MMS SIMULATION OF RSG/FW TRAIN
OF A NUCLEAR POWER PLANT
FOR DEVELOPING A
RSG LEVEL CONTROL SYSTEM

by

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ABSTRACT

The use of digital control for controlling the level of recirculation-type steam generators (RSGs) in nuclear power plants is gaining increased acceptance and implementation by the utility industry. Some of the advantages of digital control over the conventional analog control include increased hardware reliability, particularly through redundancy; reduced cost and space; increased flexibility to reconfigure; and easier use of advanced control algorithms. The characteristics of RSG level control are complex enough to justify the comprehensive use of real-time simulation in conjunction with control system hardware to significantly reduce the control system testing and tuning during installation at the plant site. This paper describes a personal computer(PC)-based interactive simulation of a typical RSG with its feedwater train, and some of the advanced digital algorithms for RSG level control.

I. INTRODUCTION

The existing Analog Feedwater Control Systems (AFCSs) in many Pressurized Water Reactors (PWRs) with RSGs are being replaced due to nonavailability of spare parts and poor level control performance and associated trips, particularly at low power (EPRI 1988). The replacement is usually done with a Digital Feedwater Control System (DFCS).
Several levels of DFCS retrofits with optional verification with respect to a plant simulation are possible:

- One-for-one replacement of existing analog control logic.
- Three-element level control over the entire range based on feedwater and steam flow measurements or their estimates at low flow rates and during flow sensor failures. The estimates are based on the Modular Modeling System (MMS) model of the RSG.
- Model-based level control over the entire range based on feedwater and steam flow measurements or their estimates at low flow rates and during flow sensor failures.
- Coordinated control of the feedwater (FW) valves in each RSG loop and the main FW pumps.
- Automatic bumpless swapping of main and bypass FW regulating valves under operator permissive.
- Automatic loading and unloading of main FW pumps.

To establish the feasibility of the above retrofit options, preliminary algorithms were developed in conjunction with MMS models of the RSG loops. Single-loop and four-loop models of the non-preheater type RSGs were developed using the UTSGA and UTSG modules from MMS (B&W 1988). These models included two main FW pumps in parallel, main and bypass FW valves in each loop, FW and steam lines in each loop, and boundary conditions for the primary hot leg and the turbine condenser. Although MMS includes a post-plotting capability, an online interactive graphic interface was also developed for effective debugging of the model and control algorithms and evaluating level control performance. Single-loop models were developed on the PC and later transported to the HP9000 minicomputer for expansion to the multiloop model. The models were tested in the range of 2% through 100% full power.

The remainder of this paper is organized as follows:

II. MODEL SPECIFICATION

To be suitable for DFCS development, the model had to:

- reflect the type of nuclear plants most likely to be candidates for DFCS retrofit in the near future, and
- be flexible to accommodate variations in such plants.

For RSGs that do not have integral preheaters, the feedwater is introduced into the downcomer. For RSGs that have an integral segmented baffle-type preheater and two FW nozzles, one in the downcomer and one in the preheater, some portion of the feedwater (probably variable with load) is fed through the auxiliary (upper) nozzle, while the remaining is fed directly into the preheater through the lower nozzle. Further, the feedwater entering the preheater travels counter to the primary flow in some RSGs, while it splits in others; i.e., some flows counter to primary flow while some flows parallel to it. There are interactions between the RSGs of a PWR with respect to total steam load sharing.

Many plants such as McGuire, Sequoyah, and Trojan use main and bypass FW valves for SG level control and variable speed pumps for controlling feedwater-to-steam header pressure drop. The SG operation calls for a programmable SG level setpoint.

In the existing FW control systems, the SG level is controlled by one-element algorithm (level feedback) in the low power range (e.g., 2% to 25% full power) and by three-element control algorithm (level, steam flow, and FW flow feedback) in the high power range (e.g., above 25% full power). In some of the original FW control systems, only manual control is provided at low power. The problem areas consist of poor level controllability in the low power range, particularly in the manual mode due to the pronounced counter-intuitive FW flow-to-level response at low power **(Singh 1989)**, non-smooth transitions between main and bypass FW valve flow paths, one-element and three-element control, and manual and automatic modes.

Based on the above information, the specification for the plant simulation model was established as follows:

> The model should have the flexibility of including two, three, or four loops with RSGs of at least three types, i.e., non-preheat type, split-flow preheat type, and counterflow preheat type. Since level control poses more of a problem at low power, the range of the model should cover low power to full power (e.g., 2% to 100%). Within this range, the model should be capable of simulating various operational transitions shown in **Figure 1**. The RSG models should include the recirculation flow dynamics and the shrink/swell phenomenon prominent in the RSGs, and should include both narrow and wide range level measurements, with the narrow range covering the drum or extending below the transition cone as appropriate. The RSG models should also include enough detail in moisture separator characteristics to represent variations in moisture carryover and steam carryunder with load and level. The RSG loops should include variations that are important from a loop interaction standpoint, e.g., lengths of steam and FW lines. The rest of the plant model should be generic requiring only change in parameter values to represent different plant ratings and flow capacities. The FW train should include two variable speed pumps and a pair of main and bypass valves per loop. For preheater-type RSGs, the FW flow should be split in a variable proportion between the upper and lower nozzle. The FW temperature should be variable with load. The steam system should include turbine throttle valves, **turbine bypass valves (TBVs), atmospheric dump valves (ADVs)**, and safety valves. The model should perform satisfactorily during simulated turbine roll and synchronization, normal load changes, reactor trip, turbine trip, and trip of one FW pump.

The specification for the control model was established as follows:

> The control model should include a choice of several algorithms such as existing logic, advanced logic as described in a recent paper on Prairie Island ADFCS **(Paris 1989)**, and the <u>B&W</u> algorithm. It should be possible to select either a fixed or a programmed level setpoint by a simple change of parameters. The control model should also include an interactive graphics interface to increase the effectiveness of understanding the level responses of various types of RSGs and of developing level control algorithms.

III. MODEL DEVELOPMENT

Since there were so many variables in the model specification, it was decided that the target simulation be achieved in steps starting with the simplest possible model. Thus initially a single-loop nonpreheater-type RSG model was developed using the MMS module UTSGA. The conventional control logic and a graphic interface were included in this model. The full automatic mode of the FW pump and valve coordination control logic during main and bypass valve swapping, FW pump loading/unloading, and other transients was developed and debugged using this model. A similar model was then developed using the simpler MMS module UTSG for developing the B&W model-based algorithms for the feedwater and steam flow estimation at low power (i.e., analytical redundancy), and the FW flow demand calculation. Once the debugging of the model with module UTSGA was nearly complete, it was transported to the HP9000 for expansion into a four- loop model with a simple reactor module replacing the primary boundary conditions.

The models were initially developed by interconnecting various MMS modules in MMS EASE+ as shown in **Figure 2**. Changes were directly entered into the model ACSL code **(Mitchell & Gauthier 1987)**. Modules of the RSG, pipe, pump, and valve were used. Various control algorithms were also simulated and a user interface for color graphic interaction was developed. To achieve a reasonable size and speed of the model on the PC and also to quickly focus on the development at hand, boundary conditions were used for the primary hot leg, FW pump suction, and turbine condenser. The models were tested over the range of 2% to 100% full power. The simulation runs in real time on a 386 PC. Linear analysis capability is immediately available for interactive use during runtime. The models exhibit key characteristics such as the recirculation flow dynamics and the shrink/swell phenomenon. **Figure 3** shows the level shrink/swell during down and up step changes in throttle valve position (i.e., 0.85 to 0.6 at t=5s and back to 0.85 at t=200s) with the level controller set to zero in manual, and with the pump speed and FW flow controllers in auto. Thus in this transient, the FW flow tracked the steam flow, but was not finetuned by the level feedback. The steam pressure changed +/-100 psi during this transient. **Figure 4** shows the marginal stability of recirculation ratio as the power approaches 2% during a ramp from 100% to 2% power at 10%/min. This is a major cause of level instability in the plants at very low power. Several other transients were run. As expected, the level response to upsets in steam flow, FW flow, FW temperature, and primary power is initially influenced in a counter-intuitive fashion by changes in void fraction in the RSG. Further, the level controller gains tuned at 100% power are too high for level control at low power due to lower FW temperature and process nonlinearities.

IV. GRAPHIC INTERFACE

The on-line interactive dynamic graphic interface was developed using the Grafmatic FORTRAN-callable EGA/VGA-compatible subroutine library by Microcompatible, Inc. **(Microcompatibles 1989)**. Figure 5 shows the graphic screen image consisting of the animated schematic, keyboard interaction legend, valve/pump demand values, and trends and current values of 17 variables including model spêed relative to real time. Included in the keyboard interaction are the following capabilities:

- Manual or auto operation of valves and pumps. For example, the Capital-M key will toggle the main FW valve between manual and auto modes, and the F1 and F2 keys will, respectively, decrease and increase the main FW valve position.
- Graphic/nongraphic interface selection with Cap-G. The normal MMS interface is nongraphic.
- Controller tuning parameter list with Cap-T.
- Load/unload pump with Cap-U.
- Alarm enable/disable with Cap-A.
- Valve swap permissive with Cap-X.

The graphic interface was incorporated into the MMS model while preserving all the MMS capabilities. Thus the model can be run as a normal MMS model, with an option to run it interactively with the graphic interface.

V. CONVENTIONAL three-ELEMENT CONTROL

At low power when the feedwater and steam flow measurements are too noisy and inaccurate to be useful for control, level is controlled in manual or by a one-element **(proportional plus integral)** PI controller using only the level measurement. Since the FW flow demand is also low at low power, the bypass FW regulating valve is dedicated as the final control element for this mode of control.

When the power, and therefore, the feedwater and steam flows are high enough, the flow measurements are usable for feedback control and a three-element control logic is used. In this mode, the steam flow is used as the nominal FW demand and the level PI controller output is used as a correction to this nominal demand. The corrected demand is compared with the measured flow in the flow PI controller and its output becomes the demand for the main FW regulating valve position. To minimize the response of the level PI controller during shrink/swell, the level measurement is lagged before it is used in the controller.

Complementing the FW control is the pump speed controller for plants having variable-speed FW pumps. The feedwater-to-steam header delta-P is compared with the header delta-P setpoint in the pump speed PI controller to determine the pump speed demand. The header delta-P setpoint is a linear function of lagged total plant steam flow; the purpose for the lag is to make the pumps follow the FW valves during FW demand changes, thus avoiding potential pump valve contention.

Relative to a typical recent DFCS requirements specification **(Duke Power 1988)**, the existing control logic has several deficiencies:

- Lack of adequate feedback at low power (i.e., no flow information).
- Increased sensitivity of level response to low FW temperature at low power.
- Complexity of tuning the level controllers to compensate for the shrink and swell and FW temperature changes.
- Inability to produce smooth transitions between one-element and three-element control modes, and bypass and main FW regulating valves.

VI. B&W ADVANCED CONTROL ALGORITHMS

A typical DFCS customer looks for the following algorithm-related key features in the DFCS:

- Smooth transition between the bypass and main FW regulating valves.
- Good coordination between FW pumps and valves during valve swapping, pump loading/unloading, and other transients.
- Good level control in the absence of accurate feedwater and steam flow measurements, particularly at low flow conditions.

Recognizing customer needs, preliminary versions of the following algorithms were developed:

Pump valve coordination:
This model-based algorithm determines the demands for the position of FW valves and the speed of the FW pumps during FW valve swapping under operator permissive, FW pump loading/unloading, and other transients, given the demands for FW flow to each RSG. The latter are determined in another algorithm based on level control. The algorithm incorporates the hydraulic characteristics of the FW valves, pumps, and the FW lines.

Feedwater/steam flow estimation at low flow:
Based upon the simpler module UTSG, this algorithm calculates the estimates of steam and FW flow from RSG level and steam pressure measurements. Expected or measured values of FW temperature and pressure, and primary flow and hot/cold leg temperatures are also required. This algorithm incorporates the shrink/swell and recirculation flow dynamics, and heat transfer. Since module UTSG represents a non-preheater type RSG, this algorithm is only suitable for such RSGs.

FW flow demand calculation:
Like the previous algorithm, this algorithm is also based on the module UTSG, and therefore has the same features and applicability. However it calculates the feedwater, and optionally the blowdown, flow demands to satisfy the RSG

level setpoint, given the steam flow and RSG level measurements. At low flow, estimated value of steam flow can be used in lieu of the measurement. **Figure 6** shows the steam pressure and flow, feedwater flow demand, and the level in response to a step increase in steam throttle valve position from 0.844 to 1.0 at 5s. **Figure 7** shows the response of a three-element controller for the same transient.

The main advantages of the B&W algorithms are:

- No low power/high power mode change; same control logic is used at low and high flows based on measured or estimated FW/steam flows
- Continuity of feedwater and steam flow measurements during transient or steady state low flow situations based on analytical redundancy provided by the FW/steam flow estimation algorithm.
- FW demand incorporates shrink/swell compensation and FW temperature adaptation based on first principles, thus minimizing tuning needs.
- Smooth pump/valve coordination during FW valve swapping, pump loading/unloading, and other transients, thus minimizing level upsets initiated from the FW train.

VII. FULL PLANT MODEL ON HP9000

The single-loop model of the RSG/FW train and the conventional control logic was installed on the HP9000 and expanded to a 4-loop model by replicating the single loop model. Preliminary transient runs indicate the run times of single and 4-loop models to be 10 times and 1.5 times faster, respectively, than real time, thus making this model suitable for DFCS development and checkout. The parameters in the four loops were defined to reflect the differences in steam and FW line lengths. The loop interactions will be studied in the follow-on work. Also simple reactor and pressurizer models will be added in the follow-on work to evaluate the interaction between primary side dynamics and RSG level response and FW control.

VIII. CONCLUSIONS

The work reported in this paper has resulted in:

- Ability to quickly and inexpensively develop a plant-specific RSG/FW train model to support DFCS contract work.
- Development of B&W DFCS algorithms that can serve as a basis for defining the B&W DFCS offering.
- Development of a FORTRAN-based graphic interface for MMS models.

Follow-on work will include model-based algorithms for preheater-type RSGs and control hardware-in-the-loop simulation.

IX. REFERENCES

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AUTHOR

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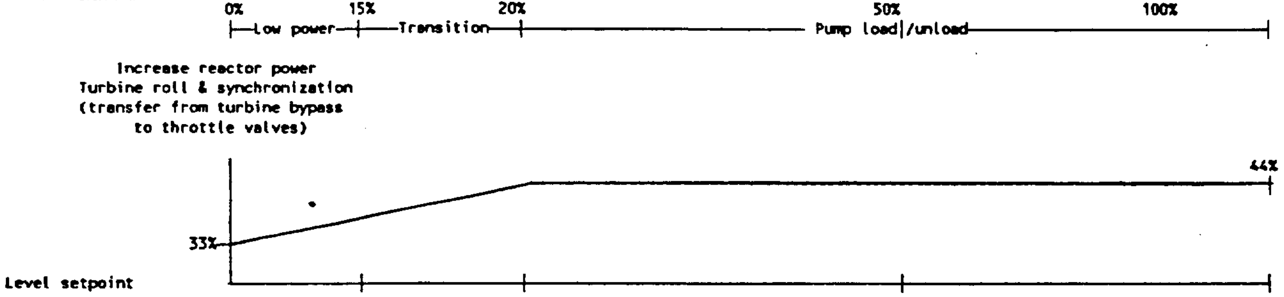
Activities prior to DFCS operation:

- Hot standby
- Reactor power 1-2%
- Feed pump warm up
- Transfer from aux fw to MFW

DFCS operation:



Signal validation	Yes	Yes	Yes
Analytical redundancy for fw & steam flow	Yes	Yes (not critical)	No (unless sensor fails)
Pseudo or normal 3-element control	Pseudo	Pseudo	Normal
Header delta-P control	Yes	yes	Yes
Main isolation valve	Closed	open	Open
Bypass isolation valve	Open	open	Closed
Main valve	Closed	Modulating open	Modulating
Bypass valve	Modulating	Modulating closed	Closed
Pump 1 on/off	On	On	On
Pump 2 on/off	Off	Off	On
Pump 1 speed	Modulating	Modulating	Modulating dn
Pump 2 speed	0	0	Modulating up

Figure 1 Typical operational transitions from zero power to full power

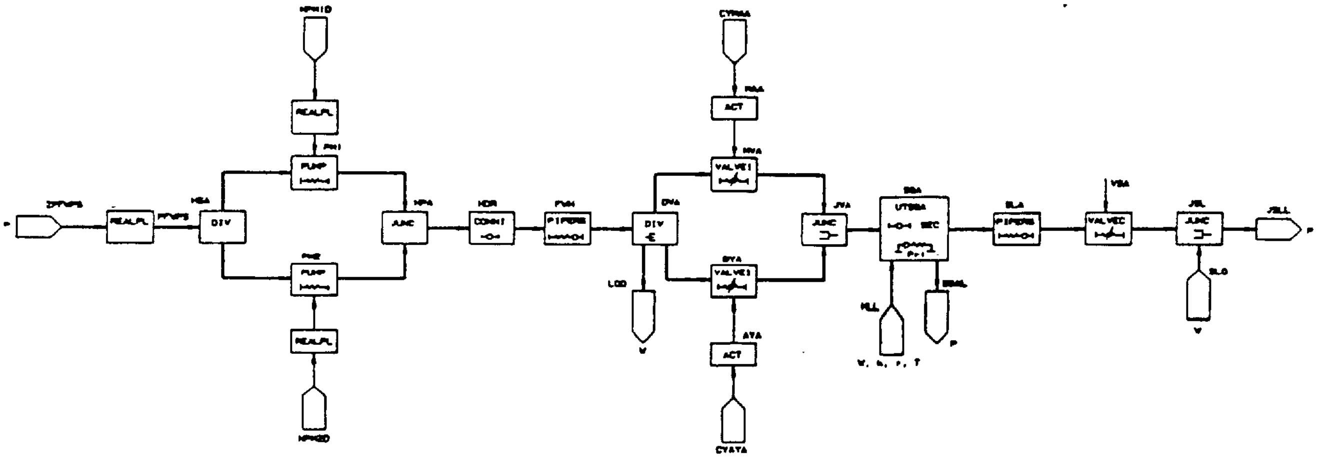


Figure 2 MMS block diagram of RSG-FW train

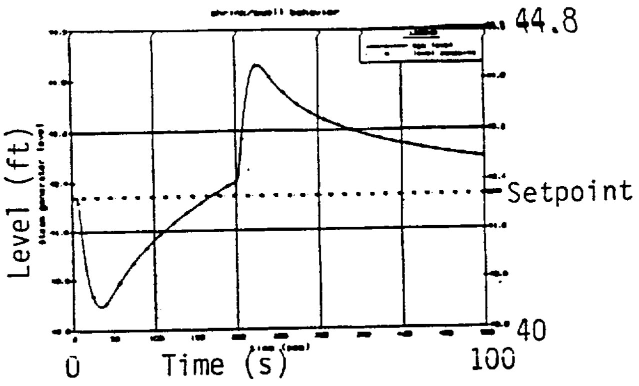


Fig.3 RSG level shrink/swell during step changes in throttle valve position.

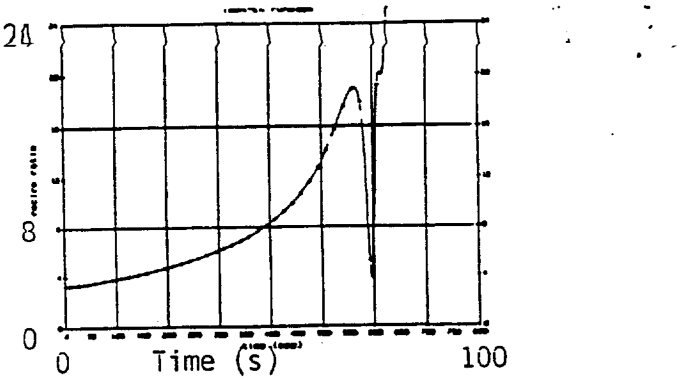
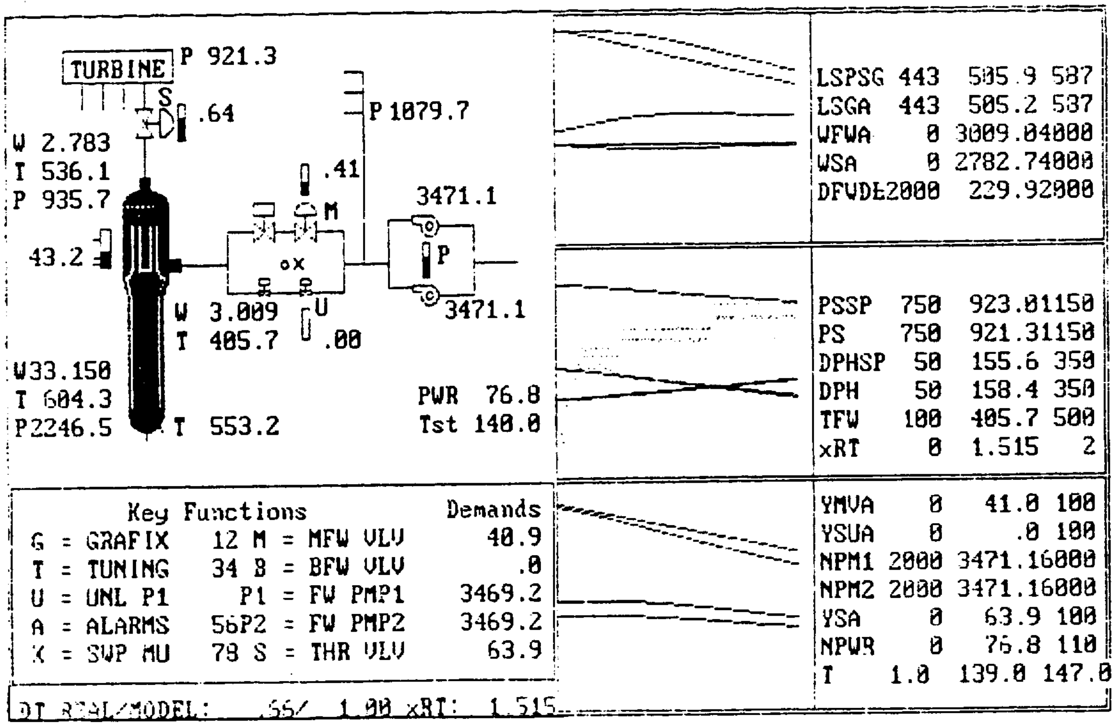


Fig. 4 RSG recirculation ratio during a power ramp from 100% to 2%.



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LSPSG 443   505.9 587
LSGA  443   505.2 537
WFWA    0 3009.04000
WSA     0 2782.74000
DFVDE2000  229.92000

PSSP  750  923.01150
PS    750  921.31150
DPHSP  50  155.6 350
DPH    50  158.4 350
TFW   100  405.7 500
xRT     0  1.515   2

YMVA    0   41.0 100
YSUA    0     .0 100
NPM1 2000 3471.16000
NPM2 2000 3471.16000
YSA     0   63.9 100
NPWR    0   76.8 110
T     1.0  139.0 147.0

        Key Functions            Demands
 G = GRAFIX   12 M = MFW VLV       40.9
 T = TUNING   34 B = BFW VLV         .0
 U = UNL P1      P1 = FW PMP1    3469.2
 A = ALARMS   56P2 = FW PMP2     3469.2
 X = SWP MU   78 S = THR VLV       63.9

DT REAL/MODEL:    .55/  1.00 xRT:  1.515
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Figure 5 Interactive dynamic color-graphic interface.

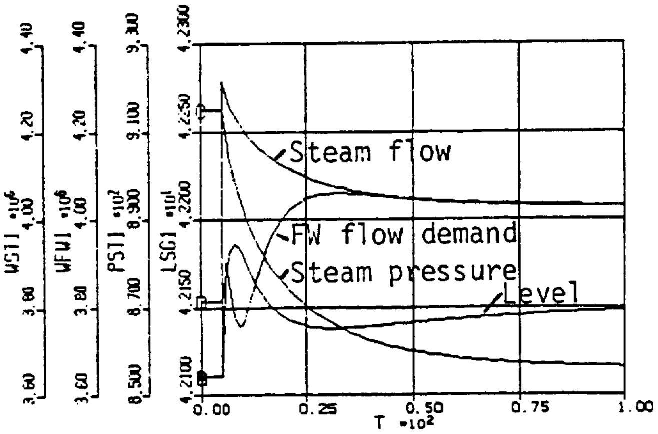

Fig. 6 Model-based FW flow demand and expected response during sudden opening of throttle valve at 5 sec.

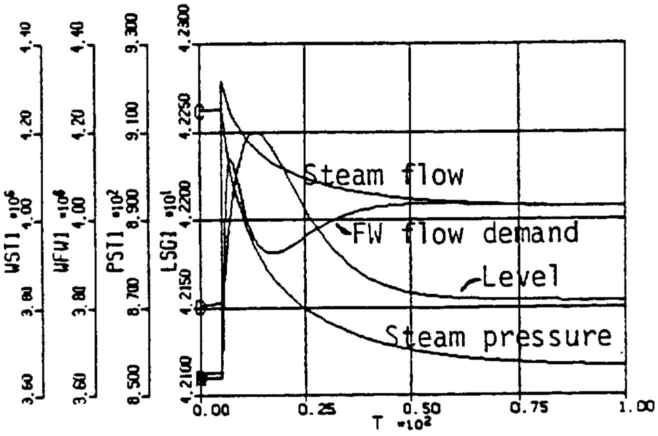

Fig. 7 3-element FW flow demand and expected response during sudden opening of throttle Valve at 5 sec.