

Sakabe, Akira. **Steam Generator Liquid Mass as a Control Input for the Movement of the Feed Control Valve in a Pressurized Water Reactor.** (Under the direction of J. Michael Doster)

The steam generator in a nuclear power plant plays an important role in cooling the reactor and producing steam for the turbine-generators. As a result, control of the water inventory in the steam generator is crucial. The water mass in the steam generator cannot be measured directly, so the water mass is generally inferred from the downcomer differential pressure as a measure of the downcomer water level.

The water level in the downcomer is a good indication of the water mass inventory at or near steady-state conditions. Conventional PI controllers are used to maintain the water level in the downcomer between relatively narrow limits to prevent excessive moisture carryover into the turbine or the uncovering of the tube bundle. Complications arise in level control with respect to mass inventory due to the short-term inverse response of downcomer level. This is also known as shrink and swell.

Due to the complications that arise from level control, one would like to directly control the mass inventory in the steam generator. Currently, the mass inventory is not a measurable quantity, but through the use of computer simulation can be calculated. Design and analysis of the new controller will be performed by simulation.

The focus of this research was to develop and design, test, and implement a liquid mass inventory controller that would allow for safe automatic operation during normal and accident scenarios. In designing the new controller, it is assumed that the normal plant safety functions are not impacted by the mass controller. Optimal settings for the new mass controller are sought such that the mass control program will have rapid response and avoid reactor trips under

automatic control if the downcomer level protection setpoints do not induce a trip for the same transient.

For future analysis, it is proposed that neural networks be used in water mass observer instead of calculated simulation results.

**Steam Generator Liquid Mass as a Control Input for the Movement of the Feed Control
Valve in a Pressurized Water Reactor**

by

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Biography

Akira Sakabe was born in Japan on May 3rd, 1976. He is the first son of Osamu and Keiko Sakabe. His family moved to the United States when he was 3 years old.

Akira received his Bachelor's Degree in Nuclear Engineering from North Carolina State University in 1998. He began his graduate work in 1998.

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I would like to express thanks for my parents, especially my mother for her support, inspiration and encouragement throughout my work.

I would also like to dedicate this dissertation to my late grandfather who inspired me when I was a young boy to think differently and beyond.

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1. Introduction

The steam generator in a nuclear power plant plays an important role in cooling the reactor and producing steam for the turbine-generators. As a result, control of the water mass inventory inside of the steam generator is crucial. The water mass in the steam generator cannot be measured directly, so the water mass is generally inferred from measurements of downcomer differential pressure as a measure of the downcomer water level.

Introduction to Problem

The water level in the downcomer is a good indication of the water mass inventory at or near steady-state conditions. Conventional PI controllers are used to maintain the water level in the downcomer between relatively narrow limits to prevent excessive moisture carryover into the turbine or the uncovering of the tube bundle. Complications arise in level control with respect to mass inventory due to the short-term inverse response of downcomer level during feedwater and steam flow changes. This is also known as shrink and swell. These problems are magnified during low power operations and automatic control schemes react poorly under these conditions. Many studies have shown that unsatisfactory performance of the level control system in nuclear reactors is a major contributing factor to plant unavailability ^(S8).

Method

The water mass inside the steam generator represents the true cooling capacity of the steam generator, so the water mass is a desirable quantity for control. Since the water mass is not a directly measurable quantity in nuclear steam generators, the design and analysis of a new controller based upon mass will be performed by simulation. Results from this analysis will become the foundation for the development of a neural net based mass estimator for closed loop

feedwater control. As a result of using the water mass for control, many of the complications that arise from level control maybe eliminated.

The water mass controller will be tested on an existing PWR simulation program developed at NCSU ^(S5). The PWR simulation program has been benchmarked against actual plant data and proven capable of modeling an actual PWR plant over a wide range of conditions. In the existing model, a conventional PI controller is used for level control in the steam generator. Results generated from both the existing level and mass controllers will be examined, and will determine if mass control is feasible for the steam generator.

Associated Earlier Work

Steam generator level control has been studied extensively for many years. Mass control has only been examined recently. Research efforts in these areas are summarized as follows:

Choi et al. ^(S2) states that replacing the current analog control loop for the steam generator water level with digital computer control expands the range of possible solutions. Their work shows that the digital computer makes it possible to accommodate highly nonlinear and advanced control schemes. The controller is based upon a low order, nonlinear, fast-running model and compensates the level measurement for shrink and swell effects which cause complications in level control during low power operations. With the stability control constraints eliminated or mitigated, the controller gain can be set for optimum capability. This model was used and verified with actual plant data. Even at lower powers, the gain that was used ensured a fast effective response in handling large perturbations with no stability problems.

Chun et al ^(S3) discusses a qualitative and quantitative modeling method for a steam generator in a nuclear power plant. Modeling of the steam generator is difficult due to the fact that the steam generator is nonminimum phase, which is mainly caused from the shrink and swell

phenomena. In order to accurately model the steam generator, Chun proposes using a logic processor, whose structure can easily be interpreted. Chun uses properties of OR and AND neurons of the logic processor to perform qualitative and quantitative modeling of the steam generator. From the logic processor model, Chun was able to obtain a quantitative model simulating the dynamics of the steam generator for each power rate and a qualitative description of the model expressing the behavior of the steam generator.

Dong et al. ^(S4) proposes a possible solution to the level control problem associated with shrink and swell at lower power levels. The paper states it is possible to use a water mass controller, which would eliminate the shrink and swell problems. Level control in the steam generator is complicated by non-minimum phase, variation of plant dynamics with operating power, and unreliable flow measurements at low power levels. The mass inventory however provides two advantages. First, it has minimum phase, which would simplify both the control system design as well as manual operation; and second, the water mass inventory is the true measure of the instantaneous cooling capacity of the steam generator. Yet, with these advantages, the water mass inventory is not a measurable quantity. Dong et al. then proposes the use of multi-layer neural networks that have been trained to observe the water mass inventory in a typical U-Tube steam generator. The water mass observer performed well at high power levels but suffered from lower performance at lower power levels.

Hoceped et al. ^(S7) discusses the inherent problems associated with steam generator level control and provides some general solutions to these difficulties. Data from the Doel nuclear power station, which is comprised of two units rated at 392 MW(e) is utilized. The paper states that the level is practically impossible to control manually because the operator would have to react instantaneously to every important perturbation. Automatic control was possible and

achieved for zero load to full load change and large-scale perturbations without encountering any trips. The paper also notes that the results from the analysis can be used for any other pressurized water reactor stations.

Irving et al. ^(S8) adopts a simple adaptive control method for the steam generator water level. The mathematical models used to describe PWR steam generators are generally of a high order of complexity, which make them inadequate for use in the design of an automatic controller. Therefore, the paper introduces simplified transfer functions models, which can be used in the design of a controller, and compares these models with the data from more detailed models.

Kothare et al. ^(S9) discusses inherent problems that arise from using a level controller for a nuclear steam generator and offers some possible solutions to these problems. In several studies, it has been shown that many reactor trips and plant unavailability have been caused from unsatisfactory performance of the feedwater control system, particularly at low power. The difficulties in steam generator level control arise from: inverse response behavior in the steam generator, known as shrink and swell; variation of plant dynamics with operating power and unreliable flow measurements at low power. Kothare proposes that a model predictive control strategy be used for the steam generator. From the analysis, Kothare states that issues such as constraints on manipulated and controller variables, use of feedforward control, tracking of varying water level set-points and state estimation in the presence of noisy measurements can all be handled using model predictive control techniques.

Lang et al. ^(S10) present a computerized water level control system for an U-tube steam generator of the type used in the Qinshan Nuclear Power Plant. Lang states that the control system uses reactor operator experience for online correction of the controller parameters. A

linear state space model is obtained by piecewise linearizing the nonlinear equations. For the steam generator controller, two state-space models were used. A complete control system contains a global database, which contains controller parameters for different power levels; a rule base, where each operating range has a set of rules; inference engine, which decides which set of rules has to be selected and executed; and an interface for user convenience. With the computerized water level control system, Lang was only able to verify full power operating transients from the knowledge of an experienced reactor operator, but finishes by stating that plant data from lower power levels would improve the functioning of the proposed controller.

Na et al. ^(S11) examine and analyze the water level control system of steam generators during low power operations. The Compact Nuclear Simulator (CNS) set up in the Korea Atomic Energy Research Institute was used for the analysis. Na states that when the steam generator of a nuclear power plant is operated at low power levels, the water level is very unstable, and is a major factor causing reactor trip during start-up operation. The water level control at low power relies on experienced operators because the existing PI control system is unreliable. Therefore Na proposes on using fuzzy logic over a conventional PI controller. From the analysis, the fuzzy logic controller proved to be a better controller over the conventional PI controller.

From these previous works, there are complications that arise when using a level controller in the control of the steam generator mass inventory. Different level control strategies using computer simulations applied to nuclear steam generators have been examined to eliminate problems that arise from the shrink and swell phenomena and low power operational procedures. Most of the new control strategies used in the steam generator inventory control use neural

networks or fuzzy logic schemes. With the use of such schemes, system parameters that could not be measured before are now estimated and can be used as an observer.

2. Background Information

Nuclear power plants are tightly coupled complex systems consisting of a nuclear heat source, some type of heat exchanger, and a heat sink. Changes within system parameters at any location, such as flows rates, pressures, and reactivity, propagate and affect other system components. Due to the complexity of these systems, a reactor simulation is used to model the dynamic response of the nuclear power plant under normal operational and design basis transients. For this research, a Westinghouse Light Water Reactor with a U-tube type steam generator was examined.

Plant Overview

Pressurized Water Reactors (PWR's) consists of three loops: primary, secondary, and tertiary. The primary loop operates at sufficiently high pressure that no net boiling occurs. The primary loop consists of a heat source, the reactor core, contained within a reactor vessel. The heat produced in the core is transferred to the moderator/coolant and pumped to the steam generator, where heat is transferred across tubes to the secondary side. The coolant is then returned to the reactor core. Steam is produced in the secondary loop and channeled to the turbines, where thermal energy is converted into electrical energy. Latent heat of vaporization is rejected to the environment in the tertiary loop through a cooling tower or large water reservoir. Figure 2.1 represents a simple schematic of a PWR plant design.

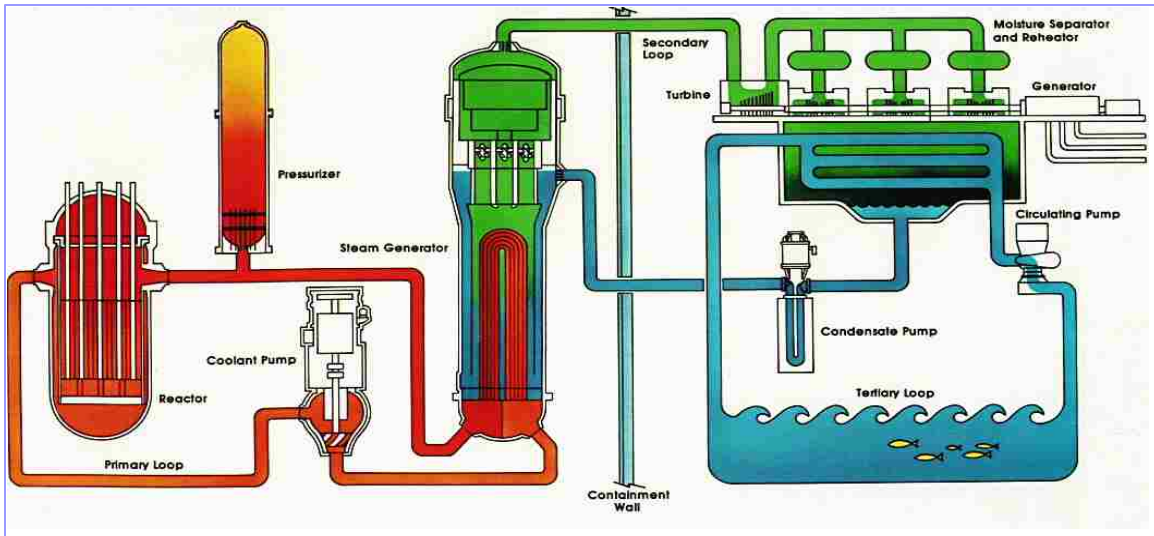


Figure 2.1: Simple Pressurized Water Reactor Design

Steam Generator

The steam generator is divided into a lower evaporator and an upper steam drum. The evaporator consists of the U-tube heat exchanger and the steam drum consists of the moisture separating equipment. On the primary side, high temperature coolant flows into the inlet plenum through the U-tubes and out through the outlet plenum. The U-tubes are welded to a tubesheet. The space under the tubesheet is divided in two sections by a divider plate, which separates the inlet and outlet high temperature primary coolant. In many steam generator designs, the feed water enters the steam generator from a nozzle located in the upper shell and is distributed by a feed water ring into the downcomer. The feed water mixes with the recirculation flow and flows down to enter the tube bundle just above the tube sheet. The steam that is generated passes through moisture separators and leaves the steam generator with a quality of approximately 99.75% (0.25% moisture content). Figure 2.2 represents a typical U-tube steam generator.

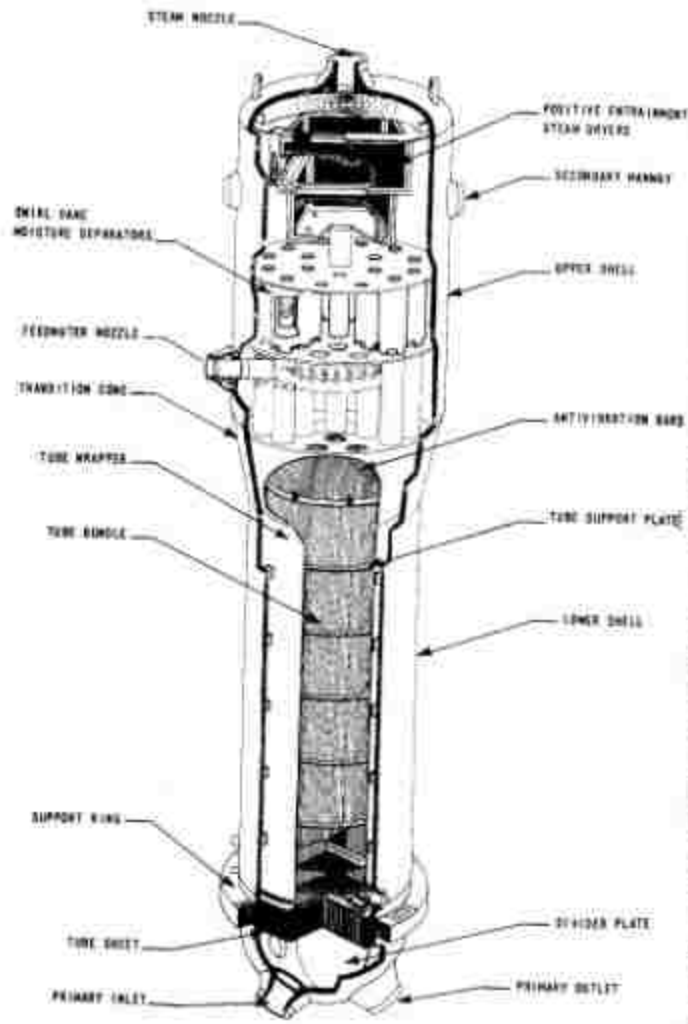


Figure 2.2: U-Tube Steam Generator

Current Steam Generator Model

The cooling capacity of the steam generator is a function of the liquid mass inventory in the tube bundle region. As the liquid mass inventory cannot be measured directly, the liquid mass inventory in the steam generator is generally inferred from the water level in the downcomer. At steady-state or near steady-state conditions, the level in the downcomer is a reasonable indication of the liquid mass.

However, under certain transient conditions, the downcomer liquid level is not a good indication of the liquid mass inventory due to complications resulting from shrink and swell.

Due to the non-linear flow dynamics within the tube bundle region, the water level in the downcomer temporarily reacts in a reverse manner to the liquid mass inventory change following a perturbation. The only true indication of the liquid mass inventory change is the flow mismatch between the steam and feed. However, at lower power levels, instrumentation uncertainties render steam and feed flow measurements unreliable.

A conventional controller is illustrated in Figure 2.3. The desired downcomer liquid level (reference level) is programmed as a function of turbine load.

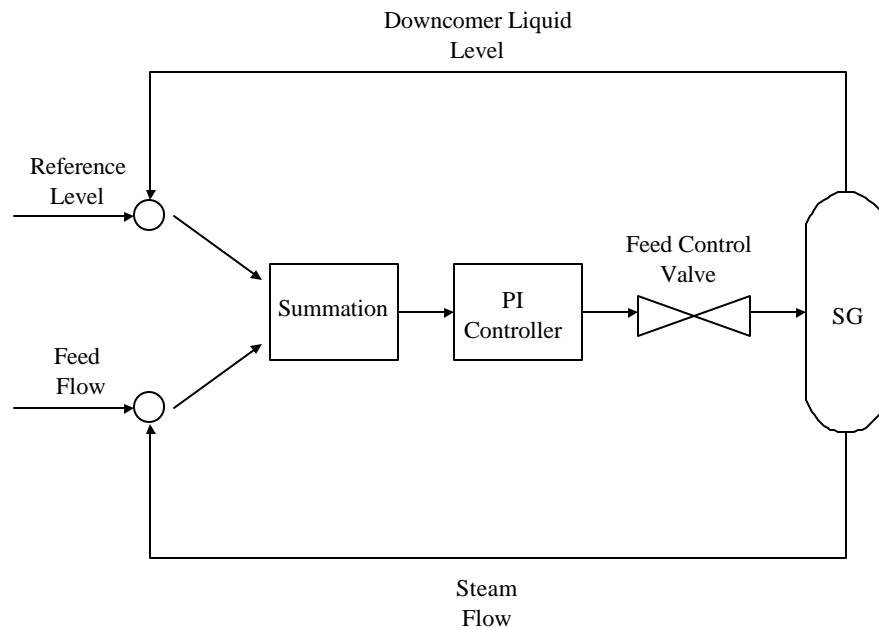


Figure 2.3: **Level Control Scheme**

A level error signal is calculated by computing the difference between the reference level and the actual measured downcomer liquid level. If the reference level is greater than the actual level, this results in a signal that opens the Feed Control Valve (FCV); if the actual level is greater than the reference level, this results in a signal that closes the FCV. A flow error signal is calculated from the difference between the feed and steam flows. If the steam flow is greater than the feed flow, this results in a signal that opens the FCV; if the feed flow is greater than the steam flow,

this results in a signal that results in a signal that closes the FCV. In a three element controller, the level error and flow error are combined to produce a single error signal, which is used to modulate the FCV.

A conventional three-element controller can be described by the following equation:

$$E_t = k_p (\omega_F e_F + \omega_L e_L) + k_i \int (\omega_F e_F + \omega_L e_L) dt \quad \text{Equation 2.1}$$

where

- E_t = Total Error Signal
- e_F = Flow error ($F_s - F_{fw}$)
- e_L = Level Error ($L_r - L_w$)
- L_r = Reference (programmed) level
- L_w = Downcomer water level
- k_p = Proportional gain
- k_i = Integral gain
- ω_L = Level error weight
- ω_F = Flow error weight
- F_{fw} = Feed flow
- F_s = steam flow

A positive error signal would result in an opening of the FCV, while a negative error signal would result in a closing of the FCV.

Steam Generator Complications Due to Shrink and Swell

The fluid in the lower part of the steam generator is a mixture of water and steam and is susceptible to a phenomena known as shrink and swell. The shrink and swell phenomena can be best understood when examining the water and steam mixture during changes in steam flow, feed flow and temperature.

When steam flow decreases due to a reduction in the turbine load, the rate of steam removal drops below the rate of steam production. At equilibrium, this change introduces an increase in pressure in the steam generator, causing the vapor in the liquid and steam mixture to collapse. With the collapse of the vapor, the volume of the liquid and vapor mixture decreases

causing the level in the downcomer to decrease. The liquid mass in the steam generator however is increasing because the feed flow is greater than the steam flow.

When the steam flow increases due to an increase in the turbine load, the rate of steam removal increases above the rate of steam production. At equilibrium, this change introduces a decrease of pressure in the steam generator, causing an expansion of the vapor in the liquid and steam mixture. With the expansion of the vapor, the volume of the liquid and steam mixture increases, causing the level in the downcomer to increase. The liquid mass in the steam generator however is decreasing because the feed flow is less than the steam flow.

Changes in temperature also cause shrink and swell. As relatively cold feed water flow increases, the inlet enthalpy entering the steam generator decreases causing the liquid and steam mixture to shrink. As feed water flow decreases, the inlet enthalpy entering the steam generator increases causing the liquid and steam mixture to swell.

Figures	Transient	Initial Power	Controller
2.4-2.7	+10% Step Increase in Load	80%	Level
2.8-2.11	-10% Step Increase in Load	80%	Level

Table 2.1 **Transients Examined for Shrink and Swell**

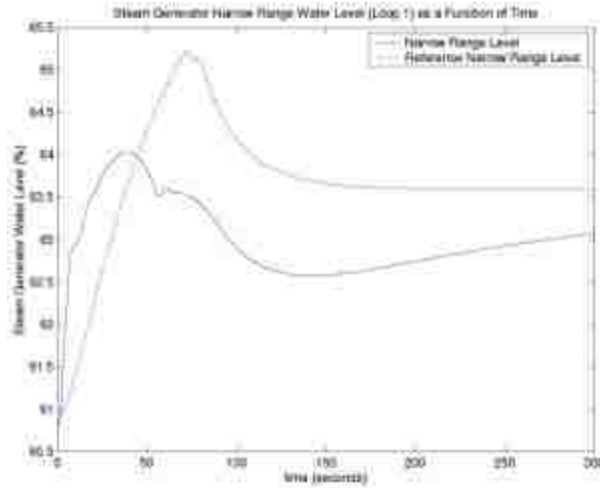


Figure 2.4

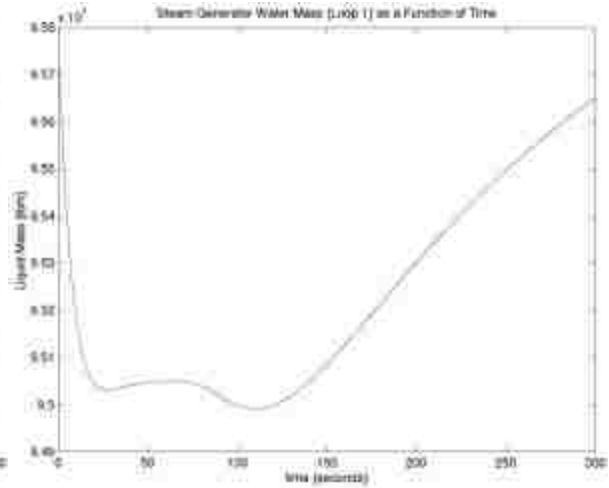


Figure 2.5

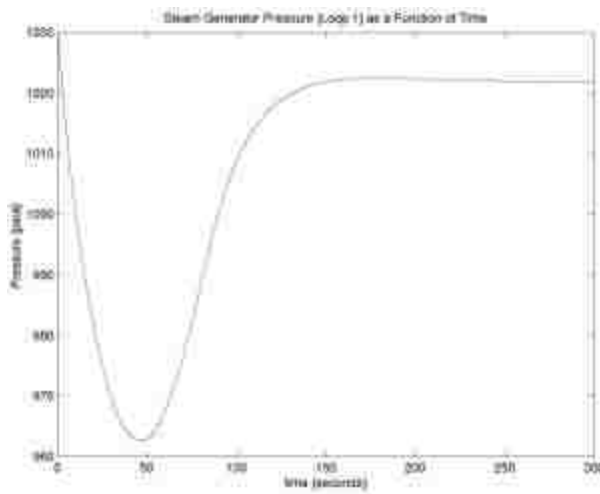


Figure 2.6

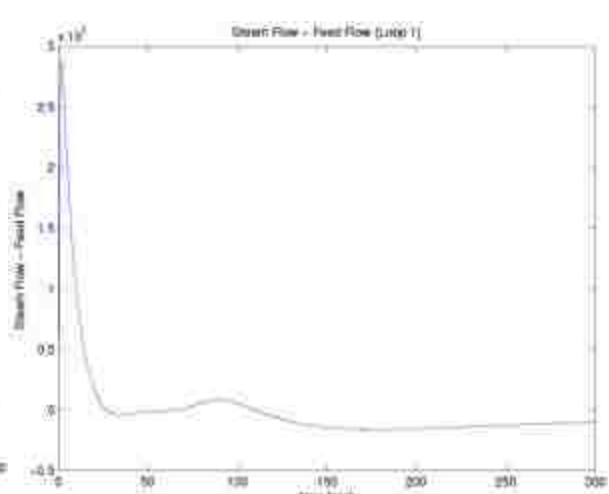


Figure 2.7

A +10% step increase transient from 80% power under level control.

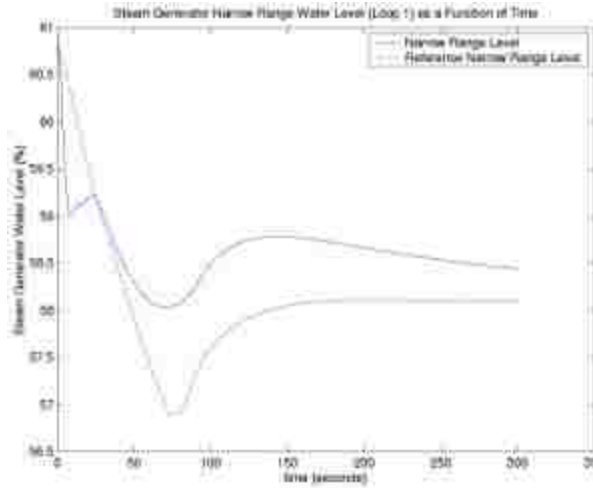


Figure 2.8

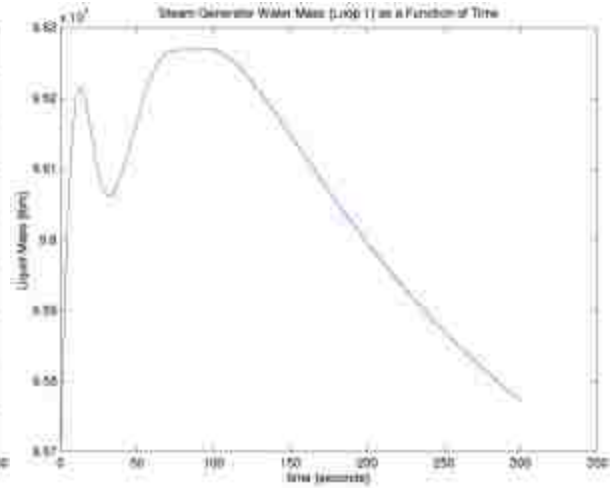


Figure 2.9

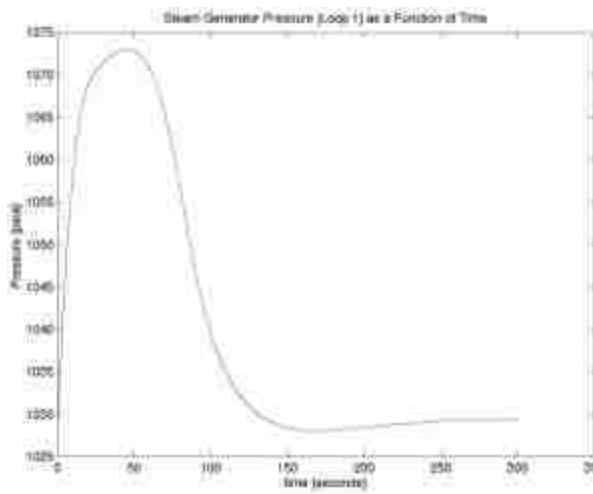


Figure 2.10

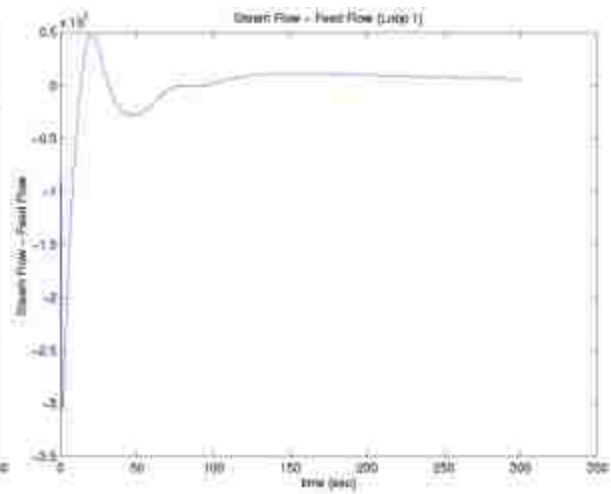


Figure 2.11

A -10% step decrease transient from 80% power under level control.

Figures 2.4-2.7 represent a +10% step increase and figures 2.8-2.11 represent a –10% reduction, both from 80% power. The steam generator level is supposed to indicate the liquid mass inventory inside of the steam generator. However from the above figures, in the early portions of the transients, the water level acts in a reverse manner to the mass. Note however that as the feed flow increases above the steam flow, there is an increase in the liquid mass inventory; as the feed flow decreases below the steam flow, there is a decrease in the mass inventory. Thus, the mass inventory is not affected by shrink and swell and would be an ideal element for control for the steam generator.

New Type of Steam Generator Controller

Due to the complications that arise from level control, one would like to directly control the mass inventory in the steam generator. Currently, the mass inventory is not a measurable quantity, but through the use of computer simulation can be calculated. Therefore, it is assumed that a mass inventory estimator can be developed to make a feasible mass controller. The focus of this research paper is to design, test, and implement a liquid mass inventory controller. The performance of the new controller will be compared to that of a conventional level controller. A design constraint for the new controller is that it would be able to handle normal operational transients as well as selected accident scenarios without causing a reactor trip if the conventional level controller does not induce a trip. Since the liquid mass in the steam generator is not a directly measurable quantity in nuclear steam generators, design and analysis of the new controller will be performed by simulation.

Design Parameters and Implementation

In designing the new controller, it is assumed that the normal plant safety functions are not impacted by the mass controller. Steam generator liquid mass inventory trips are still based on the measured level in the downcomer. Control parameters and characteristics, such as gains and time constants, can be modified to accommodate the mass control program. Optimum control settings are sought such that the mass control program will have rapid response and avoid reactor trips under automatic control if the level program does not induce a trip for the same transient.

For the liquid mass inventory controller, a PI type controller is used to control the feed water flow into the steam generator, allowing continued use of the existing controller. The output of the new controller can be described by the following equation:

$$E_t = k_p (\omega_F e_F + \omega_l e_m) + k_i \int (\omega_F e_F + \omega_l e_m) dt \quad \text{Equation 2.2}$$

where

E_t = Total Error Signal

e_F = Flow error ($F_s - F_{fw}$)

e_m = Mass Error ($m_{ref} - m_t$)

k_p = Proportional gain

k_i = Integral gain

ω_l = Level error weight

ω_F = Flow error weight

F_{fw} = Feed flow

F_s = steam flow

The liquid mass control scheme is illustrated in the following figure (Figure 2.12).

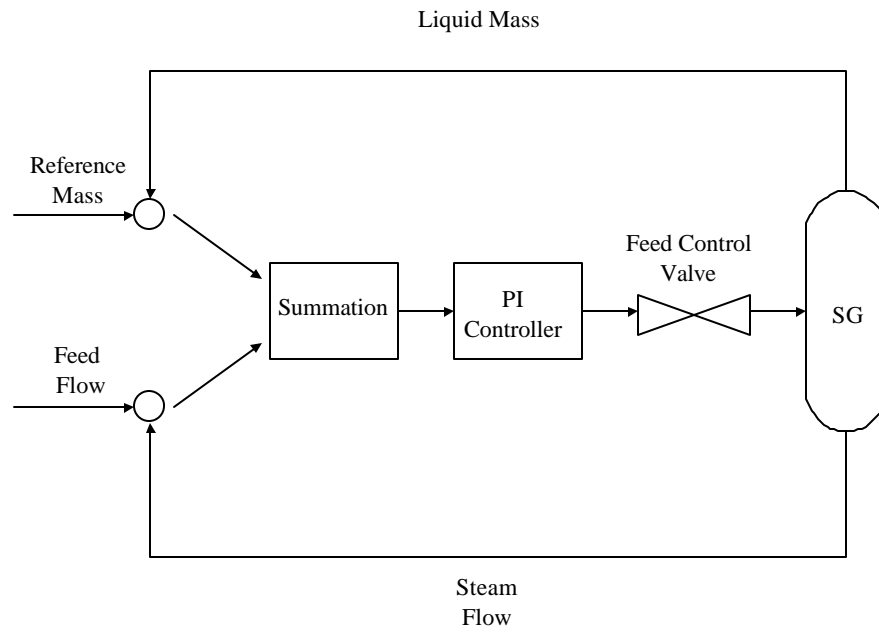


Figure 2.12: **Liquid Mass Control Scheme**

Once optimum control settings have been established, a wide range of operational, accident, and low power scenarios will be examined.

3. Results

Conventional liquid level controllers feature a reference liquid level which is a function of the plant operating power level. The steam generator programmed reference liquid level for a conventional controller is shown in Figure 3.1. The programmed reference liquid level produces a corresponding steady state liquid mass as shown in Figure 3.2.

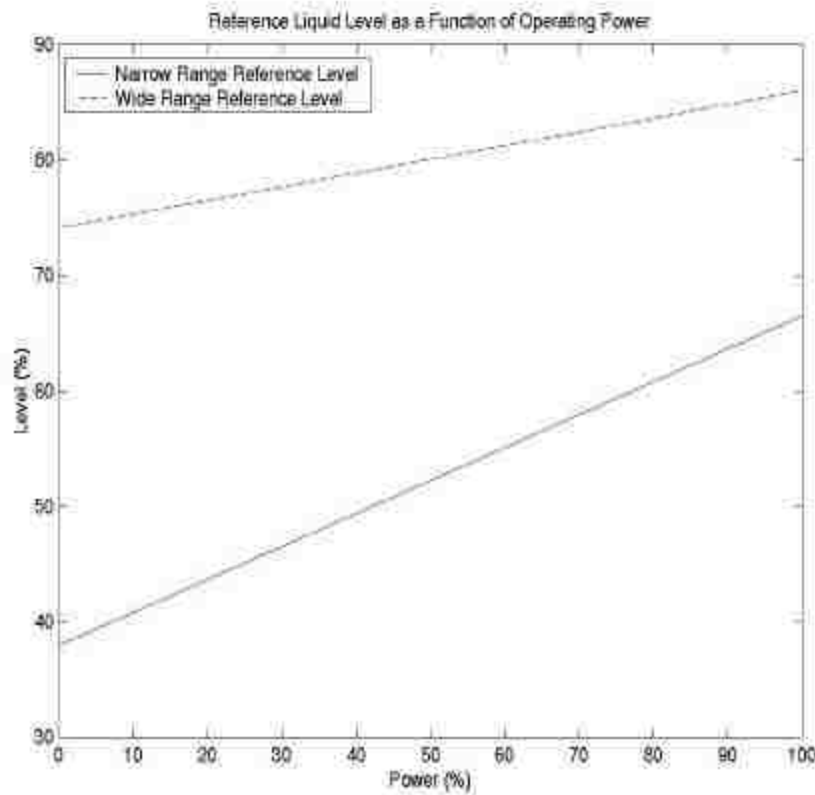


Figure 3.1

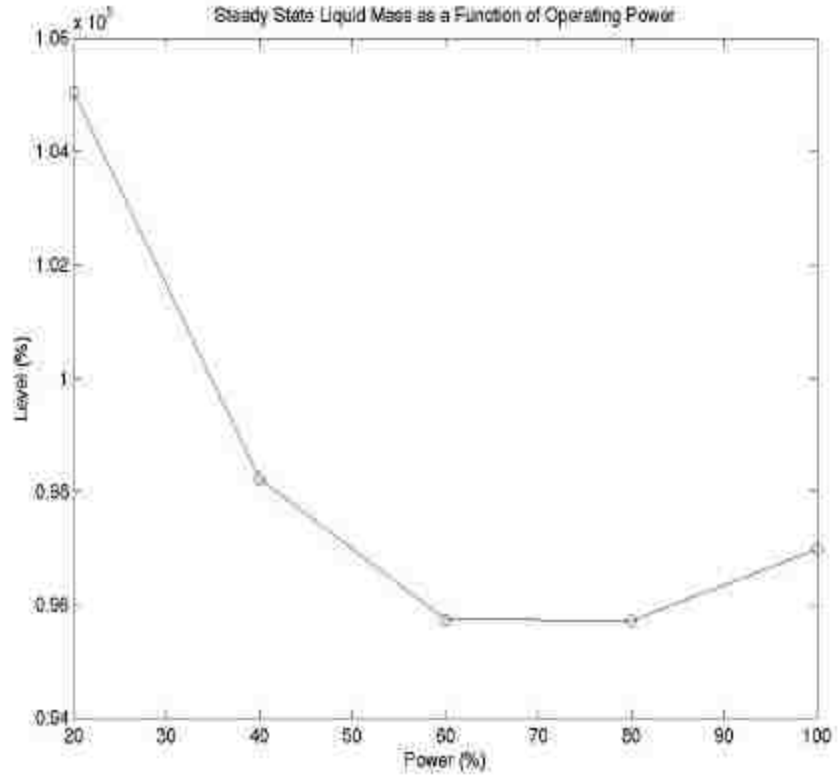


Figure 3.2

These results imply a control strategy based upon a reference mass may be desirable. Two types of control strategies were examined; the first sought to maintain a constant liquid mass in the steam generator and the second sought to control the liquid mass about some reference or programmed value.

Level Controller Transients

In the design of the mass controller, normal operational transients using the level controller were examined.

Figures	Transient	Initial Power	Controller
3.3-3.6	-10% Step Decrease in Load	100%	Level
3.7-3.10	-5% per minute Ramp Decrease in Load for 2 minutes	100%	Level
3.11-3.14	+10% Step Increase in Load	20%	Level
3.15-3.18	+5% per minute Ramp Increase in Load for 2 minutes	20%	Level

Table 3.1: Transients Examined Using a Level Controller

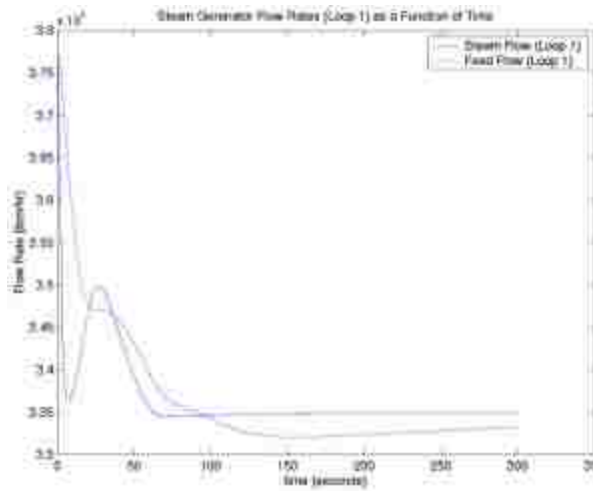


Figure 3.3

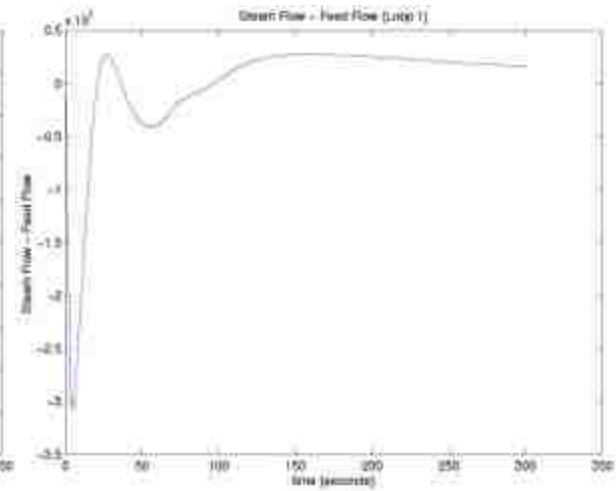


Figure 3.4

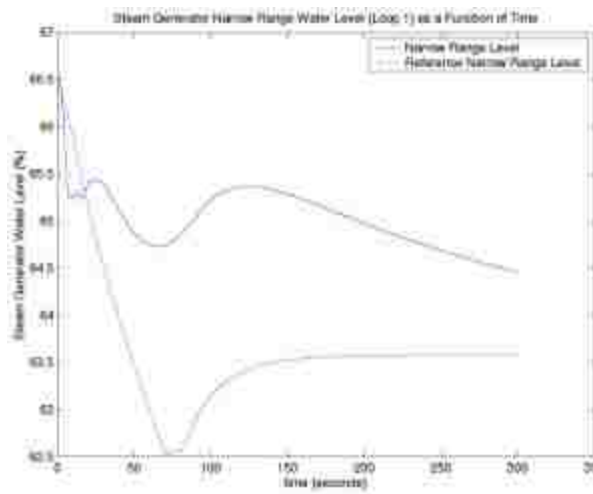


Figure 3.5

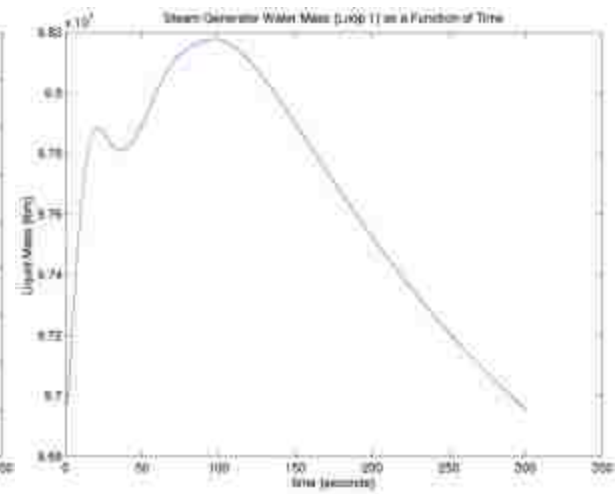


Figure 3.6

A -10% step decrease in load from 100% power transient under level control.

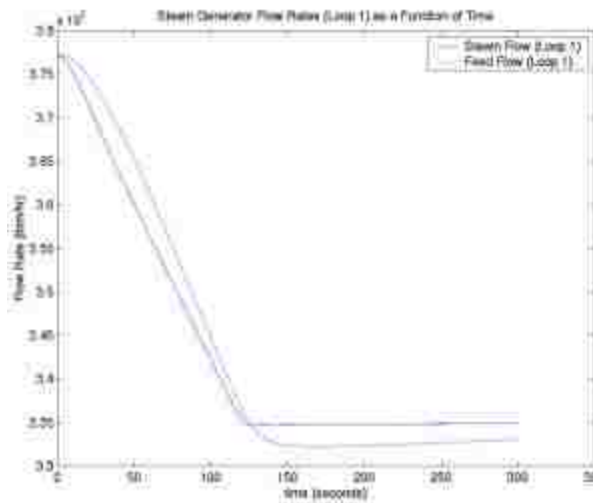


Figure 3.7

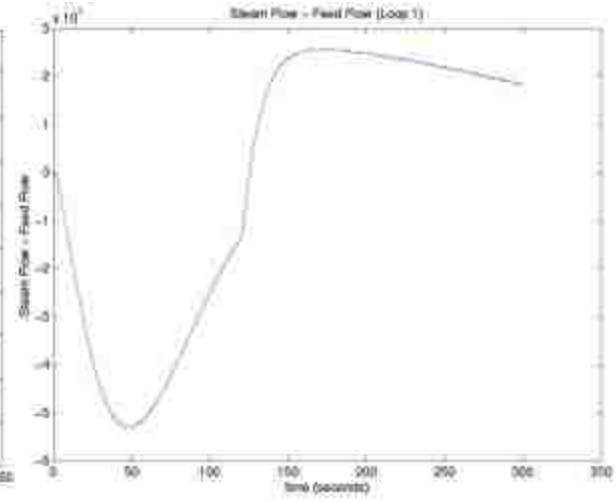


Figure 3.8

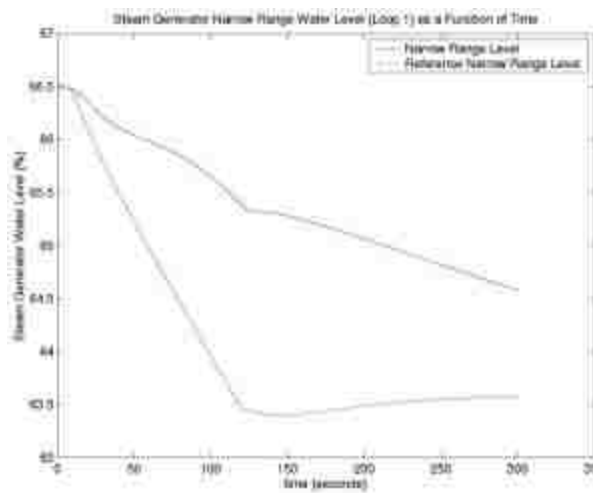


Figure 3.9

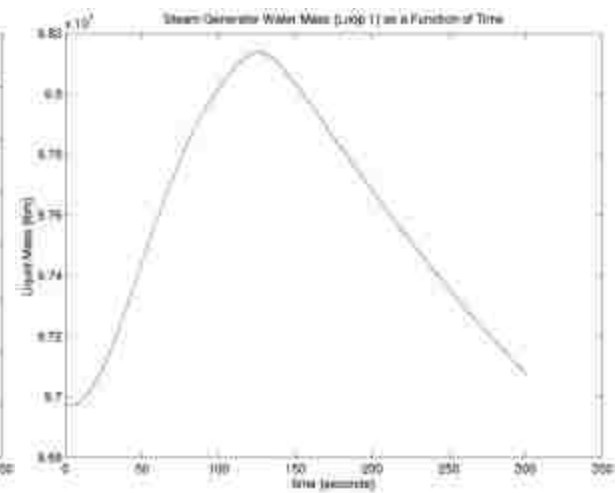


Figure 3.10

A -5% per minute ramp decrease in load for two minutes from 100% power transient under level control.

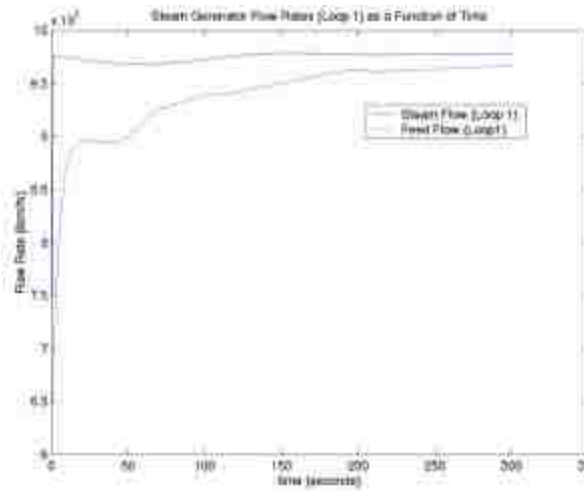


Figure 3.11

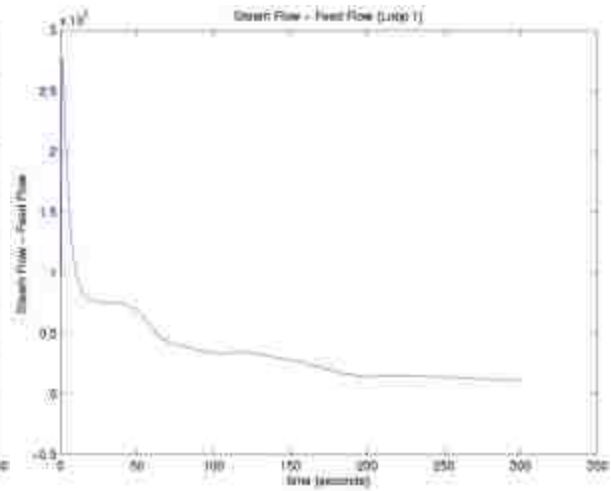


Figure 3.12

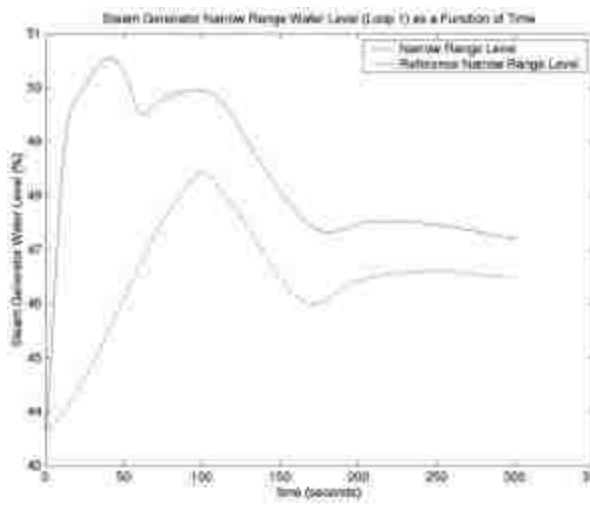


Figure 3.13

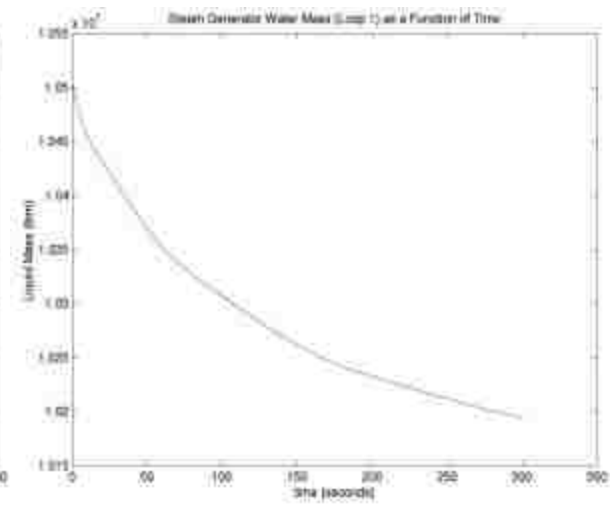


Figure 3.14

A +10% step increase in load from 20% power transient under level control.

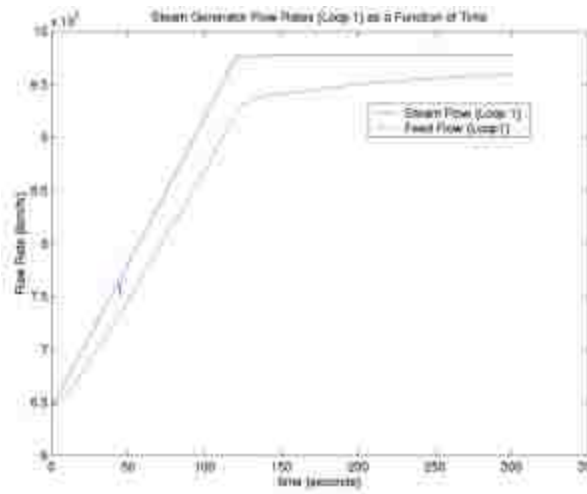


Figure 3.15

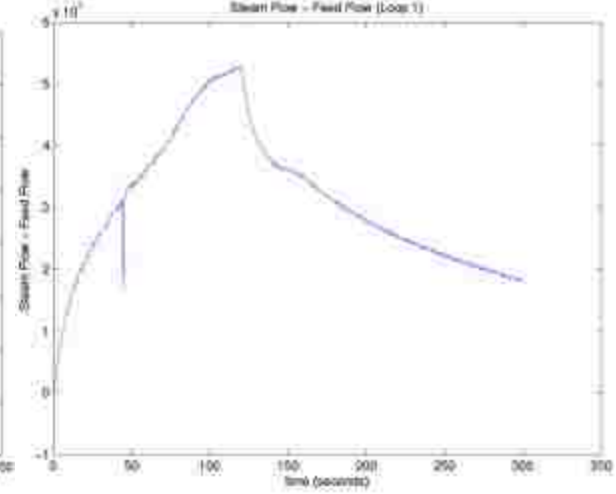


Figure 3.16

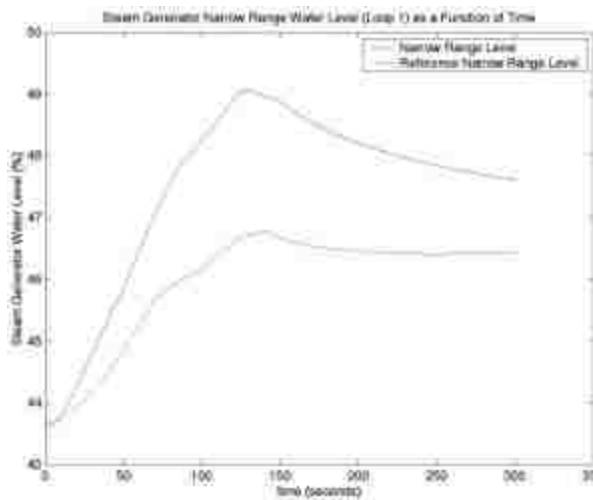


Figure 3.17

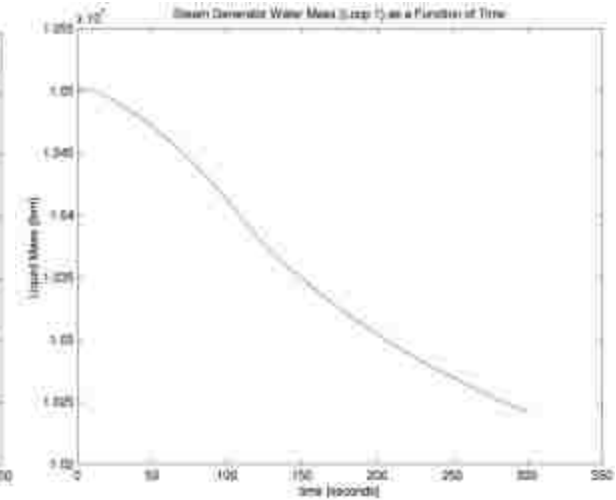


Figure 3.18

A +5% per minute ramp increase in load for two minutes from 20% power transient under level control.

From these figures, in both the step and ramp change, the steam generator liquid level showed signs of the shrink and swell phenomena. For the decreases in load, during the beginning of the transients, the liquid level in both transients is decreasing, but in fact the liquid mass is actually increasing. For the increase in load, during the beginning of the transient of the transients, the liquid level in both transients is increasing, but in fact the liquid mass is decreasing. In these transients, the level controller was capable of handling these transients.

Constant Liquid Mass

Constant mass control strategies involve maintaining a constant reference mass throughout the full operating range. The reference mass settings were found using the steady state mass from the level controller.

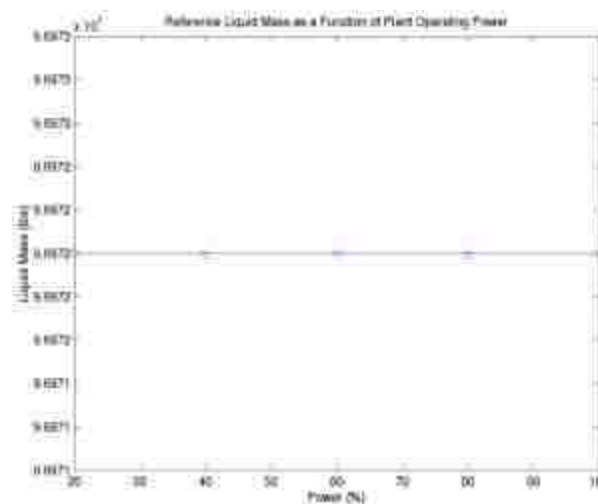


Figure 3.19
Constant Mass Control Strategy A

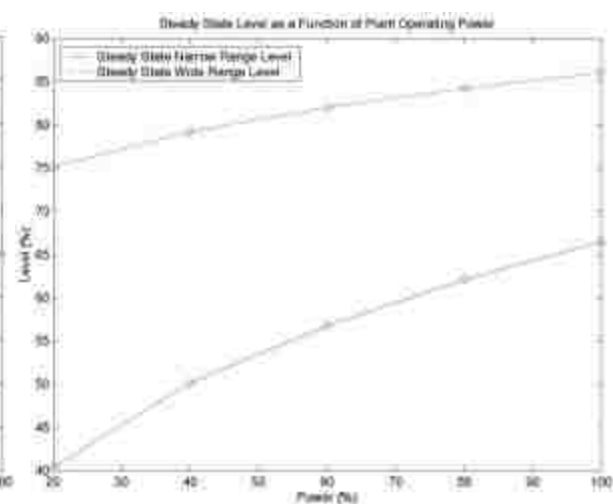


Figure 3.20

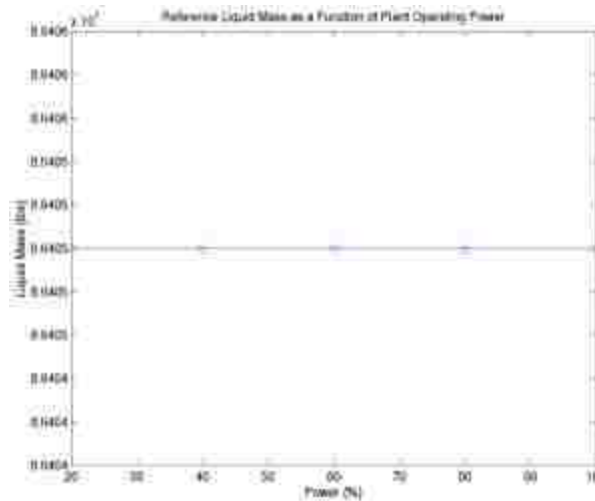


Figure 3.21

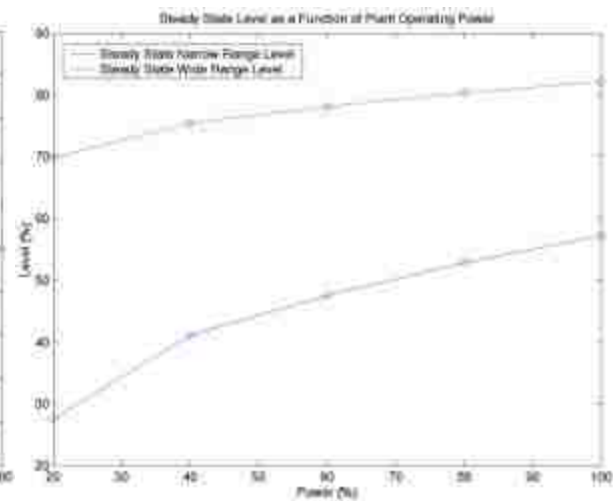


Figure 3.22

Constant Mass Control Strategy E

A large range of constant mass controllers was examined. Mass control strategies A and E are illustrated in Figures 3.19-3.22 and represent upper and lower bounds. Therefore mass control strategy A has the largest reference mass while mass control strategy E has the smallest reference mass. The reference liquid mass for Mass Control Strategy A was obtained from the steady state liquid mass of 100% power using the level controller, where the reference liquid mass for Mass Control Strategy E was obtained from the steady state liquid mass of 20% power using the level controller. From the above figures, it is interesting to note that the steady state liquid levels in the steam generator for the constant liquid mass controller are similar to the liquid level controller. Also from the above figures, the narrow range liquid levels are between 28% and 70% and are well within the safety settings of the steam generator.

Valve Characteristics for Constant Liquid Mass Controller

The current simulation code uses the steam generator water level to control the amount of feed water that enters the steam generator. The associated integral and proportional gains for the

controller are at an optimum setting for level control and are both set to 0.07. These settings may or may not be the optimal settings for a controller based upon mass.

For the constant mass controller, the different between steam and feed flows must be small such that the liquid mass inside of the steam generator does not fluctuate. When examining the normal operational transients using the level controller, the feed flow compares well with the steam flow during the ramp change due to the smaller perturbation introduced into the system. The total difference between the steam and feed flow can be calculated and used as a performance measure. Equation 3.1 represents the total error between the steam and feed flows.

$$S = \frac{\sqrt{\sum_{i=0}^{i=t} \Delta t_i \left(\frac{\text{steam flow} - \text{feed flow}}{\text{steam flow}} \right)^2}}{t} \quad \text{Equation 3.1}$$

For the constant liquid mass controller, equation 3.1 and Constant Mass Strategy A will be used to find the optimum settings for the integral and proportional gains. Again, the default setting used in the level controller may not be optimum for the mass controller. A test transient of –10% per minute ramp for 8 minutes from 100% power will be used to find the optimal setting for the integral and proportional gain settings for the constant mass controller. A ramp change introduces a relatively small perturbation into the system unlike the step transient where a large perturbation is induced into the system at the beginning of the transient. Also, a –10% per minute ramp rate is not a warranted change, and will challenge the controller so that aggressive gains can be examined.

The integral and proportional gains were examined over a range from 0.0 to 5.0. Figure 3.23 represents the total errors that were calculated using equation 3.1 over this range of integral and proportional gain settings.

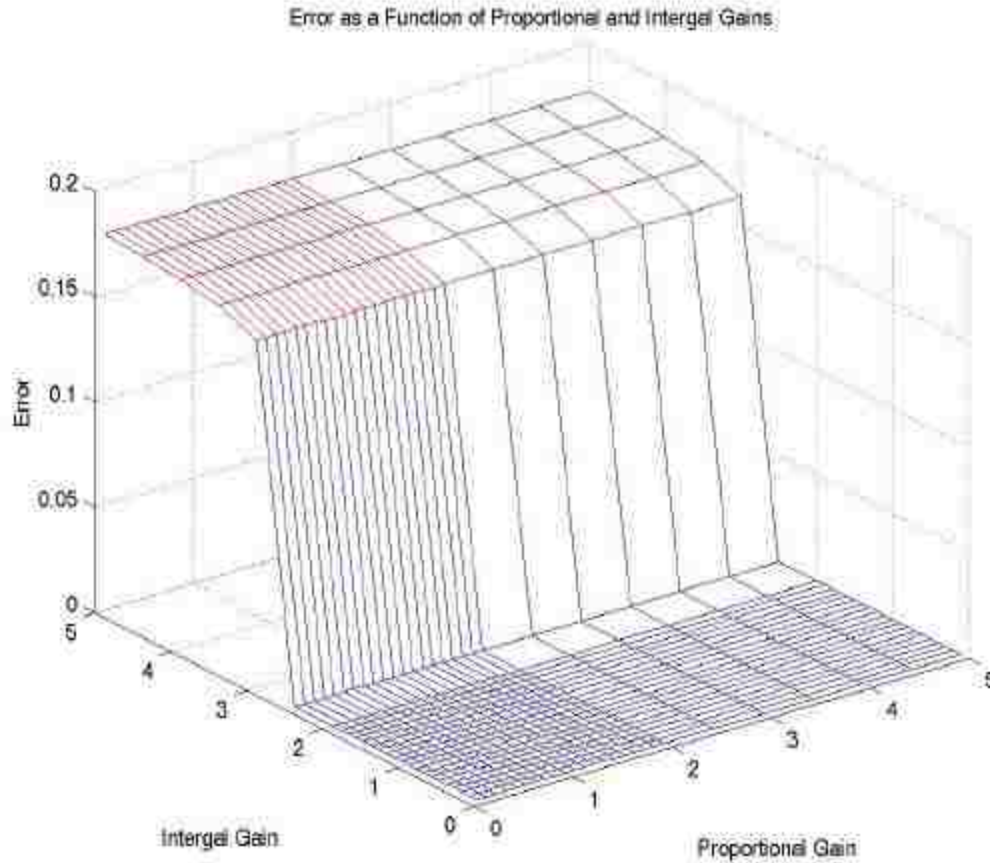


Figure 3.23

When the integral and proportional gain settings exceeded 5.0, the total error entered a flat band where the total error exceeds those with lower gain settings. These results are somewhat misleading because an increase in the integral and proportional gain settings would help increase the feed control valve sensitivity and the valve would modulate quickly to match the steam flow. When examining the feed control valve movements and the steam flow feed flow mismatch from the previous transient using the gains settings of 5.0 for both the integral and proportional settings, the controller becomes saturated from the large gain settings. The feed control valve movements and steam flow feed flow mismatch is shown in Figures 3.24 and 3.25.

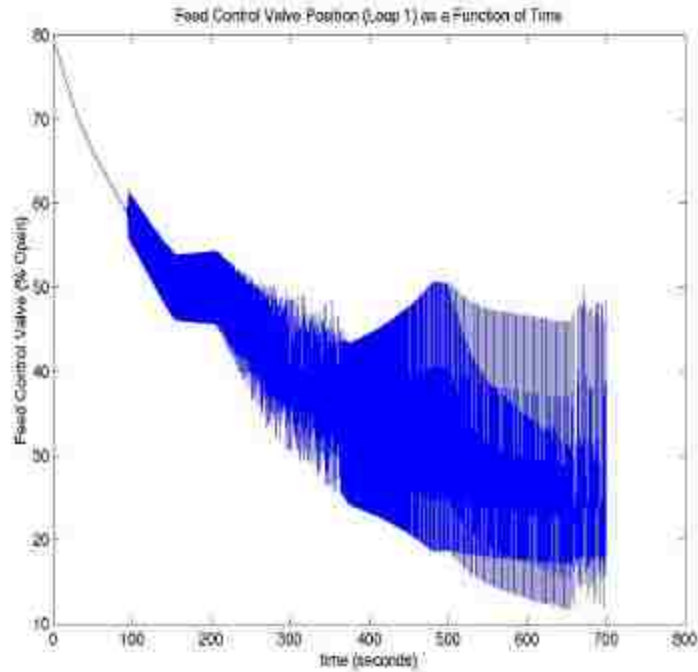


Figure 3.24

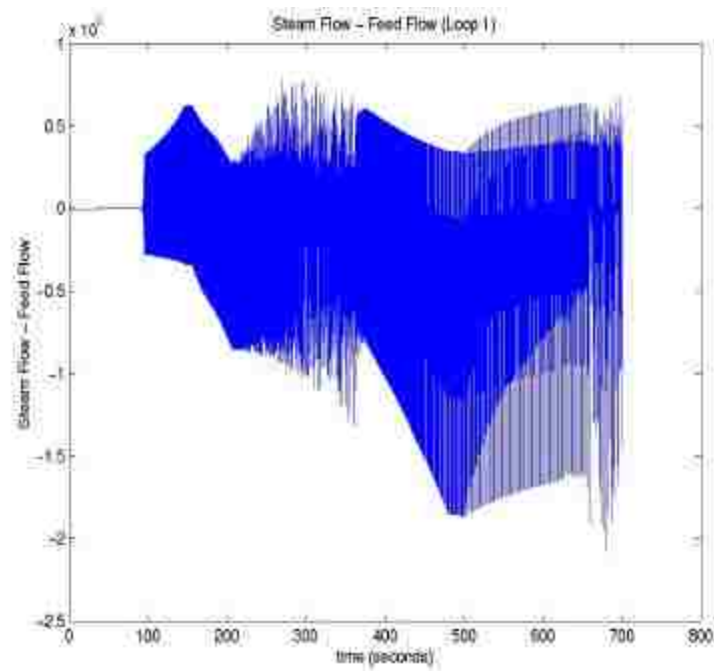


Figure 3.25

Feed control valve position and steam generator flow rates for a test transient of -10% per minute ramp for 8 minutes from 100% power using constant mass control.

Even though the feed flow matched the steam flow well in the beginning of the transient, the large fluctuations in the feed control valve are unacceptable and do not model true valve movements. With large integral and proportional gain settings, the controller was sensitive to changes between the feed and steam flows, which both help and hinder the performance of the controller. These erratic valve movements are either caused from the control valve becoming saturated or from high frequency perturbations, which are caused from the large gain settings.

To eliminate the saturation of the feed control valve, the feed control valve time constant was increased. The default time constant used for both the level and constant liquid mass controller was 0.7238 seconds. The transient was reexamined with the feed control time constant set to 20 seconds and the integral and proportional gains kept at 5.0. These results are shown in Figures 3.26 and 3.27.

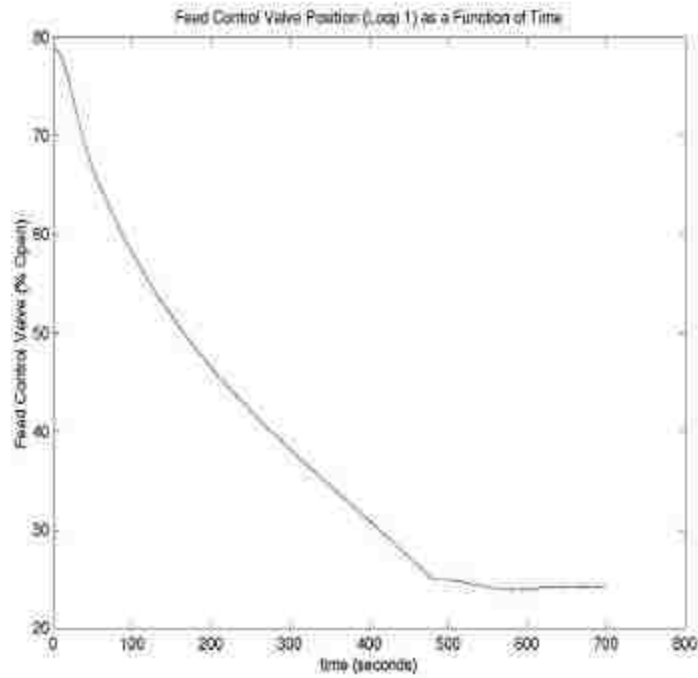


Figure 3.26

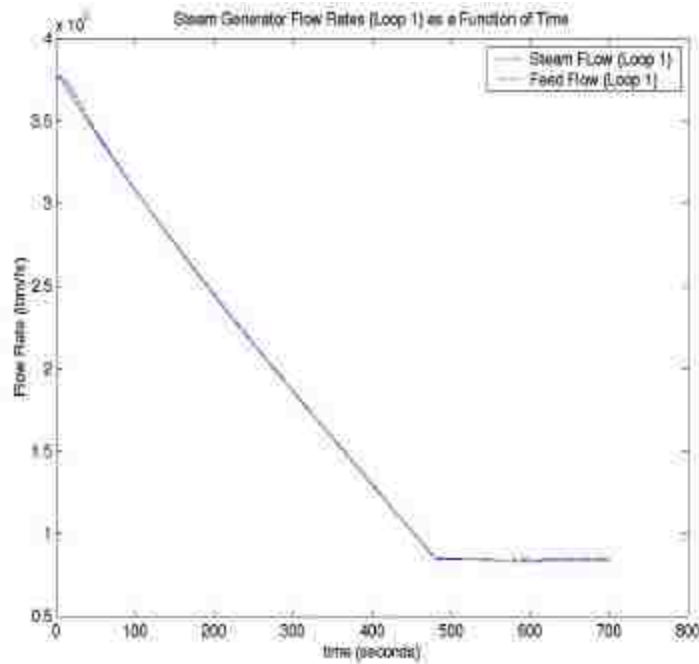


Figure 3.27

Feed control valve position and steam generator flow rates for a test transient of -10% per minute ramp for 8 minutes from 100% power using constant mass control.

From the above figures, it would seem that the large settings for both the integral and proportional gains with a large feed control valve time constant provide a good match between the feed and steam flows and show signs of valid feed control valve movement.

From Figure 3.23, it would seem that smaller integral and proportional gain settings also provide a good match between the feed and steam flows for the test transient.

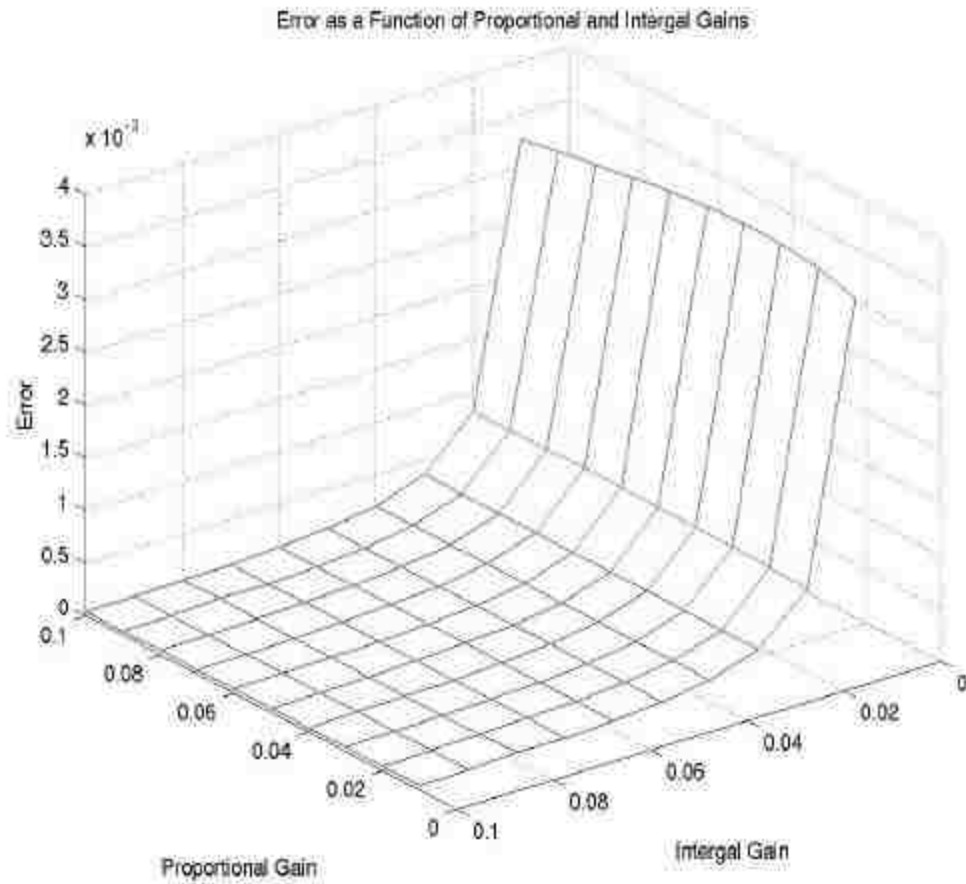


Figure 3.28

The above figure examines a smaller range of integral and proportional gain settings. The gain settings that produced the lowest minimum error using the default time constant of 0.7238 seconds can were found to be $k_p = 0.09$ and $k_i = 0.07$.

Figure 3.29 represent the feed and steam flow responses from the test transient using the smaller gain settings.

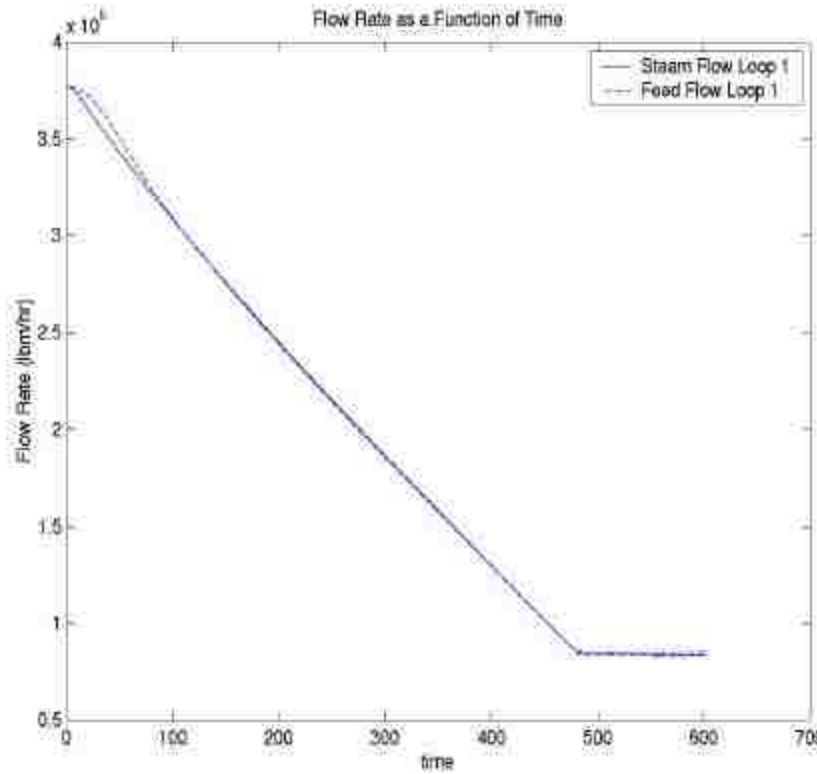


Figure 3.29

These settings were also examined using the other constant mass control strategies on the test transient. The following figures represent Mass Control Strategy E.

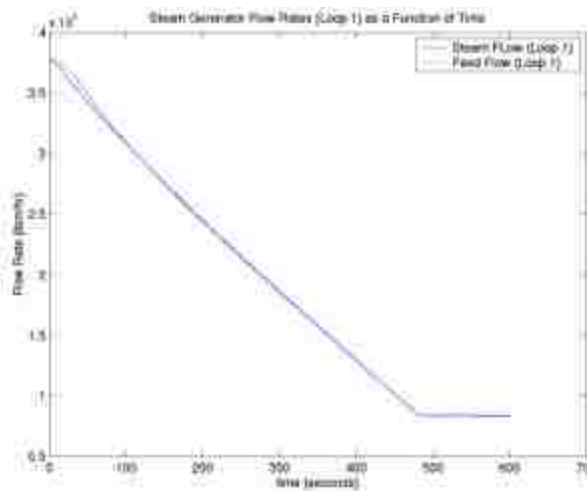


Figure 3.30

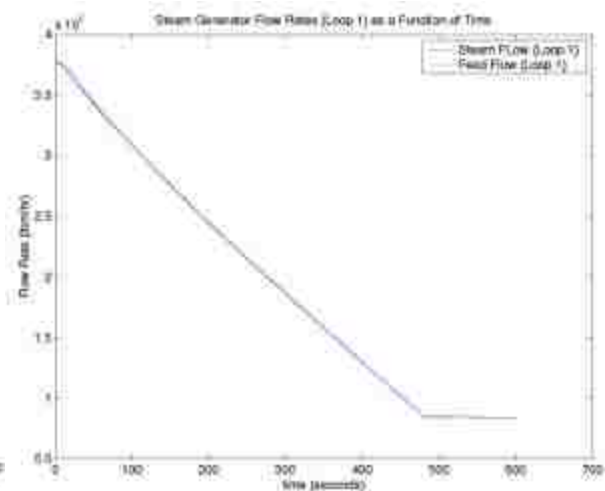


Figure 3.31

Figure 3.30 represents the steam flow feed flow mismatch using the small gain settings using the default feed control valve time constant of 0.7238 seconds. Figure 3.31 represents the

steam flow feed flow mismatch using the larger gain settings and a feed control valve constant of 20 seconds. For this test transient, two combinations of gains and time constants provide adequate matching for the feed and steam flows. One combination involves using small gain settings and the default (short) feed control valve time constants. The other involves using large gain settings and an increased feed control valve time constant. Examination of other constant mass control strategies using the small and large gain settings showed adequate control for the test transient examined, with the results similar to those found using the constant mass control strategy A.

These new controller constants and Mass Control Strategy A were examined for normal operational occurrences including a step change of -10% and a ramp change of -5% per minute for two minutes, both from full power, and a step change of $+10\%$ and a ramp change of $+5\%$ per minute for two minutes, both from 20% power. These results are shown in Figures 3.32-3.63.

Figures	Transient	Initial Power	Gains	FCV Time Constant
3.32-3.35	-10% Step Decrease in Load	100%	Small	0.7238 seconds
3.36-3.39	-5% per minute Ramp Decrease in Load for 2 minutes	100%	Small	0.7238 seconds
3.40-3.43	-10% Step Decrease in Load	100%	Large	20.0 seconds
3.44-3.47	-5% per minute Ramp Decrease in Load for 2 minutes	100%	Large	20.0 seconds
3.48-3.51	$+10\%$ Step Increase in Load	20%	Small	0.7238 seconds
3.52-3.55	$+5\%$ per minute Ramp Increase in Load for 2 minutes	20%	Small	0.7238 seconds
3.56-3.59	$+10\%$ Step Increase in Load	20%	Large	20.0 seconds
3.60-3.63	$+5\%$ per minute Ramp Increase in Load for 2 minutes	20%	Large	20.0 seconds

Table 3.2: **Different Transients Examined Using Constant Mass Control Strategy**

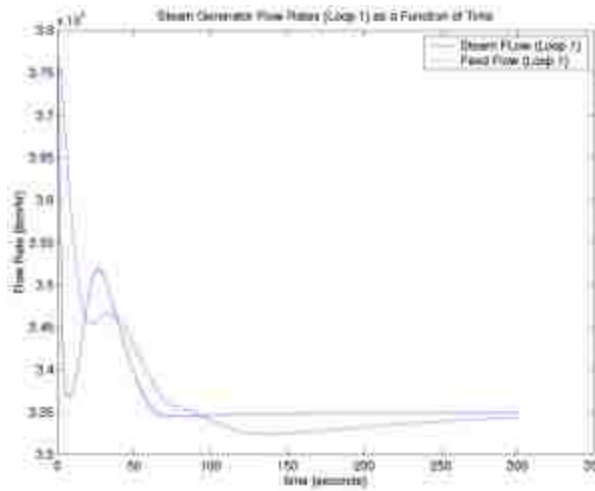


Figure 3.32

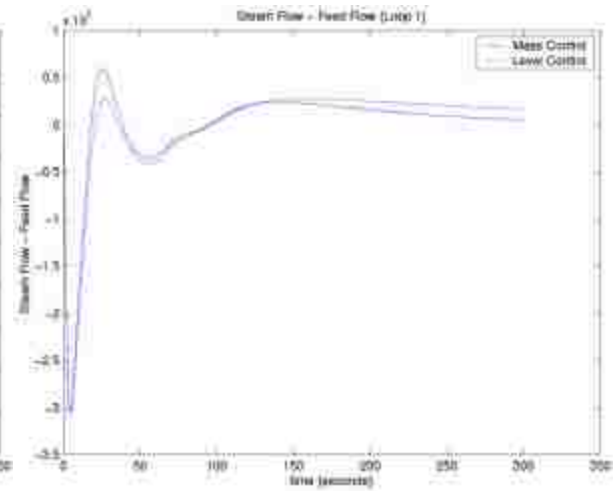


Figure 3.33

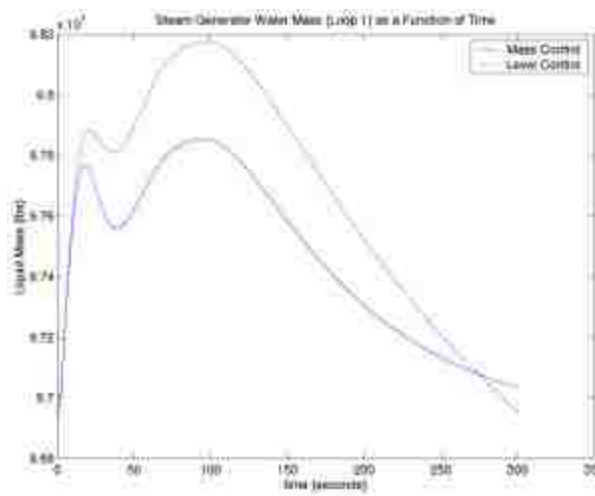


Figure 3.34

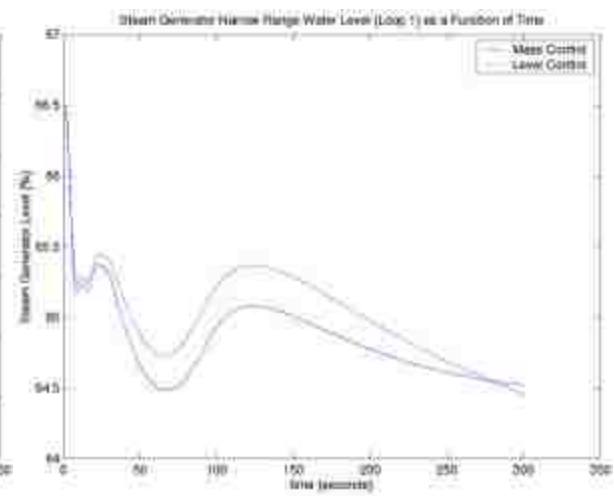


Figure 3.35

A -10% step decrease in load from 100% power using small gain settings and FCV time constant of 0.7238 seconds using a constant mass controller.

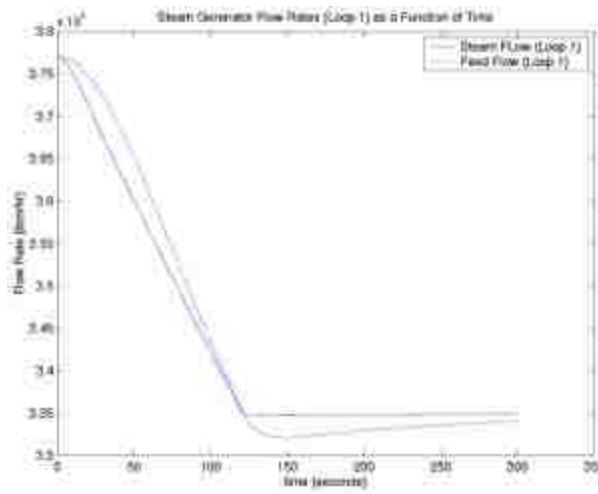


Figure 3.36

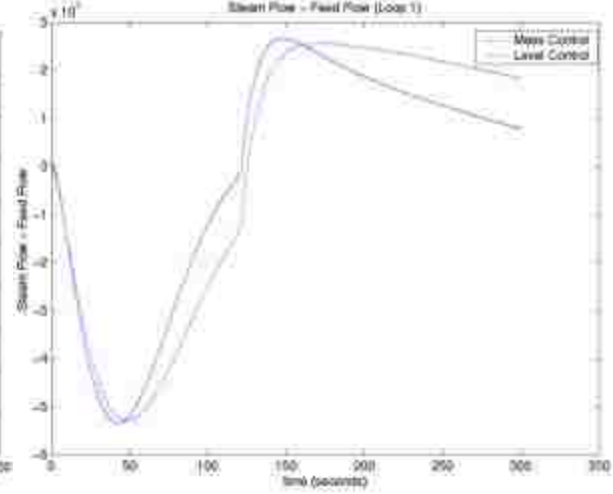


Figure 3.37

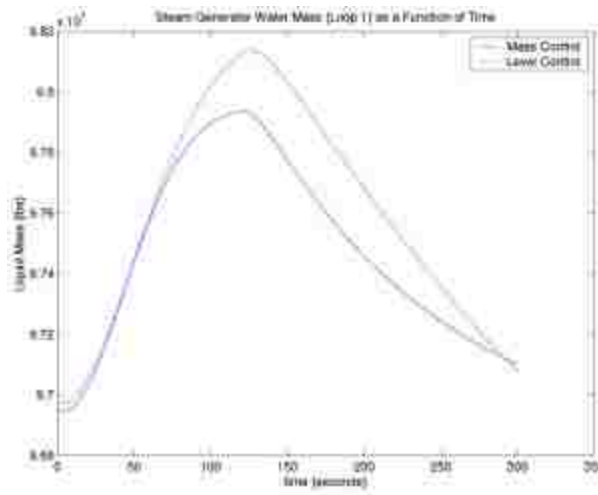


Figure 3.38

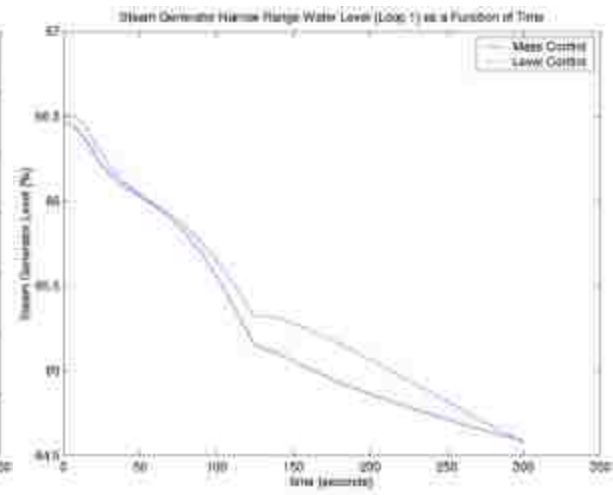


Figure 3.39

A -5% per minute ramp decrease in load for two minutes from 100% power using small gain settings and FCV time constant of 0.7238 seconds using a constant mass controller.

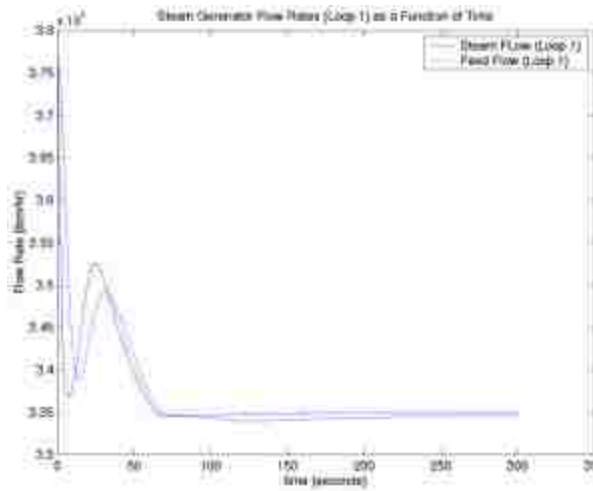


Figure 3.40

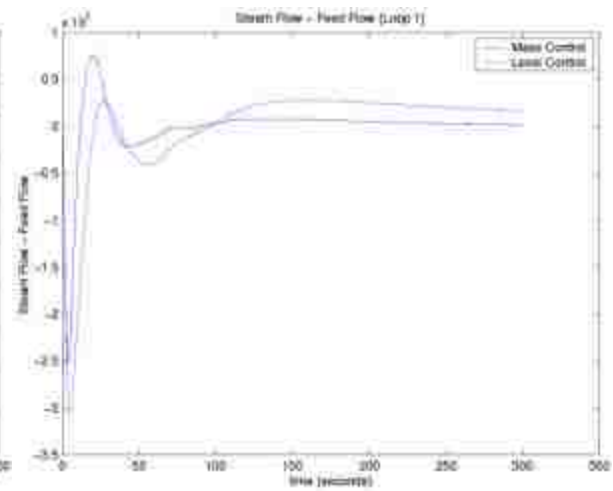


Figure 3.41

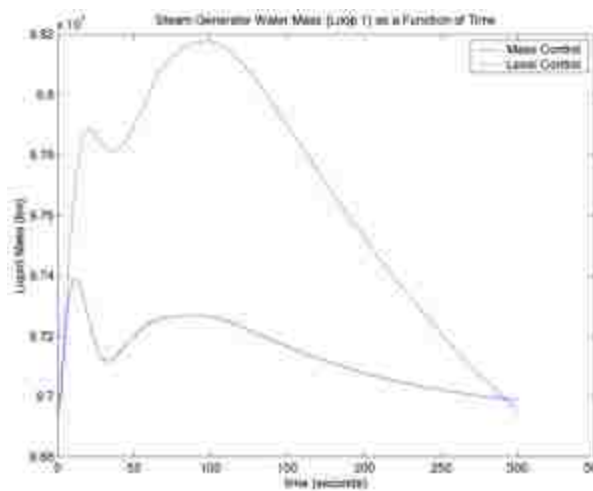


Figure 3.42

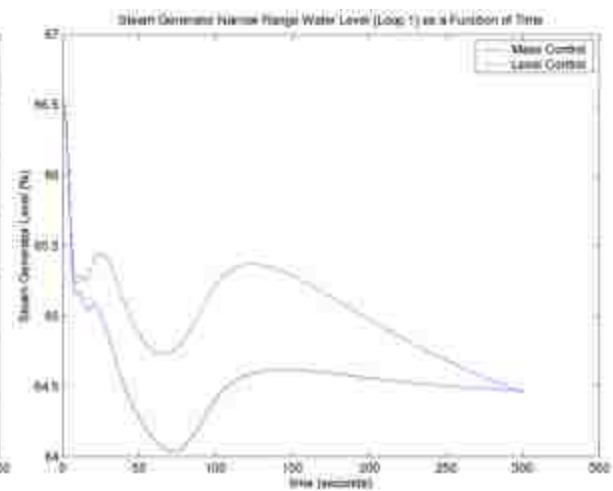


Figure 3.43

A -10% step decrease in load from 100% power using large gain settings and FCV time constant of 20.0 seconds using a constant mass controller.

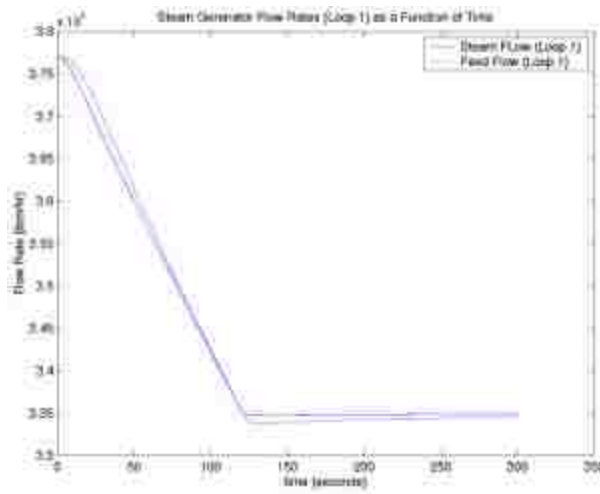


Figure 3.44

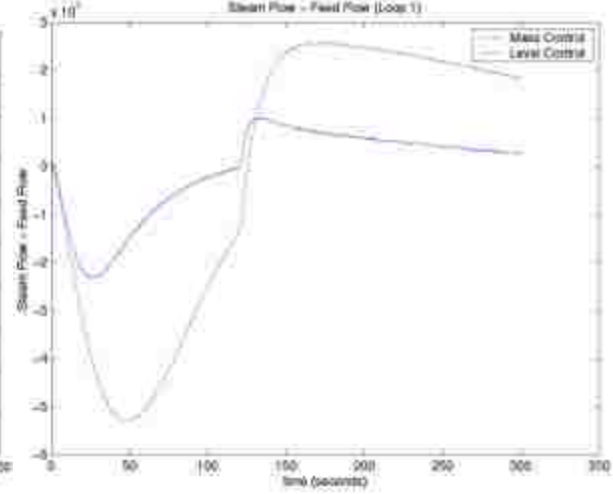


Figure 3.45

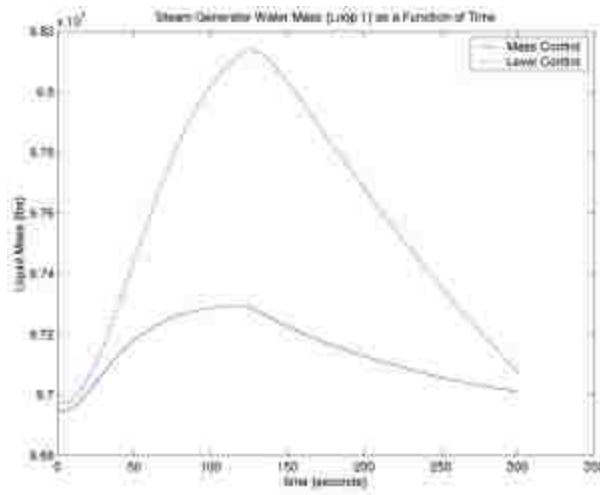


Figure 3.46

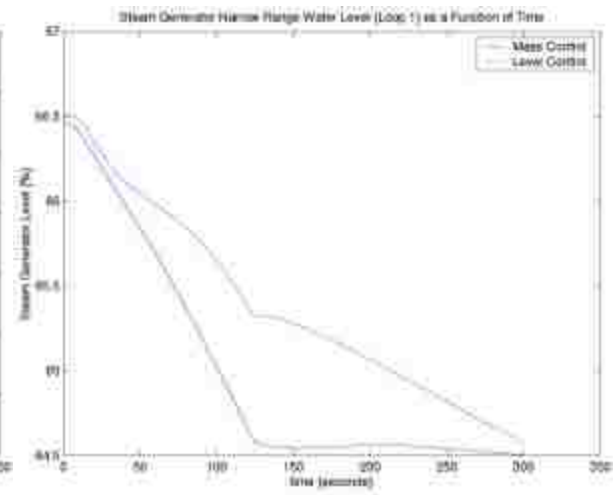


Figure 3.47

A -5% per minute ramp decrease in load for two minutes from 100% power using large gain settings and FCV time constant of 20.0 seconds using a constant mass controller.

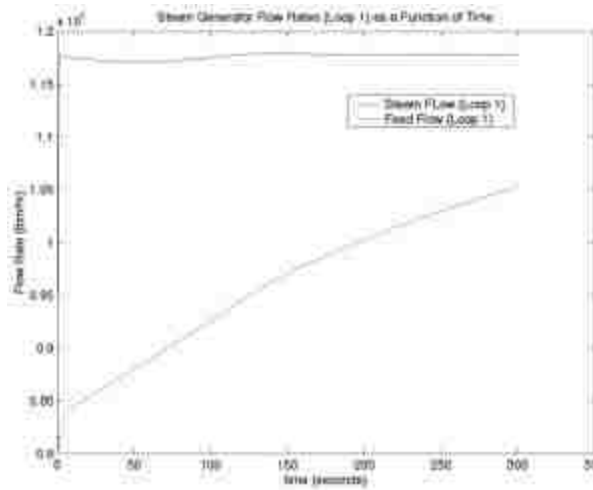


Figure 3.48

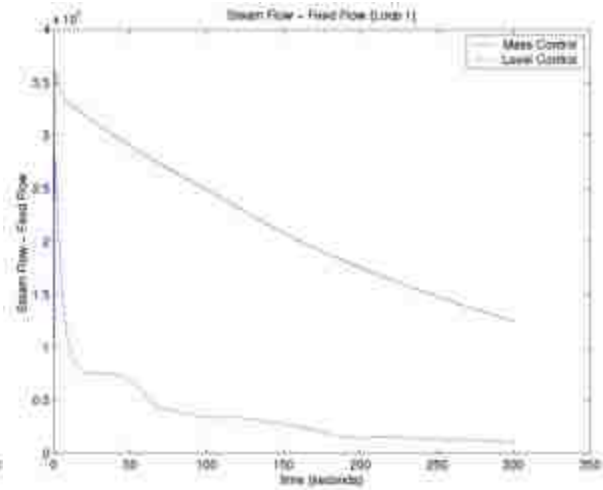


Figure 3.49

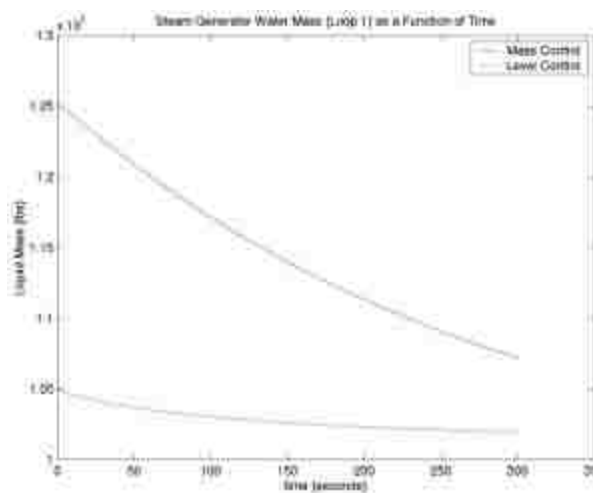


Figure 3.50

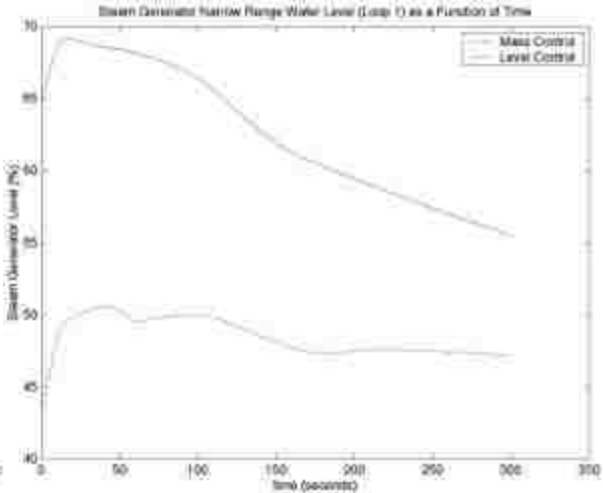


Figure 3.51

A +10% step increase in load from 20% power using small gain settings and FCV time constant of 0.7238 seconds using a constant mass controller.

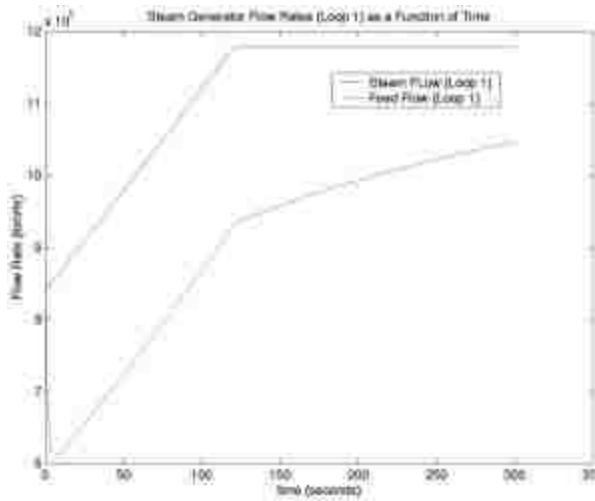


Figure 3.52

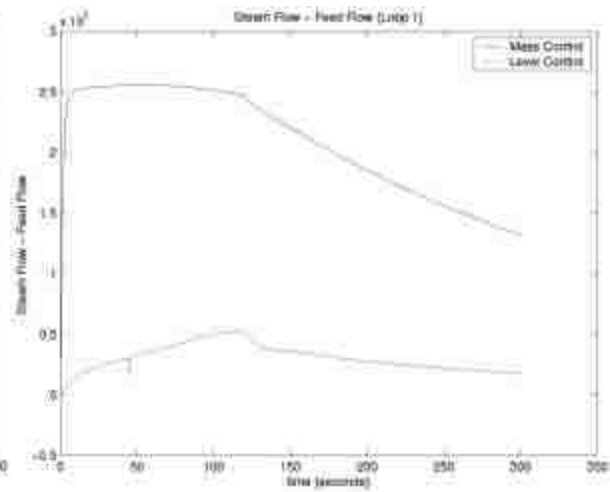


Figure 3.53

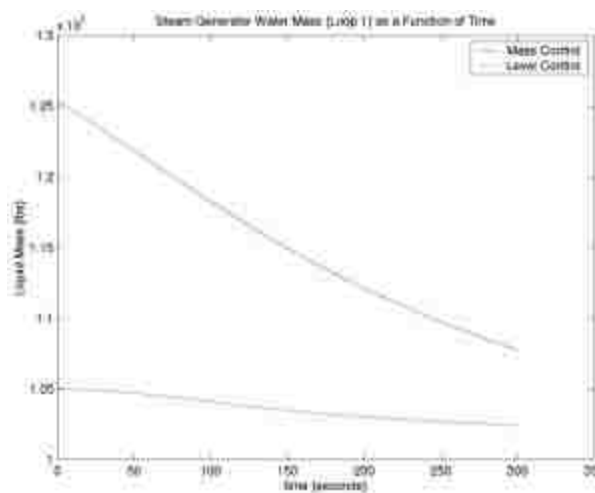


Figure 3.54

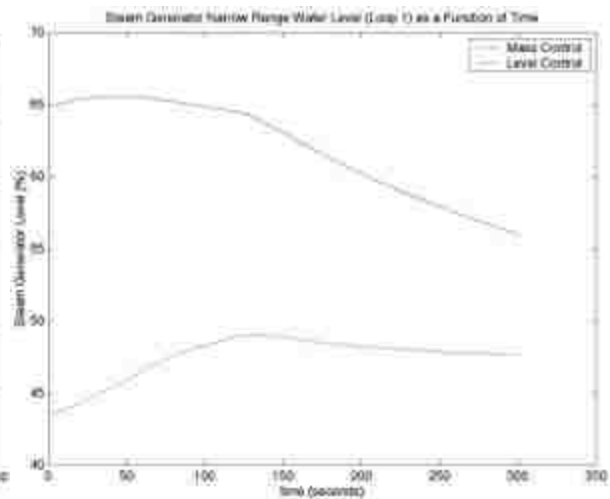


Figure 3.55

A +5% per minute ramp increase in load for two minutes from 20% power using small gain settings and FCV time constant of 0.7238 seconds using a constant mass controller.

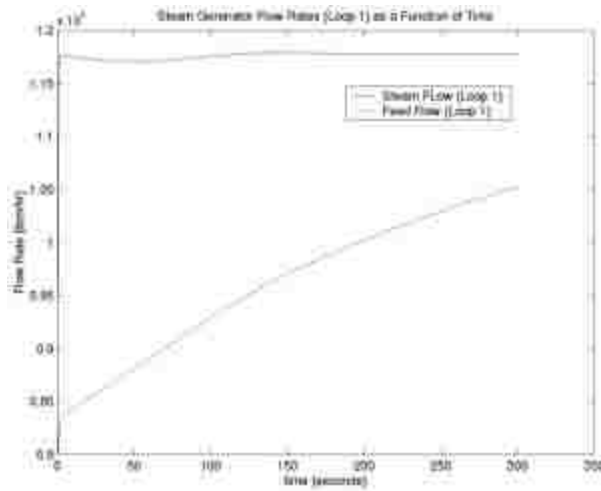


Figure 3.56

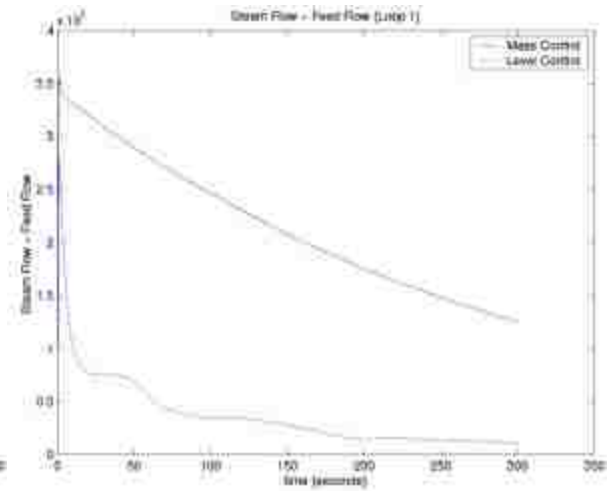


Figure 3.57

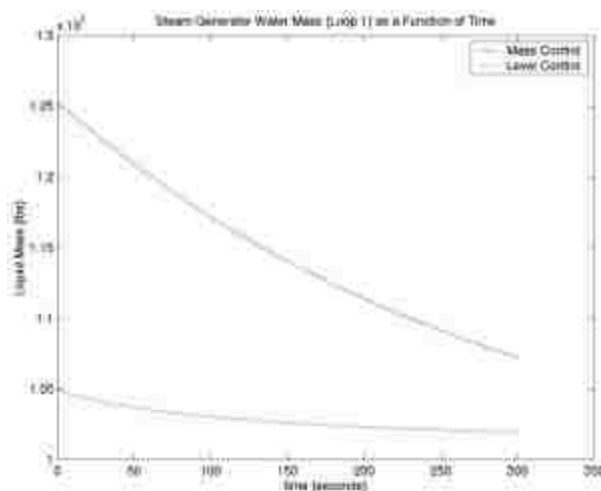


Figure 3.58

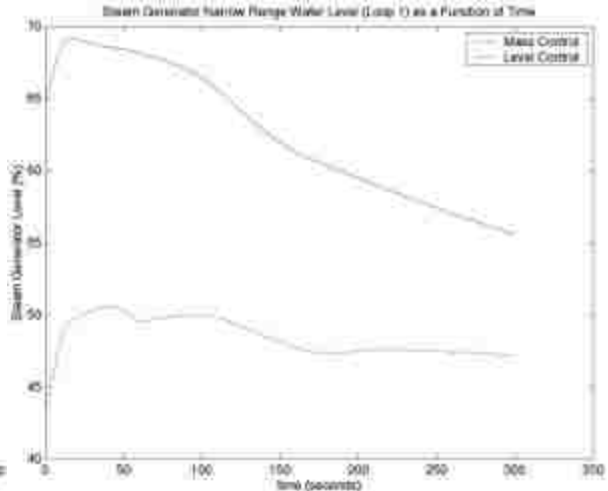


Figure 3.59

A +10% step increase in load from 20% power using large gain settings and FCV time constant of 20.0 seconds using a constant mass controller.

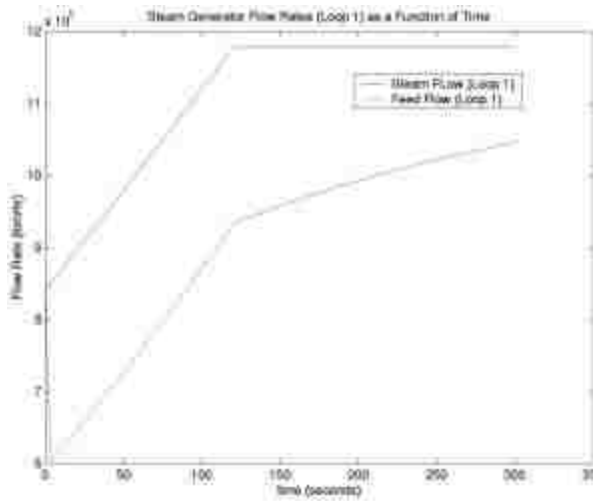


Figure 3.60

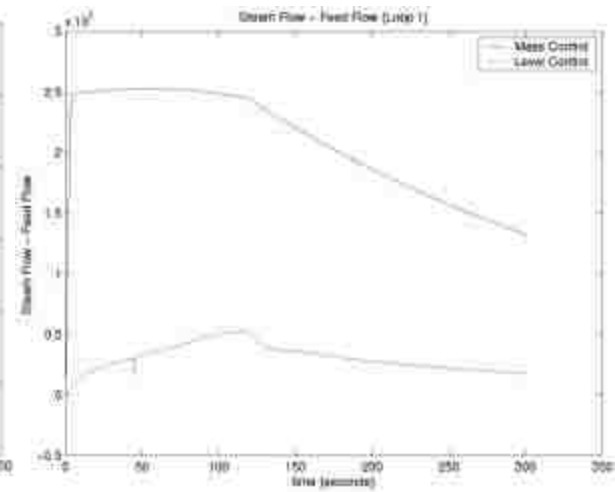


Figure 3.61

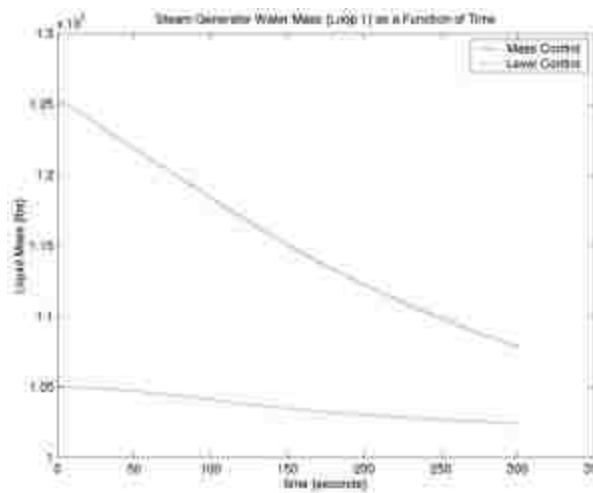


Figure 3.62

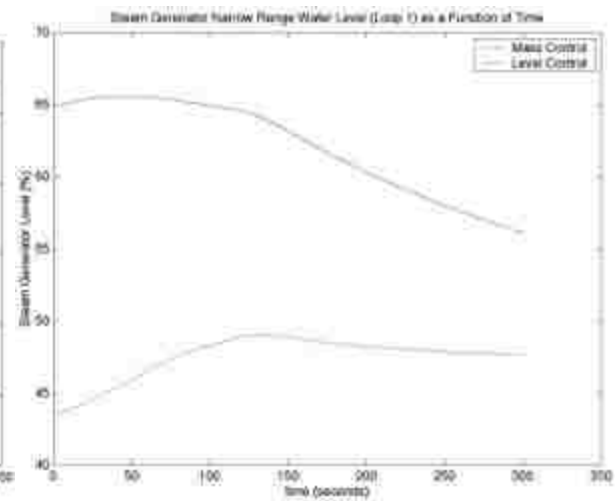


Figure 3.63

A +5% per minute ramp increase in load for two minutes from 20% power using large gain settings and FCV time constant of 20.0 seconds using a constant mass controller.

It is important to note that the initial conditions for both the level and mass controllers are different. Both of the constant liquid mass control strategies produced results similar to or better than that of the level controller. At larger powers, the mass controller using the large gain settings was more aggressive, while the mass controller using gain settings similar to level controller yielded similar results to the level control transients. Also, it is important to note that the shrink and swell phenomena can still be seen with the constant liquid mass controller. Because mass not level is the controller input, the controller does not respond to shrink and swell phenomena. Both constant liquid mass control strategies were examined for normal operational occurrences at all power ranges and produced reasonable results with no reactor trip.

Abnormal Power Transient

The two constant liquid mass control strategies proved to be adequate for steam generator control under normal operational occurrences. The two different control strategies were then examined for an abnormal power transient. A –100% step change in load from full power was examined using both constant liquid mass control strategies. This is not a warranted step change, but will challenge both control strategies. For the level controller, a –100% step change in load did not induce a reactor trip.

Figures	Transient	Controller	Gains	FCV Time Constant
3.64-3.67	–100% Step Decrease in Load	Level	-	0.7238 seconds
3.68-3.71	–100% Step Decrease in Load	Mass	Small	0.7238 seconds
3.72-3.75	–100% Step Decrease in Load	Mass	Large	20.0 seconds

Table 3.3: Abnormal Power Transient Examined Using Level and Mass Control Strategies

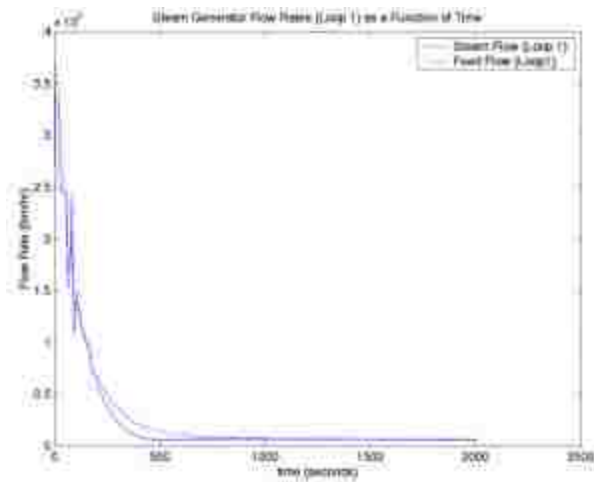


Figure 3.64

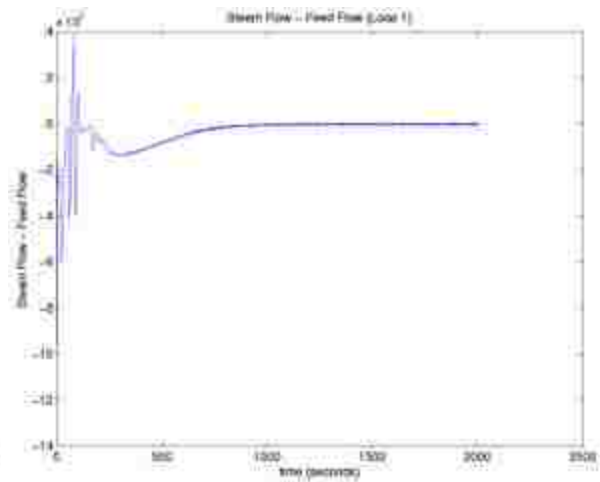


Figure 3.65

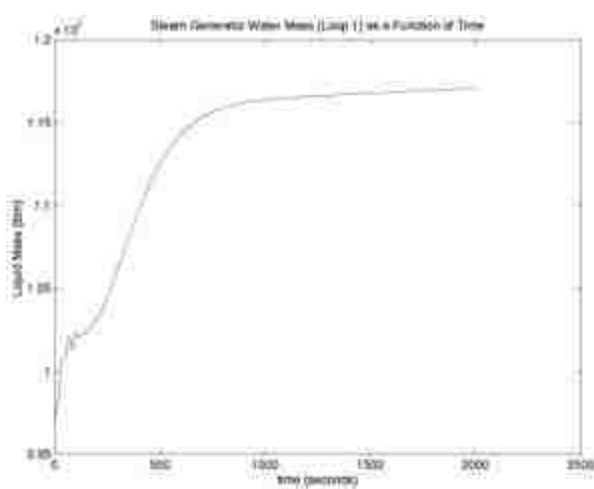


Figure 3.66

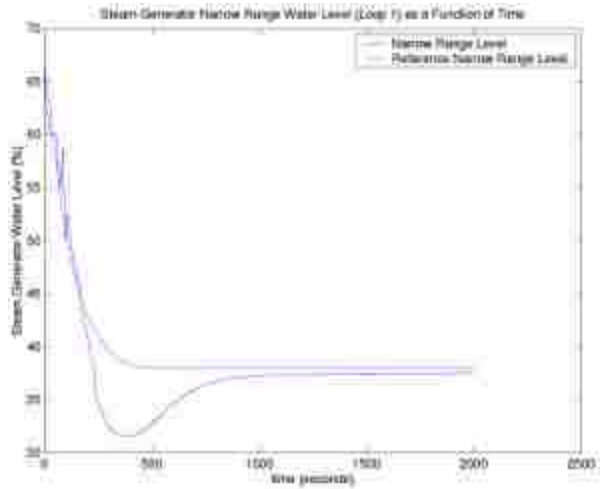


Figure 3.67

A -100% step decrease in load from 100% power using the level controller and FCV time constant of 0.7238 seconds.

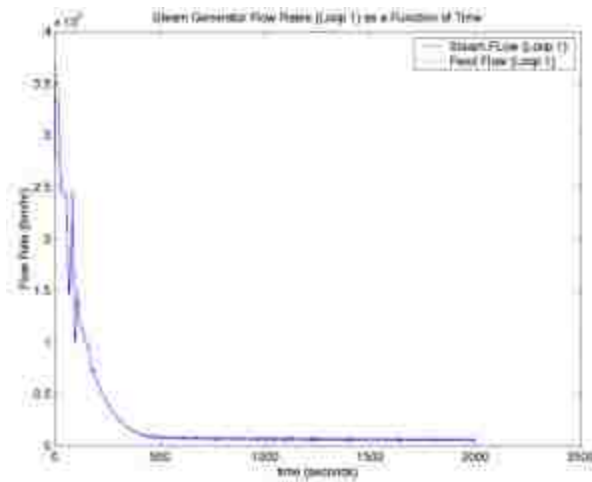


Figure 3.68

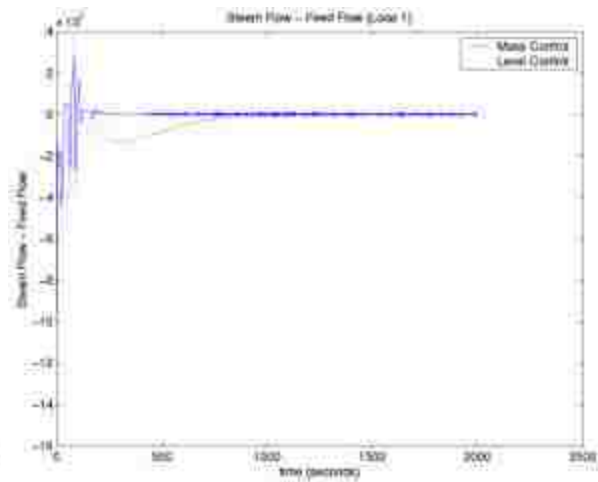


Figure 3.69

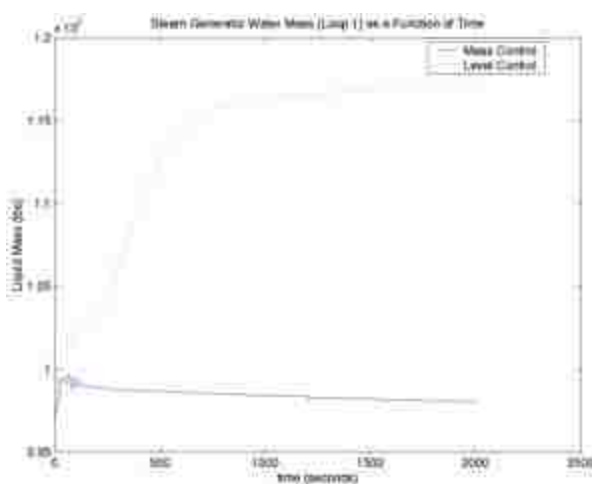


Figure 3.70

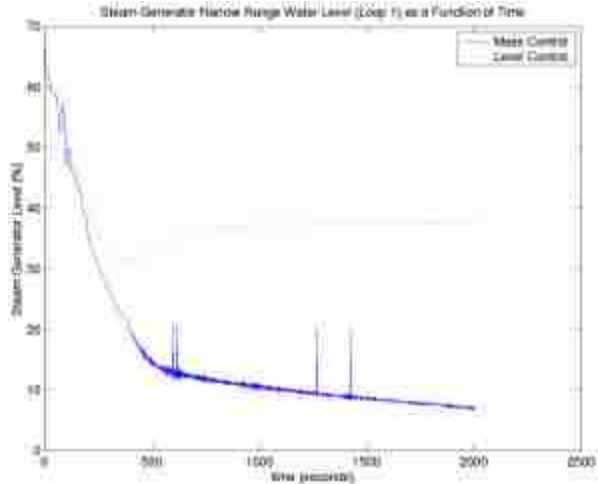


Figure 3.71

A -100% step decrease in load from 100% power using the mass controller, small gain settings, and FCV time constant of 0.7238 seconds.

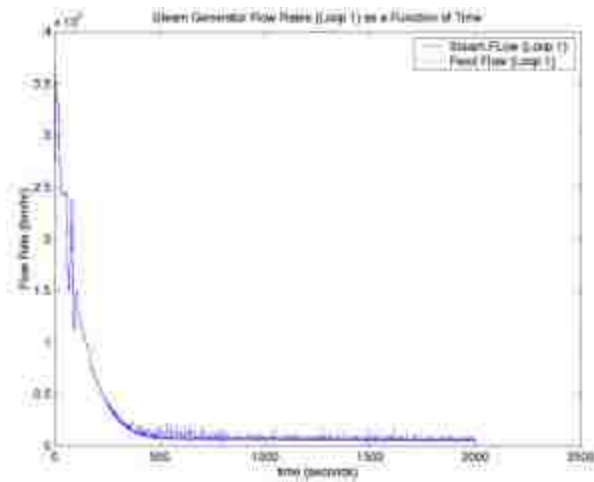


Figure 3.72

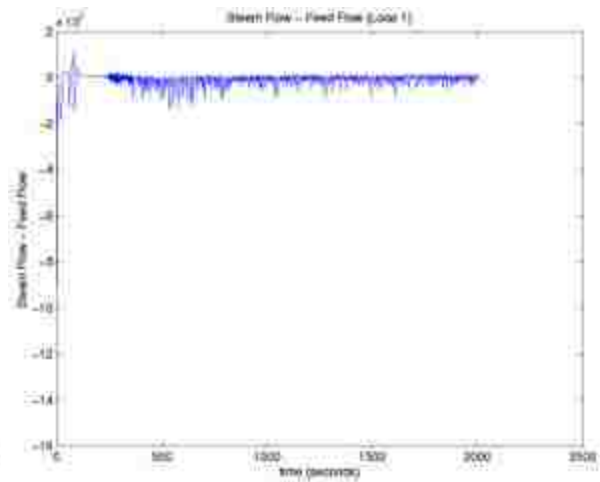


Figure 3.73

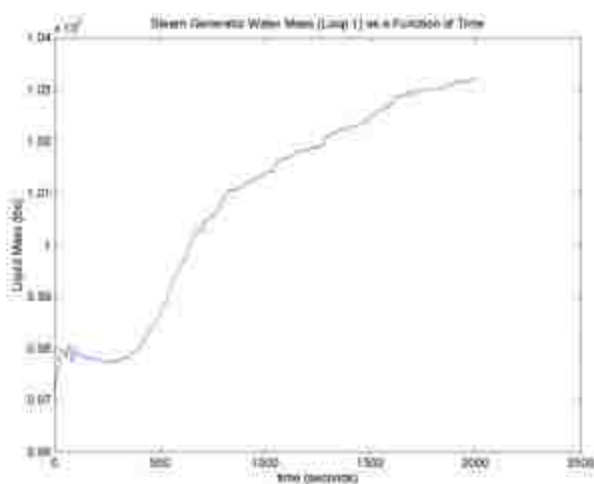


Figure 3.74

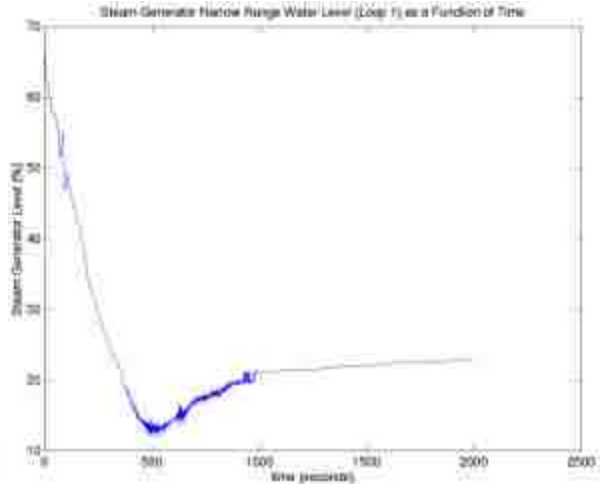


Figure 3.75

A -100% step decrease in load from 100% power using the mass controller, large gain settings, and FCV time constant of 20.0 seconds.

From the above figures, the large rejection in load from full power did not induce a reactor trip using both the level and mass control strategies. Upon further examination, when using the large gain settings, the feed flow for the transient showed signs of high oscillations after 400 seconds into the transient. Also, the liquid mass in the steam generator is increasing after 400 seconds when using a constant mass controller with large gains. The other mass controller using the smaller gains has the mass increasing in the beginning of the transient due to the step decrease in power, but the mass decreases later in the transient. The increase in the liquid mass can best be explained with the examination of the steam flow feed flow mismatch and the integral error between the two flows.

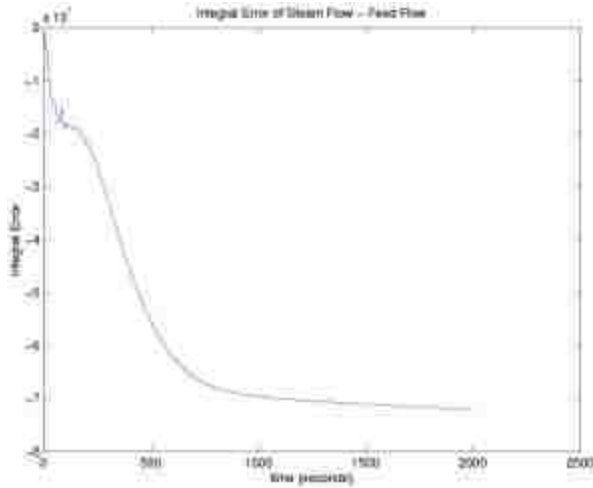


Figure 3.76

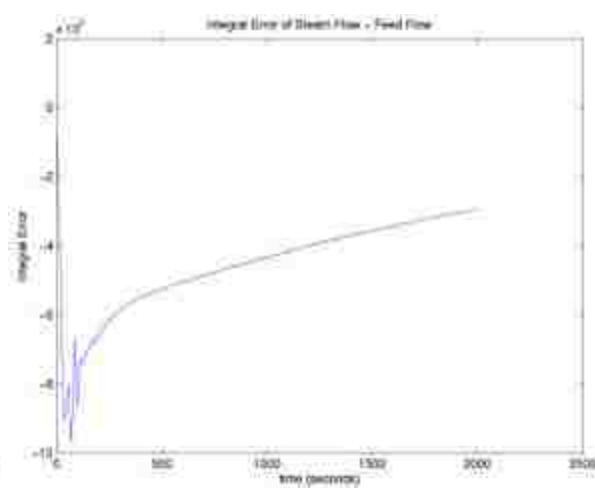


Figure 3.77

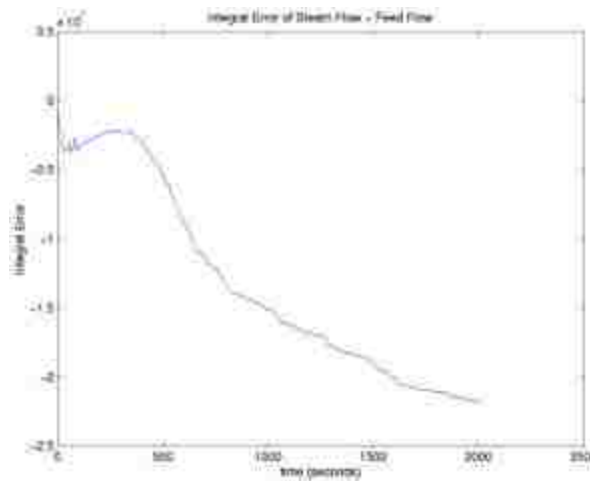


Figure 3.78

Integral errors between steam and feed flow in the steam generator under level controller, mass controller using small gains, and mass controller using large gains.

Figures 3.76, 3.77, and 3.78 represent the integral error between the steam and feed flows using the level controller, mass controller using small gains, and the mass controller using large gains respectively. From the above figures, clearly the mass controller using the larger gains has more feed flow than steam flow, while the other controllers exhibit signs of the feed flow decreasing or remaining constant with the steam flow. When examining the steam flow feed flow mismatch from the controller using large gain settings, there are large oscillations when the steam/feed

flow levels out. As a result of large gain settings, the feed control valve becomes more sensitive to changes in the steam flow and keeps increasing the mass inside of the steam generator. Also at lower power levels and low flows, changes in the feed flow become a large percentage of the feed flow itself. The combination of the two observations, promote the increase of the liquid mass in the steam generator when using the constant mass controller with large gain settings. The rise in both the liquid mass and level inside of the generator may indicate that the auxiliary feed water may have been activated due to low power operation, but upon further examination, the auxiliary feed water had not been activated. So the increase in the steam generator liquid mass and level can be attributed to the movements in the feed control valve.

The large gain settings help promote a better steam flow feed flow mismatch, but due to the sensitivity at lower power levels, the feed control valve opens/closes to match the steam flow, but the added flow becomes a large percentage of the feed flow itself. To reduce the large feed control valve “chattering”, different controller weights for the difference in the mass and the difference between steam/feed flows were examined. In the previous transients examined, the controller weighted the difference in the mass and the difference between steam/feed flows equally.

Different sets of controller weights and gains were examined to reduce the increase in the steam generator mass at lower power levels when using the large gains and a 20.0 second feed control valve time constant. First, a large array of steam/feed error weights were examined to reduce the increase of the mass in the steam generator. The steam/feed flow error and the

reference/true mass error are equally weighted. An array ranging from 0.143 and 7.00 were examined. These control strategies produced different results.

Figures	Transient	Steam/Feed Error Weight
3.79-3.83	–100% Step Decrease in Load	0.143
3.84-3.88	–100% Step Decrease in Load	7.00

Table 3.4: Abnormal Power Transient Examined Mass Control Strategy With Large Gain Settings

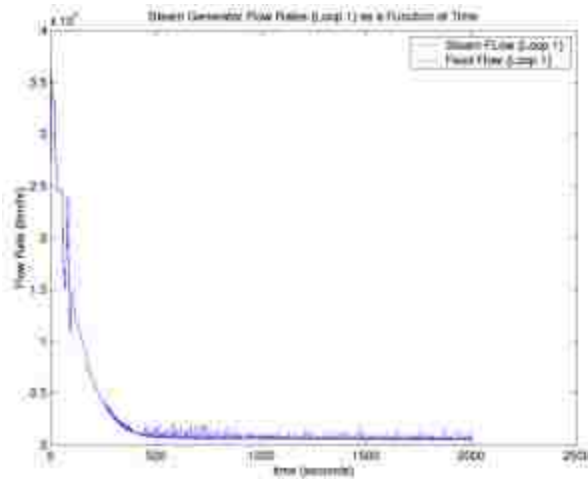


Figure 3.79

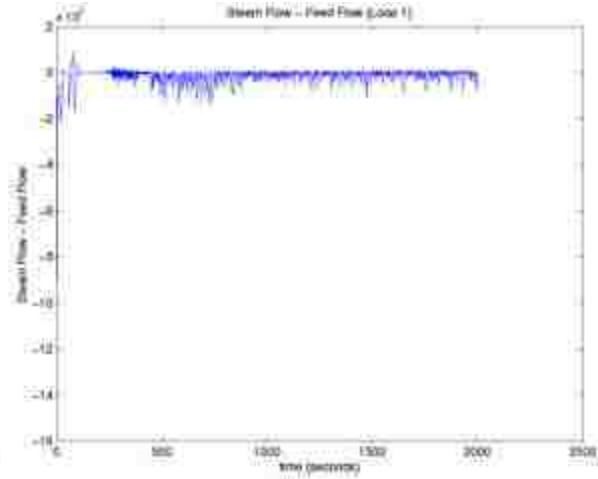


Figure 3.80

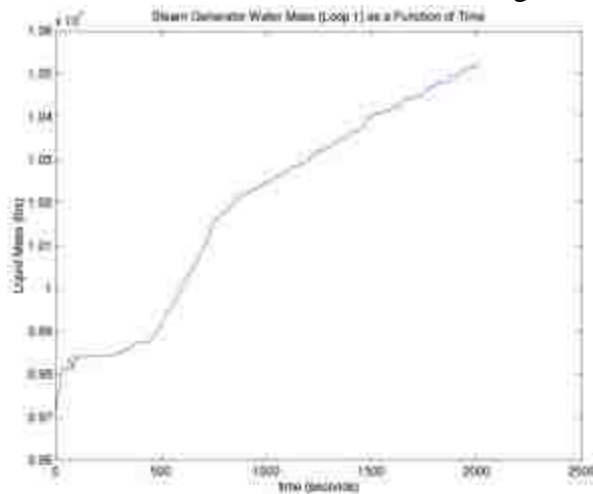


Figure 3.81

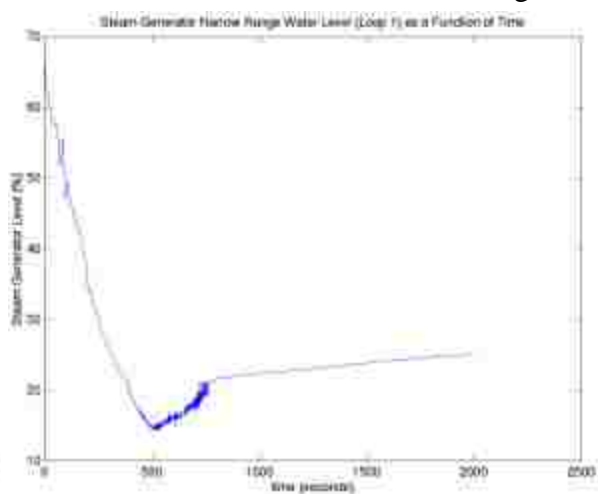


Figure 3.82

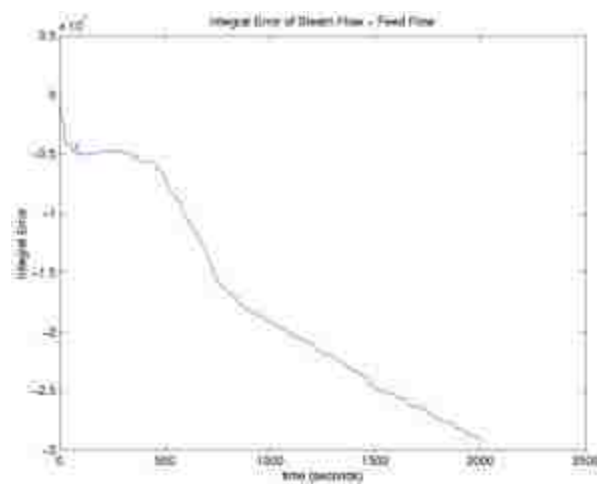


Figure 3.83

A -100% step decrease in load from 100% power using the mass controller, large gain settings, small steam/feed error weight (0.143) and FCV time constant of 20.0 seconds.

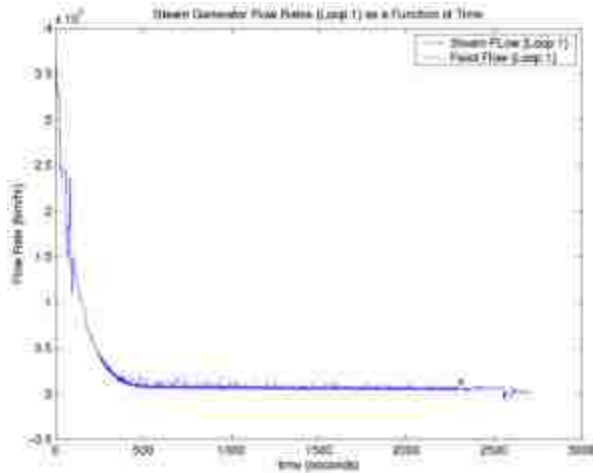


Figure 3.84

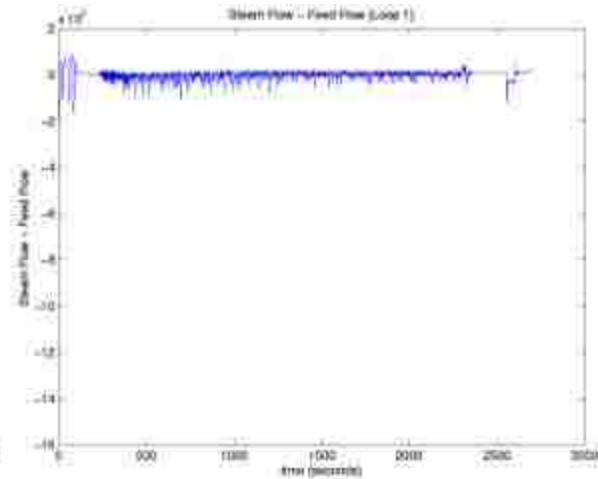


Figure 3.85

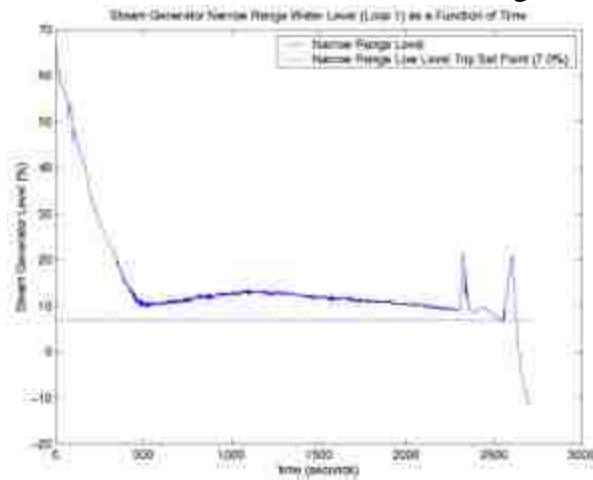


Figure 3.86



Figure 3.87

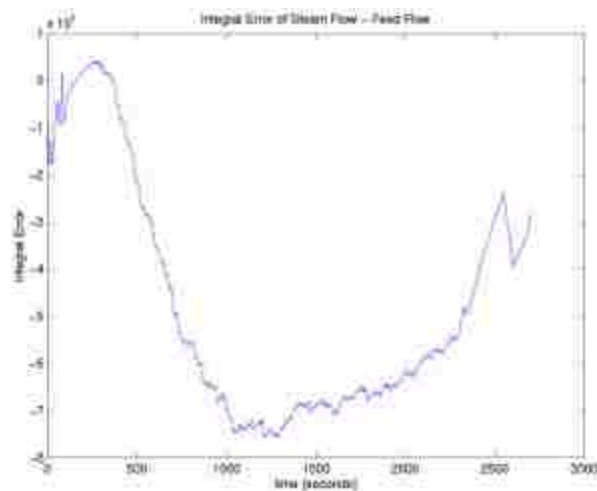


Figure 3.88

A -100% step decrease in load from 100% power using the mass controller, large gain settings, large steam/feed error weight (7.00) and FCV time constant of 20.0 seconds.

The above figures are representative of the different steam/feed error weights examined, excluding the reactor trip that was encountered when using a large steam/feed error weight of 7.00, where steam/feed error weights less than 1.00 were similar to results using 0.143 and steam/feed error weights larger than 1.00 were similar to the results using 7.00.

When using a small steam/feed flow error weight, it was assumed that less dependence upon the steam/feed flow mismatch would help reduce the increase of the steam generator liquid mass. Upon further examination, these set of parameters were worse than the default steam/feed flow error weight, where the mass keeps increasing. The next control strategy, using a large steam/feed flow error weight, produced reasonable results but induced a steam generator 2 low level trip, followed by a turbine trip. It is important to note the controller using a large steam/feed flow error weight, tries to establish a constant liquid mass before a reactor trip occurs. With the large steam/feed flow error weight, the feed control valve can modulate to match the steam/feed flow to maintain steam generator constant mass.

None of the above steam/feed error weights produced adequate steam generator mass response. Yet, when changing the steam/feed error weight impacts the gain settings used during the transient. Again a range of large gain settings were examined to help reduce the oscillation of the feed control valve and the increase of the steam generator mass.

Figures	Transient	Steam/Feed Error Weight	Gain Settings
3.89-3.93	-100% Step Decrease in Load	0.143	3.00
3.94-3.98	-100% Step Decrease in Load	2.00	3.00

Table 3.5: Abnormal Power Transient Examined Mass Control Strategy With Large Gain Settings

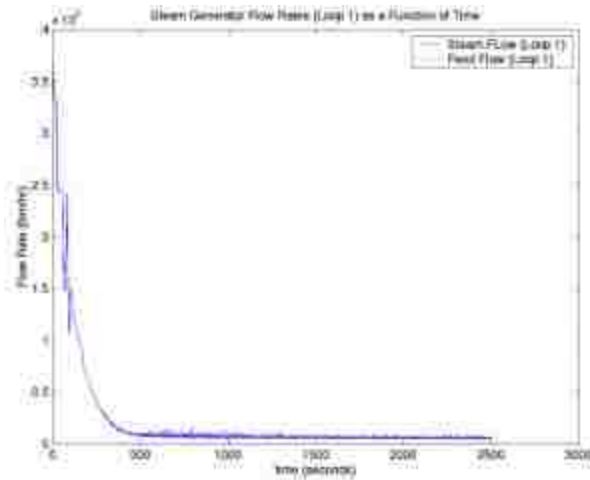


Figure 3.89

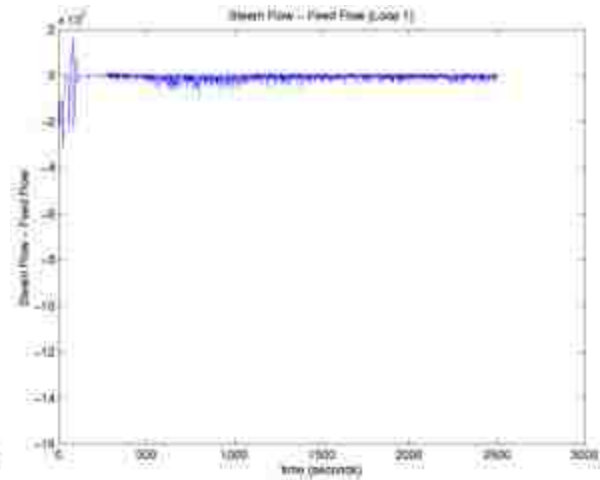


Figure 3.90

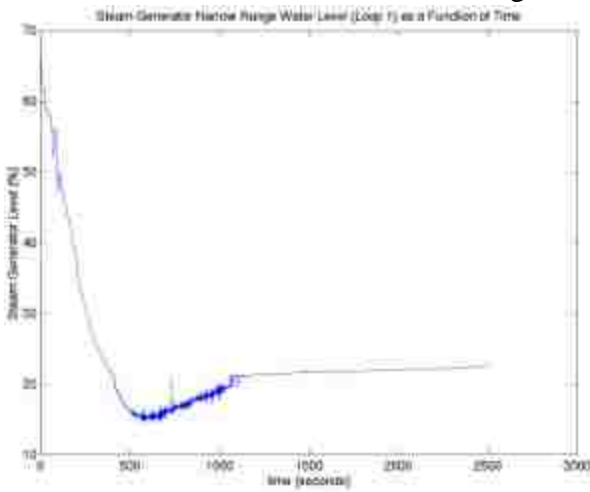


Figure 3.91

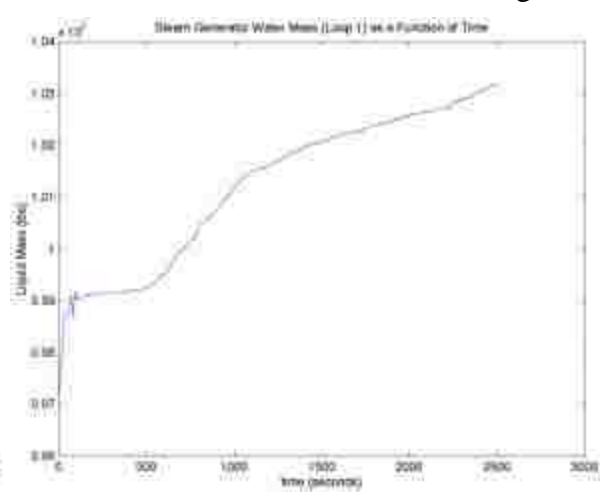


Figure 3.92

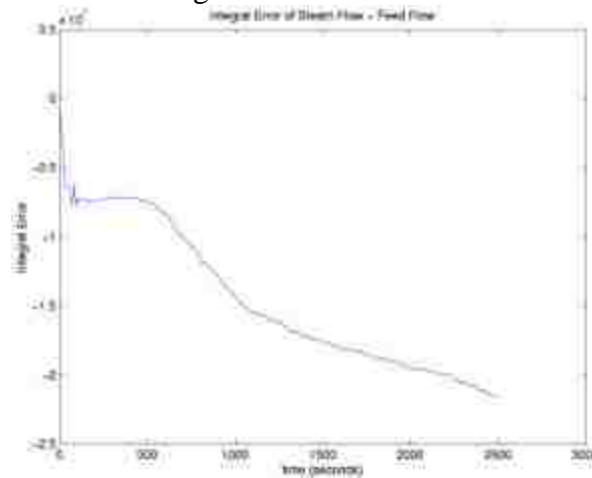


Figure 3.93

A -100% step decrease in load from 100% power using the mass controller, large gain settings (3.00), small steam/feed error weight (0.143) and FCV time constant of 20.0 seconds.

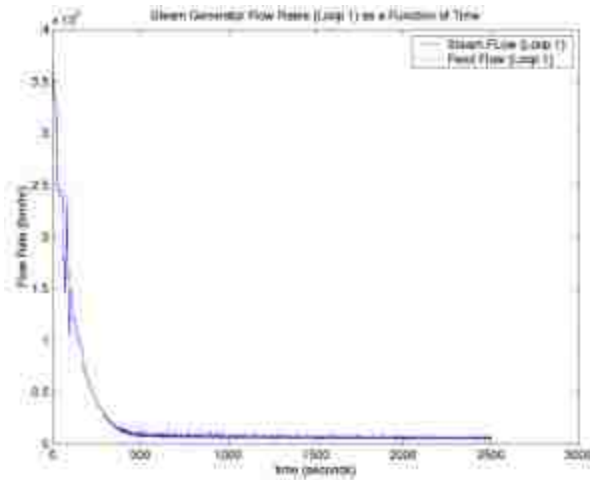


Figure 3.94

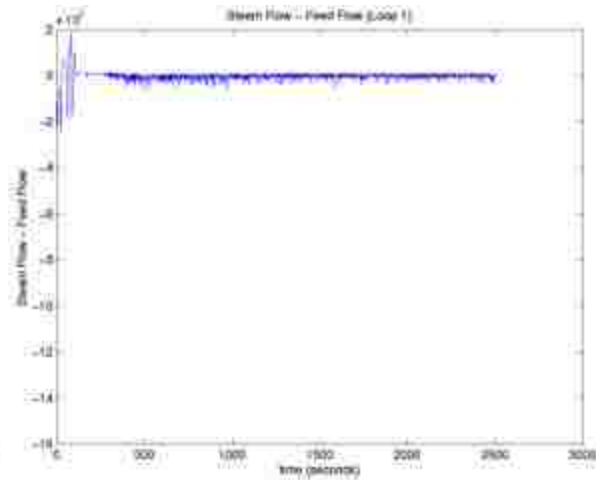


Figure 3.95

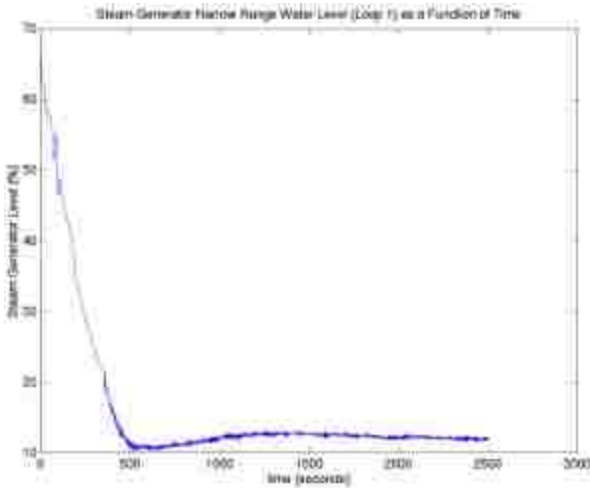


Figure 3.96

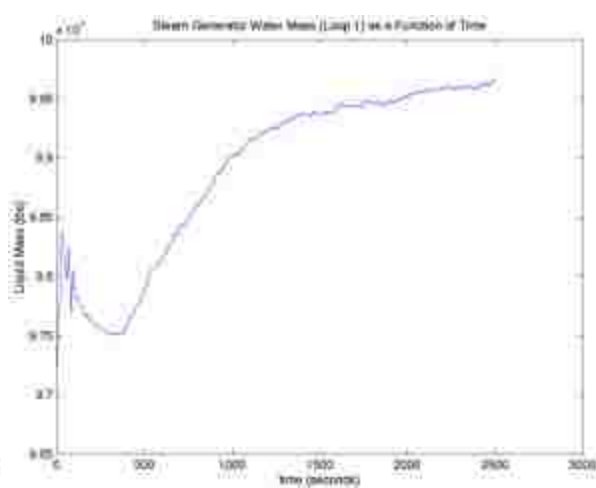


Figure 3.97

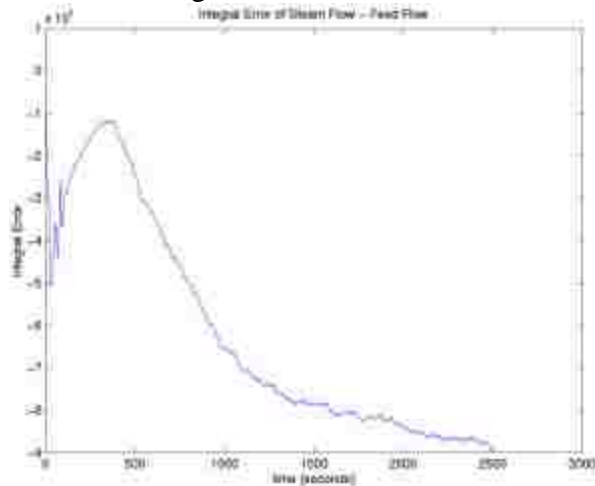


Figure 3.98

A -100% step decrease in load from 100% power using the mass controller, large gain settings (3.00), large steam/feed error weight (2.00) and FCV time constant of 20.0 seconds.

From the above figures, a large gain setting of 3.00 was used in a -100% step decrease in load from 100% power and different steam/feed error weights were used. When the gain settings were smaller than 5.00, the steam/feed error weight could not be set as high as 7.00 because it would induce a reactor trip. Therefore, lower steam/feed error weights but larger than 1.00 were used, but did not improve the increase in steam generator mass and large steam/feed flow fluctuations. Again, small steam/feed error weights did not help the decrease of the steam generator mass at lower power levels. The other mass control strategies were examined using the new controller settings with similar results.

Anticipated Operational Occurrence (Turbine Trip Without Reactor Trip)

Both constant liquid mass control strategies were examined for a turbine trip from full power without a reactor trip. Normally, a turbine trip signal is automatically followed by a reactor trip.

Figures	Transient	Gains	FCV Time Constant
3.99-3.102	Turbine Trip Without Reactor Trip	Small	0.7238 seconds
3.103-3.106	Turbine Trip Without Reactor Trip	Large	20.0 seconds

Table 3.6: Turbine Trip Without Reactor Trip Transients When Using Different Mass Control Strategies

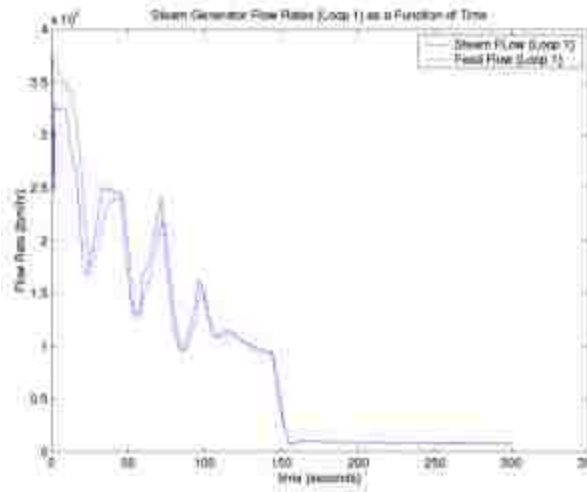


Figure 3.99

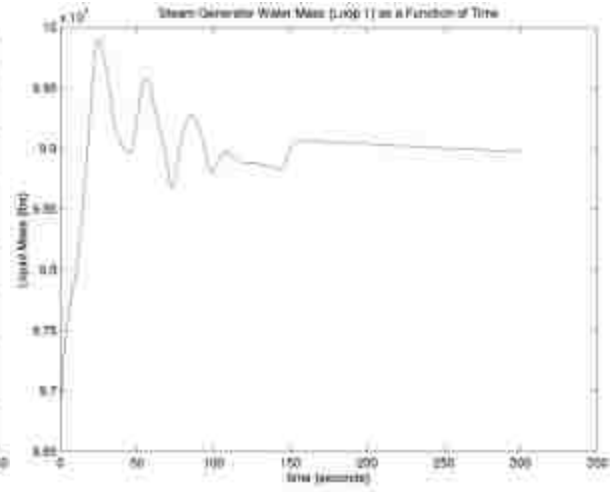


Figure 3.100

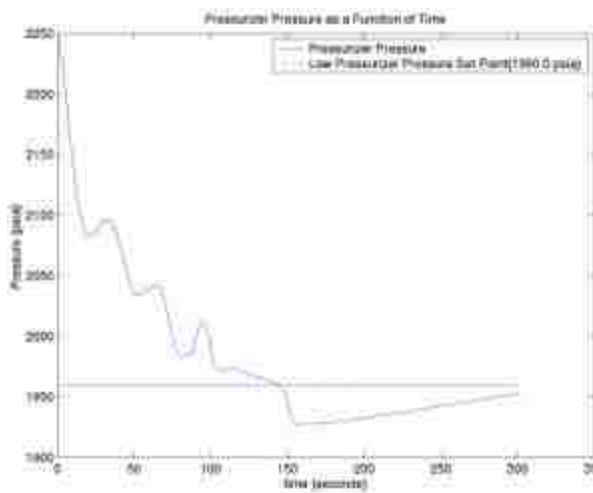


Figure 3.101

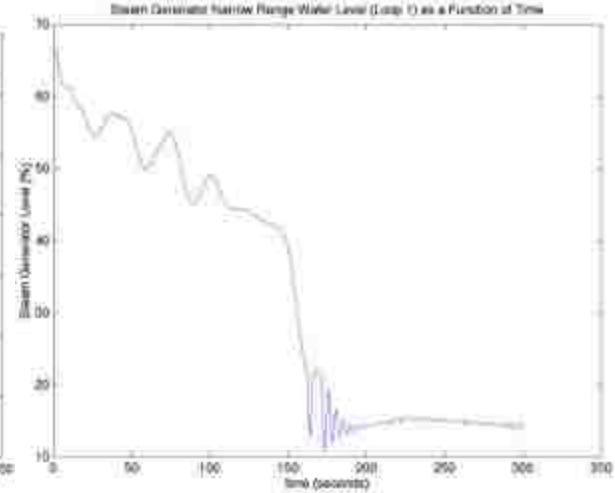


Figure 3.102

A turbine trip without a reactor trip from 100% power using the mass controller, small gain settings, and FCV time constant of 0.7238 seconds.

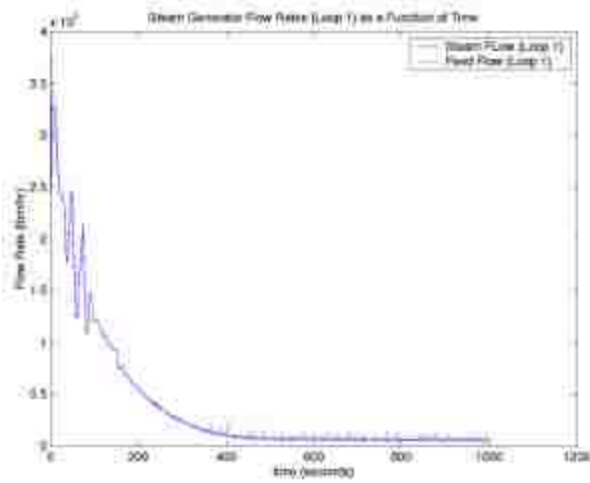


Figure 3.103

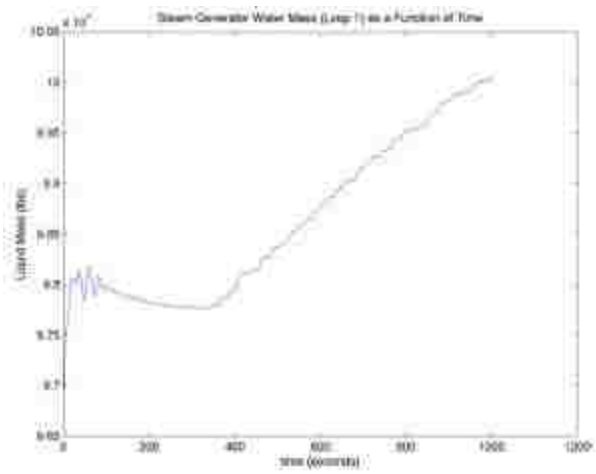


Figure 3.104

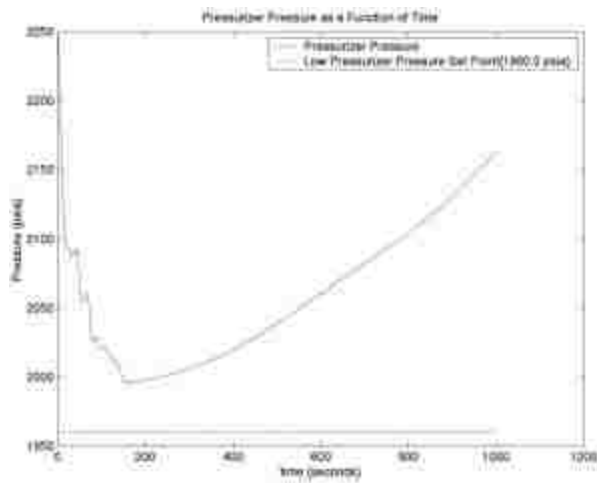


Figure 3.105

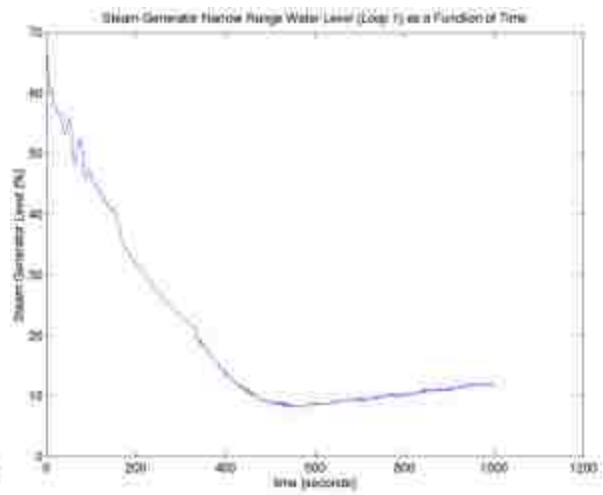


Figure 3.106

A turbine trip without a reactor trip from 100% power using the mass controller, large gain settings, and FCV time constant of 20.0 seconds.

Figures 3.99 to 3.102 represent simulation results from a turbine trip without reactor trip using the smaller gain liquid mass controller. During the transient, there was a reactor trip signal that was induced from a low pressurizer pressure trip set point at 143.97 seconds into the transient, yet the steam generator liquid mass was maintained within less than 1% from the initial time. Figures 3.103 to 3.106 represent simulation results from a turbine trip without reactor trip using the large feed control valve time constant and large gain liquid mass controller. Using this type of control avoided the low pressurizer pressure trip, but the liquid mass in the steam generator keeps increasing with time. Again, when the steam/feed flows level out, the feed control valve becomes more sensitive to changes in the steam flow and at lower power levels and low flows, and changes in the feed flow become a large percentage of the feed flow itself. As a result the liquid mass keeps increasing.

It is important to note that when using the level controller the simulation did not induce a reactor trip when running exactly the same transient. The constant liquid mass controller using the smaller gains induced a reactor trip caused from a low pressurizer pressure trip signal because the secondary side was over cooling the primary side. The next figures represent the steam flow feed flow mismatch data for both the constant liquid mass control strategies and the level control strategy.

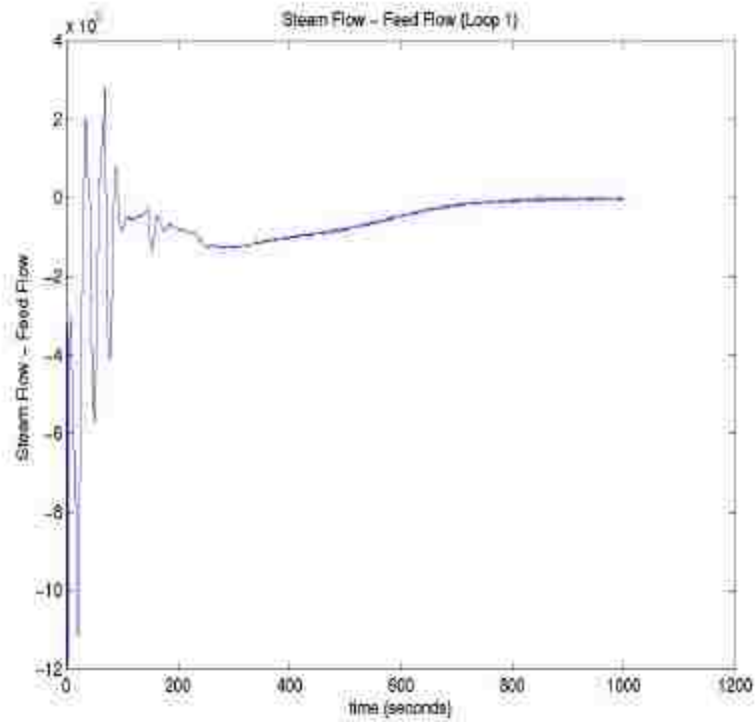


Figure 3.107

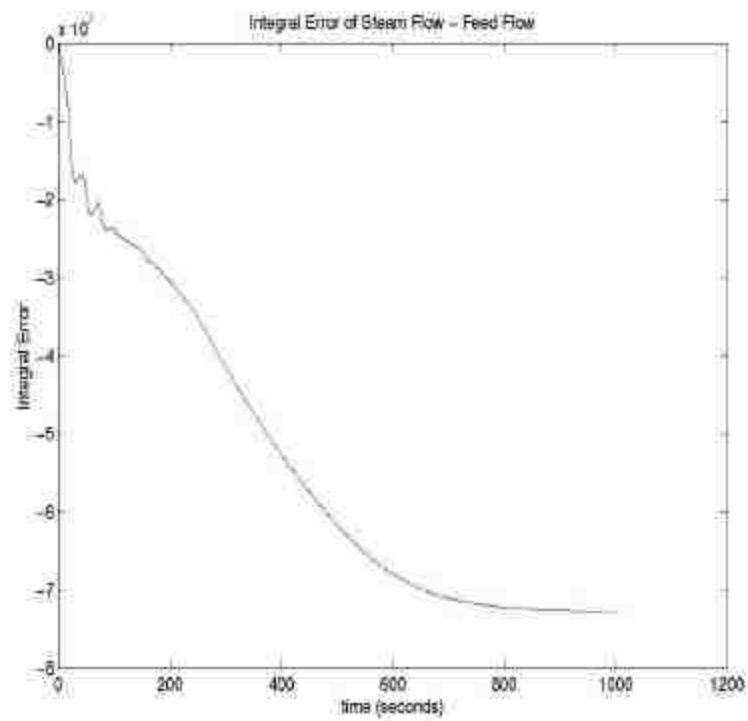


Figure 3.108

A turbine trip without a reactor trip from 100% power using the level controller.

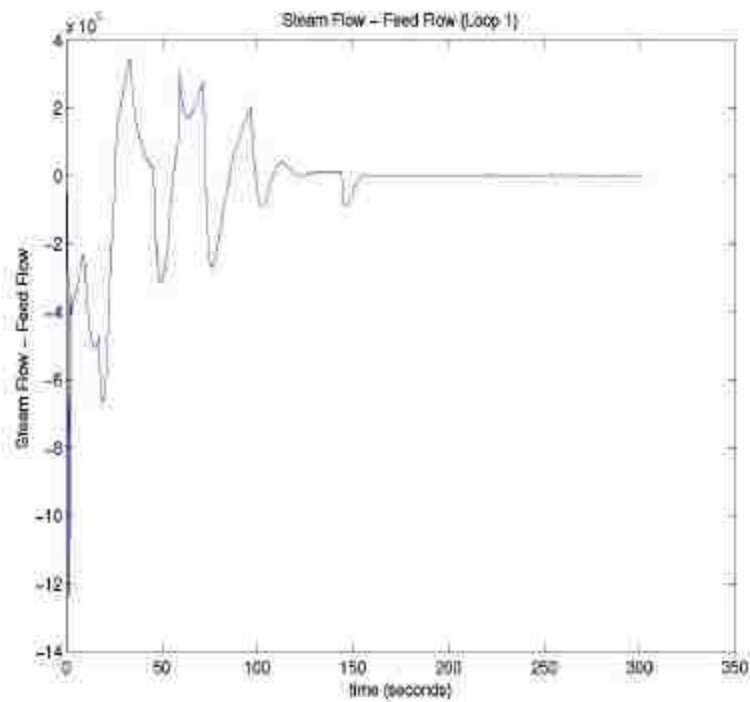


Figure 3.109

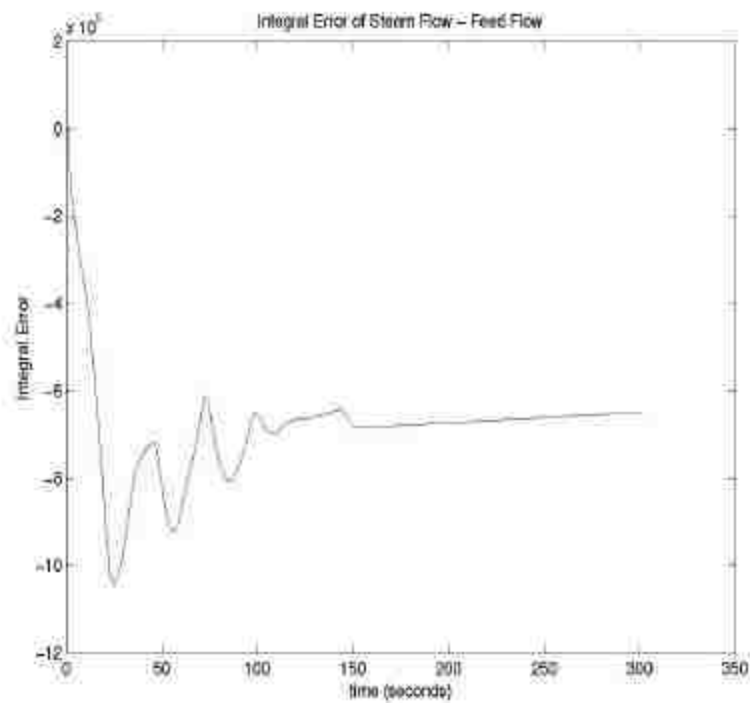


Figure 3.110

A turbine trip without a reactor trip from 100% power using the mass controller, small gain settings, and FCV time constant of 0.7238 seconds.

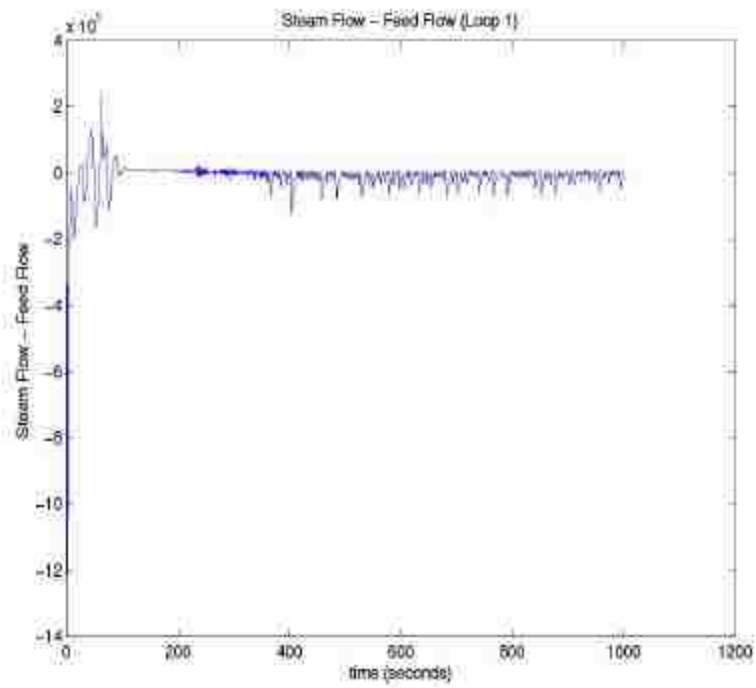


Figure 3.111

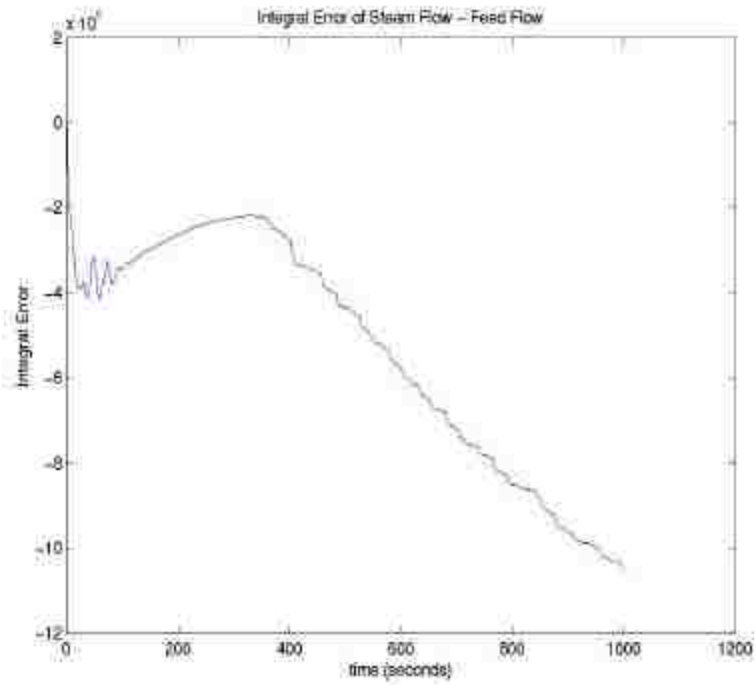


Figure 3.112

A turbine trip without a reactor trip from 100% power using the mass controller, large gain settings, and FCV time constant of 20.0 seconds.

When comparing the smaller gain mass control strategy results, to the level control strategy, the constant liquid mass control strategy has more steam flow than the level control strategy, as a result, there is more heat being transferred in the steam generator. From the increased heat transfer, there is a decrease in the pressure and temperature on the primary side causing a low pressurizer pressure trip signal.

When comparing the larger gain mass control strategy to the level control strategy, it was able to avoid any reactor trips, but the mass keeps increasing. When the larger gain liquid mass and level control strategies level out, there are large negative oscillations in the steam flow feed flow mismatch in the larger gain liquid mass strategy. As a result of added feed and due to low flow conditions, the mass in the steam generator increases.

The feed control valve movement needs to be increased in order for the smaller gain liquid mass control strategy to avoid the over cooling accident. The feed control valve time constant was decreased from the default setting of 0.7238 seconds to 0.5 seconds and the low pressurizer pressure trip was avoided, but there was a reactor trip that was induced by low steam generator level.

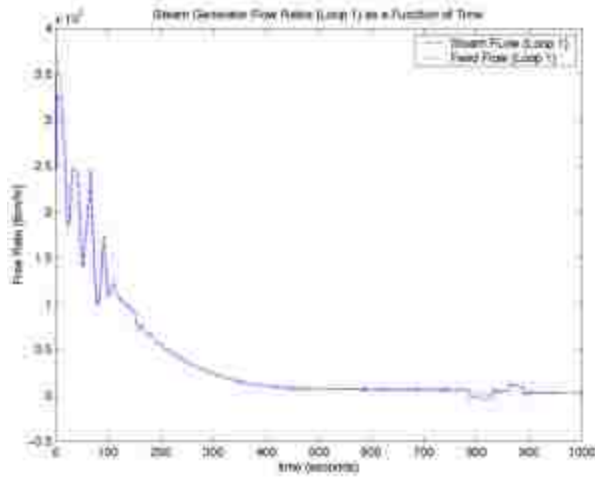


Figure 3.113

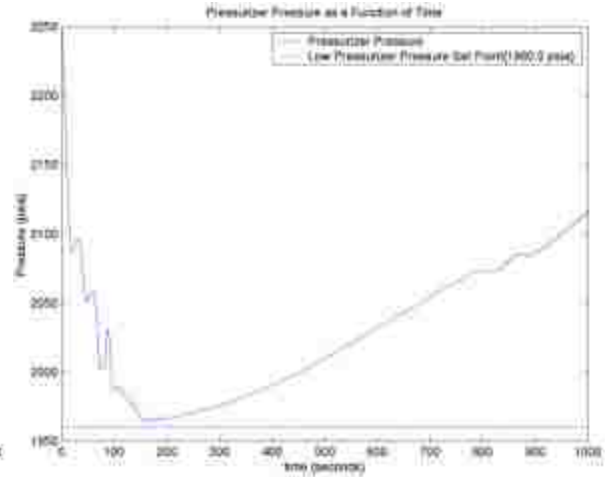


Figure 3.114



Figure 3.115

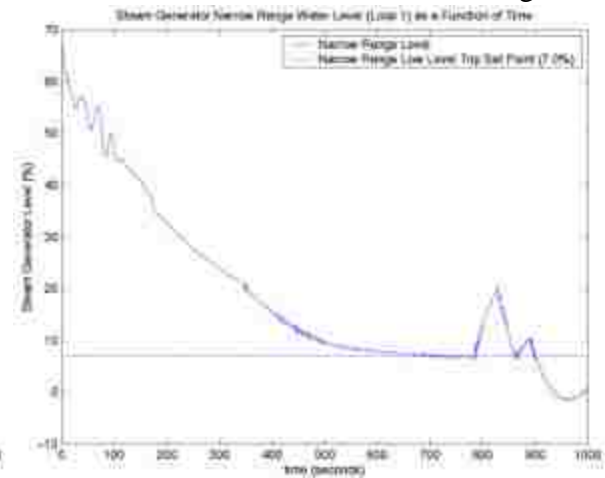


Figure 3.116

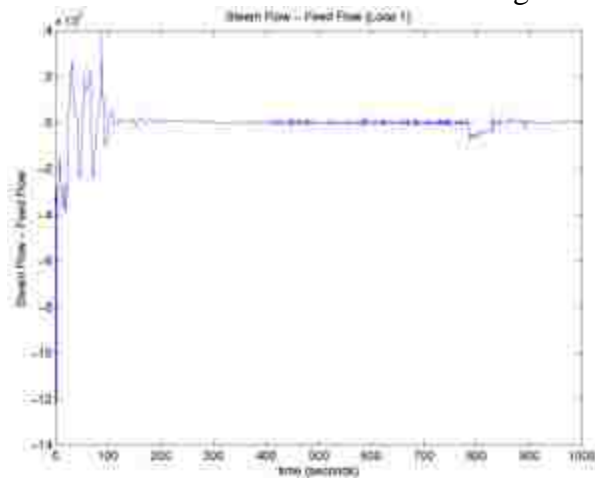


Figure 3.117

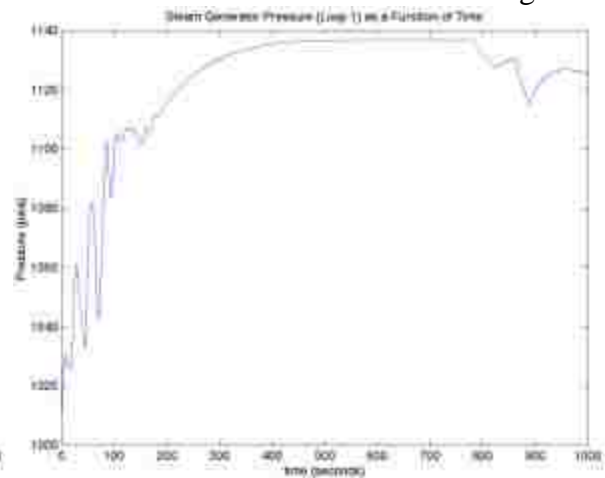


Figure 3.118

A turbine trip without a reactor trip from 100% power using the mass controller, small gain settings, and FCV time constant of 0.5 seconds.

From these results, decreasing the feed control valve time constant helped to avoid the low pressurizer pressure trip, but instead caused a low steam generator (loop 1) level trip 784.59 seconds into the transient. The low level trip was induced due to the fact that the controller was trying to maintain a constant liquid mass in the steam generator. As a result of less steam flow exiting the steam generator and the controller maintaining a relatively constant liquid mass, there is an increase in the steam generator pressure causing the vapor in the steam/liquid mixture to collapse and therefore the mixture shrinks. The level falls in the steam generator beyond the low level set point.

Variable Liquid Mass Controller

Under level control, the steady state liquid mass was a decreasing function of plant power level. Therefore, a variable liquid mass control strategy was implemented based upon this behavior. The reference liquid mass as a function of plant power level used in the simulations is shown in figure 3.119. The corresponding steady state narrow range liquid level as a function of plant power level is shown in figure 3.120.

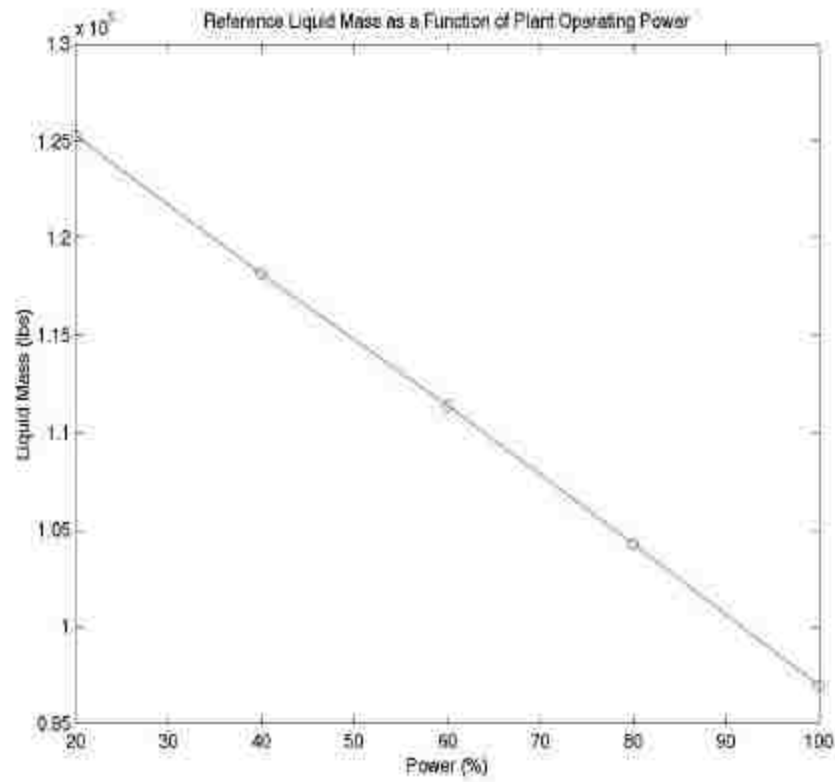


Figure 3.119

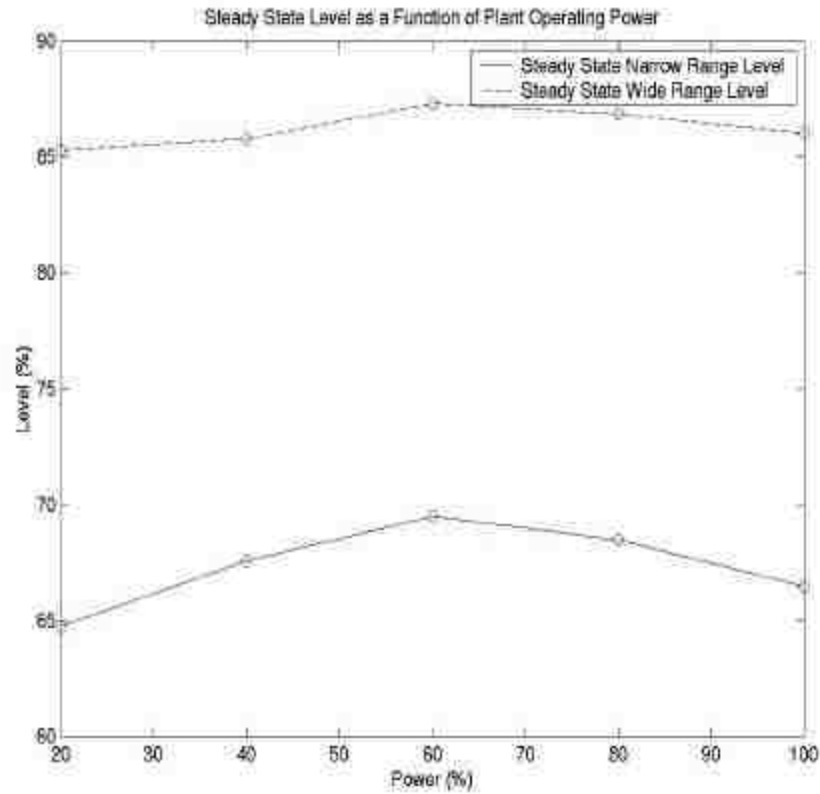


Figure 3.120

From these figures, the narrow range liquid level is between 60% and 70% and is well within the safety settings for the steam generator.

Valve Characteristics for Variable Liquid Mass Controller

The integral and proportional gain settings from the constant liquid mass controller were examined for the variable liquid mass control strategies. The new mass control strategy was examined for normal operational occurrences including a step change of –10% and a ramp change of –5% per minute for two minutes, both from full power, and a step change of +10% and a ramp change of +5% per minute for two minutes, both from 20% power.

Figures	Transient	Initial Power	Gains	FCV Time Constant
3.121-3.124	–10% Step Decrease in Load	100%	Small	0.7238 seconds
3.125-3.128	-5% per minute Ramp Decrease in Load for 2 minutes	100%	Small	0.7238 seconds
3.129-3.132	–10% Step Decrease in Load	100%	Large	20.0 seconds
3.133-3.136	-5% per minute Ramp Decrease in Load for 2 minutes	100%	Large	20.0 seconds
3.137-3.140	+10% Step Increase in Load	20%	Small	0.7238 seconds
3.141-3.144	+5% per minute Ramp Increase in Load for 2 minutes	20%	Small	0.7238 seconds
3.145-3.148	+10% Step Increase in Load	20%	Large	20.0 seconds
3.149-3.152	+5% per minute Ramp Increase in Load for 2 minutes	20%	Large	20.0 seconds

Table 3.7: **Different Transients Examined Using Variable Mass Control Strategy**

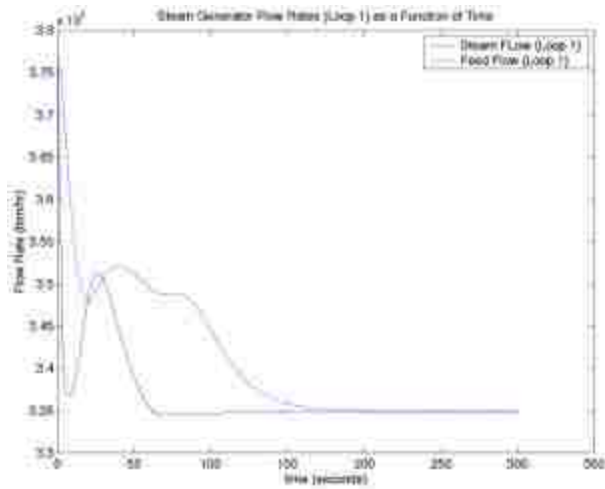


Figure 3.121

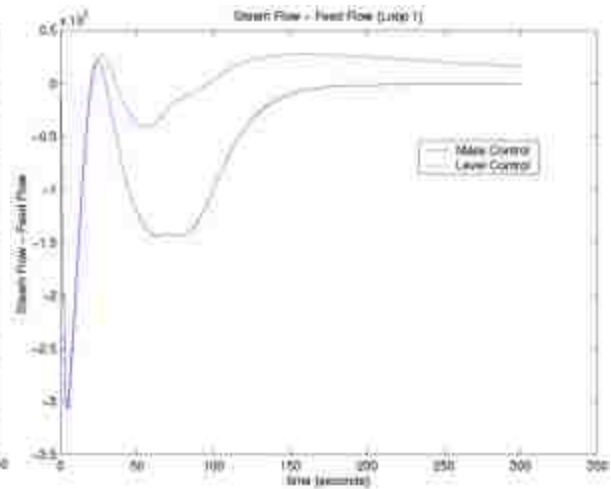


Figure 3.122

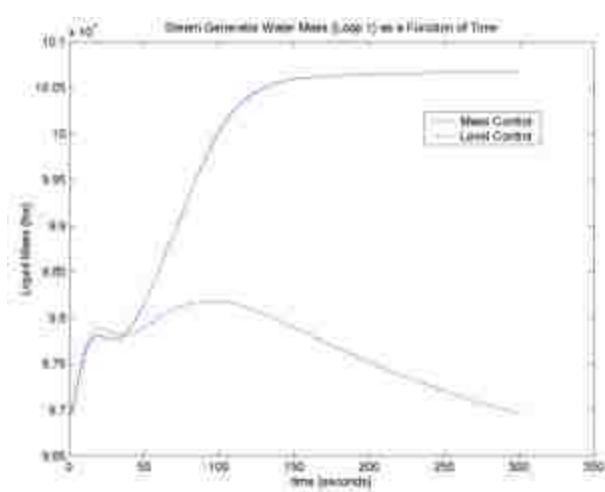


Figure 3.123

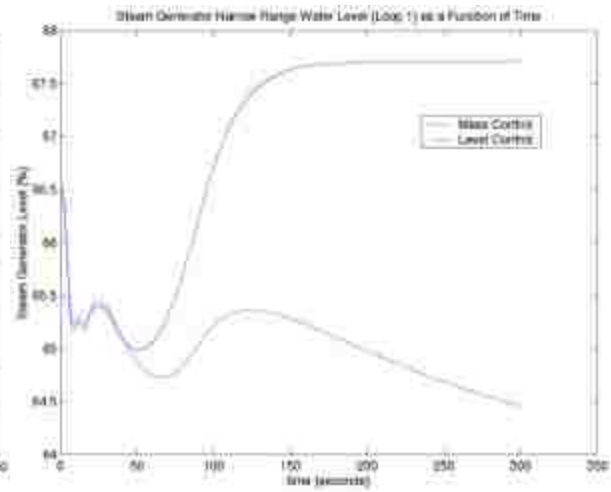


Figure 3.124

A -10% step decrease in load from 100% power using small gain settings and FCV time constant of 0.7238 seconds.

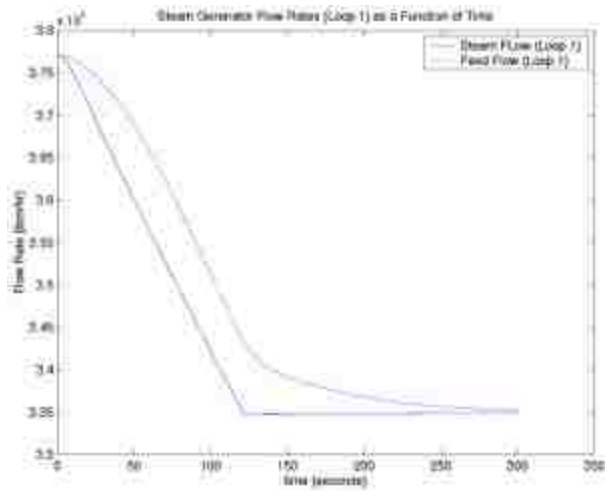


Figure 3.125

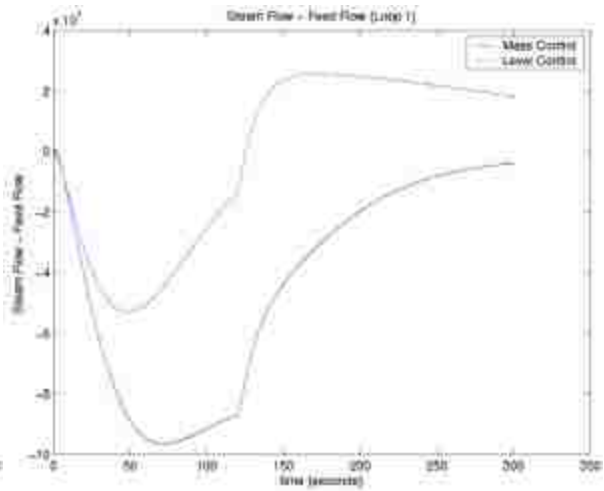


Figure 3.126

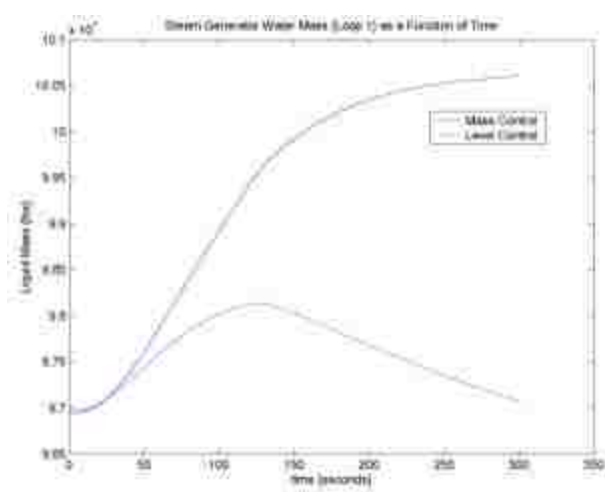


Figure 3.127

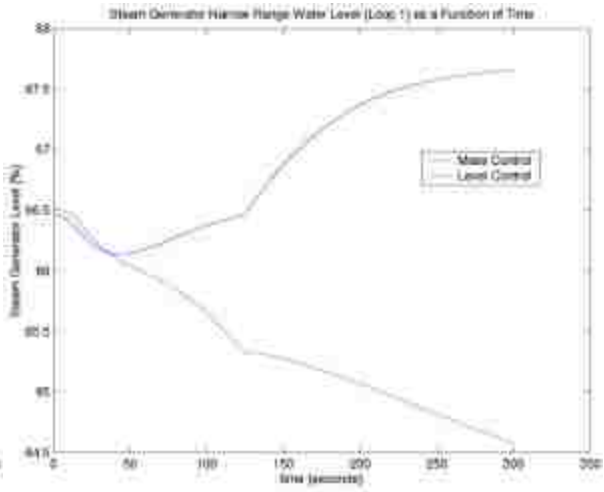


Figure 3.128

A -5% per minute ramp decrease in load for two minutes from 100% power using small gain settings and FCV time constant of 0.7238 seconds.

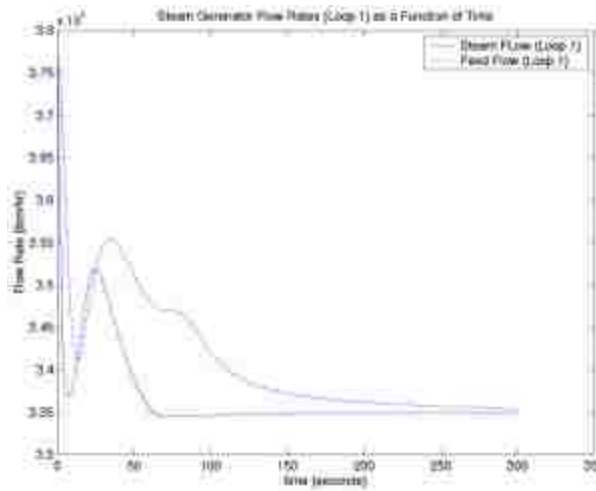


Figure 3.129

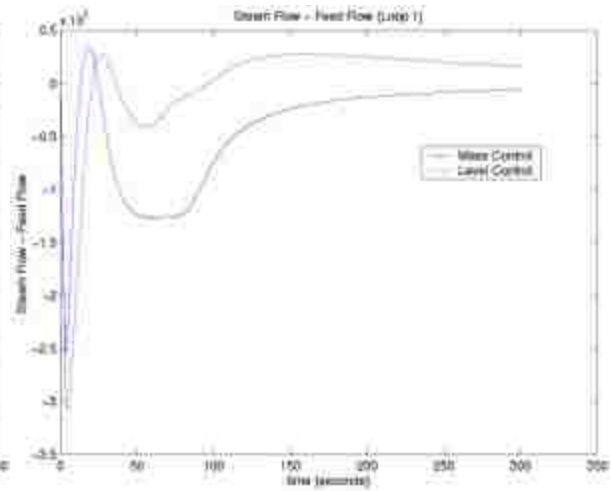


Figure 3.130

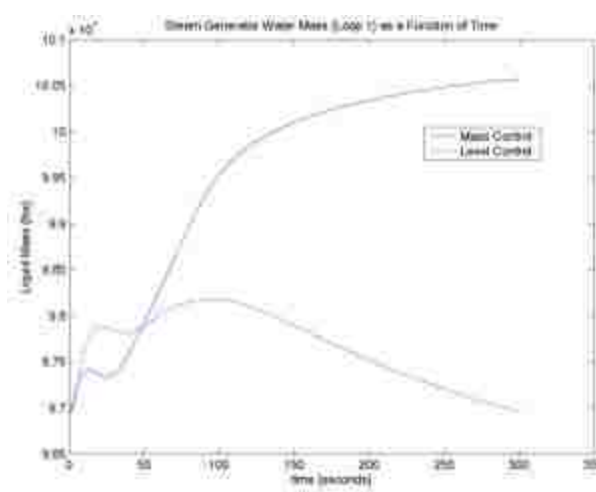


Figure 3.131

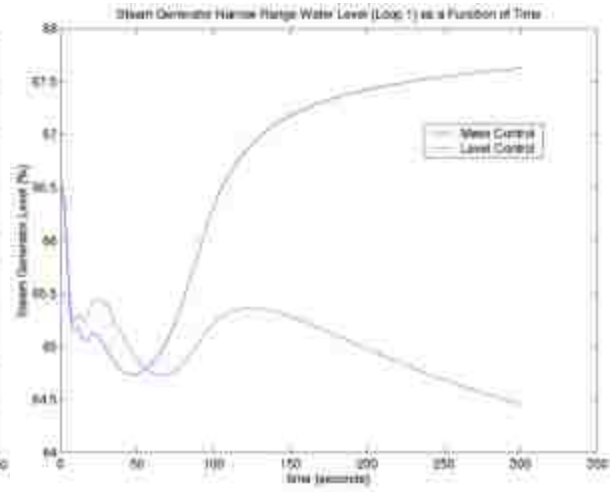


Figure 3.132

A -10% step decrease in load from 100% power using large gain settings and FCV time constant of 20.0 seconds.

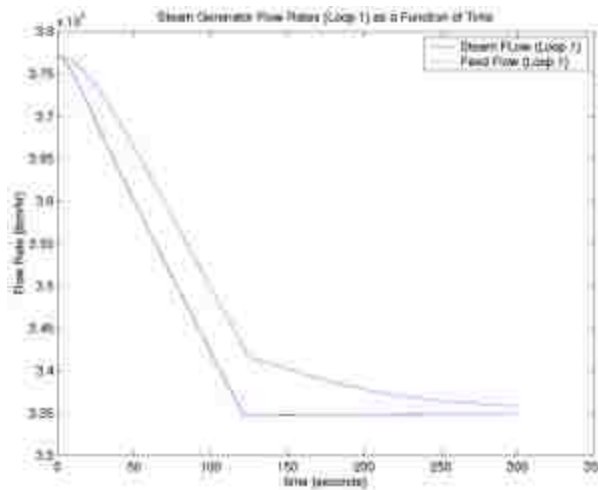


Figure 3.133

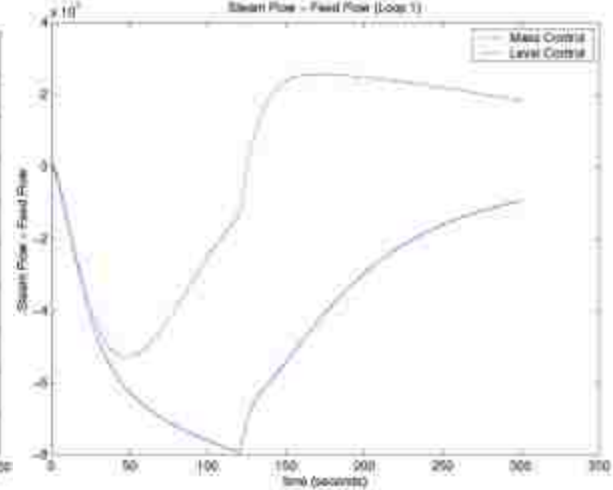


Figure 3.134

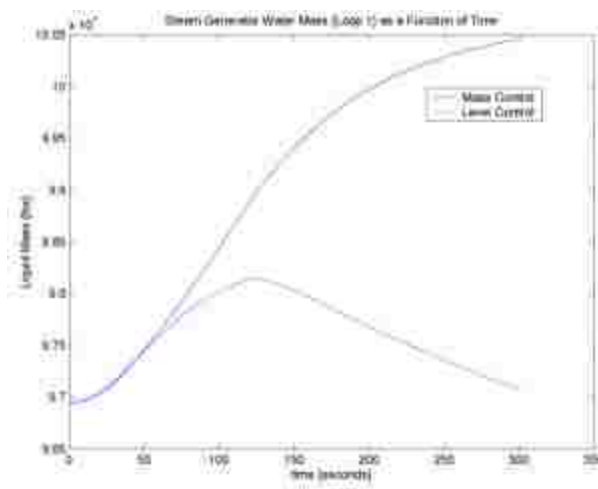


Figure 3.135

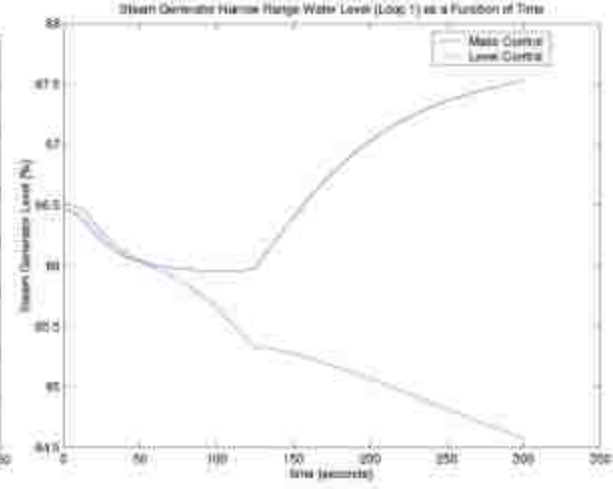


Figure 3.136

A -5% per minute ramp decrease in load for two minutes from 100% power using large gain settings and FCV time constant of 20.0 seconds.

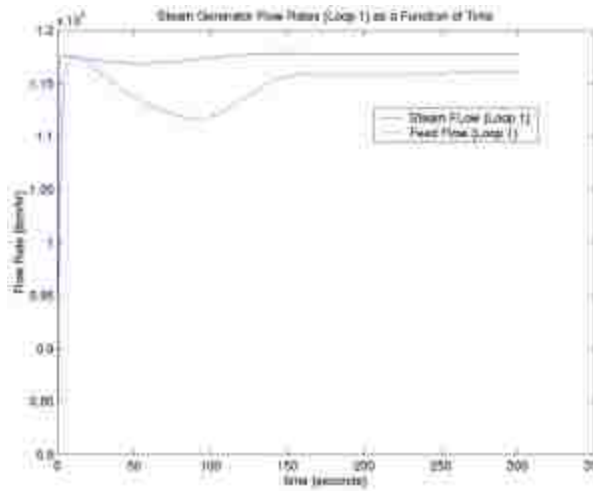


Figure 3.137

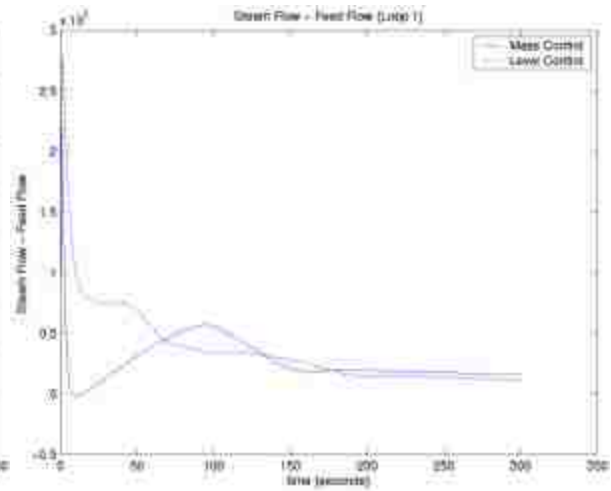


Figure 3.138

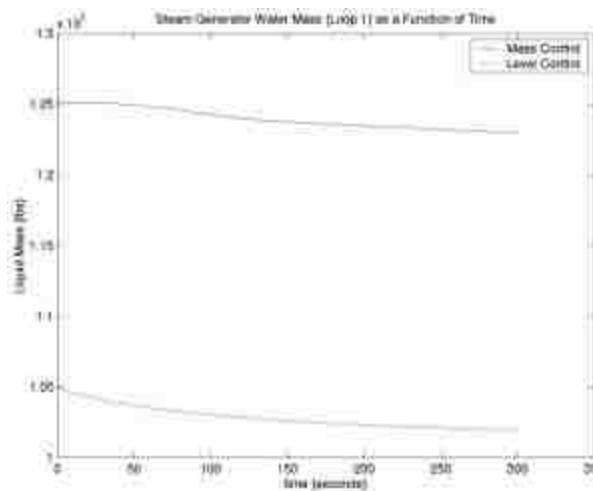


Figure 3.139

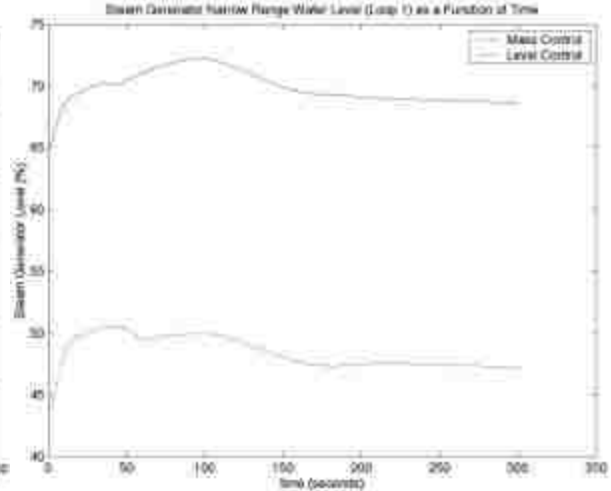


Figure 3.140

A +10% step increase in load from 20% power using small gain settings and FCV time constant of 0.7238 seconds.

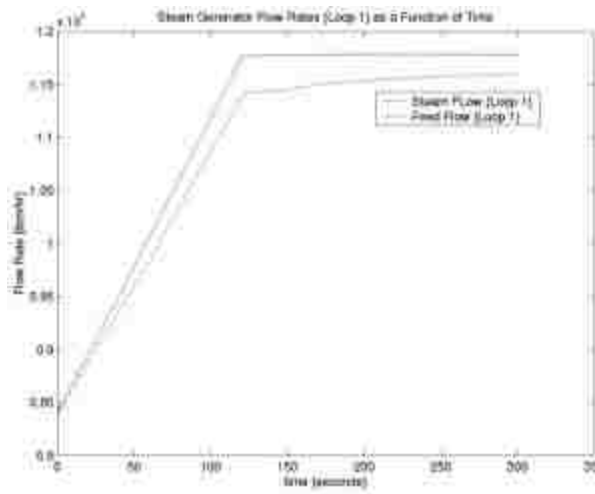


Figure 3.141

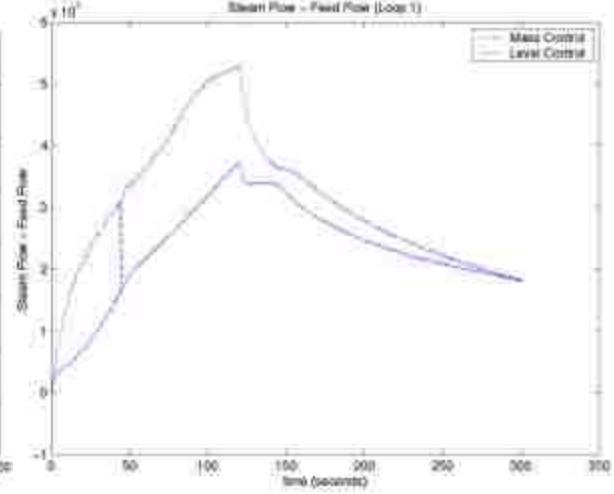


Figure 3.142

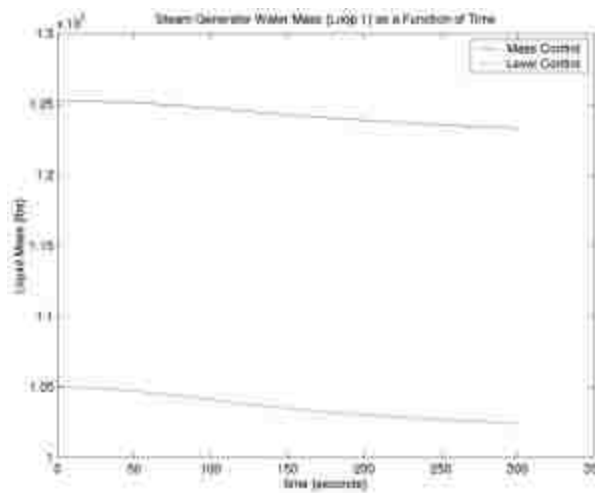


Figure 3.143

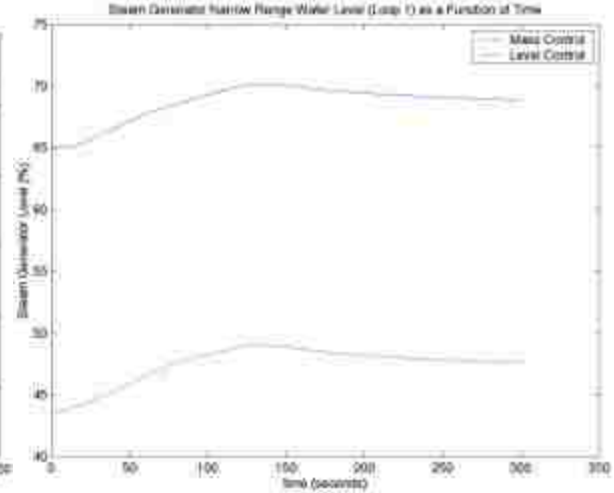


Figure 3.144

A +5% per minute ramp increase in load for two minutes from 20% power using small gain settings and FCV time constant of 0.7238 seconds.

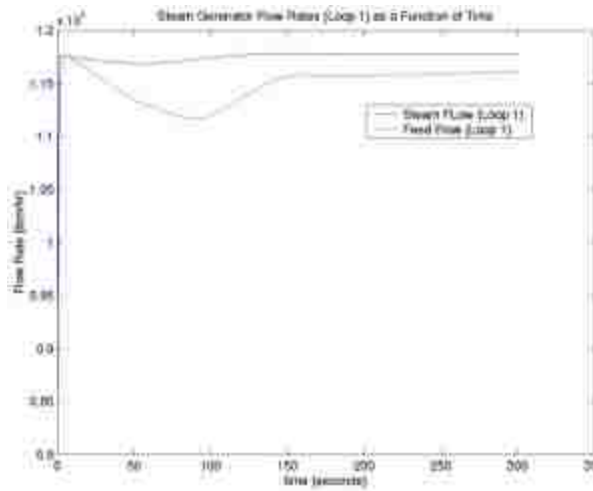


Figure 3.145

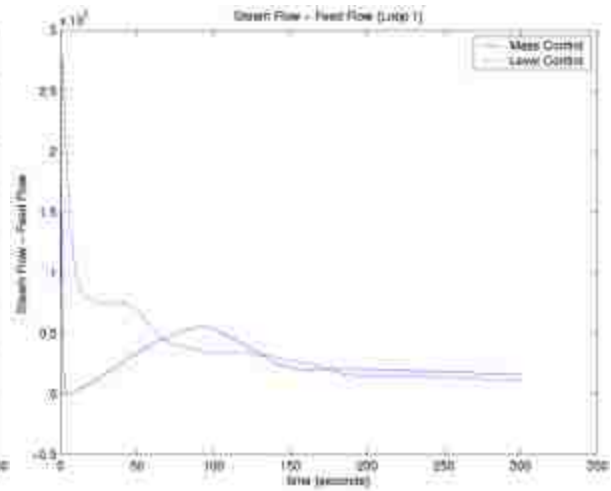


Figure 3.146

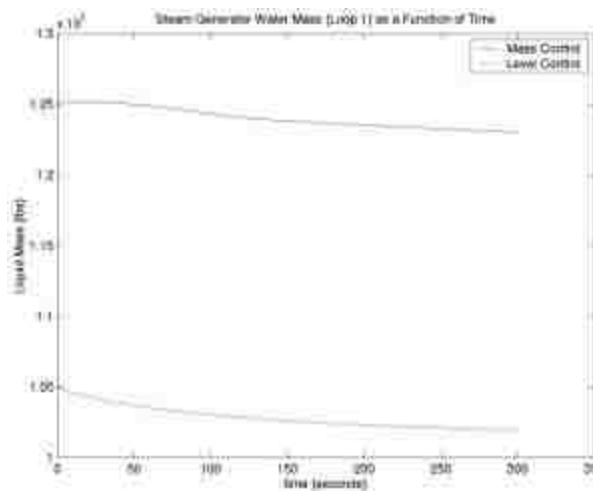


Figure 3.147

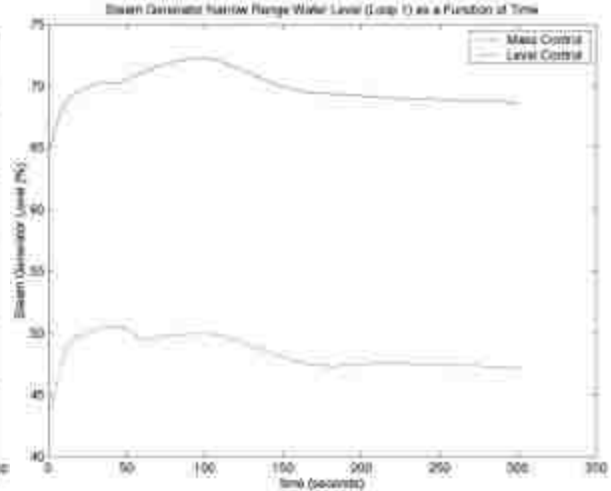


Figure 3.148

A +10% step increase in load from 20% power using large gain settings and FCV time constant of 20.0 seconds.

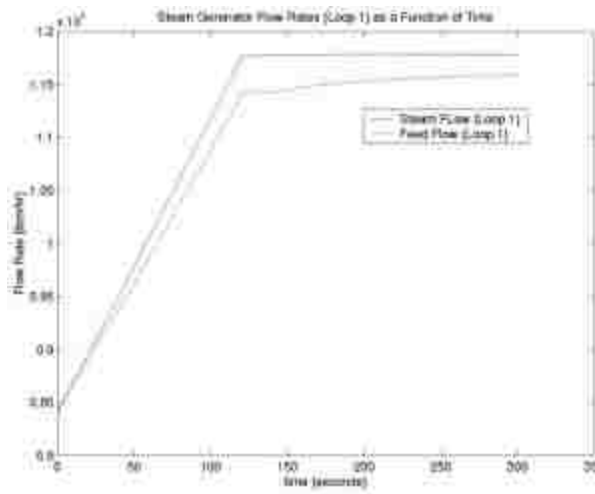


Figure 3.149

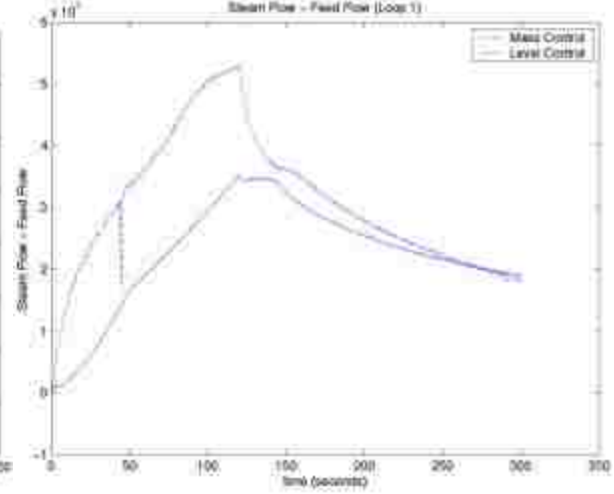


Figure 3.150

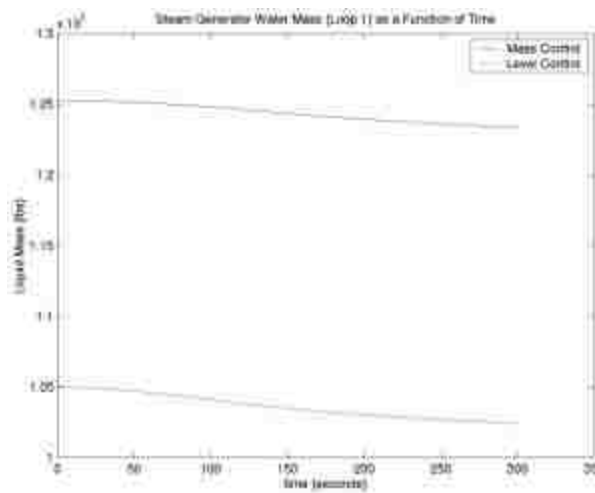


Figure 3.151

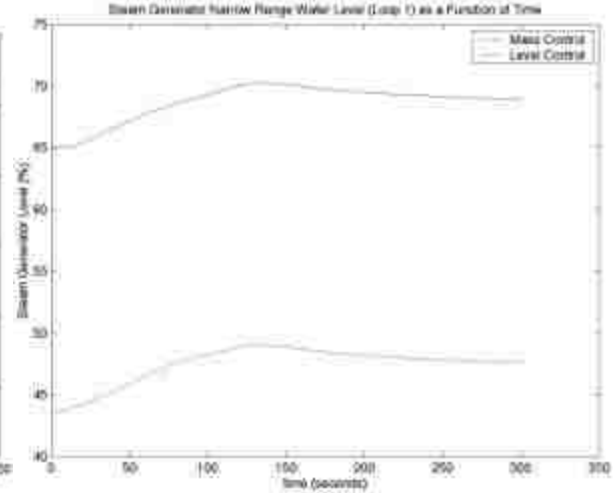


Figure 3.152

A +5% per minute ramp increase in load for two minutes from 20% power using large gain settings and FCV time constant of 20.0 seconds.

Again, it is important to note that the initial conditions for both the level and mass controllers are different. Both parameter combinations yielded similar results and did not induce a reactor trip. Also, it is important to note that the when there is a decrease in the steam flow, there is somewhat of an excess feed flow and then it matches the steam flow. The two control strategies were then examined on other normal operational occurrences at all other power ranges and produced adequate results, none of which resulted in a reactor trip.

Abnormal Power Transient

The two variable liquid mass control strategies proved to be adequate for steam generator control under normal operational occurrences. The two different control strategies were then examined on an abnormal power transient using the default steam/feed error weight of 1.0. Again a –100% step change in load from full power was examined using both variable liquid mass control strategies.

Figures	Transient	Controller	Gains	FCV Time Constant
3.153-3.156	–100% Step Decrease in Load	Mass	Small	0.7238 seconds
3.157-3.160	–100% Step Decrease in Load	Mass	Large	20.0 seconds

Table 3.8: **Abnormal Power Transient Examined Using Variable Mass Control Strategies**

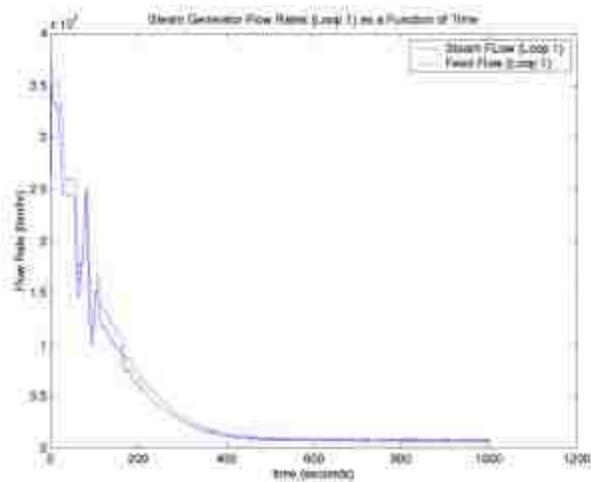


Figure 3.153

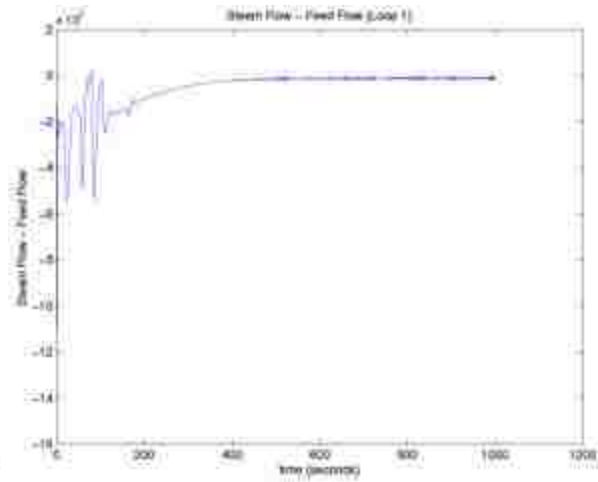


Figure 3.154

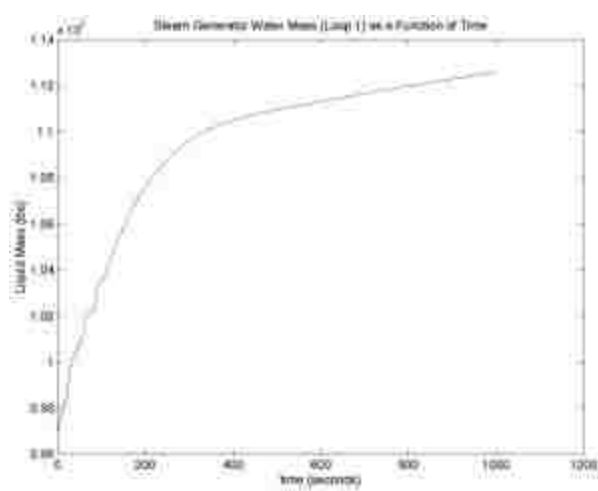


Figure 3.155

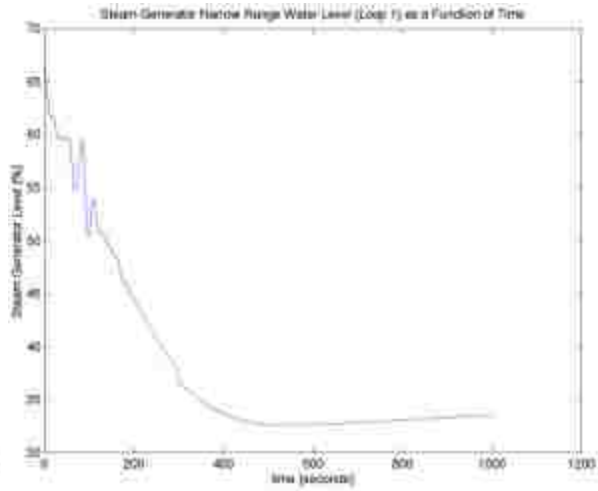


Figure 3.156

A -100% step decrease in load from 100% power using the mass controller, small gain settings, and FCV time constant of 0.7238 seconds.

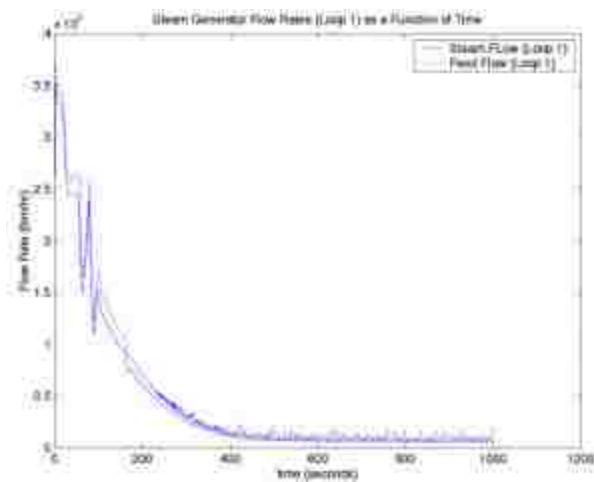


Figure 3.157

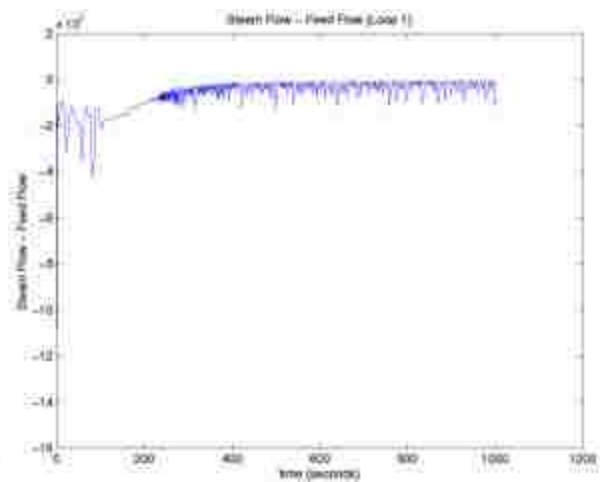


Figure 3.158

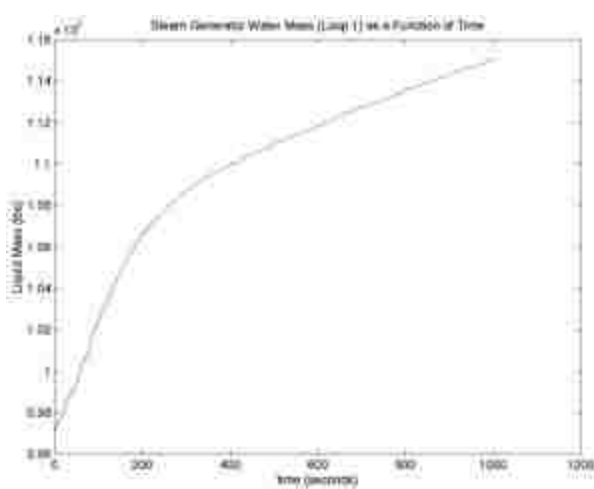


Figure 3.159

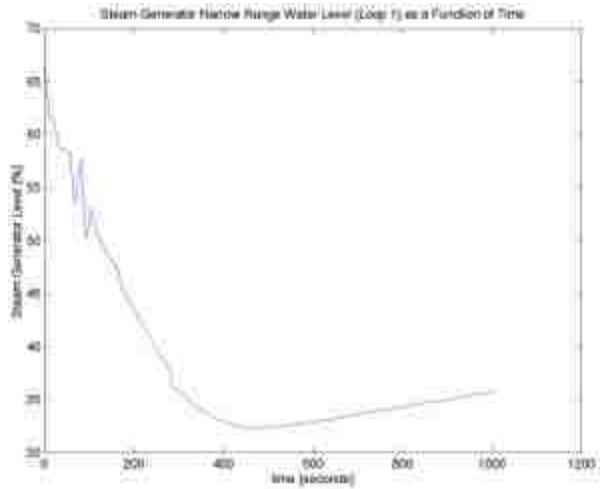


Figure 3.160

A -100% step decrease in load from 100% power using the mass controller, large gain settings, and FCV time constant of 20.0 seconds.

From the above figures, the large load rejection from full power did not induce a reactor trip using both variable liquid mass control strategies.

Anticipated Operational Occurrence (Turbine Trip Without Reactor Trip)

Both variable liquid mass control strategies were examined on an anticipated accident scenario. The transient that will be examined was a turbine trip from full power that does not induce a reactor trip from the turbine trip signal.

Figures	Transient	Gains	FCV Time Constant
3.161-3.164	Turbine Trip Without Reactor Trip	Small	0.7238 seconds
3.165-3.168	Turbine Trip Without Reactor Trip	Large	20.0 seconds

Table 3.9: **Turbine Trip Without Reactor Trip Transients When Using Variable Mass Control Strategies**

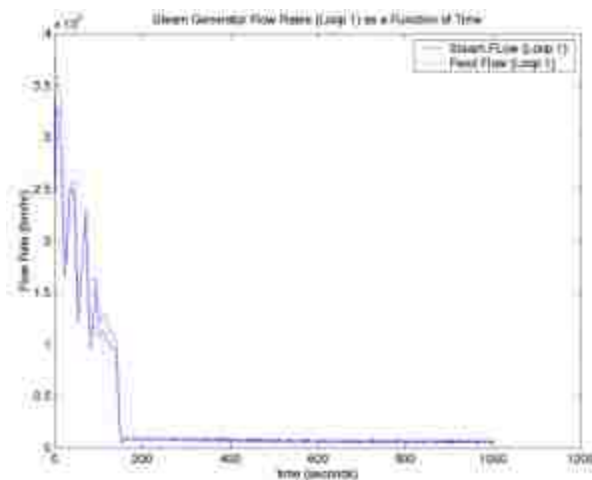


Figure 3.161

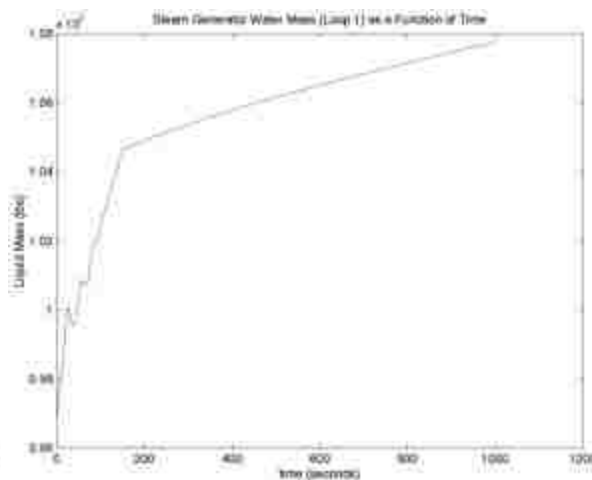


Figure 3.162

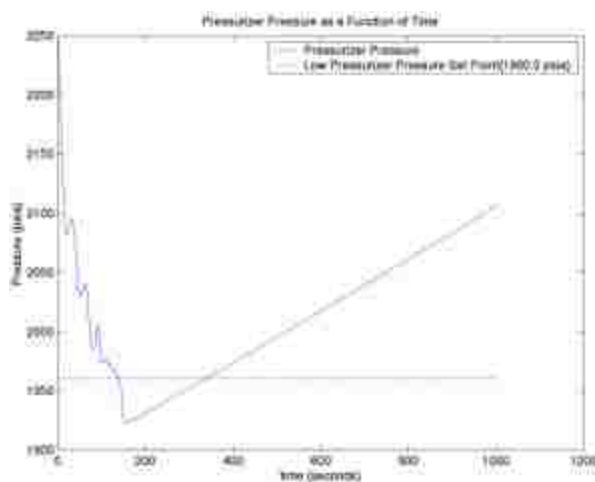


Figure 3.163

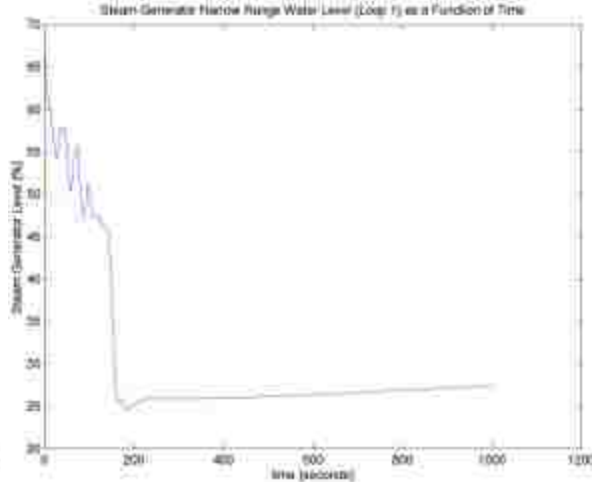


Figure 3.164

A turbine trip without a reactor trip from 100% power using the mass controller, small gain settings, and FCV time constant of 0.7238 seconds.

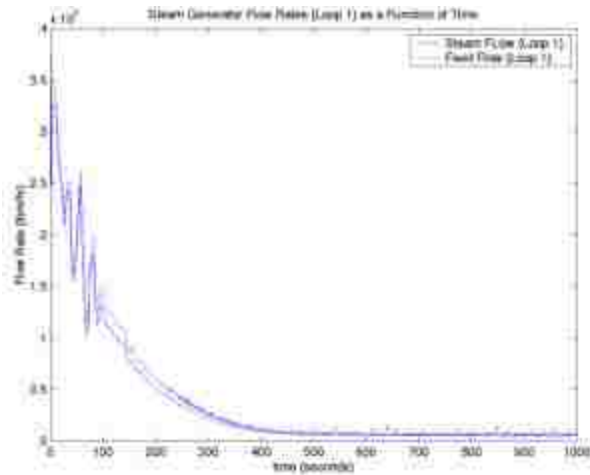


Figure 3.165

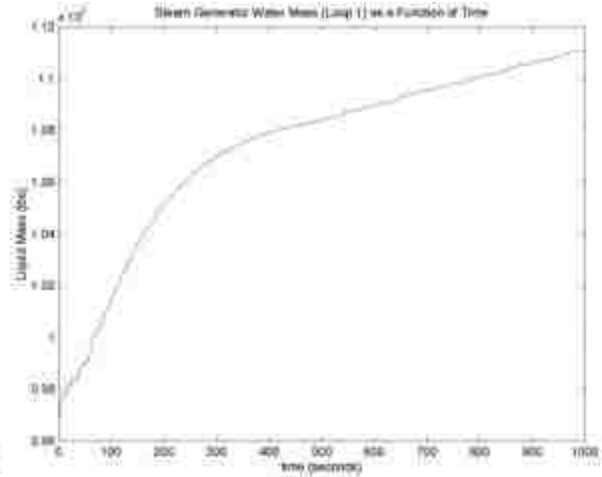


Figure 3.166

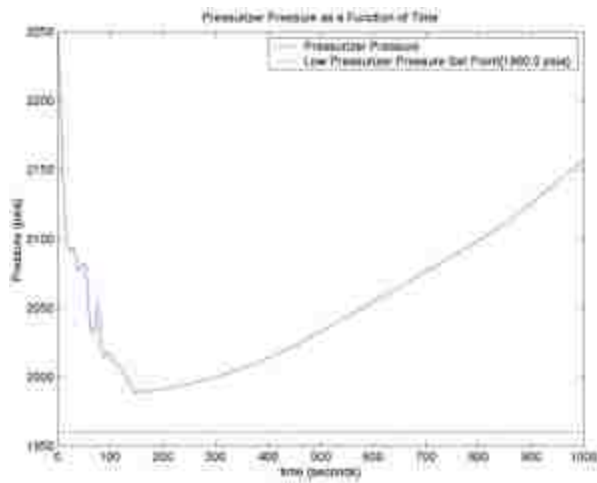


Figure 3.167

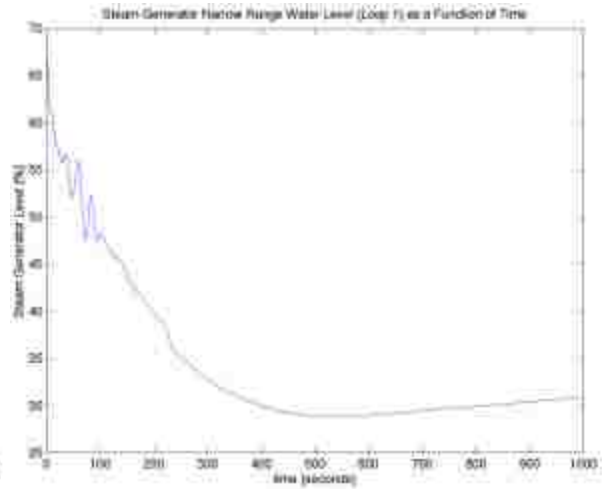


Figure 3.168

A turbine trip without a reactor trip from 100% power using the mass controller, large gain settings, and FCV time constant of 20.0 seconds.

Figures 3.161 to 3.164 represent simulation results from a turbine trip without reactor trip using the smaller gain constant liquid mass controller. During the transient, there was a reactor trip signal that was induced from a low pressurizer pressure trip set point at 140.11 seconds into the transient. Again, this transient was caused from the over cooling of the primary side. Figures 3.165 to 3.168 represent simulation results from a turbine trip without reactor trip using the large feed control valve time constant and large gain constant liquid mass controller. Using this type of control avoided the low pressurizer pressure trip.

When comparing the steam flow feed flow mismatch data with those of the constant liquid mass controller, the variable liquid mass controller performed better, but still induced a reactor trip from a low pressurizer pressure trip signal. In this transient, it is a race for the secondary side to stop the over cooling of the primary side. The next figures represent the steam flow feed flow mismatch data for both the constant liquid mass control strategies and the level control strategy.

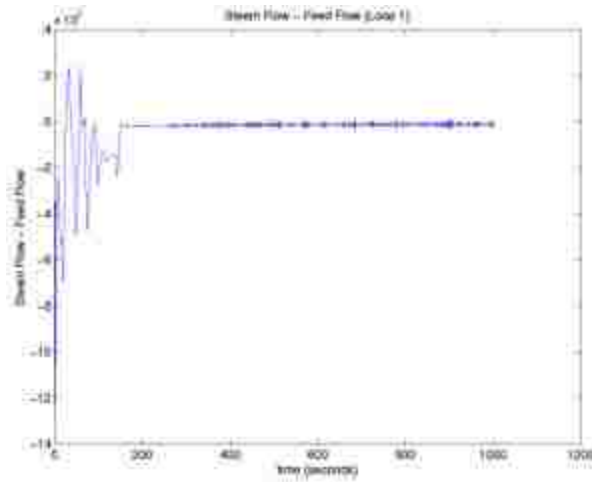


Figure 3.169

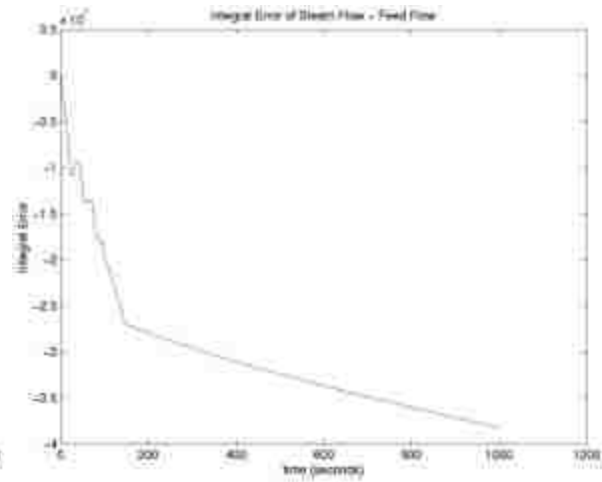


Figure 3.170

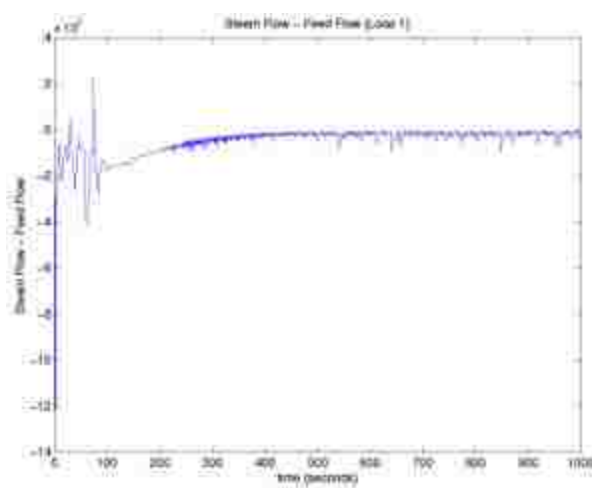


Figure 3.171

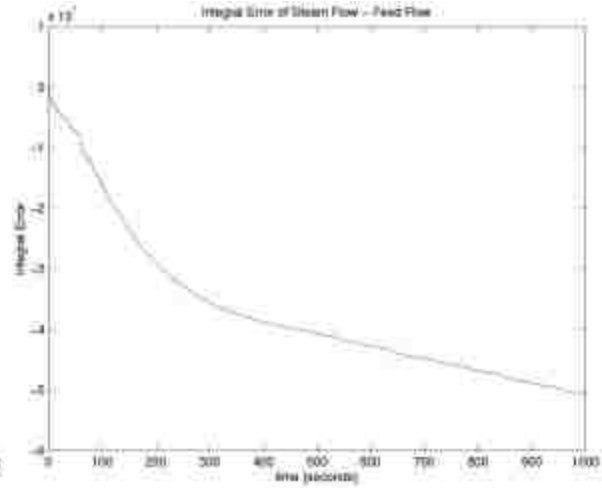


Figure 3.172

Steam/feed flow mismatch results for a turbine trip without reactor trip from 100% power using variable mass control strategy with large and small gains.

Figures 3.169 and 3.170 represent the variable liquid mass control strategy using the smaller gain settings, and figures 3.171 and 3.172 the variable liquid mass control strategy using the large feed control valve time constant and large gain settings. The variable liquid mass control strategy using the large feed control valve time constant and large gain settings again avoided the low pressurizer pressure trip set point, but the variable liquid mass control strategy using the smaller gain settings did not. Again, the large gain variable mass controller exhibits large oscillations in the steam/feed flows and prove to be unacceptable. When comparing the Figure 3.170 to the level controller steam flow feed flow mismatch, the variable liquid mass controller is still steaming more causing the pressure on the primary side to decrease. To prevent the reduction in pressure on the primary side, the feed control valve will have to open more quickly.

To increase the amount of feed flow into the steam generator, the time constant of the FCV was decreased. Currently, the level control strategy uses a FCV time constant of 0.7238 seconds. This time constant for the variable liquid mass controller using the smaller gain settings was decreased to 0.5 seconds, and the turbine trip was examined again.

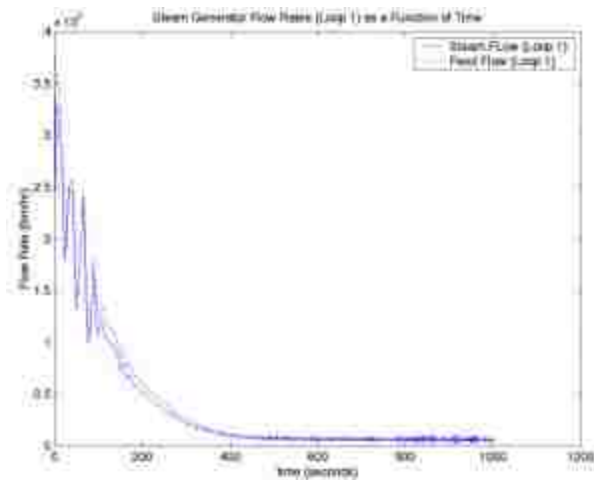


Figure 3.173

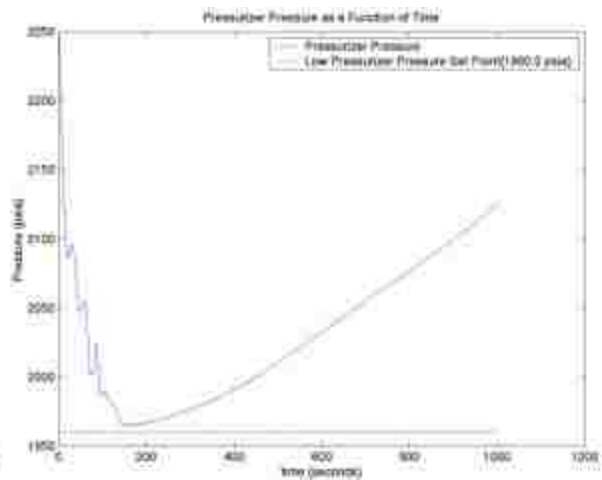


Figure 3.174

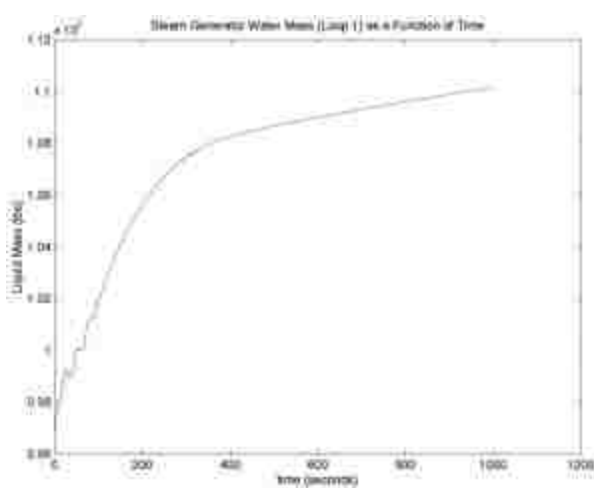


Figure 3.175

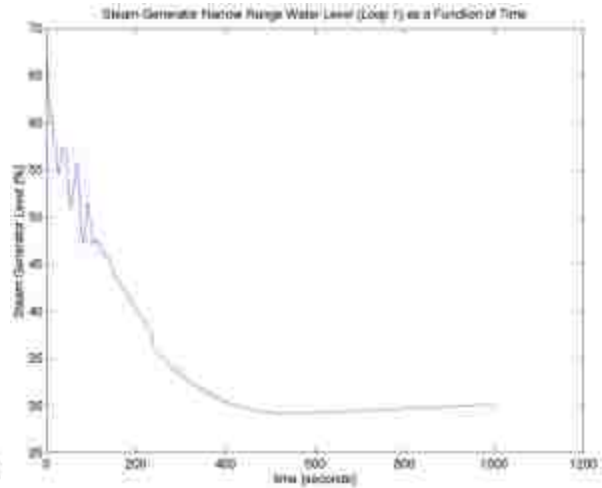


Figure 3.176

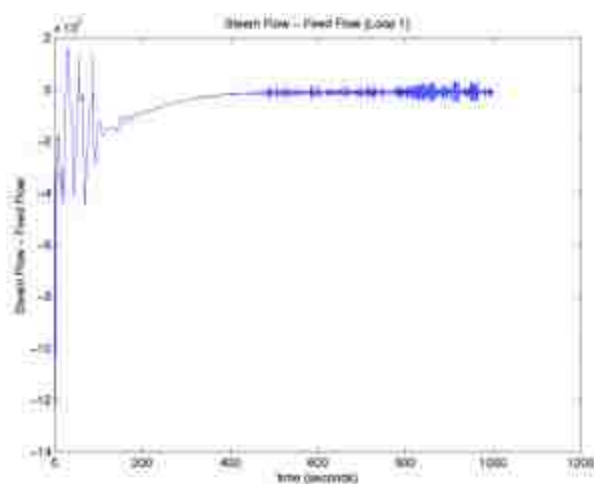


Figure 3.177

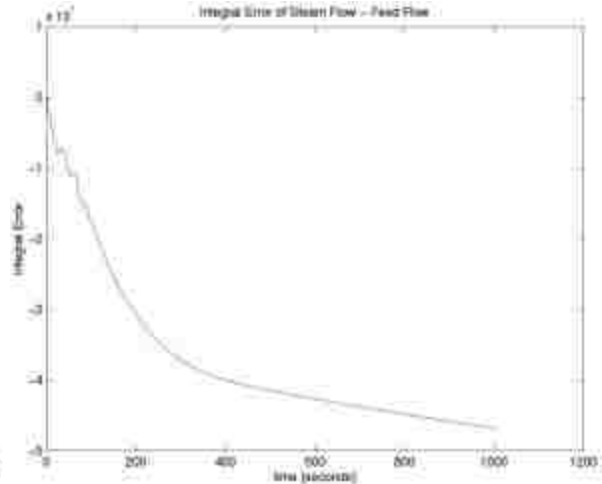


Figure 3.178

Turbine trip without reactor trip from 100% power using variable mass control strategy with small gains and a feed control valve constant of 0.5 seconds.

From the above the low pressurizer pressure trip set point was avoided and the steam generator levels were maintained between reasonable limits with the reduction in the feed control valve time constant. With the reduction in the feed control valve time constant, more feed flow was allowed to enter the steam generator, so that there would be more feed flow than steam flow to decrease the heat transfer from the primary side. .

Both the variable liquid mass control strategies were examined on other turbine trips occurring from different power levels, and these transients did not induce a reactor trip signal.

Low Power Operation

During low power operations, the dynamics of the reactor system are highly unstable. Small perturbations that are introduced into the system may cause a reactor to trip. Also, when the reactor is operating at low power levels, the steam and feed flows in the steam generator are small when compared to higher power levels. Small changes in the steam/feed flows become a large portion or become more than the steam/feed flow themselves.

Low power transients were examined using both the level and mass controllers. During the low power transients, both a three and single-element controller were examined. Different operational occurrences including a +10% step increase and a +5% ramp per minute for two minutes increase in load from 15% power using a both a three and single element level controller. These results are shown in Figures 3.179-3.202

Figures	Transient	Controller
3.179-3.182	+10% Step Increase in Load from 15% Power	Three-Element Level
3.183-3.186	+5% per minute Ramp Increase in Load for 2 minutes from 15% Power	Three-Element Level
3.187-3.190	+10% Step Increase in Load from 15% Power	Single-Element Level
3.191-3.194	+5% per minute Ramp Increase in Load for 2 minutes from 15% Power	Single-Element Level
3.195-3.198	+10% Step Increase in Load from 15% Power (With Noise)	Three-Element Level
3.199-3.202	+5% per minute Ramp Increase in Load for 2 minutes from 15% Power (With Noise)	Three-Element Level

Table 3.10: **Low Power Operation Using Level Controller**

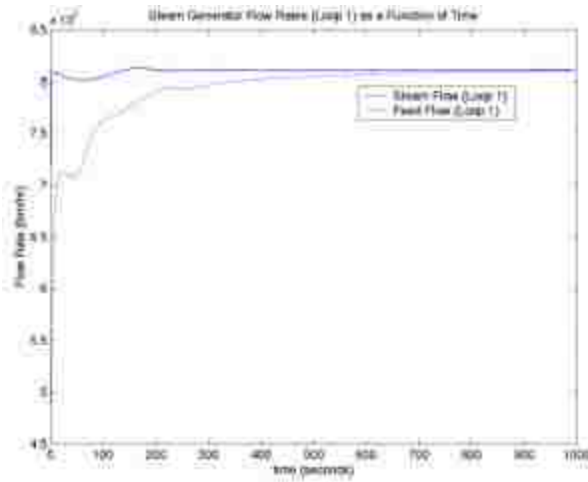


Figure 3.179

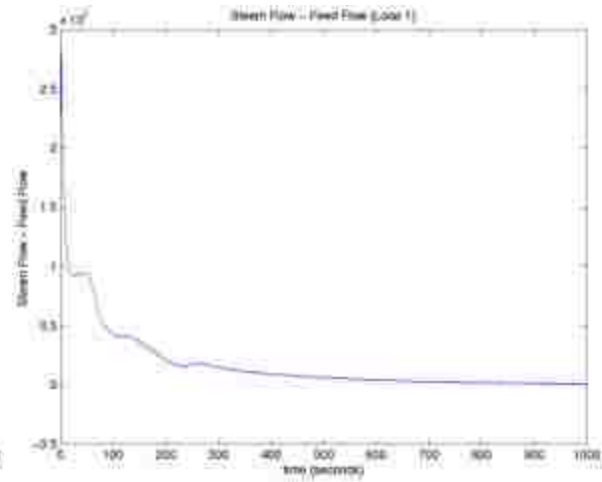


Figure 3.180

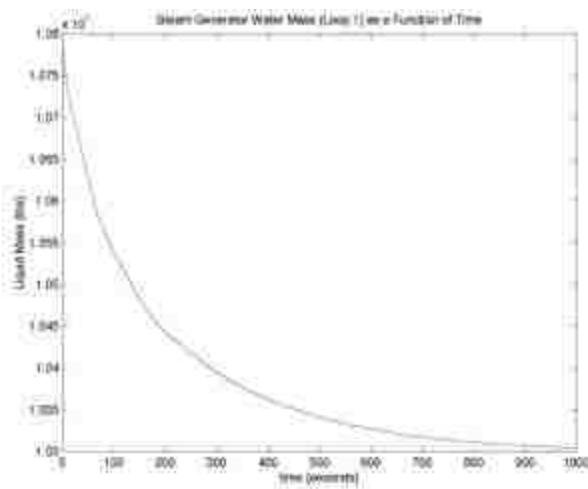


Figure 3.181

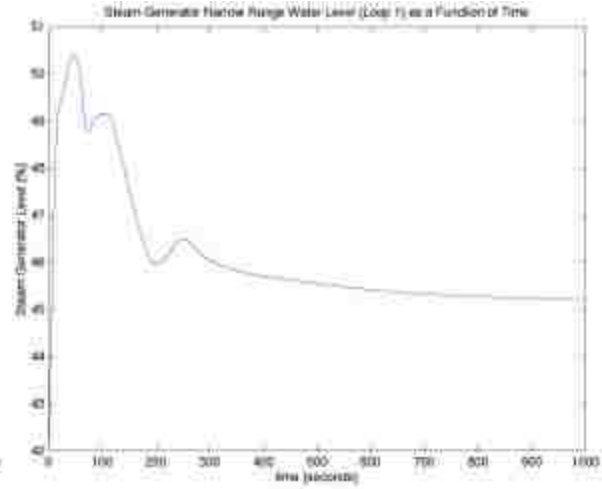


Figure 3.182

A +10% step increase in load from 15% power using a three-element level controller.

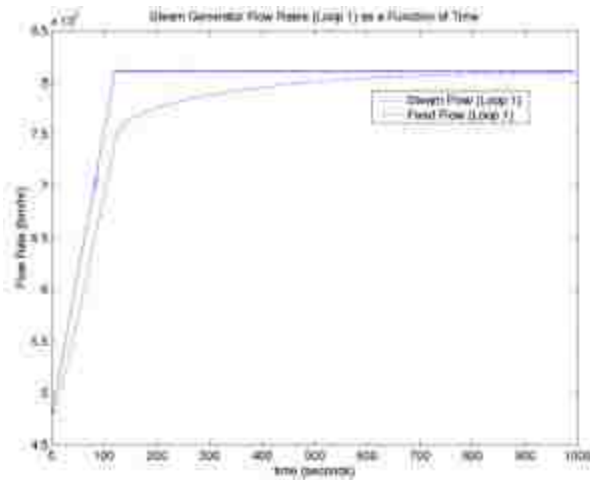


Figure 3.183

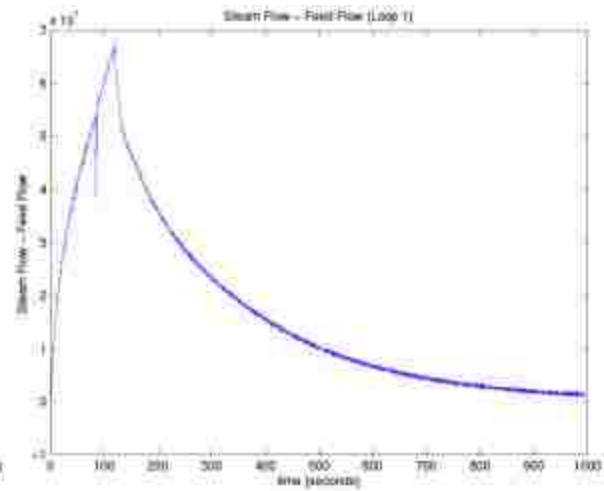


Figure 3.184

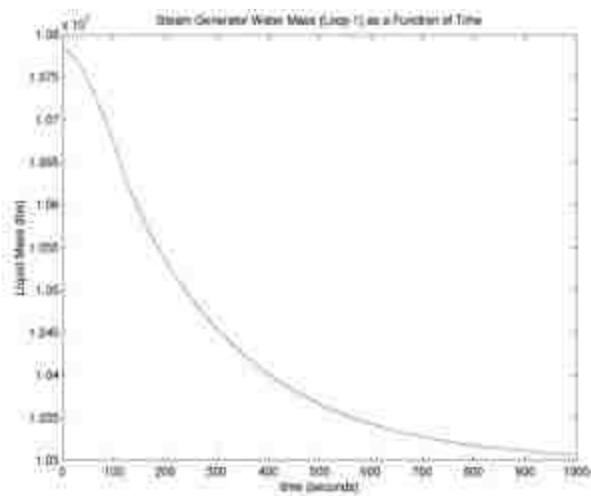


Figure 3.185

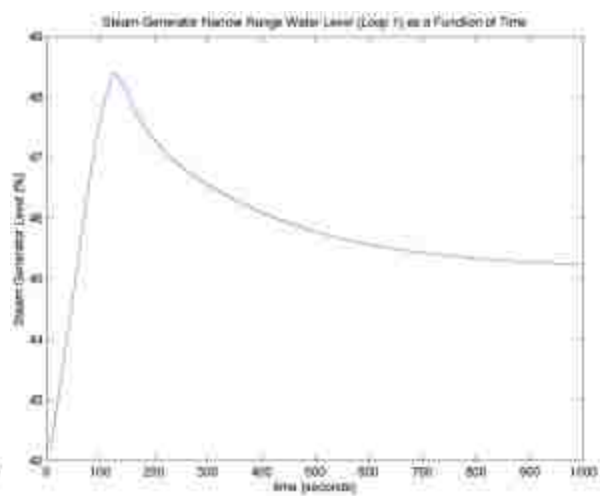


Figure 3.186

A +5% per minute ramp increase in load for two minutes from 15% power using a three-element level controller.

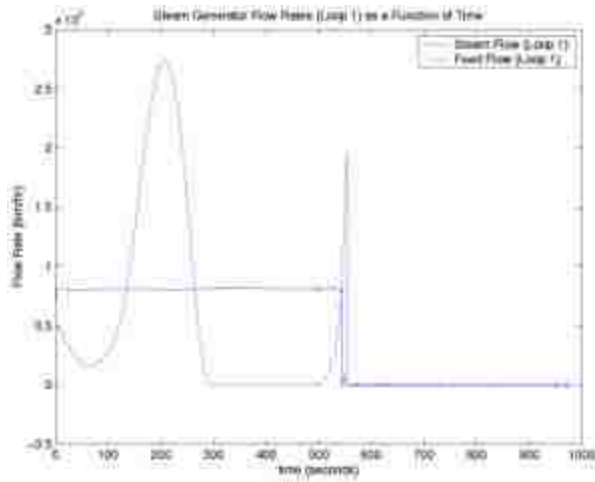


Figure 3.187

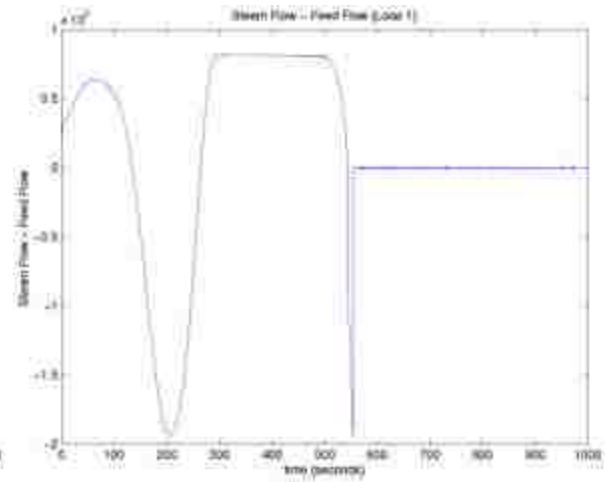


Figure 3.188

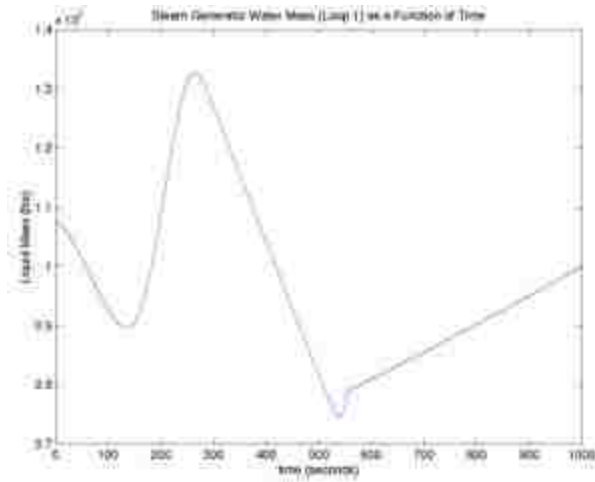


Figure 3.189

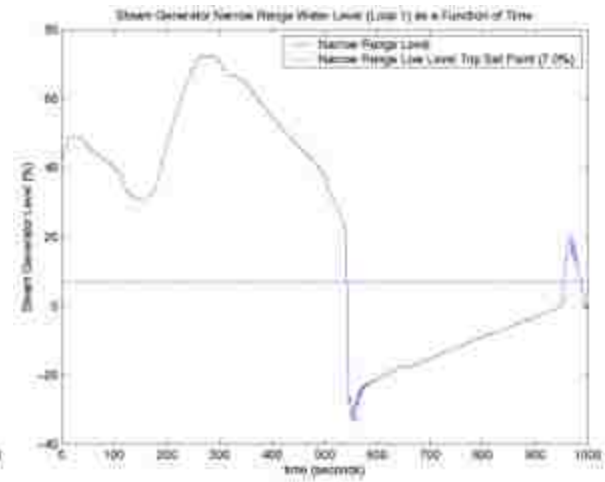


Figure 3.190

A +10% step increase in load from 15% power using and a single-element level controller.

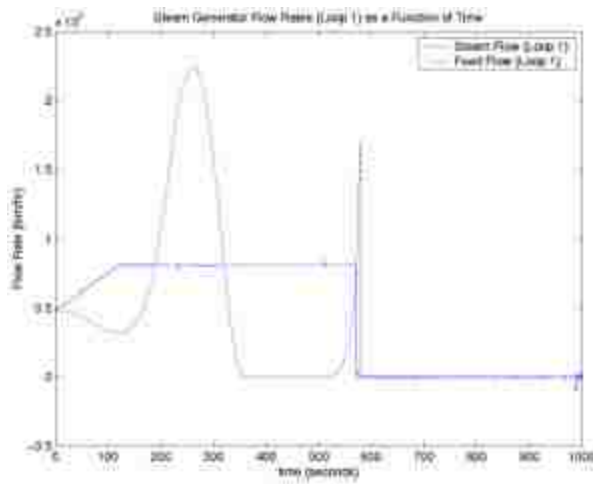


Figure 3.191

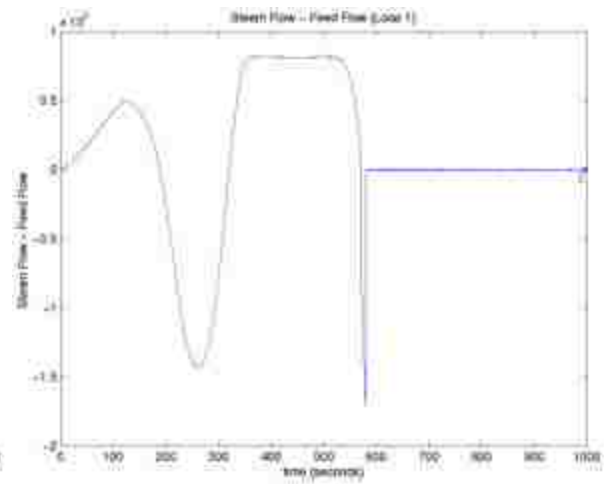


Figure 3.192

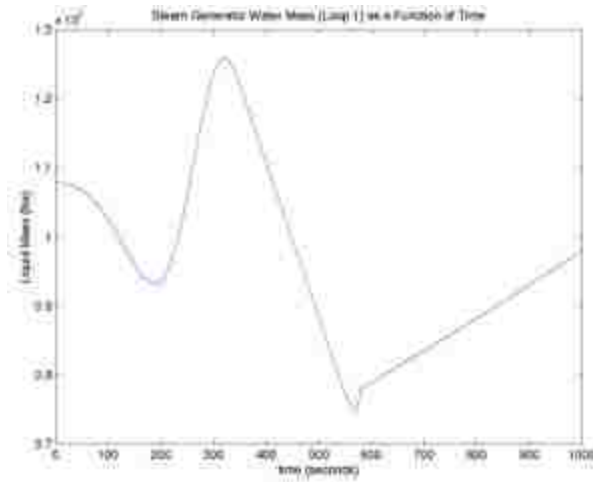


Figure 3.193

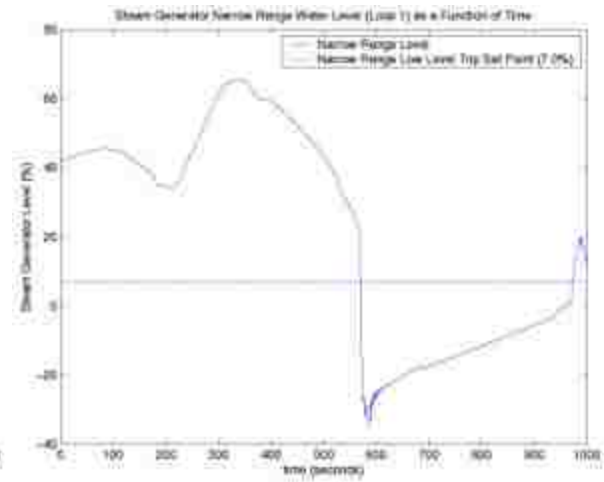


Figure 3.194

A +5% per minute ramp increase in load for two minutes from 15% power using and a single-element level controller.

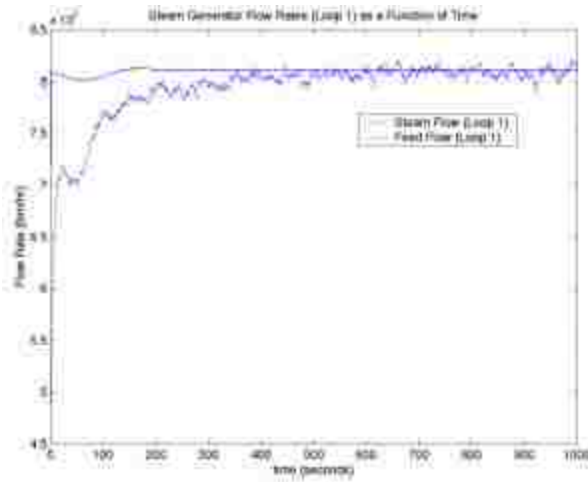


Figure 3.195

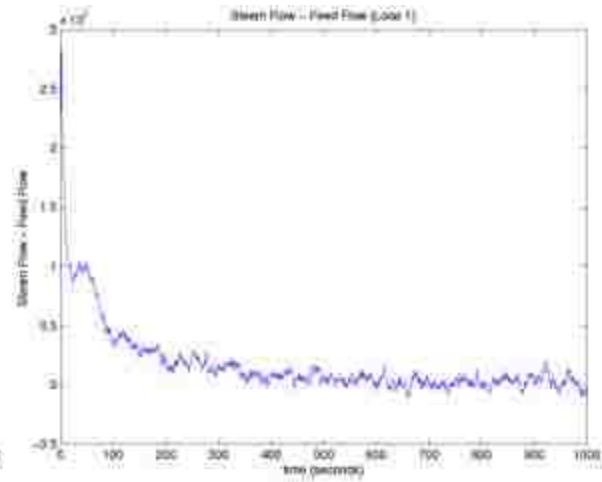


Figure 3.196

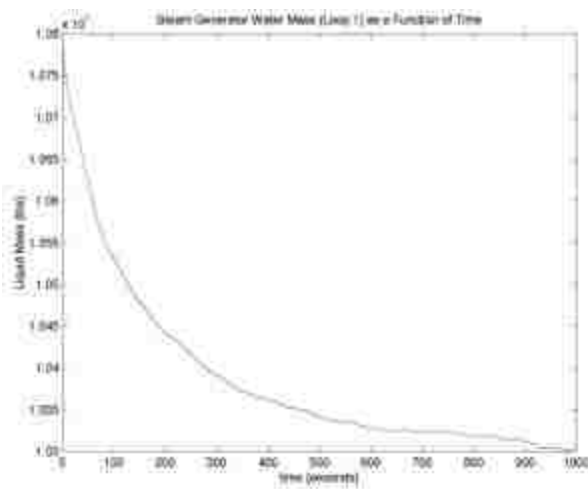


Figure 3.197

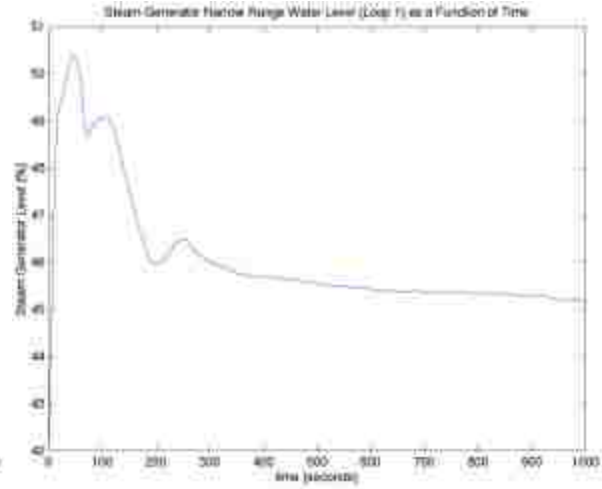


Figure 3.198

A +10% step increase in load from 15% power using a three-element level controller with 1% noise in steam and feed flows.

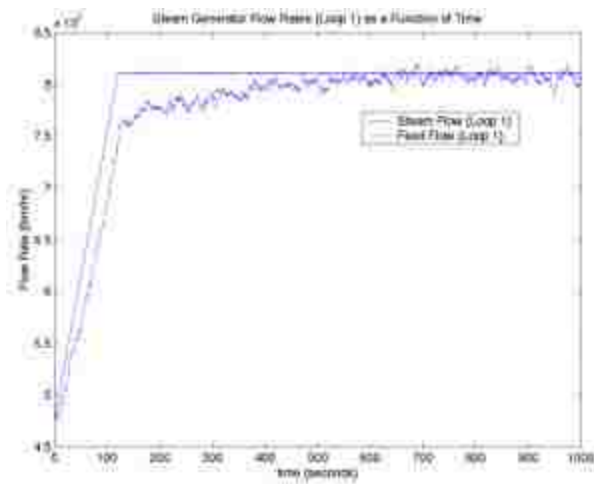


Figure 3.199

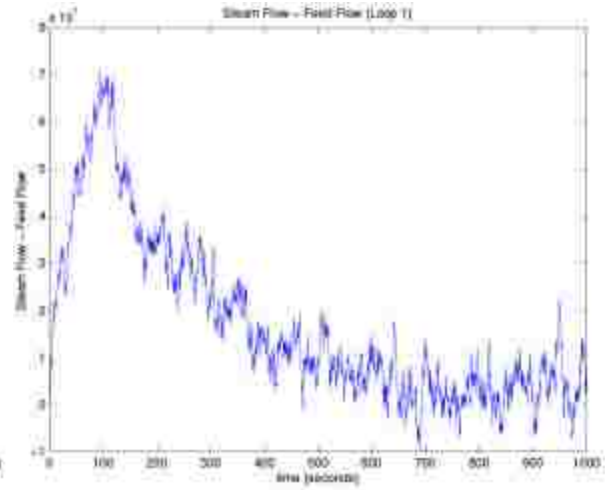


Figure 3.200

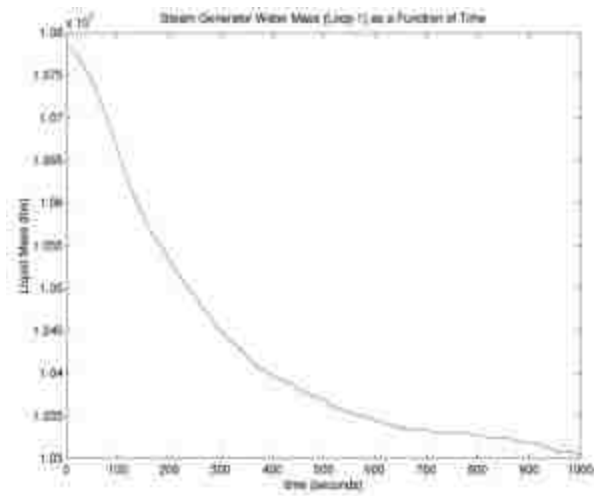


Figure 3.201

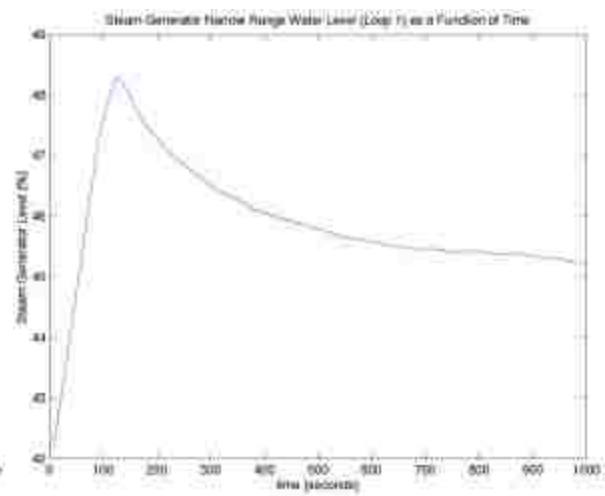


Figure 3.202

A +5% per minute ramp increase in load for two minutes from 15% power using a three-element level controller with 1% noise in steam and feed flows.

From the above figures, the three-element level controller was able to handle both type of load increase transient, with and without noise. When using a single-element controller, both transients tripped due to a low steam generator level signal.

The same transients examined using the level controller were then examined using the mass controller. Again different operational occurrences including a +10% step increase and a +5% ramp per minute for two minutes increase in load from 15% power using both a three and single element mass controllers. These results are shown in Figures 3.203-3.247.

Figures	Transient	Controller	FCV Time Constant (sec)	Gain Settings
3.203-3.207	+10% Step Increase in Load from 15% Power	Three-Element Mass	0.5	Small
3.208-3.212	+10% Step Increase in Load from 15% Power	Three-Element Mass	20.0	Large
3.213-3.217	+5% per minute Ramp Increase in Load for 2 minutes from 15% Power	Three-Element Mass	0.5	Small
3.218-3.222	+5% per minute Ramp Increase in Load for 2 minutes from 15% Power	Three-Element Mass	20.0	Large
3.223-3.226	+10% Step Increase in Load from 15% Power	Single-Element Mass	0.5	Small
3.227-3.230	+10% Step Increase in Load from 15% Power	Single-Element Mass	20.0	Large
3.231-3.234	+5% per minute Ramp Increase in Load for 2 minutes from 15% Power	Single-Element Mass	0.5	Small
3.235-3.238	+5% per minute Ramp Increase in Load for 2 minutes from 15% Power	Single-Element Mass	20.0	Large
3.239-3.243	+10% Step Increase in Load from 15% Power (With Noise)	Three-Element Mass	0.5	Small
3.244-3.248	+10% Step Increase in Load from 15% Power (With Noise)	Three-Element Mass	20.0	Large
3.249-3.253	+5% per minute Ramp Increase in Load for 2 minutes from 15% Power (With Noise)	Three-Element Mass	0.5	Small
3.254-3.258	+5% per minute Ramp Increase in Load for 2 minutes from 15% Power (With Noise)	Three-Element Mass	20.0	Large

Table 3.11: Low Power Operation Using Mass Controller

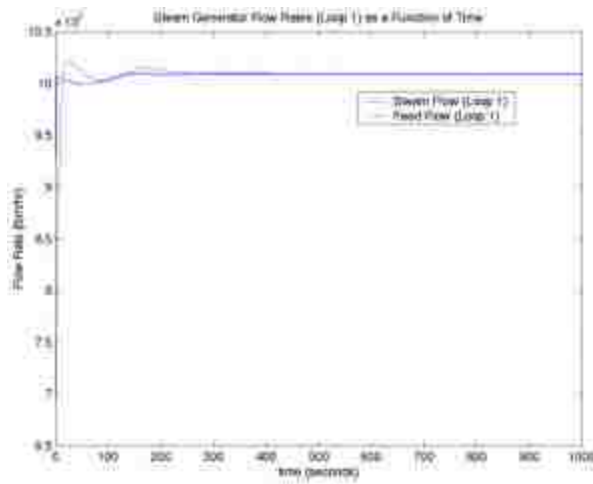


Figure 3.203

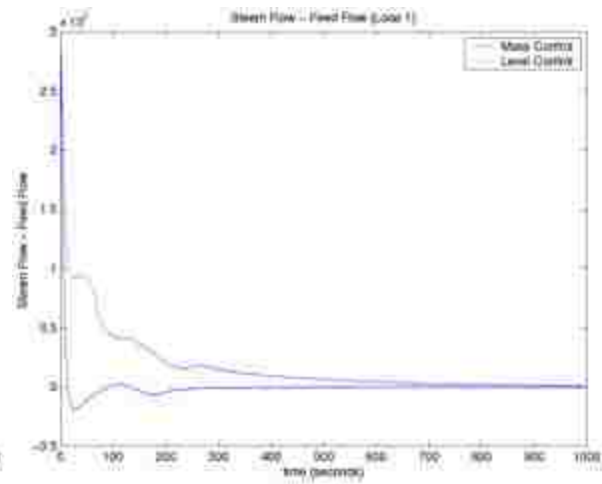


Figure 3.204

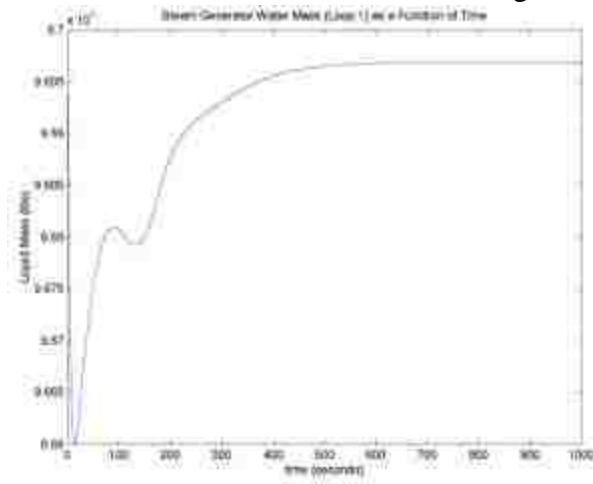


Figure 3.205

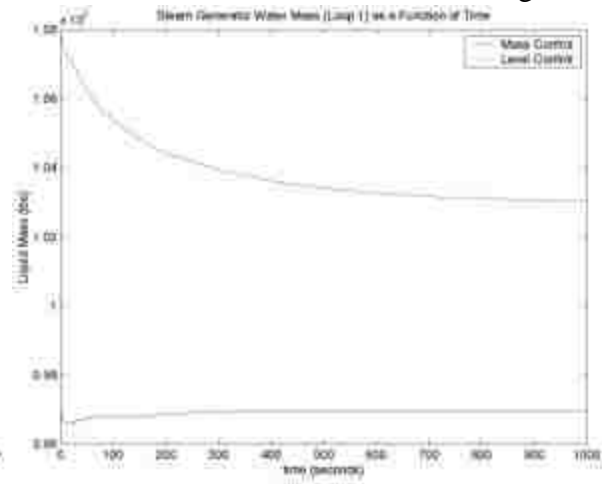


Figure 3.206

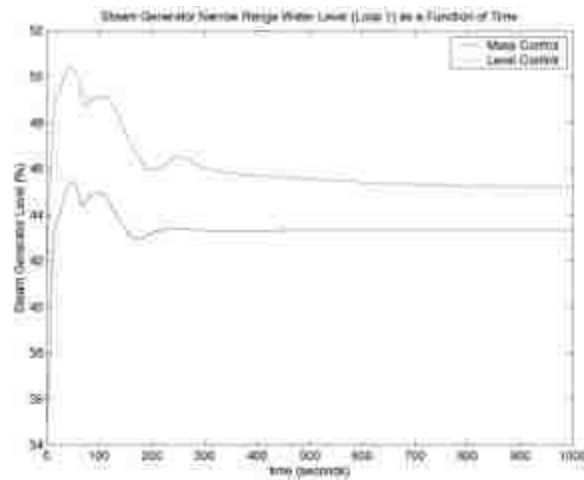


Figure 3.207

A +10% step increase in load from 15% power using small gain settings, FCV time constant of 0.5 seconds under a three-element mass controller.

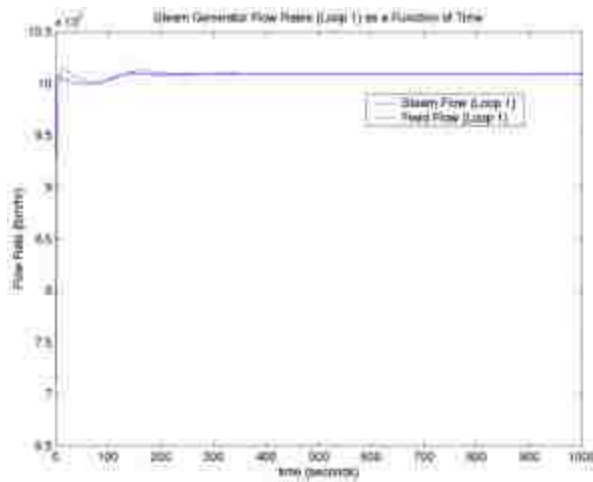


Figure 3.208

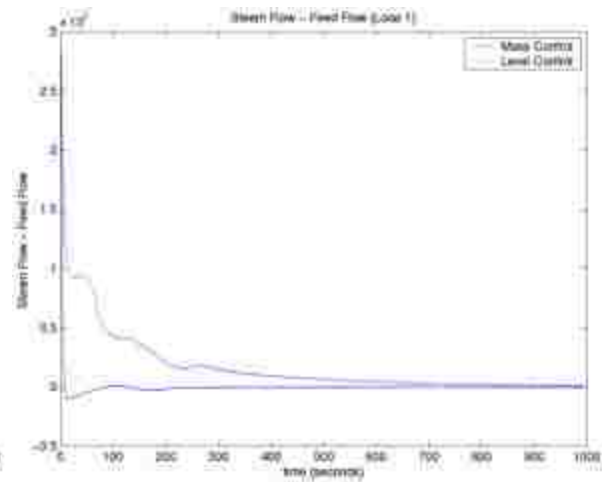


Figure 3.209

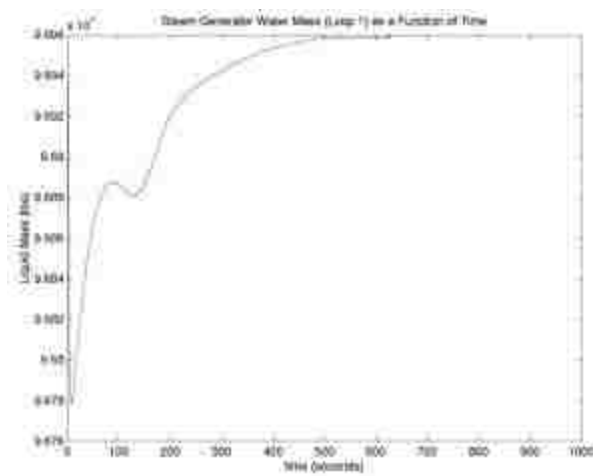


Figure 3.210

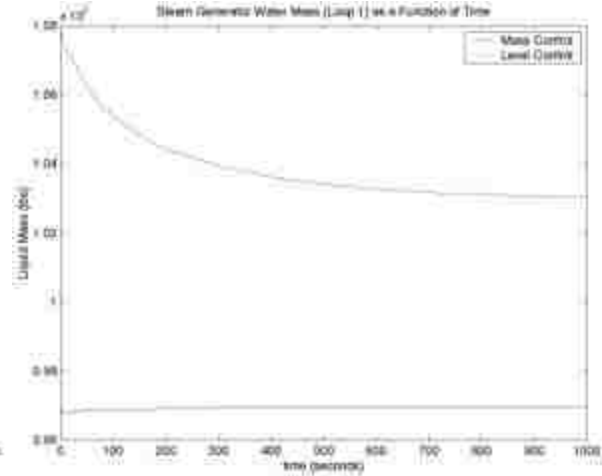


Figure 3.211

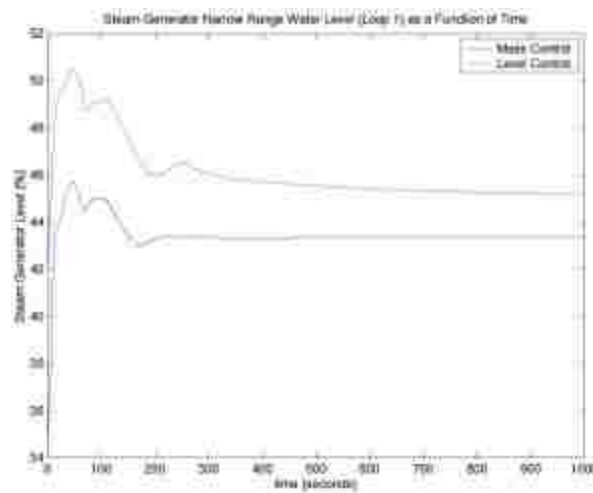


Figure 3.212

A +10% step increase in load from 15% power using large gain settings, FCV time constant of 20.0 seconds under a three-element mass controller.

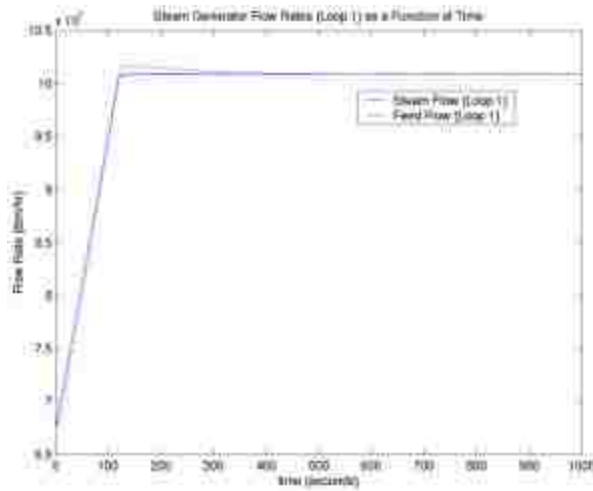


Figure 3.213

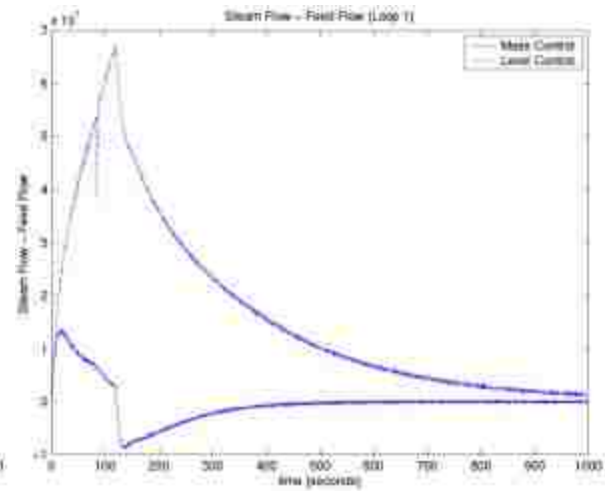


Figure 3.214

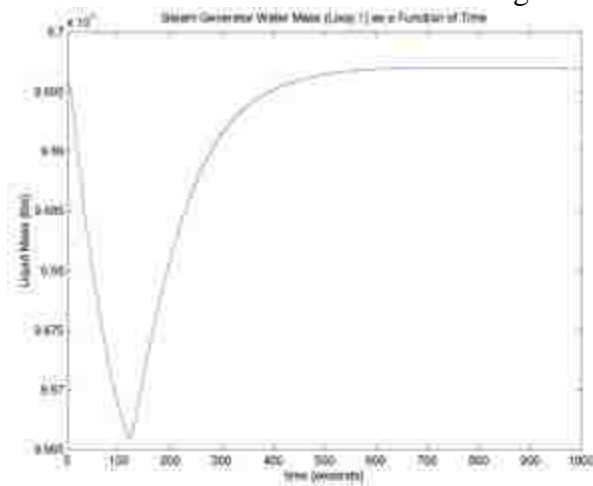


Figure 3.215

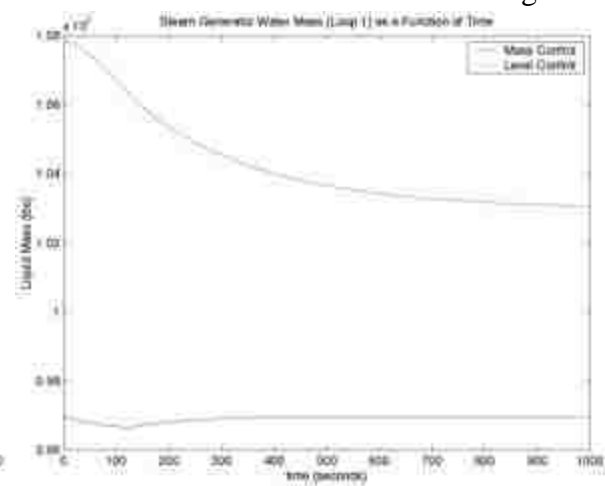


Figure 3.216

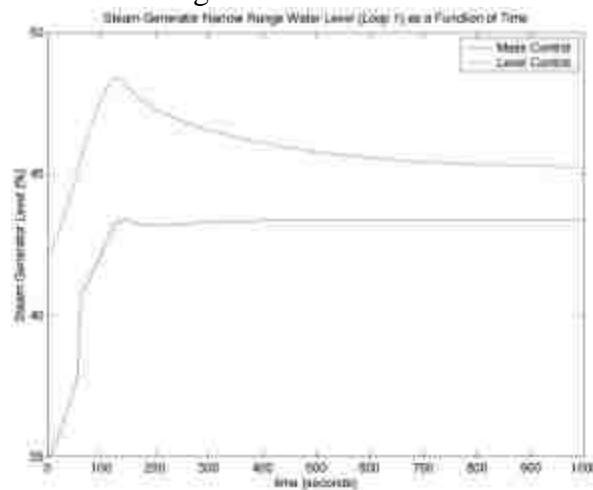


Figure 3.217

A +5% per minute ramp increase in load for two minutes from 15% power using small gain settings, FCV time constant of 0.5 seconds under a three-element mass controller.

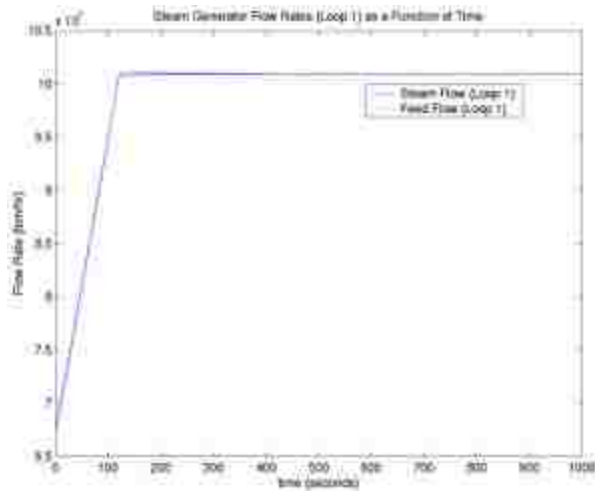


Figure 3.218

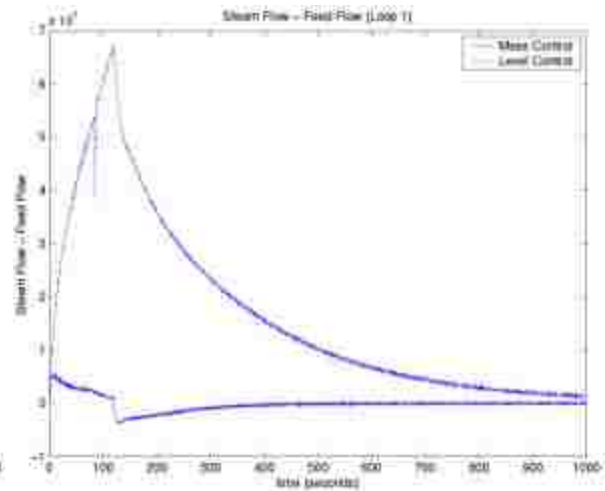


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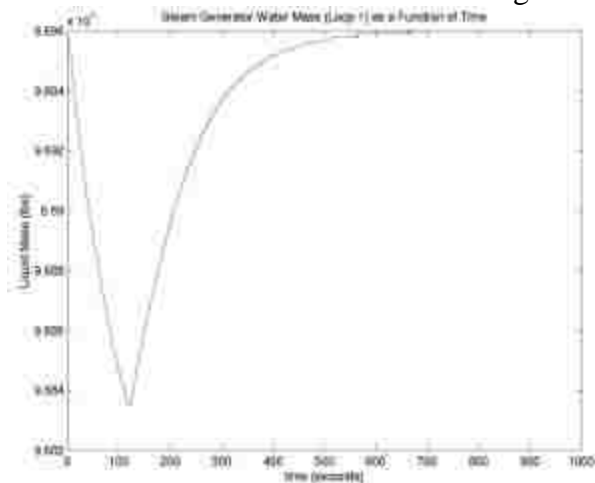


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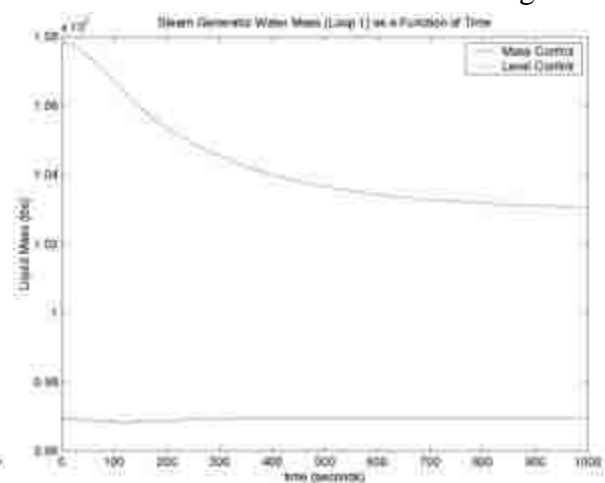


Figure 3.221

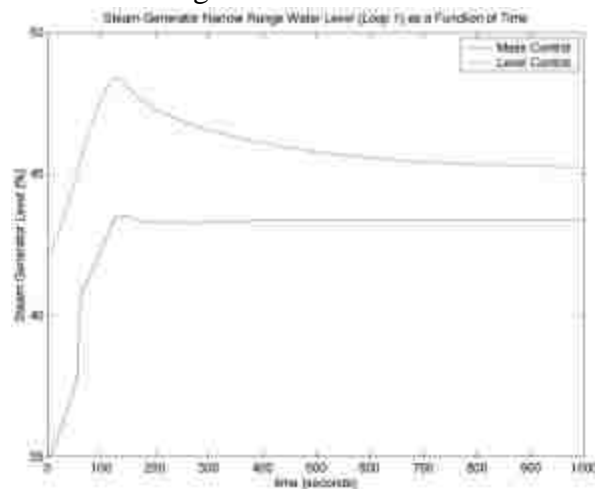


Figure 3.222

A +5% per minute ramp increase in load for two minutes from 15% power using large gain settings, FCV time constant of 20.0 seconds under a three-element mass controller.

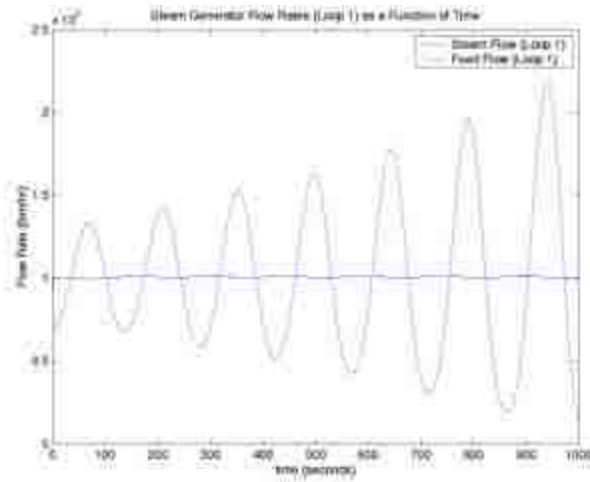


Figure 3.223

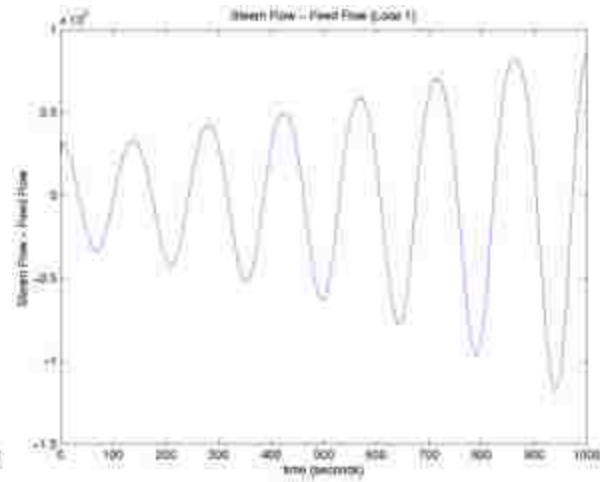


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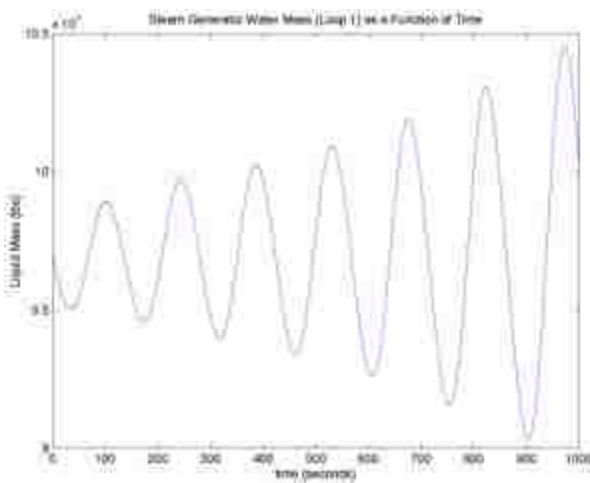


Figure 3.225

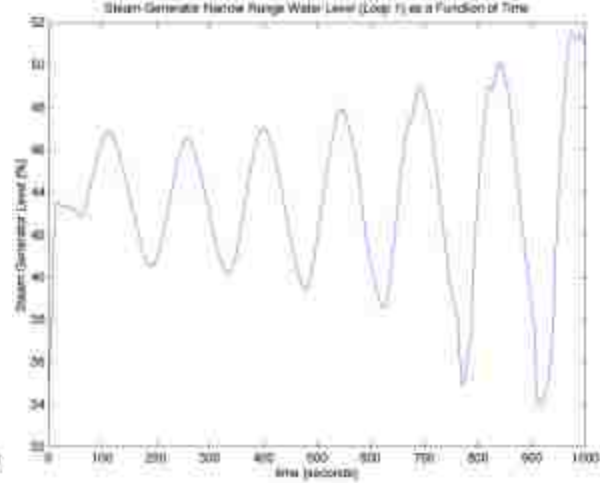


Figure 3.226

A +10% step increase in load from 15% power using small gain settings, FCV time constant of 0.5 seconds under a single-element mass controller.

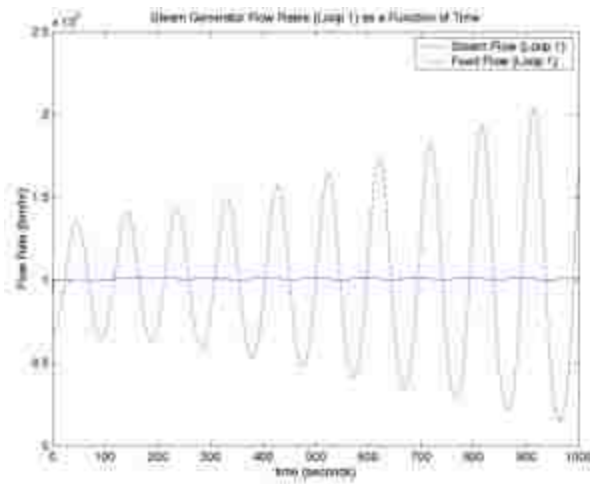


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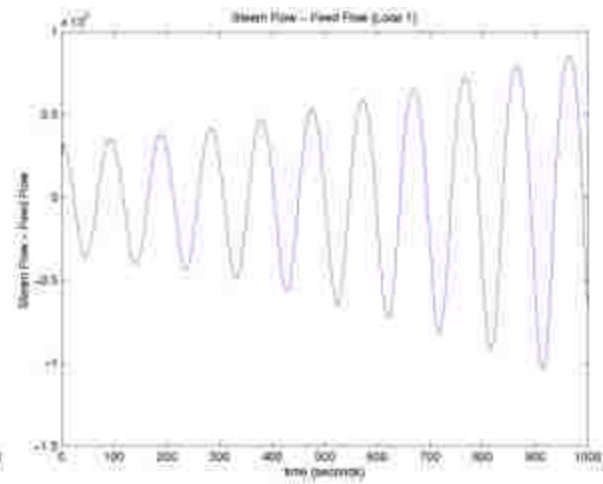


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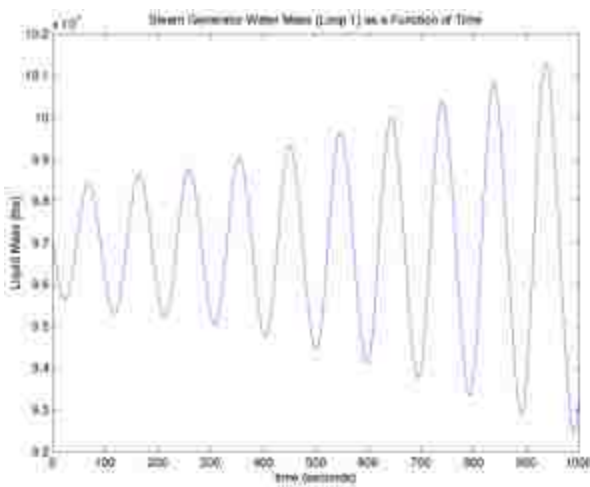


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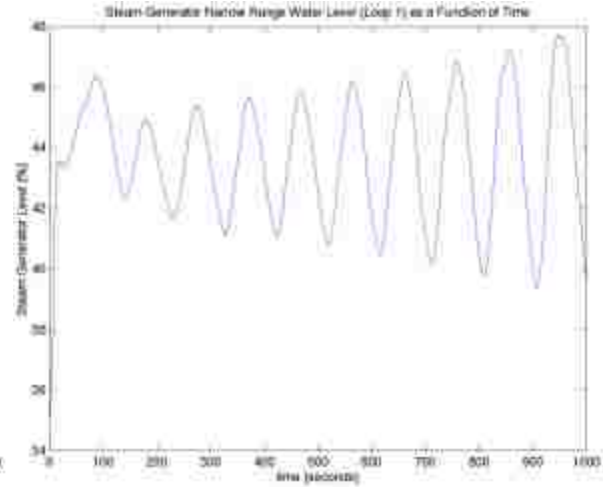


Figure 3.230

A +10% step increase in load from 15% power using large gain settings, FCV time constant of 20.0 seconds under a single-element mass controller.

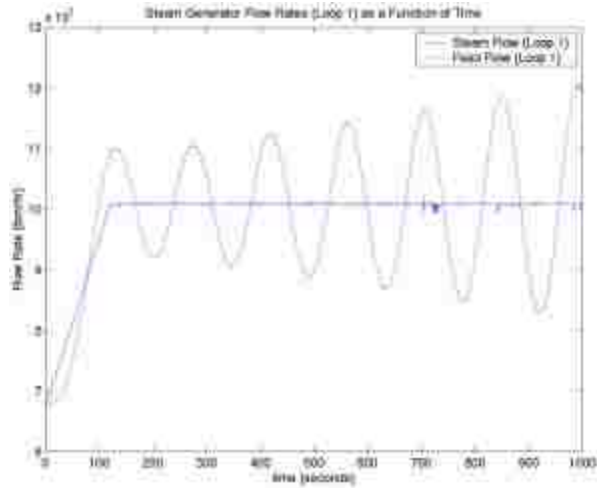


Figure 3.231

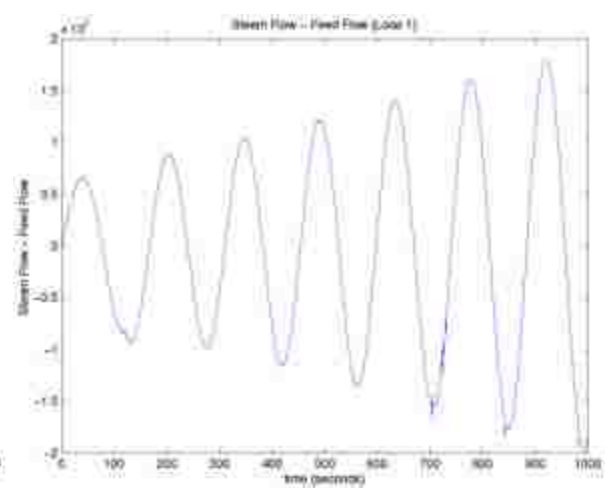


Figure 3.232

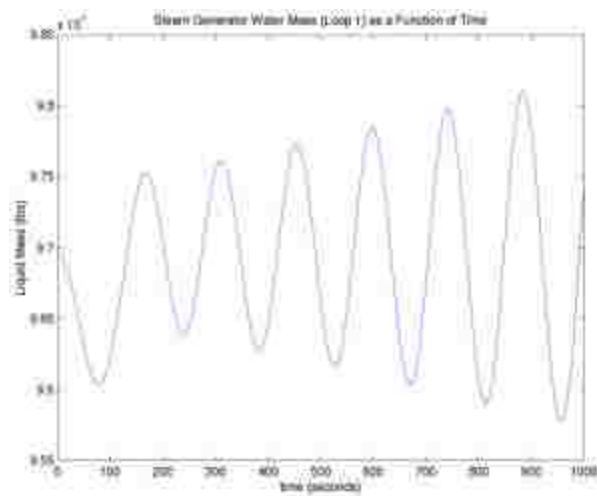


Figure 3.233

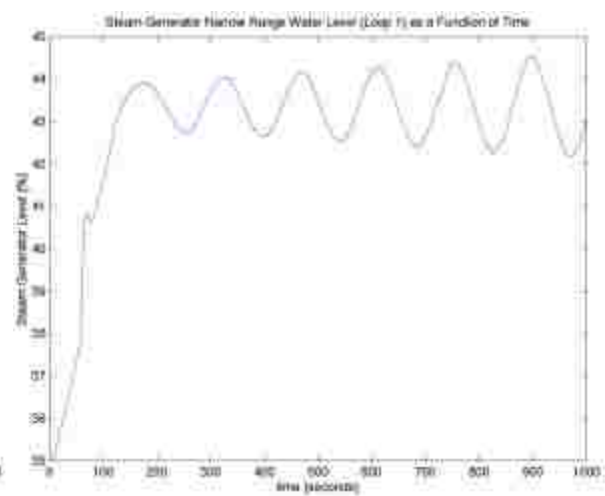


Figure 3.234

A +5% per minute ramp increase in load for two minutes from 15% power using small gain settings, FCV time constant of 0.5 seconds under a single-element mass controller.

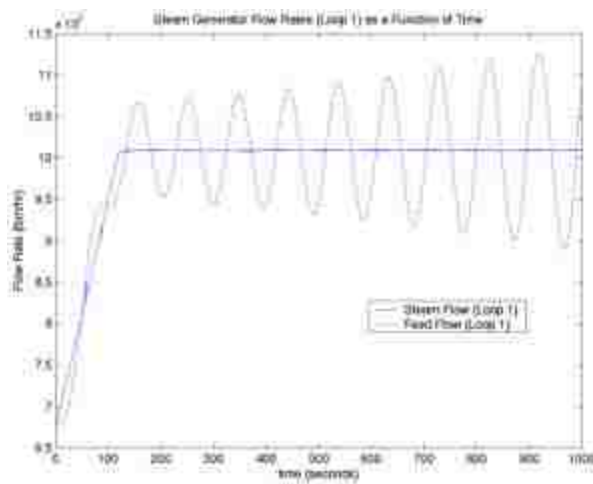


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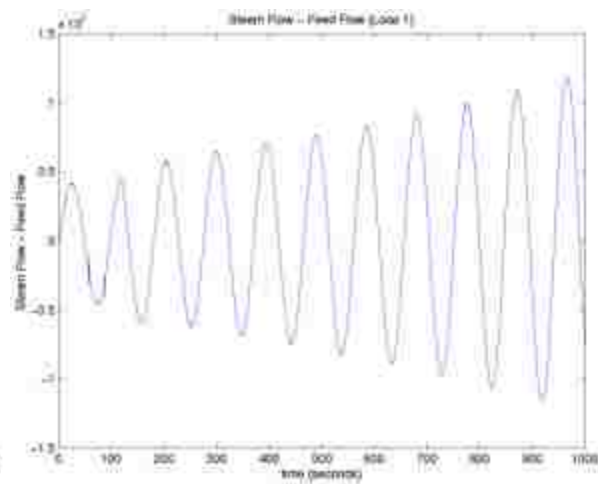


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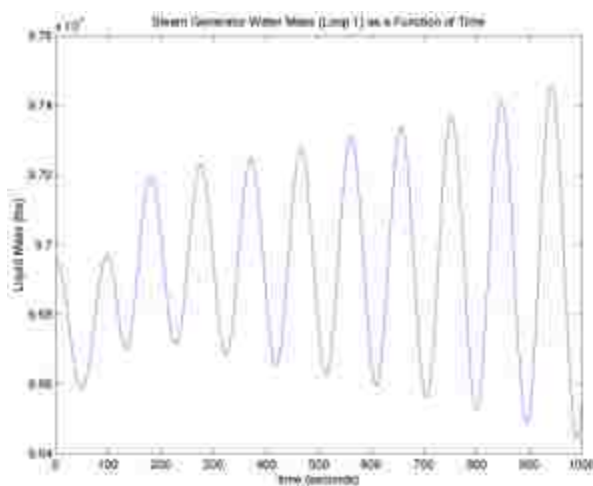


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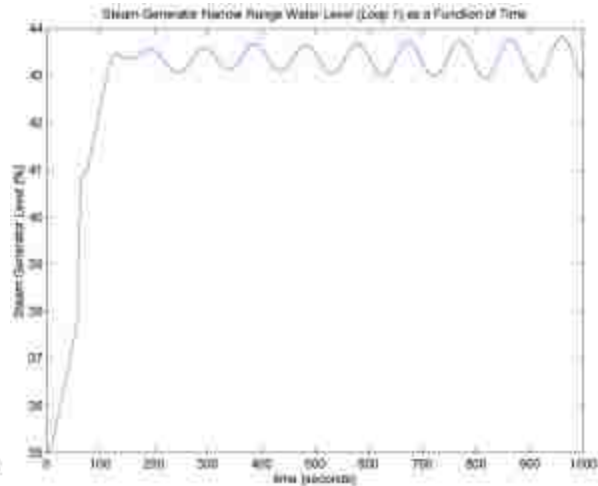


Figure 3.238

A +5% per minute ramp increase in load for two minutes from 15% power using large gain settings, FCV time constant of 20.0 seconds under a single-element mass controller.

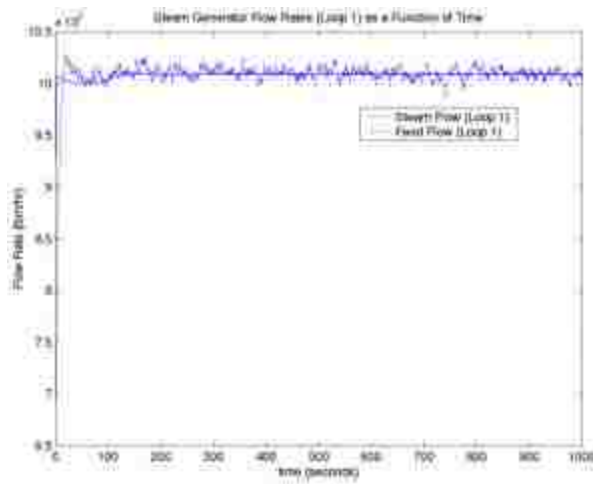


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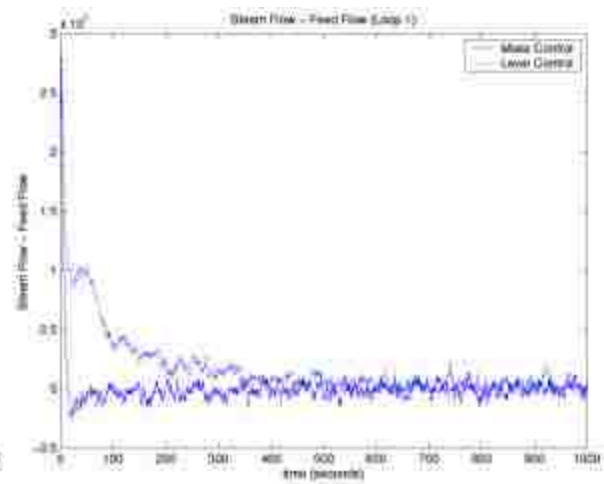


Figure 3.240



Figure 3.241

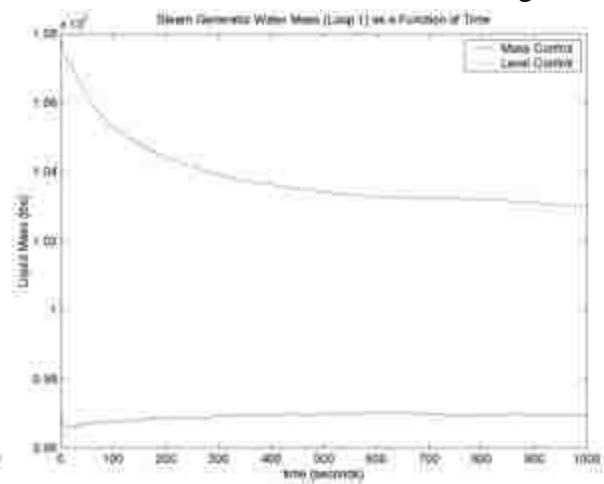


Figure 3.242



Figure 3.243

A +10% step increase in load from 15% power using small gain settings, FCV time constant of 0.5 seconds under a three-element mass controller with 1% noise in steam and feed flows.

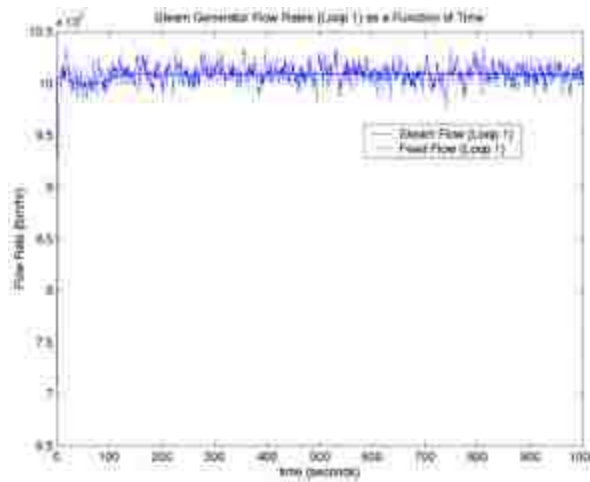


Figure 3.244

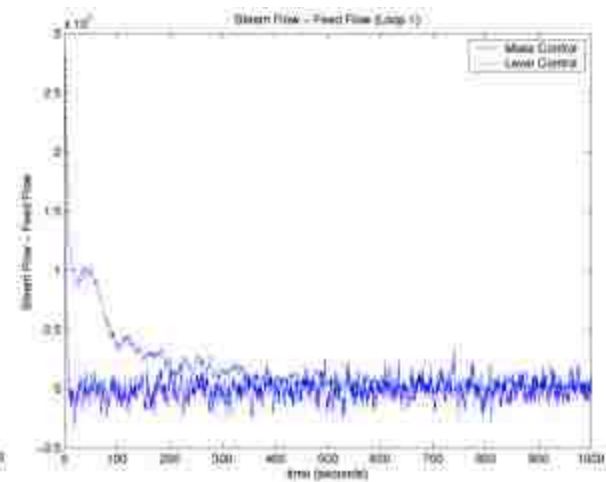


Figure 3.245



Figure 3.246

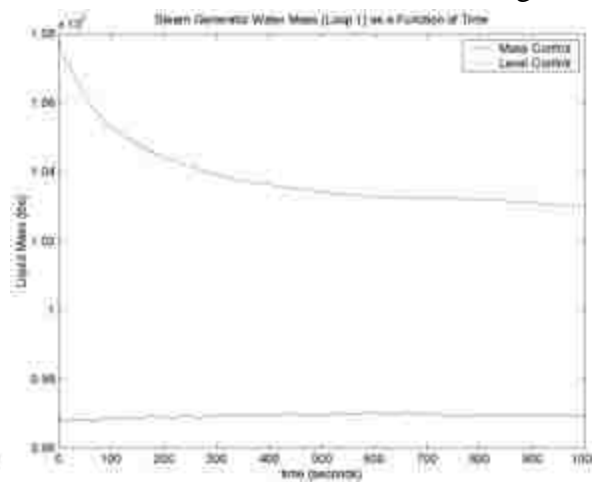


Figure 3.247



Figure 3.248

A +10% step increase in load from 15% power using large gain settings, FCV time constant of 20.0 seconds under a three-element mass controller with 1% noise in steam and feed flows.

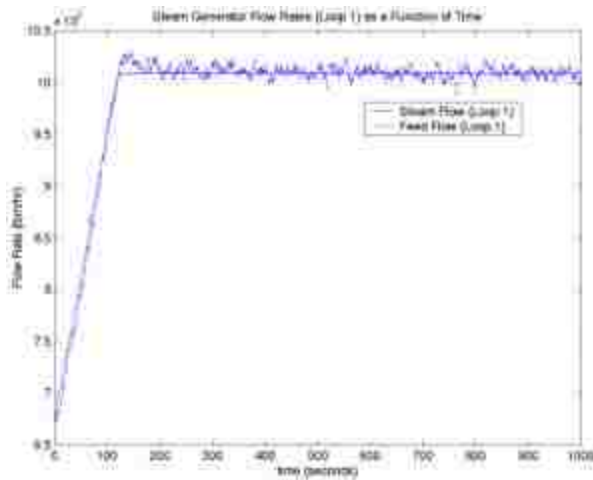


Figure 3.249

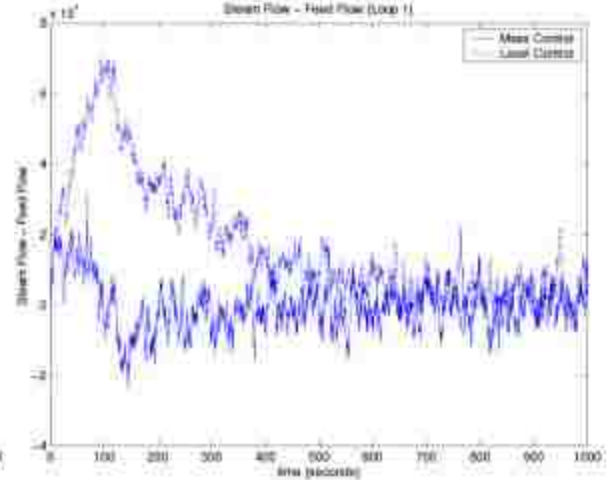


Figure 3.250



Figure 3.251

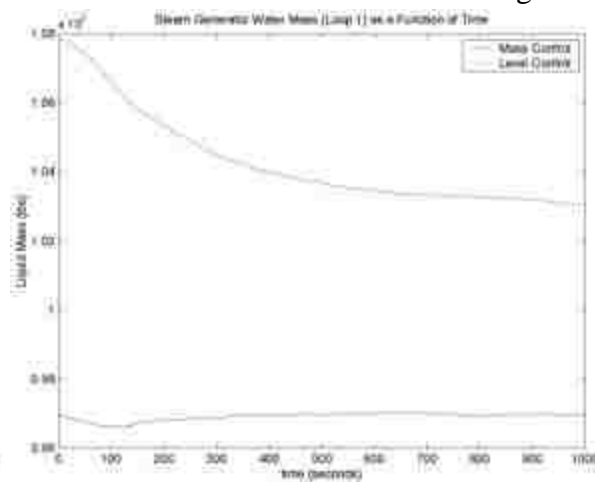


Figure 3.252

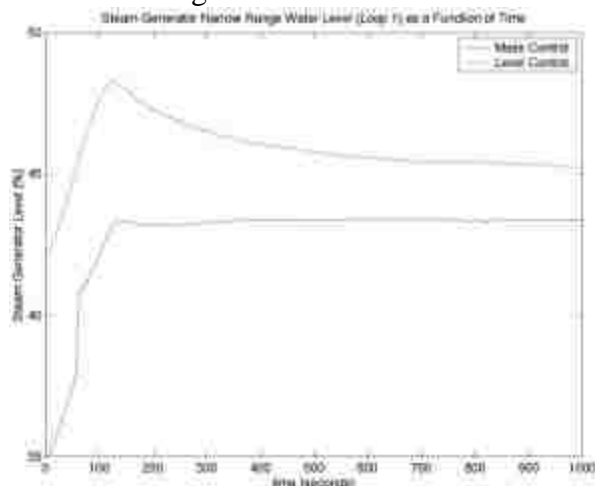


Figure 3.253

A +5% per minute ramp increase in load for two minutes from 15% power using small gain settings, FCV time constant of 0.5 seconds under a three-element mass controller with 1% noise in steam and feed flows.

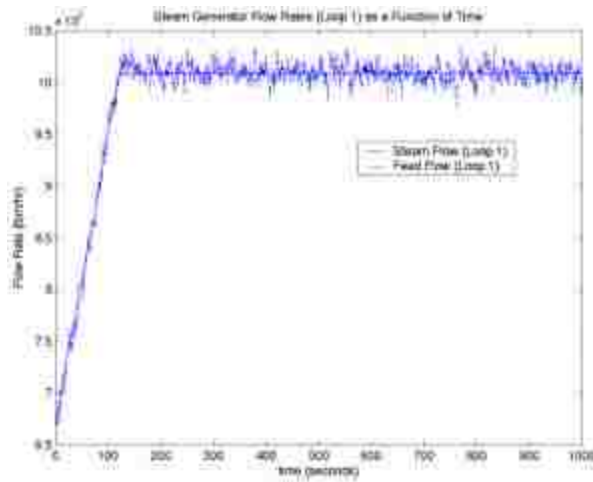


Figure 3.254

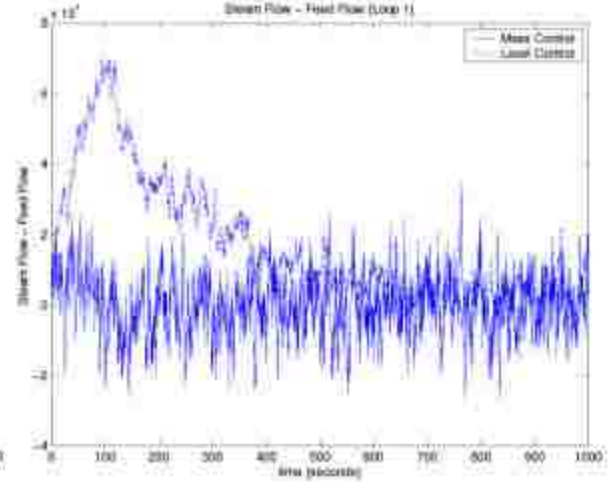


Figure 3.255



Figure 3.256

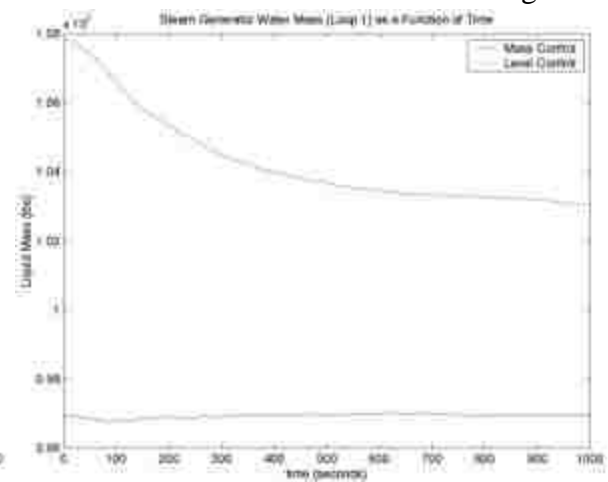


Figure 3.257

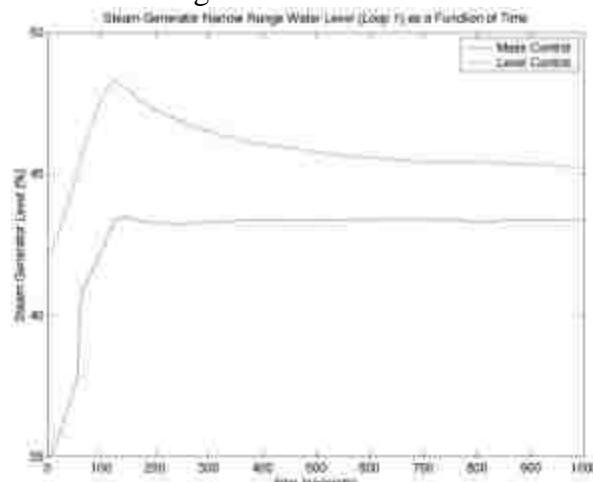


Figure 3.258

A +5% per minute ramp increase in load for two minutes from 15% power using large gain settings, FCV time constant of 20.0 seconds under a three-element mass controller with 1% noise in steam and feed flows.

Again, from the above figures, the three-element mass controller using either small or large gains were able to handle both type of load increase transient, with and without noise. When using a single-element controller, the transient behavior exhibited oscillatory results. With an increase in the gains, the oscillatory results were amplified. As a result, a single-element mass controller using even smaller gains were examined. A sample of the results are shown in Figures 3.259-3.266.

Figures	Transient	Controller	FCV Time Constant (sec)	Gain Settings
3.259-3.262	+10% Step Increase in Load from 15% Power	Single-Element Mass	0.5	0.01
3.263-3.266	+5% per minute Ramp Increase in Load for 2 minutes from 15% Power	Single-Element Mass	0.5	0.01

Table 3.12: **Low Power Operation Using Mass Controller**

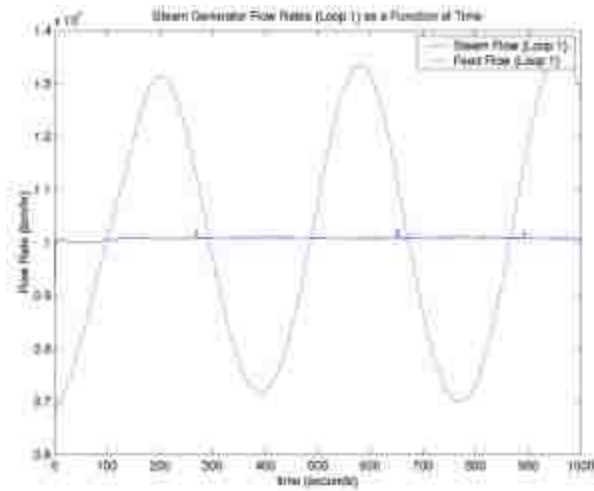


Figure 3.259

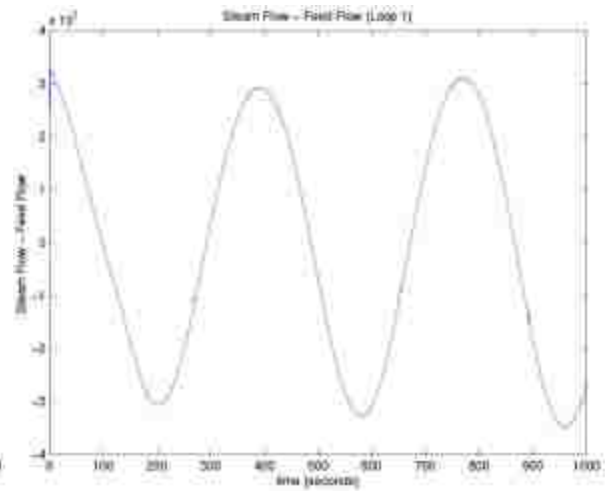


Figure 3.260

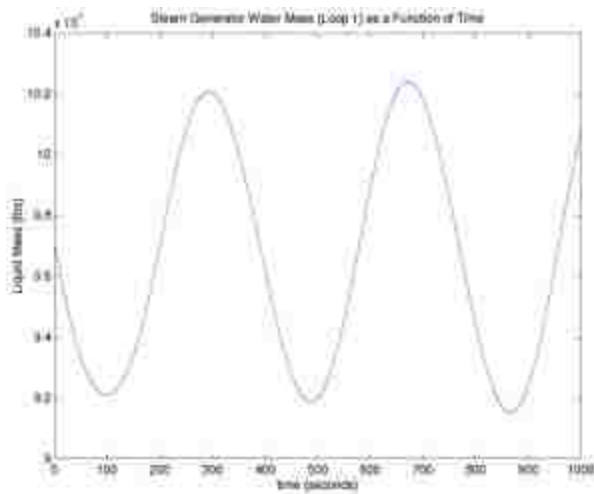


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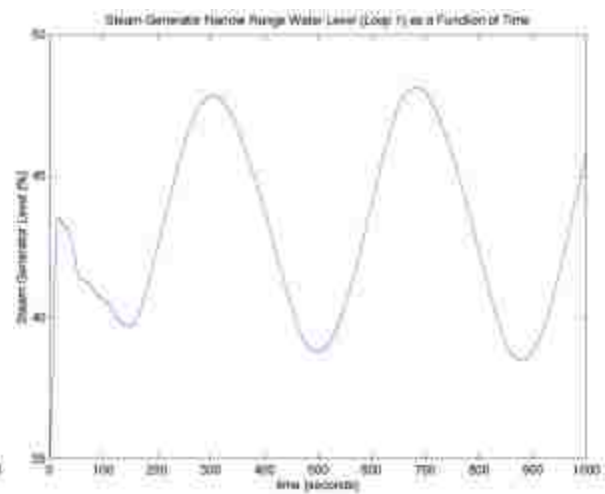


Figure 3.262

A +10% step increase in load from 15% power using 0.01 for the proportional and integral gain settings, FCV time constant of 0.5 seconds under a single-element mass controller.

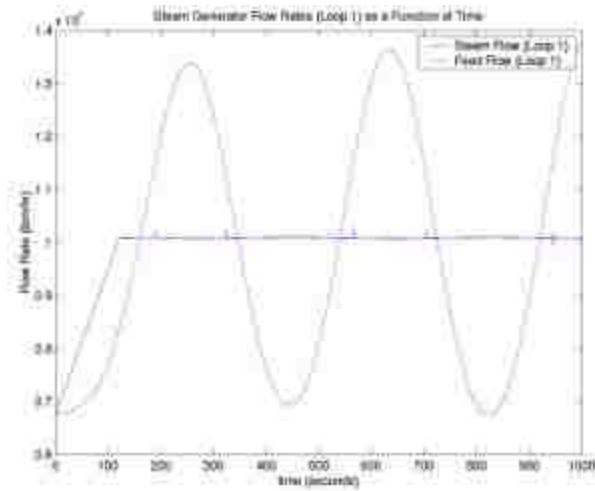


Figure 3.263

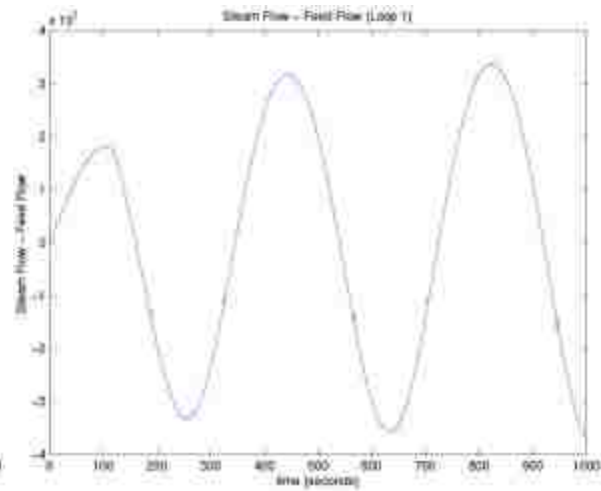


Figure 3.264

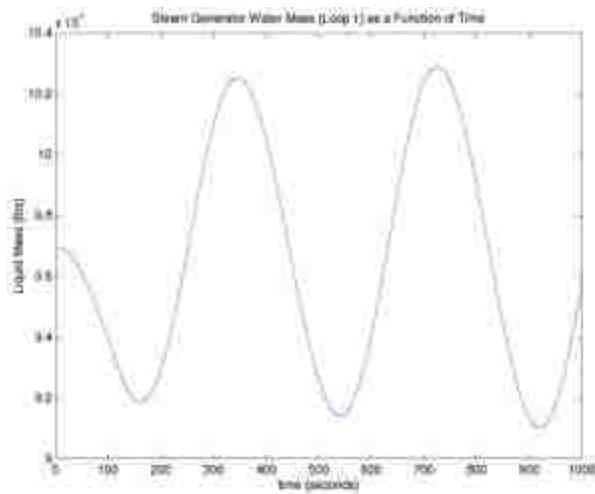


Figure 3.265



Figure 3.266

A +5% per minute ramp increase in load for two minutes from 15% power using 0.01 for the proportional and integral gain settings, FCV time constant of 0.5 seconds under a single-element mass controller.

Different proportional and integral gains were examined, but did not dampen the oscillations. As the gains decreased, the oscillations became smaller and smaller, yet there was a point of diminishing returns. Very small gain settings induced a reactor trip caused from a low steam generator level set point.

4. Summary and Conclusion

This paper focused on designing, implementing, and controlling the feed water system directly through the liquid mass inventory, which is the direct measurement of the cooling capacity of the reactor. From the analysis, a liquid mass control strategy proved to be a valid control for the feed control valve movements in a U-tube steam generator. In some instances, the liquid mass controller proves to be a better controller than the level controller used in the simulations.

Conclusion

The liquid mass inventory inside of the U-tube steam generator is an important parameter because it is used to ensure proper cooling of the reactor. Controlling liquid mass inventory through the steam generator level can cause complications with automatic control from thermo hydraulic characteristics, shrink and swell, of the liquid/vapor mixture. It is proposed that a controller based upon the liquid mass inventory because it is the true measure of the cooling capacity of the reactor.

Two different liquid mass control strategies were examined for the steam generator, constant and variable liquid mass. Different valve characteristics for the liquid mass controller were also examined. Each control strategy resulted in different simulation results.

The first control strategy that was examined was a constant liquid mass controller. For the constant liquid mass control strategy, two different types of valve characteristics were also used: large and small values for the integral and proportional gains, and different feed control valve time constants.

The constant liquid mass control strategy using small integral and proportional gains proved to be an adequate control for the steam generator when small perturbations were

introduced into the system. When a turbine trip without a reactor trip transient was induced, the controller failed to provide adequate control of the steam generator. This transient triggered a low pressurizer pressure trip signal causing the reactor to trip offline. The trip was caused from the over cooling of the primary side. To prevent the reduction of the primary side pressure, the feed control valve time constant was decreased to enable more feed water to enter the turbine to counteract the over cooling. This strategy prevented the low pressurizer pressure trip but instead induced a low steam generator level trip, which is caused from the reduction in the steam generator pressure.

Another constant liquid mass control strategy was examined using larger integral and proportional gains. With the large gain settings, the feed control valve would be more sensitive to changes in the mass. Using large gain settings proved to help the steam flow feed flow mismatch during the beginning of the transient, but also introduced large oscillations in the feed control valve, which is caused from the controller becoming saturated. To help relieve the problem, a large feed control valve time constant was used. As a result, the constant liquid mass controller was capable of handling such large transients, such as a turbine trip without reactor trip from full power.

The other control strategy that was examined was a variable liquid mass controller. Upon examination the steady state liquid mass in the level controller, the liquid mass was a decreasing function of power plant level. Therefore, a similar type of variable liquid mass control strategy was implemented to emulate a level control strategy. Also the gain settings used in the constant liquid mass control strategy were used, along with the large feed control valve time constant for the liquid mass control strategy that involved the large gain settings.

The variable liquid mass control strategy using the large gain settings also proved to be an adequate control for the steam generator when relatively small perturbations were introduced into the system. This controller was also able to handle large perturbations such as a turbine trip without reactor trip from full power.

The other variable liquid mass control strategy using the small gain settings also proved to be an adequate control for the steam generator when relatively small perturbations were introduced into the system. Yet, this type of controller was not capable of preventing low pressurizer pressure trip that was caused from the over cooling of the primary side. To prevent the over cooling of the primary side, the feed control valve time constant was decreased to allow for more feed water to enter the steam generator to prevent the over cooling accident. With the new feed control valve setting, the controller was capable of handling a turbine trip without reactor trip.

Using both the constant and variable liquid mass control strategies, low power operations were also examined. A range of increase in the load from 15% power was examined using the three-element level or mass controllers with and without noise. Both controllers produced adequate results. Yet, when using a single-element level or mass controller, yielded unstable results. When using the single-element level controller, increases in the load resulted in a reactor trip caused from a low steam generator level trip set point. When using the single-element mass controller, increases in the load resulted in an unstable plant behavior, where steam/feed flows would display oscillatory behavior that were undamped. At low powers, the reactor dynamics are highly unstable, and the single-element controller is not capable of handling perturbations introduced into the system.

From the low power analysis, it would seem that none of the single element control strategies provide adequate control for the feedwater. Both the level and mass controller settings yielded unstable results because the erratic movements in the FCV. Again, changes in the feed flow at low powers become a large portion if not larger than the flows themselves. In current reactor systems, there is a bypass line in the feedwater train that allows for fine control during low flow conditions. Yet, in the current simulation model used for this analysis, there is no such feed bypass line. Therefore, all feed flow is regulated by the FCV. The results from the low power analysis indicate that fine control over the feed flow would help eliminate unstable conditions at low power levels.

From the analysis, the feed control valve movements based upon liquid mass is a feasible type of control in the steam generator. It was shown that a quick response in the feed control valve movements, whether it was from large integral and proportional gains along with a large feed control valve time constant or, from small integral and proportional gains along with a small feed control valve time constant.

Future Work and Recommendations

This paper focused on using the calculated liquid mass in the steam generator as an input for control, but when in fact it is not a measurable quantity. Therefore, neural networks are used to predict the liquid mass in the steam generator. It is suggested that a controller using both the predicted liquid mass and level be used for steam generator control. Using both inputs a better controller maybe able to be designed. Also, it is suggested that the model of the feedwater train used in the simulation be updated to reflect current reactor designs.

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