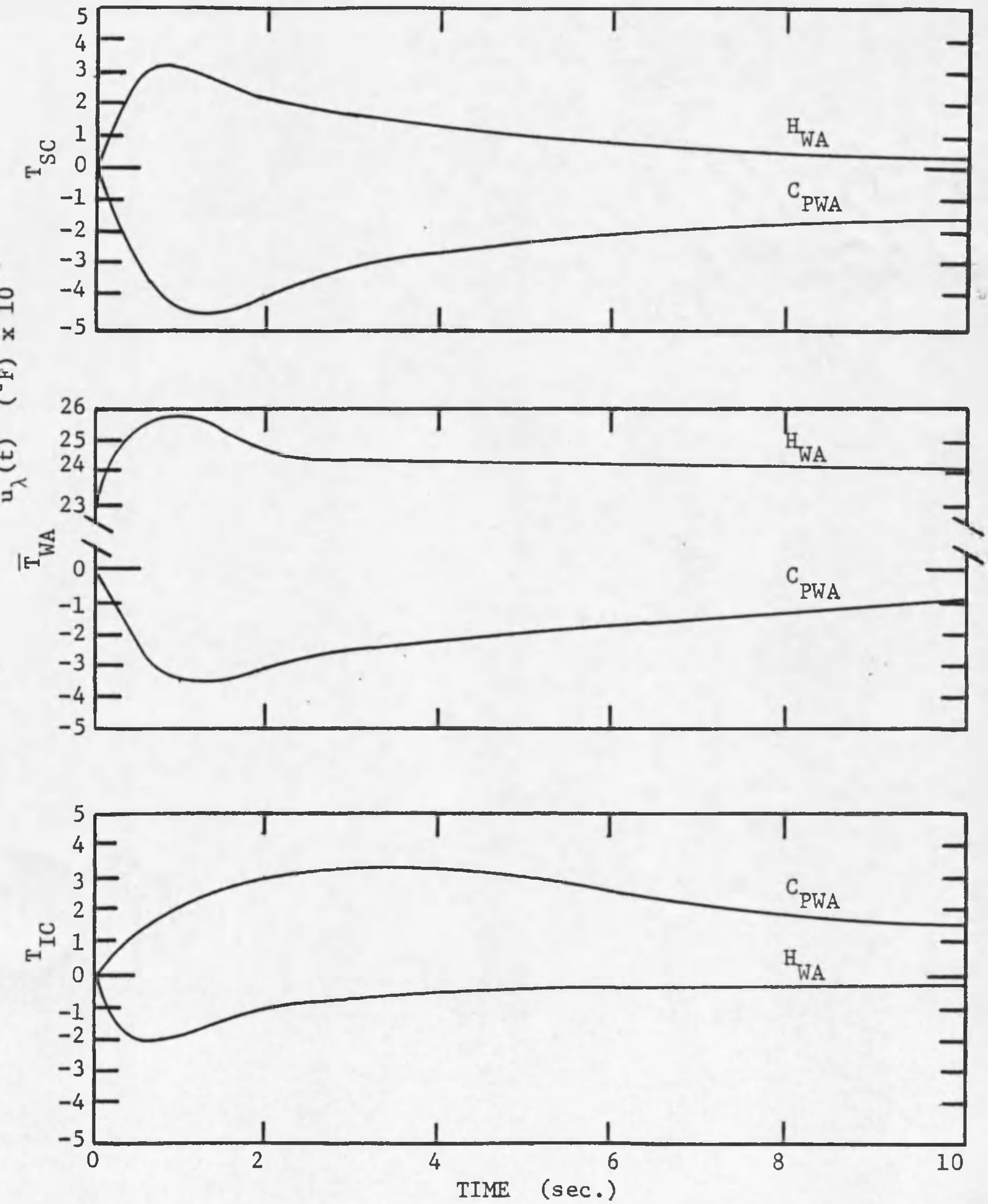


Figure 2-3 -- Time Domain Sensitivity of the 3rd Order Superheater Model Following a 20° F Step in the Sodium Inlet Temperature.

related to the transient response and show just how much each part of the response is affected by the parameters.

This wealth of information is not in a compact form, however, since the sensitivity functions are time dependent. For purposes of comparison, it is convenient to have a sensitivity measure that yields a single real number. Previous authors have overcome this problem by adopting the following two sensitivity measures which utilize the time dependent sensitivity function plots.

The first measure is known as integral output sensitivity and is defined as

$$\bar{u}_\lambda = \frac{1}{T}\int_o^T u_\lambda(t)dt \tag{2-6}$$

where T is a time interval large enough to allow x(t) (the step response) to reach its final value. This measure, in effect, gives the average sensitivity over the time interval. The second measure is known as peak sensitivity and is defined as

$$u_\lambda^* = u_\lambda(T) \tag{2-7}$$

where T is the time at which $|u_\lambda(t)|$ is a maximum. The convenience in using these two measures must be paid for by accepting the loss of information inherent in their use.

It was decided that the use of peak sensitivity was ideal for the type of parameter sensitivity study performed on this simulator. It is ideal because it not only yields a single number necessary for comparing a large number of parameters, but its very nature is safety oriented.

From results obtained with its use the analyst can estimate which parameters are the most "safety sensitive." An added feature of its use is that this information can be used to put first order bounds on a transient due to parameter error. This feature is discussed in Section 3.4.

Integral output sensitivity was abandoned because of the many extremely long simulation times required for the sensitivity function to reach its final value. Its measure was felt to be of much less importance for the type of safety related study conducted here.

CHAPTER 3

PARAMETER SENSITIVITY STUDY OF A CRBRP DYNAMIC SIMULATOR

In this chapter the time domain sensitivity function discussed in Chapter 2 will be applied to the CRBRP dynamic simulator. To begin the discussion, a section will be devoted to the rationale behind the approach of the study. Following this, measures of parameter sensitivity with appropriate comments on reactor safety will be presented.

3.1 Approach

In the early phases of this work it became apparent that measures of parameter sensitivity could not be practically made by simulating the dynamics of the CRBRP as a whole. If this approach were to be taken, extremely long simulation times would be necessary for the effect of a parameter variation to be felt by all the state variables describing the plant. This is due to the large transport time delays in plant piping and large system time constants associated with the heat capacities of several of the plant components. The computer costs associated with such long simulations is a prohibiting factor because of the large number of parameters to be tested. To circumvent this problem the simulator was split into two sections.

The first section includes the equations describing the reactor, intermediate heat exchanger, and the fluid flow between them. Together they represent the primary loop of the CRBRP. A diagram of this portion of the plant can be found in Figure 3-1. It can be noted from Figure 1-1

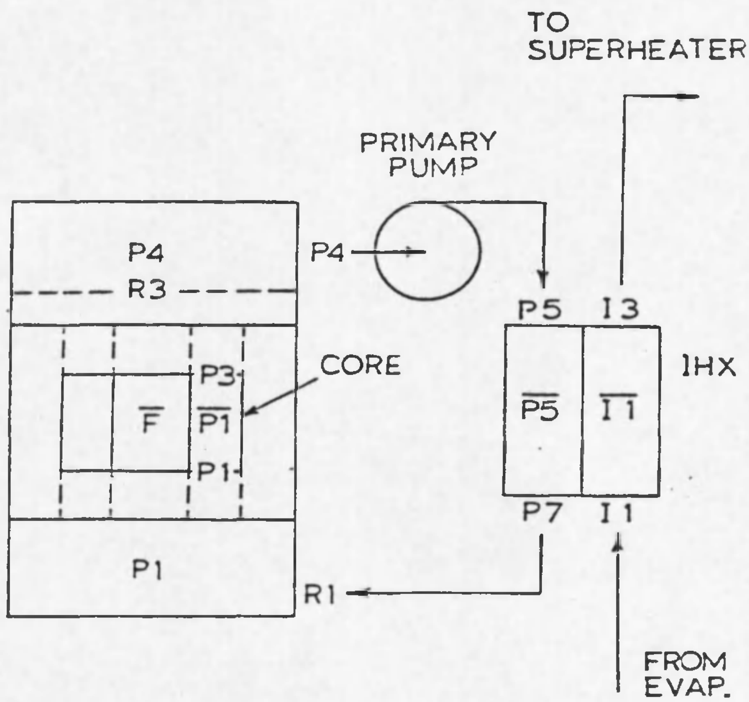


Figure 3-1 -- Schematic Diagram of the Primary Loop.

that the "cut" was made at the point of the largest transport time delay. By making the cut here, it was hoped that the major effects that parameter variations have on a transient initiated in the reactor would be felt by the state variables in the primary loop before any significant feedback effects could be felt from the intermediate loop. Ignoring these feedback effects is equivalent to assuming a constant inlet sodium temperature and flow rate at the inlet to the IHX on the intermediate side.

The second section includes the equations describing the steam generation system of the power plant, excluding the steam turbine and feedwater model. During the course of this study it was found that this latter section of the model exhibited unrealistic behavior when subjected to various transients. The major difficulty was the large magnitude of flow mismatch between the superheated steam flow to the turbine and the feedwater flow from the condenser. At steady state operating conditions these flows are equal. It would then be expected that for mild transients, the deviation from the steady state flow rates should be relatively small. The problem in the feedwater and turbine model is that it is over-simplified in that the explicit dynamics of such components as the condenser and feedwater heaters were not considered. The sensitivity study was therefore conducted on the open loop steam generator depicted in Figure 3-2. The open loop assumption is equivalent to setting the intermediate sodium, feedwater, and superheated steam flows, as well as the feedwater temperature, to constants.

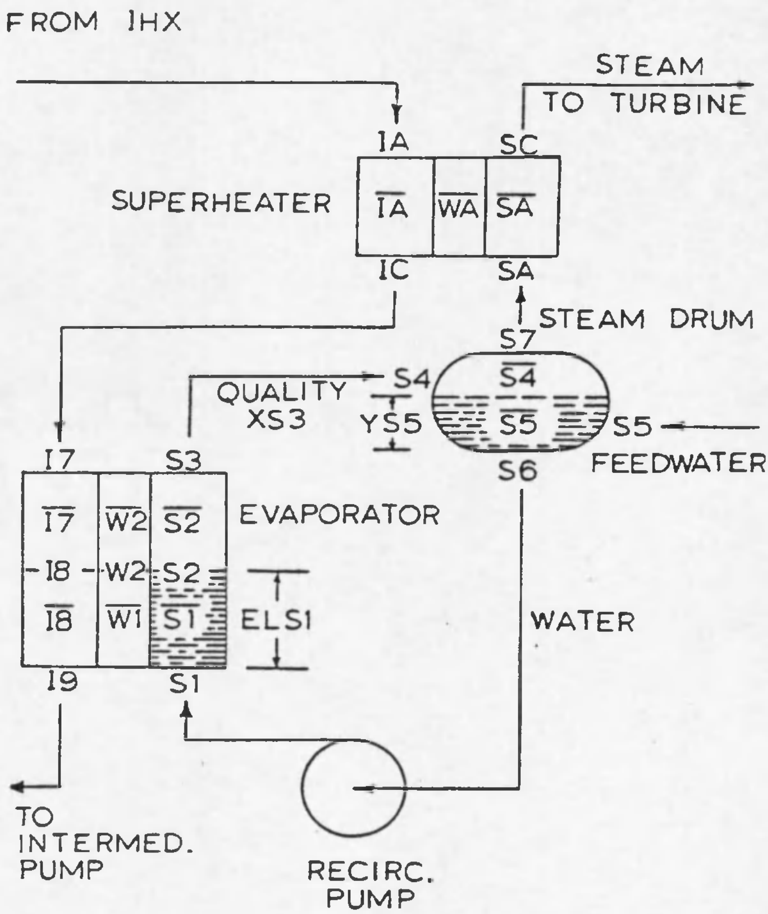


Figure 3-2 -- Schematic Diagram of the Open Loop Steam Generator.

The magnitudes of the transients impressed on both sections were chosen to be small enough to allow the system of equations to exhibit an approximate linear behavior. In this way the superposition property of linear differential equations can be used to approximate the behavior of sensitivity functions for various magnitudes of the same type of transient (i.e., step).

As mentioned earlier the system of equations is nonlinear. Hence the sensitivity of a parameter is dependent on the operating point. Since the CRBRP simulator was intended to study transients in the 40-100% power range, it would seem appropriate to study the sensitivity of parameters over this range. This was done in Section 3.2.2 for the most sensitive parameters in the primary loop.

3.2 Parameter Sensitivity in the Primary Loop

3.2.1 100% Power Level

The transient chosen to determine parameter sensitivity was a 10¢ step in control rod reactivity. It was chosen because it approximates a realistic system transient and was mild enough for the system of equations to exhibit an approximate linear behavior.

By observing simulations of the total plant dynamics following the 10¢ step, it was noticed that significant feedback effects from the steam generation section to the intermediate sodium inlet of the IHX did not occur for 120 seconds. This was the simulation time chosen to stop the sensitivity runs in the primary loop. This cutoff time is also practical from a reactor safety standpoint in that it covers the first important minutes following transient initiation.

The parameters chosen to be tested for sensitivity were those most susceptible to estimation error. Those are namely the nuclear and thermohydraulic properties of the system. A list of those tested is given in Table 3-1.

The following procedure was then employed to test for their sensitivity.

1. The parameter of interest was increased by 1%.
2. Certain system equations were rebalanced, if necessary, to match the PSAR steady state design conditions at 100% power.
3. With the use of equation (2-6) the model was simulated at steady state for a significant time to check for noise in the sensitivity function due to rebalancing error.
4. The simulator was then run for 120 seconds following a 10¢ step in reactivity.
5. Magnitudes of the sensitivity function for the steady state and 10¢ step simulations were compared.
6. If the numerical value of the sensitivity function found in Step 4 was several orders of magnitude greater than that found in Step 3, then a good sensitivity measure had been determined. If this condition was not met, then Step 2 was repated with greater accuracy. This was then followed by Steps 3, 4, 5, and 6.
7. Once a good sensitivity measure had been made, the time dependent sensitivity curves were observed for all the safety related state variables and the value of peak sensitivity was recorded.

Table 3-1 List of Parameters in the Primary Loop.

Type	Name	Symbol	Nominal Value
Nuclear Feedback Coefficients	Doppler	DC	-0.0058
	Axial Expansion	AXECC	-0.023 (¢/°F)
	Radial Expansion	RECC	-0.21 (¢/°F)
	Sodium Density	SODDCC	-0.006 (¢/°F)
Delayed Neutron Fractions	1st Group	β_1	0.00008254
	2nd Group	β_2	0.00077560
	3rd Group	β_3	0.00066600
	4th Group	β_4	0.00135400
	5th Group	β_5	0.00059080
	6th Group	β_6	0.00018100
Delayed Neutron Time Constants	1st Group	λ_1	0.0129 (sec^{-1})
	2nd Group	λ_2	0.0312 (sec^{-1})
	3rd Group	λ_3	0.1330 (sec^{-1})
	4th Group	λ_4	0.3450 (sec^{-1})
	5th Group	λ_5	1.4100 (sec^{-1})
	6th Group	λ_6	3.7500 (sec^{-1})
Thermal Properties of Fuel Pin	Fuel Therm. Cond.	AKF	a
	Gap Conductance	HDG	784.4 (Btu/(hr ft^2 °F))
	Fuel Specific Heat	C_{PF}	0.076 (Btu/(lbm °F))
	Clad Therm. Cond.	K_C	13.4 (Btu/(hr ft °F))
	Sodium Film Cond.	H_C	a
Core Parameters	Fraction of Power Generated in Core	FPGC	0.9239
	Fraction of Primary Flow in Core	FFC	0.80
Primary Pump Parameters	Efficiency	ETAPP	a
	Inertia	AIPP	497.3 (lb_f-ft-sec^2/rad^2)
IHX Thermal Properties	Heat Transfer Coefficient	HNIP	a

a) See Shinaishin (1976) for equation used.

A specific example as to how the above procedure was applied to the Doppler feedback coefficient can be found in Appendix B. This example also shows how the inclusion of the steam generator feedback affects the sensitivity function at 120 seconds.

Results of the sensitivity runs can be found in Table 3-2. This table lists the peak sensitivities of the temperature state variables located throughout the primary loop. Other state variables, describing the delayed neutron precursors, are not listed because they are not directly related to the safety of the system.

Entries signified by Δ indicate that the sensitivity function was non zero at the beginning of the simulation. This is caused, as mentioned in the superheater example of Chapter 2, by the needed change in inititial conditions of these state variables to meet the PSAR design conditions.

Those results designated by an asterisk (*) are ones for which the sensitivity function was still increasing at the time of the cutoff. For these instances the value of the sensitivity function was taken at this time. This is due to the relative location of the parameter in the loop and how the parameter effects the time constants describing the dynamics of the loop. Generally, it can be noticed that most of these types of measures occur for parameters located in the reactor core model at the state variable locations T_{P7} , T_{I3}, and T_{P1}. The main reason for this is that these locations are physically the most distant from the reactor core. This type of behavior can also be seen in other parameters in the loop. One example of this is HNIP which is located in the

Table 3-2 Peak Sensitivity Results from the Primary Loop at 100% Power Level.

($°F \times 10^{2}$)

Parameter \ State Variable	$\overline{T}_F$	T_{P3}	T_{R3}	T_{P4}	T_{P7}	T_{I3}	T_{P1}
DC	-80.0	-15.0	-13.1	-12.0	-2.5 *	-9.3 *	-2.1 *
FPGC	1670.0 Δ	316.0 Δ	-10.2	-9.5 *	-2.0 *	-7.3 *	-1.6 *
AKF	-824.0 Δ	7.8	7.0	6.3 *	1.34 *	5.0 *	1.1 *
AXECC	-32.0	-5.9	-5.3	-4.8 *	-0.96 *	-3.7 *	-0.81 *
β_4	32.0	5.7	5.3	4.8	0.97 *	3.7 *	0.83 *
HDG	-707.0 Δ	3.3	2.8	2.8	0.63 *	2.1 *	0.47 *
β_2	16.8	3.5	2.8	3.0	0.63 *	2.1 *	0.46 *
β_3	15.4	2.8	2.5	2.4	0.47 *	1.8 *	0.39 *
β_5	13.9	2.5	2.4	2.1	0.43 *	1.6 *	0.37 *
RECC	---	-1.3 *	-0.55 *	-0.50 *	-0.05 *	-0.24 *	-0.019 *
β_6	4.3	0.76	0.68	0.66	0.13 *	0.50 *	0.11 *
FFC	-132.0 Δ	-322.0 Δ	0.60	0.59 *	0.12 *	0.45 *	0.096 *

Table 3-2. Continued

State Variable / Parameter	$\overline{T}_F$	T_{P3}	T_{R3}	T_{P4}	T_{P7}	T_{I3}	T_{P1}
λ_2	5.4	0.95	0.8	0.59	0.13	0.49	0.13
C_{PF}	-30.0	-5.1	0.63	0.51	0.12	0.42	0.10
β_1	1.5 *	0.28 *	0.18 *	0.18 *	0.032 *	0.13 *	0.025 *
λ_3	4.0	0.70	0.24	0.19	0.042	0.15	0.038
SODDCC	---	-0.17	-0.13	-0.12 *	-0.023 *	-0.09 *	-0.019 *
λ_4	---	1.5	0.20	0.16	0.035	0.13	0.032
λ_1	0.60	0.11	0.092	0.086	0.016 *	0.061 *	0.012 *
H_C	-19.3 Δ	0.09	0.076	0.08	0.015 *	0.056 *	0.013 *
K_C	-48.5 Δ	0.24	0.20	0.19	0.040 *	0.150 *	0.031 *
λ_5	1.14	---	0.018	0.017	0.0039	0.014	0.0035
ETAPP	---	0.012	---	0.0049	-0.0063	-0.0043	-0.0055
AIPP	---	0.010	---	0.0047	-0.0061	-0.0042	-0.0053
λ_6	---	---	0.0024	0.002	0.00045	0.0017	0.0004
HNIP	---	-0.001 *	---	-0.0068 *	-0.0029 *	0.00264	-0.0026 *
FRICTION FACTORS			INSENSITIVE				

IHX. For this parameter the peak sensitivity first occurs at T_{I3} which is in the IHX. This is not the total picture, however, as can be seen by the sensitivities of the $\lambda^{'s}$. The first delayed neutron group decay constant, λ_1, has the longest half life of the six listed (53.72 sec.), whereas the other five range from 22.21 seconds to 0.18 seconds. It would therefore be expected that an error in a parameter associated with a long time constant would take longer to affect the transient than a short one. This is the case here since the sensitivity for λ_1 has not yet peaked at the cutoff time at locations T_{P7}, T_{I3}, and T_{P1}, while those for λ_2 through λ_6 have done so.

It can also be noted from Table 3-2 that some of the parameters are listed as "insensitive." The reason for this is the way they are used in the equations of the model. The best explanation of this type of parameter is shown by an example (see Appendix C).

Table 3-3 gives the results of Table 3-2 normalized to the most "safety sensitive" parameter, namely the Doppler coefficient. It can be noted that the ratio of peak sensitivities for a given parameter in the core, relative to the Doppler coefficient, are approximately equal for all the state variable locations. Though the peaks generally occurred at different simulation times, these parameters represent a distinct class. The reason for this pattern is that each of these parameters directly affects the fuel temperature first. Once the difference in fuel temperature appears, this signal is filtered through the different differential equations describing the loop, affecting each subsequent state variable proportionately. A notable exception to this is the

Table 3-3 The Absolute Value of the Peak Sensitivity Results Normalized to the Doppler Coefficient at 100% Power Level in the Primary Loop.

Parameter \ State Variable	$\bar{T}_F$	T_{P3}	T_{R3}	T_{P4}	T_{P7}	T_{I3}	T_{P1}
DC	1.0	1.0	1.0	1.0	1.0	1.0	1.0
FPGC	21.0	21.0	0.78	0.80	0.78	0.78	0.78
AKF	10.0	0.53	0.53	0.53	0.53	0.53	0.53
AXECC	0.40	0.39	0.40	0.40	0.38	0.40	0.39
β_4	0.40	0.38	0.40	0.40	0.39	0.40	0.40
HDG	8.8	0.24	0.21	0.23	0.25	0.23	0.21
β_2	0.20	0.22	0.21	0.21	0.21	0.21	0.21
β_3	0.19	0.19	0.19	0.20	0.19	0.17	0.19
β_5	0.17	0.17	0.18	0.18	0.17	0.16	0.18
RECC	---	0.087	0.042	0.042	0.020	0.026	0.0091
β_6	0.054	0.051	0.052	0.055	0.052	0.054	0.052
FFC	1.65	21.5	0.046	0.049	0.048	0.048	0.046

Table 3-3, Continued

State Variable / Parameter	$\overline{T}_F$	T_{P3}	T_{R3}	T_{P4}	T_{P7}	T_{I3}	T_{P1}
λ_2	0.068	0.063	0.060	0.049	0.052	0.053	0.062
C_{PF}	0.38	0.34	0.048	0.043	0.048	0.045	0.048
β_1	0.019	0.019	0.014	0.015	0.013	0.014	0.012
λ_3	0.050	0.047	0.018	0.016	0.017	0.016	0.018
SODDCC	0.013	0.011	0.010	0.010	0.0092	0.0097	0.0091
λ_4	---	0.10	0.015	0.013	0.014	0.014	0.015
λ_1	0.0075	0.0073	0.0070	0.0072	0.0064	0.0066	0.0057
H_C	0.24	0.006	0.006	0.007	0.006	0.006	0.0062
K_C	0.640	0.016	0.015	0.016	0.016	0.016	0.015
λ_5	0.014	---	0.0014	0.0014	0.0016	0.0015	0.0017
ETAPP	---	0.00080	---	0.00041	0.0025	0.00046	0.0026
AIPP	---	0.00067	---	0.00039	0.0024	0.00045	0.0025
λ_6	---	---	0.00019	0.00017	0.00018	0.00018	0.00019
HNIP	---	0.00007	---	0.00057	0.0012	0.00028	0.0012

parameter RECC. The reason that its results do not exhibit the proportionality is because it is a long term feedback affect which depends on the inlet core temperature. The 120 second simulation cutoff was evidently not long enough for the sensitivity function, which was propagated from the fuel temperature first, to be transmitted around the loop.

Another distinct class of parameters is represented by ETAPP and AIPP. It can be seen that their relative sensitivities are approximately equal but do not exhibit the same pattern as the core parameters.

In summary, the first nine parameters in Table 3-3 can be deemed sensitive enough to make them of primary concern when studying step reactivity transients. Special attention should be paid to those parameters which change the initial condition because this is where the major extremes occur. The parameters FFC, KC and HC should therefore be included in this "sensitive list." Table 3-2 is useful for putting approximate bounds on a particular step transient because it gives the actual magnitudes of the peak sensitivities due to parameter estimate error.

3.2.2 70% and 40% Power Levels

In this section the peak sensitivities for the most important parameters of the previous section were recomputed at 70% and 40% of full power.

The procedure employed in obtaining them was essentially the same as the previous section except that the primary loop was rebalanced to meet the PSAR design conditions at these power levels. These design conditions are given in Table 3-4. In order to meet these design conditions it should be noted that the heat transfer fouling resistance term

Table 3-4 PSAR Design Conditions at 40% and 70% Power Level.

State Variable	40% Power	70% Power
T_{P1}	685°F	704°F
T_{P7}	685°F	704°F
T_{P4}	949°F	969°F
T_{I1}	604°F	620°F
T_{I3}	916°F	922°F
Primary Flow Rate	4611 lbm/sec	8056 lbm/sec
Intermediate Flow Rate	3880 lbm/sec	7028 lbm/sec
Primary Pump Speed	457 RPM	777 RPM

in the IHX had to be adjusted. Since the author of the simulator assumed this to be constant throughout the 40-100% power range, this is a problem which should be dealt with in future work on this project.

From Table 3-4 it can be noted that the primary and secondary sodium flow rates are considerably lower than those at 100% power. Therefore, the delay times in the piping of the plant and the cut off time at which to stop the sensitivity runs will be longer. These cutoff times were estimated in accordance with the procedures outlined in Appendix D. These estimations were found to be 180 seconds at 70% power and 330 seconds at 40% power.

The results at these power levels can be found in Table 3-5 and 3-6. By comparing Tables 3-2, 3-3, and 3-6, it can be noted that both the magnitude and relative peak sensitivities change as a function of power level. This, as mentioned earlier, is due to the nonlinear nature of the system of equations. Figures 3-3 and 3-4 show plots of the absolute value of the peak sensitivity magnitudes in the 40-100% power range for the state variables $\bar{T}_F$ and T_{P4}.

3.3 Parameter Sensitivity in the Open Loop Steam Generator

The transient chosen for this section of the plant was a 20°F step in superheater inlet sodium temperature.

Parameters to be tested for sensitivity are those listed in Table 3-7.

The cut-off time was chosen to be 100 seconds. This value was estimated by observing the sensitivity runs and noting when significant feedback effects occurred.

Table 3-5 Peak Sensitivity Results from the Primary Loop at 40% and 70% Power Level.

State Variable / Parameter	$\bar{T}_F$	T_{P3}	T_{R3}	T_{P4}	T_{P7}	T_{I3}	T_{P1}
40% Power (°F x 10^2)							
DC	-68.0	-29.0	-24.0	-23.0	-5.3	-21.0	-4.6 *
FPGC	700.0 Δ	319.2 Δ	-24.0	-23.0	-5.3	-21.0	-4.7 *
AKF	-232.0 Δ	13.0	10.3	9.8	2.2	8.9	2.0 *
HDG	-304.4 Δ	11.3	9.4	8.7	2.0	7.8	1.8 *
β_4	26.0	11.0	9.4	8.7	2.0	7.8	1.8 *
AXECC	-18.0	-7.8	-6.2	-6.2	-1.4	-5.6	-1.2 *
70% Power (°F x 10^2)							
DC	-75.0	-19.0	-16.0	-16.0	-3.4 *	-13.0 *	-3.0 *
FPGC	1186.0 Δ	314.0 Δ	-16.0	-16.0	-3.5 *	-13.0 *	-3.1 *
AKF	-502.0 Δ	11.0	9.0	8.9	1.9 *	7.2 *	1.6 *
β_4	29.0	7.3	6.3	6.2	1.3 *	5.0 *	1.2 *
HDG	-521.0 Δ	6.7	5.6	5.4	1.2 *	4.4 *	1.0 *
AXECC	-25.0	-6.3	-5.3	-5.2	-1.1 *	-4.2 *	-0.97 *

Table 3-6 The Absolute Value of the Peak Sensitivity Results Normalized to the Doppler Coefficient at 40% and 70% Power Level in the Primary Loop.

Parameter \ State Variable	$\overline{T}_F$	T_{P3}	T_{R3}	T_{P4}	T_{P7}	T_{I3}	T_{P1}
40% Power (°F x 10 ^{2})							
DC	1.0	1.0	1.0	1.0	1.0	1.0	1.0
FPGC	10.3	11.0	1.0	1.0	1.0	1.0	1.0
AKF	3.4	0.45	0.43	0.43	0.42	0.42	0.43
HDG	4.5	0.39	0.39	0.38	0.38	0.37	0.39
β_4	0.38	0.38	0.39	0.38	0.38	0.37	0.39
AXECC	0.27	0.27	0.26	0.27	0.26	0.27	0.26
70% Power (°F x 10 ^{2})							
DC	1.0	1.0	1.0	1.0	1.0	1.0	1.0
FPGC	16.0	17.0	1.0	1.0	1.0	1.0	1.0
AKF	6.7	0.58	0.56	0.56	0.56	0.56	0.53
β_4	0.39	0.39	0.39	0.39	0.38	0.38	0.40
HDG	6.95	0.35	0.35	0.34	0.35	0.34	0.33
AXECC	0.33	0.33	0.33	0.33	0.32	0.32	0.32

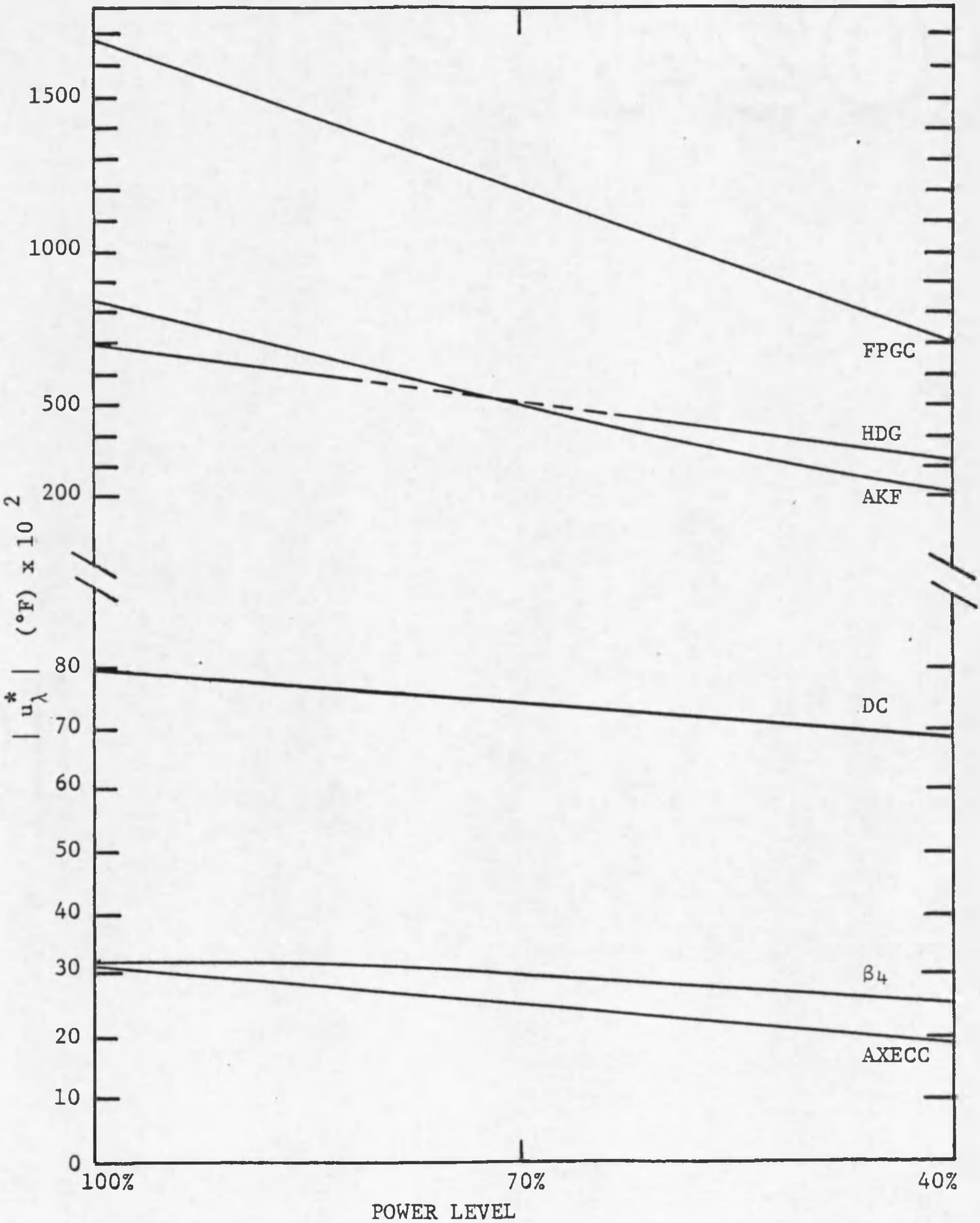


Figure 3-3 -- The Absolute Value of the Fuel Temperature Peak Sensitivity in the 40-100% Power Range .

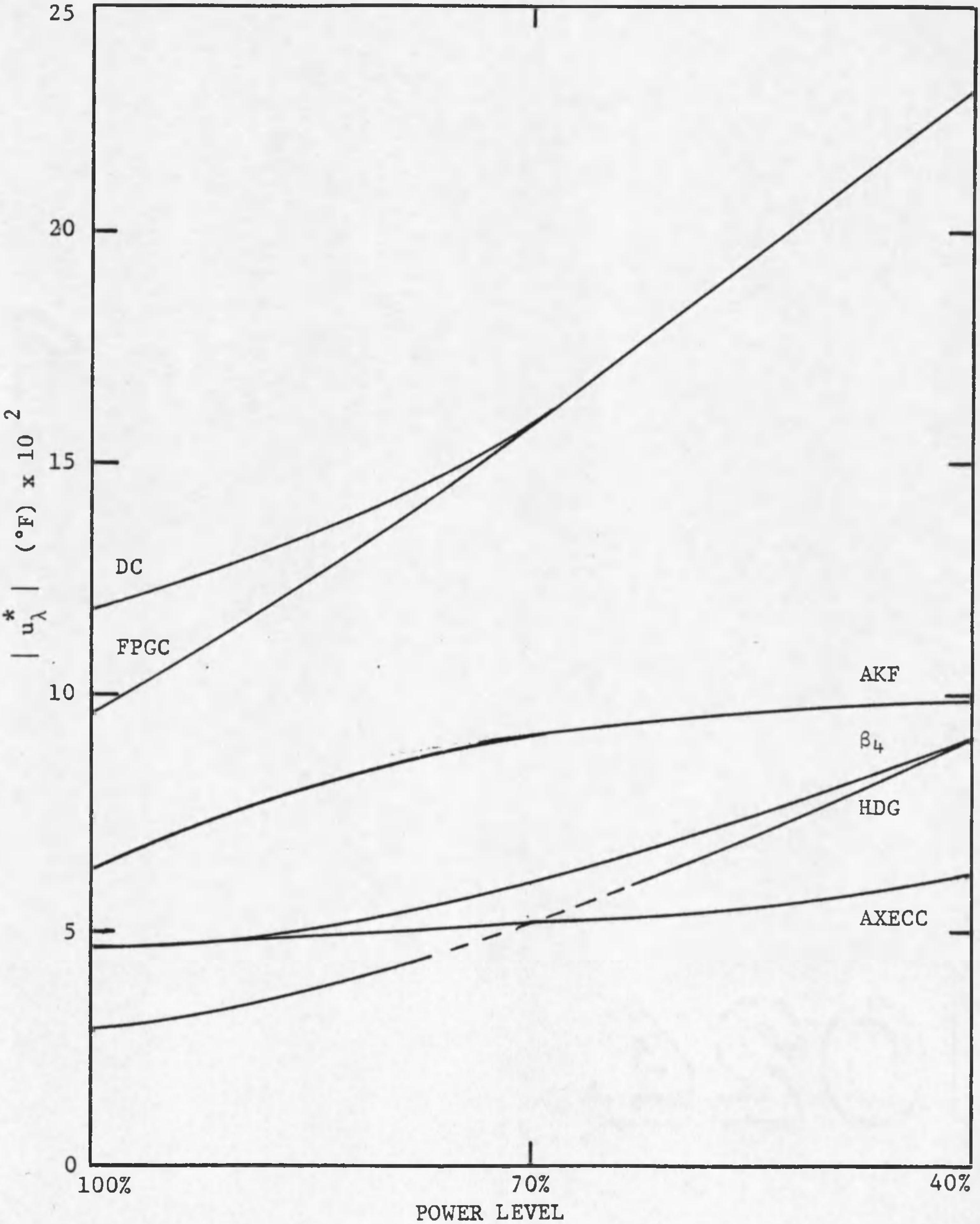


Figure 3-4 -- The Absolute Value of the Reactor Exit Temperature Peak Sensitivity in the 40-100% Power Range.

Table 3-7 List of Parameters in the Steam Generator.

Type	Name	Symbol	Nominal Value
Heat Transfer Coefficients	Sodium to Wall in Superheater	H_{NS}	a
	Wall to Water in Evaporator	H_{WE}	a
	Sodium to Wall in Evaporator	H_{NE}	a
Tube Wall Specific Heats	Specific Heat in Superheater	C_{PWA}	0.12 (Btu/lbm-°F)
	Specific Heat in Evaporator	C_{PWE}	0.12 (Btu/lbm-°F)
Tube Wall Thermal Conductivities	Thermal Conductivity in Superheater	K_{WA}	22.0 (Btu/hr-ft-°F)
	Thermal Conductivity in Evaporator	K_{WE}	22.0 (Btu/hr-ft-°F)
Friction Factors	Two Phase Flow Friction Multiplier	RD	a
	Evaporator Friction Factor	F_{S1A}	a
	Evaporator Friction Factor	F_{S2A}	a
Slip Ratio	Slip Ratio in Evaporator	SR	1.00

a) See Shinaishin (1976) for equation used.

The procedure employed was that outlined in Section 3.2.1 as applied to the steam generator section of the plant.

Results of the sensitivity runs can be found in Tables 3-8 and 3-9. Table 3-8 gives the magnitudes of the peak sensitivities while Table 3-9 gives the relative sensitivities. From Table 3-8 it can be seen that, in general, the most sensitive parameters by component model are C_{PWA} in the superheater, H_{WE} and C_{PWE} in the evaporator, and RD and F_{S2A} which appear in the evaporator-steam drum loop momentum equations. As stated earlier, special attention should be paid to those parameters which affect the initial conditions of certain state variables. By looking at the relative sensitivities in Table 3-8, one can determine which parameters are the most important in terms of their overall influence on the steam generator dynamics. It will be noticed that C_{PWA} affects the superheater state variables the most, while RD and F_{S2A} are the most important in their effects on the evaporator and steam drum loop state variables.

3.4 A Method for Putting First Order Bounds on Simulation Transients

The results of the previous three sections can be used to put approximate bounds on the transients studied in the primary loop and steam generator. This can be done in the following way.

The Taylor series expansion, equation (2-4), written for more than one parameter is

$$x(t) = x_o(t) + \sum_{i=1}^{n} \frac{\partial x}{\partial \lambda_i}(t)\, \Delta\lambda_i + \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\partial^2 x}{\partial \lambda_i \partial \lambda_j}(t)\, \Delta\lambda_i \Delta\lambda_j + \ldots \tag{3-1}$$

Table 3-8 Peak Sensitivity Results from the Open Loop Steam Generator.

(x 10 ^{2})

Parameter \ State Variable	T_{IC}	$\overline{T}_{WA}$	T_{SC}	T_{I8}	T_{I9}	$\overline{T}_{W1}$	$\overline{T}_{W2}$
H_{NS}	-0.78	10.5 Δ	1.2	-0.13	-0.052	-0.08	-0.20
K_{WA}	-1.16	15.6 Δ	1.8	-0.19	-0.078	-0.12	-0.30
C_{PWA}	-3.24	-3.4	-4.4	-1.83	-0.70	-1.1	-1.4
H_{WE}	0.055 *	0.043 *	-0.61 *	-0.53	-0.52	-2.5 Δ	4.25 Δ
H_{NE}	0.005	0.0039	-0.056	-0.26	-0.236	12.7 Δ	23.6 Δ
C_{PWE}	-0.06	-0.047	0.65	-1.4	-1.1	-1.2	-0.9
RD	-0.20 *	-0.16 *	-2.30 *	-2.6	-1.5	-1.75 *	-2.0 *
F_{S1A}	0.012 *	0.0091 *	-0.13 *	0.13	0.071	0.085 *	0.094 *
F_{S2A}	-0.20 *	-0.16 *	-2.30 *	-2.6	-1.5	-1.75 *	-2.0 *
SR	-0.021	-0.019	0.21	-0.48	-0.07	-0.24	-0.25
K_{WE}	0.005	0.004	-0.057	-0.26	-0.24	13.0 Δ	24.0 Δ

Table 3-8, Continued

Parameter \ State Variable	L_{S1}	$\overline{P}_{S2}$	M_{S4}	M_{S5}	$\overline{P}_{S4}$	H_{S6}
H_{NS}	-0.0144	-0.93	-2.1	3.5	-0.94	-0.0303
K_{WA}	-0.022	-1.4	-3.2	5.2	-1.4	-0.045
C_{PWA}	-0.20	-13.0	-30.0	48.0	-1.33	-0.52
H_{WE}	-2.0 Δ	11.0 *	31.0 *	-67.0 *	12.0 *	0.78 *
H_{NE}	0.028	1.1	2.5	-3.5	1.1	0.06 *
C_{PWE}	-0.134	-12.1	-28.0	44.0	-12.0	-0.57
RD	0.35	-47.0 *	-100.0 *	150.0 *	-43.0 *	3.5 *
F_{S1A}	-0.018	2.2 *	5.7 *	-8.0 *	2.5 *	-0.16 *
F_{S2A}	0.35	-47.0 *	-100.0 *	150.0 *	-43.0 *	3.5 *
SR	-0.097	-4.1	-9.0	-48.0 *	-4.2	-0.24
K_{WE}	0.029	1.05	2.5	-3.5	1.06	0.057 *

Table 3-9 The Absolute Value of the Peak Sensitivity Results Normalized to the Most Sensitive Parameters in the Steam Generator.

Parameter \ State Variable	T_{IC}	$\bar{T}_{WA}$	T_{SC}	T_{I8}	T_{I9}	$\bar{T}_{W1}$	$\bar{T}_{W2}$
H_{NS}	0.24	3.1	0.27	0.05	0.035	0.046	0.10
K_{WA}	0.36	4.6	0.41	0.073	0.052	0.069	0.15
C_{PWA}	1.0	1.0	1.0	0.70	0.47	0.63	0.70
H_{WE}	0.017	0.013	0.14	0.20	0.35	1.4	2.1
H_{NE}	0.0015	0.0012	0.013	0.010	0.16	7.3	11.8
C_{PWE}	0.019	0.014	0.15	0.54	0.73	0.69	0.45
RD	0.062	0.047	0.54	1.0	1.0	1.0	1.0
F_{S1A}	0.0037	0.0027	0.030	0.050	0.047	0.049	0.047
F_{S2A}	0.062	0.047	0.54	1.0	1.0	1.0	1.0
SR	0.0065	0.0056	0.048	0.19	0.047	0.14	0.13
K_{WE}	0.0015	0.0012	0.013	0.10	0.16	7.5	12.0

Table 3-9, Continued

State Variable / Parameter	$\bar{L}_{S1}$	$\bar{P}_{S2}$	M_{S4}	M_{S5}	$\bar{P}_{S4}$	H_{S6}
H_{NS}	0.041	0.020	0.021	0.023	0.022	0.0087
K_{WA}	0.063	0.030	0.032	0.035	0.033	0.013
C_{PWA}	0.57	0.28	0.30	0.32	0.031	0.15
H_{WE}	5.7	0.23	0.31	0.45	0.28	0.22
H_{NE}	0.08	0.024	0.025	0.024	0.026	0.017
C_{PWE}	0.38	0.26	0.28	0.29	0.28	0.16
RD	1.0	1.0	1.0	1.0	1.0	1.0
F_{S1A}	0.051	0.047	0.057	0.053	0.058	0.046
F_{S2A}	1.0	1.0	1.0	1.0	1.0	1.0
SR	0.28	0.087	0.090	0.32	0.098	0.069
K_{WE}	0.083	0.023	0.025	0.0233	0.025	0.016

If t is chosen at the time of the peak sensitivity, and assuming that all peaks occur at the same time τ, the first order terms can be rewritten

$$x(\tau) - x_o(\tau) \simeq \sum_{i=1}^{n} \frac{\partial x}{\partial \lambda_i}(\tau)\, \Delta\lambda_i$$

To put this equation in a form useful for bounding transients we write

$$\varepsilon_{sv} \simeq \sum_{i=1}^{n} \left| u^*_{\lambda_i} \right| \; T_{\lambda_i} \tag{3-2}$$

where

ε_{sv} ≡ approximate bounding tolerance on the response of a particular state variable

$|u^*_{\lambda_i}|$ ≡ absolute value of the peak sensitivity for the parameter λ_i

T_{λ_i} ≡ relative tolerance of parameter expressed in percent

As discussed earlier, the peak sensitivities do not generally occur at the same time; assuming they do is definitely on the conservative side. This conservatism is most acceptable when juding reactor safety.

An example of how equation (3-2) was applied can be found in Appendix E.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

In this thesis the use of peak sensitivity was found to be ideal in determining the most "safety sensitive" parameters in a system model. Through its use the most important parameters in the CRBRP dynamic simulator were identified for the type of step transients considered.

From the results obtained in the primary loop section of the plant, it was found for step reactivity transients that the parameters which directly affected the fuel temperature were the most sensitive. Of these the Doppler feedback coefficient and the fraction of power generated in the core were generally the most important parameters in the 40-100% power range. Other important parameters include the fuel thermal conductivity, axial expansion feedback coefficient, gap conductance, the fraction of flow in the core, clad thermal conductivity, fuel specific heat and the second through fifth delayed neutron fractions. Results obtained from the steam generator revealed which parameters should be given special attention and how they affect different components of the model. Important parameters here include the two phase flow friction multiplier, superheater and evaporator wall specific heats and several parameters which affected the initial condition of a safety related state variable.

Another advantage of using peak sensitivity is that approximate bounds can be put on a transient due to parameter estimate error. This is very useful from a reactor safety standpoint.

4.2 Recommendations

As stated in Chapter 2, the sensitivity function is dependent on on the type of transient initiator. The step in reactivity was chosen because it approximates a transient expected under normal power plant operation. (Sensitivity runs conduced on terminated ramp inputs spread over 10 seconds showed results very similar to those for the step.) A load perturbation transient would also be expected under normal operation. Once the problem in the turbine-feedwater model has been rectified, a sensitivity analysis for this type of perturbation should be conducted.

It has been discussed that in order to determine parameter sensitivity of the CRBRP simulator in a practical fashion the simulator was split into two sections. These sections were the primary loop and steam generation system respectively. Because of this split it was not possible to test how a parameter located in the primary loop affected the dynamics of the steam generator and vice versa. As soon as the computer costs associated with the testing the whole CRBRP simulator are reduced, this type of study should be conducted.

It has been shown that approximate bounds can be put on the transients studied. This was done without further use of the computer. If warranted, a more accurate determination of these bounds can be made by further computer simulations where only the more sensitive parameters need be considered (see Section A.5).

Future work to be conducted on the CRBRP dynamic simulator includes the analysis of the existing automatic controllers to insure adequate stability margins. The results of this study should be taken into consideration such that the stability of the controllers will not be affected appreciably due to parameter estimate error. Future work will undoubtedly include the upgrading and refinement of the existing plant models. When such changes are made sensitivity studies should be conducted and compared with the results of this thesis.

APPENDIX A

PROCEDURE FOR MEETING PSAR DESIGN CONDITIONS IN THE SUPERHEATER EXAMPLE

The following procedure is necessary to meet the design inlet and outlet superheater temperatures following a one percent change in a parameter from nominal.

From Figure 1-1 the design inlet and outlet temperatures are

	Sodium Side	Steam Side
Superheater Inlet	T_{IA} = 936 F°	T_{SA} = 615.2 °F
Superheater Outlet	T_{IC} = 855 F°	T_{SC} = 905 F°
Superheater Flow Rate	$W_I = 3.834 \times 10^7$ lbm/hr	$W_{SA} = 3.34 \times 10^6$ lbm/hr

The differential equations representing the energy balances in each of the three radial regions are:

I. Sodium Side

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

II. Tube Wall

$$\frac{dT_{WA}}{dt} = \frac{1}{C_{PWA}M_{WA}} [H_{WA}(\bar{T}_{IA} - \bar{T}_{WA}) - H_{SSA}(\bar{T}_{WA} - \bar{T}_{SA})] \quad \text{(A-2)}$$

III. Steam Side

$$\frac{dT_{SC}}{dt} = \left(\frac{1}{C_{PS}V_{SA}\bar{\rho}_{SA}}\right)[H_{SSA}(\bar{T}_{WA} - \bar{T}_{SA}) - W_{SA}(h_{SC} - h_{SA})] \qquad \text{(A-3)}$$

where

C_p ≡ specific heat of region

V ≡ volume of region

M ≡ mass of region

h_N ≡ enthalpy at node N

W_{IA} ≡ intermediate flow rate

W_{SA} ≡ superheated steam flow rate

T_N ≡ temperature at node N

H_{WA} ≡ sodium to tube mid wall heat transfer coefficient

H_{SSA} ≡ tube mid wall to superheated steam heat transfer coefficient

A.1 H_{WA} Sensitivity

The nominal value of H_{WA} at steady state and with a constant sodium flow rate is 40267846.8 Btu/hr/F°.[1] From this value one finds that $\bar{T}_{WA}$ = 872.253 F° and H_{SSA} = 8345829.46 Btu/hr/F°. Increasing H_{WA} by one percent yields 40670525.2 Btu/hr/F°. At steady state set

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1. Nine significant figures were carried through most calculations to reduce the noise in the sensitivity function.

$$\frac{dT_{IC}}{dt} = \frac{d\overline{T}_{WA}}{dt} = \frac{dT_{SC}}{dt} = 0 \ .$$

Solving for the new tube wall temperature initial condition gives

$$\overline{T}_{IA} = \frac{T_{IA} + T_{IC}}{2} = 895.5 \text{ F°}$$

therefore

$$\overline{T}_{WA} = \overline{T}_{IA} - \frac{W_I C_{PIA}(T_{IA} - T_{IC})}{H_{WA}} = 872.4885 \text{ F°}$$

but

$$\overline{T}_{SA} = \frac{T_{SA} + T_{SC}}{2} = 760.1 \text{ F°}$$

and

$$H_{SSA} = \frac{W_{SA}(h_{SC} - h_{SA})}{(\overline{T}_{WA} - \overline{T}_{SA})} = 8328507.3 \text{ Btu/hr/F°}$$

$$= \frac{328189.6}{(0.02518 + \frac{29.484029}{h_{FS}})}$$

so that

$$h_{FS} = 2072.6077 \text{ Btu/hr/F°/ft}^2.$$

Therefore, to test for the sensitivity of H_{WA}, two simulation runs are made. One run should use the nominal value of H_{WA} and the other the + 1% value. Equation (2-5) is applied to yield the plots in Figure 2-2.

A.2 C_{PWA} Sensitivity

The nominal value of C_{PWA} is 0.12 Btu/lbm/F°. Increasing this value by 1% yields 0.1212 Btu/lbm/F°. From equation (A-2) at steady state it can be seen that C_{PWA} does not affect the initial conditions of any of the state variables and parameters. Therefore the design conditions are already met and rebalancing is not necessary.

APPENDIX B

SENSITIVITY OF DOPPLER FEEDBACK COEFFICIENT

The procedure outlined in Section 3.2.1 will now be applied to determine the sensitivity of the Doppler coefficient.

1. Increasing the DC by 1%, we get $DC_{+1\%} = .005858$.

2. The DC is used in the following reactivity feedback equation

$$\rho_{FB} = (100 \times DC/\beta)\ln\left(\frac{460 + \bar{T}_F}{460 + T_I}\right) + AXECC\ (\bar{T}_F - T_I)$$

$$+ SODDCC(\bar{T}_{P1} - T_I) + RECC\ (T_{P1} - T_I)\ . \qquad \text{(B-1)}$$

   Increasing DC by 1% will cause a greater initial reactivity feedback. To compensate for this the steady state control rod position was adjusted.

3. The sensitivity function was applied and the primary loop model was simulated at steady state. Ideally the sensitivity function should be zero at steady state. However, because of a balancing error in Step 2 and computer round off error, there will be some noise in the sensitivity function.

4. The simulator was then run for 120 sec following a 10¢ step in reactivity. Figure B-1 is a sample sensitivity function plot for the fuel temperature. The noise found in Step 3 is also plotted.

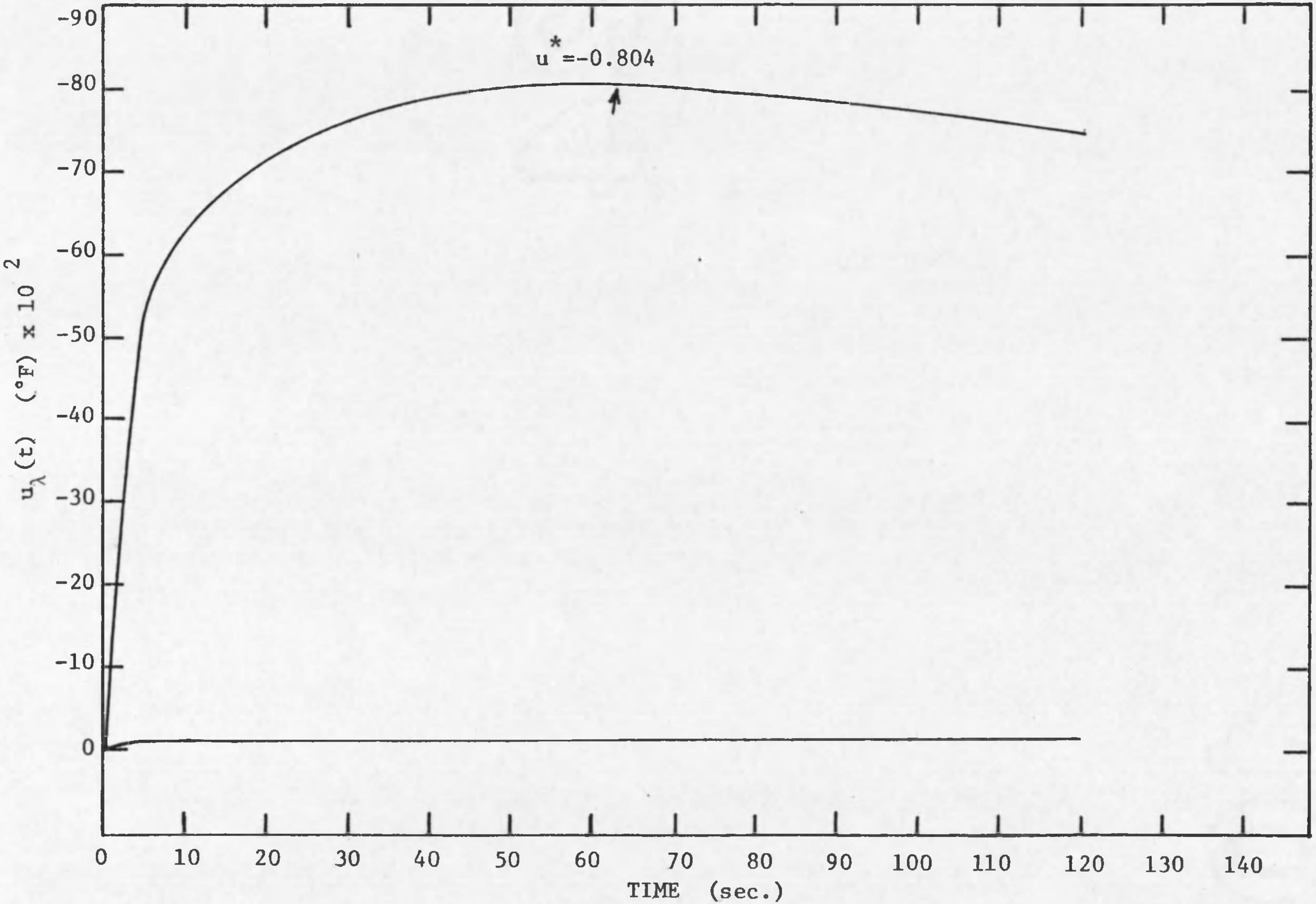

Figure B-1 -- Doppler Feedback Coefficient Sensitivity of the Fuel Temperature Following a 10¢ Step in Reactivity.

5. From Figure B-1 it can be seen that the noise is neglible.

6. A good sensitivity measure has been determined.

7. From Figure B-1, the peak sensitivity has been found to be - 0.80.

Figure B-2 shows the sensitivity function applied to the state variable T_{P7} both with and without feedback from the steam generator. It can be noted that both runs are essentially the same up to the 120 second cutoff time.

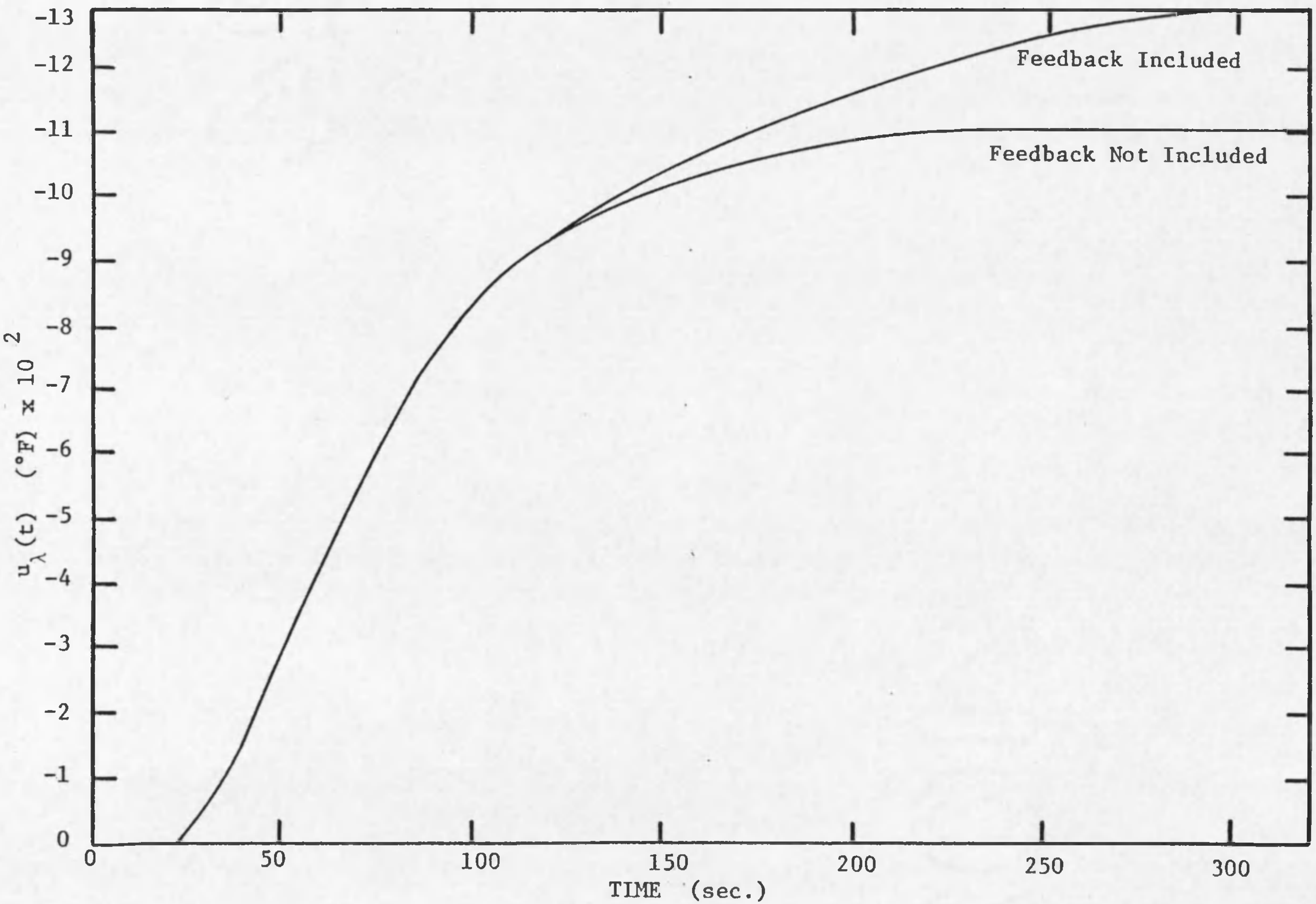

Figure B-2 -- Effects of Steam Generator Feedback on the Sensitivity of the IHX Intermediate Sodium Outlet Temperature.

APPENDIX C

AN EXAMPLE OF INSENSITIVITY OF CERTAIN PARAMETERS

The momentum equation for the primary loop is of the form

$$\frac{dW_{PS}}{dt} = \frac{1}{A} \{\text{sum of elevation head terms + pump head}$$

$$- W_{PS}^{2} \text{ [sum of constant friction factors]}\} \qquad \text{(C-1)}$$

where

$A \equiv$ constant

$W_{PS} \equiv$ primary flow rate

If one of the friction factors is varied by 1%, the momentum equation is unbalanced at steady state (set $\frac{dW_{PS}}{dt} = 0$). Therefore to rebalance the loop, either the elevation head term, the pump head, or another friction factor must be adjusted. Since the first two terms are fixed due to design conditions, another friction factor must be readjusted. From the above equation it can be seen that the identity of a particular friction factor is lost because all of them are multiplied by the same W_{PS}^{2} term. Therefore the dynamics of the momentum equation will not be affected.

APPENDIX D

ESTIMATION OF CUT-OFF TIME AT 40% AND 70% POWER LEVEL

Since the steam generator was not simulated at 40% and 70% power levels, it was not possible to observe the cut-off time needed to avoid significant feedback effects on the primary loop sensitivity runs. To estimate these times the following procedure was employed.

By direct observation of the simulation runs at the different power levels, it was noted that the following times were needed for the reactivity transient initiated in the reactor to reach the IHX.

Power Level	Time to IHX
100%	28 sec
70%	40 sec
40%	70 sec

At 100% power, it will be remembered that 120 seconds was chosen as the cut-off time. This implies that approximately 94 seconds was the time required for the feedback effects to travel the intermediate loop (i.e., 120 - 28 = 94).

The mass in the intermediate loop is the same at all power levels and the following equation may be written

$$\text{Mass in Loop} = W_{100}t_{100} = W_{70}t_{20} = W_{40}t_{40} \qquad \text{(D-1)}$$

where

$W_N \equiv$ flow rate at power level N

$t_N \equiv$ time required for flow to travel the loop at power level N.

Assuming that the time constants for heat transfer in the different components in the steam generator are the same at all power levels, a rough estimate can be made of the cut-off time by adding the observed time to reach the IHX with the time calculated from equation (D-1). Therefore:

<u>at 70% power</u> $$40 \text{ sec} + \frac{W_{100} t_{100}}{W_{70}} = 180 \text{ sec} ,$$

and

<u>at 40% power</u> $$70 \text{ sec} + \frac{W_{100} t_{100}}{W_{40}} = 330 \text{ sec} .$$

APPENDIX E

AN EXAMPLE OF PUTTING FIRST ORDER BOUNDS ON A STEP REACTIVITY TRANSIENT

For this example, assume that the uncertainties in DC and AXECC are $\pm$ 20% and $\pm$ 10% respectively. From the magnitudes of their peak sensitivities found in Table 3-2 and with use of equation (3-2), the bounds on the fuel temperature following a 10¢ step in reactivity can be estimated as

$$\varepsilon_{\bar{T}_F} \simeq |-0.80| * 20 + |-0.32| * 10 = \pm 19.2 \text{ F}° .$$

In a similar manner, approximate bounds can be put on the other safety related state variables located throughout the primary loop.

As a check, a computer run was made which showed the actual bounding tolerance. Results comparing the estimate with the actual bounding tolerances are listed below.

State Variable	Estimate	Actual
$\bar{T}_F$	$\pm$ 19.2 F°	$\pm$ 16.6 F°
T_{P3}	$\pm$ 3.59 F°	$\pm$ 3.13 F°
T_{P4}	$\pm$ 2.88 F°	$\pm$ 2.5 F°
T_{P7}	$\pm$ 0.60 F°	$\pm$ 0.51 F°
T_{I3}	$\pm$ 2.23 F°	$\pm$ 1.92 F°
T_{P1}	$\pm$ 0.50 F°	$\pm$ 0.43 F°

It can be noted that in this case the estimate is conservative with regard to reactor safety.

Bounding estimates can also be made on other magnitudes of step reactivity transients by applying the superposition property of linear differential equations. To include this feature, equation (3-2) can be written as

$$\varepsilon_{SV} \simeq \frac{X}{10} \sum_{i=1}^{n} |u^*_{\lambda_i}| \, T_{\lambda_i} \tag{E-1}$$

where X is the magnitude of the step in reactivity expressed in cents.

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