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International Agreement Report

Assessment of TRAC-PF1/MOD1 Against an Inadvertent Feedwater Line Isolation Transient in the Ringhals 4 Power Plant

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Office of Nuclear Regulatory Research
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Prepared as part of
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ICAP
ASSESSMENT OF TRAC-PF1/MOD1 AGAINST AN INADVERTENT FEEDWATER LINE ISOLATION TRANSIENT IN THE RINGHALS 4 POWER PLANT

Abstract

An inadvertent feedwater line isolation transient in a three loop Westinghouse PWR has been simulated with the frozen version of the TRAC-PF1/MOD1 computer code. The results reveal the capacity of the code to quantitatively predict the different pertinent phenomena. For accurate predictions of the system response it was found that a careful nodalization of the steam generator downcomer was essential for accurate pressure distribution and associated level prediction. Also the core moderator temperature reactivity coefficient was recommended to be decreased somewhat (be less negative) whereas the fuel gap conductance should be rather low in order to increase the initial stored energy of the fuel rods. It was also found during the course of the calculations that some restrictions had to be imposed on the allowable maximum timestep size in order not to violate the convergence of the solution procedure.

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Executive summary

A TRAC-PF1/MOD1 simulation has been conducted to assess the capability of the code to predict a feedwater line isolation.

The measured data was obtained from an inadvertent feedwater line isolation at full power operation in the Ringhals 4 power plant. Ringhals 4 is a Westinghouse PWR with three loops and two turbines of Stal-Laval design. The nominal thermal power is 2 775 MW and 915 MW electrical. It is equipped with three Westinghouse steam generators model D3 with a feedwater preheater section located at the cold leg side of the U-tube bundle and a division is made of the feedwater flow between this lower feedwater inlet and the top inlet at the upper part of the downcomer.

During the pretransient stationary phase the total feedwater was apportioned so that about 10 % of the flow was delivered to the top inlet and the rest to the preheater. The circulation ratio at this condition was about 2.43.

The transient was initiated by a failure in an electronic logical circuit causing the feedwater line isolation valves to close in all three loops. Following the closure of the valves the steam flow through the feedwater preheater train ceased and a corresponding increase of the flow through the turbine was obtained. This was automatically compensated for by the throttling of the turbine valves. The impulse chamber pressure of the turbines was as a consequence decreased by about 10 per cent. This was felt by the control logic of the turbines as a corresponding load rejection resulting in deblocking of 25 per cent steam dumping capacity.

Because of the loss of main feedwater flow the average temperature of the primary coolant was increased while the reference temperature was decreased due to the reduced impulse chamber pressure. This deviation resulted in a dump demand signal and about 14 s after the feedwater isolation steam dumping from the turbines was initiated.

The continued steam flow resulted in depletion of steam generator liquid inventory and reactor scram was obtained on low downcomer level signal Isolation of the turbines was activated as well as initiation of auxiliary feedwater supply. The level was as a consequence slowly increased and finally resumed normal value.

In the TRAC-simulation only a single loop representation was used and the core was modeled by the TRAC neutron point kinetics specified with middle-of-cycle conditions. The complete model comprised 37 components made up by 144 nodes with the boundary condition components excluded.

The boundary conditions were either taken directly from the recordings of the plant computer or were inferred from these. The following conditions were used:

- Main feedwater flow and temperature vs time
- Steam flow vs time, trip controlled
- Scram reactivity vs time, trip controlled
- Auxiliary feedwater flow and temperature vs time, trip controlled
- Decay heat

The pressurizer control system was modeled in detail and also the trip logic for the scram, steam flow and auxiliary feedwater flow.

The result of the simulation revealed a satisfactory agreement with measured data. However, for accurate predictions of some basic and important parameters the obtained result indicated areas of model improvements. Because of sensitivity of system response on steam generator downcomer conditions a thorough nodalization of this part was essential. Also modifications in the moderator temperature reactivity coefficient as well as the gap conductance of the fuel improved the results. Finally some changes in the originally assumed long term steam flow boundary conditions were found to be beneficial for the outcome of the simulation.

From the run statistics it was found that a 310 s transient without any restarts used 1 068 timesteps with a maximum allowable timestep size of 0.5 s. This required 4 784 CPU-s on a CDC Cyber 180-835 computer.

It was observed that when letting the code freely determine the timestep size an abnormal termination was obtained after about 160 s transient time because of convergence failure of the numerical solution procedure. This was remedied by decreasing the maximum timestep size to 0.5 s.

1 Introduction

This study was conducted under the auspices of the Swedish State Power Board and the Swedish Nuclear Power Inspectorate. Analytical assistance during preparation of the input deck and early phases of the steady state analysis, was obtained from Mr F Pelayo, Consejo de Seguridad Nuclear, Spain and was much appreciated.

The International Thermal-Hydraulic Code Assessment and Application Program (ICAP) is being conducted by several countries and coordinated by the USNRC. The goal of ICAP is to make quantitative statements regarding the accuracy of the current state-of-the-art thermal-hydraulic computer programs developed under the auspices of the USNRC.

Sweden's contribution to ICAP relates both to TRAC-PWR [Ref 1] and RELAP5 [Ref 2]. The assessment calculations of TRAC have earlier been carried out as a joint effort between the Swedish State Power Board (SSPB) and Studsvik AB whereas the RELAP5 calculations have been conducted by Studsvik for the Swedish Nuclear Power Inspectorate (SKI).

Recently a Swedish group was formed for coordination of Swedish efforts within ICAP. This group has representatives from SSPB, SKI and Studsvik and has emphasized the importance of using plant transients for assessment purposes. Accordingly the Swedish future efforts will basically concentrate on analyzing plant transients with the TRAC-PF1 code. The current assessment matrix is shown in table 1.

In this report the results of an assessment of TRAC-PF1/MOD1 against a main feedwater line isolation transient are presented. The ability of TRAC to simulate this transient is assessed by comparison to measured data from an inadvertent isolation occurrence at 100 per cent power in the Ringhals 4 power plant.

This report is organized as follows: Section 2 describes briefly the Ringhals 4 power plant and the transient which originated from the feedwater line isolation. In section 3 the TRAC model used to simulate the transient is described and section 4 is a review of the procedure used to obtain the specified steady state. Section 5 presents the results from the simulation as well as performance of the TRAC-code. Also some run statistics are given. Conclusions are presented in section 6.

Table 1

ICAP Assessment Matrix - Sweden.

Code	Facility	Type	Description
TRAC-PF1	Ringhals 4	Integral, full scale	Full load rejection
TRAC-PF1	Ringhals 2	Integral, full scale	Inadvertent steam line isolation valve closure in one loop
TRAC-PF1	Ringhals 4	Integral, full scale	Symmetric loss of feedwater
TRAC-PF1	SPEC	Intergral, small scale	Symmetric loss of feedwater

2 Plant and transient description

Ringhals 4 is a 3-loop, 2 turbine PWR of Westinghouse-Stål Laval design. The power is nominally 2 775 MW thermal and 915 MW electrical. It is equipped with three Westinghouse steam generators model D3 with a feedwater preheater section located at the cold leg side of the U-tube bundle. The feedwater is divided between the top feedwater inlet, which enters into the upper part of the downcomer, and the preheater section at the lower end of the riser. Normally only a smaller part of the total feedwater flow is delivered to the top inlet and the rest to the preheater.

In the preheater section the flow is apportioned due to the flow restrictions in support plates etc. According to specifications at nominal load and no top feedwater 54.5 % of the flow is fed to the upper part of the riser (U-tube boiler section) while the remaining flow is fed downward and enters the lower end of the riser on the hotleg side where it mixes with the downcomer flow. The circulation ratio at this condition is specified to be 2.43.

Prior to the transient the plant was operating at full power with about equally loaded turbines. Because of malfunction of an electronic logical circuit a spurious feedwater isolation signal was created resulting in closure of the feedwater line isolation valves to all three steam generators. Thus the feedwater flow ceased but still the reactor and the turbines were operating at full load.

As the high and low pressure feedwater preheaters are in series with the feedwater trains the steam drainage from the high pressure turbines through the preheaters decreased when the feedwater flow ceased. Consequently the steam flow through the turbines increased as well as the power. This was automatically compensated for by throttling the turbine valves (the control oil pressure was decreased). The impulsechamber pressure of the turbines was then decreased by about 10 per cent. This was felt by the control logic of the turbines as a corresponding load rejection resulting in deblocking of 25 per cent steam dump capacity.

When the feedwater flow ceased the steam generators were less efficient as heat sinks for the primary side and as a consequence the average temperature of the primary coolant was increased.

The primary side reference temperature was decreased because of the lower impulsechamber pressure of the turbines. Thus a deviation between the primary side average temperature and the reference temperature was obtained resulting in a dump demand signal and about 14 seconds after the feedwater isolation, steam dumping from both turbines was initiated.

By continued steam flow (about 100 per cent) from the steam generators the downcomer levels decreased and about 37 s after the feedwater isolation reactor scram was obtained due to extreme low level in steam generator 2. This resulted also in turbine trip as well as turbine isolation. The other two steam generators experienced about the same level decrease. Auxiliary feedwater flow was initiated immediately after scram and two motordriven pumps (steam generators 1 and 2) and one turbine driven pump (steam generator 3) were started. During the next 40 seconds the steam flow slowly decreased to about zero flow as a result of decreased dump demand.

Indicated narrow range downcomer level was reaching zero almost immediately after scram and a minimum level of about 20 per cent on the wide range level indication was obtained approximately 73 seconds after feedwater isolation. The level was from then on slowly increased due to continued auxiliary feedwater flow.

The faulty equipments were replaced and about 14 hours after scram the reactor was critical and after another 10 hours full power was resumed.

Throughout the transient important plant signals were monitored and stored on the plant computer. From the plant signal follower, which records the time sequence of trips and control signals, and pertinent time plots a sequence of events was obtair his is shown in table 2, left column, w ll the recorded time points have been shi ed so that the time 10 seconds corresponds to the time when the feedwater isolation signal occurred.

Table 2

Sequence of Major Events

Recorded time (s)	Calculated time (s)	Event
0.0	0.0	Pretransient stationary operation
10.0	10.0	Feedwater line isolation
12.1	12.1	Throttling of turbine valves
13.3	-	Deblocking of 25 per cent steam dumping
23.5	23.5	Initiation of steam dumping
47.4	47.9	Reactorscram due to low-low level in SG2
47.5	47.9	Trip of both turbines
47.5	49.3	Initiation of auxiliary feed-water flow
88.1	77.1	Minimum wide range SG level
92.0	94.0	Closing of steam dump valves
138.6	80.0	Extreme low primary T-average (< 289.4°C)
143.3	-	Extreme low primary T-average, condition P12: Blocking of steam dump, however, manual bypass allowed to provide max 25 per cent dump if necessary
426.4	-	Extreme low pressurizer level (< 15 per cent): Let-down isolation
~ 1 367	-	Manual initiation of steam line isolation to prevent additional cooldown of RCS
~ 1 800	-	The plant resumed normal zero-load condition

3 Code and model description

The simulation of the transient was made with version 14.0 of the TRAC-PF1/MOD1 computer code [Ref 1] with an additional update to provide proper functioning of the restart capability of the core component. The program was run on a CDC Cyber 180-835 computer under the NOS 2.6 operating system with no SCM and LCM partition of the memory. Instead the central processor primary memory was used together with an extended memory capability. TRAC was also locally modified to allow writing of signal variables and control block output on a separate file for later plotting with a separate program. Thus the EXCON and TRAP auxiliary programs were not used for producing the graphics to this simulation.

In the simulation only a single loop representation was used as shown in figure 1. Differences between the three loops were considered to produce effects of secondary order during the transient. It should be noted that trip margins are usually dependent on conditions in individual loops. For instance, the reactor scram on low steam generator level was initiated by the conditions in steam generator 2, though closely followed by the other two. Also the turbine driven auxiliary feedwater pump provided about twice as much flow to steam generator 3 as the motor driven pumps to steam generators 1 and 2. Thus the symmetry between the loops was not perfect and this will have some influence on the comparison between calculated and measured results.

The basic TRAC-model of Ringhals 4 nuclear steam supply system for this analysis is depicted in figures 1 and 2. Only minor modifications have been introduced compared to the model used in the loss of load transient [Ref 3]. A new pressuriser model has been implemented though. The nodalization comprised 17 components with 81 nodes on the primary side and 20 components with 63 nodes on the secondary side making a total of 37 components with 144 nodes if the boundary condition components are excluded.

3.1 Primary system nodalization

The reactor core, denoted by component 5, was divided into seven vertical nodes; five nodes representing the active core and one unheated inlet and outlet node respectively. The axial power distribution was preserved throughout the transient. Default point kinetics together with reactivity feedback with middle-of-cycle characteristics were used to simulate the neutronic response of the fuel during the transient. The decay heat was calculated according to ANSI 5.1.

The upper plenum (component 6) and hot leg inlet was divided into three nodes. The hot leg and surge line, denoted 710, was represented by a tee-component with five nodes in each branch.

The primary side of the steam generator was modeled by 18 nodes; one each for the inlet and outlet plena and sixteen nodes for U-tube bundle and the thermal interaction with the secondary side.

The cold leg leading from the steam generator to the vessel inlet was represented by 10 nodes; five on each side of the recirculation pump. The vessel inlet section was modeled by three nodes, and the downcomer and lower plenum were represented by two nodes and one node, respectively.

The recirculation pump was set up to also provide heating power to the coolant. As the energy dissipation terms in the conservation equations are omitted no conversions of mechanical energy (wall friction and pump pressure) into coolant internal energy are accounted for when passing through the loop. A crude compensation for this was introduced by adding a specified power to the pump component wall structure.

The pressurizer was modeled according to recommendations given in the TRAC User's Guide [Ref 4]. The bottom of the pressurizer was modeled by using a pipe component divided into four cells to assure proper draining and accurate pressure loss computation (component 400). The length of this component was specified to equal the length of the electrical heaters and the heater power was assumed to be deposited directly in the fluid. The main body of the pressurizer was modeled as a tee component number 410. Six cells were considered reasonable to simulate the pressure transients and level behavior. The side tube at the very top of this component was used to model connections to the pressure relief and safety valves. The top hemisphere of the pressurizer was represented by a "prizer" component number 420. One feature of this component was to serve as a pressure boundary condition during the steady state calculations.

The spray flow was simulated by attaching a fill component to the upper end of the "prizer" component. The corresponding junction flow area was specified such that the liquid velocity was 4 m/s at a spray flow rate of 19.4 kg/s. This would activate the enhanced interfacial condensation model in the "prizer" component and thus allowed for adequate condensation of vapor when a reasonable spray flow was maintained.

The pressurizer walls were simulated by heat structures with four radial nodes. The heat losses to the environment were chosen so that they balanced the steady state heater power when a specified spray flow was maintained. The losses were then about 178 kW.

All the pressurizer valves were sized, as suggested in ref 4, to their rated capacities under choked flow conditions. The pressurizer pressure control was modeled in detail and was earlier tested in connection with a Ringhals 2 analysis [Ref 5]. Although the level control was modeled it was bypassed for this specific transient.

3.2 Secondary system nodalization

An outline of the steam generator base model is depicted in figure 2. Feedwater was supplied to the steam generator at two locations. Ten per cent of the feedwater was supplied as top feed into the downcomer and ninety per cent into the preheater section near the outlet of the cold leg side of the U-tube. All the auxiliary feedwater was supplied to the top feed connection through the dummy tee-component 745 as shown in figure 1.

The hot leg boiler and the explicitly modeled preheater section were both divided into five nodes with the node boundaries located at the same elevations. The U-tube boiler was represented by three nodes. An ideal separator which allowed only steam to escape upwards was assumed at the top of the riser. A connection was made between the separator node and the upper separator drain flow path. The downcomer was represented by totally ten nodes.

The steam generator level measurements represented by differential pressures, were explicitly modeled in order to estimate dynamic contributions from flow and mass content. Both the narrow range and the wide range level indications were simulated.

The steam line was divided into a number of tee-components and the secondary pressure (steam line pressure) was measured in the tee-component 752, figure 1. Also safety and relief valves were connected to the steam line. According to the report of the isolation occurrence none of these valves were activated during the transient. However, in the model the activation logic was modeled. The part of the steam line denoted by 753 was represented by a valve component with two nodes simulating the main steam isolation valve.

The steam flow was measured by means of a differential pressure between the steam dome pressure tap and a tap in the relief valve header. In order to avoid disturbances from the flow contraction between the steam dome and steam line (junction 750) the noding in the very first part of the steam line was made somewhat more dense than elsewhere. This is according to recommendations given in ref 4.

The steam flow was divided into two streams - one for each turbine - in the steam line header (754) which was represented by three nodes. The line for each turbine was further split into two flow paths - one containing the turbine valve and the other containing the dump valve.

During the transient there was no stem position measurement of the dump and turbine valves. Thus it would have been difficult to accurately evaluate the involved control logic and operation of these valves and the corresponding influence on the flow. For simplicity the actual operation of these valves was not simulated in the current analysis. In the analysis the dump valves remained fully closed throughout the transient whereas the turbine valves were fully opened. The flow response of the actual valve operations was simulated by providing the measured steam flow as boundary conditions downstream the turbine valves.

3.3 Control system and trip logic modeling

The TRAC control system and trip capability was used to initiate the transient and to introduce several actions from auxiliary- and safety systems. In this way it was possible to make the calculation dependent on the initial event only, that is the isolation of the feedwater line.

The following systems were simulated:

- Pressurizer pressure control
- Trip logic based on level indication of steam generator downcomer. The occurrence of narrow range low level subsequently resulted in:
  - Reactor scram
  - Turbine trip
  - Initiation of auxiliary feedwater

The pressurizer pressure and level control is schematically shown in figure 3. This system was taken from an earlier made Ringhals 2 analysis [Ref 5]. It was found during that calculation that unphysical oscillations in the output of the PI-controller occurred regularly. By replacing the PI-controller by the equivalent set of control blocks this problem was eliminated.

It was also apparent that due to the explicitness of the control block numerics, the efficiency of the control system depends upon timestep size, particularly if the rate of change of the variable being controlled is large.

Both the steam generator narrow range and wide range level were simulated by means of calculations of differences between cell pressures without any compensation for vapor columns. The narrow range level was calculated from the pressure difference between cells 731 (4) and 738 (1), figure 2. The wide range level was similarly calculated from pressures in cells 731 (1) and 738 (1). Scaling factors were obtained first by equating the narrow range signal with the corresponding collapsed level during steady state. Next, also during steady state, the wide range level should be equal to the narrow range level. These scaling factors remained constant throughout the simulation.

4 Steady state calculation

Prior to the transient simulation the TRAC model was adjusted to replicate the plant stationary pre-transient conditions. This had earlier been done for the current power level (100 %) in connection with analysis of the load rejection transient [Ref 3]. Only minor changes had to be introduced for this analysis.

A heat balance calculation of the plant during the stationary phase provided valuable information of recirculation pump power and primary coolant massflow which were not known from measurements. A simple pump speed controller was introduced in the model in order to attain a specified mass flow target during steady state. It was set up in such a way that when switching TRAC to transient mode the so obtained pump speed remained constant.

The full plant model was taken from the load rejection analysis and all the initial condition were manually updated to correspond to the pertinent situation. Only minor changes had to be introduced. The steady state calculation was then performed in two steps. After specifying measured feedwater flow (= steam flow) and temperature on secondary side and pressurizer pressure and core power as well as coolant massflow target on primary side the system was allowed to stabilize. Thus during this first step a system steady state with the new primary massflow was obtained.

During the second step the transient mode was activated and a null transient was run. The pressurizer pressure boundary condition was thus deactivated and the core kinetics implemented. The so obtained steady state is shown in table 3.

The model steady state condition was saved on a dumpfile for later retrieval at the transient simulation.

The total steady state analysis was run for 180 seconds with a maximum time step of about 4 seconds (obtained rather late in the calculation). This required 985 CP-seconds and relevant statistics for the steady state were:

CPU-time/problem time = 5.47

CPU-time/cell and timestep = 0.034 s

Table 3

Results of steady state analysis.

Primary side

Parameter	Measured/ specified	Calculated
Core power (MW)	2 775	2 780
Coolant flow (kg/s)	13 790	13 792
RCP speed (rad/s)	-	150.4
T hot leg (K)	594.5	594.6
T cold leg (K)	558.6	558.3
Prz pressure (MPa)	15.52	15.54
Prz level (%)	46.5	46.2

Secondary side

Parameter	Measured/ specified	Calculated
SG dome pressure (MPa)	-	6.22
Steam line pressure (MPa)	6.19	6.11
SG level (%)	61.9	61.7
CR-ratio (-)	-	2.45
Feedwater flow (kg/s)	1 528.9*)	1 528.9
Feedwater temperature (K)	495.9	495.9
Steam flow (kg/s)	1 530.0	1 529.0

*) During the steady state 10 per cent of the total feedwater flow was supplied to the top nozzle and the rest to the bottom nozzle.

5 Data comparison

The simulation was made using a single loop representation. The measured thermal-hydraulic data were obtained mainly for loop 2 with some few data taken in loop 1 and 3. Thus an averaging and extrapolating procedure had to be applied in order to provide data for an average single loop. The data processed in this way were

- Steam flow
- Main feedwater flow
- Narrow range steam generator level
- Wide range steam generator level
- Auxiliary feedwater flow

During the steady state as well as the transient simulation it was thus assumed that complete symmetry prevailed between the loops.

5.1 Boundary conditions

The main heat source during the transient was the core power and decay heat. The core reactivity parameters were specified to correspond to middle of cycle condition. Otherwise default kinetic parameters were used. The decay heat was simulated according to the ANSI-curve assuming equilibrium conditions. The rod insertion following the reactor trip signal (low steam generator level) was specified according to Ringhals 4 FSAR chapter 15. A time delay of 2.0 seconds was used from the time point the trip was true to the time point the control rod reactivity insertion started. It has to be realized that this yields conservative reactivity insertion and is intended for safety analysis.

The (conservative) control rod reactivity insertion curve used in the analysis is shown in figure 4. The maximum reactivity worth of the control rods was -0.08385.

The speed of the reactor recirculation pumps was maintained constant at the steady state value throughout the transient.

The pressurizer control was fully modeled using the rated values for the proportional and back-up heaters. The spray flow was taken from loop seal and was allowed to vary from its trickle flow to its maximum rated value. This flow was extracted from loop seal by means of FILL-component 715 (figure 1) and the same flow was entered as spray flow through FILL-component 500. For simplicity a constant spray water temperature was assumed corresponding to the steady state cold leg temperature. This temperature was only slightly changed during the transient thus justifying this assumption.

The feedwater isolation was introduced by a trip controlled table providing the main feedwater flow as boundary conditions to top and bottom inlet nozzles, FILL-components 741 and 744 in figure 1. A careful review of pertinent timeplots and signals revealed a feedwater time function after trip as a linear ramp from normal flow to zero flow during 2.5 seconds.

The auxiliary feedwater flow was taken form measurements. This flow was measured for each steam generator and thus the total flow was obtained by summing the three separate flows. The measured flow from the turbine driven pump to steam generator 3 was not correctly recorded as a saturation was obtained at 30 kg/s. According to specification this pump should deliver 48 kg/s and this latter flow was used when specifying the auxiliary feedwater flow boundary condition. The flow was entered as a trip controlled table to FILL-component 743, figure 1. As the feedwater isolation occurred in December with fairly cold weather, and the auxiliary feedwater was taken from an outdoor located storage tank the temperature of this water was assumed to be rather low. A reasonable temperature according to the SSPB was about 298 K which was used throughout the simulation. The auxiliary feedwater flow as function of time after the steam generator low level trip is shown in figure 5.

The operation of the turbine stop valves and steam dump valves was not explicitly modeled. Instead this operation was imposed on the TRAC-model by applying the measured steam flow as boundary condition. When doing this it has to be realized that the steam flow time history must be separated in two parts; one describing the flow prior to reactor scram signal that caused turbine isolation and the other describing the flow after scram. The measured steam flow from loop 2 taken as a pressure difference between steam dome and steam line is shown in figure 6.

The low steam generator level trip occurred at 37.4 seconds after the feedwater isolation. In order to let the TRAC-model fully control the steamflow behavior it was assumed that the measured steamflow immediately before the low level trip would have remained even if the trip occurred at a later timepoint. Thus the first part of the steamflow boundary condition was assumed to be described by the curve in figure 7 and this curve was applicable until the low level trip occurred.

Once this trip has occurred the steam flow will follow the curve in figure 8.

5.2 Results from the simulation

The transient was simulated for 300 s including 10 s of pretransient steady state condition. At 10 s the feedwater isolation started with top and bottom feed flow being ramped from fully flow to zero flow during 2.5 s. From that time and on the calculated transient developed as the time sequence of events listed in table 2 above indicates. The results are shown in figures 9 to 28. The plotted calculated variables were usually filtered by means of a first order lag function with 0.5 s time constant in order to some degree simulate the plant signal processing. In some cases other time constants were used as indicated in the figures.

The simulation was carried out in basically two separate stages. First a basecase was run with nodalization and boundary conditions as described above. Second some modifications of the nodalization were introduced and sensitivity studies were carried out for a few important parameters. The results from the basecase are discussed first.

5.2.1 Basecase simulation

The steam flow (specified as boundary condition) continued after the feedwater isolation and experienced a reduction due to the throttling of the turbine valves and a later increase when the steam dumping started. In figure 9 the steam flow at the outlet of the steam generator is shown and compared to measured values. The direct flow indicates the total flow as represented by a TRAC signal variable. This flow was in fully agreement with the imposed flow boundary conditions downstream of the turbine valves. The flow as taken as differential pressure between the steam generator dome and the steam line revealed a discrepancy from the direct flow when the flow was reduced and the pressure increased, figure 10. The basic reason for this behaviour was the omission of pressure dependence in the flow algorithm. Also some minor influences originated from the nodalization of the very first part of the steam line and the steam line pressure drop distribution. Modifications were introduced for the calculations in the following stage.

The steam generator narrow range level is shown in figure 11. A satisfactory agreement between the calculated level from a differential pressure and the measured signal was obtained until the low level trip setpoint (33 %) was reached at 45.9 s. At that time point an oscillation in the calculated level signal was encountered that had no correspondence in the collapsed level nor in the measurements. This is more easily seen in figure 12 showing the same phenomenon in another time scale.

No changes in the boundary conditions were encountered at the time when the oscillation started. The auxiliary feedwater flow trip was not latched meaning that when the level signal recovered the trip condition became false again as shown in figure 13 and consequently no flow had time to be introduced until the trip was true the second time at about 50 s. The sharp decrease of steam flow did not occur until the reactor trip was true. This trip was latched and delayed 2 s from the time point the low level was obtained. Thus the reactor power was maintained during the time for the oscillation. A careful review of the lower and upper pressure tap pressure behavior, figure 14 marked area, revealed a high sensitivity of level signal on small dissimilar variations in lower and upper tap pressures. Especially the lower tap pressure was strongly influenced by the conditions in the downcomer. For instance at the time for level oscillation a vapor content of downcomer cell 4 had just become apparent, the void fraction being rather low though, figure 15. The void fraction time derivative was changing somewhat due to variations in vapor generation, figure 16, which will have some influence on the cell pressure as the volume of cell 4 was rather small compared to surrounding cells. A more careful nodalization of the downcomer would have alleviated the problem and was introduced for the simulations in the second stage.

On the primary side prior to reactor trip the temperature increased, figure 17, because of the less efficient heat removal on the secondary side when the feedwater flow ceased and the throttling of the turbine valves was activated. The difference between the measured high average temperature and the calculated values could stem from the fact that the measurement represented the highest value from three loops whereas the calculated temperature represented average values from the three loops. However, the pressurizer level, which could be interpreted as a measure of the average temperature of the primary side, revealed a somewhat higher measured temperature than calculated, figure 18. It is also clear that the calculated core power during this part of the transient before reactor trip was somewhat lower than the measured power, figure 19, indicating that the specified moderator temperature reactivity coefficient in the model was somewhat too high (too negative).

Once the low steam generator level signal was obtained at about 50 s, figure 11, the isolation of the turbines was initiated and the steam flow according to figure 8 was imposed as boundary condition in the model. Also auxiliary feedwater, figure 5, was fed to the top feedwater nozzle and reactor trip occurred, figure 19.

The steam flow decrease after trip as represented by the differential pressure across the steam generator outlet nozzle, figure 9, revealed an excellent agreement with the measurement until the actual steamflow was approaching zero flow. Although the imposed steamflow apparently was zero a non-zero value was obtained from the dp-calculation. This fictitious flow corresponds to the elevation pressure difference between the pressure tap locations and was not compensated for in the model.

The measurement indicated a positive constant small steamflow prevailing for the rest of the transient. This was an extrapolated value from the only available steamflow measurement (steam line 2). In the operational report of this occurrence there was no explanation whether it was a true flow or a signal error from the measurement device. In view of the time history plots of other variables as outline below, it can be reasonable to assume that a small steamflow actually was existent during the latter part of the transient.

The calculated steam line pressure after reactor trip was somewhat low compared to measurement, figure 10. The difference was about 0.2 MPa. This low pressure was caused by a somewhat low primary temperature (about 2 K), figure 17. The low calculated primary temperature was also revealed from the pressurizer level response, figure 18. Thus it seemed apparent that the calculated power generated on the primary side after reactor trip was too low.

The calculated core power was following very closely to the measured curve, figure 19. It should be emphasized when interpreting figure 19 that once the reactor was scrammed the output from the PRM-detectors was not highly accurate, especially when realizing that the basic heat source then was from γ-decay. The simulation would have been improved if the stored energy in the fuel was increased. This could have been obtained if a lower gap conductance was used. This will also delay the energy equalization process between the fuel and coolant. A value of 10 kW/m^2K was used in the basecase calculation. For the later simulations two new values for the gap conductance were suggested; 7.5 and 5.0 kW/m^2K.

Quite rapidly after the reactor and turbine trip the liquid level in the steam generator downcomer decreased below the narrow range lower pressure tap, figure 11. Both the measured signal and the calculated signal from a differential pressure retained a positive non-zero level. This was caused by the elevation head between the taps and was not corrected for in the model, nor in the plant.

The wide range level is shown in figure 20. It seemed that the water content of the steam generator was somewhat low in the simulation which became apparent when the internal circulation ceased at about 80 s. From that time and on the increase in level had its origin in the auxiliary feedwater flow. The slope of the measured and calculated curves was during this time about the same. This indicates that the auxiliary feedwater flow in the model was about what was used in reality and that the assumption of using design flow when the measurement was uncertain was adequate.

From the long term behavior of the primary average temperature, figure 17, the pressurizer level, figure 18, and the pressurizer pressure, figure 21 it could be concluded that the calculated cooling of the primary side was less than the measurements indicated. As the auxiliary feedwater flow seemed to be adequately modeled it is reasonable to assume that a small steam flow actually was prevailing during the major part of the transient. A fact is that the turbine driven auxiliary feedwater pump was operating by steam from one or two of the loops. However, the steam flow through this device was not known. A crude estimation revealed that a steam flow of about 10-15 kg/s was required to decrease the calculated primary temperature with a rate similar to the measurement. A sensitivity study was suggested with the steam flows 10 and 15 kg/s.

5.2.2 Second stage simulations

In view of the results from the basecase simulation the original model was somewhat modified before the second set of calculations was carried out.

First the steam line downstream of the steam generator was somewhat more dense nodalized in order to see any possible nodalization effect on the pressure drop across the dome outlet. Also the pressure drop distribution of the entire steam line was slightly modified to correspond more closely to measured values obtained at an earlier made plant performance test.

Second the nodalization of the steam generator downcomer was changed to avoid the oscillation in liquid level when taken as function of differential pressure. The new nodalization is shown in figure 22. The number of cells in the downcomer was increased from 8 in the basecase model to 17 in the new model.

Four new calculations were carried out. The fuel gap conductance was reduced from the basecase 10 kW/m^2K to 7.5 kW/m^2K and 5.0 kW/m^2K. This would successively increase the stored energy in the fuel (increase the fuel temperature) prior to the transient. During the transient the increased initial fuel energy would increase the primary side coolant temperature and increase the secondary side pressure. Before the transient simulation a new core steady state had to be obtained for each new gap conductance. These steady state conditions were saved on files for later retrieval at the transient runs.

For each new gap conductance two different long term steam flow values were used: 10 kg/s and 15 kg/s. This steam flow could partly be considered to pass through the turbine driven auxiliary feedwater pump. An estimate revealed that the needed steam flow to provide the specified feedwater flow under assumption of reasonable losses was comparable or below these values.

Also the moderator temperature reactivity coefficient was decreased (i.e. was made less negative) in order to increase the core power during the very first part of the transient prior to reactor trip when the primary coolant temperature was increasing. A scrutiny of the fuel conditions at MOL as given in the nuclear design report revealed that th coefficient could be changed by about 3 pcm.

The results of the new simulations with the above mentioned modifications are presented in figures 23 through 28 where some important variables are plotted. From figure 23 and earlier figure 10 it was clear that the more dense nodalization of the upstream part of the steam line did not have any significant influence on the pressure drop across the steam dome outlet. Thus the nodalization was conceived to be converged with respect to dome exit pressure drop calculation and deficiencies in steam flow obtained as function of this pressure drop had to be attributed to the flow algorithm. This will be discussed later.

The influence from initial store energy in the fuel and the long term steam flow on the transient is seen in figures 23 through 25. When the fuel gap conductance was decreased more energy was initially stored in the fuel. This energy was transferred to the primary coolant during the transient. Consequently a higher coolant average temperature (or pressurizer level) and pressure were attained when the gap conductance was reduced as is found in figures 23 and 24. This resulted also in a higher steam line pressure which is revealed by figure 25. It was realized that for the used values of gap conductance the lowest value (5.0 kW/m^2K) resulted in the best comparison with measurements.

During the later phase of the transient the steam flow had an easily perceived influence on the cooling of the reactor coolant system. This effect is clearly seen in figures 23 through 25 starting at about 100 s. The steam flow resulted in a similar calculated behaviour of the pressurizer level and primary and secondary pressures as corresponding measurements. It seems that a steam flow of 15 kg/s somewhat overpredicted the cooling whereas 10 kg/s resulted in a more adequate system response.

With the more dense nodalization of the steam generator downcomer the pressure distribution experienced a more smooth behaviour. The earlier found oscillation in the downcomer narrow range level when specified as function of a differential pressure, figures 11 and 12, was not found with the new nodalization, figure 26. This figure shows the result for just one simulation. However, the other simulations revealed the same behaviour free from oscillations. Thus a careful nodalization of the downcomer upper part was essential for proper pressure response when the liquid level decreased.

The suggested change in the moderator temperature reactivity coefficient did not result in any noticeable improvement of the core power when the core coolant temperature was increased, figure 27. If compared to the basecase result, figure 19, the new calculation resulted in an even more pronounced power decrease before reactor trip. The reason seemed to be that in the new case the coolant temperature experienced a higher increase than in the basecase. Although the reactivity coefficient had been changed the amount of change was obviously not enough to also compensate for the higher coolant temperature. Similar behaviour was also obtained for the other simulations.

Finally an investigation was made of the importance of including pressure compensation to the steam flow when calculated as function of dome outlet pressure drop. In the basecase no such compensation was made and a deficiency was obtained when the flow decreased simultaneously with a pressure increase, figure 9. Two compensations were introduced. First a compensation for the elevation head was made and second the compensation also included the absolute pressure influence through the density. The result is shown in figure 28 revealing the importance of pressure compensation and at low flow rates also the compensation for elevation head.

5.3 Code performance

In a first attempt the 310 s basecase transient was executed with no limitation by input of the timestep. Thus TRAC was allowed to use as big a timestep as the solution method permitted. In that calculation the execution was terminated after about 160 s transient time because of converging problems in the steam generator downcomer component. The timestep size at this instance was about 1.32 s. The very same case was subsequently rerun but now with a maximum allowable timestep size of 0.5 s. The execution was now successfully completed. Thus it seems that the timestep size algorithm is not efficient enough to control the numerical solution to a convergent state under all conceivable circumstances.

The 310 s transient was executed without any restarts. These 310 s required 1 068 timesteps and needed 4 784 CPU-s on the CDC Cyber 170-835

6 Conclusions

An assessment of TRAC-PF1/MOD1 version 14.0 against an inadvertent feedwater line isolation in the Ringhals 4 PWR power plant was conducted. Extensive use of results from Ringhals 4 data aquisition system was made to derive the initial conditions and also to specify the necessary boundary conditions.

The results from the TRAC simulation were compared to measured data. From this comparison it was clear that the used TRAC-version was capable of performing a satisfactory simulation.

However, the results also indicated some areas of model improvements which were investigated in later calculations. The steam flow taken as proportional to the square root of a pressure drop revealed for the basecase a discrepancy when compared to measurement. It was found by a nodalization analysis that a change to a more dense nodalization of the upstream part of the steam line had only a minor influence on the pressure drop. The basic reason for the discrepancy was found to be the omission of pressure compensation in the flow algorithm. When this compensation was introduced a favorable comparison with measured steam flow was obtained.

During the course of steam generator level decrease an oscillation was initiated in the narrow range level signal of the model. The level signal was expressed as a differential pressure between specified taps in the downcomer. The oscillation had no correspondence in the measured signal nor in the collapsed level calculation of the model. It seemed that this behavior was caused by the vapor flow into the downcomer cells in combination with the condensation of the vapor in the cells as long as subcooled conditions prevailed. A denser nodalization especially of the downcomer upper part helped to alleviate the problem.

It was also found from the early core power response of the model that the specified moderator temperature coefficient was somewhat too high. Despite the too low calculated core coolant temperature increase the core power decrease was excessively predicted. A lower (less negative) reactivity coefficient would have resulted in a higher core power that in turn would have raised the primary temperature level during this part of the transient. It was found in later calculations that the suggested change in reactivity coefficient was not enough to result in any noticeable improvement in the core power response.

The primary temperature in the basecase model was too low compared to measurements. An increase of the initial stored energy of the fuel would have raised the coolant temperature. An increase of the stored energy was obtained by decreasing the gap conductance of the fuel. In the basecase a value of 10.0 kW/m^2K was used for the gap conductance. A sensitivity analysis was carried out with successively lower values. A value of 5.0 kW/m^2K was resulting in a reasonable response of the reactor system when compared to measurement.

The long term development of the primary temperature revealed in the basecase a less efficient cooling of the primary side in the TRAC-model than in the plant. A small steam flow of about 10-15 kg/s was estimated to provide this additional cooling. From the measurements there was some supportive indications that a steam flow actually was prevailing during major parts of the transient. Clearly the turbine driven auxiliary feedwater pump was operating during this part of the transient; however, the steam flow through this device was not known. Sensitivity analysis was performed to establish the influence of the long term flow. It was found that a flow rate of 10 kg/s was needed to adequately predict the long term cooling.

External restriction on the maximum allowable timestep size had to be imposed for convergence of the solution procedure. It was found that 0.5 s was adequate for the simulation to proceed throughout the transient. For the 310 s transient under this restriction 4 748 CPU-s was needed on a CDC Cyber 170-835 computer.

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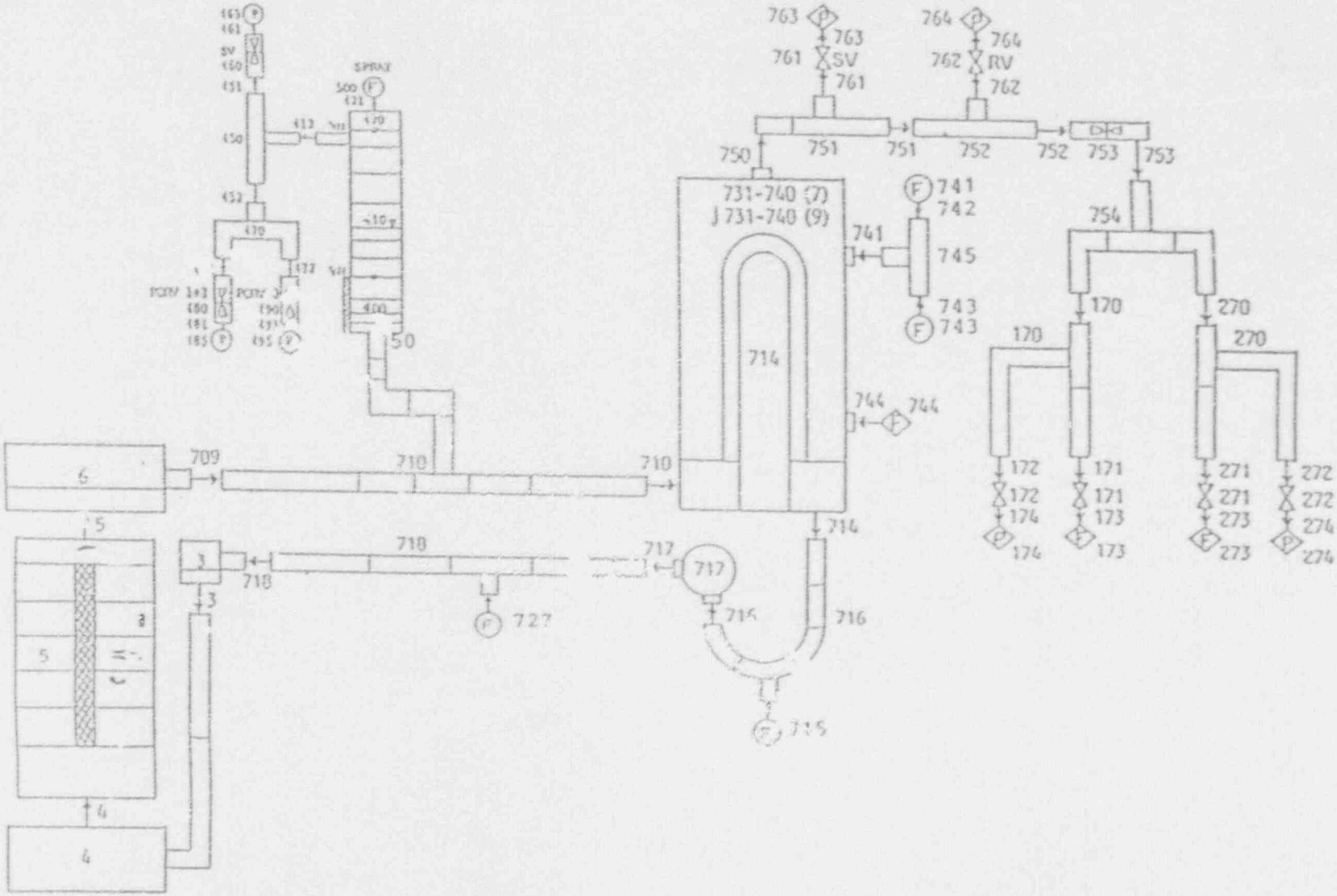


Figure 1

TRAC-PF1/MOD1 model of Ringhals 4.

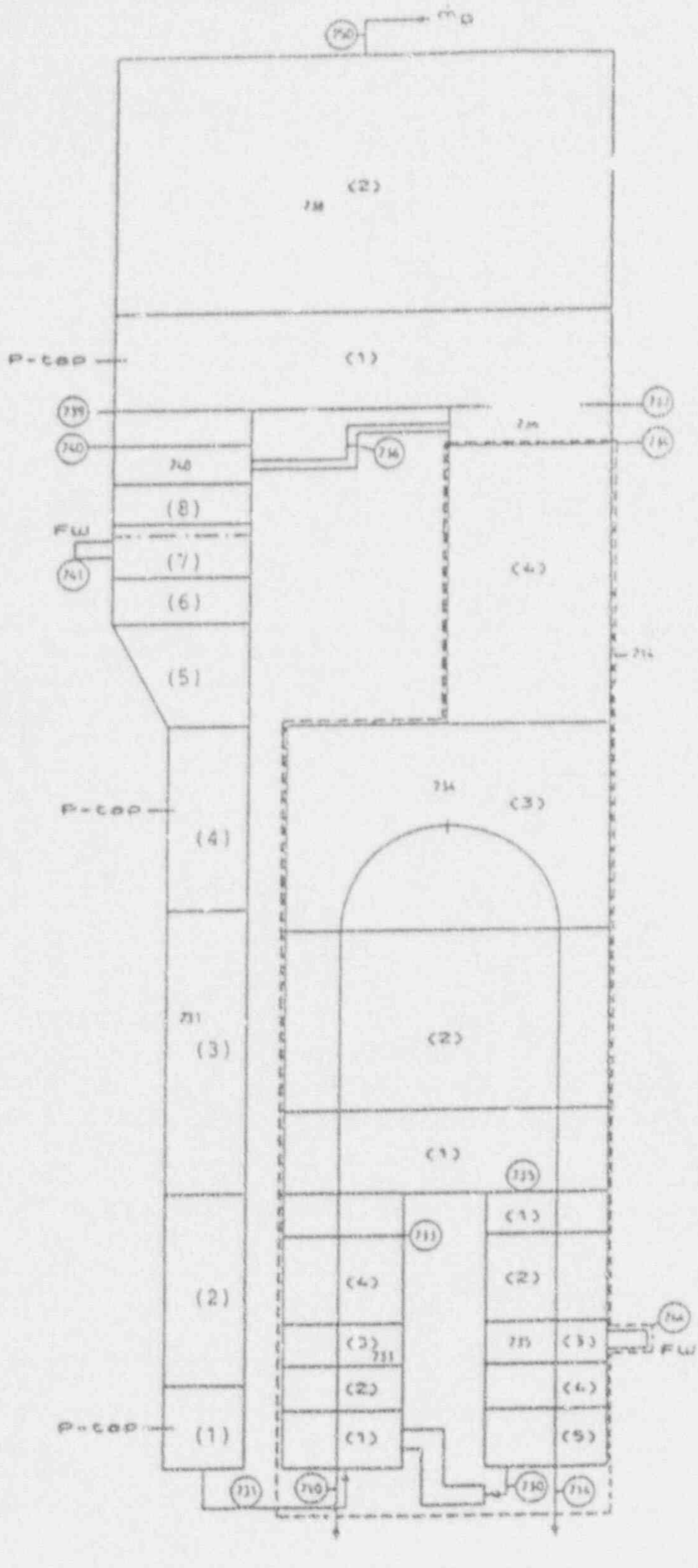


Figure 2

Steam generator nodalization.

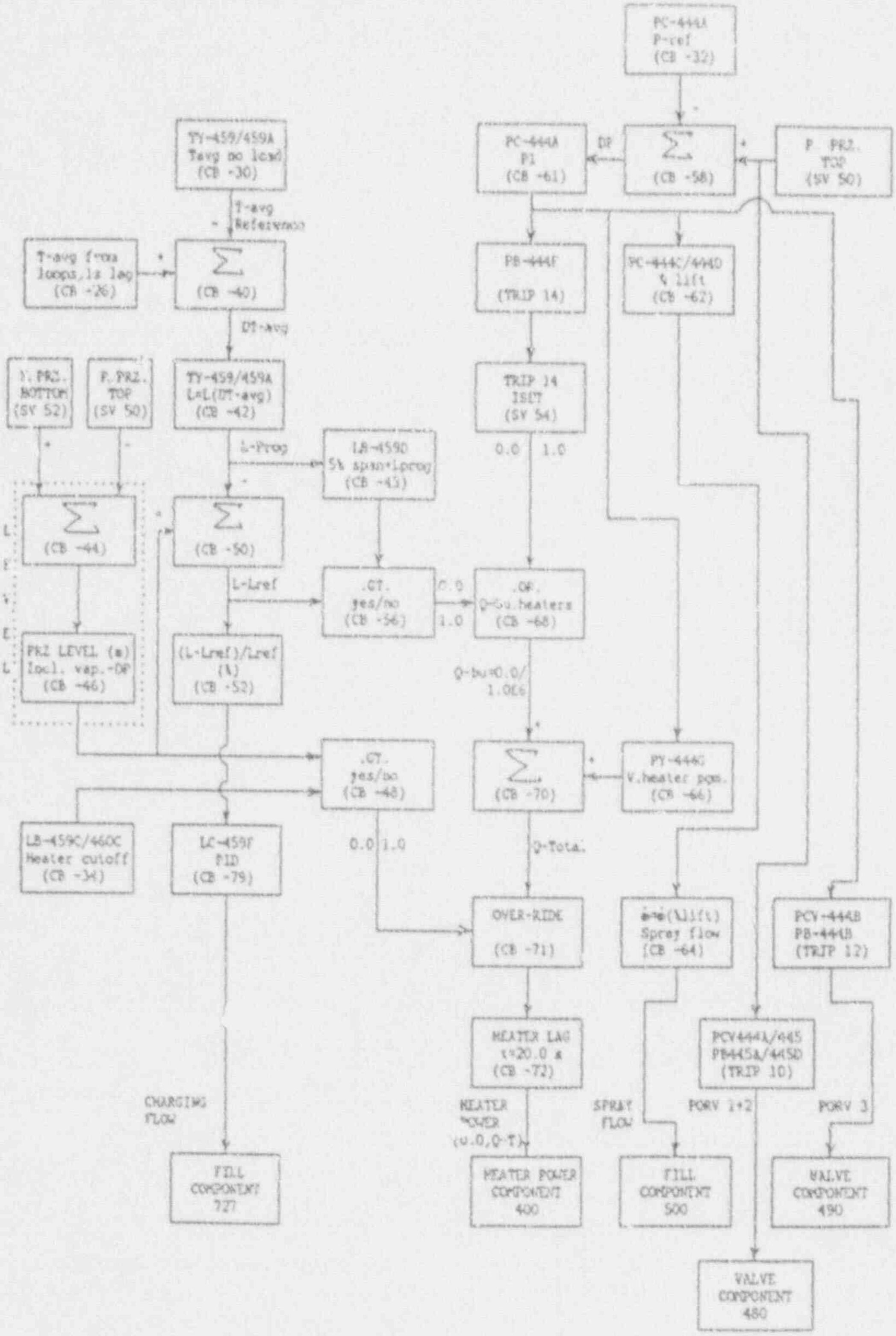


Figure 3

Pressurizer pressure and level control logic.

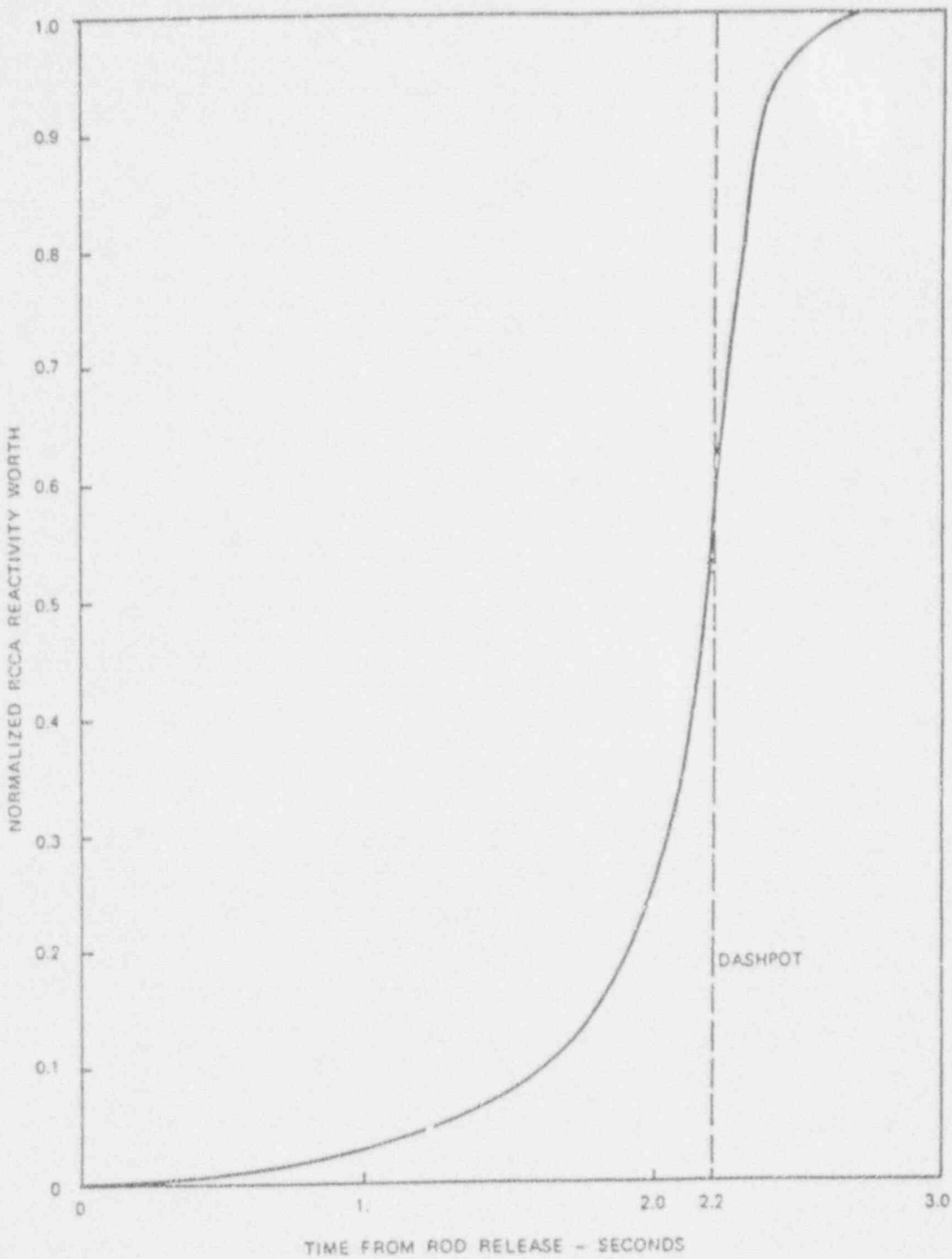


Figure 4

Control rod reactivity insertion curve.

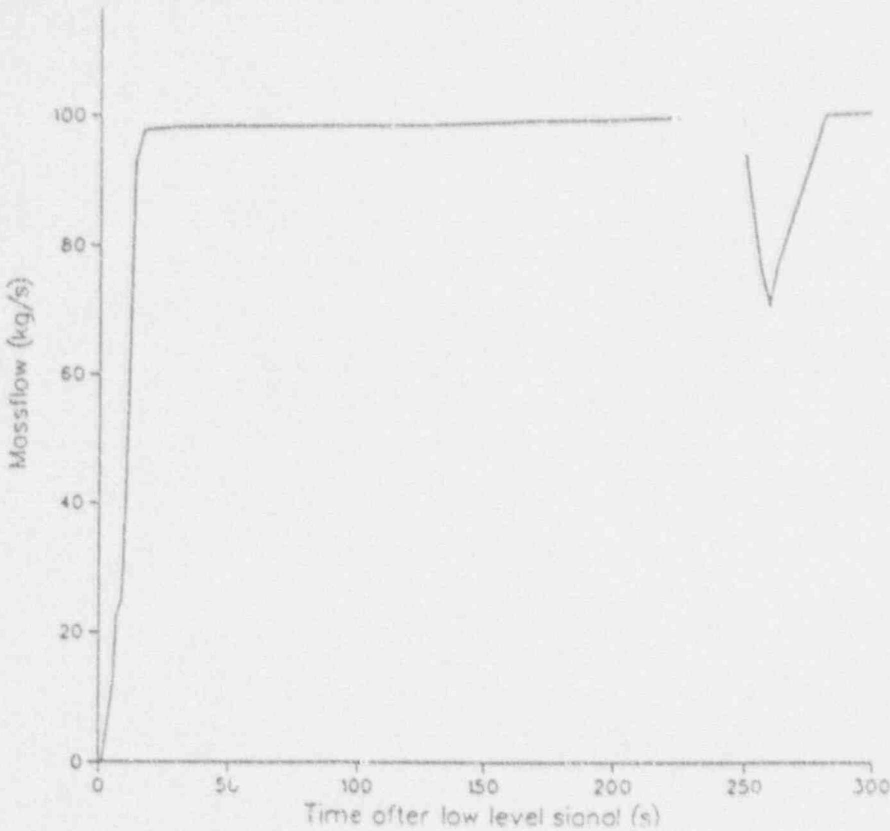
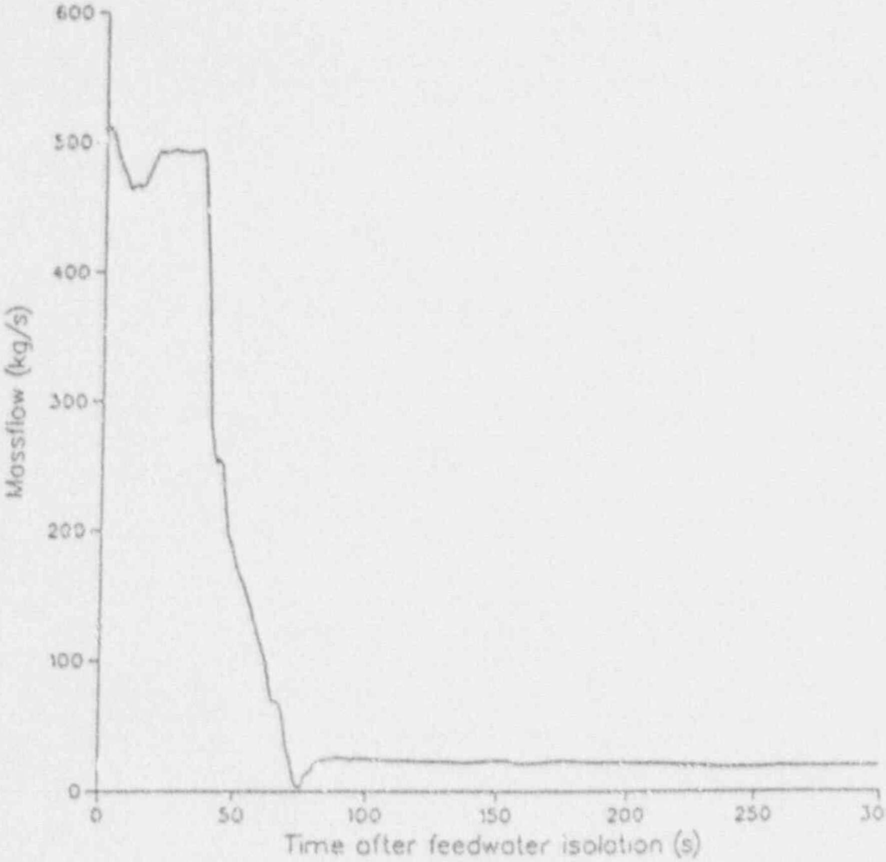


Figure 5

Auxiliary feedwater flow vs time.



<u>Figure 6</u>

Measured steamflow.

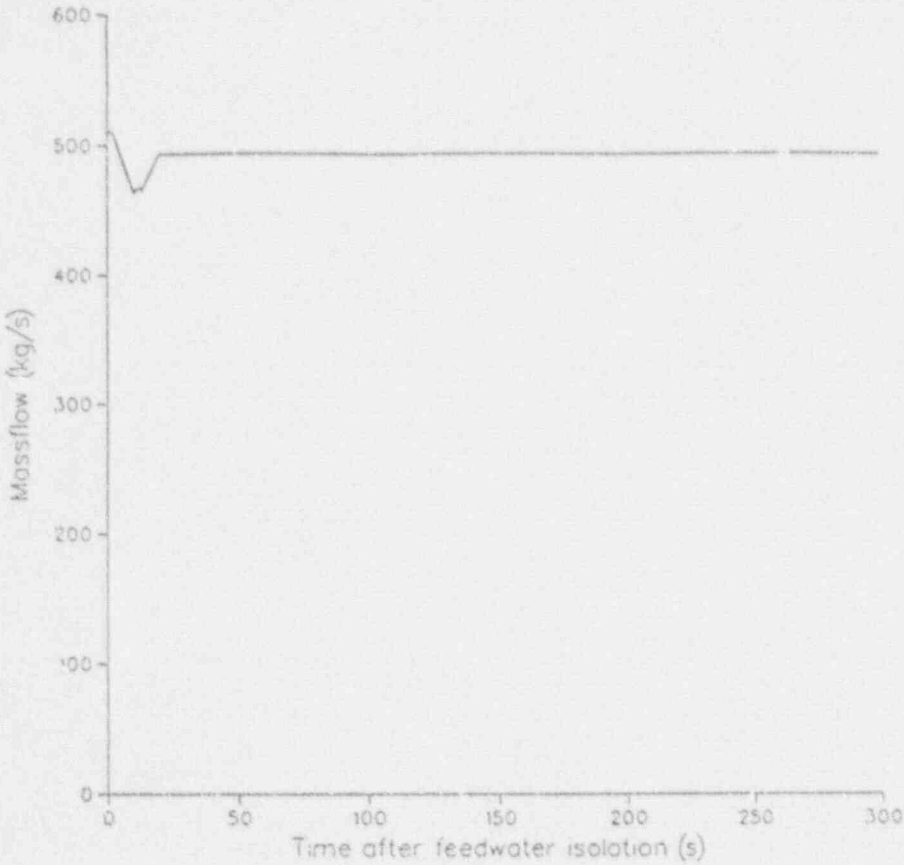
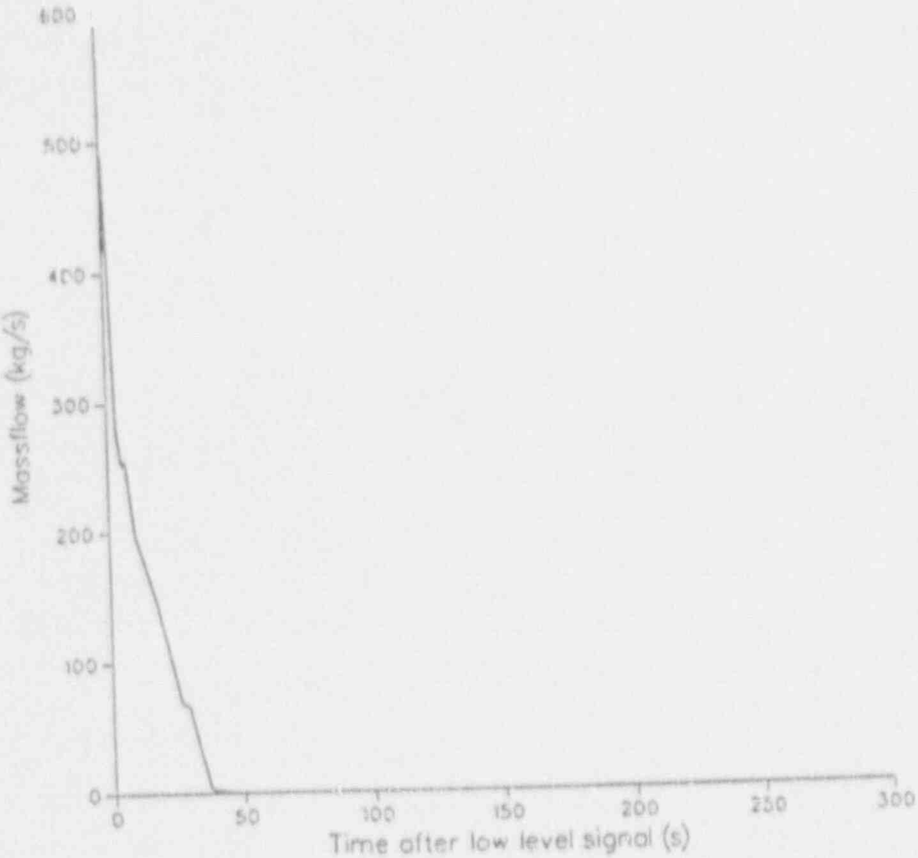


Figure 7

Steamflow prior to low level signal.



Figure

Steamflow after low level signal.

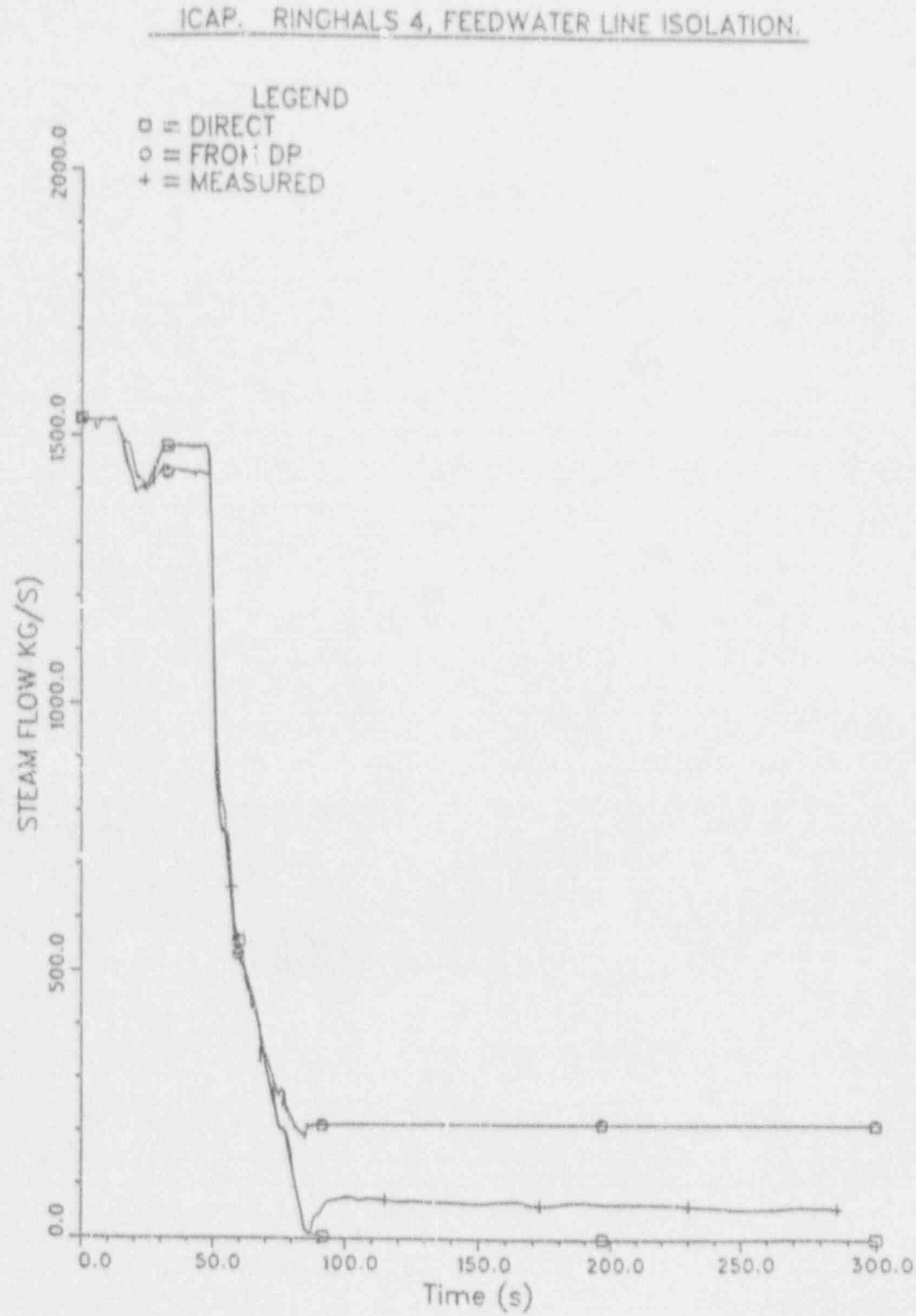


Figure 9

Steamflow at steam generator outlet nozzle.

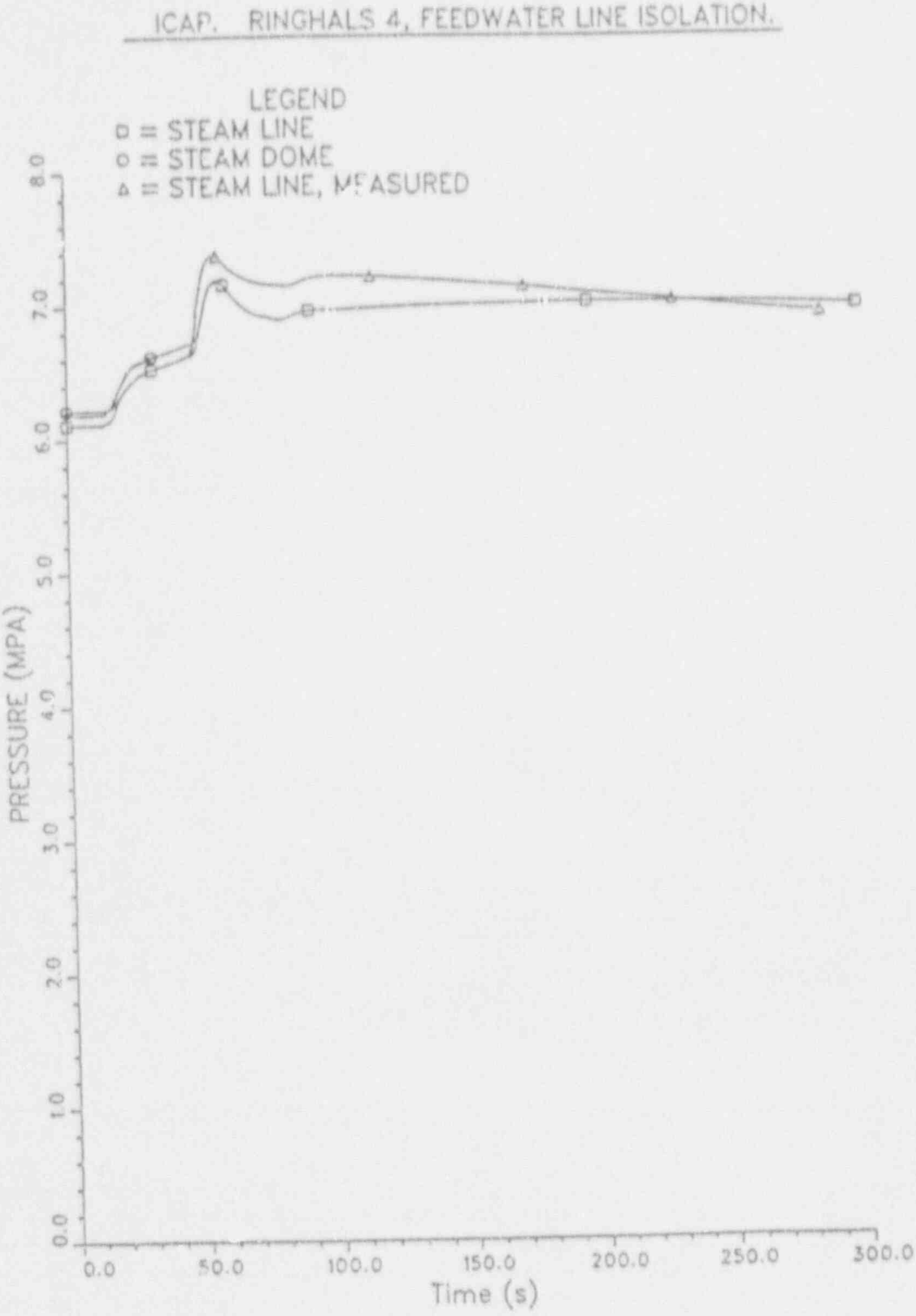


Figure 10

Secondary side pressure.

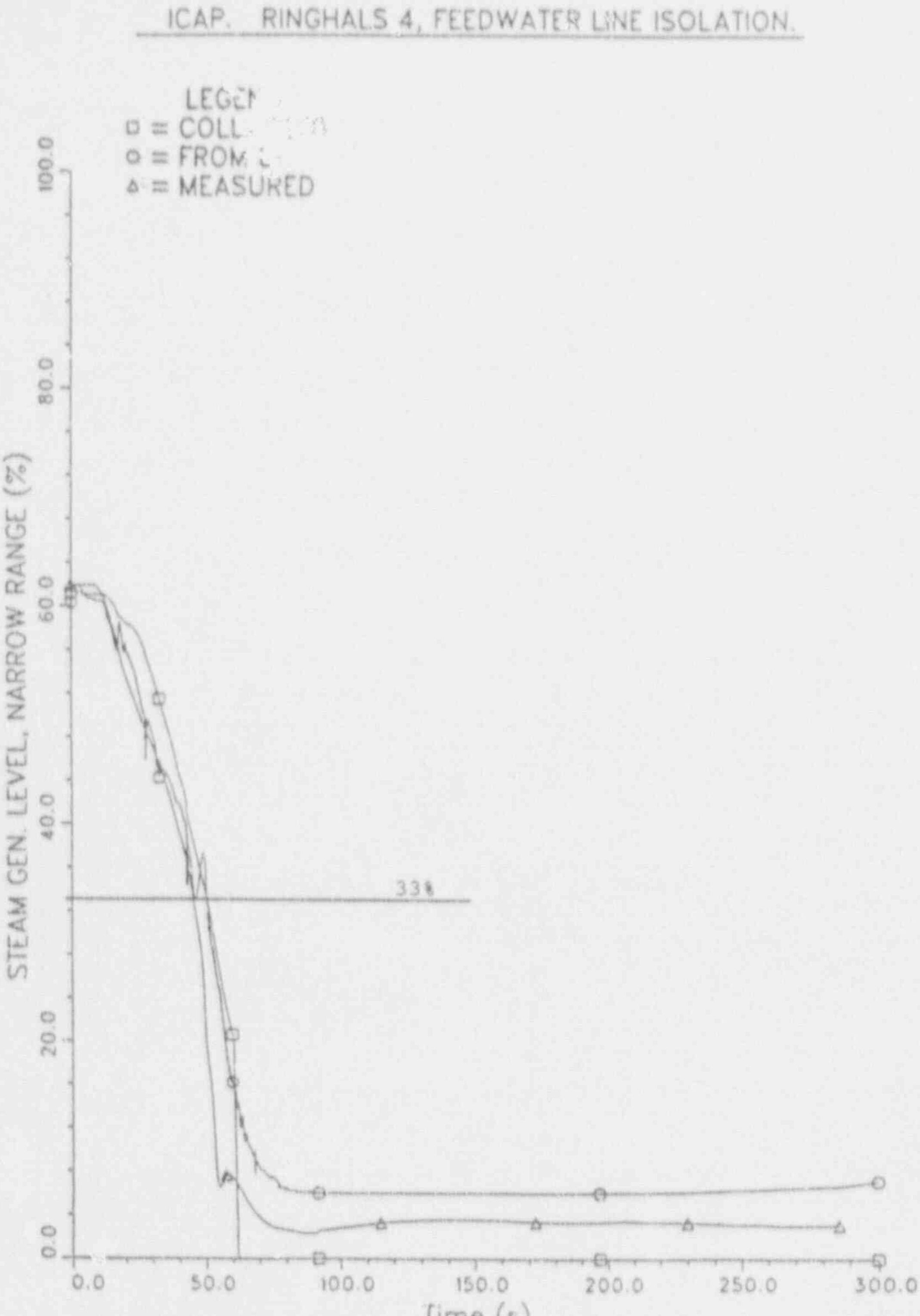


Figure 11

Steam generator narrow range level.

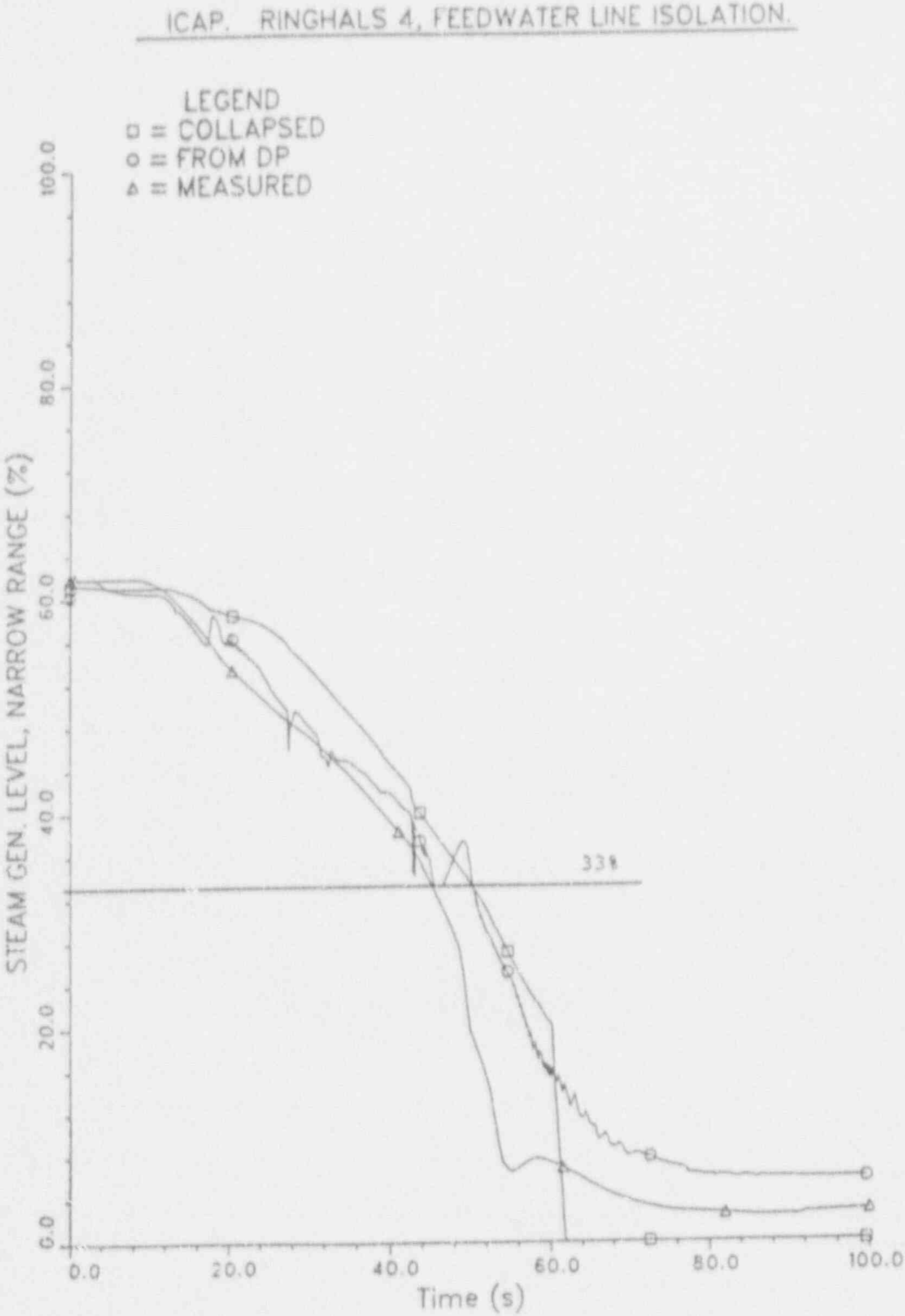


Figure 12

Steam generator narrow range level, expanded time scale.

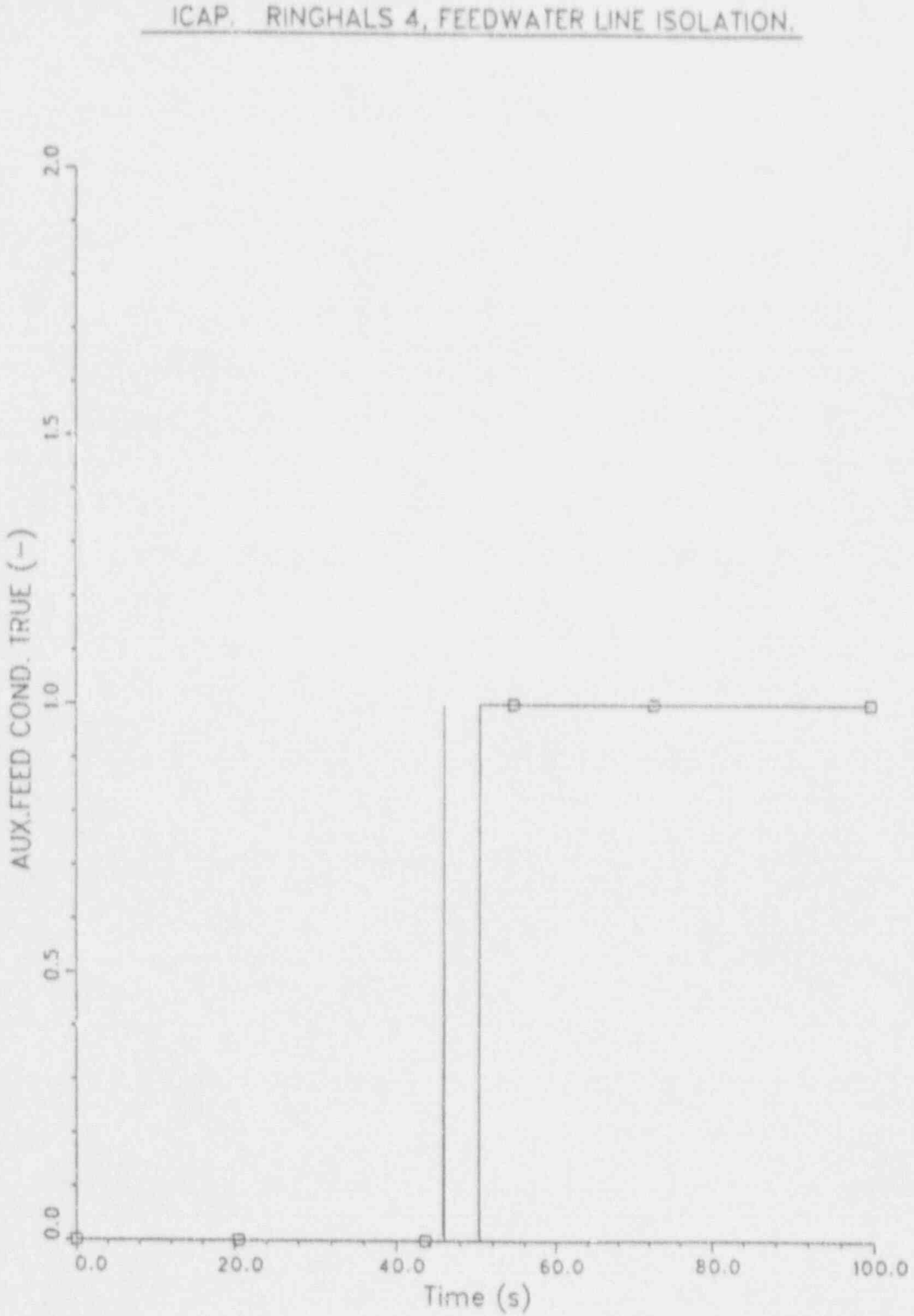


Figure 13

Auxiliary feedwater flow control trip signal.

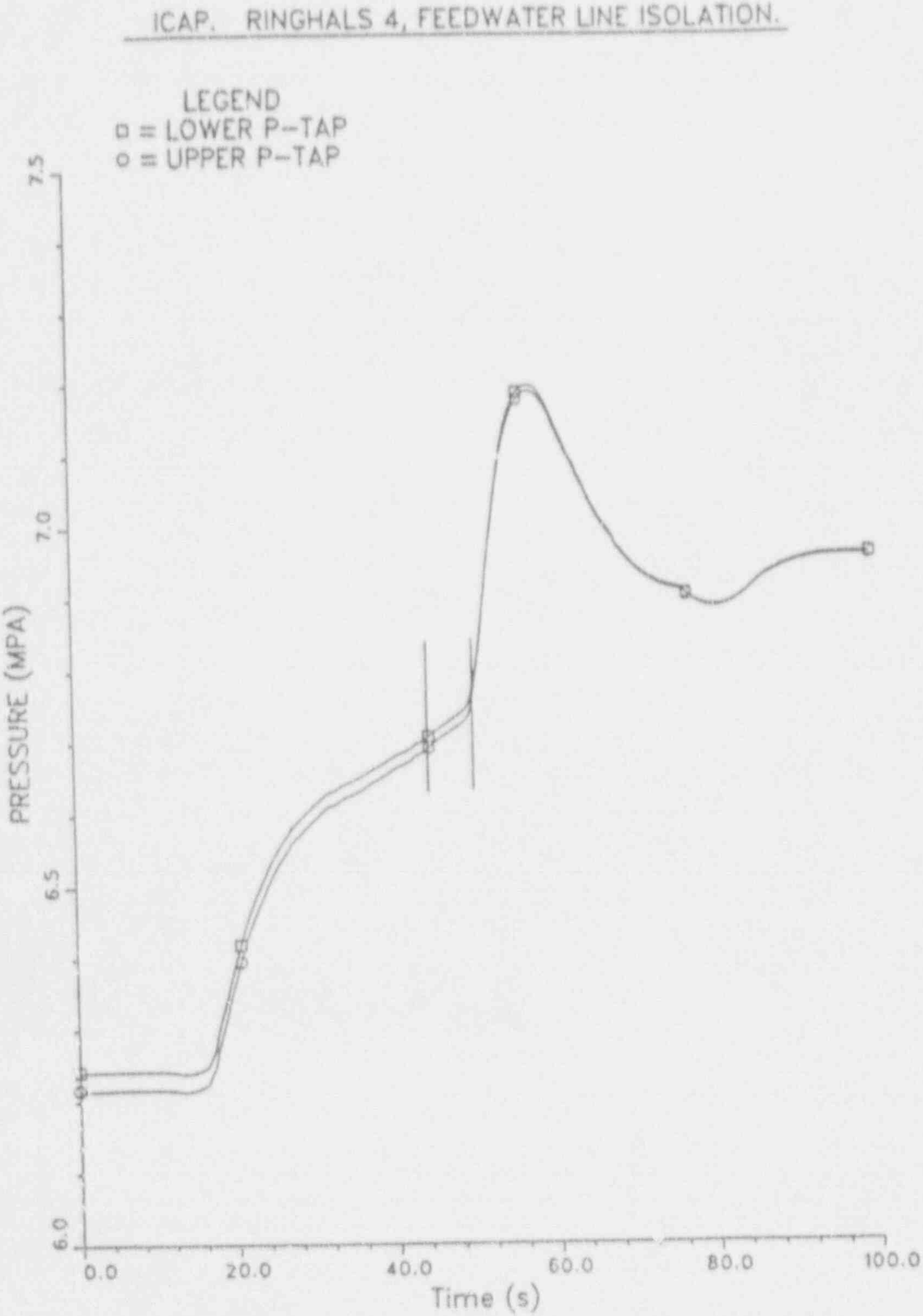


Figure 14

Steam generator downcomer pressures.

STURAPP NPS/AH

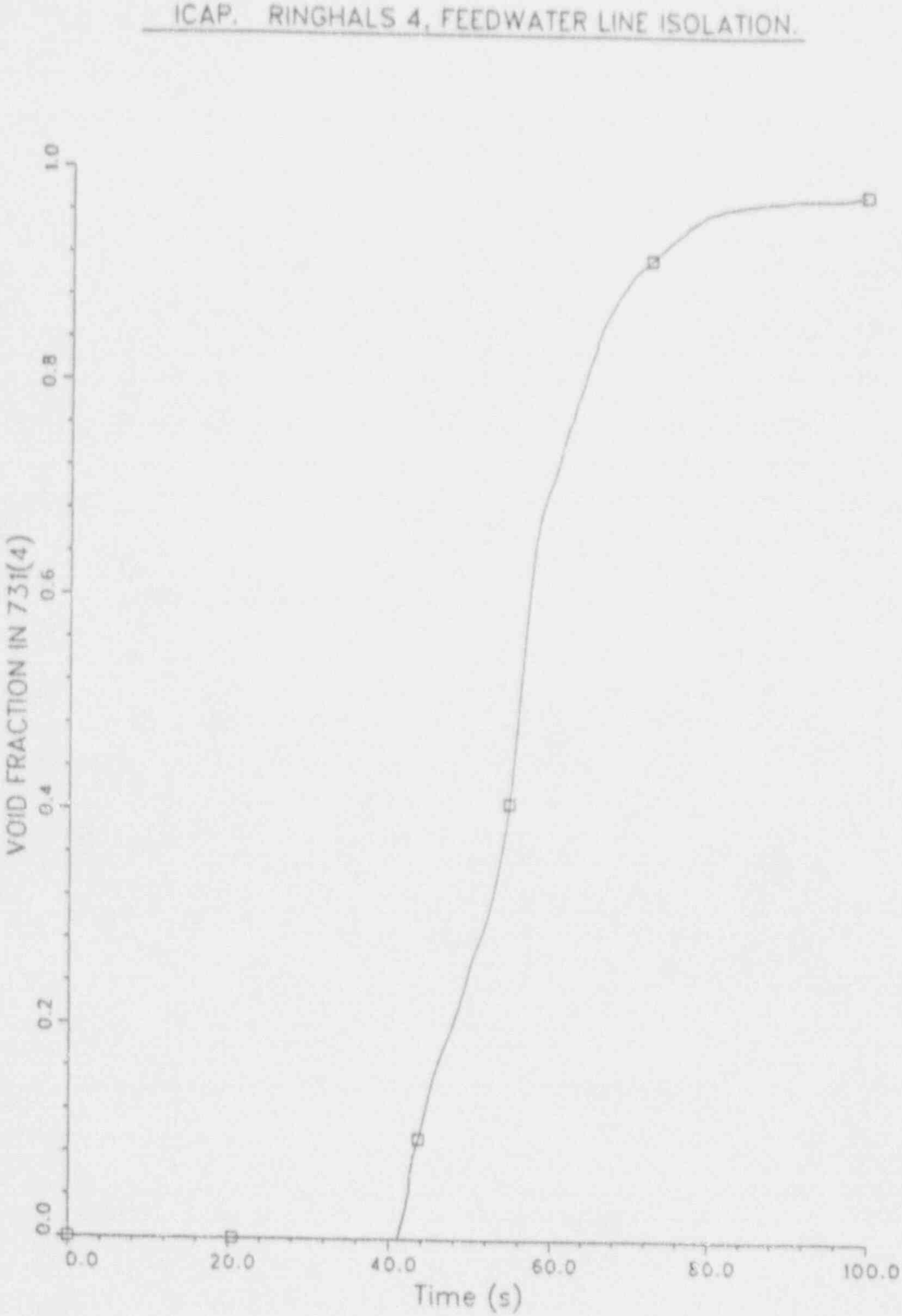


Figure 15

Steam generator downcomer cell void fraction.

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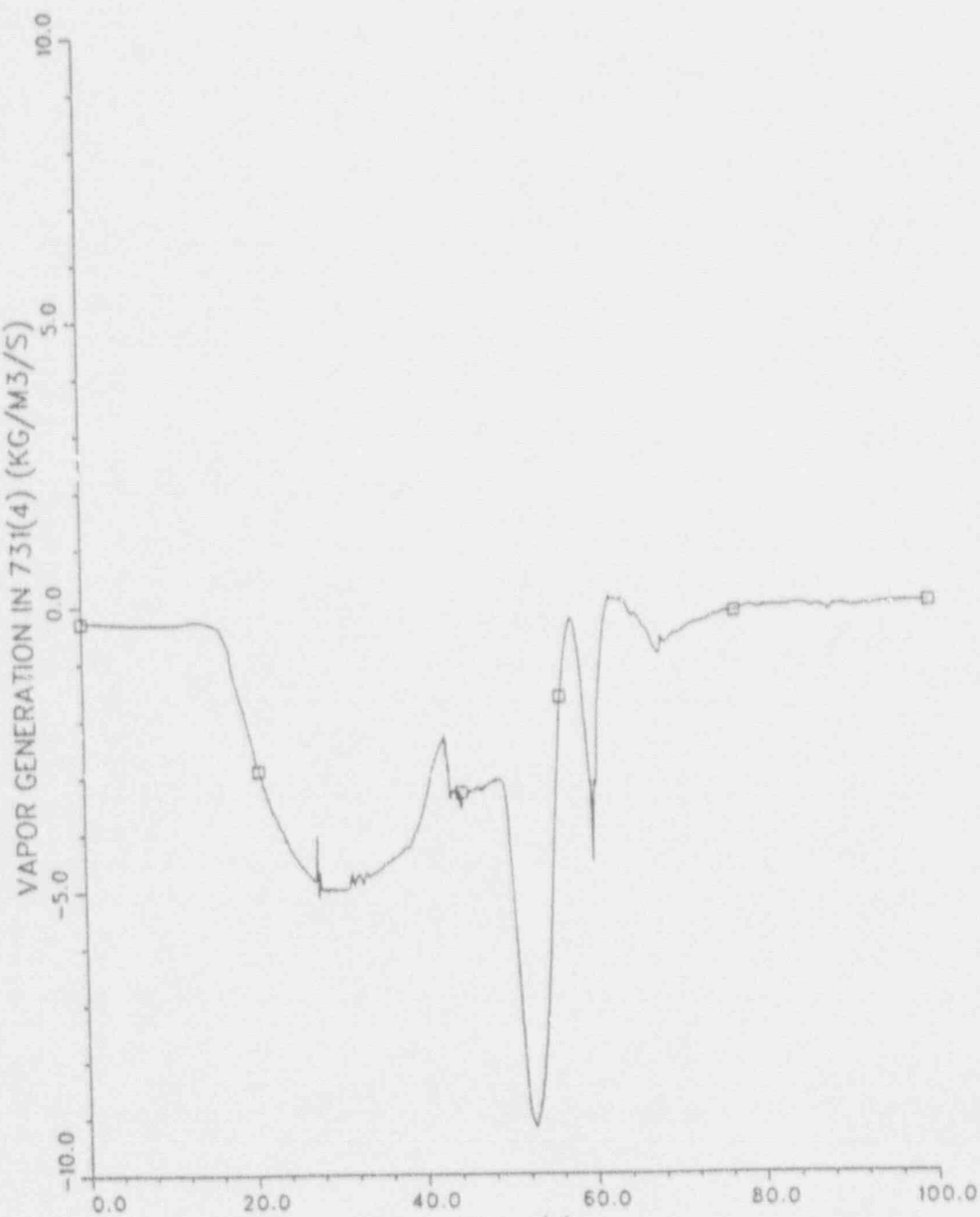

Figure 16

Steam generator downcomer cell vapor generation term.

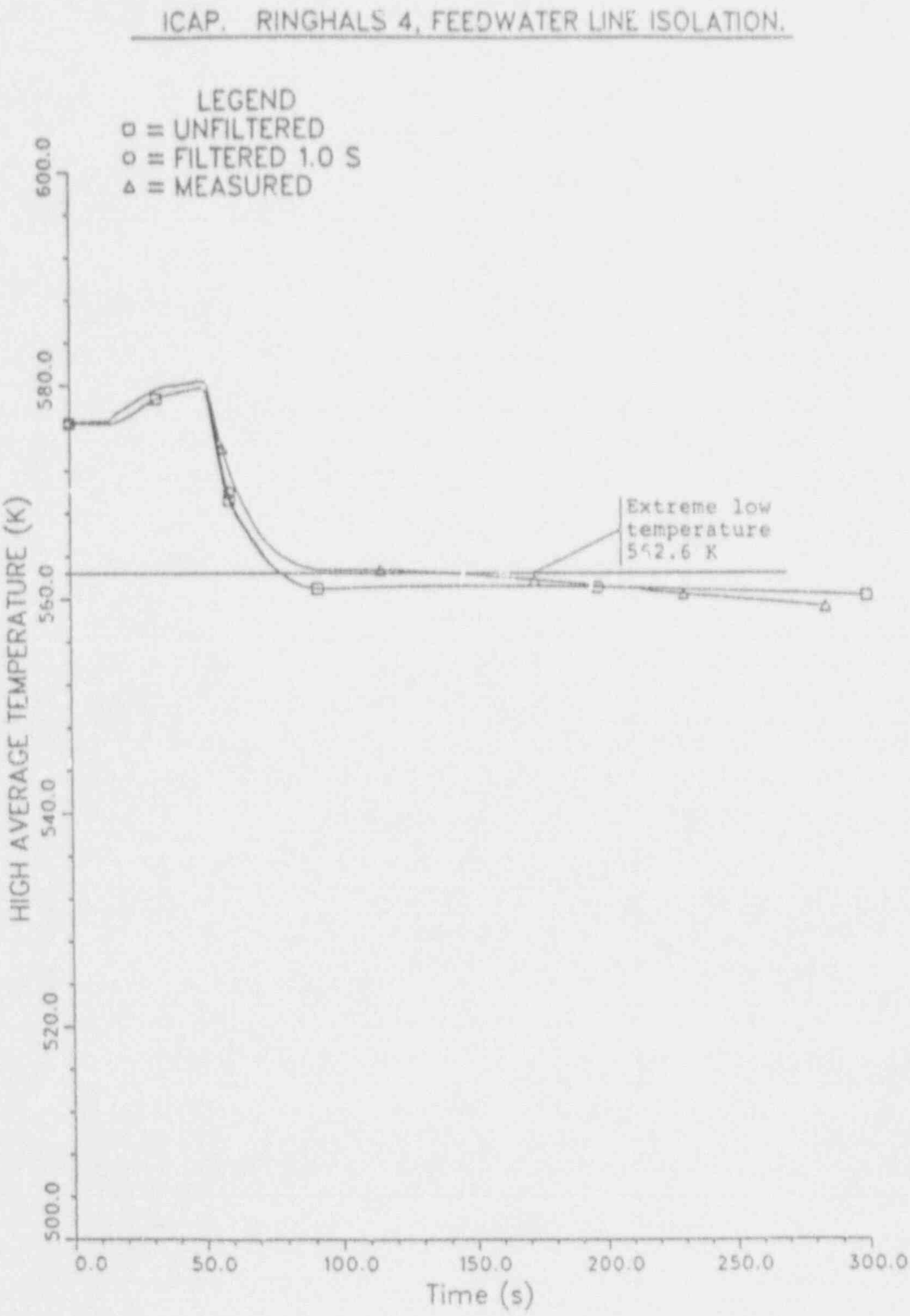

Figure 17

Primary side average temperature.

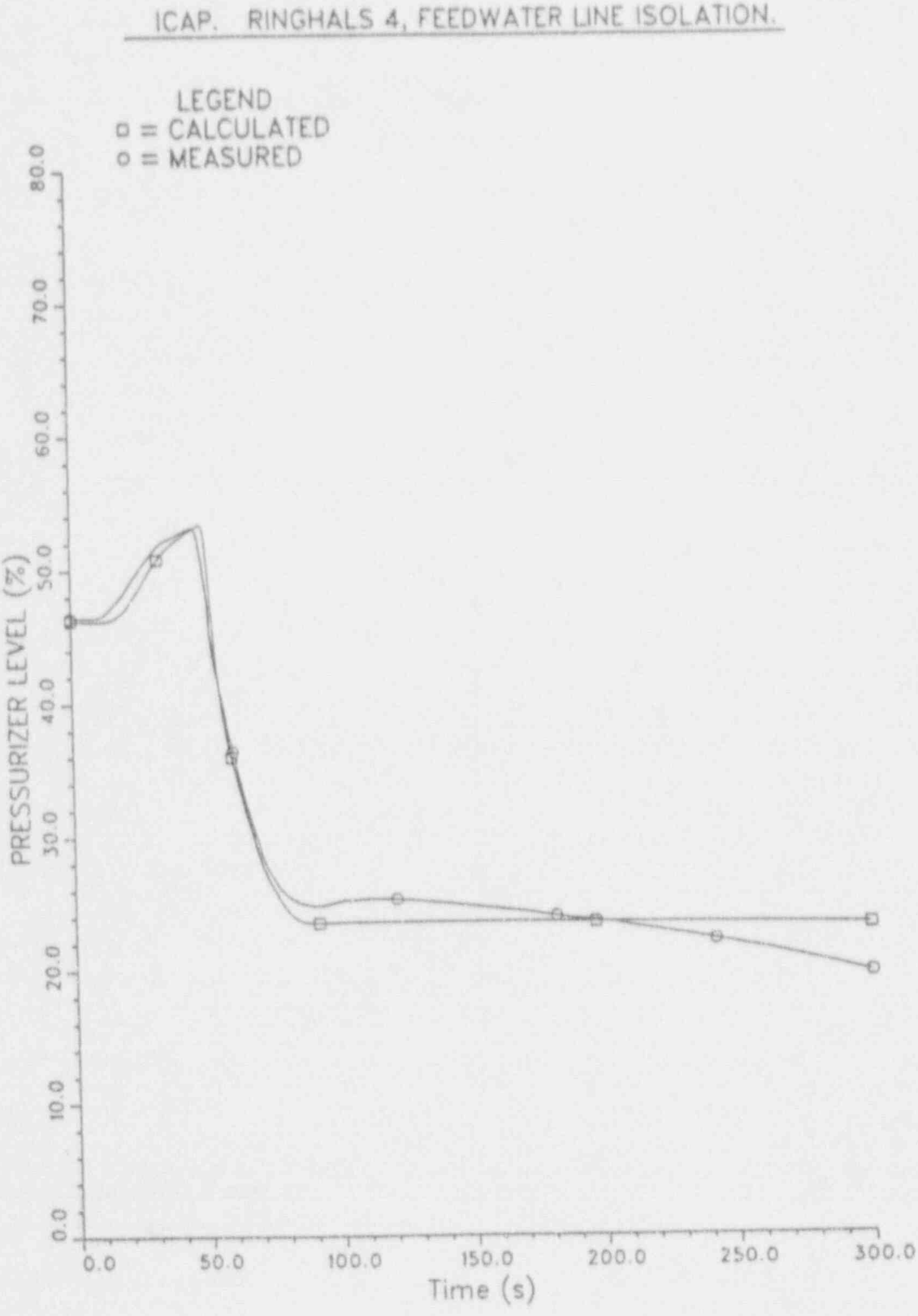

Figure 18

Pressurizer level signal.

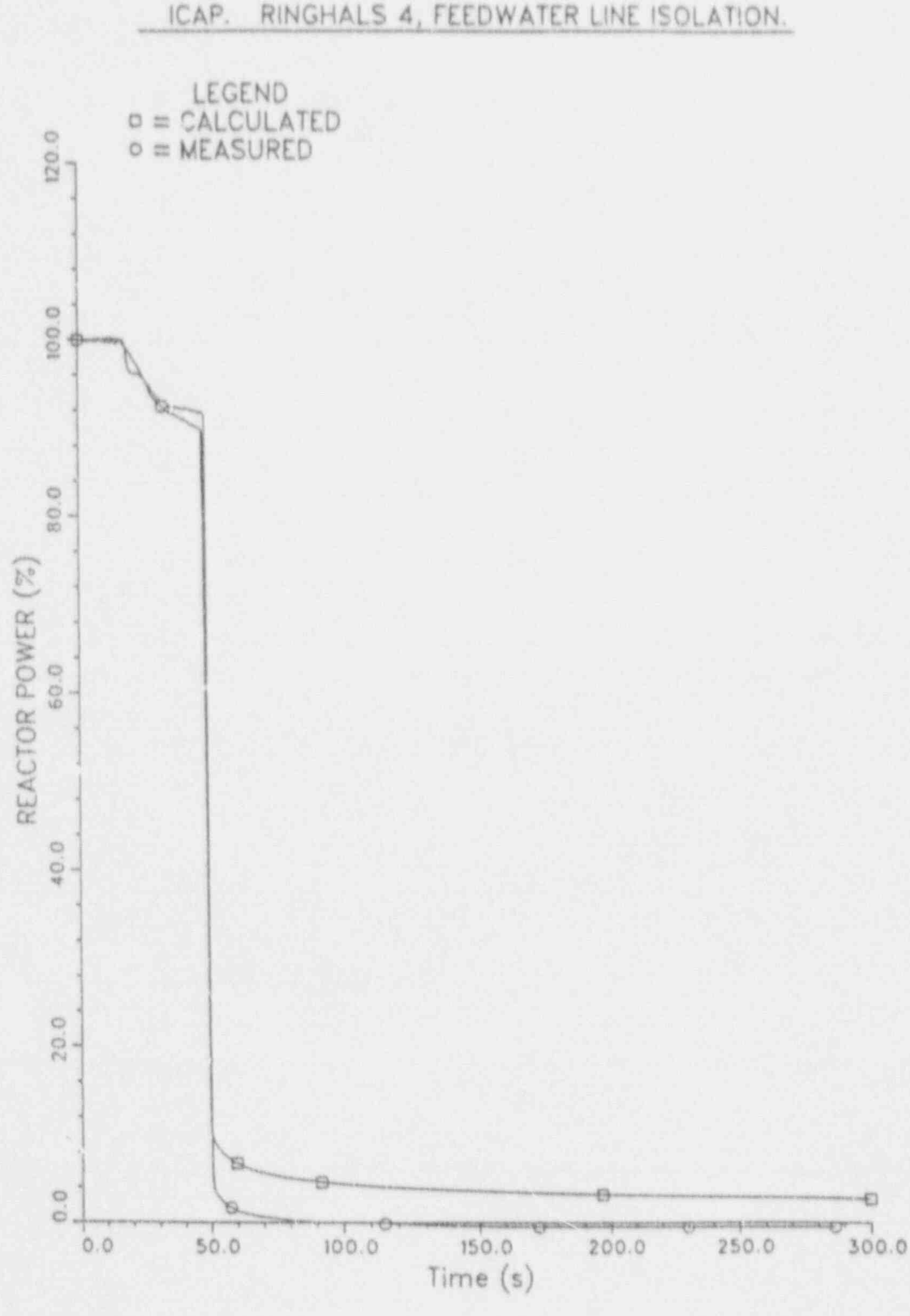

Figure 19

Reactor core power.

STURAPP NPS/AH

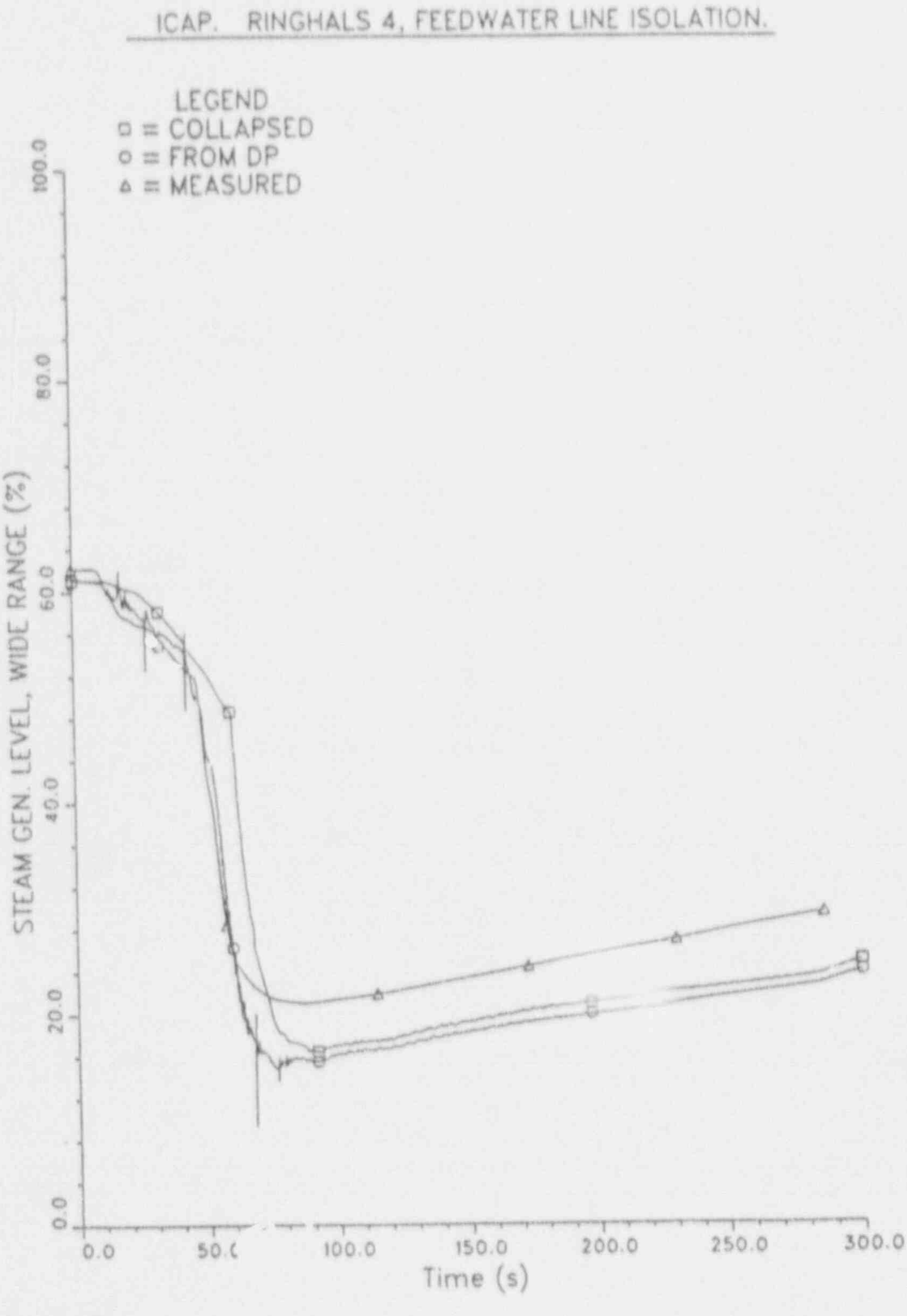

Figure 20

Steam generator wide range level.

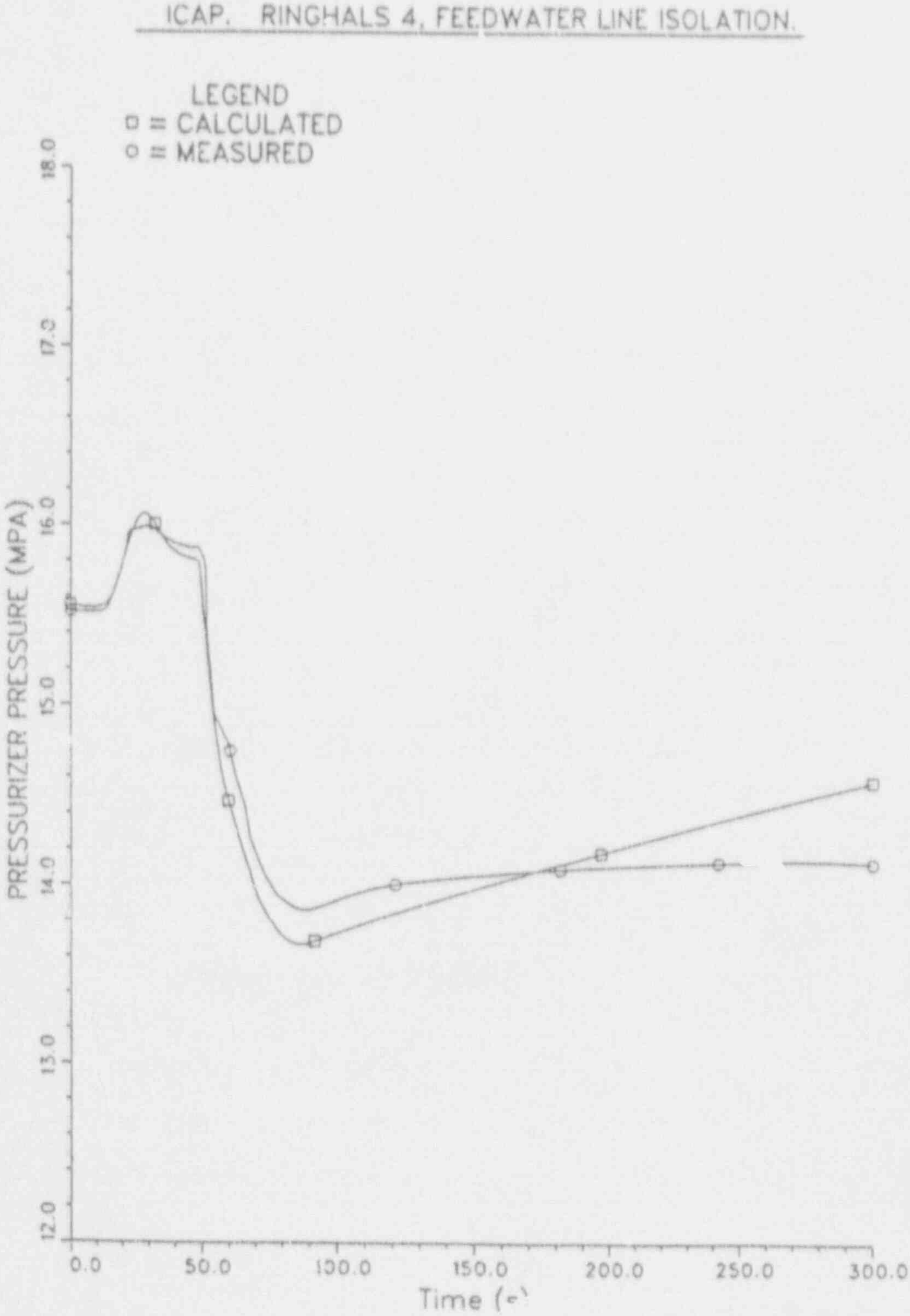

Figure 21

Pressurizer pressure.

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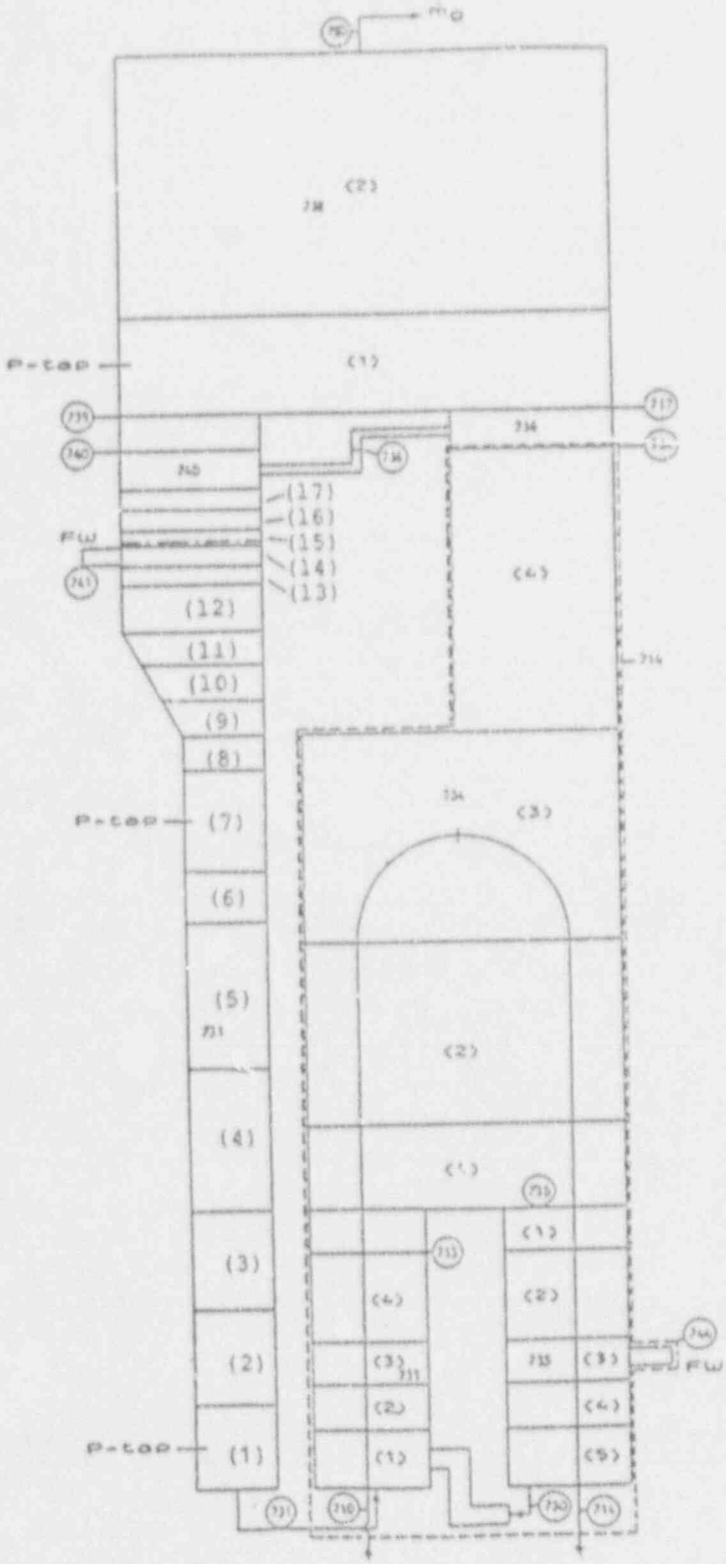

Figure 22

Modified steam generator nodalization.

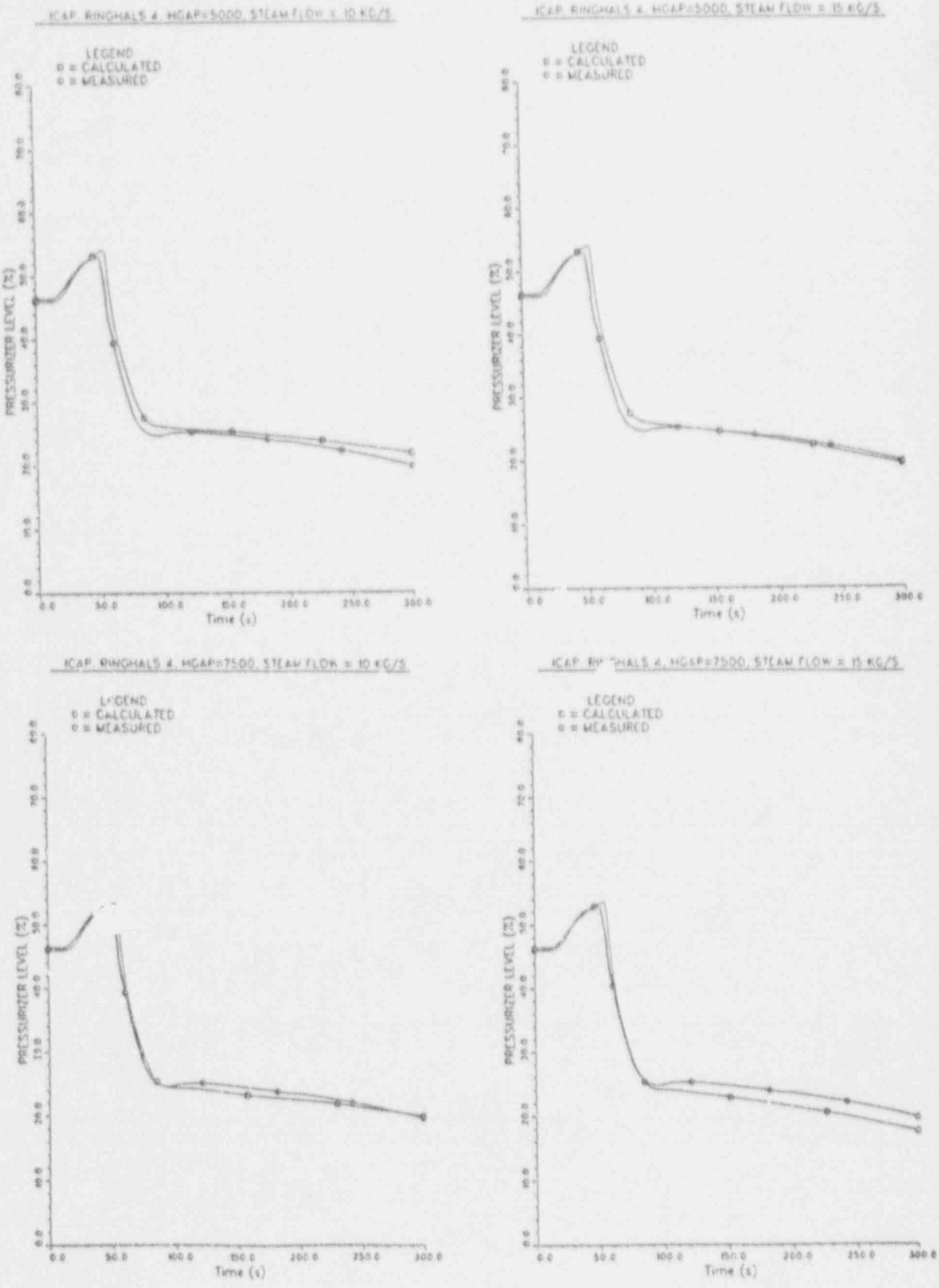

Figure 23

Pressurizer level signal.

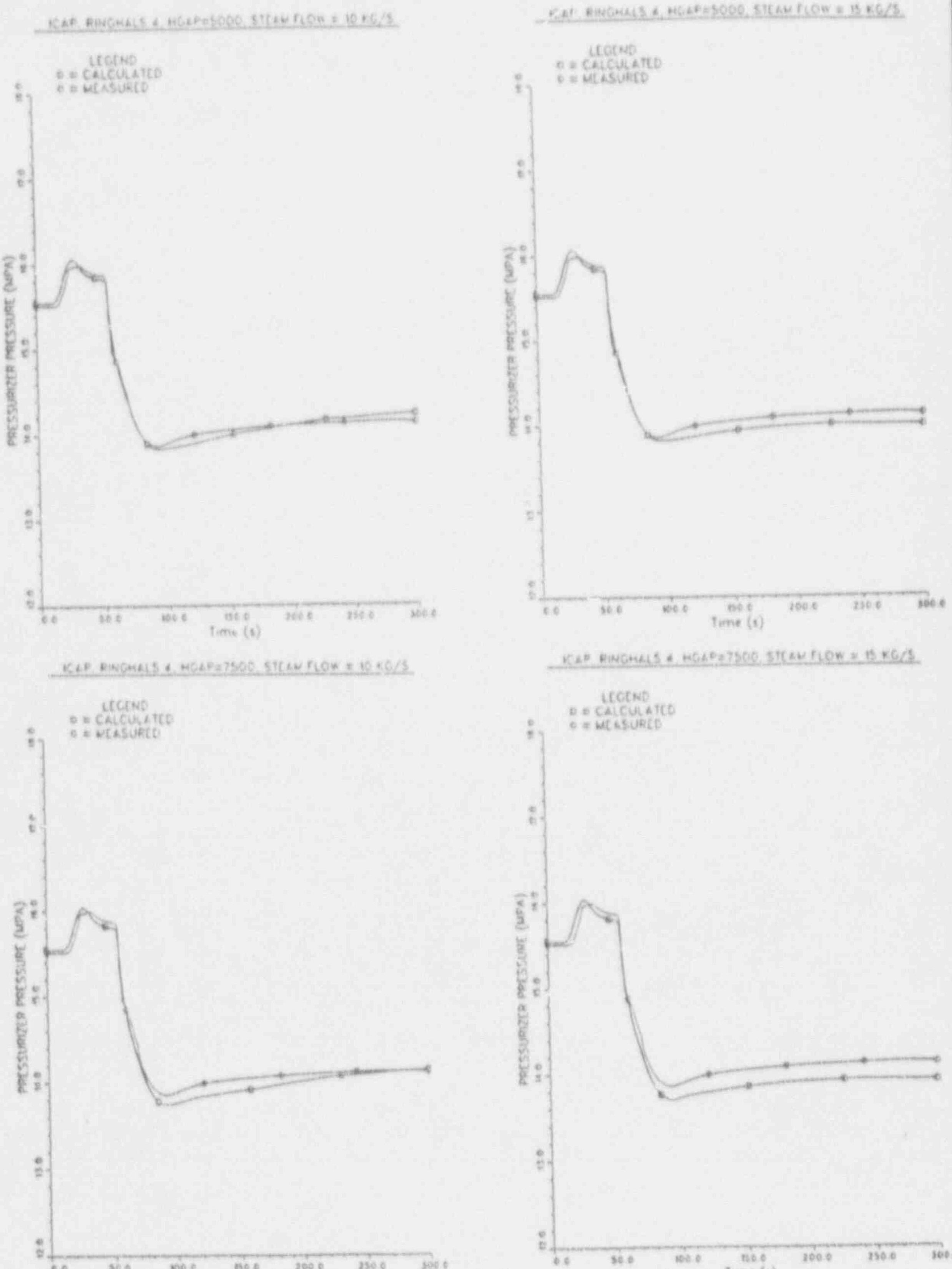

Figure 24

Pressurizer pressure.

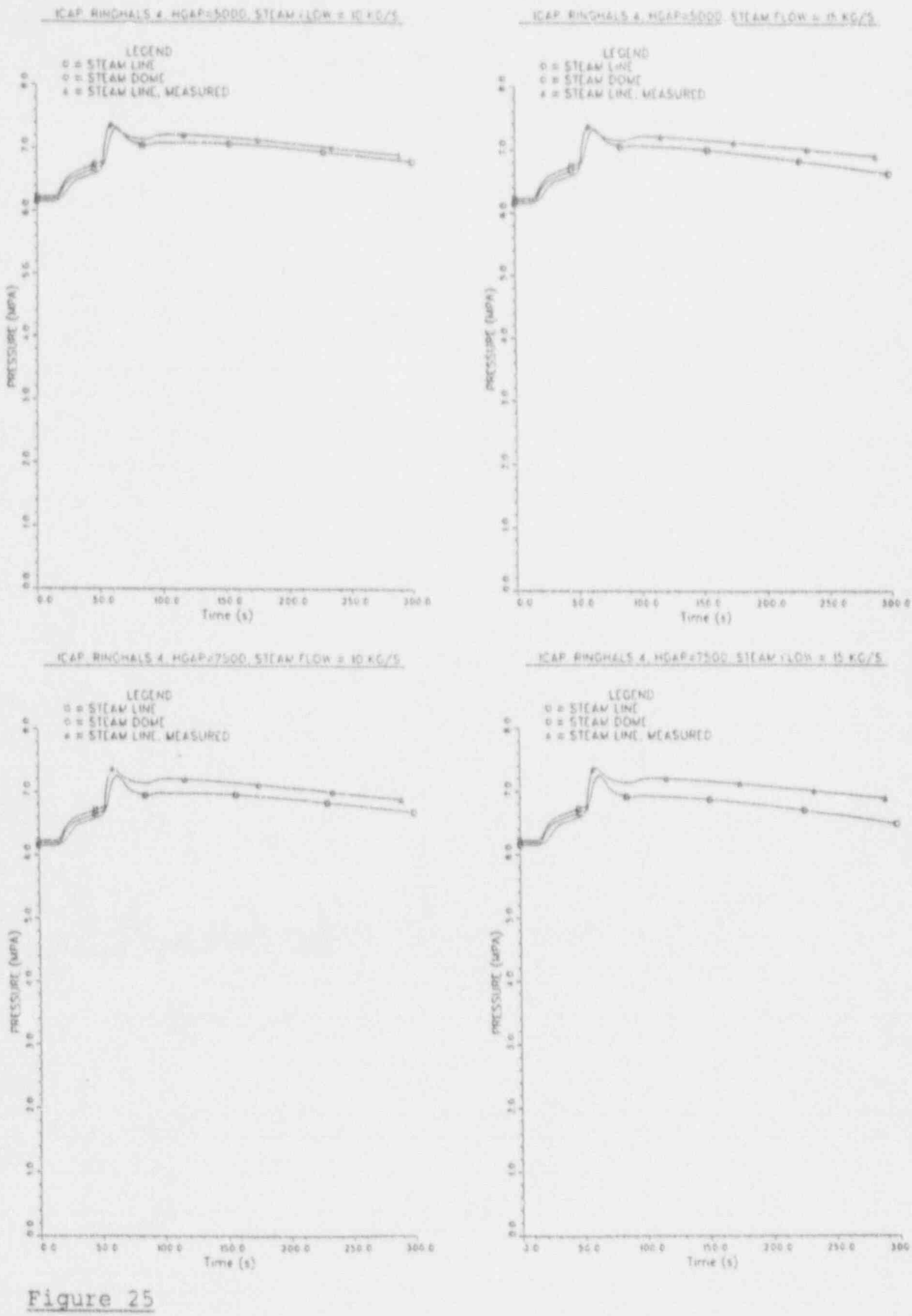

Figure 25

Secondary side pressure.

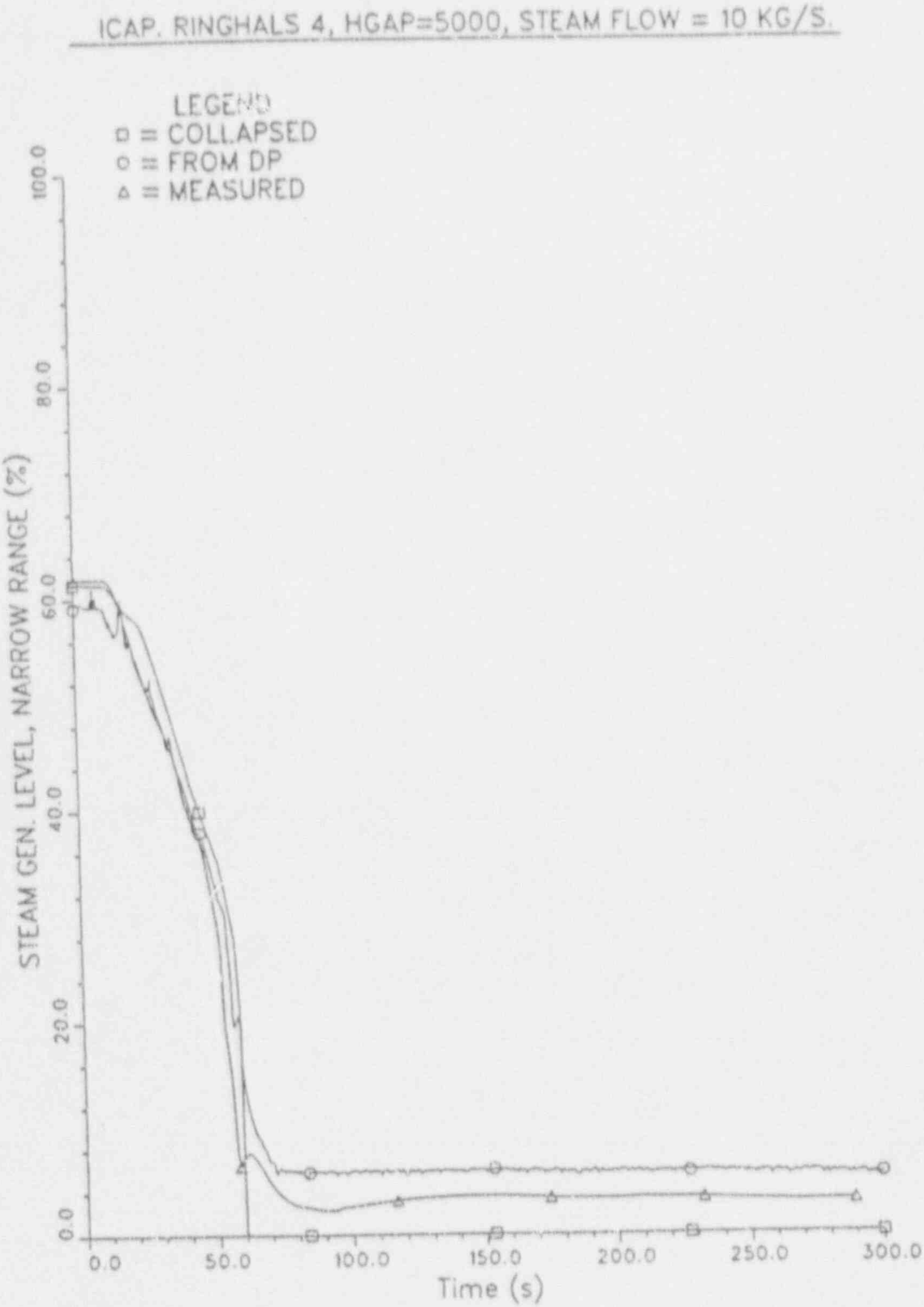

Figure 26

Steam generator narrow range level.

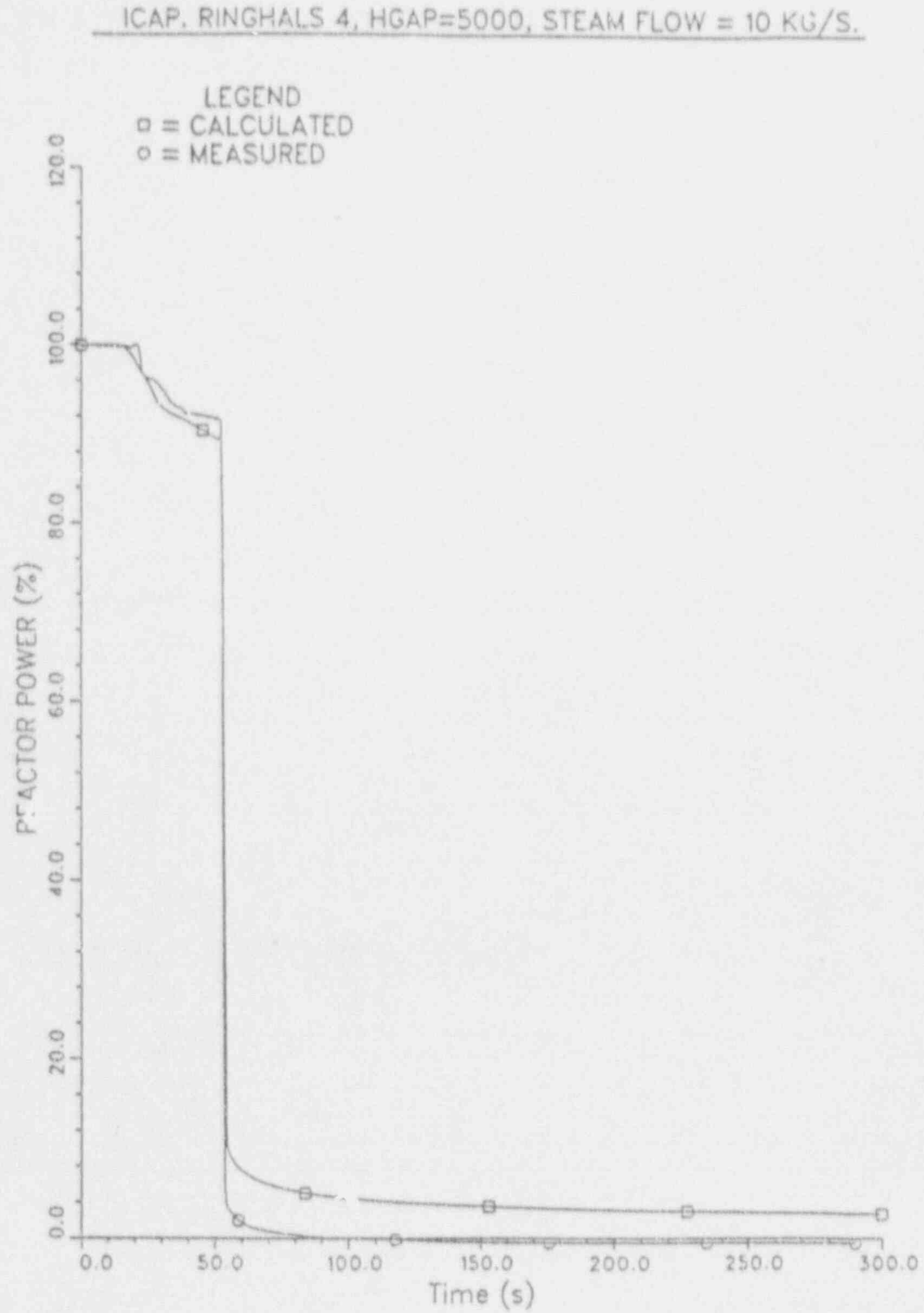

Figure 27

Reactor core power.

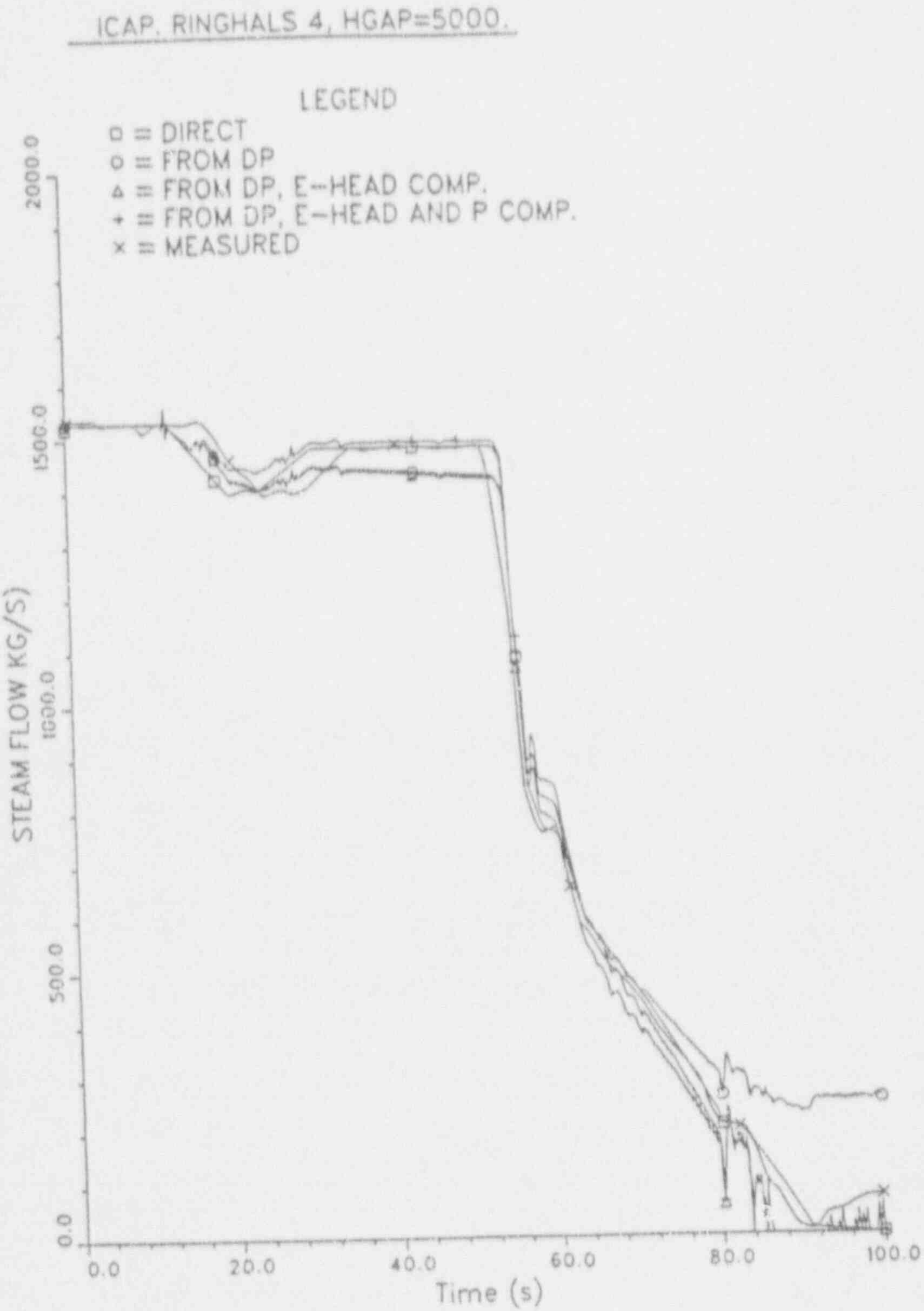

Figure 28

Steamflow at steam generator outlet nozzle.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

An inadvertent feedwater line isolation transient in a three loop Westinghouse PWR has been simulated with the frozen version of the TRAC-PF1/MOD1 computer code. The results revealed the capacity of the code to quantitatively predict the different pertinent phenomena.

For accurate predictions of the system response, particular care was required in the nodalization of the steam generator downcomer and restrictions had to be imposed on the allowable maximum time step.

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MARCH 1992