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ASSESSMENT OF RELAP5/MOD3 VERSION 7
BASED ON THE BETHSY TEST 6.2 TC

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ABSTRACT

A post-test analysis of the 5% cold leg side break, BETHSY test 6.2 TC, was performed to partially assess the RELAP5/MOD3 version 7 code. The calculation was completed using a DEC-Station 5000 Workstation.

The BETHSY facility is a 1/100 volumetrically scaled model, with 1:1 elevation scaling, of a 900 MWe Framatome three loop PWR. The BETHSY facility, located in Grenoble, France, is designed to simulate most PWR accident scenarios of interest while minimizing the distortions of relevant physical phenomena. Because BETHSY has three equally-sized loops that differ only in the possible break geometries and in the presence of a pressurizer in loop 1, the facility is ideal to investigate potentially asymmetric phenomena which can occur in a large number of accident scenarios. Hot legs and cold legs were scaled to preserve the Froude number to properly simulate countercurrent flow, transition from one flow regime to another, and stratified flow in horizontal pipe runs.

The RELAP5/MOD3 code was developed at the Idaho National Engineering Laboratory (INEL) to provide best-estimate predictions of postulated accidents and transients in light water reactor (LWR) systems. The code features a two-phase, two-fluid nonequilibrium hydrodynamic model with many generic component models and special process models.

The RELAP5/MOD3 models of particular interest for this assessment are the interphase drag model, the vapor entrainment/liquid pull-through models (used to predict the flow from an orifice or nozzle adjacent to a partially liquid-filled pipe), the countercurrent flow limiting (CCFL) model, and the behavior of the ECCMIX component (unique to MOD3 - created to model mixing of subcooled ECC fluid injection with resident cold leg inventory).

The chronology of major predicted and calculated events show reasonable agreement. Following the break initiation, the primary pressure rapidly depressurized to a value slightly greater than the secondary pressure. As the primary fluid inventory decreased, the loop seal inventory was depressed and thus caused the core liquid level to also decrease. Maximum core collapsed liquid level was reached at 150 s and showed the effects of liquid holdup in the steam generator U-tubes and plena. Following loop seal clearing, the primary pressure decreased to values less than the secondary pressure and the break flow quality increased. The experimental data showed little heatup in the core heater rods either during the core liquid level depression or the core boiloff phase of the transient.

INTRODUCTION

The thermal-hydraulic behavior of a Westinghouse-type pressurized water reactor (PWR) during a cold leg small break loss-of-coolant accident (SBLOCA) has received much attention through various experiments and best estimate calculations.

The best estimate thermal-hydraulic code RELAP5/MOD3 includes new models and correlations such as the countercurrent flow limiting (CCFL) model and the ECCMIX component. The interfacial drag models in MOD3 are also different from those in MOD2. Therefore, a benchmark test calculation using the experimental data is valuable for the assessment of the code.

BETHSY test 6.2 TC was conducted to investigate thermal hydraulic phenomena during a 5 % cold leg SBLOCA and to provide high quality data for advanced thermal-hydraulic code assessment. In this paper BETHSY test 6.2 TC was analyzed using RELAP5/MOD3 version 7o.

FACILITY AND TEST DESCRIPTION

Facility Description

The BETHSY facility is a 1/100 volumetrically scaled model, with 1:1 elevation scaling, of a 900 MWe Framatome three loop PWR designed to simulate most PWR accident situations of interest while minimizing the distortions of relevant physical phenomena. Because BETHSY has three equally sized loops that differ only in the possible break geometries and in the presence of a pressurizer in loop 1, the facility is ideal to investigate asymmetric phenomena which can occur in a large number of accident scenarios. Hot legs and cold legs were scaled to preserve the Froude number to properly simulate countercurrent flow, transition from one flow regime to another, and stratified flow in horizontal pipe runs.

The primary coolant system consists of a pressure vessel which contains an electrically heated core and an external downcomer and three identical loops (except loop 1 includes the pressurizer) each equipped with an active pump and an active steam generator. The cylindrical core is composed of 428 heated rods and 29 guide thimbles simulating 17 x 17 fuel assemblies. It also models the various reference PWR vessel internal structures and leakage paths. Each primary coolant pump has the capability of operating at scaled nominal conditions. Each steam generator has 34 inverted U-tubes of the same radial dimensions and heights as those of the reference steam generator. The pressurizer is equipped with six electrical heater rods, normal and auxiliary spray circuits, and a relief circuit. The secondary coolant system is composed of three steam generators, steam lines, a spray condenser, the main feedwater and auxiliary feedwater systems.

The BETHSY safety injection systems have the same capabilities as the reference PWR with some enhancements for sensitivity studies. It is composed of a high pressure injection system (HPIS), accumulators, and a low pressure injection system (LPIS). The break system consists of a break unit and a discharge line including spool pieces and blowdown tanks. A trace heating system is installed to compensate for unavoidable heat losses to the environment that are approximately 100 kW (primary and secondary) at nominal conditions.

BETHSY is designed to be operated at the reference PWR operating pressure and temperatures. Operating primary conditions are 17.2 MPa and 400 °C. The maximum secondary pressure is 8 MPa. However, BETHSY can operate at a maximum power of only 3 MW (10 % of rated scaled power). The facility is described in detail in References 1, 2, and 3.

Test Description

BETHSY Test 6.2 TC, a 5% cold leg SBLOCA, was conducted not only to provide additional SBLOCA transient data suitable for assessment of advanced thermal-hydraulic codes, but also to study the scaling of such transients between two experimental facilities, i.e., BETHSY and the ROSA-IV Program's Large Scale Test Facility (LSTF). The LSTF is a 1/48 volumetrically-scaled Westinghouse-type PWR simulator built with a 1:1 elevation scaling and located at the Japan Atomic Energy Research Institute (JAERI) in Tokai, Japan. To produce the best possible comparison with comparable LSTF data, BETHSY was modified to have a similar break geometry and similar operating conditions including a 0.28% bypass (i.e., 0.28% of the total loop flow) between the vessel upper head and downcomer. The test was conducted with the loop 1 accumulator isolated. In addition, the core power decay boundary condition was defined to be equivalent to that used in the LSTF. The ratio of the LSTF power decay to that normally used in the BETHSY facility ranges from 2.8 to 1.5 during the first 200s after scram.

Initial conditions are shown in Table 1. Initial core power was 2.863 $\pm$0.03 MW. The core temperature increase was 31 $\pm$1 °C. The pumps were operated initially at reduced speeds (237 - 241 rpm) to restrict the core mass flow rate to 10% of the rated scaled value so the reference PWR temperature distribution is simulated in the primary loop. The pressurizer pressure was 15.38 $\pm$0.15MPa, and the steam generator pressure was 6.84 $\pm$0.07Mpa. The primary mass inventory, excluding the pressurizer, was 1812 $\pm$50kg.

Operational setpoints and boundary conditions, including the ECCS actuation logic, is summarized in Table 2. After the break was initiated, the primary system began to depressurize. At a pressurizer pressure of 13.0 MPa, the reactor scrammed. It was assumed that the offsite power was lost concurrently with the reactor scram and the primary coolant pumps were tripped. Also, the condensers were isolated and the main feedwater pumps were shot off. The trace heating system was de-energized when the break was opened. The steam generator discharge valve's setpoints were 7.2 MPa. Core power was maintained at 2863 kW for 53 s and then was decreased using the pre-programmed LSTF conservative decay curve [4]. The steam generator auxiliary feedwater systems were assumed to fail. At a pressurizer pressure of 11.7 MPa, the safety signal was generated. However, the high pressure injection system (HPIS) was assumed to fail. Accumulator water was injected into the loop 2 and loop 3 cold legs when the pressurizer pressure had decreased to 4.2 MPa. Accumulator flow was terminated from each accumulator when a preset scaled quantity of accumulator fluid had been injected into the respective cold legs. The break orifice was a side-oriented nozzle with a throat diameter 0.01548 m, located in the loop 1 cold leg. The nozzle had a length to diameter ratio of 10. The total mass expelled through the break orifice was between 2130 and 2251 kg. The test was terminated when the pressurizer pressure reached 0.7 MPa. For more information, see References 5 and 6.

CODE AND MODELLING DESCRIPTION

Code Description

The RELAP5/MOD3 code was developed at the Idaho National Engineering Laboratory (INEL) to provide best-estimate predictions of postulated accidents and transients in light water reactor (LWR) systems. The code features a two-phase, two-fluid nonequilibrium hydrodynamic model with many generic component models and special process models [7]. Version 7o was used for the analysis described herein.

The RELAP5/MOD3 models of particular interest for this assessment are the interphase drag model, the vapor entrainment/liquid pull through models (in simulating break flow), the CCFL model, and the behavior of the ECCMIX component (unique to MOD3 - created to model mixing of subcooled ECC fluid injection with resident cold leg inventory).

Input Model Description

The RELAP5 nodalization for BETHSY test 6.2 TC is shown in Fig. 1. It consists of 259 volumes, 266 junctions, and 297 heat structures. The following paragraphs describe the detailed input models.

The RELAP5 model was assembled using standard practices and procedures outlined in the BETHSY Tests 4.1a TC and 5.1a analysis report (see Reference 8). Changes to the original model, initiated to better simulate the phenomena present in Test 6.2 were:

1. The loop seal nodalization was subdivided to create over three times more cells (see component 135 - Fig. 1). This change was motivated by the detection of a code deficiency that prevented an accurate calculation of loop seal pipe draining. Thus, to increase calculational accuracy, the cell length was decreased.

2. The break nozzle (see component 152 - Fig. 1) was modeled by using a single volume with a flow area representative for a 5% break. The nozzle frictional pressure loss was simulated by using a hydraulic diameter equivalent to that of the upstream pipe together with the length necessary to obtain the proper nozzle length to diameter ratio. The input discharge coefficients for subcooled, two-phase, and single-phase vapor are 0.92, 1.25, and 0.97 respectively.

3. The core nodalization (see component 13 - Fig. 1) was subdivided to allow a more rigorous calculation of core uncovery during the core depression and core boiloff phases of the transient.

4. Energy loss to the environment was simulated by connecting the outer surface of primary and secondary system component masses to the component 900 (see Fig. 1).

RESULTS AND DISCUSSIONS

The assessment calculations described in the following paragraphs have been valuable in that several code deficiencies were identified. Aside from the loop seal nodalization (described in item 1 above) required to properly calculate loop seal draining, it was also found that the CCFL model needs additional work and the interphase drag model is suspect. For these reasons, following the description of the steady-state calculation, the baseline transient calculation is described without the CCFL option. The sensitivity calculation, described immediately after the baseline calculation, shows the effect of including the CCFL option at the U-tube entrance. Another difference between the sensitivity calculation and the baseline calculation lies in the use of the ECCMIX component in the sensitivity calculation. However, the effect of the presence of the ECCMIX component is not very noticeable.

Steady State Calculation

During the stabilizing process, care was taken to obtain a satisfactory steady-state model condition to initiate transient calculation. A general method for obtaining steady state conditions was described in Ref. 7.

The boundary conditions were the pressurizer pressure, the core power, the primary pump velocities, and the feed water injection rates. The steady-state condition was obtained by connecting a temporary time dependent volume to the pressurizer top. The downcomer-to-upper head bypass flow rate was matched by adjusting the area of a single junction between the downcomer inlet and the upper head.

It should be noted that without adjusting the steam generator secondary U-tube heated equivalent diameter, the correct primary-to-secondary energy transfer could only be obtained with an average primary temperature that was too large. Consequently, the U-tube heated equivalent diameter was adjusted accordingly (this dimension is set to the minimum tube-to-tube spacing to adjust for multi-dimensional flow patterns in the steam generator secondary - see Reference 9).

Table 1 shows a comparison between measured and calculated values. Most parameters were obtained within the experimental uncertainty range except the pressurizer level and steam generator differential pressures. However, these differences exerted a negligible influence on the calculation.

Transient Calculation

This section describes a comparison between test results and predictions obtained using the input model without the CCFL option and ECCMIX components. Key results are illustrated in Figs. 2 through 7; solid lines represent RELAP5 calculations and broken lines represent experimental data.

The chronology of major predicted and calculated events are compared in Table 3. The chronology prior to the time when the secondary pressure level exceeded the primary pressure level, i.e., primary/secondary pressure reversal, shows good agreement with measured values. However, after the secondary pressure exceeded the primary pressure the chronology shows the calculated events occurred before the measured events.

The calculated and measured break mass flow rates are compared in Fig. 2. The correspondence between the calculated and measured values is reasonable throughout most of the transient. The calculated values are usually greater than the data although the calculated transition, resulting from loop seal clearing, occurs at about the same time as the data.

Fig. 3 shows that agreement between measured and calculated pressures is reasonable. After the loop seal clearance (about 137 s), the primary pressure drops below secondary pressure. The predicted primary depressurization rate is too high between 150 and 350 s. In this study, the calculated primary pressure is probably less than the data due to an overcalculated break mass flow and a faulty calculated primary mass distribution, i.e., less saturated inventory in the core than present in the test. Analysis of these effects is continuing. Similar primary calculated pressure behavior was reported in an assessment study of RELAP5/MOD2 cycle 36.05 based on the ROSA IV LSTF SB-CL-18 by G. Rouel and L. Vanhoenacker [10]. They explained the low calculated primary pressure could be caused by a low calculated core steaming rate. After 300 to 350 s, the pressure is sustained when inventory provided to the core, following accumulator injection, reaches saturation and boils.

A comparison between the calculated and measured secondary pressure (see Fig. 3) shows the secondary pressure increases after the break opening because of energy transfer from the primary system and isolation of the condenser. After the relief valve opened (from 19 to 156 s), the secondary pressure decreased because of energy loss to the environment. These effects were clearly shown in the calculation.

The integrated injection flow rate from the loop 2 accumulator is plotted in Fig. 4. The measured accumulator injection was continuous whereas the calculated accumulator injection was intermittently terminated. The calculated periodic interruptions in the accumulator flow, apparent in Fig. 4, result from short-lived decreases in the primary depressurization rate such that the difference between the accumulator and cold leg pressures was not great enough to sustain injection.

The total calculated and measured primary fluid inventory history is plotted in Fig. 5. The calculated and measured values show good agreement until loop seal clearance. Afterwards, the calculated decrease is larger than the experimental value until accumulator injection. The divergence between the calculated and measured values results from the difference in the break flows shown in Fig. 2.

The calculated and measured core collapsed liquid levels are compared in Fig. 6. Both the calculation and the data indicate the minimum core liquid level at 150 s following loop seal clearing. It should be noted that even though the BETHSY loop seal lower elevation is located at the core midplane, i.e., 1.8 m above the bottom of the heater rods, the core level was depressed to the 1 m elevation in the data and 0.8 m in the calculation. Consequently, some of the primary inventory was held up in the U-tubes and possibly the steam generator inlet plena. Following loop seal clearing, the calculated core level was in general below the measured value. Such a difference indicates that the calculated primary mass distribution is different from that of the test. The difference may indicate a flaw in the code's interphase drag model.

Fig. 7 shows the calculated and measured rod surface temperature history at the 2.028 m elevation from heated fuel rod bottom. It should be noted that even though a heatup was indicated by some of the heater rod temperature data at the time of core liquid level depression (see Fig. 7), most of the data showed no heatup. Core heatup just before loop seal clearing was not predicted in agreement with most of the heater rod data. Later in the transient, the calculation indicated that the core would heatup during the core boiloff. This was caused by the underpredicted core collapsed liquid level following loop seal clearing since the code was unable to match the measured primary inventory distribution (see Fig. 6).

Sensitivity Calculation

This section describes the impact of changes in the input data caused by including the CCFL option and ECCMIX components. The CCFL option was used at junctions at the entrance to the U-tube bundles. The Wallis flooding correlation was used to calculate CCFL at the U-tube inlets. The ECCMIX components were used in the cold leg components where accumulator liquid was injected. The results of the sensitivity calculation were similar to the results of the base calculation. However, the liquid held up in the U-tubes and the quantity of steam condensed during the accumulator injection differed in the two calculations.

Fig. 8 shows the effects of the CCFL option at the U-tubes inlet junction. The circles denote the results obtained in the base calculation without CCFL model while the cross symbols denote the results of the sensitivity calculation. The data are for the transient times indicated. The dotted line shows the flooding envelope described by the Wallis flooding correlation. The CCFL model lessens the liquid reflux so additional liquid holdup is calculated in the steam generator upflow side. However, the predicted results showed the CCFL model was activated intermittently under countercurrent flow conditions rather than at every time step when CCFL conditions should prevail. This code deficiency is under investigation.

To investigate the effect of using the ECCMIX component, a model developed for a large break LOCA analysis, condensation rates at the injection location are plotted in Fig. 9. The figure shows larger quantities of condensation when the ECCMIX components are used than observed in the base calculation. However, the larger condensation rates did not appreciably affect the transient thermal-hydraulic behavior and do not appear to be unduly large. Consequently, no conclusions were reached concerning whether the ECCMIX component should be used for a SBLOCA transient of this sort.

The collapsed liquid level in the core is compared in Fig. 10 for the two calculations and the data. The maximum depression before loop seal clearing was increased by increased liquid holdup due to the CCFl model in the sensitivity calculation. As a result, the calculation including the effect of the CCFL model shows less agreement with the data than the baseline calculation at the time of the core liquid level depression.

CONCLUSIONS

The post-test calculation of the BETHSY test 6.2 TC cold leg SBLOCA was performed using RELAP5/MOD3 version 7o, and the predicted results were compared with experimental data. The overall conclusions of the assessment calculations are as follows:

1. The code calculation showed reasonable agreement with the data.

2. The RELAP5/MOD3 CCFL model was found to be deficient.

3. Further analysis is required to evaluate the code's capability to calculate primary mass distribution during SBLOCAs.

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Table 1. Initial and boundary conditions for BETHSY test 6.2 TC

Parameters	Experimental	RELAP5
Core Power* (kW)	2863 ±30	2863
Pressurizer Pressure* (MPa)	15.38 ±0.15	15.38
Pressurizer Level (m)	7.45 ±0.2	7.19
Pressurizer DP (kPa)	39.69 ±1.2	39.78
Primary Pump Speed* (rpm)		
VP1	238 ±6	238
VP2	237 ±6	237
VP3	241 ±6	241
Core Inlet Temperature (°C)	284 ±1	284.6
Core Outlet Temperature (°C)	315 ±1	315.6
Core Delta T (°C)	31 ±1	31.0
Primary System Mass (kg)	1984 ±50	1972
- w/o Pressurizer (kg)	1812 ±50	1798
Seconaary System Pressure (MPa)		
SG 1	6.86 ±0.07	6.81
SG 2	6.84 ±0.07	6.81
SG 3	6.84 ±0.07	6.81
Steam Generator Level (m)		
SG 1	11.2 ±0.5	11.2
SG 2	11.1 ±0.5	11.2
SG 3	11.1 ±0.5	11.2
Steam Generator DP (kPa)		
SG 1	80.86 ±1.8	75.96
SG 2	80.62 ±1.8	76.04
SG 3	80.70 ±1.8	75.73
Feed Water Temperature* (°C)	250 ±4	250
Feed Water Flow* (kg/s)	0.55	0.55
UH/DC Bypass flow (%)	0.28	0.27
Environmental Heat Loss (kW)	54.82	54.61

Note: * denotes the boundary condition for calculations

Table 2. Chronology of BETHSY test 6.2 TC

Time(s)	Events
0	Break valve opening
8	Reactor scrammed (P < 13.0 MPa)
	- Core power was decayed following the JAERI conservative curve after 53 s delay time
	- Primary pumps stop
	- Main feed water supply stop
	- Condenser was isolated
	- SG relief valves were set to 7.2 MPa
12	SI signal (P < 11.7 MPa)
	- No action (no HPI)
341	Accumulator activated with 4 delay time (P < 4.2 MPa)
948	Accumulator 3 was stopped by a level criterion
976	Accumulator 2 was stopped by a level criterion
2179	Test stopped (P < 0.7 MPa)

Table 3. Comparisons of calculated and measured Test 6.2 TC chronology

Events	Experimental	Base Cal.
Scram Signal (s)	8	5.34
SI Signal (s)	12	10.58
Loop Seal Clearing (s)	134	137
Primary/Secondary Pressure Reversal (s)	172	161
First Core Uncovery		
- Minimum CCLL (m)	1.0 $\pm$0.1	0.82
- Maximum Rod Temperature Rise (°C)	70	0
Second Core Uncovery		
- Minimum CCLL (m)	1.6 $\pm$0.1	1.18
- Maximum Rod Temperature (°C)	0	30
Loop 2 Accumulator Injection (s)	345 - 948	294 - 701
Loop 3 Accumulator Injection (s)	345 - 976	294 - 693
Test Stop (s)	2179	1800.3

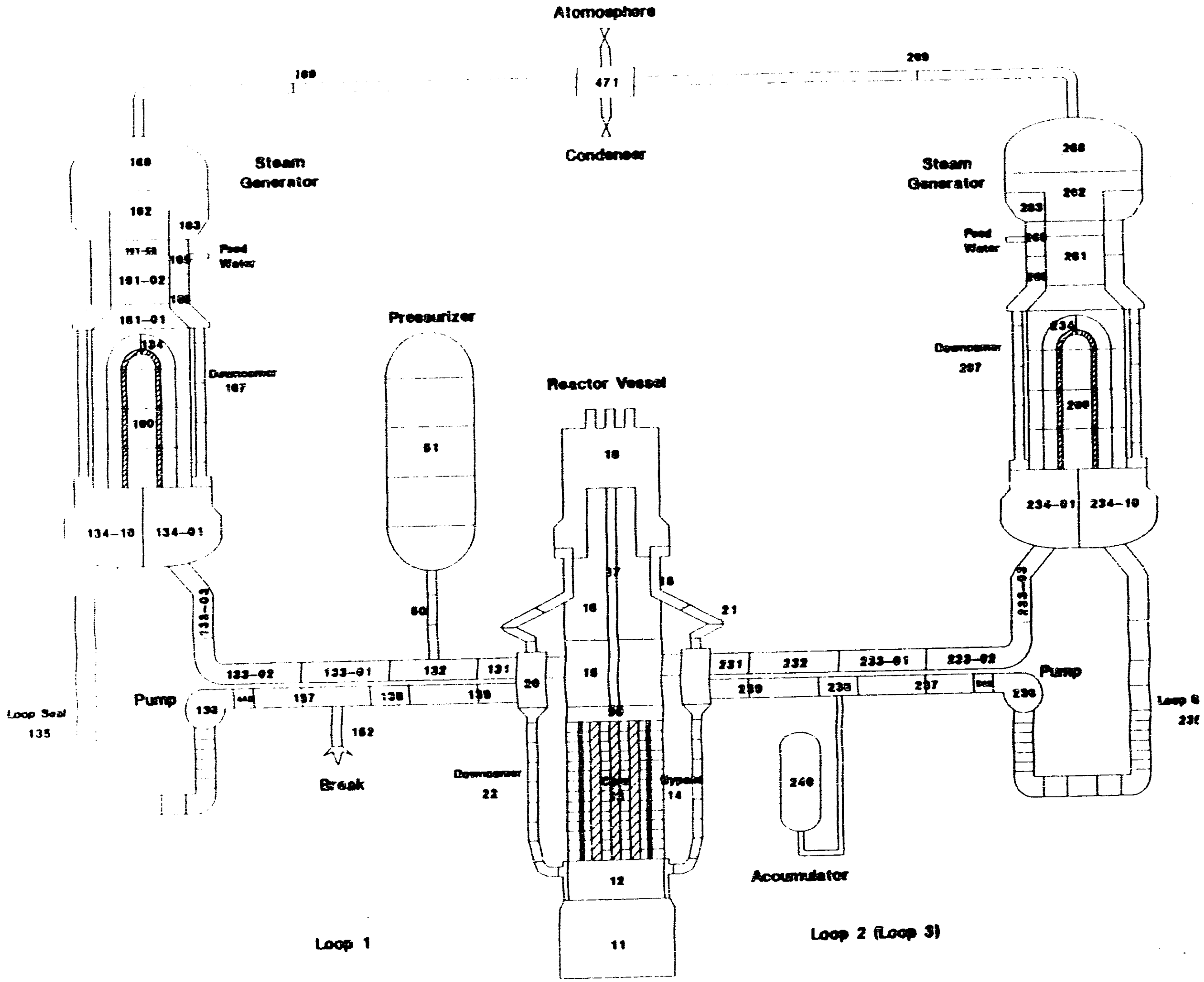

Fig.1 RELAP5 nodalization diagram of the BETHSY integral facility

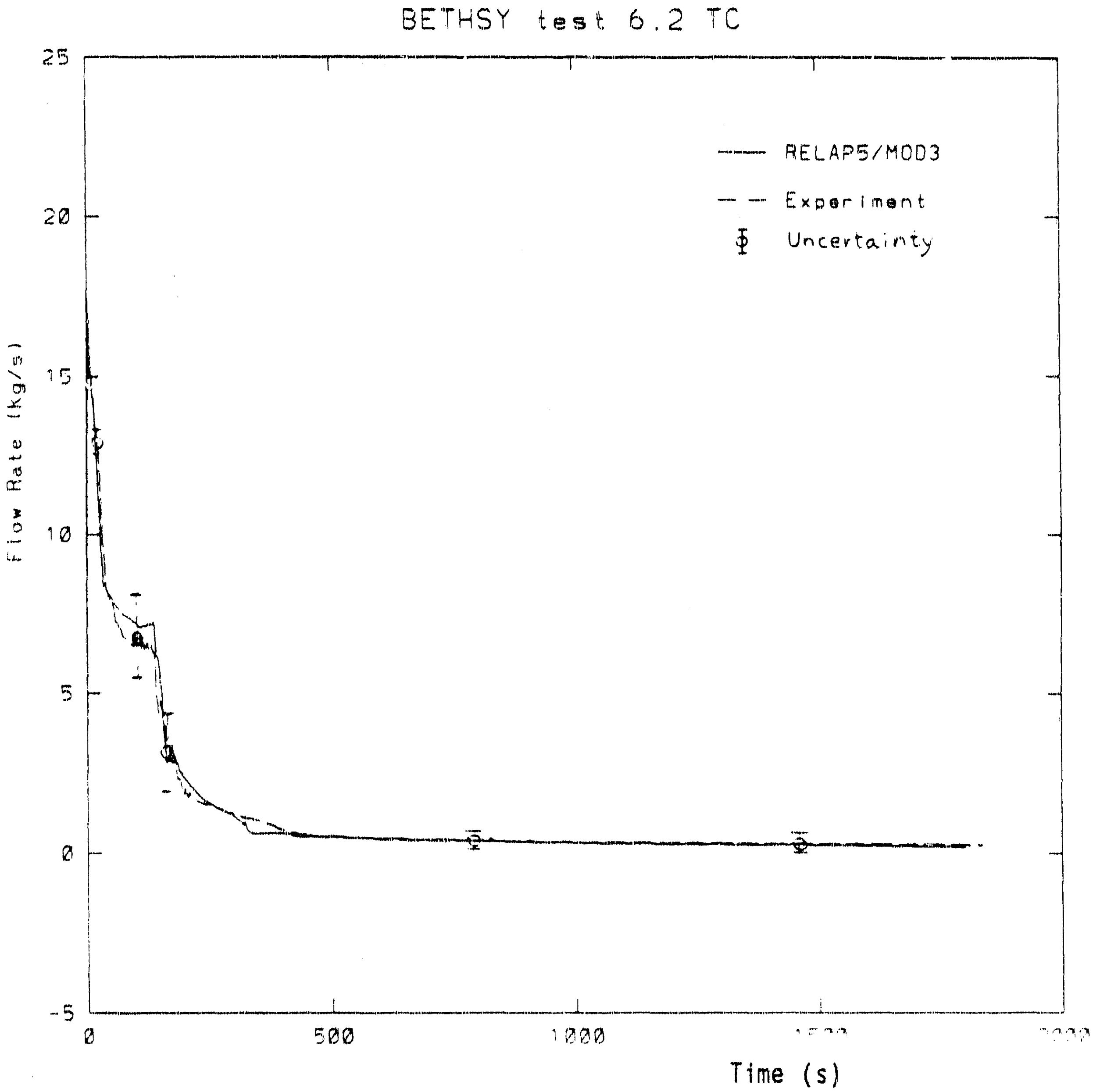

Fig.2 Break mass flow rate

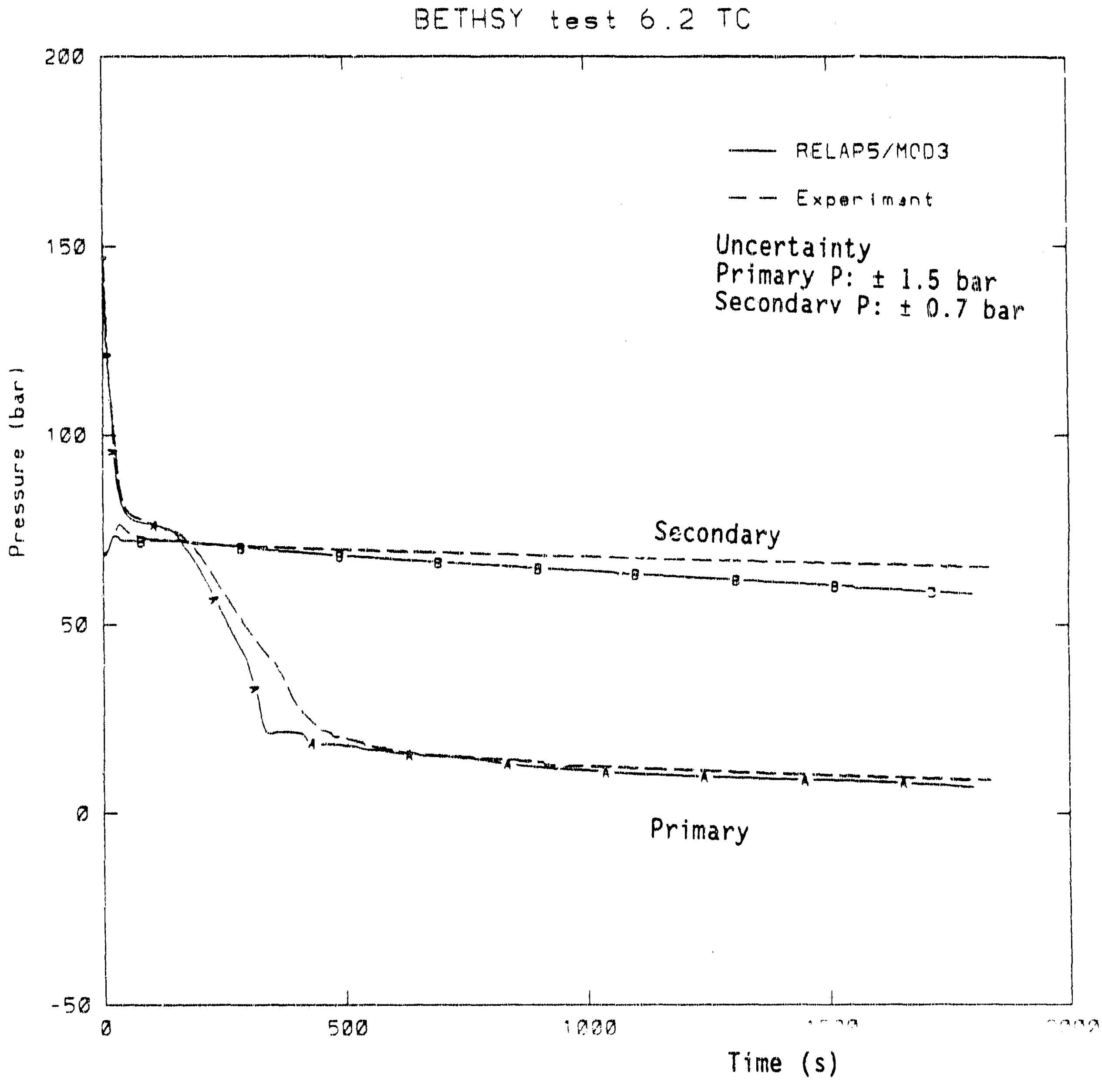

Fig.3 Primary system pressure at the pressurizer top and secondary system pressure at the steam generator of Loop 1

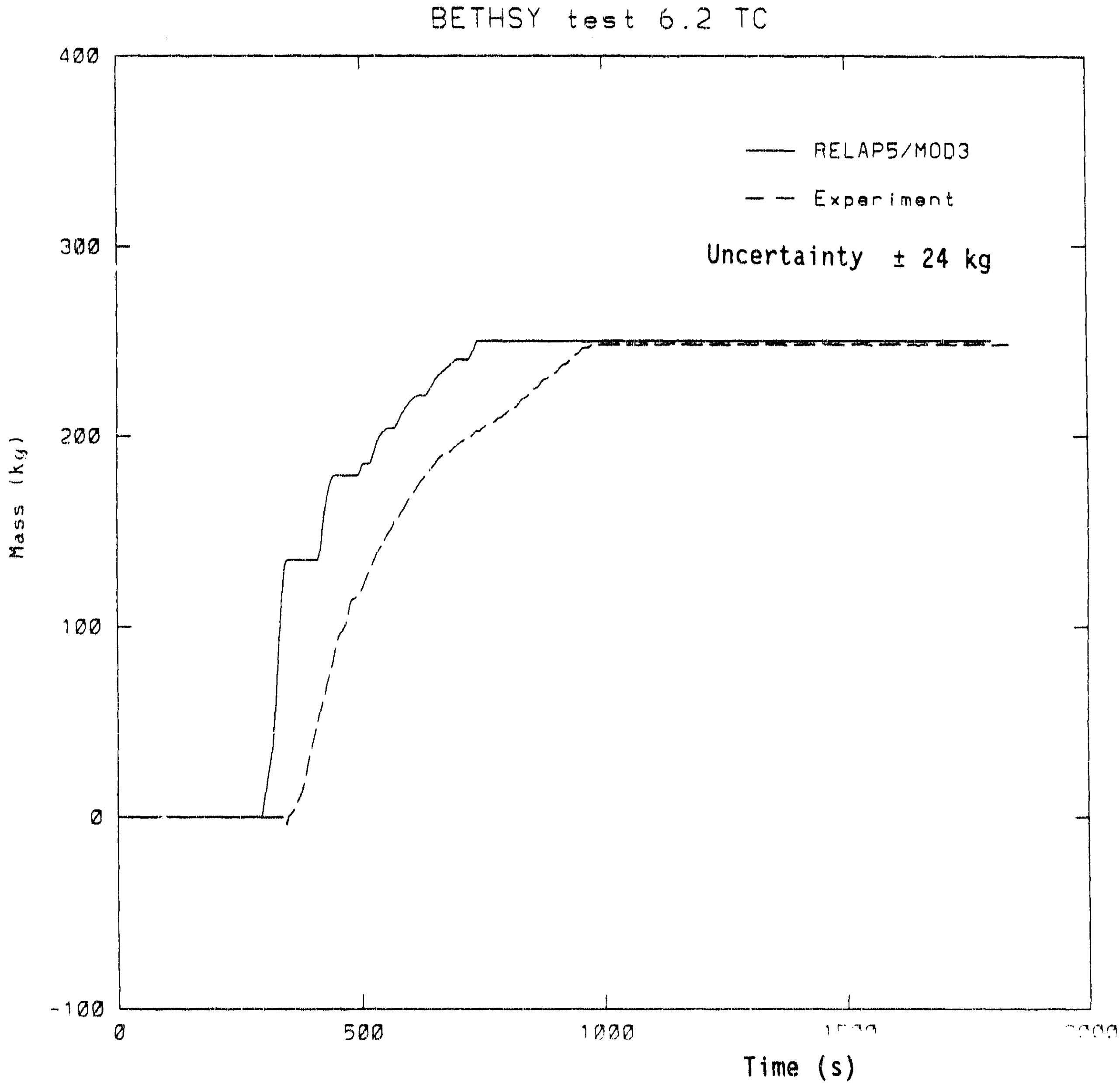

Fig.4 Integrated accumulator injection mass flow

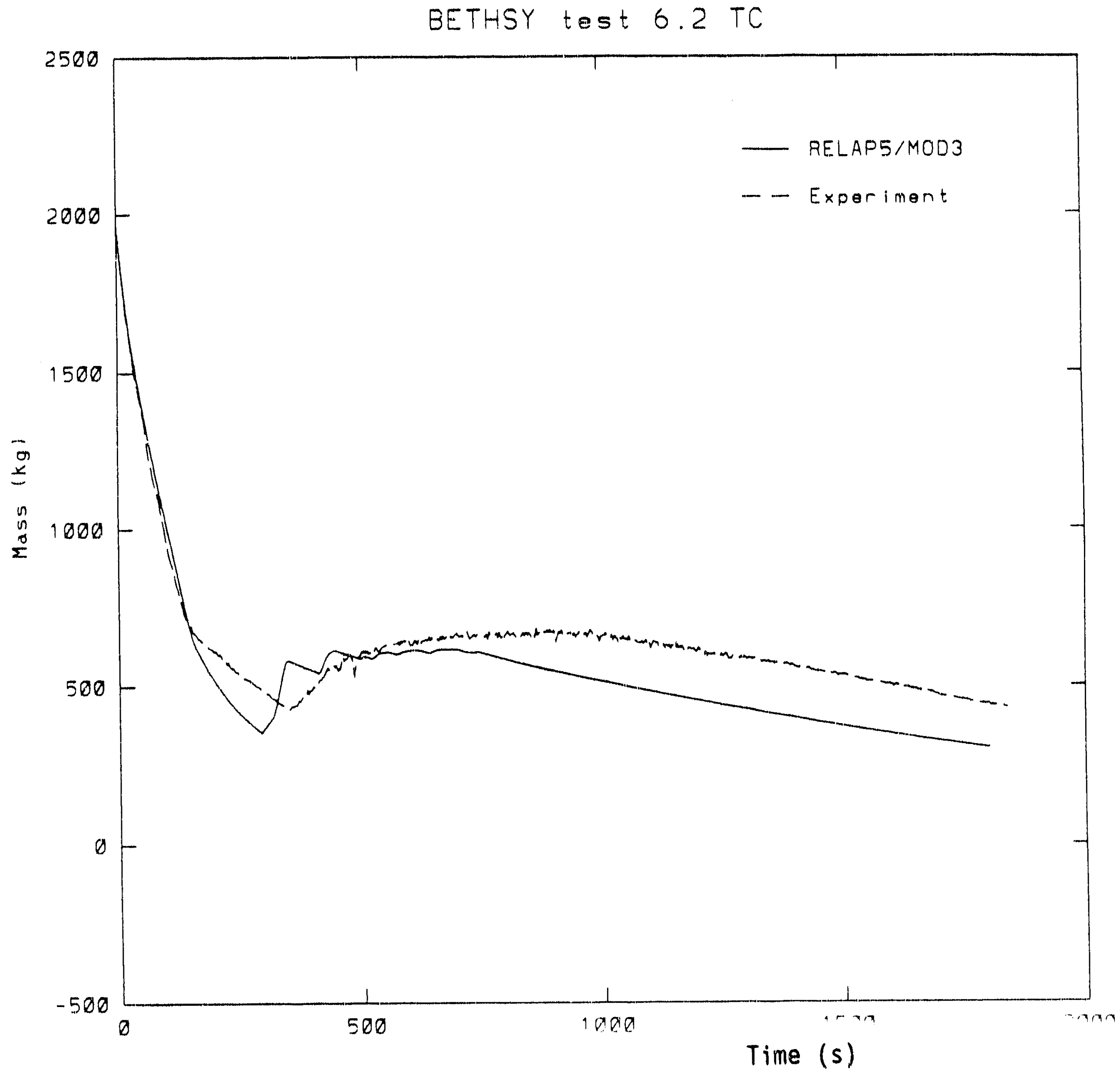

Fig.5 Total amount of primary system mass

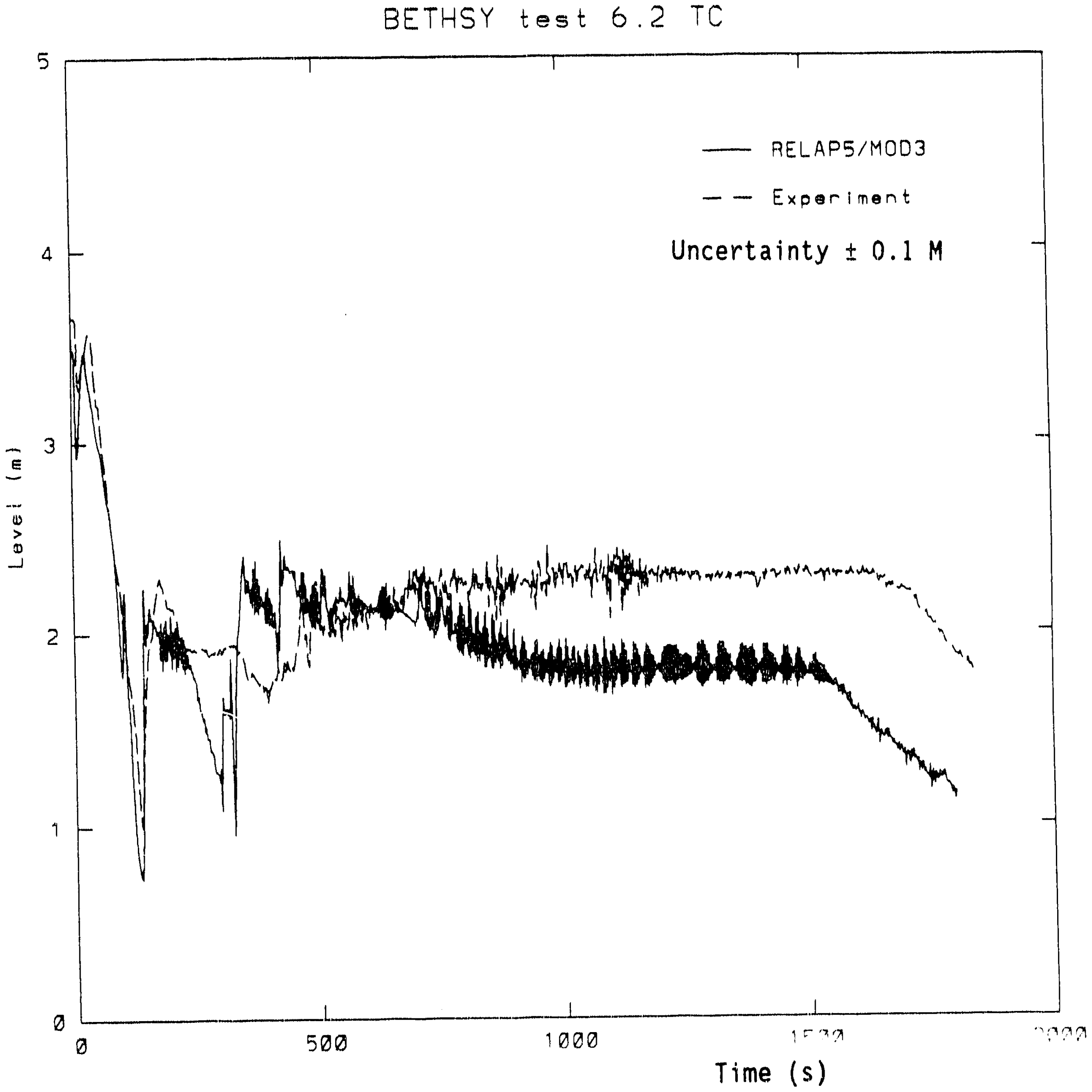

Fig.6 Collapsed liquid level in the heated core

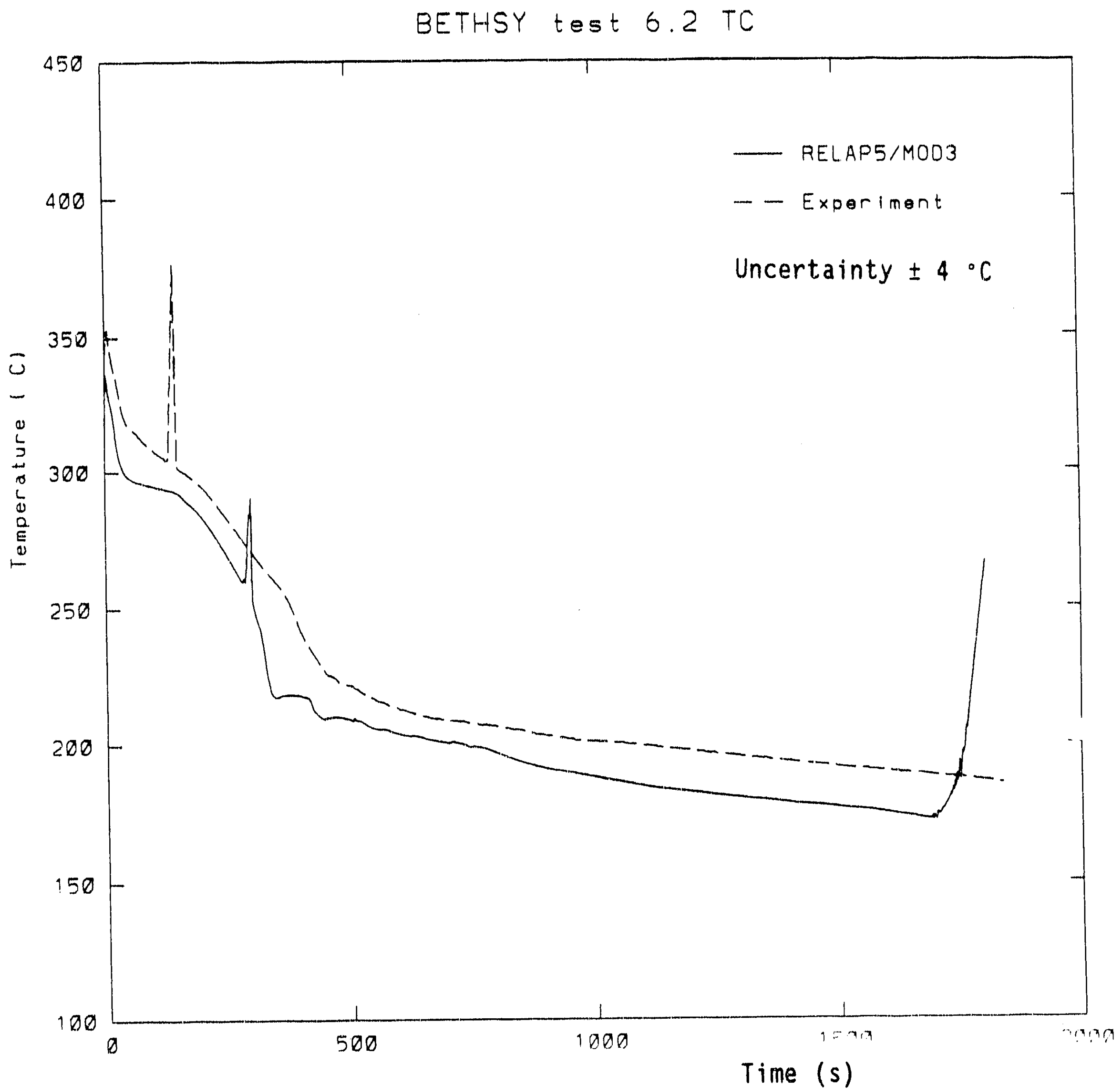

Fig.7 Rod surface temperature at 1.628 m elevation

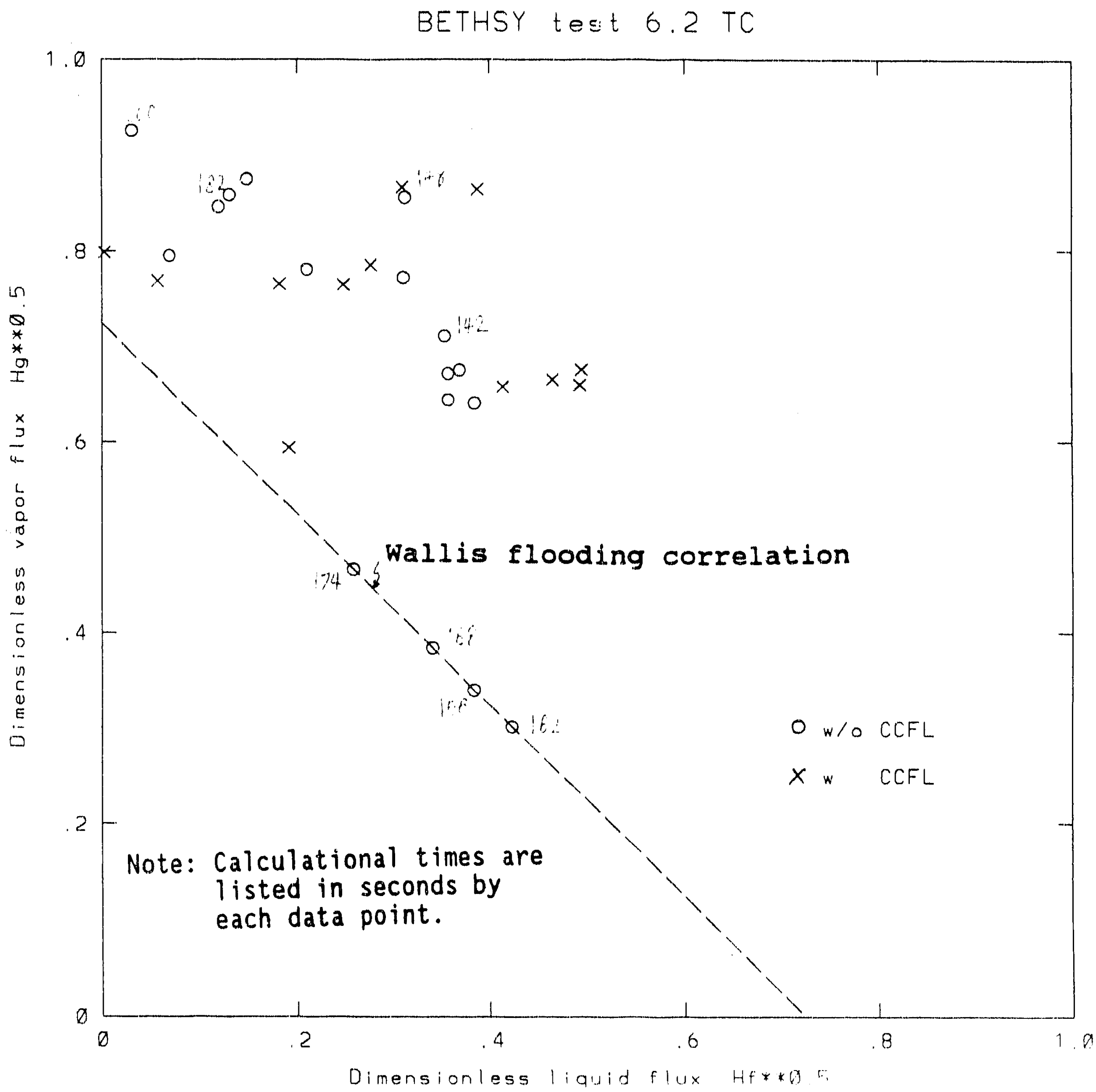

Fig.8 CCFL in the broken loop steam generator U-tubes

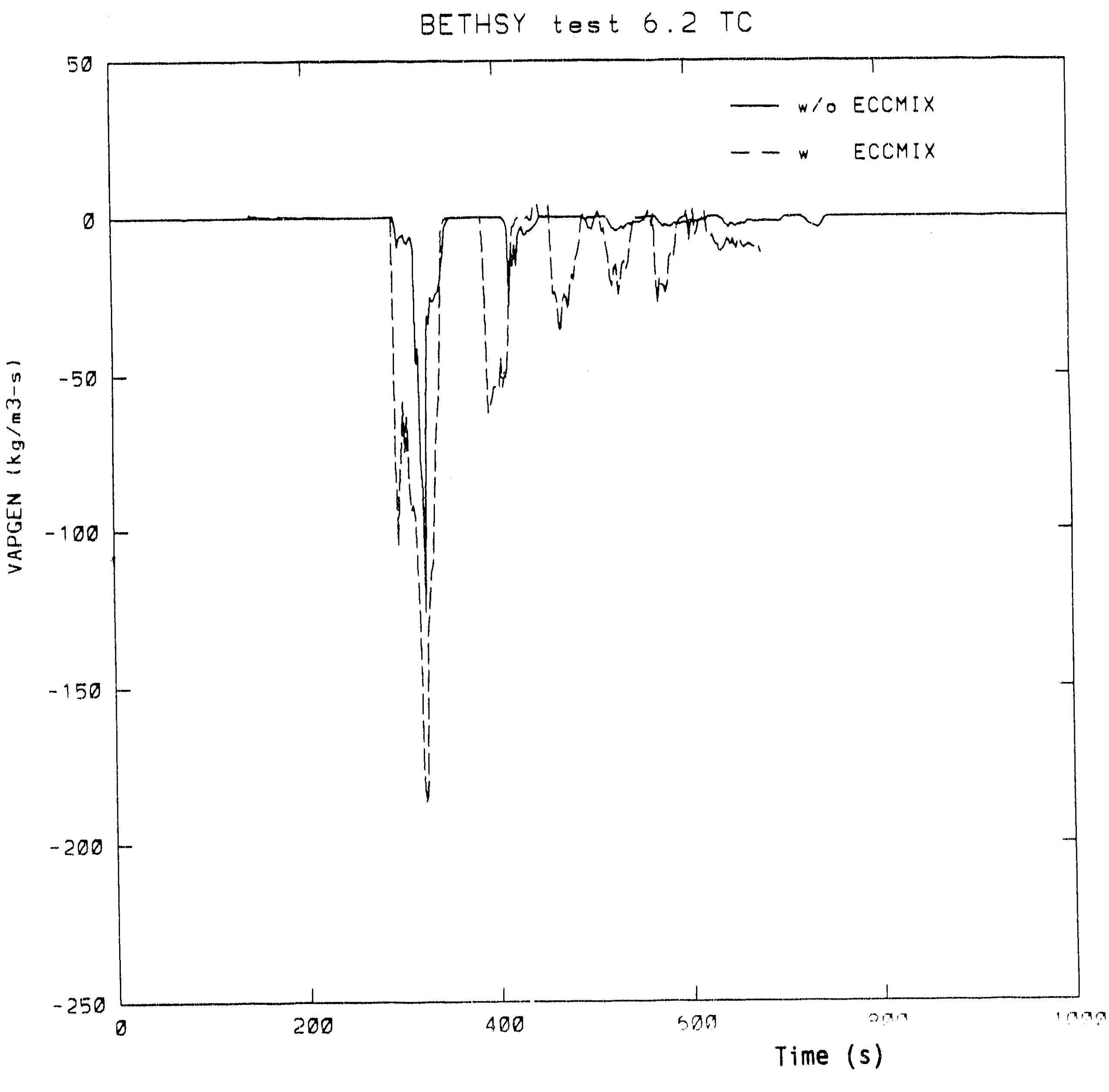

Fig.9 Condensation rate per unit volume ar the ECCMIX component

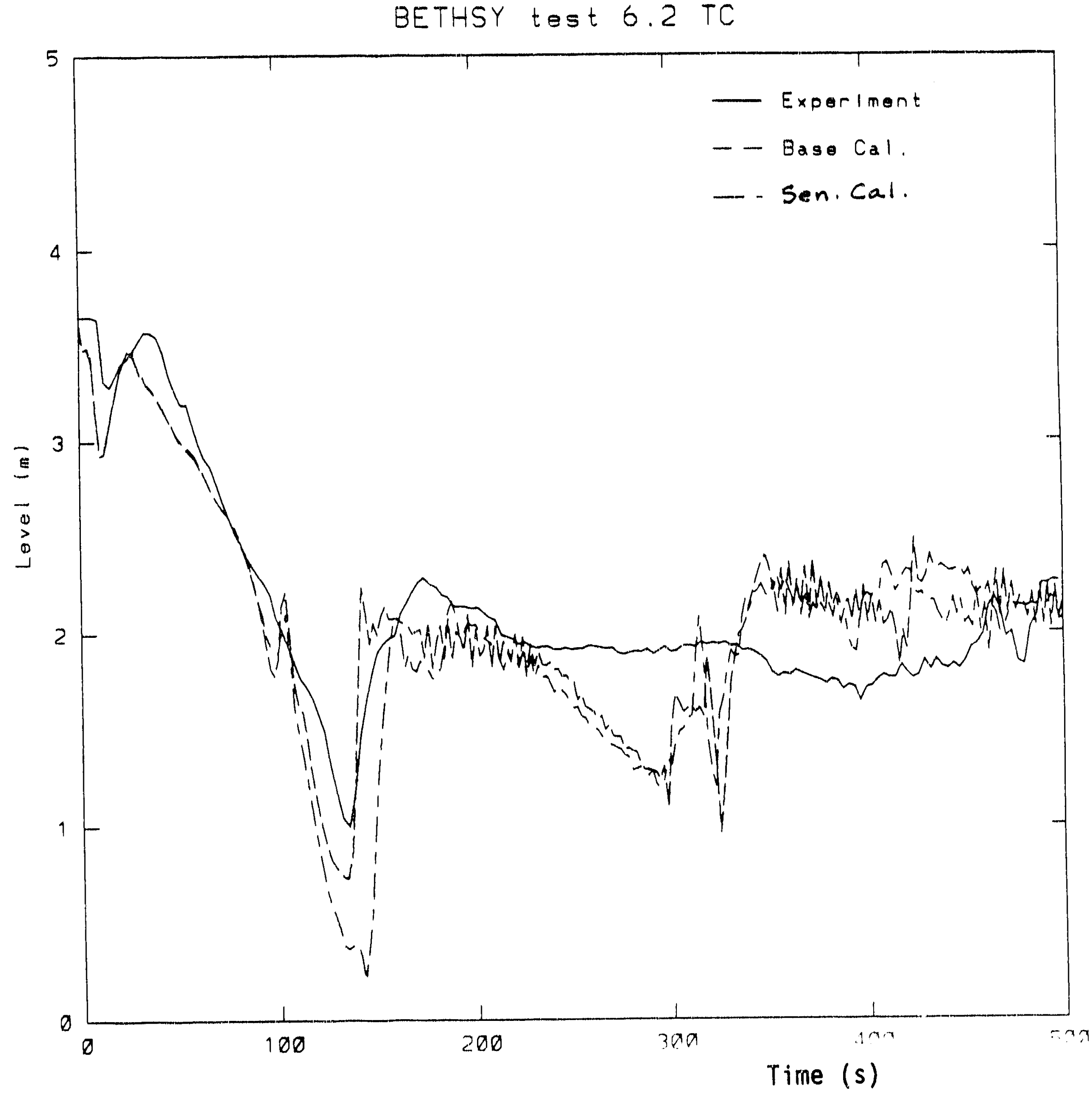

Fig.10 Comparison of collapsed liquid level in the heated core

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