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Title : Dynamic Simulation of a Westinghouse PWR Four-Loop Plant During Steam Generator Tube Rupture Event

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This study addresses the application of a full reactor system computer code to simulate the reactor primary and secondary loop thermal hydraulics, plant control and protection systems during the steam generator tube rupture (SGTR) events. The Trojan nuclear plant which is owned and operated by the Portland General Electric (PGE) served as the basis for this computer simulation.

The primary objective was to investigate the response a four-loop PWR to a steam generator tube rupture and the effect of various operator actions. To achieve this objective, several models were developed to simulate the behaviour of automatic control systems and the plant's operator actions. A lumped two-loop RETRAN model, which

represents the actual four-loop PWR plant, had been developed previously and was used as a starting point. The involved control systems and control actions which play important roles in SGTR transient conditions are incorporated into the two-loop model by using the control system option of RETRAN.

The predicted results show the rapid depressurization and level deviation, which characterize the SGTR event, in the pressurizer. The depressurization rate can be affected by operator actions such as increasing the charging flow rate or reducing the reactor power. The feedwater controller on the intact lumped triple-loop side functions normally and maintains the same water level, while on the ruptured one-loop side the water level significantly deviates from the normal level and causes a steam-flow/feed-flow mismatch alarm.

Dynamic Simulation of a Westinghouse PWR Four-Loop Plant During Steam Generator Tube Rupture Event

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I dedicate this thesis to my wife, Pi Chun Huang, for her unfailing encouragement, sacrifice, and understanding throughout the period of my graduate study.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

SUM :	summer or comparator
INT :	integrator
MUL :	multiplier
FNG :	function generator
LAG :	lag network and compensation
MAX :	the maximum value of input
MIN :	the minimum value of input
RCS :	reactor coolant syatem
SIS :	safety injection system
TRIP :	trip activation status
CONS :	a constant assigned by user
MSIV :	main steam isolation valve
PORV :	power operated relief valve
SGTR :	steam generator tube rupture
ECCS :	emergency core cooling system

DYNAMIC SIMULATION OF A WESTINGHOUSE PWR FOUR-LOOP PLANT DURING STEAM GENERATOR TUBE RUPTURE EVENT

1. INTRODUCTION

The steam generator tube rupture (SGTR) event in a PWR system is primarily characterized by the depressurization of the primary system. This event is usually identified by the receiving of a steam and feedwater flow mismatch signal and the steam generator water level deviation alarm in the control room. During the rapid depressurization process in the Reactor Coolant System (RCS), some of the plant control systems will play important roles. Mitigation of consequences of a steam generator tube rupture event is through a series of actions taken by the plant automatic control systems and the reactor operators in order to bring the plant to cool shut-down conditions. This study addresses the application of a full reactor system code to simulate the reactor primary and secondary loop thermal hydraulics, plant control and safety systems during the SGTR event.

Under plant normal operational conditions, the RCS pressure and the mass inventory of the primary system are automatically controlled by the charging flow, letdown flow, makeup flow, and pressurizer heater control system. On the secondary side, the steam flow, feedwater flow and water level are controlled either automatically or manually by a three-element controller with proportional plus integral (PI) characteristics. During a steam generator tube rupture event the control system performance, in general, and the feedwater controller behavior, in particular, are greatly influenced by the rapid changes in the RCS thermal hydraulic conditions as well as by the operator actions. Therefore, a full scale analysis of the plant behavior under such transient conditions requires a comprehensive modeling of the plant system thermal hydraulics and control systems along with the operator actions.

In this study a Westinghouse four-loop plant experiencing a hypothetical steam generator tube rupture event is modeled by using the RETRAN computer code. RETRAN, which is primarily designed to provide a best-estimate of the system's thermal hydraulic conditions, is capable of modeling the feedwater controller and the other control systems involved in the transient. Using the control elements which are available in RETRAN, the response of various plant control systems and the operator actions can be simulated on a digital computer. The control elements include integrators, multipliers, dividers, delays and function generators. Simulation of these control elements is common to both digital and analog computers; however, there are a few that can be modeled by an analog computer only with significant difficulty.

The SGTR event simulation of this study primarily emphasizes on the initial period (0 - 420 seconds) which contains most of the important control system behaviors and the operator actions. This period ends after the reactor trip and the initialization of safety injection.

2. BACKGROUND INFORMATION

2.1 SURVEY OF PAST SGTR ANALYSES

Two SGTR events have previously been analyzed and modeled for the Ginna and the Prairie Island-1 two-loop PWRs. The post-accident analysis demonstrated that the use of thermal hydraulic codes such as RETRAN could provide consistent predictions with actual plant behavior as described in Reference 1, 2 and 3. Most of the work was devoted to establishing the timing of events and to evaluating the operator actions for the SGTR transients. Such information was useful in evaluating the plant Emergency Response Guidelines.

Compared to Ginna and Prairie Island-1 systems, the major difference is that the Trojan plant is a four-loop PWR with more advanced safety and control systems. Based on this fact, simulation of a hypothetical SGTR event for a four-loop PWR plant is of primary interest and can provide useful information by predicting the system response to such an event. Futhermore, previous work on SGTR event modeling and analysis have not mentioned the feedwater controller behavior and the steam generator level variations during the beginning of the SGTR event.

In fact, such information is important when the simulation emphasizes on the initial period during which the operator actions are crucial and are based upon the plant response.

Therefore, a detailed steam generator model was used as the basis for tube rupture modeling. This model can provide a realistic steam generator level indication corresponding to that of the in-plant level gauge by using the collapsed liquid level calculation option of RETRAN. An elaborate feedwater controller model was developed to simulate the steam generator water level control. This feedwater controller had the features of three-element control: lag compensation, flow controller, and valve dynamics.

For the SGTR event modeling, other improvements include a step letdown function and a charging flow controller with manual control ability. A detailed description of these models can be found in section 3.

2.2 STEAM GENERATOR DESCRIPTION

The Trojan PWR has four Westinghouse Model 51 steam generators, one in each primary coolant loop (see Figures 1 and 2). Each steam generator consists of an evaporator section in the lower half and a moisture separator section in the upper half.

The evaporator section contains 3388 nested Inconel U-tubes between inlet and outlet plenums of the primary coolant. Heat generated in the reactor core is absorbed by the primary coolant and transferred to the secondary coolant via the walls of steam generator U-tubes. The walls of U-tubes provide approximately 51,400 sq. ft. of heat transfer area. During normal operation, the primary coolant is maintained subcooled at a pressure 2235 psia, and the secondary coolant is pressurized to 1105 psia. A mixture of saturated steam and water is formed in this section when the secondary feedwater flows past and contacts the U-tubes. Afterwards, the mixture flows upward into the moisture separator section.

In the moisture separator section, swirl vanes (see Figure 3) are used to remove most of the entrained water from the steam. A set of peerless steam dryers (see Figure 4) located on the top section of each steam generator then increases the steam quality to a minimum of 99.75 percent before the steam flows out of the steam generator to the turbines. The saturated liquid and a small amount of moisture removed in this section return to the top of the annular downcomer area and combine with the secondary feedwater. This then flows through the downcomer and reenters the bottom of the evaporator section. The annular downcomer area is between the U-tubes bundle wrapper sheet and the steam generator outer shell.

More detailed information about the steam generator can be found in Reference 4.

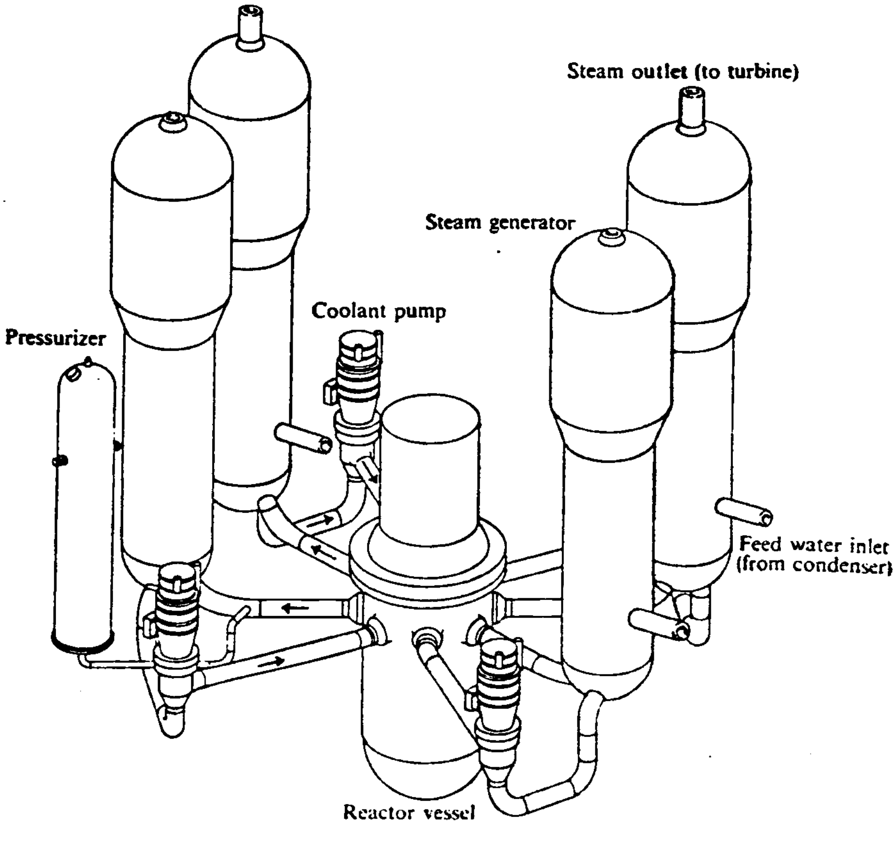


FIGURE 1. PRIMARY SYSTEM OF A PWR

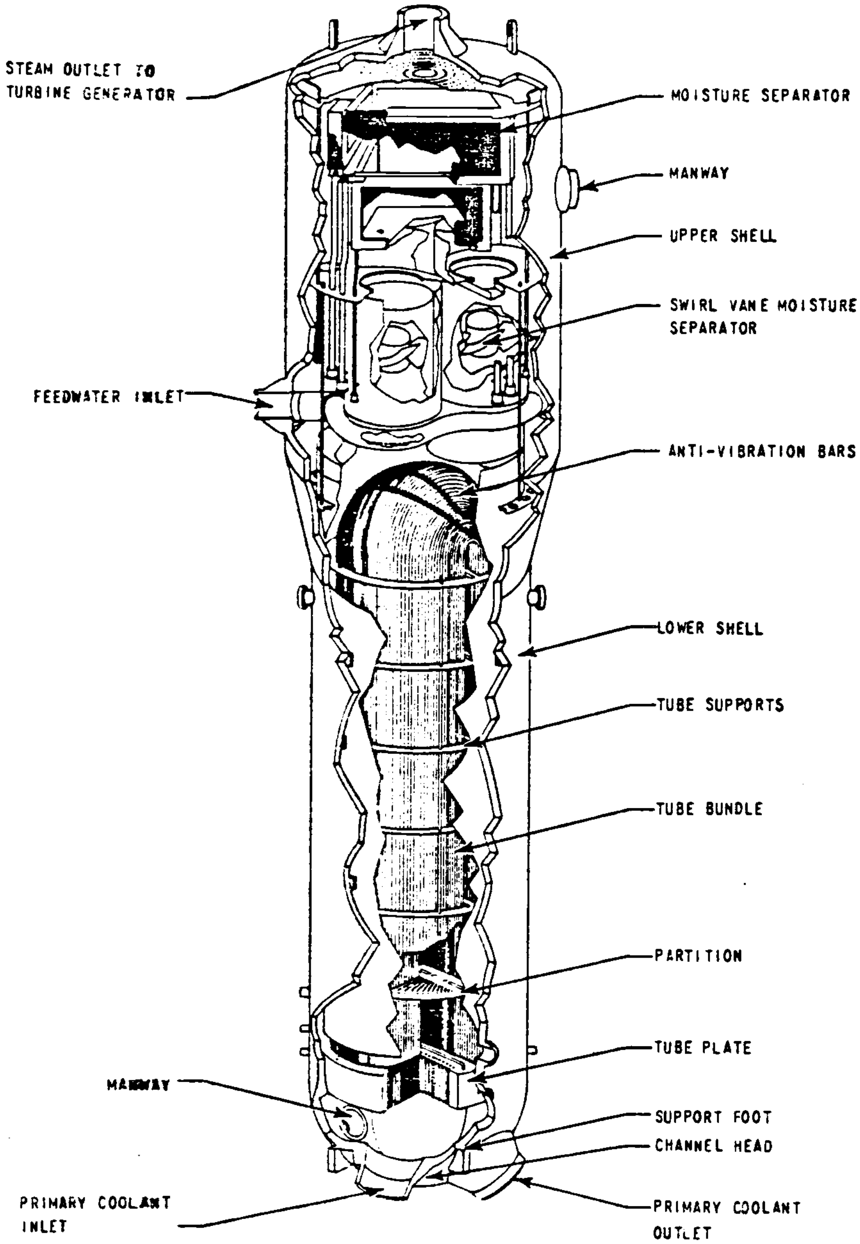


FIGURE 2. STEAM GENERATOR

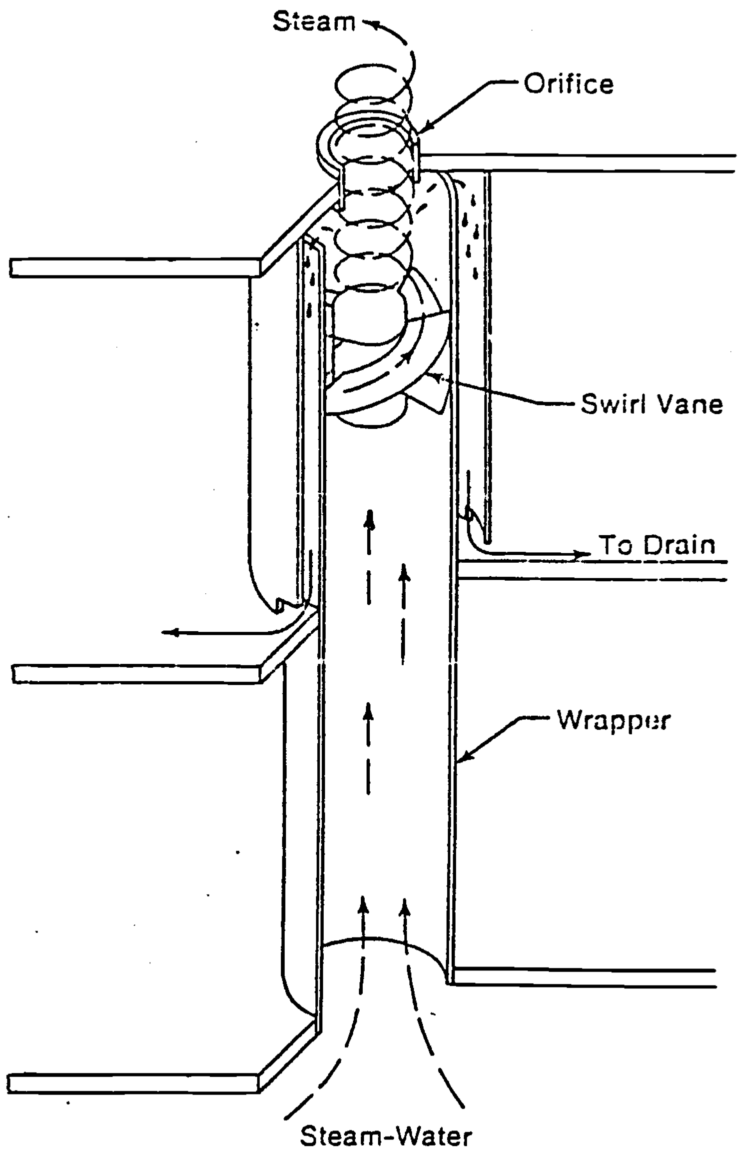


FIGURE 3. STEAM GENERATOR SWIRL VANE

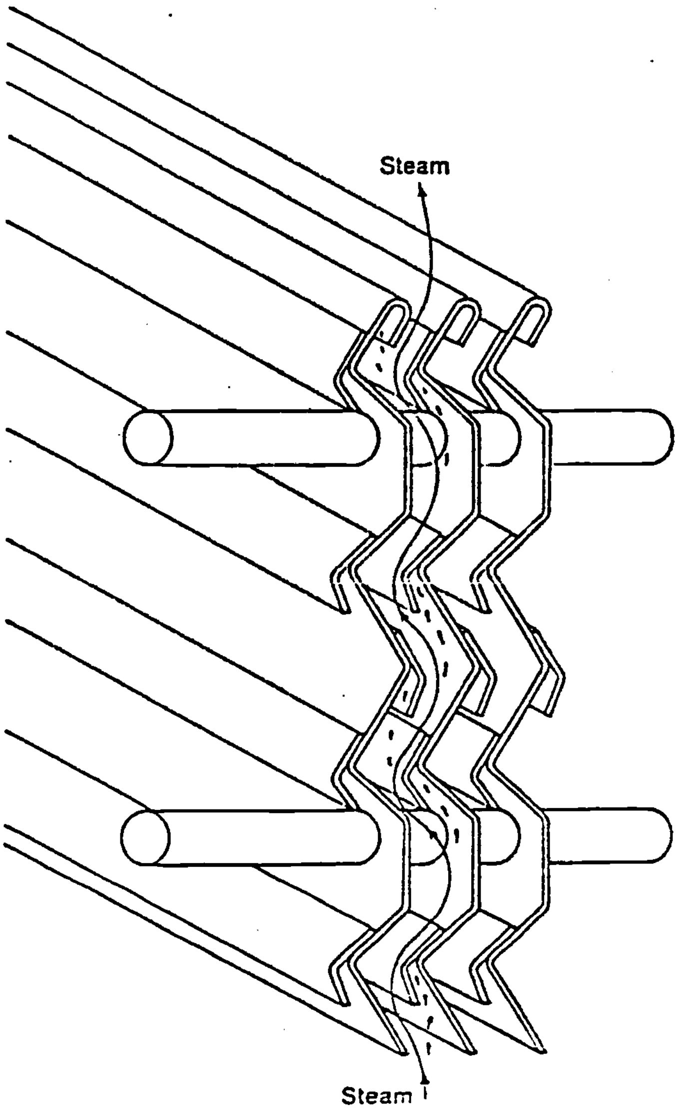


FIGURE 4. STEAM GENERATOR DRYER

2.3 RETRAN DESCRIPTION

RETRAN (RELAP4 TRANSIENT) is a computer code developed from the RELAP series of computer codes to describe the transient thermal-hydraulic behavior of a light-water reactor. It is designed to provide best the estimate solution to accident and operational transient problems of complex fluid systems.

The fluid system is nodalized and represented by volumes and connecting junctions. The user only has to provide numerical input data which completely define the components of the system. These data include geometric specifications for all the volumes and junctions as well as initial temperature-pressure distributions and fluid boundary conditions. The boundary conditions can be modeled by using fill junctions to specify either inlet or outlet fluid flow conditions. The crictical flow models provided by RETRAN are Extended Henry-Fauske, Moody, and Isoenthalpic Expansion.

The reactor power generation can be modeled using either point reactor kinetics or as an explicit function of a power data table.

Other features included are the specifications for heat sources, material properties for heat conductors, control system parameters, and descriptions of components such as pumps, valves, turbines, heat exchangers, etc.

Basically, RETRAN is a sophisticated application of advanced numerical methods based on the conservation equations for mass, momentum and energy coupled with the fluid state equations of each volume. If the system is properly specified, RETRAN can generate desired numerical solutions through iterative computations. Detailed descriptions and other features of RETRAN such as the steady state self-initialization option, automatic step-size control, etc., are described in Reference 5. The derivations of the governing equations, the empirical correlations and the numerical solution techniques can be found in Reference 6.

2.4 CONTROL SYSTEMS DESCRIPTION

2.4.1 Reactor Control System

The block diagram for the plant kinetics model is shown in Figure 5. The total system reactivity is normally the linear combination of the various contributing reactivities, namely:

$$\delta k = \delta k_f + \delta k_p + \delta k_T + \delta k_c$$

where δk_f = reactivity determined by fuel depletion

δk_p = reactivity determined by poisons

δk_T = reactivity determined by temperature effect

δk_c = reactivity determined by control rod position

At steady state, δk_f and δk_p can be considered as constants. Thus, their concentration changes have a negligible effect on over-all reactivity compared to the effects of fuel temperature and control rod position. However, the effect of poisons is quite important during start-up and shut-down procedures.

In addition, the practical operation of a reactor requires the temperature coefficient of the reactivity to

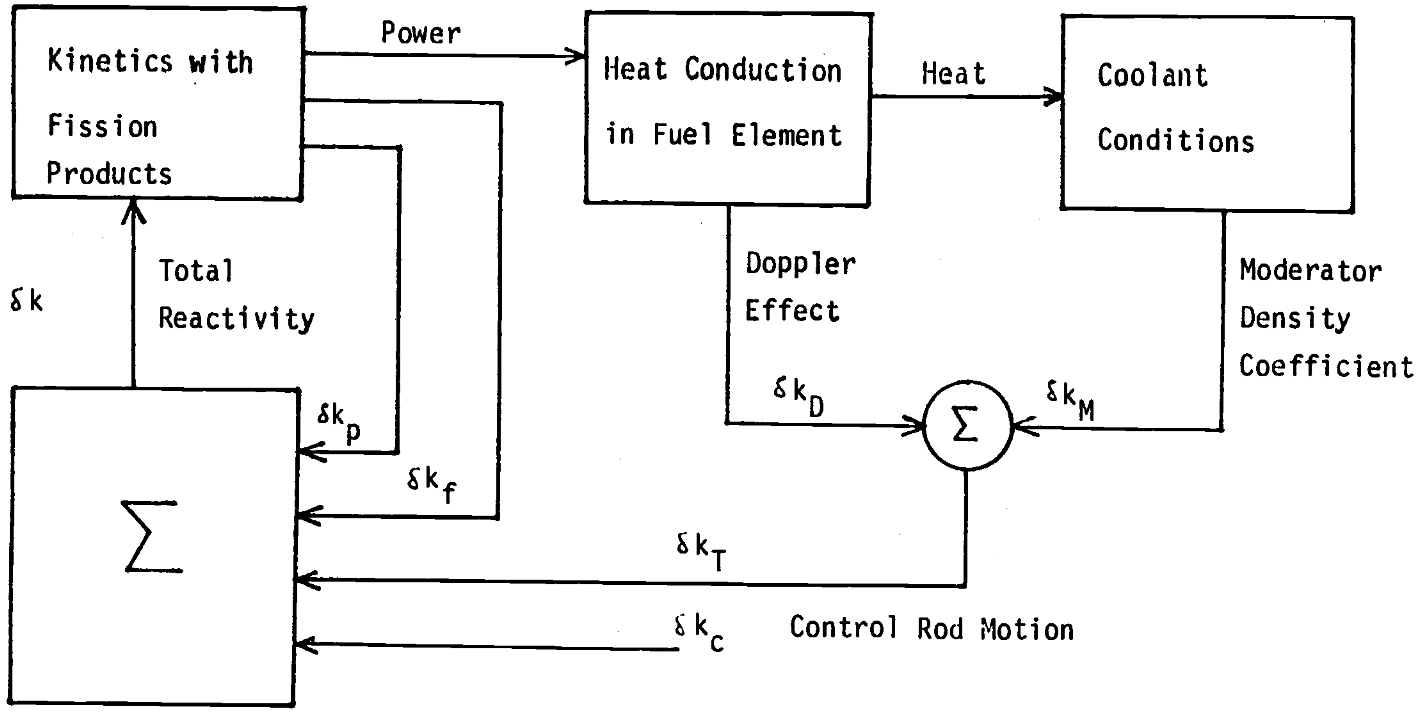


FIGURE 5. KINETICS MODEL OF REACTIVITY FEEDBACK

be small so that a steady state can be maintained by means of the control rods in spite of moderate fluctuations in temperature.

2.4.2 Charging, Letdown and Makeup Water Control System

The charging and letdown functions are used to maintain a programmed water level in the Reactor Coolant System (RCS) pressurizer such that a proper coolant inventory in the primary loop can be maintained during all phases of plant operation. This control function is achieved by means of a continuous charge and discharge procedure during which the charge rate is automatically controlled by a proportional plus integral (PI) controller based on pressurizer water level. The discharge rate or letdown rate can be chosen to suit various plant operational requirements by selecting the proper combination of letdown orifices in the letdown flow path. There are three letdown orifices in Trojan, one at a discharge rate of 75 gallon per minute (gpm) and two others at 25 gpm each. Figure 6 shows the block diagram of the charging and letdown flow rate control based on pressurizer water level. The plant operation data for charging and letdown flow rate control are shown in Table 1.

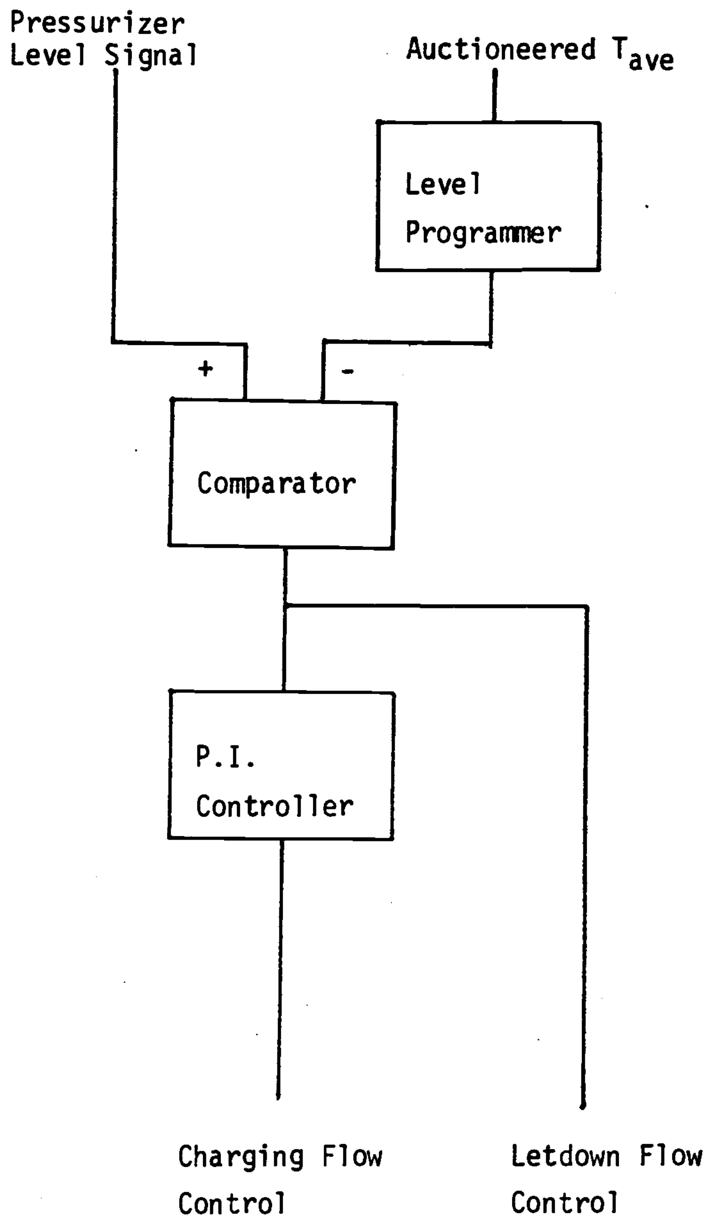


FIGURE 6. BLOCK DIAGRAM OF PRESSURIZER LEVEL CONTROL SYSTEM

TABLE 1

PLANT DATA FOR CHARGING AND LETDOWN FLOW SYSTEM

CHARGING FLOW :	
NORMAL, gpm	55.0
MAXIMUM, gpm	100.0
LETDOWN FLOW :	
NORMAL, gpm	75.0
MINIMUM, gpm	45.0
MAXIMUM, gpm	120.0
TEMPERATURE OF LETDOWN REACTOR COOLANT ENTERING SYSTEM, °F	552.5
TEMPERATURE OF CHARGING FLOW DIRECTED TO RCS, °F	503.5

The makeup control functions maintain the desired operating fluid inventory in the primary system and to adjust the reactor coolant boron concentration for reactivity control. Both the letdown flow and makeup flow control functions are determined by the operator during plant operation.

2.4.3 Pressurizer Pressure Control System

The pressurizer pressure (or RCS pressure) is controlled by using either the heaters (in the water region) or the spray (in the steam region) of the pressurizer. A portion of the heaters serves as a proportional heater to control pressure variations within a small range. The other heaters are turned on when the pressurizer pressure drops below a certain set point.

The spray causes steam condensation in the steam region and reduces the pressurizer pressure. At normal operation, a small continuous spray is usually maintained in order to maintain the correct temperature in the pressurizer. Figure 7 shows the simplified block diagram of the pressurizer pressure control system.

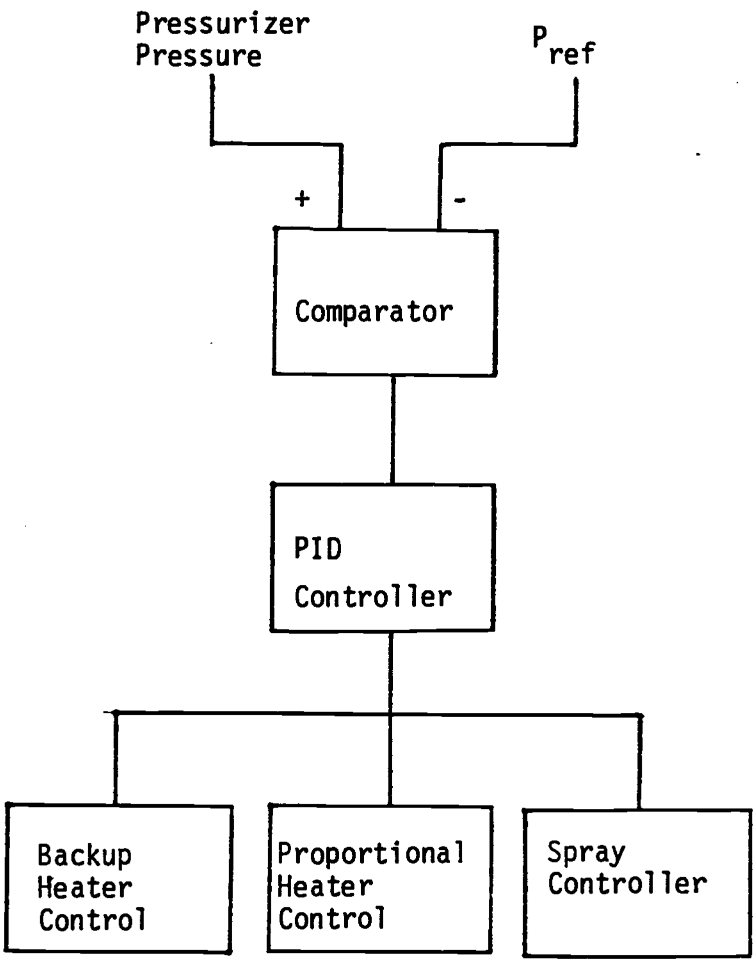


FIGURE 7. BLOCK DIAGRAM OF PRESSURIZER PRESSURE CONTROL SYSTEM

2.4.4 Feedwater Control System

The feedwater flow control system is used to automatically or manually control the feedwater flow rate to the steam generator. The entire system is composed of two individual but interdependent subsystems. These subsystems are :

1. the feedwater pump speed control system
2. the steam generator water level control system

The function of the feedwater pump is to increase the pressure of the inlet feedwater to ensure the required amount of flow to the steam generators. The pressure difference between the feedwater system and the steam system is maintained by the feedwater pump speed control system according to a programmed pressure difference signal which is a linear function of power level.

The water level in a steam generator is automatically maintained at a programmed level by the steam generator water level control system. The control system is a three-element controller based on feedwater flow rate, steam flow rate and water level signals. The programmed water level is maintained at 44 percent within the turbine load range of 20 percent to 100 percent (see Figure 8). The output signal of this level control

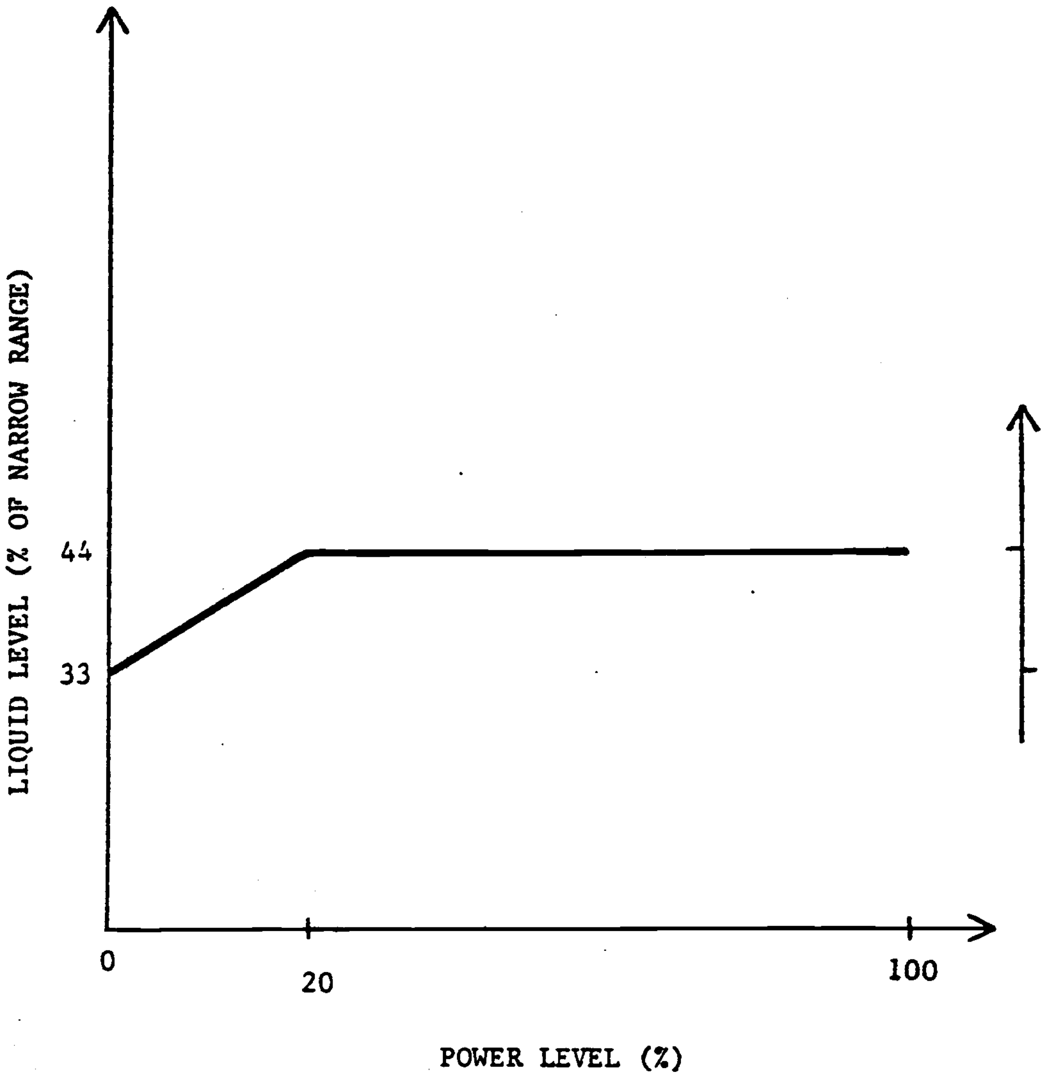


FIGURE 8. STEAM GENERATOR LEVEL vs. POWER LEVEL

system is used to position the feedwater regulation valve and thus control the feedwater flow rate for each of the steam generators. The feedwater flow rate versus power level is also shown in Figure 9.

In general, the steam generator water level control system controls the desired water level, which is based on turbine load. The feedwater pump speed control system is designed to compliment the operation of the water level control system.

The water level control system of the steam generator is composed of two comparators and two proportional plus integral (PI) controllers. One comparator is used to generate an error signal which is proportional to the difference between the actual and the programmed water level. The other comparator is used to generate an error signal which is proportional to the difference between the steam flow and the feedwater flow. The two PI controllers are used to achieve the desired characteristics of the control function. The functional block diagram of the steam generator water level control system is shown in Figure 10.

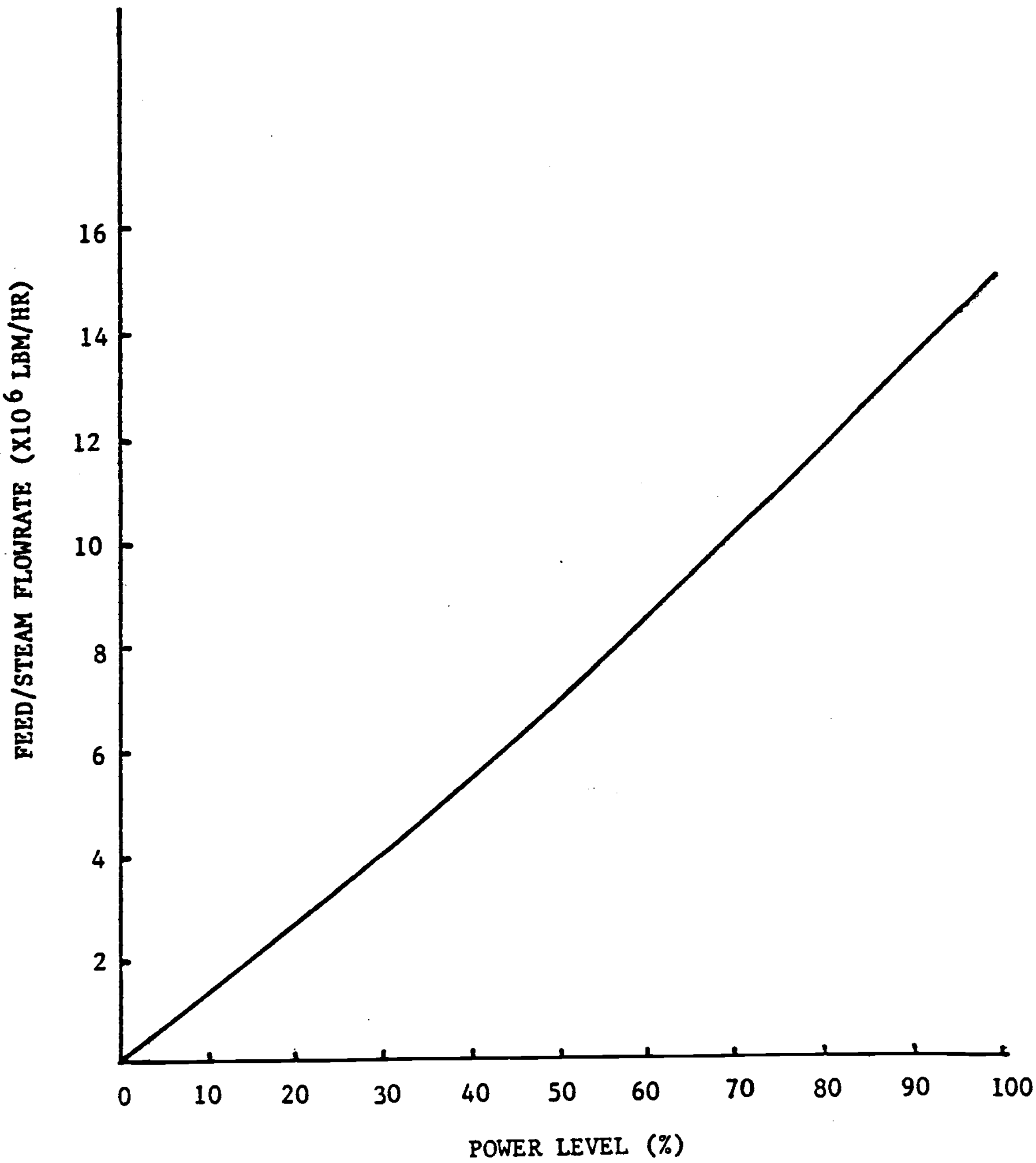


FIGURE 9. FEEDWATER FLOW RATE vs. POWER LEVEL

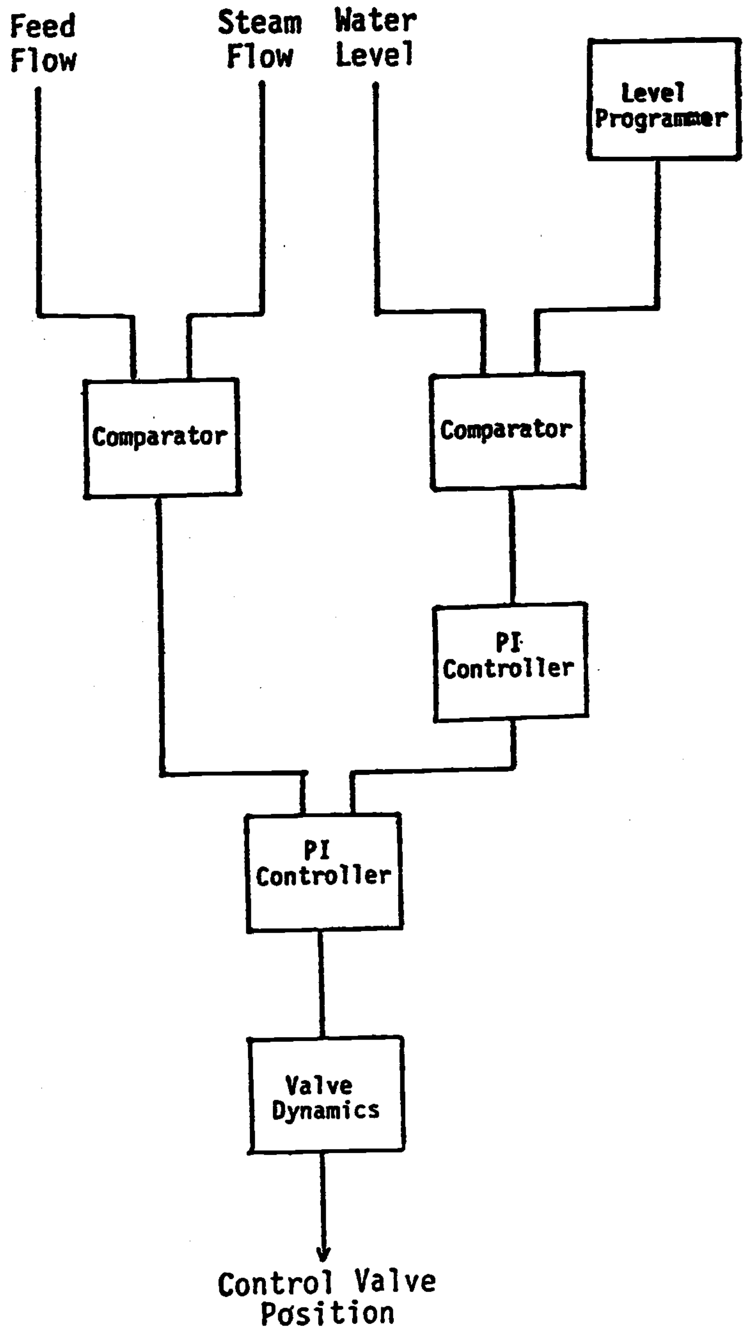


FIGURE 10. BLOCK DIAGRAM OF STEAM GENERATOR WATER LEVEL CONTROL SYSTEM

2.4.5 Auxiliary Feedwater Control System

The auxiliary feedwater system is a redundant system which can supply feedwater for removing heat from the reactor coolant during emergency conditions. There are two pumps in the auxiliary feedwater system. Each pump can provide 960 gpm to all four steam generators to cool the RCS in order to prevent release of reactor coolant through the pressurizer safety valve. During the SGTR event, the auxiliary feedwater system is activated after the main feedwater system is isolated by the safety injection signal.

2.4.6 Safety Injection Control System

The safety injection system is part of the Emergency Core Cooling System (ECCS). The emergency core cooling system is initiated by the safety injection signal. This signal is actuated by low pressurizer pressure in conjunction with low pressurizer water level during a steam generator tube rupture (SGTR) event.

During the injection mode of ECCS, the safety injection pumps deliver borated water into the RCS. The safety injection pumps begin to deliver water to the RCS after the pressure has fallen below the pressure set point, and the injection rate is determined by the RCS pressure.

3. RETRAN MODEL OF A PWR

3.1 THE LUMPED TWO-LOOP PWR MODEL

The two-loop RETRAN model of the Trojan PWR plant is shown in Figure 11. The primary system and steam generators are lumped into two modeling loops. One modeling loop (triple loop) represents the actual three loops, and the other modeling loop (single loop) represents the actual one loop. This feature allows the simulation of a transient introduced in a single loop in contrast to the original one-loop model which requires introduction of the transient in all four loops simultaneously. A complete description of this model can be found in Reference 7.

For the purpose of a steam generator tube rupture simulation, some modifications have been made to this model. The reactor core is divided into three volumes (excluding the bypass volume), since the consideration of long transient time of the event requires a more detailed representation of the reactor core is necessary. An infinite volume (volume 800) is added to the pressurizer to represent the entire piping system downstream of the

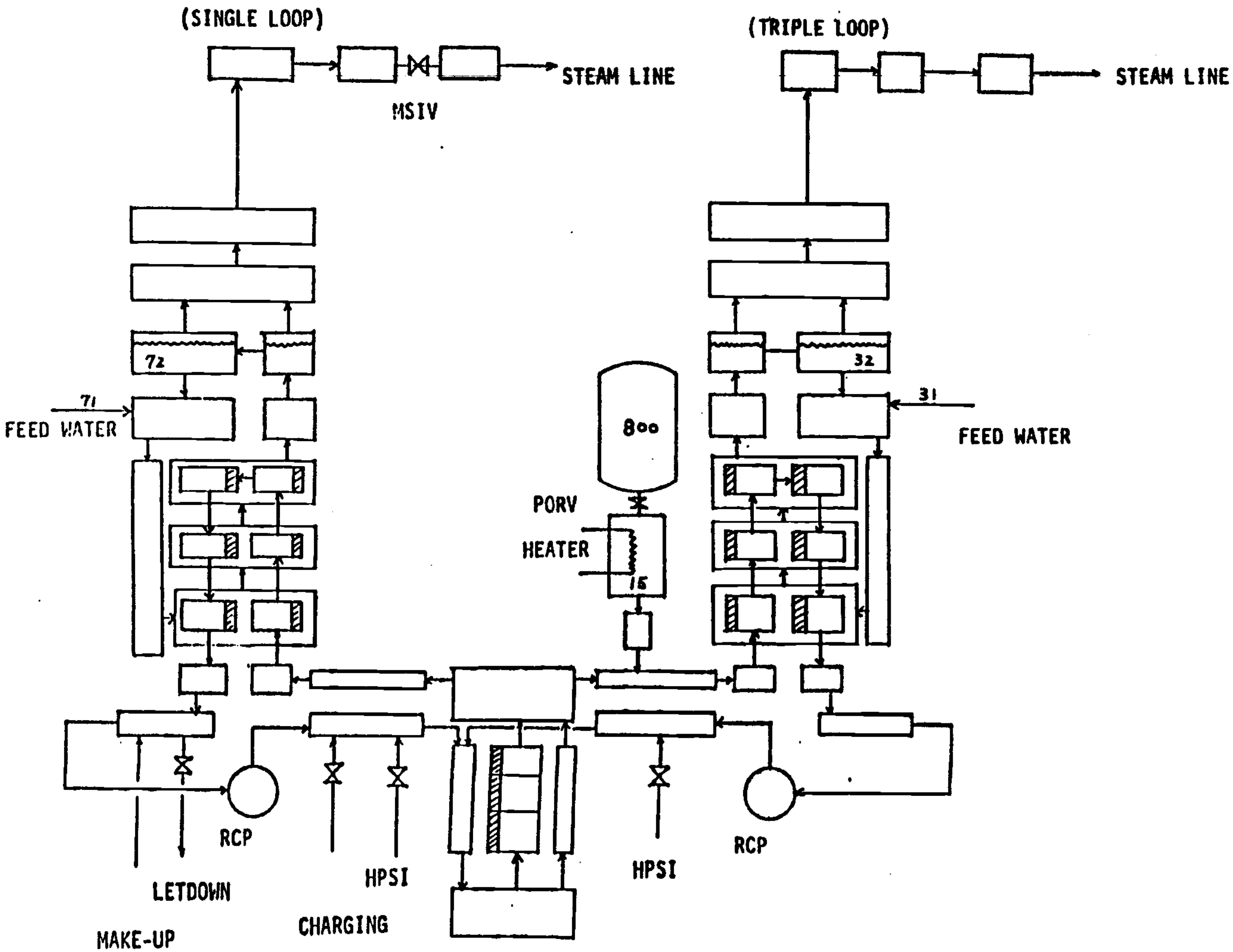


FIGURE 11. THE LUMPED TWO-LOOP PWR RETRAN MODEL

power operated relief valve (PORV), whose operation is controlled either automatically or manually by the operator. A main steam isolation valve (MSIV) is added to the single loop and can be used to isolate the ruptured steam generators if necessary during the event. More detailed information about the functions of the PORV and the MSIV can be found in Reference 8. Other changes associated with the application of the control systems will be described later.

3.2 AUTOMATIC CONTROLLERS AND COMPONENTS

3.2.1 Control Rod Controller

During the SGTR event simulation, the load reductions are modeled by using a simplified control rod controller with PI characteristics to add negative reactivity to match the load demand which is an input as a function of time. The principal parameters of this PI controller are listed in Table 2. Reactor trip is initialized at low pressurizer pressure (1900 psia), and the scram reactivity is supplied as a function of time starting from the time the scram signal is received. A block diagram of the control rod controller is shown in Figure 12.

3.2.2 Charging Flow Controller

The charging flow is modeled with a fill junction (junction 946). The normal charging flow rate is maintained at 55 gpm by an automatic controller with PI characteristics. A comparator is used to generate an error signal proportional to the difference between the actual and the programmed level of the pressurizer. The

TABLE 2

PRINCIPAL PARAMETERS OF CONTROL ROD CONTROLLER

SIGNIFICANCE	VALUE
SENSED POWER LEVEL, gain	1.0
ERROR SIGNAL, gain	1.0
ROD CONTROLLER, proportional gain	1.0
reset gain	0.1

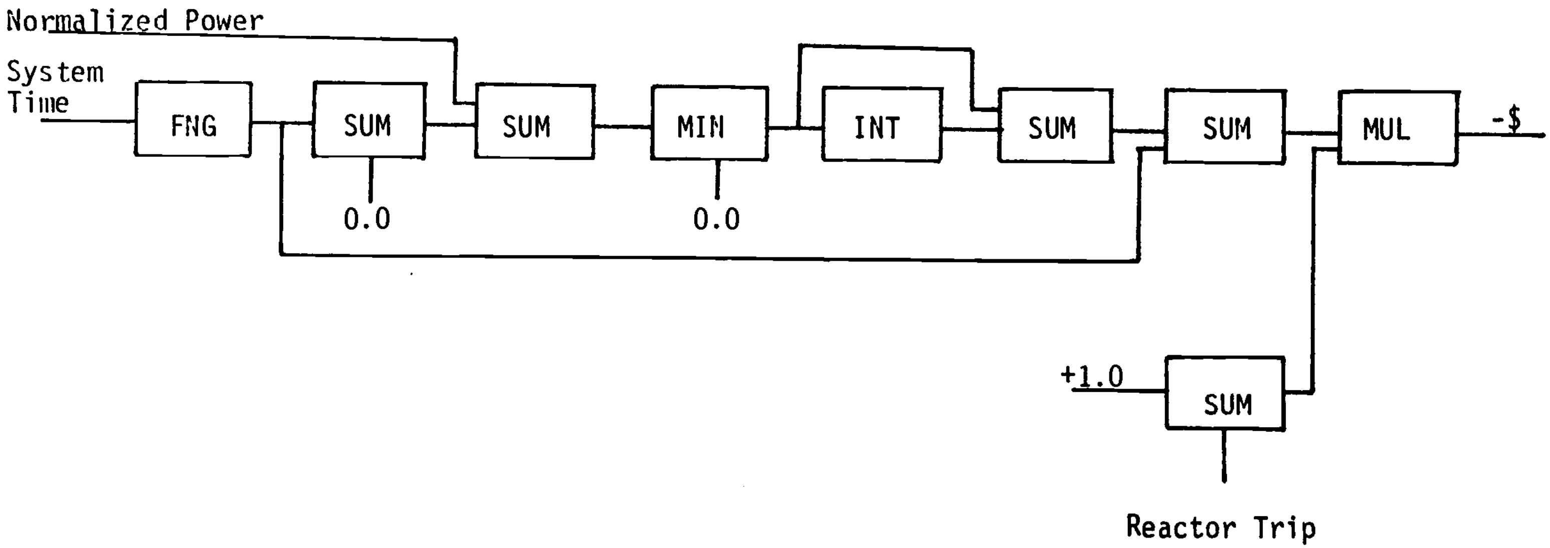


FIGURE 12. BLOCK DIAGRAM OF CONTROL ROD CONTROLLER

output of this comparator serves as the input to the PI controller. The maximum charging rate of 100 gpm of the PI controller is modeled with a limit summer. This automatic charging flow controller is isolated when the safety injection signal is received. Table 3 lists the principal parameters of this controller.

The level programmer (Figure 13) is a linear function of the average temperature of the hot leg and the cold leg of the primary loop. The average temperature of the hot leg and the cold leg can be calculated from the heat removal rate at different power levels. The average temperature determines the programmed water level of the pressurizer.

The charging pumps No. 2 and No. 3 are initialized at low pressurizer levels of 27 feet and 22 feet respectively. Each of these two pumps can provide 150 gpm to the RCS, and also serves as a safety injection pump under the safety injection mode operation of ECCS. A block diagram of this charging flow controller is shown in Figure 14.

3.2.3 Letdown Flow Controller

TABLE 3

PRINCIPAL PARAMETERS OF CHARGING FLOW CONTROLLER

SIGNIFICANCE	VALUE
PRESSURIZER LEVEL SENSOR, time constant	0.25
SENSED PRESSURIZER LEVEL (VOLUME 15), gain	1.0
SENSED LEVEL ERROR, gain	1.0
FLOW CONTROLLER, proportional gain	1.0
reset gain	1.0

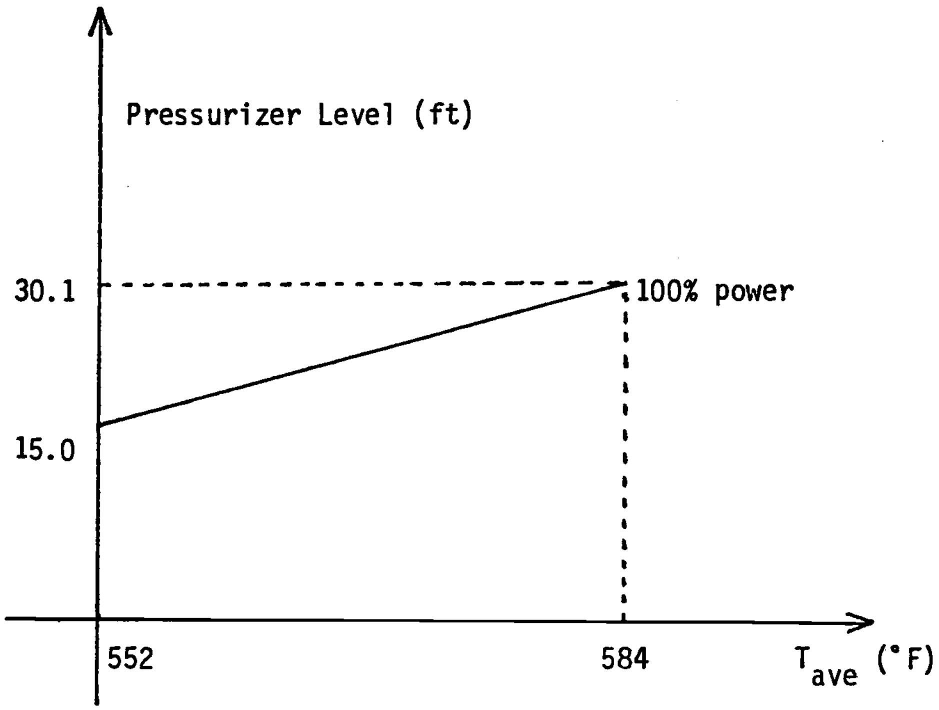


FIGURE 13. PROGRAMMED LEVEL OF PRESSURIZER vs. AVERAGE TEMPERATURE

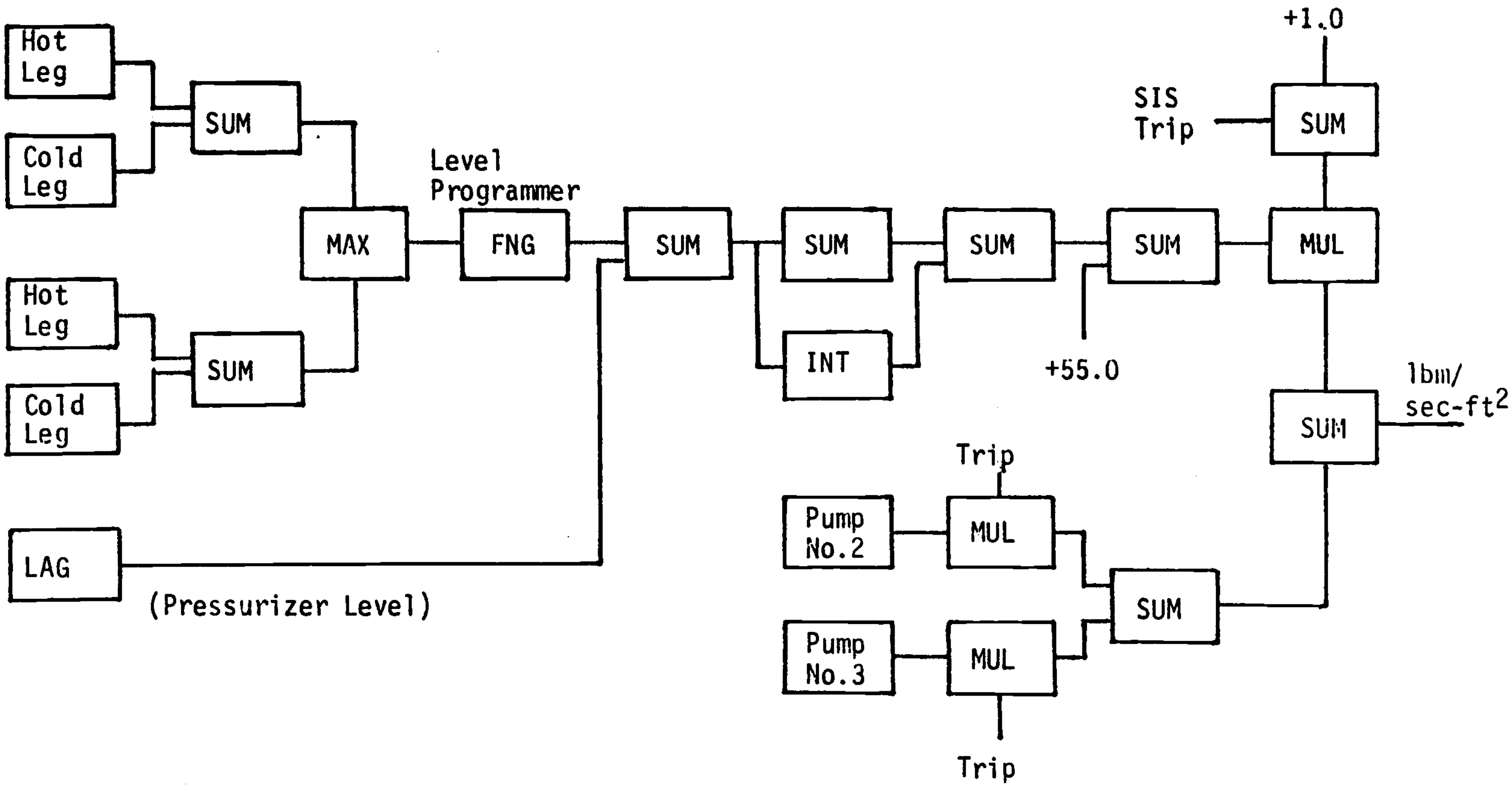


FIGURE 14. BLOCK DIAGRAM OF CHARGING FLOW CONTROLLER

The letdown flow is modeled by using fill junction (junction 944) with a negative flow rate to the RCS. As mentioned before, the letdown rate is determined by selecting the proper combinations of letdown orifices. Therefore, the letdown function is a step function rather than a continuous function. For SGTR simulation, the letdown rate is an input as a function of time measured from the beginning of transient. The letdown isolation valve is fully closed 5 seconds after the letdown isolation signal is received. An on-off controller for letdown is shown in Figure 15. The step changes of the letdown rate, which represents the operator action, are also shown in Figure 16.

3.2.4 Pressurizer Heaters Controller

The pressurizer pressure is partially controlled by the heaters which are modeled with the non-conducting heat exchanger option. The maximum output of the heaters is 1.8 MW. One third of the heaters serves as the proportional heater which has a maximum 0.6 MW output power. The proportional heater is fully off at 2235 psia and fully on at 2233 psia. At pressure below 2233 psia, the back up heaters are turned on (shown in Figure 17). All heaters are turned off at low pressurizer level 8.51

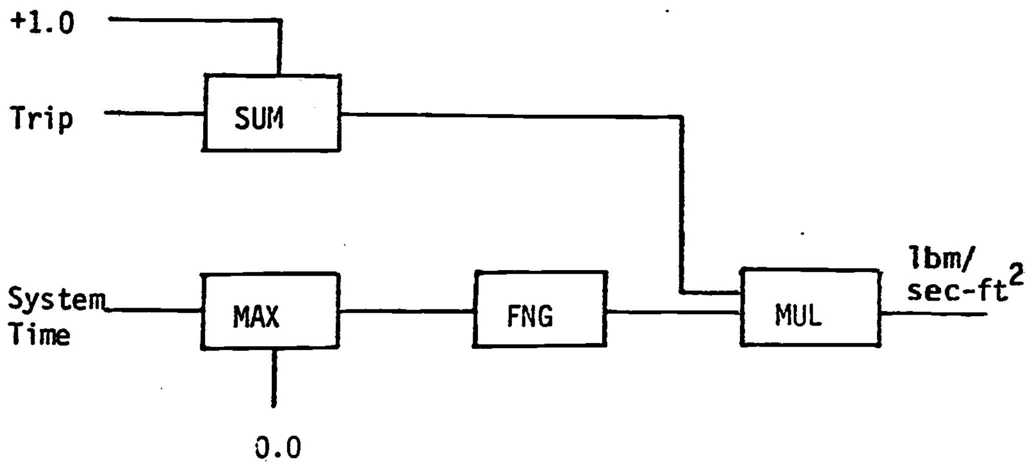


FIGURE 15. BLOCK DIAGRAM OF LETDOWN FLOW CONTROLLER

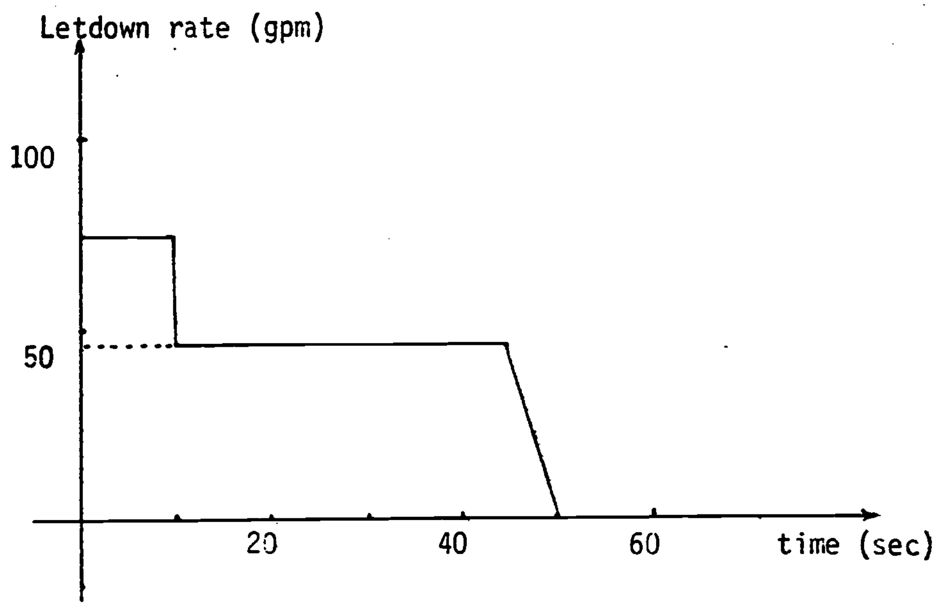


FIGURE 16. LETDOWN FUNCTION DURING SGTR EVENT

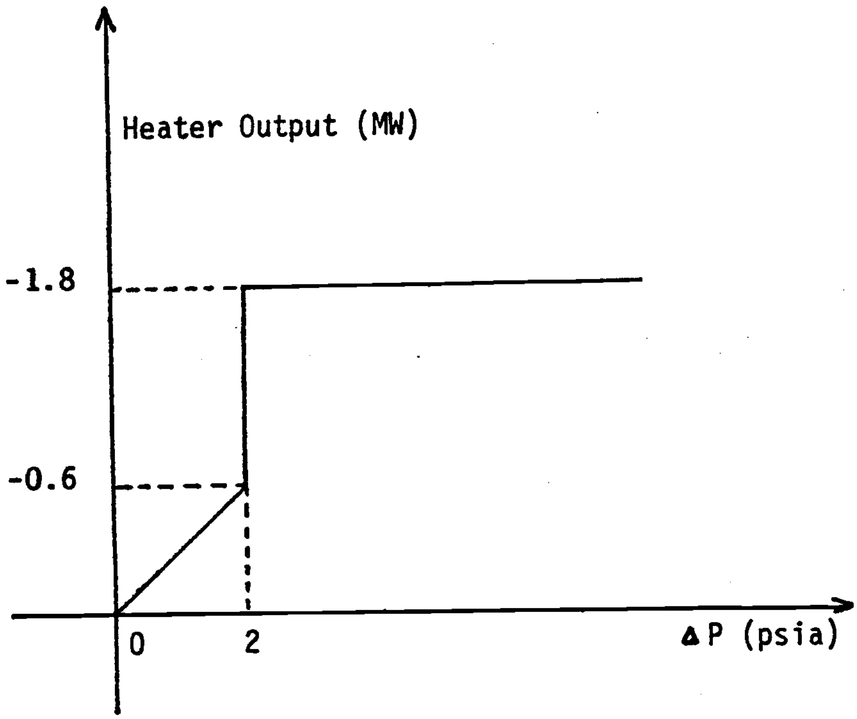


FIGURE 17. CONTROL FUNCTION OF PRESSURIZER HEATER

feet (17%). A block diagram of the pressurizer heater controller is shown in Figure 18.

3.2.5 Feedwater and Auxiliary Feedwater Controller

The main feedwater is modeled with fill junctions 31 and 71 for the triple loop and single loop, respectively. The feedwater flow of each steam generator is determined independently by a three-element controller. The principal parameters of this controller are listed in Table 4. The time constants of the steam flow and feedwater flow LAG networks are large such that the overall response of this controller will be dominated by the level error signal during the transient. This feature should provide a better control on the feedwater flow and steam generator level. After the transient, the controller makes minor adjustments between the feedwater and the steam flow rate.

The flow demand versus flow controller output is a linear function as shown in Figure 19. The valve dynamics are represented by a stable second order system in the following form:

$$\frac{1}{s^2 + 1.414 \cdot s + 1}$$

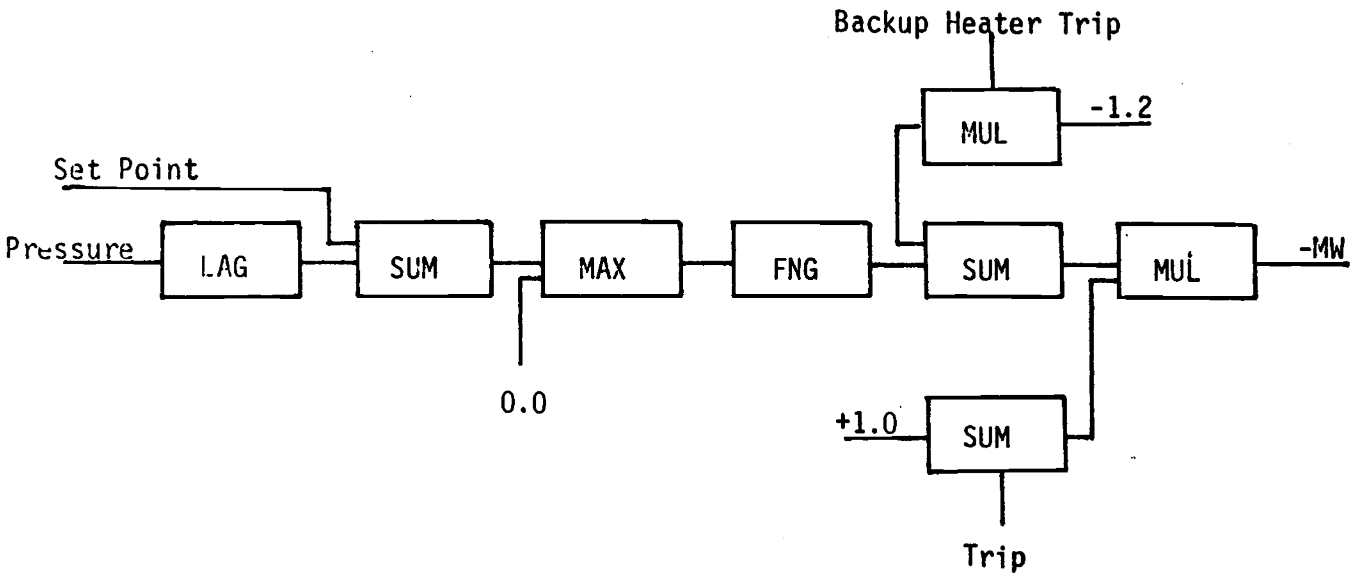


FIGURE 18. BLOCK DIAGRAM OF PRESSURIZER HEATER CONTROLLER

TABLE 4

PRINCIPAL PARAMETERS OF FEEDWATER CONTROLLER

SIGNIFICANCE	VALUE
LEVEL SENSOR, time constant	5.0
STEAM FLOW SENSOR, time constant	120.0
FEED FLOW SENSOR, time constant	120.0
SENSED WATER LEVEL (VOLUME 32), gain	1.0
SENSED STEAM FLOW (JUNCTION 62), gain	0.001
SENSED FEED FLOW (JUNCTION 71), gain	-0.001
LEVEL CONTROLLER, proportional gain	1.0
reset gain	1.0
FLOW CONTROLLER, proportional gain	50.0
reset gain	1.67
LEVEL SET POINT, programmed level	see FIGURE 8

Detailed information about second order systems can be found in Reference 9. Figure 20 shows the feedwater flow rate versus valve dynamics output. The magnitudes of these two linear functions are roughly estimated from the maximum output of involved control elements during the transient operation.

The auxiliary feedwater flow is initialized at the receipt of the safety injection signal and at the isolation of the main feedwater flow. A block diagram for the feedwater and auxiliary feedwater controller is shown in Figure 21. The feedwater enthalpy, which is a function of power level (Table 5), is controlled by a feedwater enthalpy controller shown in Figure 22.

3.2.6 High Pressure Safety Injection Controller

The safety injections are modeled with junctions 97 and 947 for each loop. The safety injection is initialized when the RCS pressure drops below 1800 psia. The injection rate, which is a function of RCS pressure, is shown in Figure 23. The block diagram for the simple safety injection controller is shown in Figure 24.

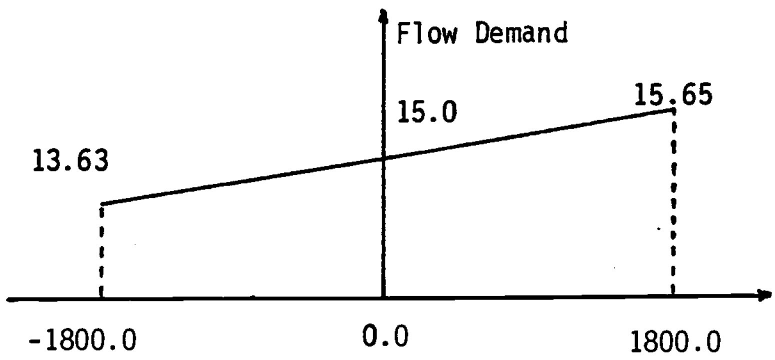


FIGURE 19. FLOW DEMAND vs. FLOW CONTROLLER OUTPUT

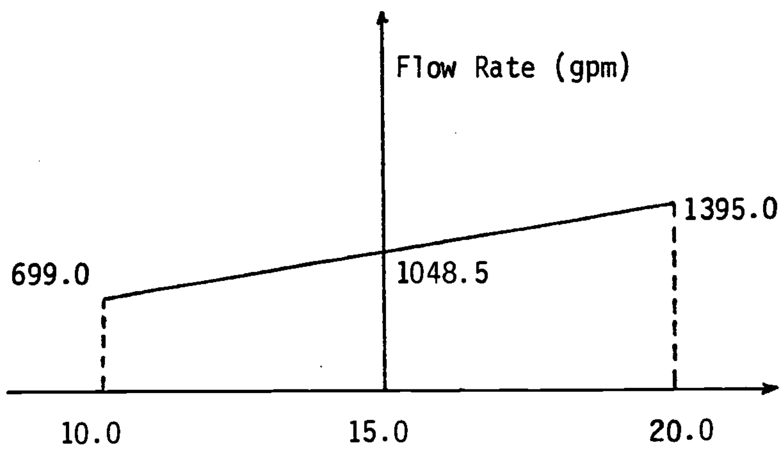


FIGURE 20. FEEDWATER FLOW RATE vs. VALVE DYNAMICS OUTPUT

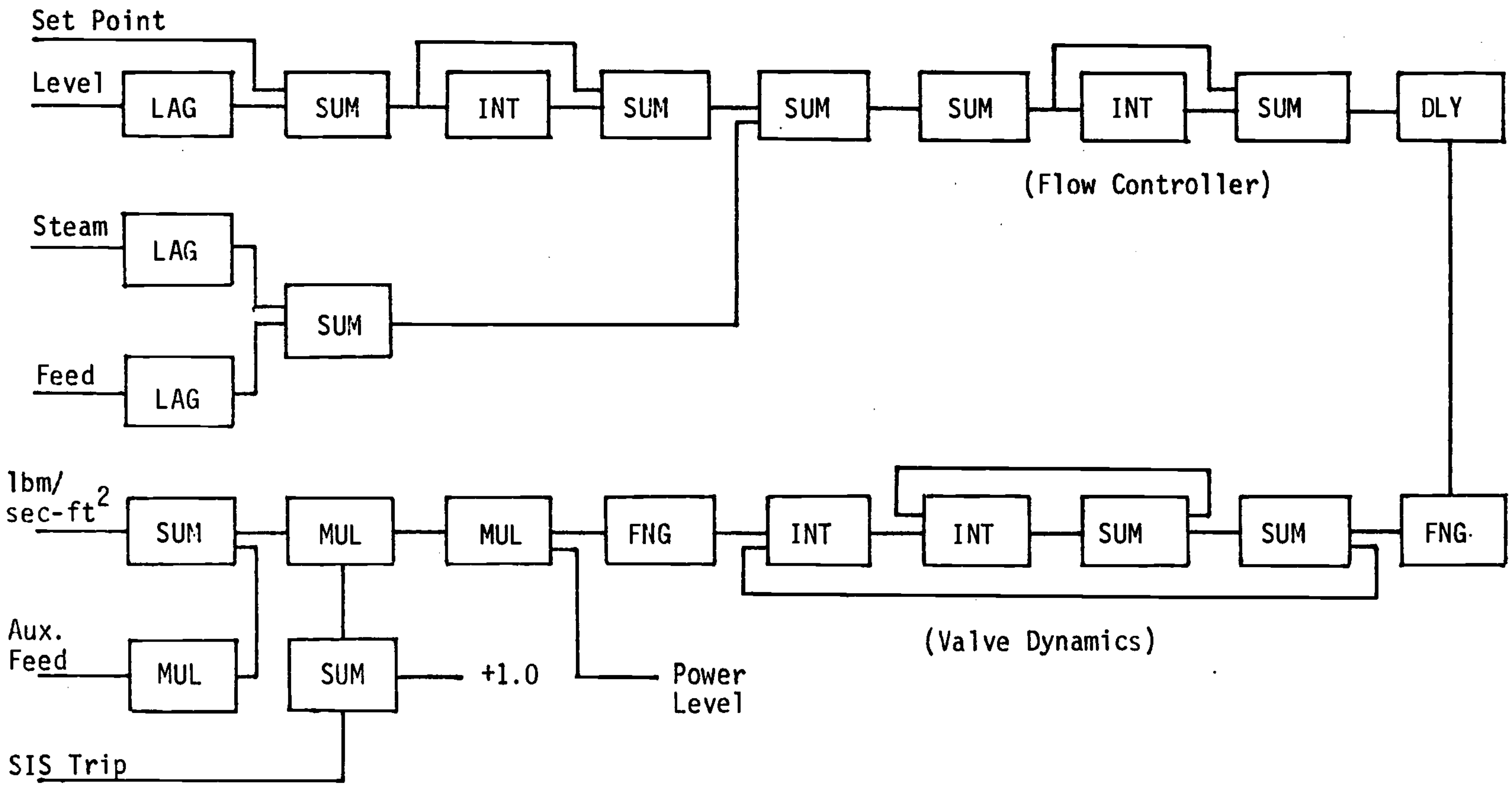


FIGURE 21. BLOCK DIAGRAM OF FEEDWATER AND AUXILIARY FEEDWATER CONTROLLER

TABLE 5

MAIN FEEDWATER ENTHALPY

% OF RATED POWER	ENTHALPY (Btu/lbm)
100.0	419.6
80.0	392.2
70.0	377.1
60.0	360.6
40.0	320.6
20.0	277.3

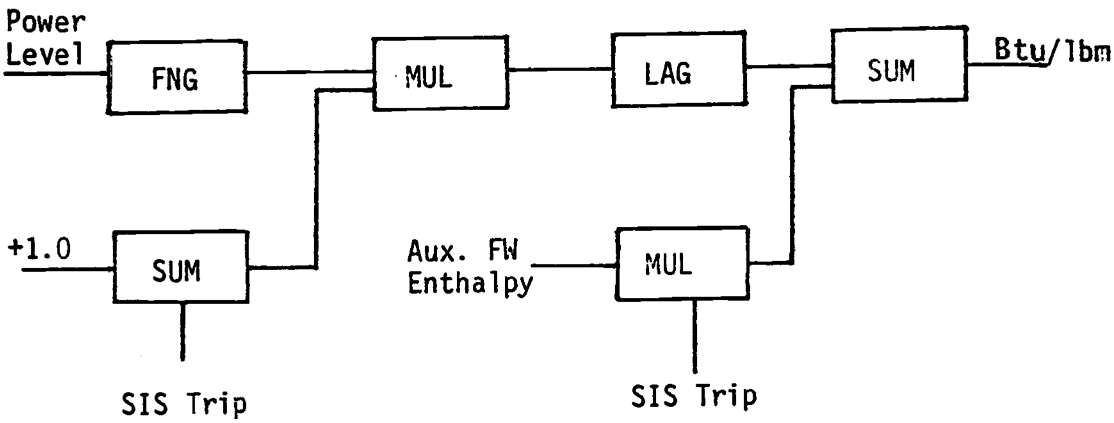


FIGURE 22. BLOCK DIAGRAM OF FEEDWATER ENTHALPY CONTROLLER

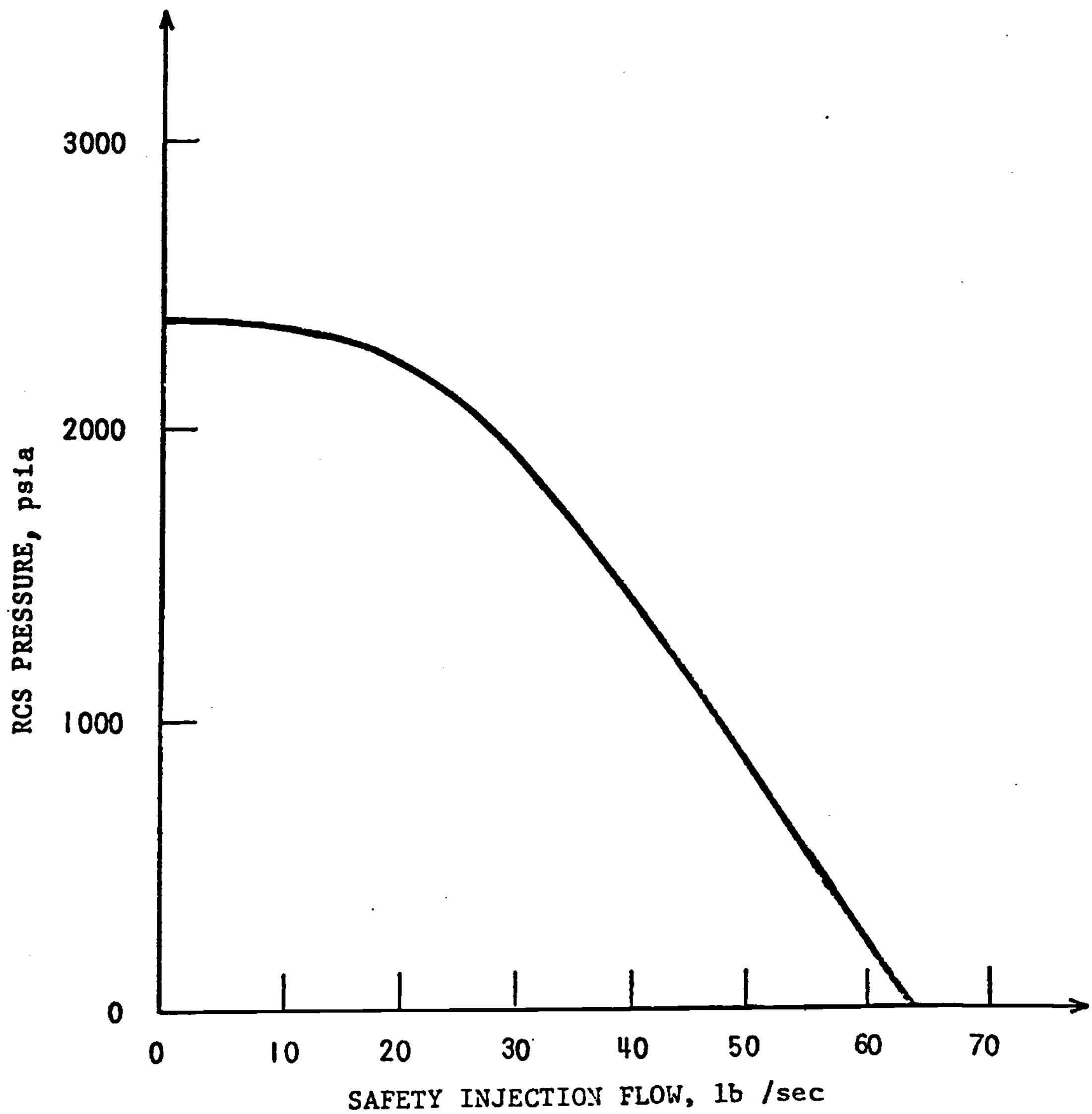


FIGURE 23. SAFETY INJECTION RATE vs. RCS PRESSURE

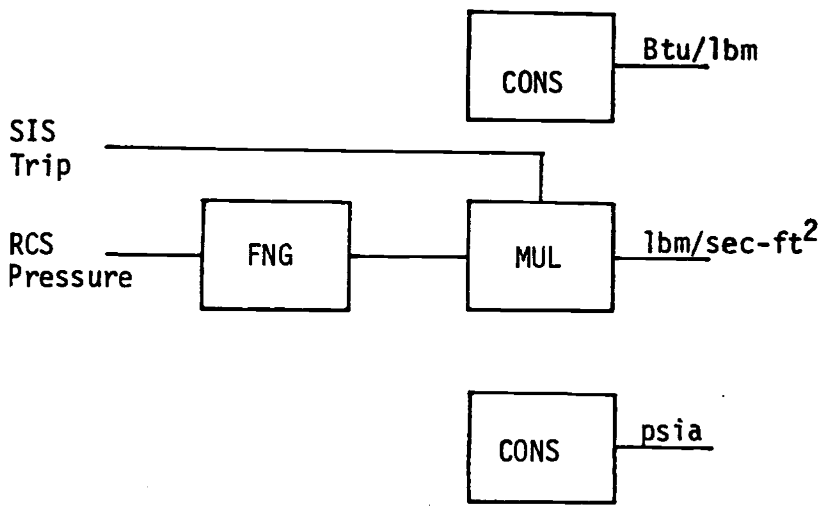


FIGURE 24. BLOCK DIAGRAM OF SAFETY INJECTION CONTROLLER

3.2.7 MSIV and PORV

A MSIV is added to the outlet of the ruptured steam generator. This valve is fully opened at normal operation and closed by operator action in order to isolate the ruptured steam generator. The MSIV can be fully closed in 5 seconds.

The PORV is modeled with a valve fully closed at normal operation. In fact, this valve can be either closed or opened by operator actions during the SGTR event. The operations of both PORV and MSIV are modeled with RETRAN trip control cards.

4. SIMULATION OF SGTR EVENT

4.1 INITIAL CONDITIONS

The initial conditions are obtained from the plant operational data and the Trojan FSAR. The data used for the steady-state initialization in the two-loop PWR model are presented in Table 6.

4.2 THE TUBE RUPTURE MODEL

The steam generator tube rupture event is modeled with a junction connecting volume 58 and 64 about 16 feet above the hot leg inlet on the single loop side (see Figure 25). The junction contains a valve which is initially closed and is fully open at 0.01 seconds after the initiation of the transient calculation. The rupture area is assumed to be 0.005 ft^2 as it is described in Reference 10. The extended Henry-Fauske critical flow model is used for this case. The discharge coefficient is 0.9 as recommended in Reference 3. A schematic diagram of the tube rupture model is shown in Figure 26.

TABLE 6

INITIAL CONDITIONS

POWER	3411.0 MW
PRESSURIZER PRESSURE	2219.6 psia
STEAM PRESSURE	910.0 psia
HOT LEG TEMPERATURE	616.07 °F
COLD LEG TEMPERATURE	552.49 °F
STEAM GENERATOR LEVEL (COLLAPSED LIQUID LEVEL OF VOLUME 32)	3.53 ft
FEEDWATER FLOW RATE (PER SG)	1048.5 lbm/sec
CHARGING FLOW RATE	55.0 gpm
LETDOWN FLOW RATE	75.0 gpm
MAKEUP FLOW RATE	20.0 gpm

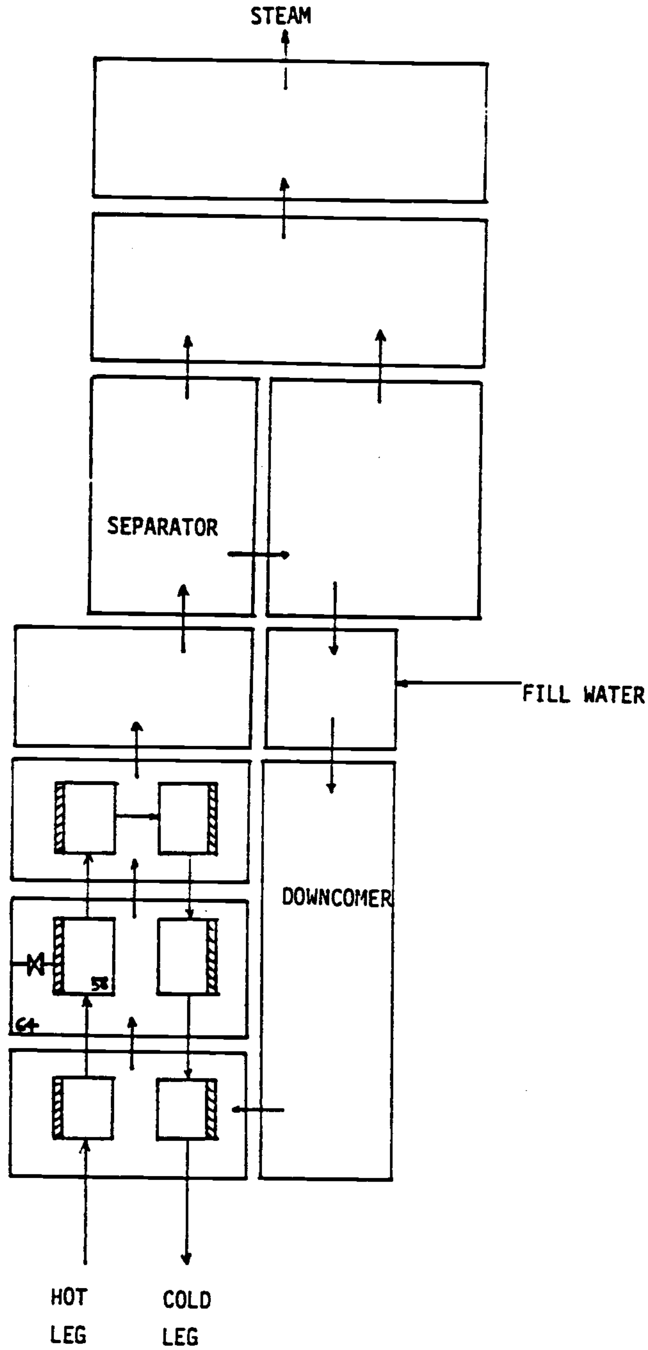
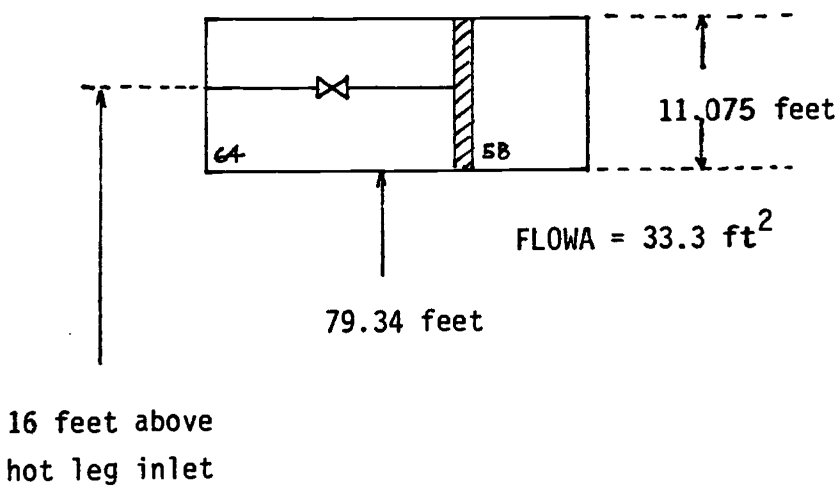


FIGURE 25. STEAM GENERATOR WITH TUBE RUPTURE



TUBE RUPTURE SIZE = 0.005 ft^2 (AJUN)

FIGURE 26. THE TUBE RUPTURE MODEL

5. RESULTS

At the initiation of tube rupture, the depressurization rate in the pressurizer was approximately 1.0 psia/sec (see Figure 27) and the break flow was 93.7 lbm/sec or 674 gpm (see Figure 28). All heaters were turned on at 1.9 seconds after initiation of the transient. Letdown flow was minimized at 15.0 seconds and was isolated at 45.0 seconds. The normal charging flow reached its maximum value at about 20.0 seconds and the second charging pump was manually started at 134.5 seconds (see Figure 29). At this point the pressurizer depressurization rate was reduced to 0.65 psia/sec because of the increased charging flow. After the 10% power reduction at 150.0 seconds, the depressurization rate was increased to 1.4 psia/sec. At 233.2 seconds, the third charging pump was manually started. The depressurization rate was reduced to 0.60 psia/sec and gradually leveled off after this point. At 380.0 seconds the reactor tripped at low pressurizer pressure of 1900.0 psia. The pressurizer pressure decreased rapidly following the reactor trip because of the volume shrinkage in the primary loop. Figure 30 shows the level deviation in the pressurizer. The pressurizer was depleted at about 390.0 seconds after

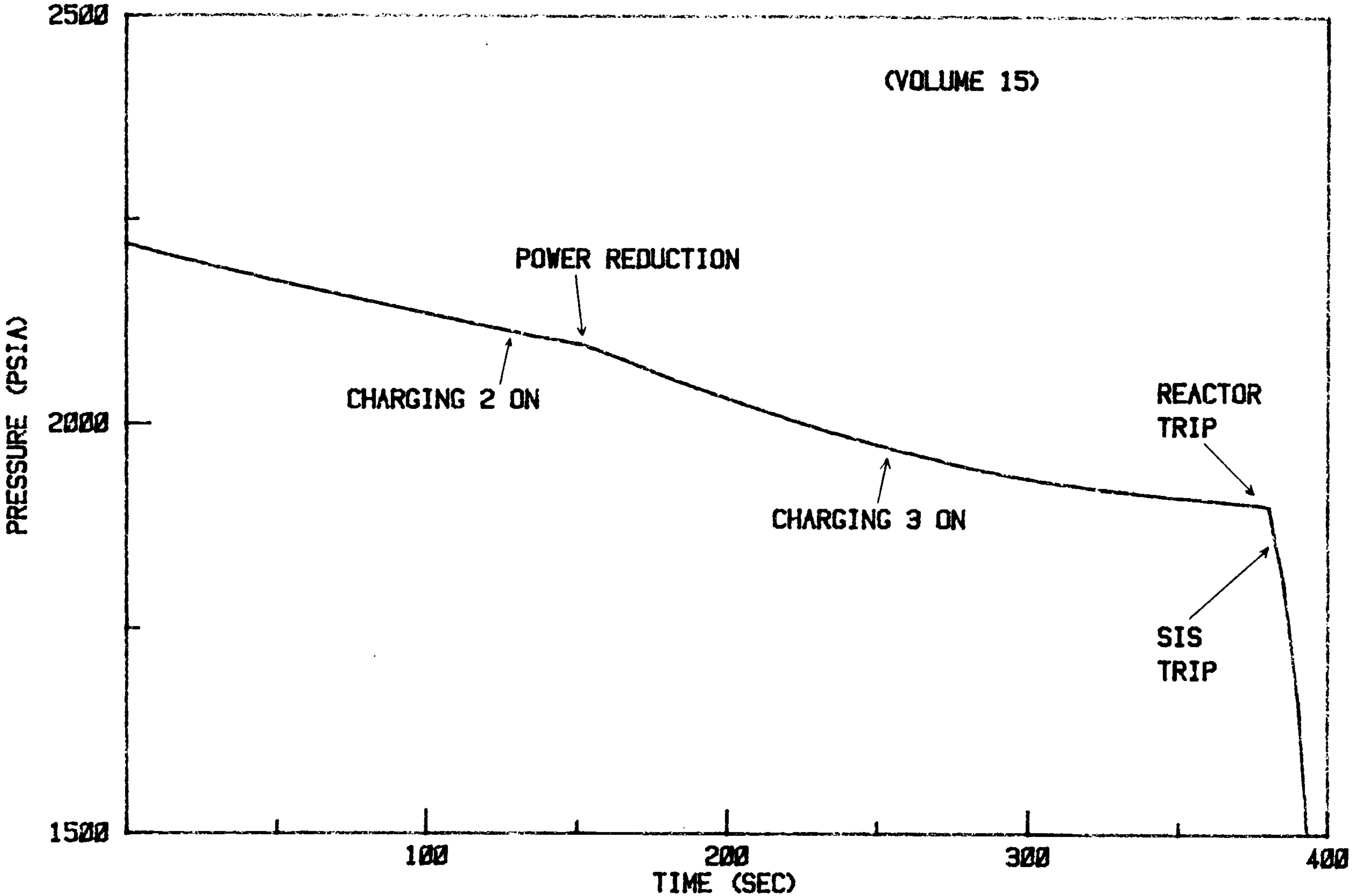


FIGURE 27. PRESSURIZER PRESSURE vs. TIME

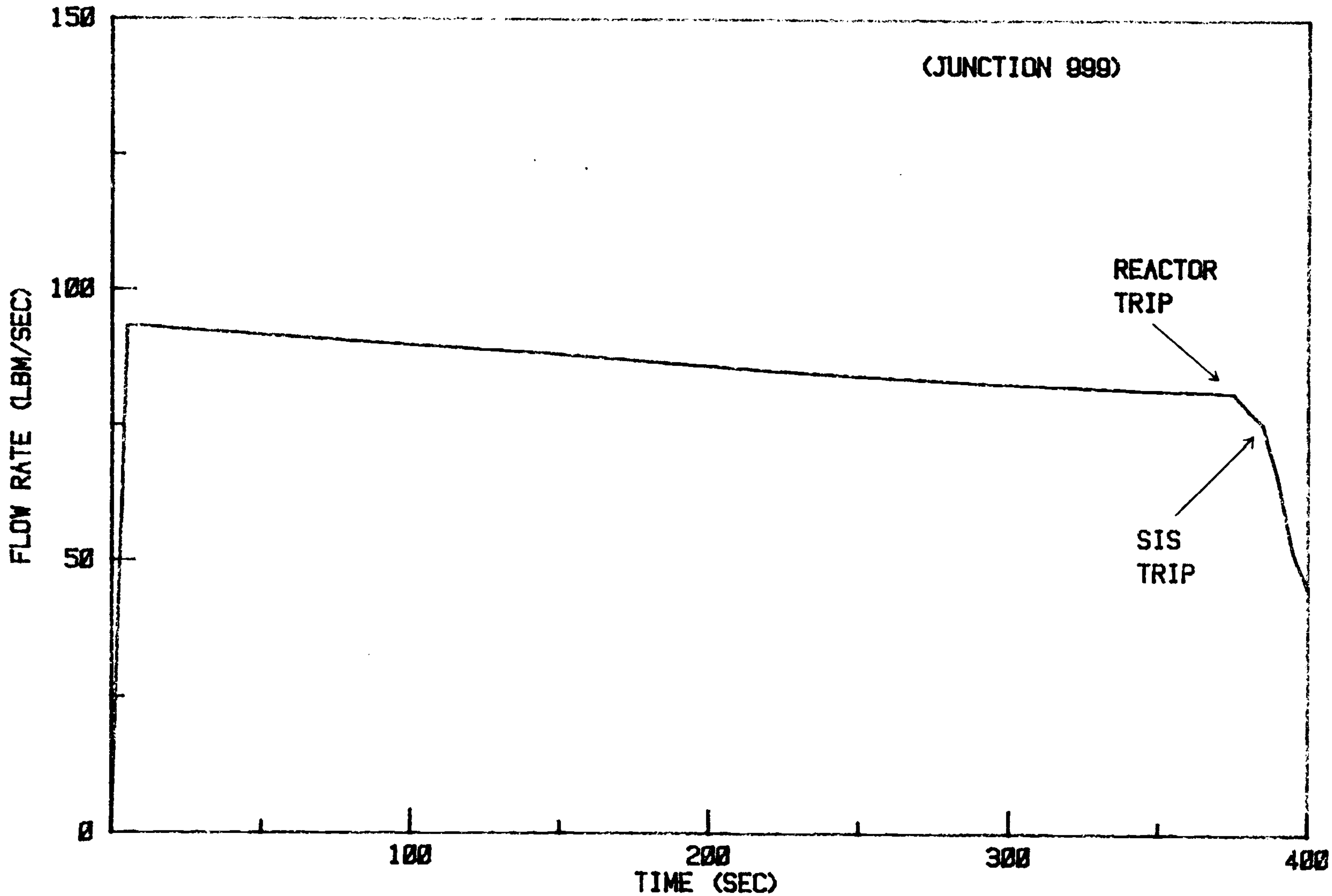


FIGURE 28. BREAK FLOW RATE vs. TIME

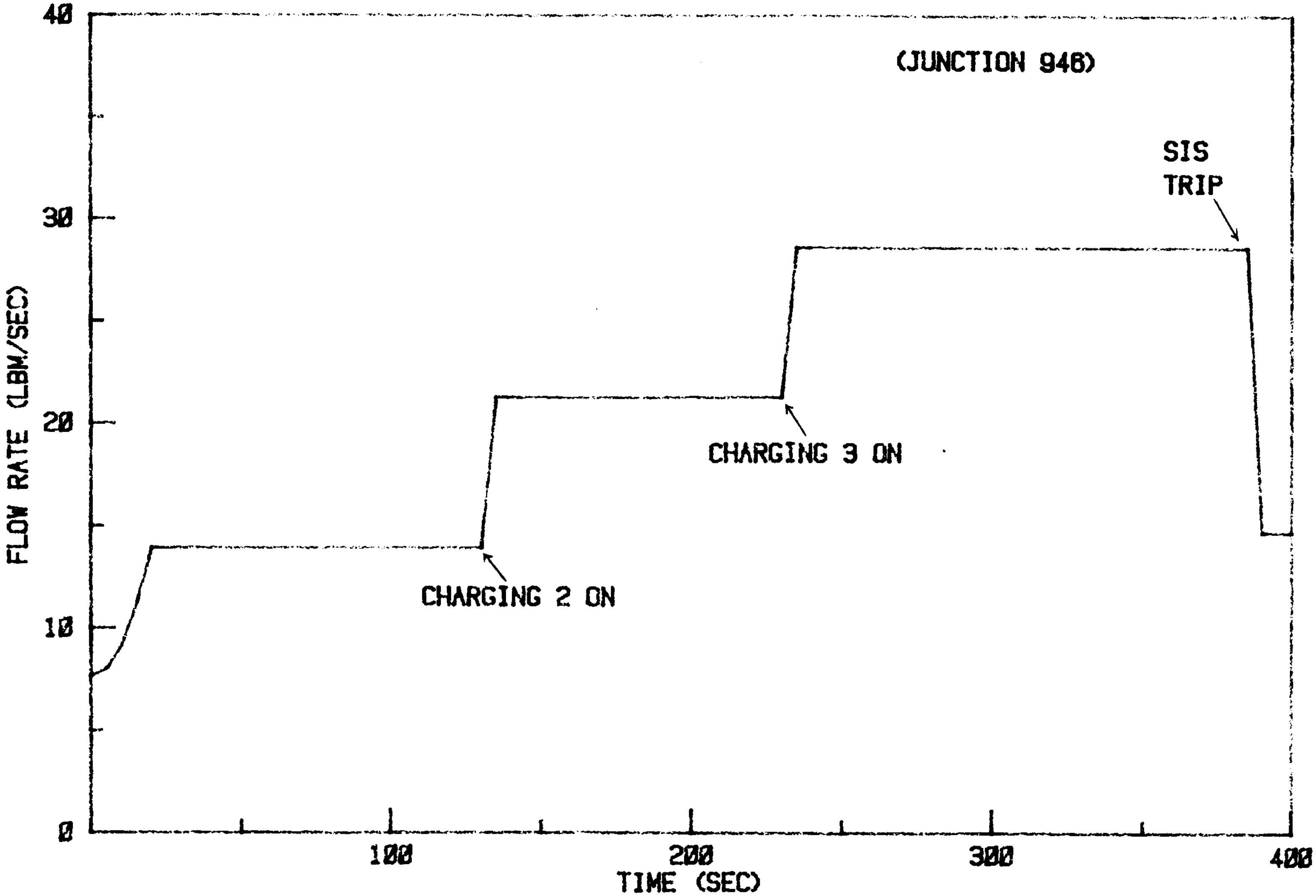


FIGURE 29. CHARGING FLOW RATE vs. TIME

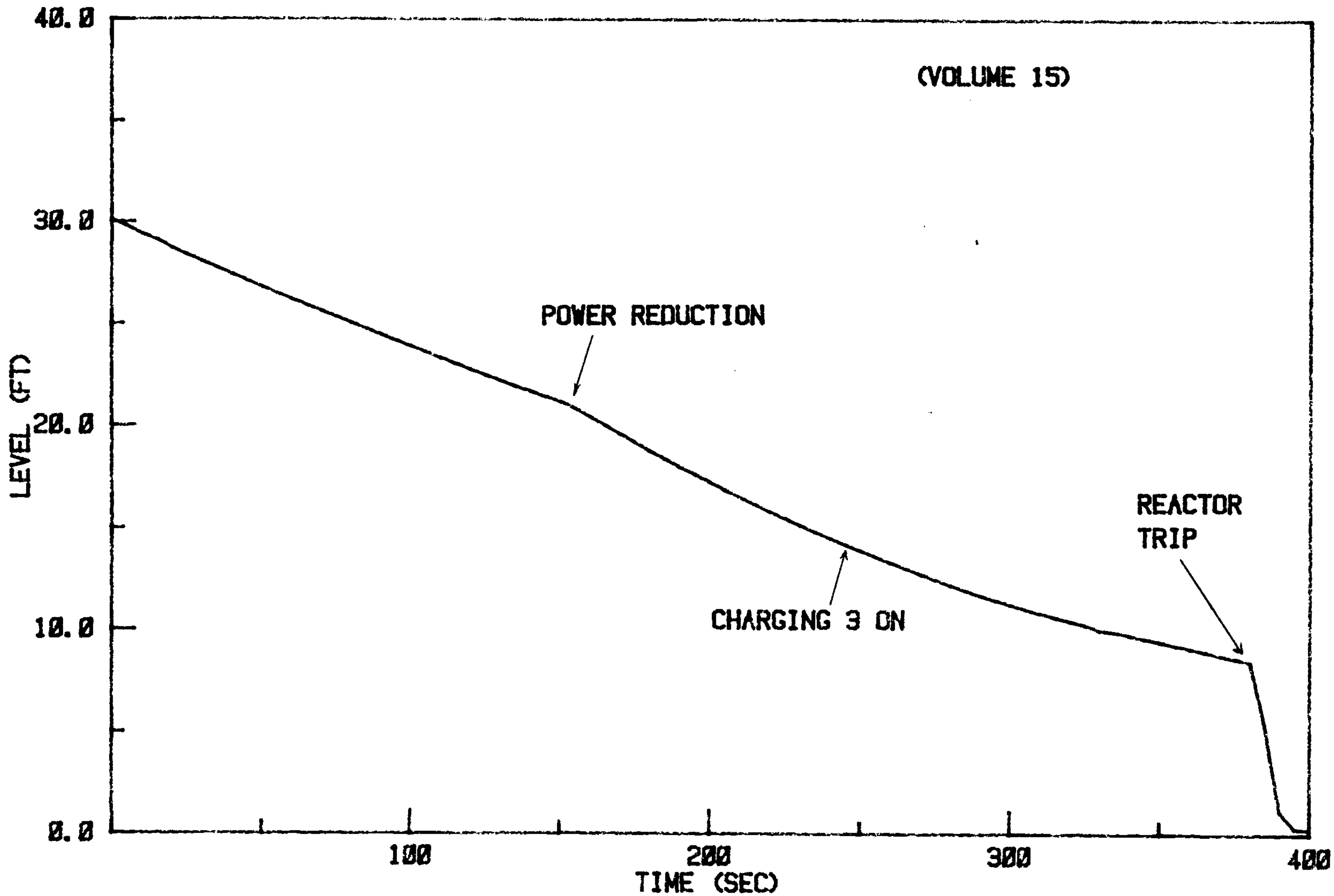


FIGURE 30. PRESSURIZER LEVEL vs. TIME

reactor tripped.

The system normalized power is shown in Figure 31. The reactor power was reduced to 90% of full power following the 10% power reduction at 150.0 seconds. The reactor was tripped at 380.0 seconds due to low pressurizer pressure of 1900.0 psia. The safety injection system was initiated at about 387.0 seconds when the pressure dropped to 1800.0 psia.

Figures 32 and 33 show the water level in the ruptured and the intact steam generators. The water level in the ruptured steam generator significantly deviated from the normal level of 44% narrow range because of the break flow from the primary side to the secondary side. This water level deviation caused the steam flow and feedwater flow mismatch as shown in Figure 34 and 35. In the intact steam generator, the water level was maintained at the normal level by the feedwater controller. The steam flow and feedwater flow were also maintained at the normal value as shown in Figure 36 and 37. The feedwater controller started to adjust the variations in the steam flow, feedwater flow and water level after the 10% power reduction. After the reactor tripped, the steam flow of both two steam generators decreased rapidly. This is an expected behavior of any

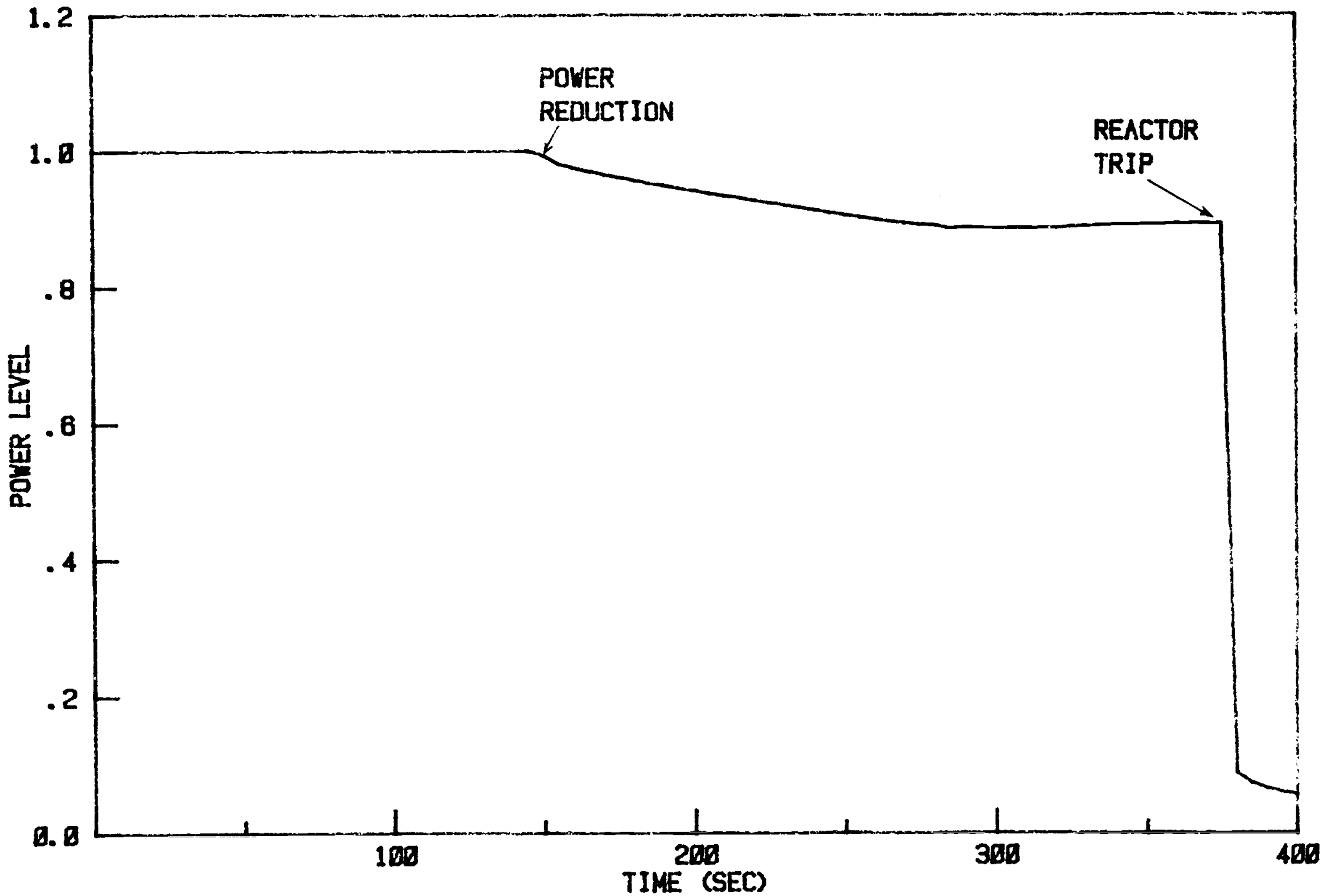


FIGURE 31. NORMALIZED POWER LEVEL vs. TIME

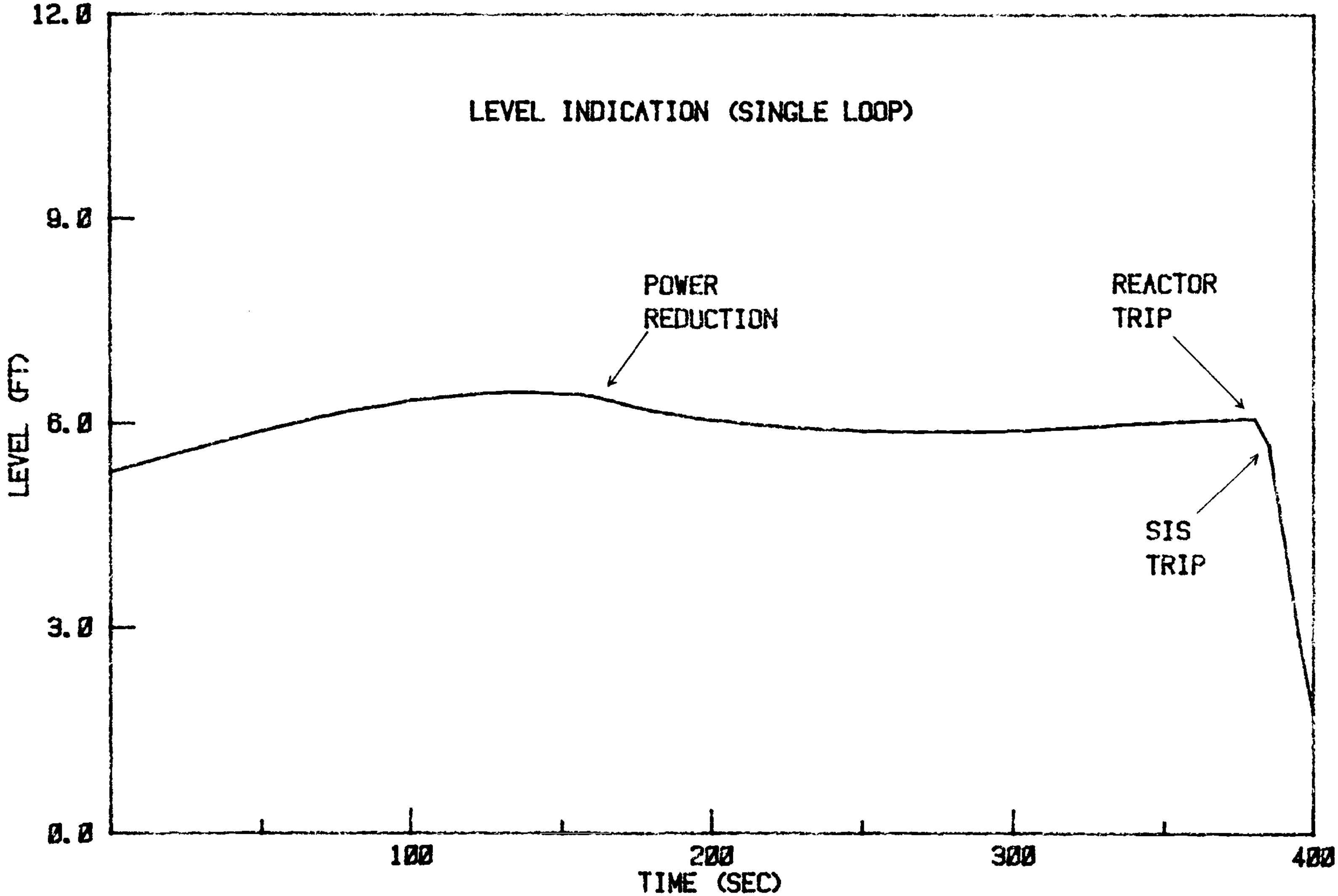


FIGURE 32. STEAM GENERATOR LEVEL (SINGLE LOOP) vs. TIME

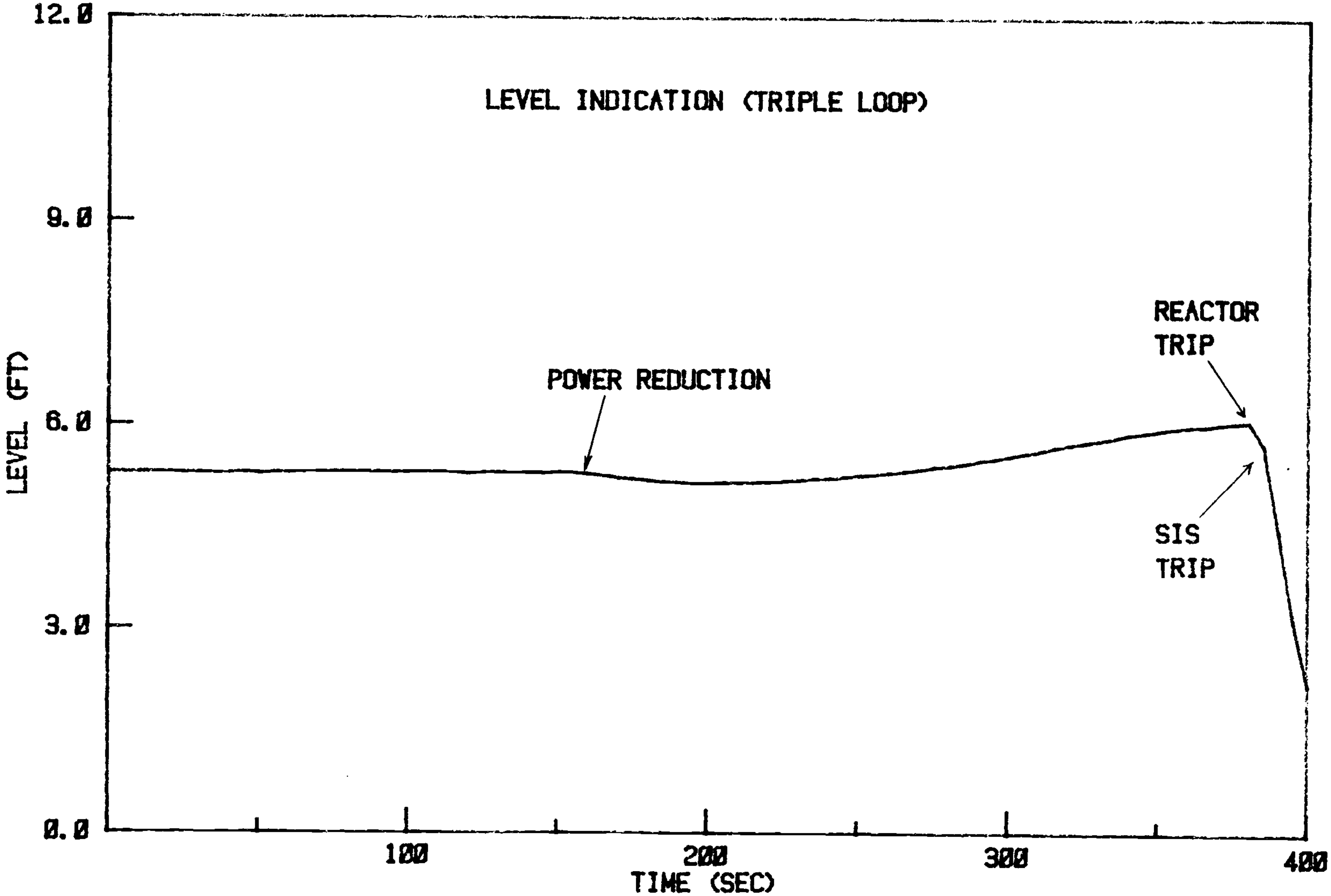


FIGURE 33. STEAM GENERATOR LEVEL (TRIPLE LOOP) vs. TIME

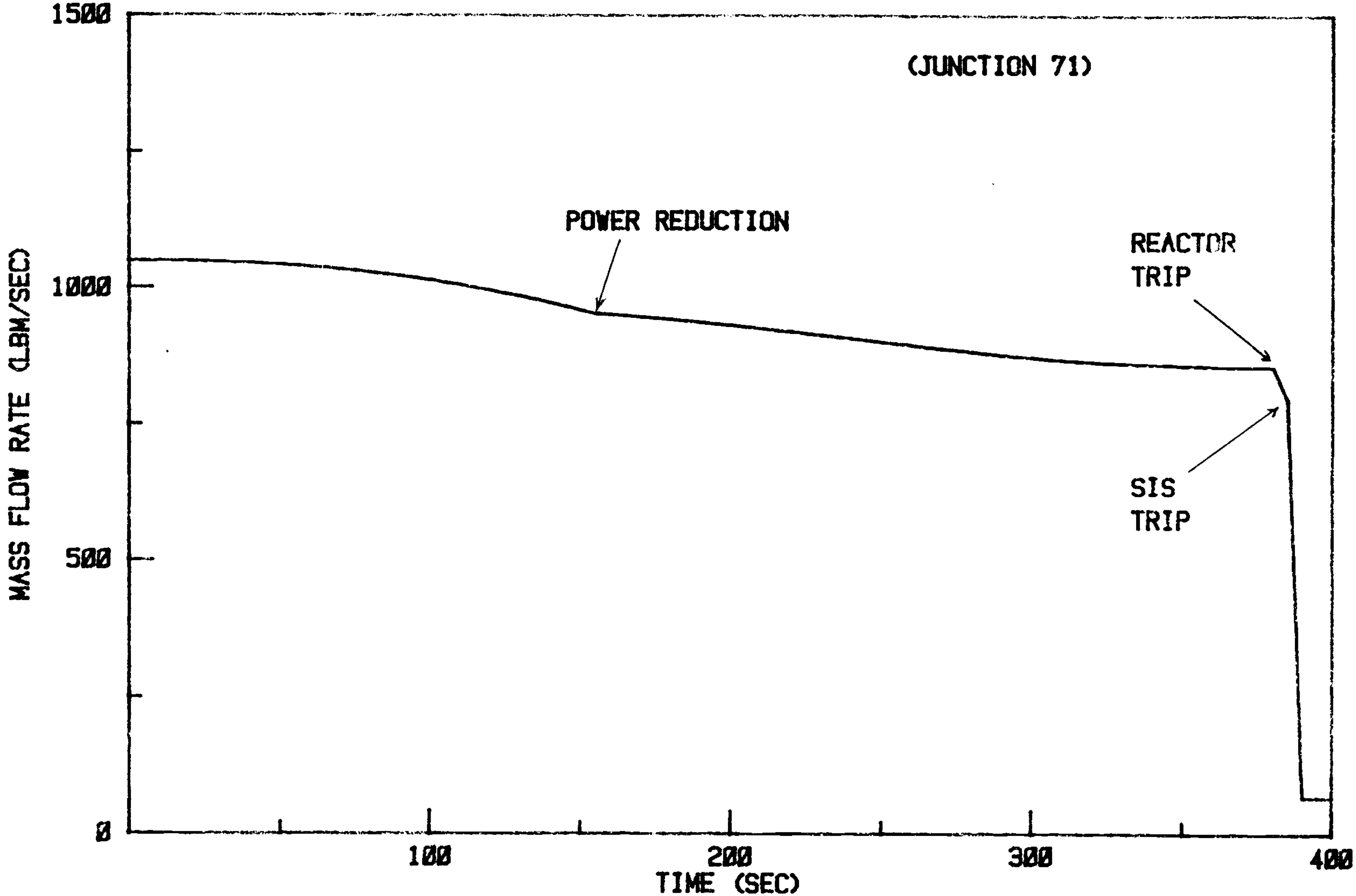


FIGURE 34. FEEDWATER FLOW RATE (SINGLE LOOP) vs. TIME

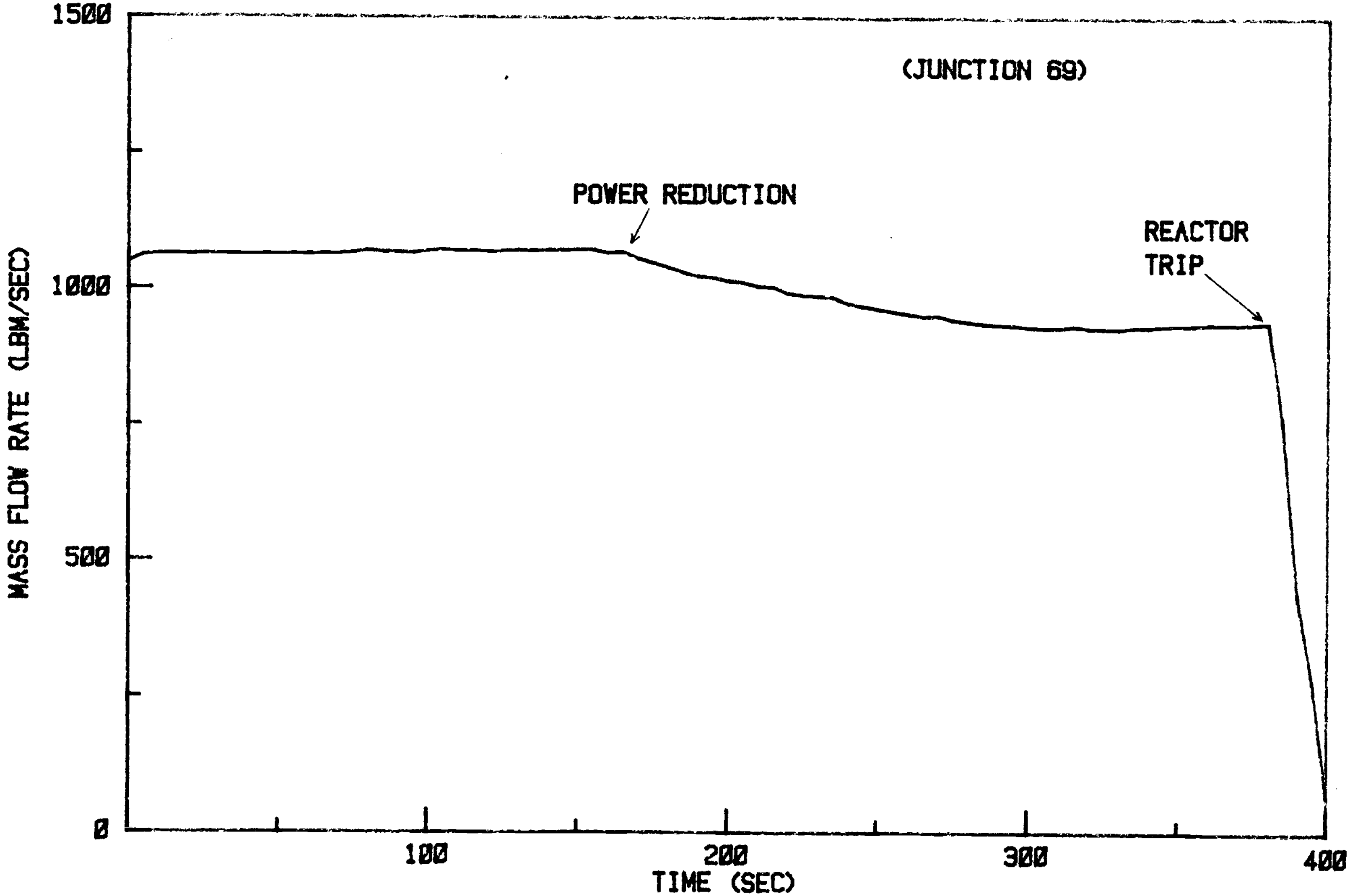


FIGURE 35. STEAM FLOW RATE (SINGLE LOOP) vs. TIME

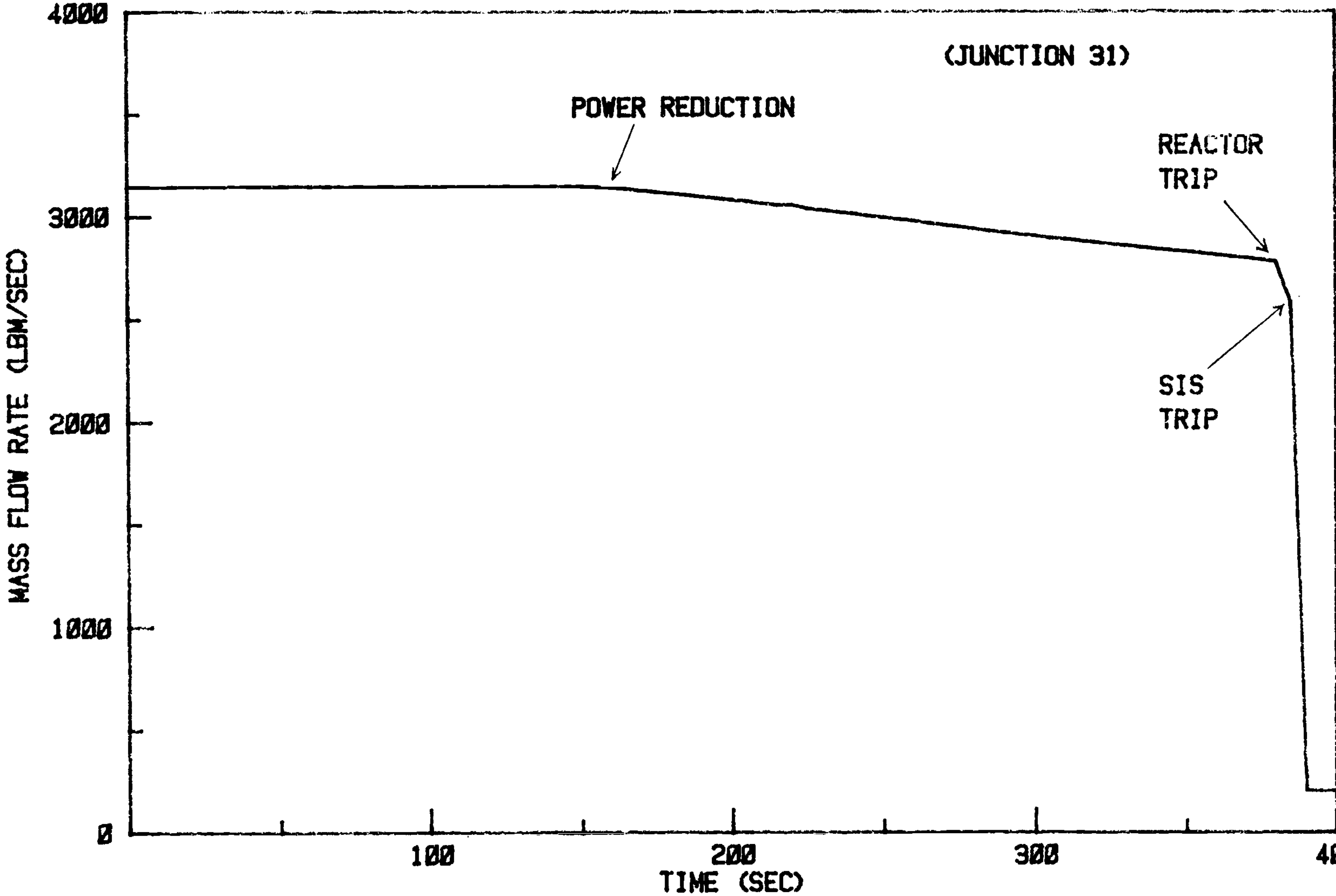


FIGURE 36. FEEDWATER FLOW RATE (TRIPLE LOOP) vs. TIME

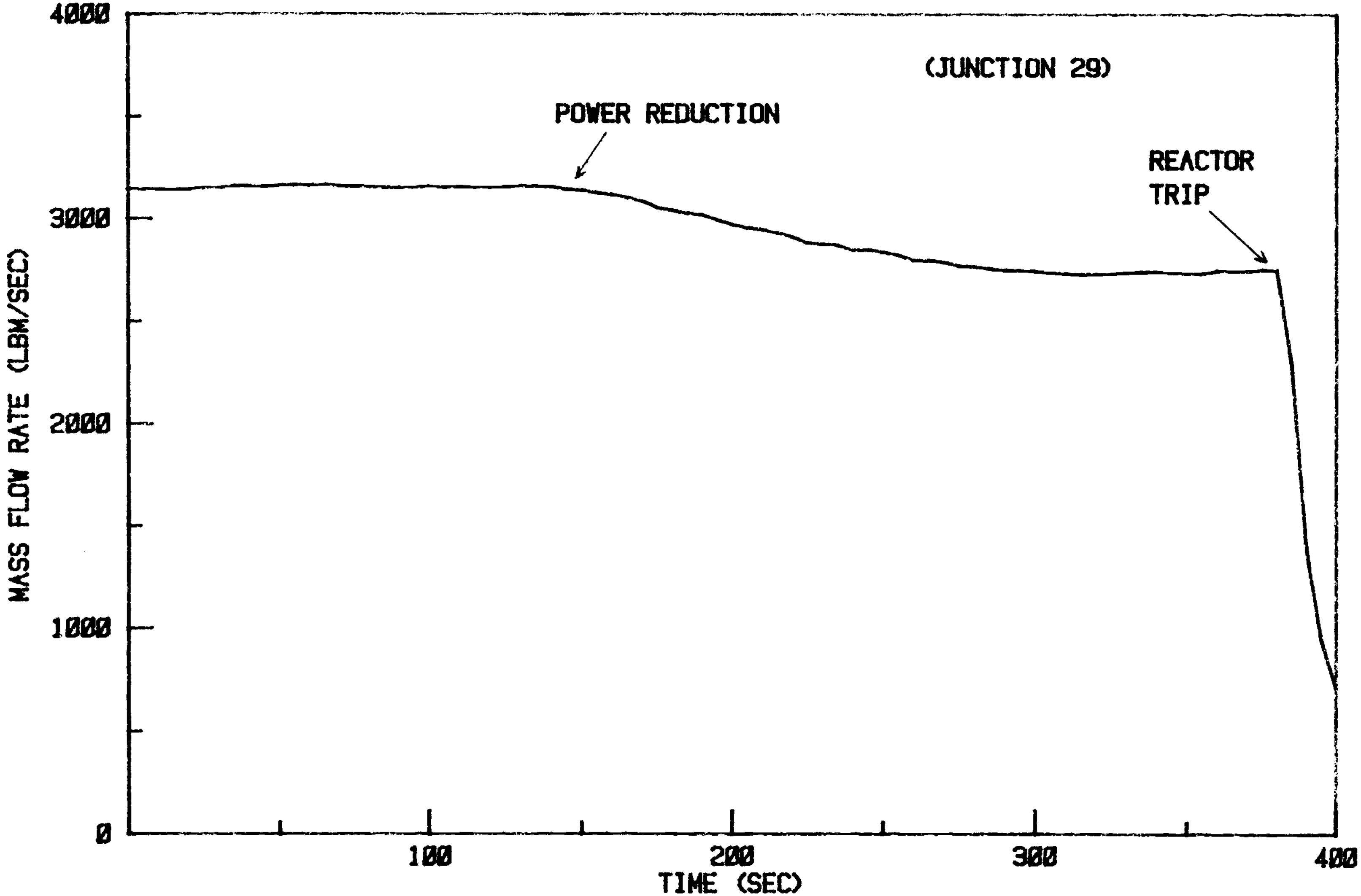


FIGURE 37. STEAM FLOW RATE (TRIPLE LOOP) vs. TIME

two-phase saturated system in the case of a sudden increase in the pressure. The pressure rise caused the volume of liquid/vapor mass in the evaporator section to suddenly decrease. The increased water flow from the downcomer region into the evaporator section resulted in a lower water level after the reactor was tripped. The main feedwater flow was isolated and the auxiliary feedwater flow was started when the safety injection system was initiated.

Table 7 lists the sequence of events in this simulation.

TABLE 7

SEQUENCE OF EVENTS IN SGTR SIMULATION

Transient Time (sec)	Event
0.01	Tube rupture occured
1.00	All heaters were turned on
15.00	Letdown flow was minimized
20.00	Normal charging flow reached maximum value
45.00	Letdown flow was isolated
134.50	Second charging pump was started
150.00	10% power reduction
233.20	Third charging pump was started
380.00	Reactor scrammed
387.0	Safety injection was started

6. CONCLUSIONS

A simulation of the Trojan SGTR event was performed by using the RETRAN two-loop model. The scenario of this simulation was based on the assumption that all the safety systems functioned normally. Operator actions were also included in this modeling.

The predicted results show the rapid depressurization and the level depletion in the pressurizer which characterize the SGTR accident. The ruptured tube steam generator is identified by the steam generator level deviation and steam-flow/feedwater-flow mismatch. The operator actions, which are available in the initial period, can change the depressurization rate by either increasing the charging flow or reducing the reactor power based on the plant response. After the reactor tripped and the safety injection system was activated, the plant began another long and slowly varying transient until normal cooldown. However, it should be noted that the predictions of variations in the steam generator level have not been compared with any other similar predicted or measured values, since such data has not yet been available.

One disadvantage of this transient simulation is the long period of a SGTR event which requires a significantly long computation time. Therefore, this study was focused only on the case of a single tube rupture in the hot leg. In addtion, a larger time step size is also recommended for such a simulation (see Appendix B). Other cases such as those of a large tube break, a tube rupture in the cold leg, and multiple tube ruptures also can be modeled by following the same procedure.

Two major difficulties were encountered in this SGTR event simulation. First, a realistic modeling of the feedwater controller requires detailed information on the amplification gains and time constants of the relevant control elements. Due to the lack of information, engineering judgements were applied in the selection of those system parameters which were not specified. The second difficulty arose from the fact that RETRAN code can not handle the water level fluctuations greater than the length of a computational fluid volume. This limitation results in a large enthalpy error in the junction calculation of the corresponding volume. To avoid this difficulty, a lumped steam generator model rather than that of the nodalized volume representation is recommended (see Reference 11). In general, a lumped steam generator model uses only one large volume to represent the actual evaporator and steam separator sections and does not have the necessary features of the detailed one.

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APPENDIX

8. APPENDIX A

PROPORTIONAL PLUS INTEGRAL AUTOMATIC CONTROLLER

An automatic controller compares the actual value of the plant output with the desired value, determines the deviation and, produces the control signal which will reduce the deviation to zero or to a small value. Figure A1 shows a block diagram of an automatic controller together with a measuring element. The manner in which the automatic controller produces the control signal is called an control action.

There are two types of control actions involved in a proportional plus integral controller, namely :

1. the Proportional Control Action
2. the Integral Control Action

For a controller with proportional control action, the relationship between the output of the controller m(t) and the actuating error signal e(t) is

$$m(t) = K_p \cdot e(t)$$

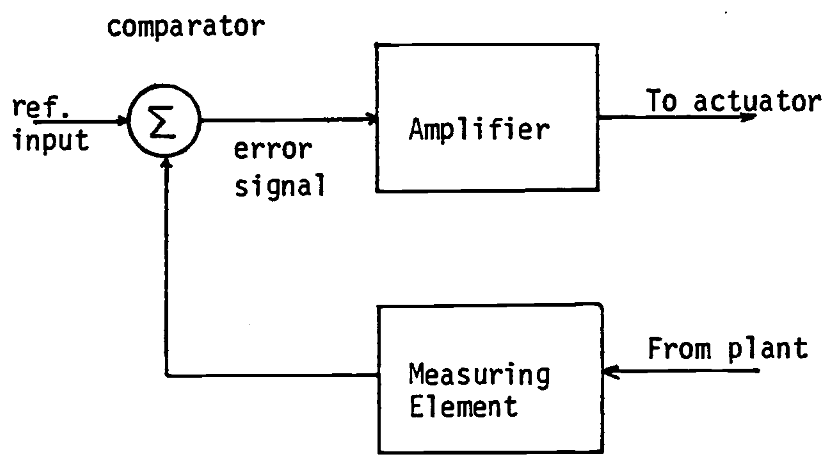

FIGURE A1. BLOCK DIAGRAM OF AN AUTOMATIC CONTROLLER AND MEASURING ELEMENT or in Laplace Transform representation

$$K_p = \frac{M(s)}{E(s)}$$

where K_p is the amplification gain.
A block diagram of such a controller is shown in Figure A2(a)

In a controller with integral control action, the value of the control output m(t) is changed at a rate proportional to the actuating signal e(t), namely

$$\frac{d\,m(t)}{d\,t} = K_i \cdot e(t)$$

or

$$m(t) = K_i \cdot \int_0^t e(t) \cdot dt$$

where K_i is an adjustable gain.
The transfer function of the integral controller is

$$\frac{M(s)}{E(s)} = \frac{K_i}{s}$$

Figure A2(b) shows the block diagram of such a controller.

Combining the two types of controllers described

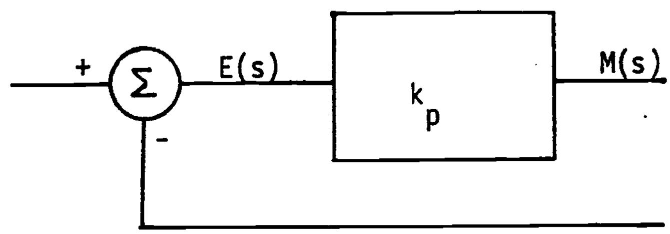

FIGURE A2(a). BLOCK DIAGRAM OF A PROPORTIONAL CONTROLLER

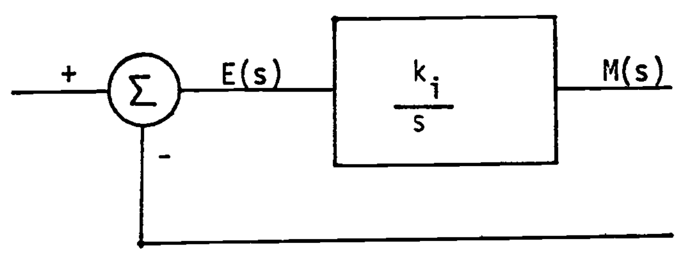

FIGURE A2(b). BLOCK DIAGRAM OF AN INTEGRAL CONTROLLER above, then the control action of a PI controller can then be defined by the following equation :

$$m(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(t) \cdot dt$$

$$= K_p \cdot e(t) + \frac{K_p}{T_i} \cdot \int_0^t e(t) \cdot dt$$

or the transfer function of the controller is

$$\frac{M(s)}{E(s)} = K_p \cdot \left(1 + \frac{1}{T_i \cdot s} \right)$$

where T_i represents the integral time. The inverse of T_i is called the reset rate. Figure A3(a) shows the block diagram of such a controller. If the error signal e(t) is a unit-step function as shown in Figure A.3(b), then the controller output m(t) becomes that shown in Figure A3(c).

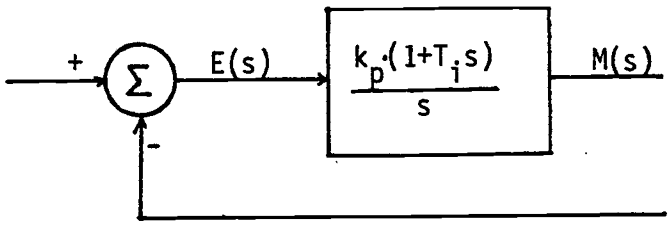

FIGURE A3(a). BLOCK DIAGRAM OF A PROPORTIONAL PLUS INTEGRAL CONTROLLER

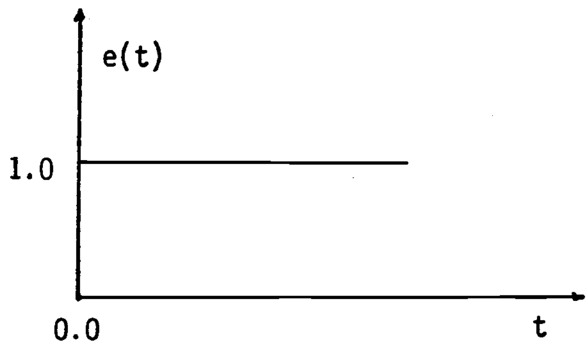

FIGURE A3(b). A UNIT-STEP INPUT

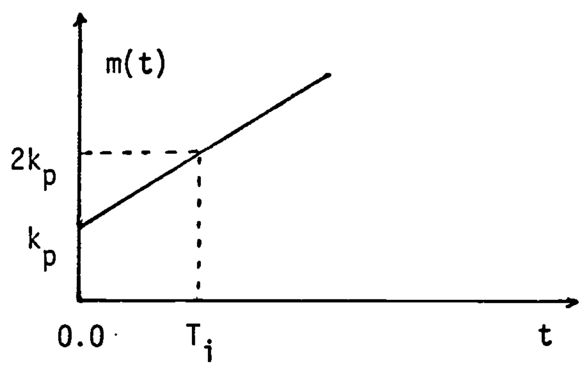

FIGURE A3(c). THE CONTROLLER OUTPUT

9. APPENDIX B

COMPUTATION RESULTS WITH DIFFERENT STEP SIZE

As shown in the foregoing sections, a step size of 5.0 seconds is used for this SGTR event simulation. This section shows the computation results with the step size of 1.0 second for the first 150.0 seconds into the transient.

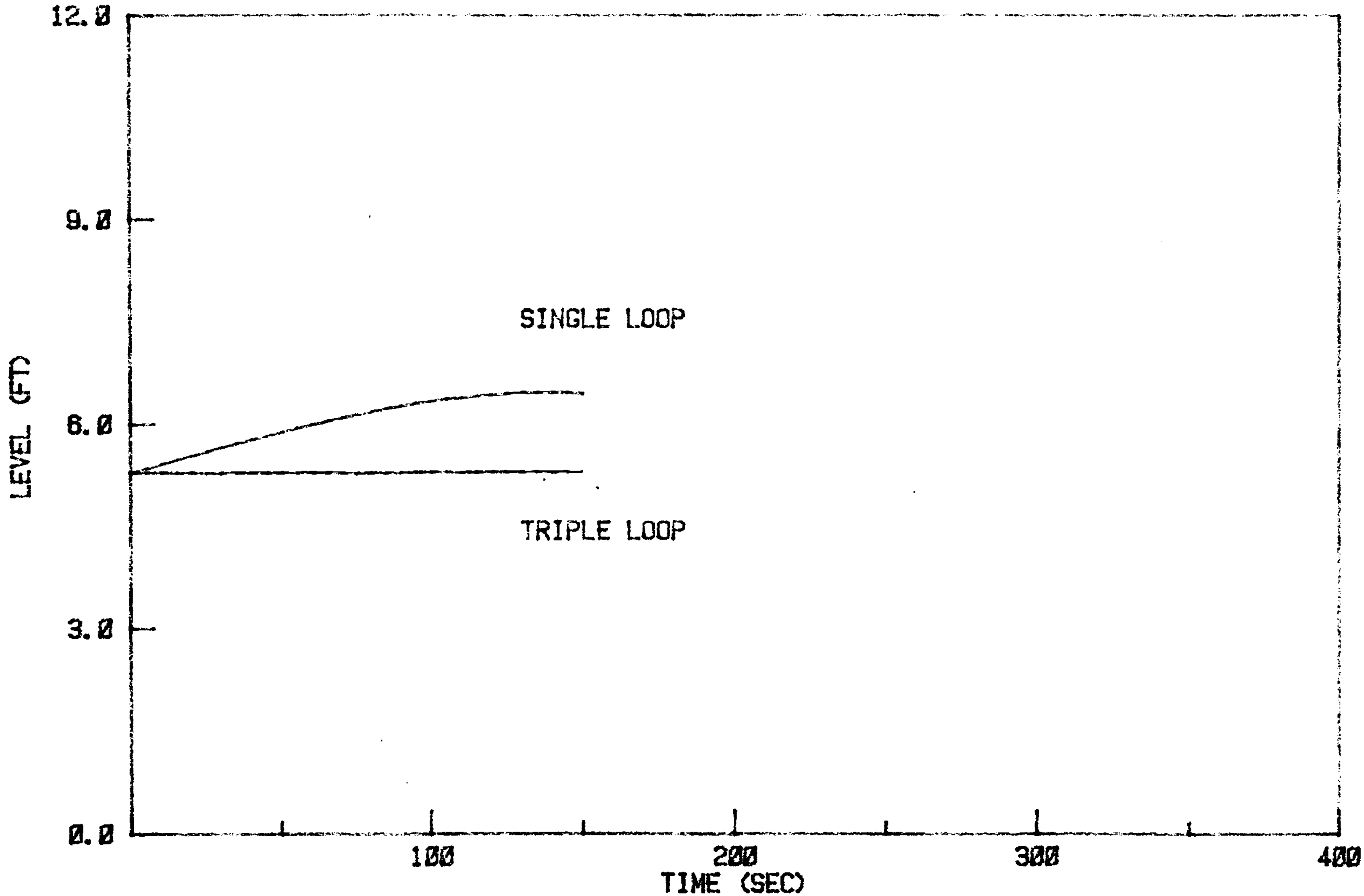

FIGURE B1. STEAM GENERATORS LEVEL INDICATION

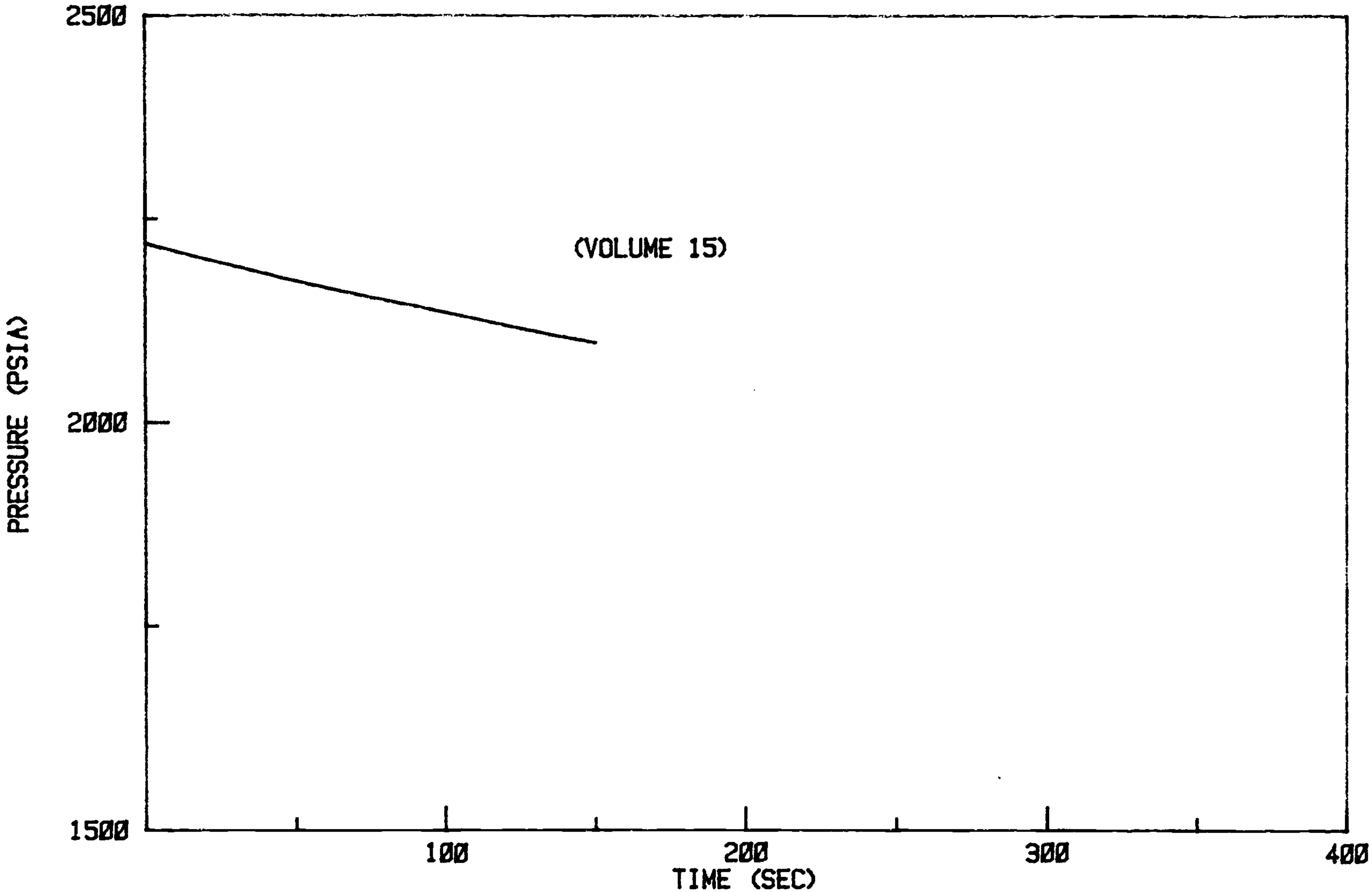

FIGURE B2. PRESSURIZER PRESSURE

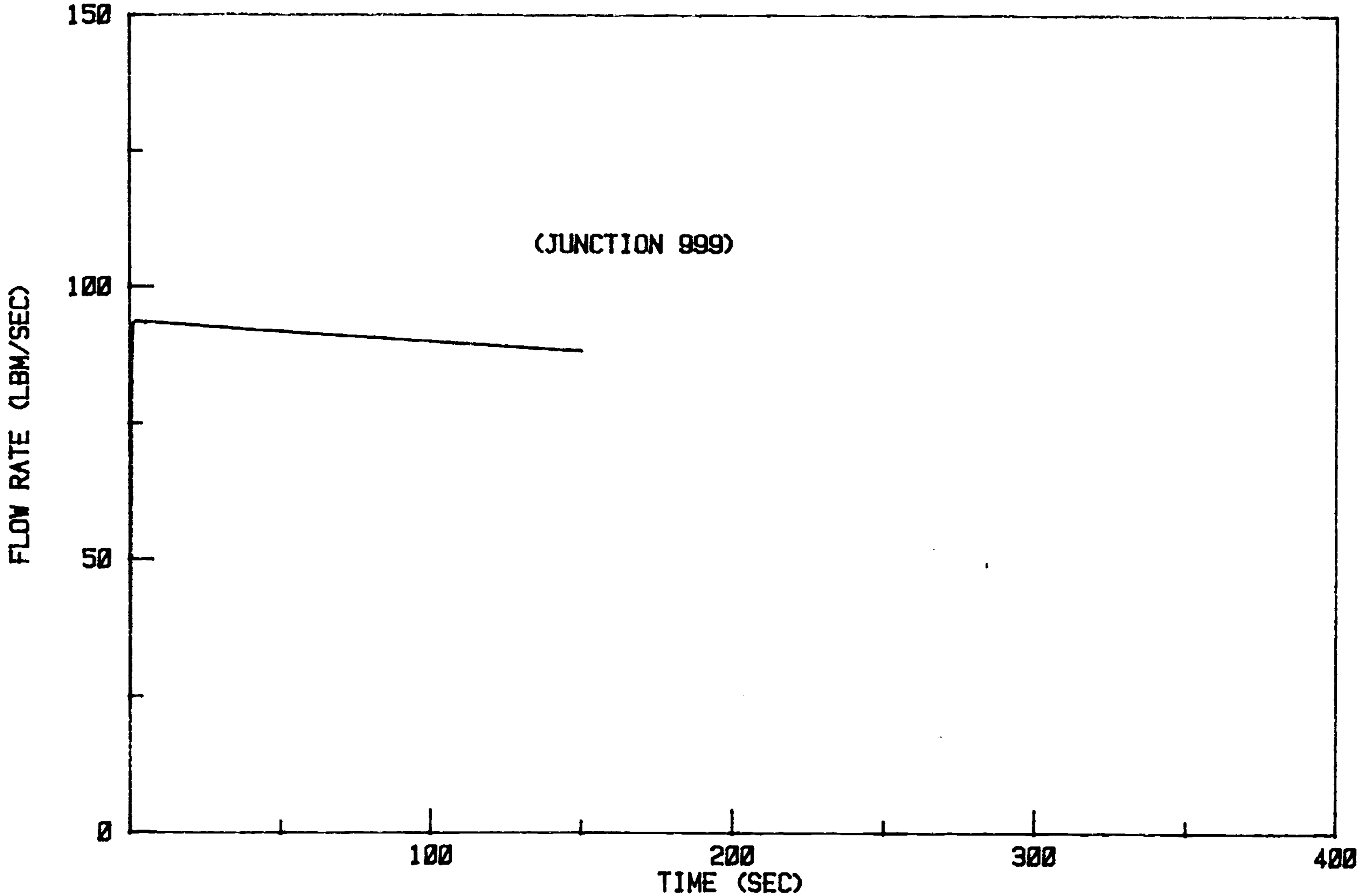

FIGURE B3. BREAK FLOW RATE

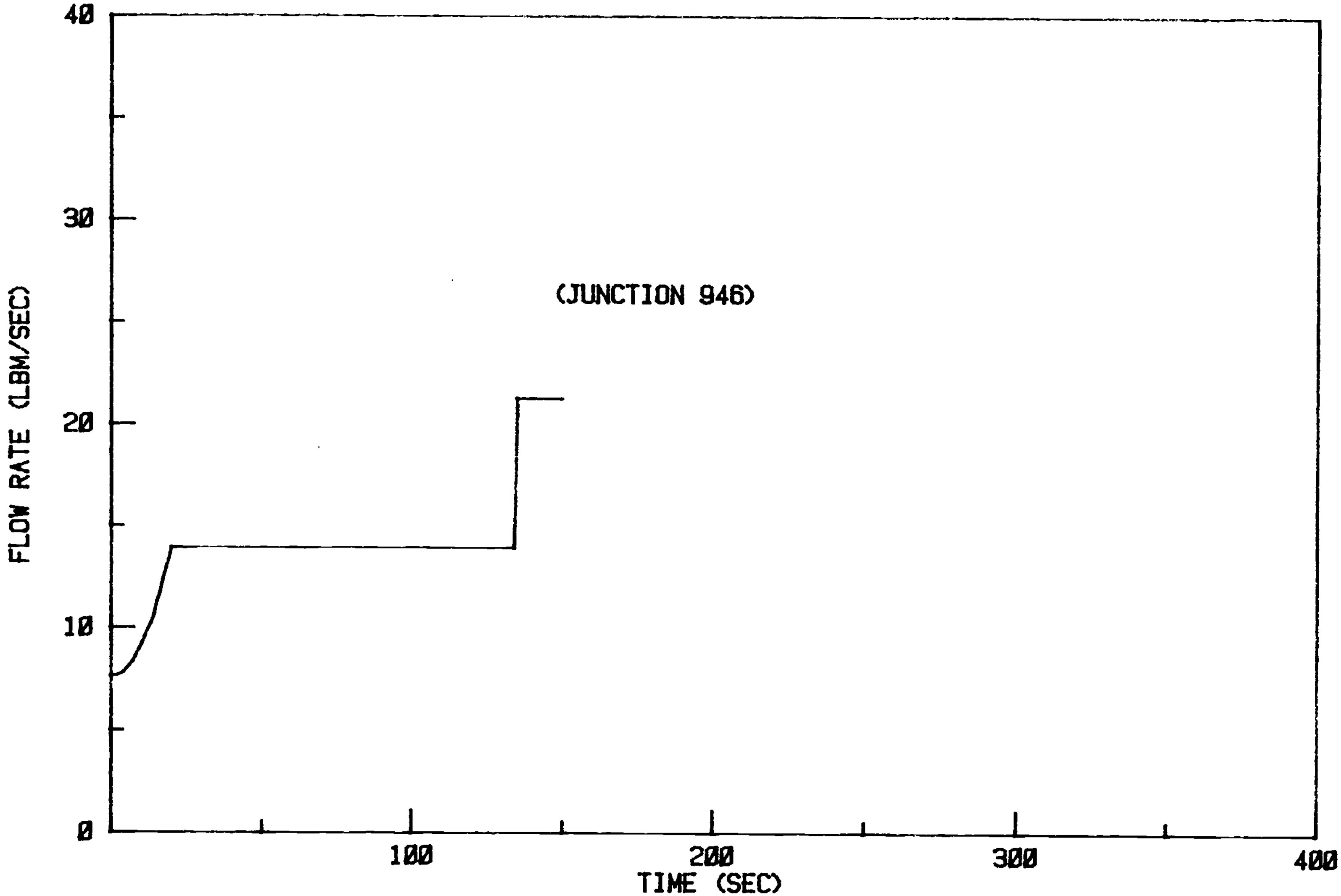

FIGURE B4. OUTPUT OF CHARGING FLOW CONTROLLER

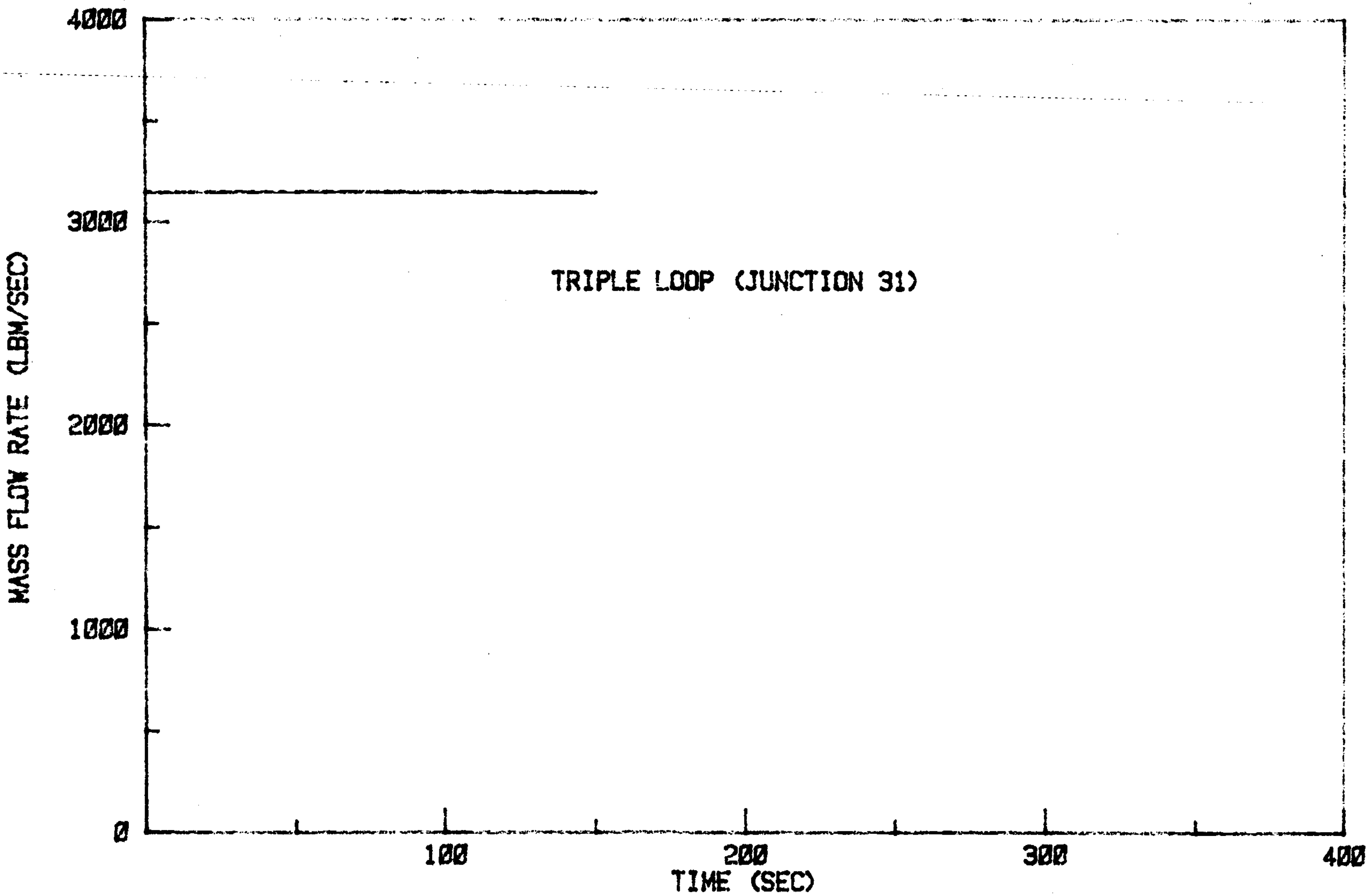

FIGURE B5. OUTPUT OF FEEDWATER CONTROLLER (TRIPLE LOOP)

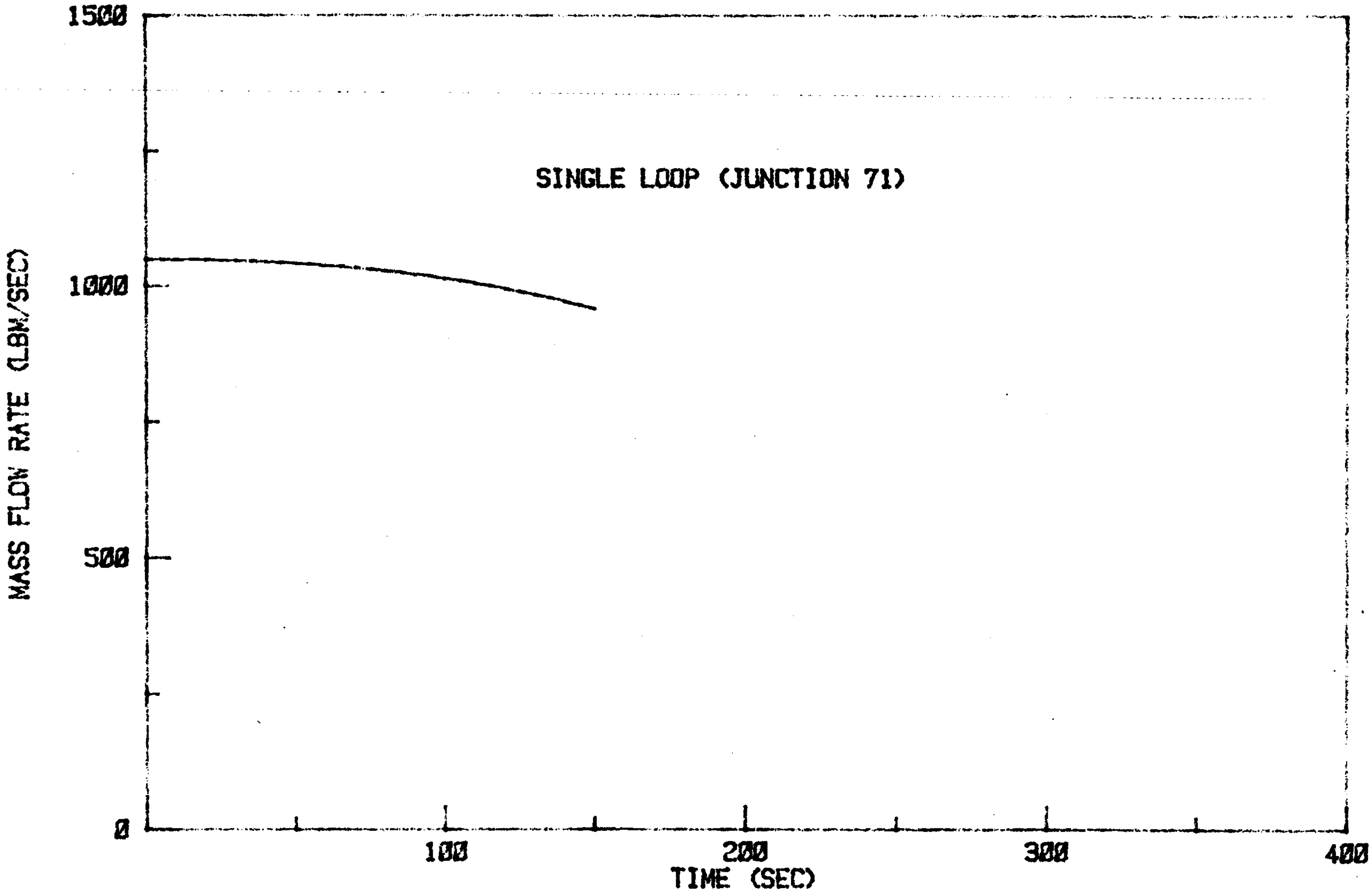

FIGURE B6. OUTPUT OF FEEDWATER CONTROLLER (SINGLE LOOP)

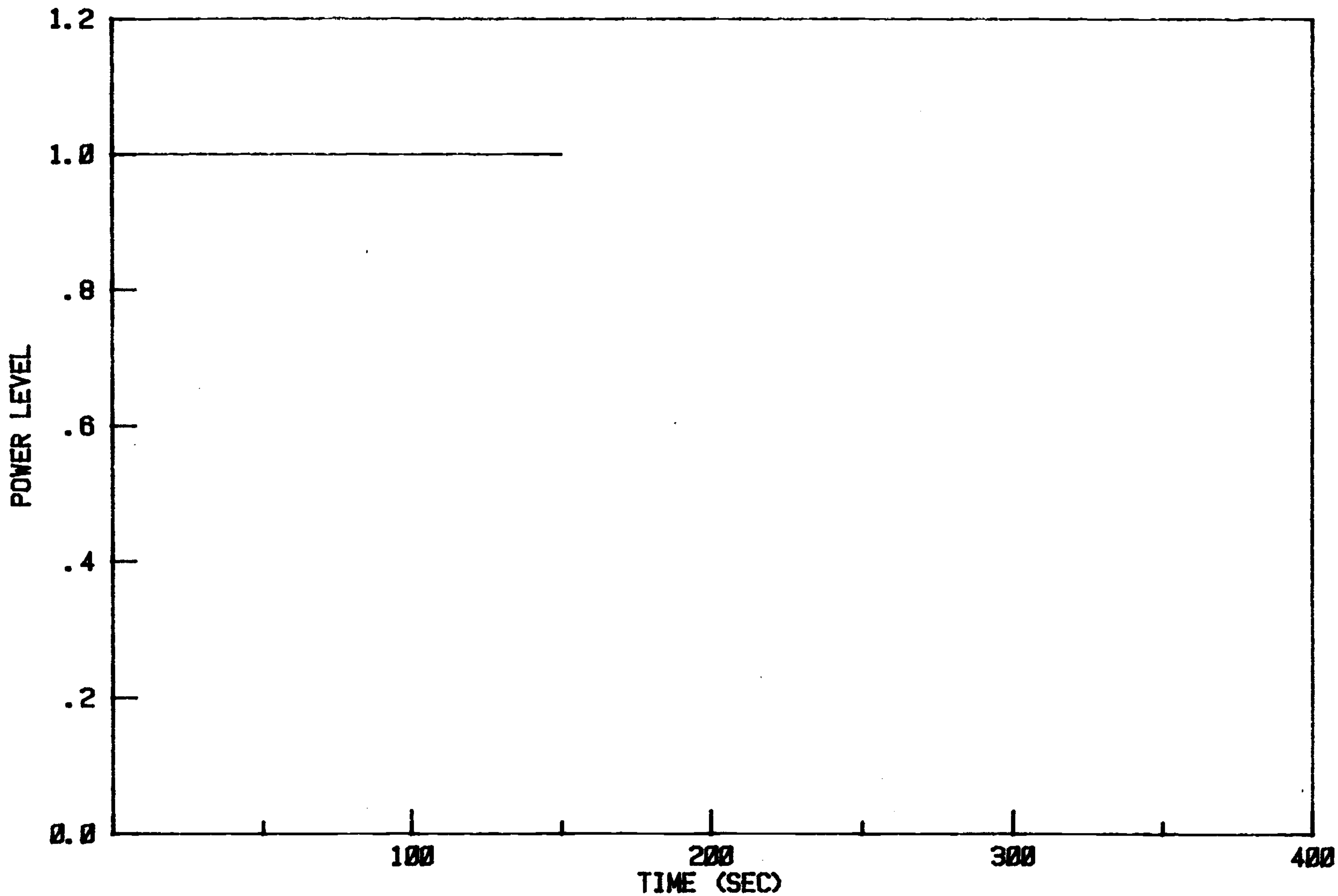

FIGURE B7. OUTPUT OF CONTROL ROD CONTROLLER