Template OCIO-032

NUREG/IA-0173

International Agreement Report

Simulation of a Station Black-Out in a PWR Under Midloop Conditions Using RELAP5/MOD3.2

Prepared by
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Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555–0001

February 2000

Prepared as part of
The Agreement on Research Participation and Technical Exchange
under the International Code Application and Maintenance Program (CAMP)

Published by
U.S. Nuclear Regulatory Commission

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EXECUTIVE SUMMARY

In this paper the simulation of the loss of the residual heat removal system (RHRS) due to a station black-out in mid-loop conditions is presented, using the RELAP5/MOD3.2 thermal-hydraulic code. Although this code was primarily developed to perform LOCA transients at full power, the use of the code to simulate transients with the plant in other operational modes is being also considered. In this case, the interest is focused on studying all the phenomena involved in a loss of the residual heat removal system (RHRS) due to an external station black-out (SBO) during mid-loop operation.

The residual heat removal system is part of the emergency core cooling system (ECCS) in a nuclear reactor, which is responsible of the residual heat removal under low power and shutdown conditions. Sometimes, the RHR system is required to work with the primary inventory level reduced to the height of the primary loop, and the upper part of the reactor coolant system (RCS) filled with air. This mode of operation is called mid-loop operation.

This study is part of the code applications and maintenance program (CAMP), which is focused on studying some transients described in the PSA for low power and low pressure conditions. It was conducted by the Chemical and Nuclear Engineering Department of the Polytechnic University of Valencia (UPV), in collaboration with the Consejo de Seguridad Nuclear (CSN) of Spain.

The main objectives of this paper are the verification of the success criteria foreseen in the plant probabilistic safety assessment (PSA), and the evaluation of the RELAP5/MOD3.2 code capability for simulating transients under mid-loop operation.

The plant chosen for simulating the transient was Vandellos II, which is a three loop pressurized water reactor plant, designed by Westinghouse, of 2775 Mwt of nominal thermal power. The plant is initially in mid-loop with the pressurizer manway opened.

Under these conditions the plant is stable in Mode 5 and, when the station black out is produced, it is supposed that there is no possibility of recovering the external electric power supply, and that the only way for removing the residual heat produced is by gravity feed from the refueling water storage tank through the connection with the low pressure injection system of the residual heat removal system, being 2820 seconds the maximum time available for taking this action.

In the plant PSA it is supposed that when the SBO transient is produced, following the actions above explained, the plant will tend to a stable situation, and no damage to the core is expected to occur.

With regard to the initial conditions, in the original plant nodalization at full power conditions, some changes were realized to model the RHRS in order to allow recirculation mode, as it is demanded in the initial conditions.

From the transient development we have obtained the evolutions of the plant most important thermal-hydraulic variables. The calculations were run in a CONVEX SPP 1000 owned by the University Polytechnic of Valencia. The time consumed in the transient simulation has been considerable, due to the time steps needed for achieving a correct transient simulation, and to the large periods of time that had to be simulated in order to appreciate changes in the evolutions of the most important thermal-hydraulic parameters. Such a large time being simulated results in a high cost of CPU time needed for this transient

It seems from the simulation results that there is a misfunction of the code in the presence of noncondensable. It was specially important in this simulation due to the amount of noncondensable species present in the primary system, that produces an important increase of the time needed for calculations, since the code requires a lower maximum time step to obtain a coherent solution. The introduction of noncondensables also seems to produce an underestimation of the heat transmission coefficients.

It can also be concluded that the simulation results obtained with RELAP5/MOD3.2 reproduce, satisfactorily, the success criteria foreseen in the PSA, although experimental data would be necessary to verify that they are the correct values and also to validate the code proper performance.

ABSTRACT

The present study consists of the simulation of a station black-out (SBO) transient, when the plant is in mid-loop conditions, using the thermal-hydraulic code RELAP5/MOD3.2.

This transient has been simulated on a typical three loop, Westinghouse design, pressurized water reactor (PWR) model working under mid-loop conditions.

The study was focused on obtaining the most important thermal-hydraulic variables in order to check the validity of the success criteria described in the plant probabilistic safety analysis (PSA), and also to analyze the code capability to simulate such conditions.

As a result of this study, it can be concluded that the main thermal-hydraulic plant features follow what it is foreseen in the plant PSA, although the values that are reached can not be completely taken as the correct ones due to the lack of experimental data to validate RELAP5 under these conditions.

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1. INTRODUCTION

The RELAP5 is a thermal-hydraulic code widely used for studying transients in pressurized water reactor (PWR) plants. This code was primarily developed to perform loss-of-coolant (LOCA) accidents when the system is working at full power.

Nevertheless, the use of the code to simulate transients with the plant in other operational modes is being considered. In our case, we are interested in studying all the phenomena involved in a loss of the residual heat removal system (RHRS) due to an external station black-out during mid-loop operation.

The residual heat removal system is part of the emergency core cooling system (ECCS) in a nuclear reactor, which is responsible of removing the residual heat during low power and shutdown conditions.

Sometimes, the RHR system is required to work with the primary inventory level reduced to the height of the primary loop, and the upper part of the reactor coolant system (RCS) filled with air. This mode of operation is called mid-loop operation.

Under this working conditions it is of great interest to study those transients that cause the loss of the RHR system, in order to check the capability of the alternative ways foreseen in the PSA to evacuate the residual heat.

The ultimate objective of this study was to validate, considering the results obtained and the limitations encountered, the success conditions established in a probabilistic safety analysis (PSA) for a PWR plant in these operational conditions.

This study is part of the code applications and maintenance program (CAMP), and is focused on studying some transients described in the PSA for low power and low pressure conditions. It has been conducted by the Chemical and Nuclear Engineering Department of the Polytechnic University of Valencia (UPV), in collaboration with the Consejo de Seguridad Nuclear (CSN) of Spain.

This document is organized as follows. In chapter two, a brief plant description is presented, highlighting its most important features. The description of the transient being simulated, SBO, is also presented in this chapter. The input file used for reaching initial conditions of the transient is explained in chapter three, together with specific nodalization modifications needed to simulate the transient. Chapter four contains the results of the simulation, showing the time-dependent evolutions of some thermal-hydraulic variables considered as important. It also contains the discussions of the additional sensitivity studies performed and some recommendations on the aspects that should be subject of a future study. Chapter five gives information about the time steps utilized along the transient simulation and the time consumed in the transient development. The conclusions derived from the whole study, and the most important recommendations for other users, are discussed in chapter six. All the references needed in the elaboration of this study are detailed in chapter seven. Finally, the tables and figures referenced in the text are shown at the end of this report.

2. PLANT AND TRANSIENT DESCRIPTION

2.1. PLANT DESCRIPTION.

The plant chosen for simulating the transient was Vandellos II, which is a three loop pressurized water reactor plant, designed by Westinghouse, of 2775 Mwt of nominal thermal power. The plant is equipped with three U-tube steam generators without preheaters, and uses the seawater as final heat sink. The reactor vessel is cold head type. In table 1, the most important plant features are presented.

Figure 1 shows the nodalization diagram used in RELAP5/MOD3.2 for the plant under low power and low pressure conditions. In this diagram there are three loops, with a steam generator each, a reactor vessel, and a pressurizer. The RHRS is also modeled, which includes the high pressure coolant injection system (HPCIS) and the low pressure coolant injection system (LPCIS), adapted for recirculation.

The RHR system consists of two lines, A and B, with their low pressure coolant injection part connected with loops 1 and 2 of the main reactor coolant system (RCS) and with the refueling water storage tank (RWST). When the plant is in Mode 5, the RHR system extracts water from the hot legs of loops 1 and 2, which is recirculated by the RHR pumps towards the heat exchangers, to the cold legs of the three loops. In Mode 5, with the primary level in mid-loop only one of the RHR pumps recirculates water to the three loops with a total mass flow rate of 90 kg/sec.

2.2 TRANSIENT DESCRIPTION

The experiment consists of simulating the loss of the residual heat removal system due to an external station black-out (SBO) with the plant working in mid-loop conditions in Mode 5, according to the following characteristics:

- Pressurizer manway opened.

- Primary level of the RCS hot legs reduced up to 10± 3 cm above the vessel entry.

Under these conditions the reactor coolant system (RCS) average temperature is close to 60 °C and there is only one pump of the RHR system working, which injects in the three loops a total mass flow rate of 90 kg/sec. Then, the plant is stable in Mode 5, when the station black out occurs. We suppose that there is no possibility of recovering the external electric power supply, and that the only way of removing the residual heat produced is by gravity feed from the refueling water storage tank through the connection with the low pressure injection system of the residual heat removal system, being 2820 seconds the maximum time available for taking this action manually.

3. CODE INPUT AND MODEL DESCRIPTION.

3.1. SYSTEM DESCRIPTION

The simulation has been run on a typical three loop pressurized water reactor full scaled model, Figure 1, in which the low and high pressure injection systems are also modeled, and the latter has been modified to allow recirculation.

At the beginning of this study, we had the plant nodalization for full power conditions, and we needed to adapt the model to work under mid-loop conditions, as this was the previous state of the plant for starting the transient.

An important nodalization change was the RHR system modification to work in recirculation mode, as it is demanded in the initial conditions. By this reason, some volumes have been added, simulating the pipes that connect the hot legs of loops 1 and 2 of the primary system with the lines A (vols.300, 301, 302, 303) and B (vols. 320, 321, 322, 323) of the low pressure injection system. Among these added volumes we can find the RHR heat exchangers (vols. 308, 309 328, 329), which are able to remove all the residual power generated.

From the input deck, the volumes that simulate the turbine, the steam dump, the MSRV's and the accumulators have been eliminated, since they are not used in the transients simulated.

The most important change in the RCS was made in the pumps (vols. 118, 148, 178), for adjusting them to the new working conditions, as the characteristic curve was not prepared for simulating them when they are stopped. The solution was found modifying the suction and discharge loss coefficients until the mass flow rate through the RCS was the same as the one measured in plant.

At the secondary of the steam generators the water injection through the main and auxiliary feedwater systems have been deactivated, although have not been removed since they could be required in future transients under low power conditions.

At this point, the plant model was adapted for working in low power conditions, but for simulating mid-loop operation is necessary to add the volumes that simulate the pressurizer manway. The top of the pressurizer is connected with a time dependent volume (vol. 347) that simulates the atmosphere through a trip controlled valve (vol. 346) which has as main characteristics the utilization of the abrupt area change model and the choking model.

To avoid the problems the choking model may present when simulating shutdown conditions, the current recommendation given in the RELAP5/MOD3.2 code manual [12] is to use homogeneous and choked for break junctions and other connections to the atmosphere. That will produce mass fluxes close to the homogeneous equilibrium critical flow model. Instead, it is suggested to invoke nonhomogeneous model with the choking model turned off for internal junctions

As we know, in the transient development the gravity injection system is required. In this way, the refueling water storage tank is modeled by four branches, two of them connected with the low pressure injection system (vols. 852 and 854). The pipes between the tank and the low pressure injection lines are simulated by two branches (vols. 835 and 840) that connect it with the RHR through two trip controlled valves (vols. 304 and 324), which open when the gravity injection is required.

3.2. INITIAL CONDITIONS.

A new input deck was made with the above modifications, to simulate the plant state previous to the transient in mid-loop operation with the following features:

- Pressurizer manway opened.

- Primary level of the hot legs reduced up to 10± 3 cm above the vessel entry.

Other data measured in plant were added to the requirements above exposed. Table 2 shows a list of the most important variables calculated with RELAP5/MOD3.2 code, and their comparison with the values required or measured in plant, for the initial state.

Once the initial conditions were reached, and having checked that the plant was in a stable state, two new input decks were built, considering the values of the variables at this point, to perform the transient simulation.

3.3 TRANSIENT SIMULATION

In the SBO transient, due to the low RCS mass flow which leads to a misfunction of the code, it was necessary to activate the countercurrent flow limitation model. This model was invoked only in the internals junctions where it was likely to occur, following the suggestions of RELAP5/MOD3.2 code manual [12] [13]. In our case, it was activated in the core and in the core by-pass, in the vessel downcomer, in the steam generators U-tubes, in the hot legs, and in the entrance to the vessel.

In all the junctions the Wallis CCFL correlation is used by default. The values for the Wallis correlation parameters, m and c, were taken from the literature [4], [12]. These values have been obtained from the experimental data of other experiments with similar working conditions to our situation.

After all the changes were made, the SBO transient was simulated following the sequence showed in figure 2, which describes the scenario foreseen in the plant PSA under these conditions.

In the transient simulation we wait for 50 seconds before taking any action to assure the initial conditions were reached. After that, the RHR pump A that is working in mid-loop operation is stopped. No other action is taken until 2820 seconds after the pump stops, when the gravity injection from the reactor water storage tank is manually activated.

4. RESULTS.

From the transient development we have obtained the evolutions of plant most important thermal-hydraulic variables. Some of the most interesting evolutions are presented in this chapter.

About 25000 sec. of the station black-out transient were simulated to find significant results in the thermal-hydraulic variables.

As we can see in figure 3, the reactor core level has no important change during the simulation. In fact it remains with no change until 14000 sec., at this time it starts to decrease, but no core damage occurs since the core is never uncovered.

The behavior of the most significant temperatures is presented in figure 4. In this figure we can observe how the core outlet and clad temperatures rise before the injection. When the water from the RWST is injected there is a decrease in all the temperatures, but once the injection has finished they start to rise again, but not so fast as before the injection.

The mass injected from the RWST is presented in figure 5. In this figure we can observe that all the water is injected around 2870 sec. after the SBO, and no other injection is produced in the simulation. A certain quantity of the water injected fills the RCS loops, figure 6, which where partially filled with air at the beginning of the simulation. The water injected is also utilized to fill the pressurizer, which was completely empty before the injection. This can be seen in figure 7, where the pressurizer level is presented.

Finally, figures 8 and 9 represent the mass flow rates through the hot and clod legs respectively. In both evolutions the most important feature is the oscillating behavior of the mass fluxes, which is specially important in the first period of the simulation for the hot leg mass flow rates, when the RCS loops were partially filled with air.

5. RUN STATISTICS.

The calculations have been made in a CONVEX SPP 1000 owned by the UPV, using SPP-UX-3.1 as operating system, and For77-HP as compiler. Table 3 presents the information about time steps used in each simulation and the CPU times consumed.

Figure 10 shows the CPU values versus time simulated for the SBO, and in figure 11 the time step versus time simulated for the same transient is represented.

6. CONCLUSIONS AND RECOMMENDATIONS

Although the thermal-hydraulic parameters evolution agrees with the success criteria foreseen in the plant PSA, it can not be assured that the values they reach are the actual ones, due to the lack experimental data to validate them.

The misfunction of the code when simulating noncondensable presence was noted. It was specially important in the simulation due to the amount of noncondensable species present in the primary system. The presence of noncondensables produces an important increase of the time needed for calculations, since the code requires a lower maximum time step to obtain a coherent solution. The introduction of noncondensables also produces an underestimation of the transmission heat coefficients.

It can not be assured that the constants used in the CCFL model are the most suitable ones, because the values encountered in others studies with only similar working conditions were adopted. In addition, it can not be assured that the correlation used was the most adequate for our studies. Probably, the correlation used is not the proper one, as it seems not to work properly at low pressure situations [6]. In this case, it should be necessary a further study in which a comparison of the results obtained with different correlations should be done. This study also requires experimental data in order to validate the results.

So, the most important impediment for concluding that the results obtained with RELAP5/MOD3.2 are completely corrects is the lack of experimental data needed to assess the code capability under low power conditions. It would be interesting the performance of experiments in these conditions to develop a more detailed study on the code models.

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Table 1: Main plant characteristics.

Thermal Reactor Power (Mwt)	2775.
Electrical Power (Mwe)	992.
Fuel	UO2
Number of assemblies	157
Number of coolant loops	3
Cladding tube material	Zircaloy 4
Absorber material	B4C + Ag-In-Cd
Reactor Operating Pressure (MPa)	15.4
Coolant Average Temperature Zero load (°K)	564.8
Coolant Average Temperature 100% load (°K)	582.3
Stem Generator	Westinghouse type F
Number of tubes in SG	5626
Total tube length (m)	98759.
Inner diameter tubes (m)	0.0156
Tube Material	Inconel
Pumps type	Westinghouse D 100
Discharge head of pumps (bar)	18.8
Design flow rate (m^3/sec))	6.156
Speed of pumps (rad/sec)	155.
Primary volume (m^3)	106.19
Pressurizer Volume (m^3)	39.65
Heating Power of the heaters rods (KW)	1400.
Maximum spray flow (kg/sec)	44.2
Steam mass flow rate at 100% (kg/sec)	1515.

Table 2: Initial values

Reference parameters	Problem Data	Obtained RELAP-5/3.2
Nuclear Power (%) - Residual Heat	0.05 (i)	0.05 (i)
RCS Pressure (MPa)	0.1	0.1
Pressurizer level (%)	-	-
RCS average temperature (°K) – loops 1/2/3	333.	335.3
RCS hot leg temperature (°K) – loops1/2/3	--	338.8
RCS clod leg temperature (°K) - loops 1/2/3	--	328.4
Core outlet temperature (°K) – loops 1/2/3	--	336.33
Clad temperature (°K)	--	343.8
Core level (%)	--	6.6556
Primary GVs mass flow (Kg/s) - loops 1/2/3	--	0.0
Steam generator level (%) (Average)	--	95.46
Total RHR mass flow (Kg/s)	90	89.924
Hot legs average level (m)	0.4683	0.4975

(i) Nominal power for 100% load is 2775.0 MW (1.3875 MW for 0.05%).

Table 3: Run statistics.

RT	CPU	TS	CPU/RT	C	DT	GT
24900	2.91E6	0.001	11.6867	284	24901414	0.4115

RT: Transient time
CPU: Total execution time.
TS: Maximum time step.
C: Total number of volumes in the model.
DT: Total number of time steps
GT: Grind time (msec.) GT=(CPU*1000)/(C*DT)

Figure 1: Vandellos II nodalization for RELAP5/MOD3.2 under mid-loop conditions

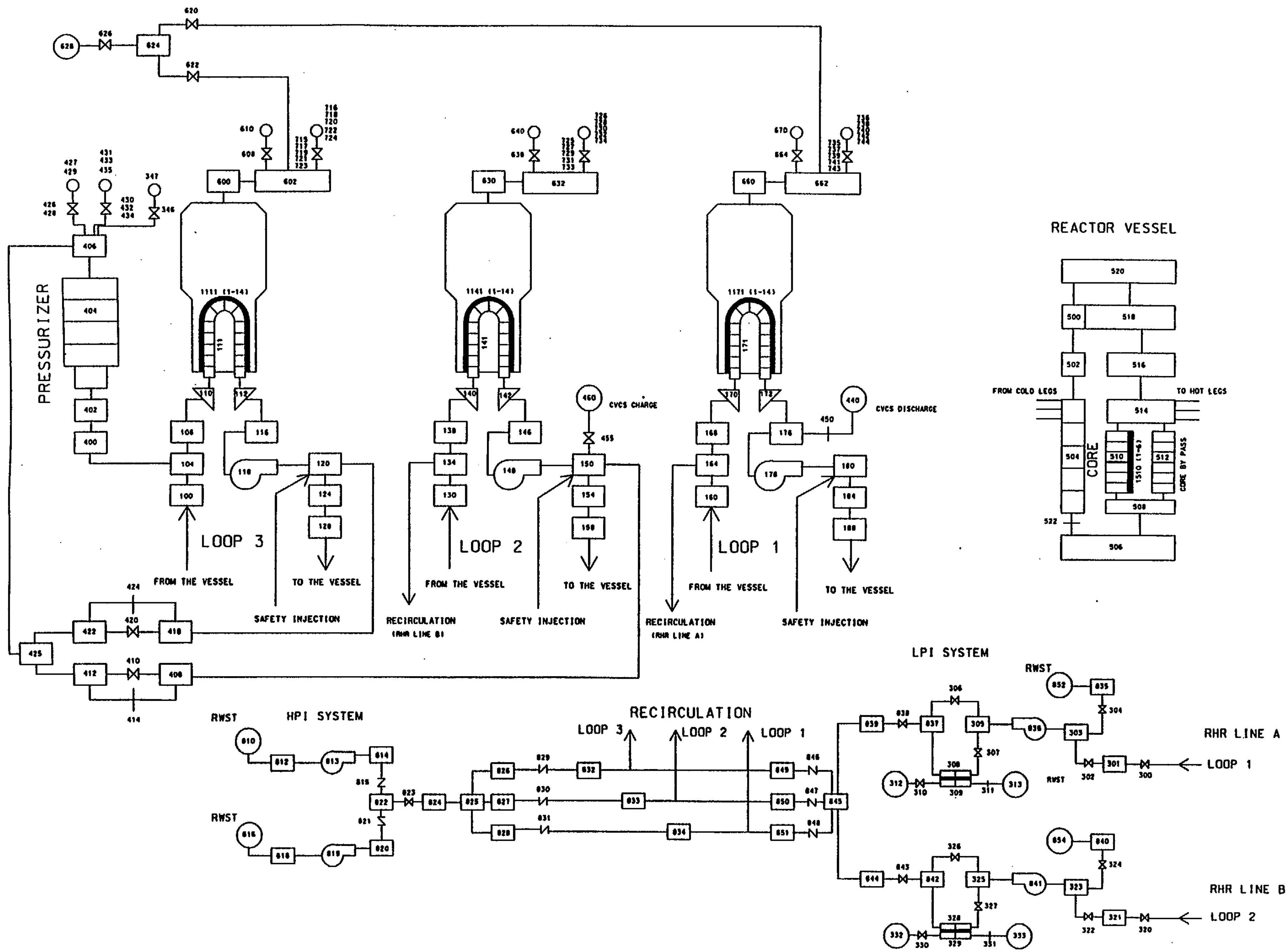


Figure 2: SBO transient simulation.

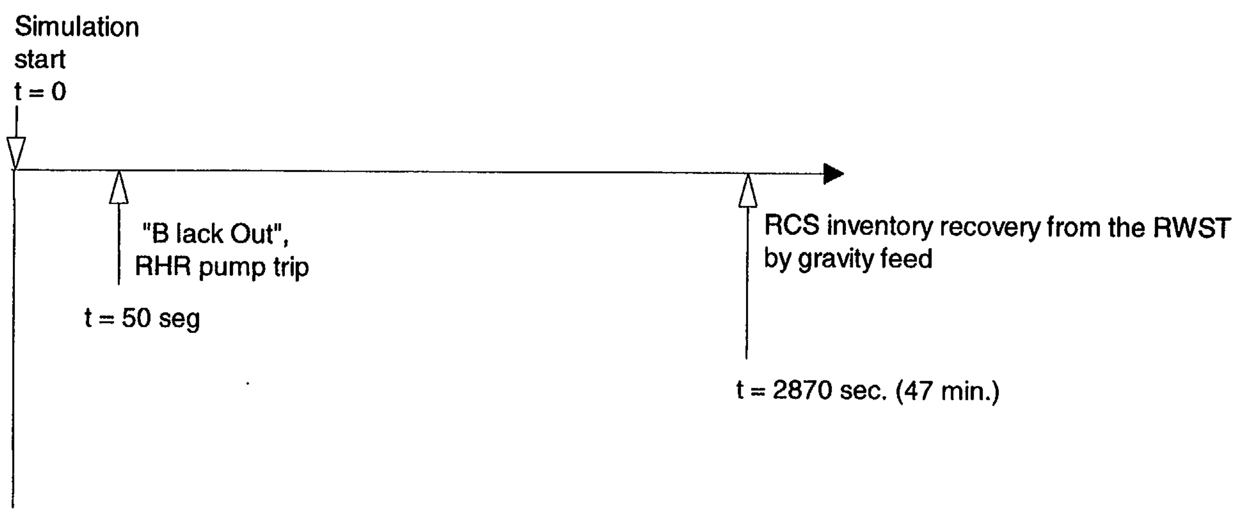


Figure 3: Core level.

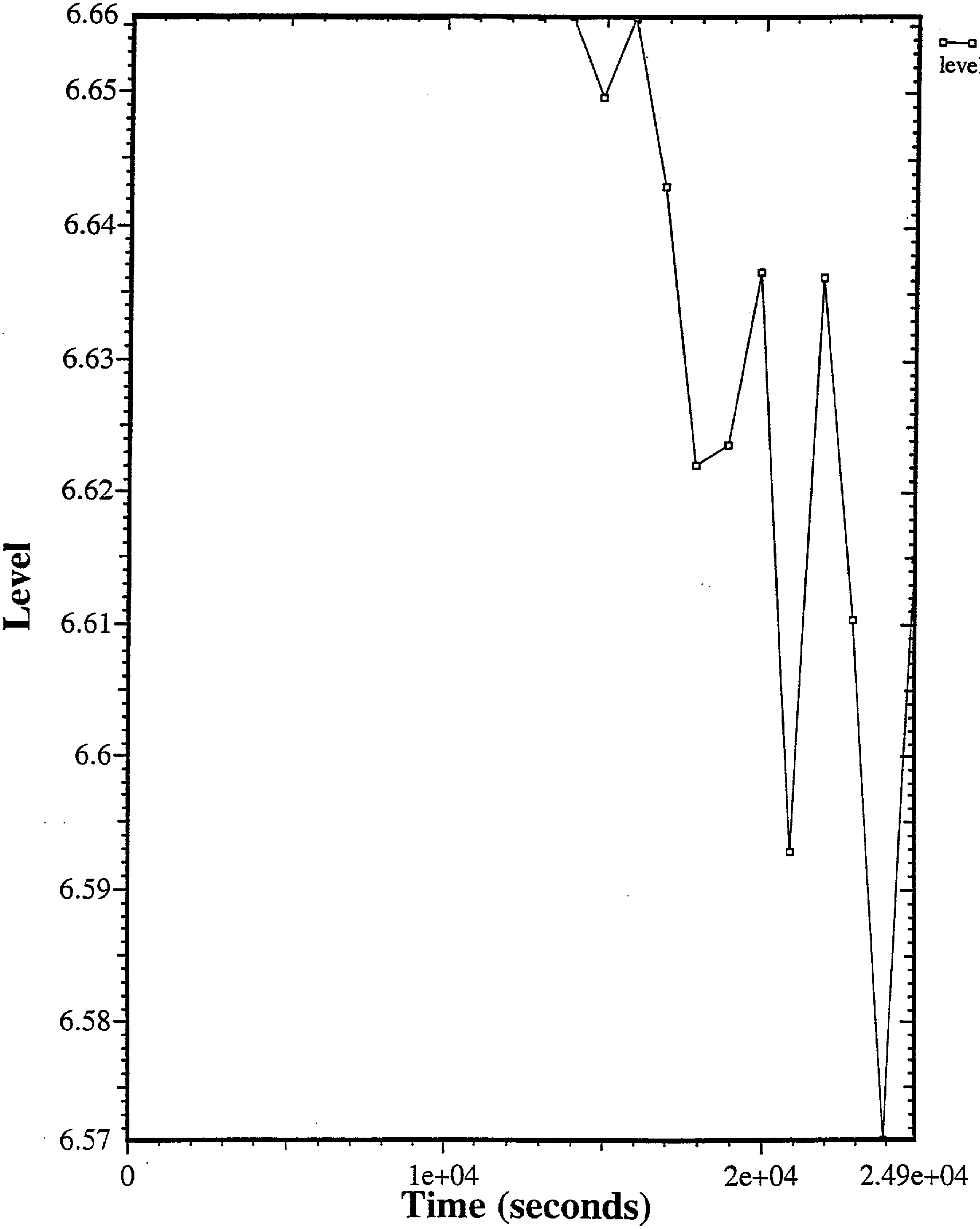


Figure 4: Core outlet and clad temperatures.

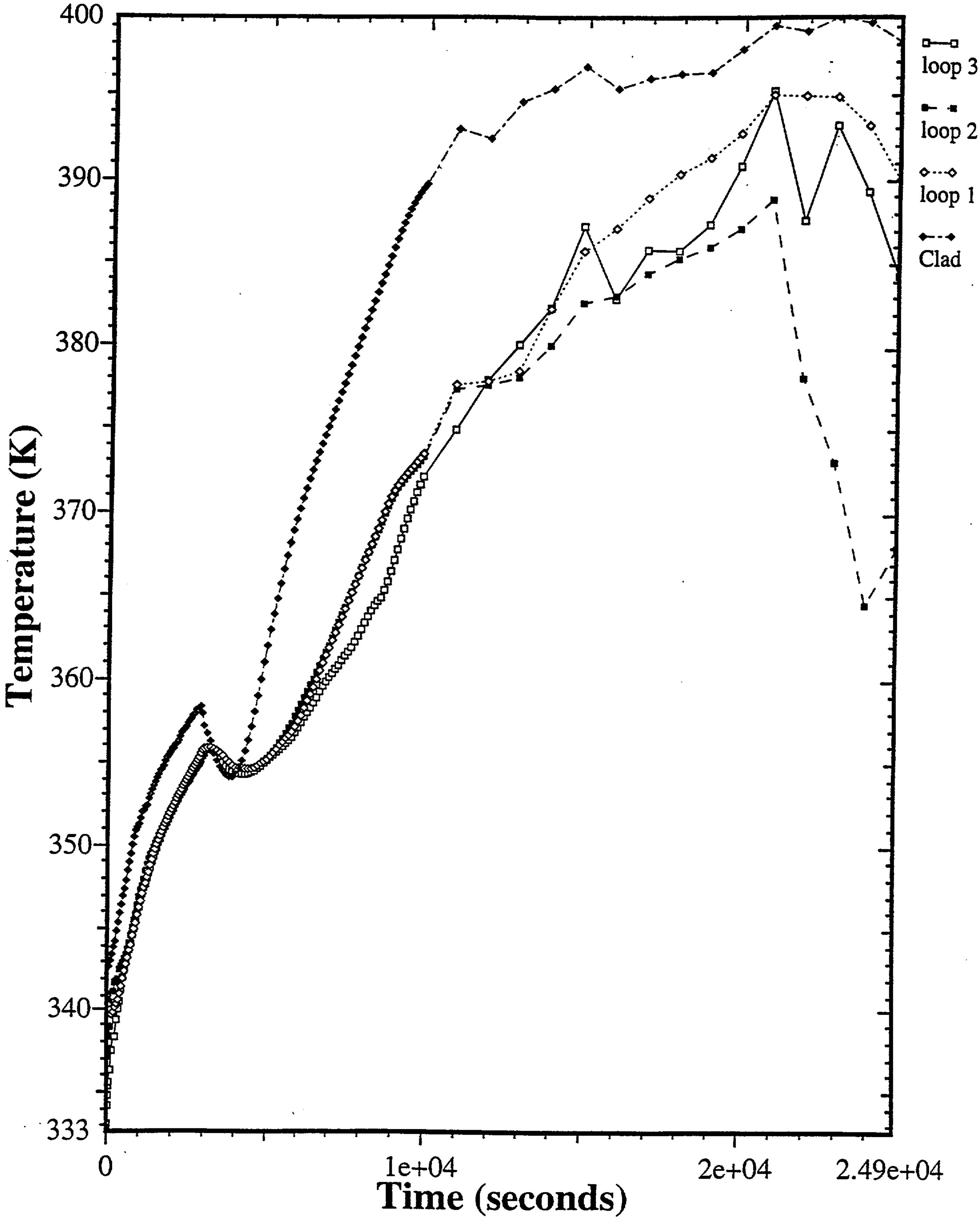


Figure 5: Gravity injected mass.

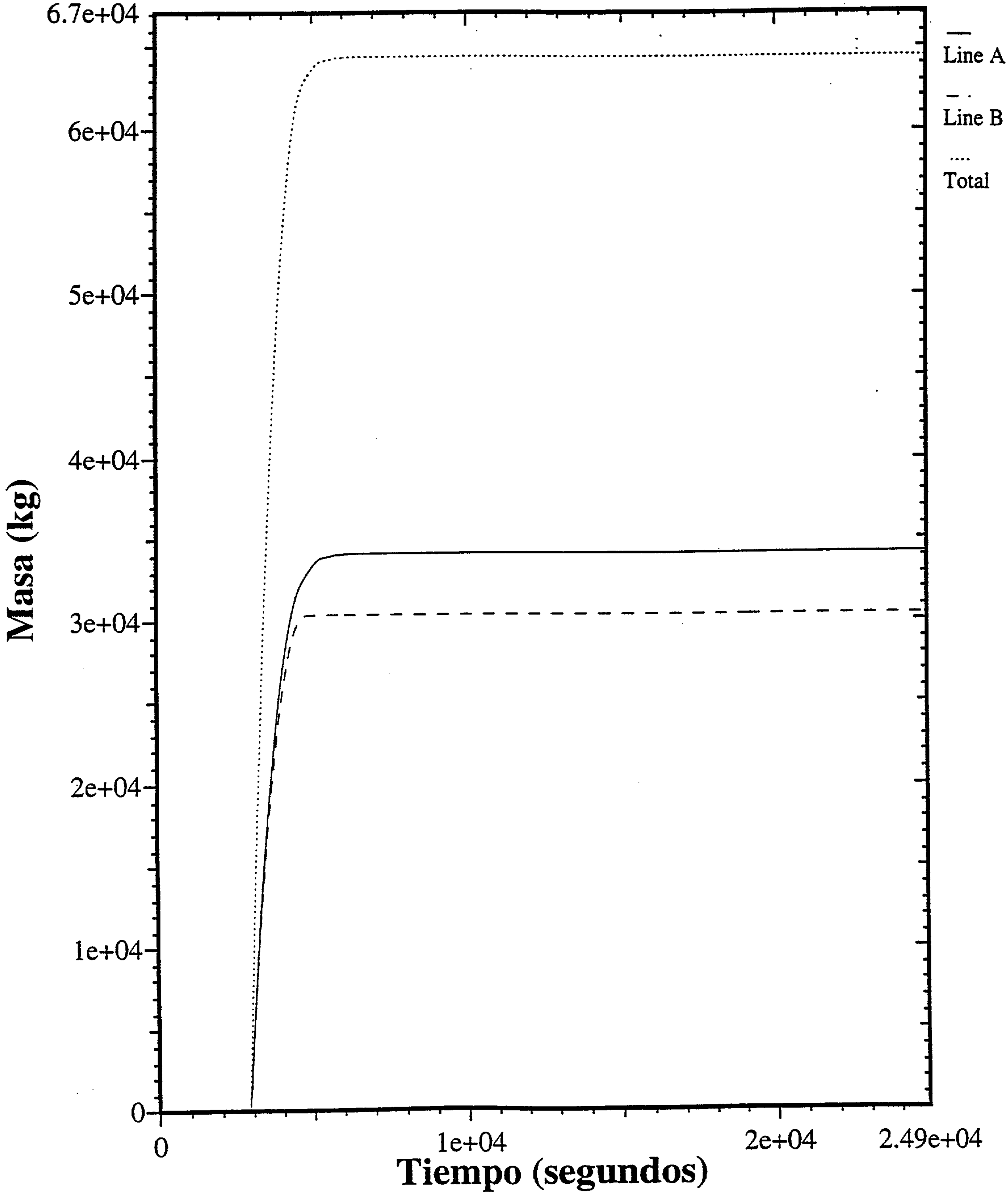


Figure 6: Mass inside the primary loops.

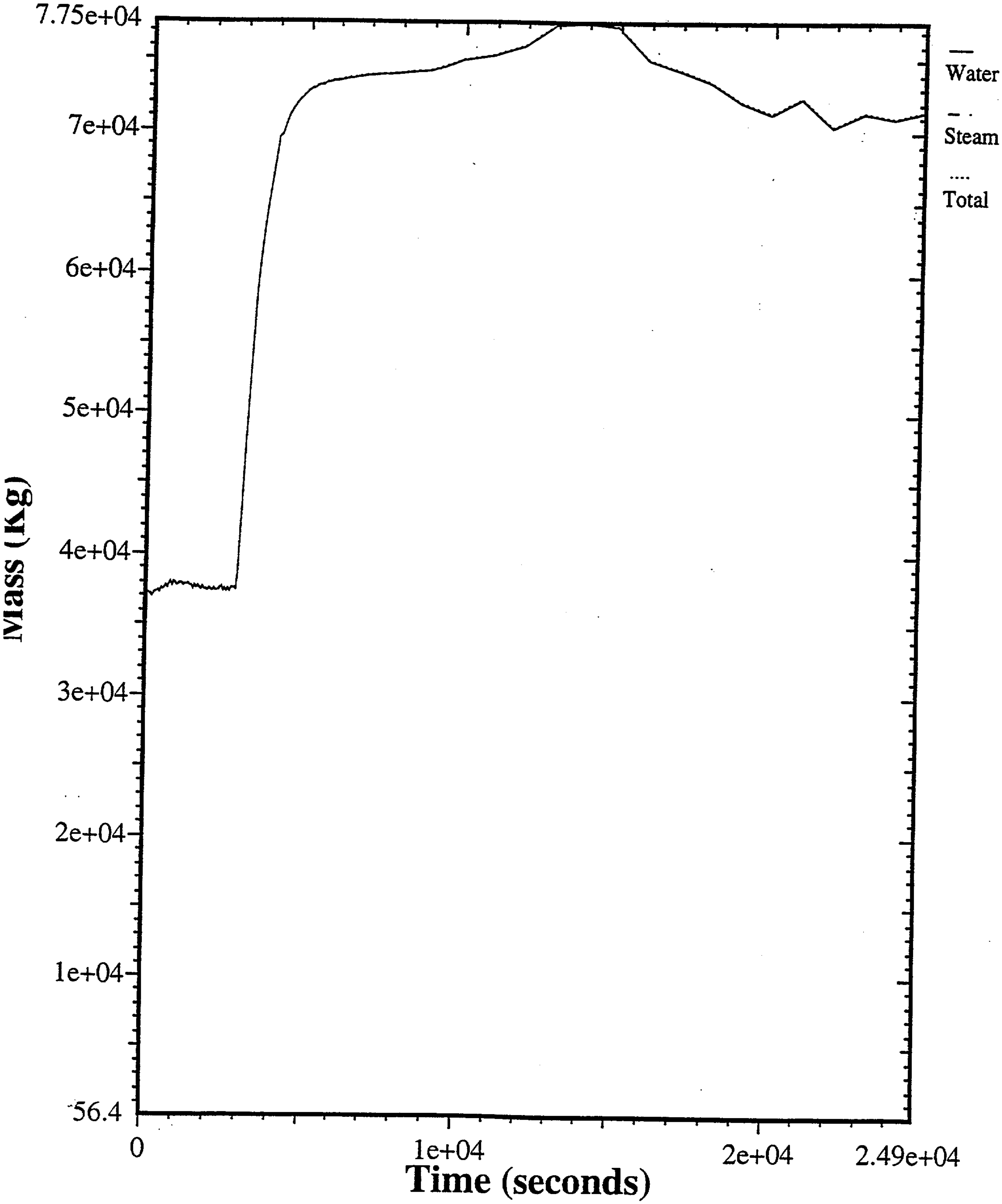


Figure 7: Pressurizer level.

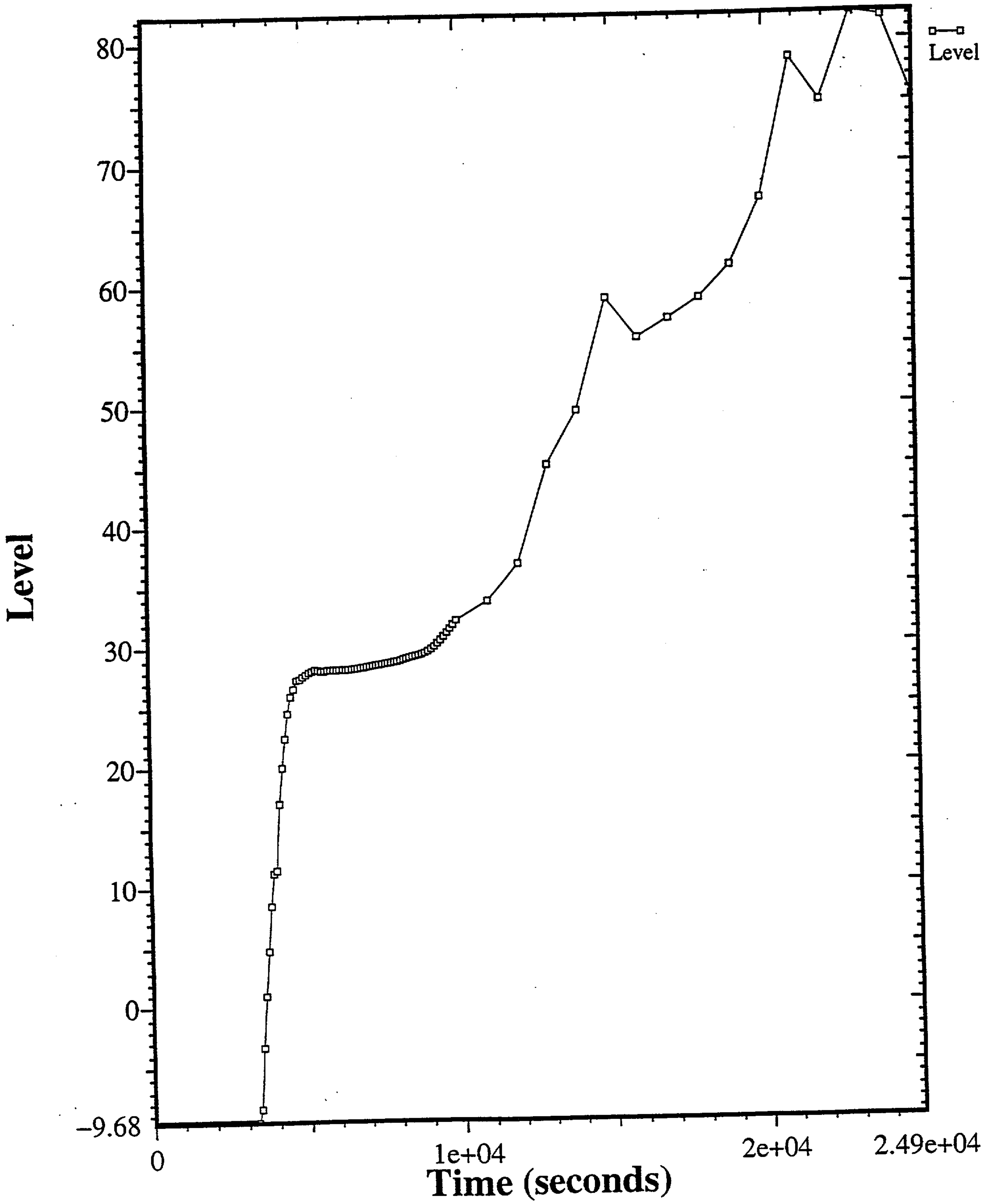


Figure 8: Hot leg mass flow rates.

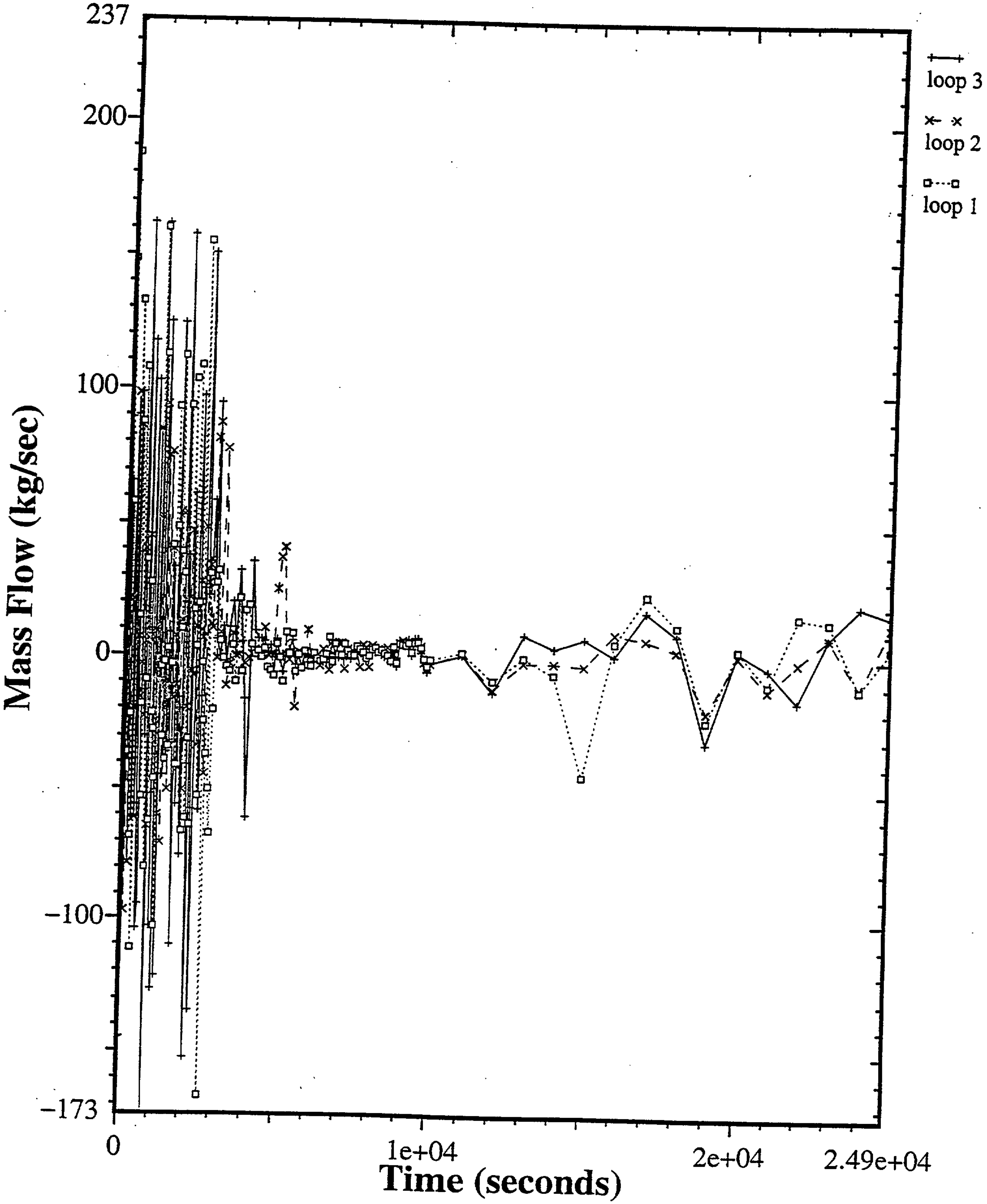


Figure 9: Cold leg mass flow rates.

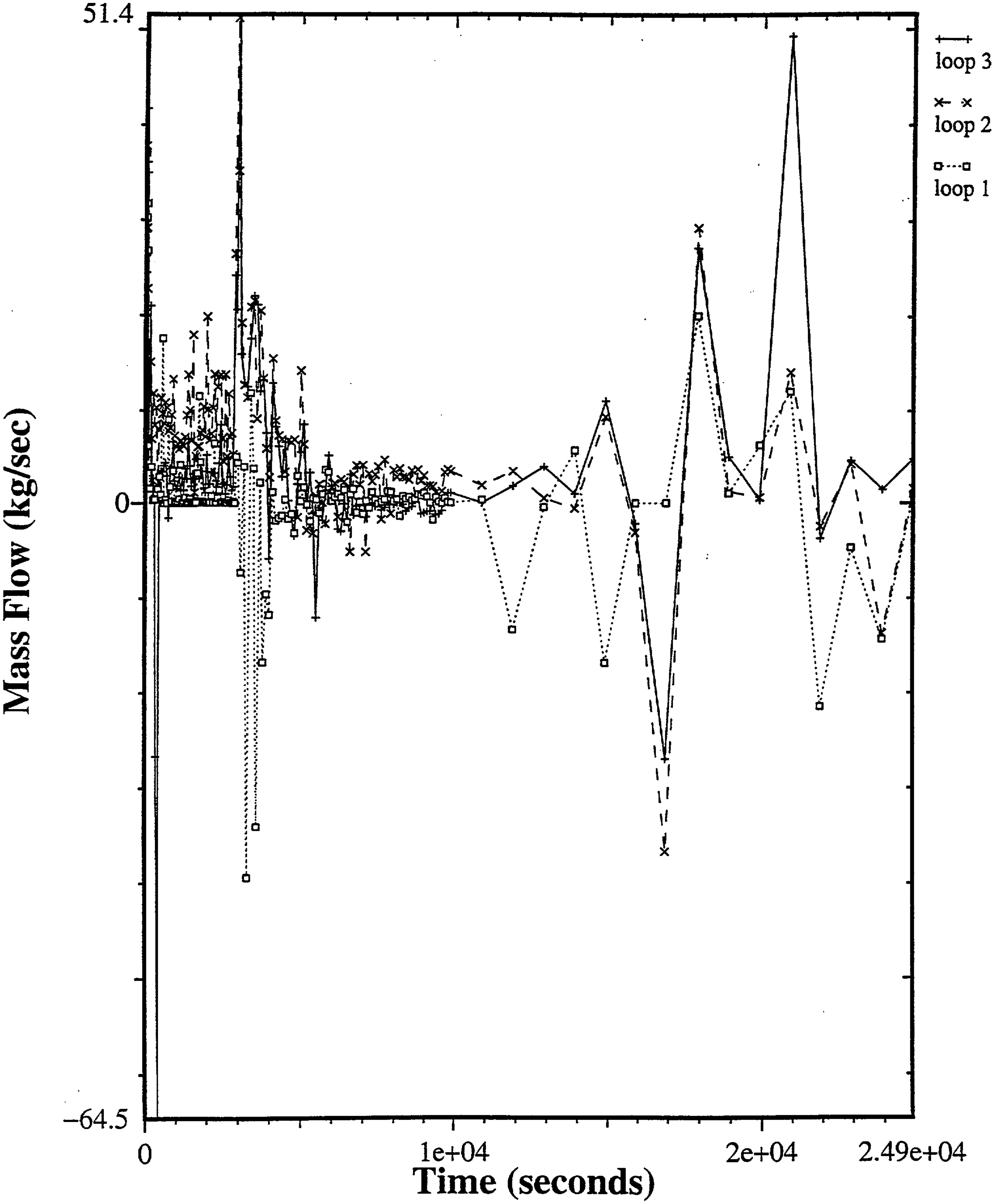


Figure 10: CPU time.

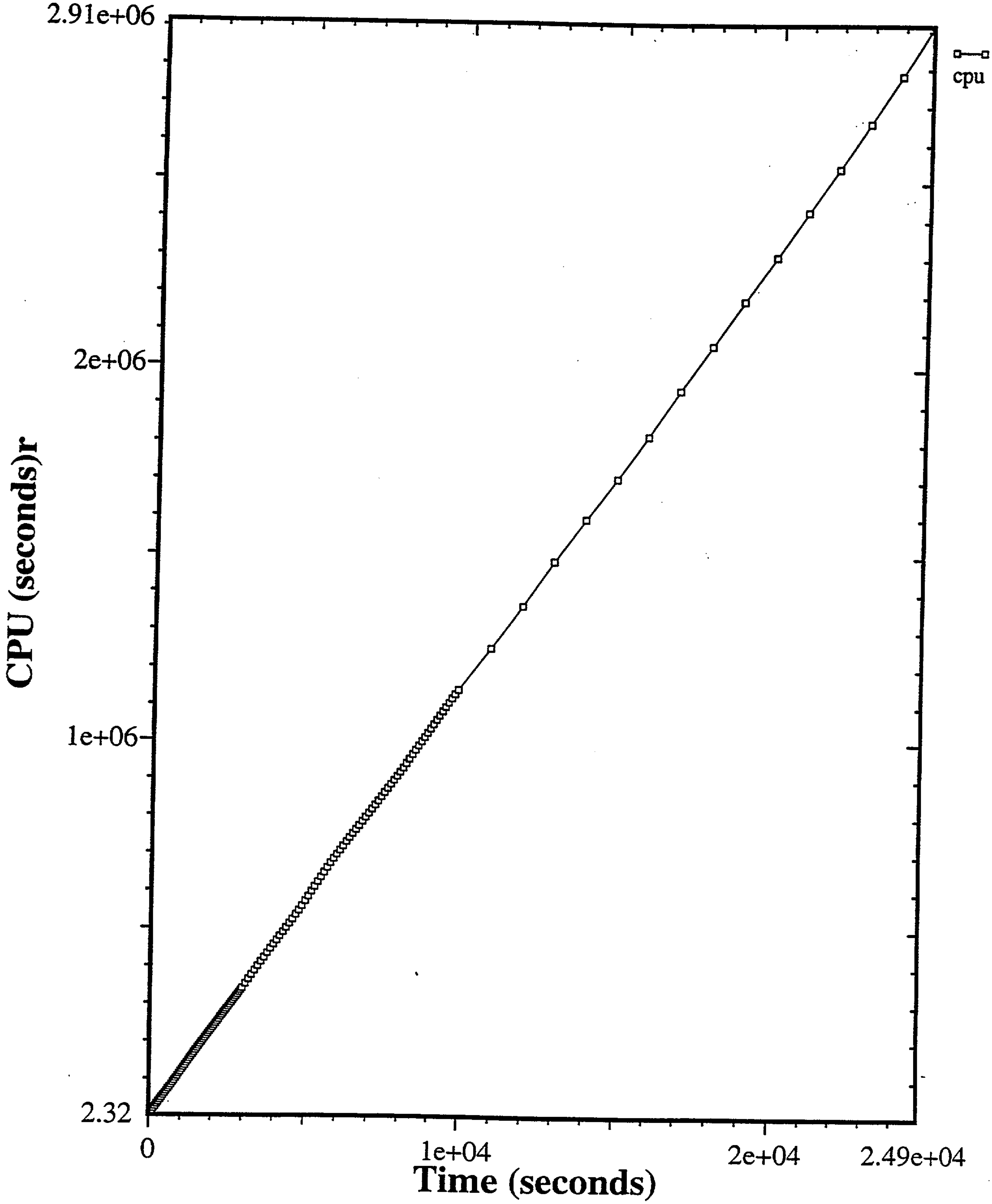
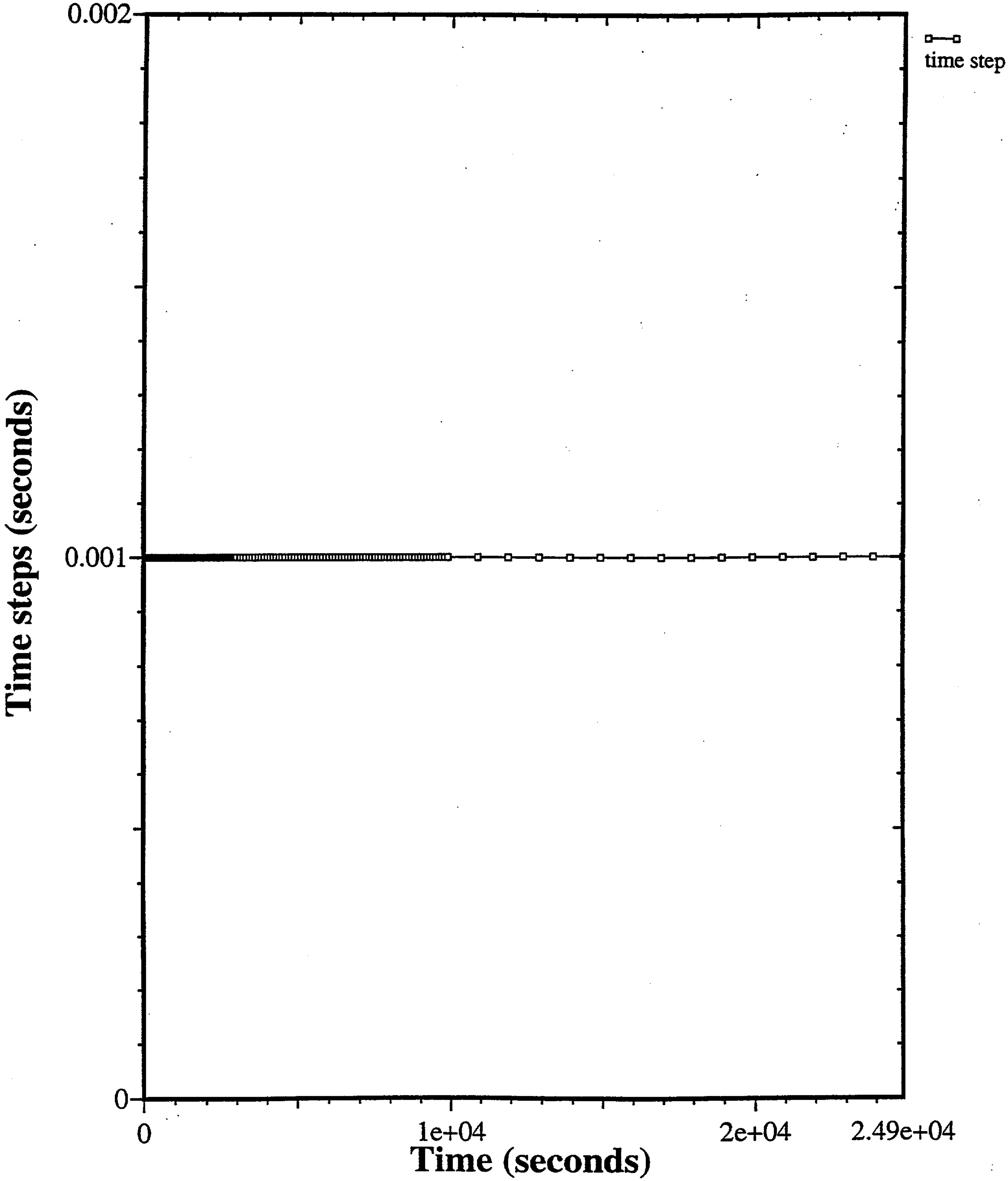


Figure 11: Time steps.



NRC FORM 335 (2-89) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/IA-0173

2. TITLE AND SUBTITLE

Simulation of a Station Black-Out in a PWR Under Midloop Conditions Using RELAP5/MOD3.2

3. DATE REPORT PUBLISHED

MONTH	YEAR
February	2000

4. FIN OR GRANT NUMBER

5. AUTHOR(S)

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J. Rodenas, R. Miro, C. Llopis*

6. TYPE OF REPORT

Technical

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

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9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of System Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

The present study consists of the simulation of a station black-out (SBO) transient, when the plant is in mid-loop conditions, using the thermal-hydraulic code RELAP5/MOD3.2. This transient has been simulated on a typical three loop, Westinghouse design, pressurized water reactor (PWR) model working under mid-loop conditions. The study was focused on obtaining the most important thermal-hydraulic variables in order to check the validity of the success criteria described in the plant probabilistic safety analysis (PSA), and also to analyze the code capability to simulate such conditions. As a result of this study, it can be concluded that the main thermal-hydraulic plant features follow what it has foreseen in the plant PSA, although the values that are reached can not be completely taken as the correct ones due to the lack of experimental data to validate RELAP5 under these conditions.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

RELAP5
LOCA
RHR

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

(This Page)
unclassified

(This Report)
unclassified

15. NUMBER OF PAGES

16. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

1975 25 2000
years

FIRST CLASS MAIL
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USNRC
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