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International Agreement Report

RELAP5/MOD3 Analysis of BETHSY Test 6.9c: Loss of RHRS: SG Manway Open

Prepared by

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ABSTRACT

Accidents associated with a loss of the Residual Heat Removal System (RHRS) during PWR shutdown operation have received attention in recent years. Typically such events occur at low pressure and low core power.

A series of tests, 6-9a-d, has been performed in the BETHSY Integral Test Facility at Grenoble, France, to address the safety issues posed in this type of incident. The data from Tests 6.9a,c & d are available to the AEA Technology through its membership of the BETHSY Club.

Tests 6.9a & d have been analyzed in previous years. Test 6.9c, the subject of this report differs from previous tests as it simulates plant conditions following a loss of RHRS when the primary circuit is open in two places; one at the pressuriser manway and the other at the steam generator outlet plenum. There is thus the potential for a large inventory loss from the primary circuit and a deep core uncovery. This did in fact occur. The analysis of this test is directly relevant to PWR thermal hydraulics safety issues associated with loss of RHRS.

The analysis has been performed using the latest release version of RELAP5, i.e. MOD3.2. The main phenomena occurring during this rest are well represented by the calculation. The calculated primary circuit peak pressure matches the experimental value. The reduction in pressure following the peak is, however, delayed due to water draining from the steam generator and being entrained into the pressuriser.

The cladding temperature rise is delayed and the start of the gravity feed is about 150s late. Ultimately, however, the experimental peak clad temperature is matched to within 15°C. The mass error associated with the calculation is less than 10% for most of the transient.

It is concluded that the broad characteristics of the transient would be experienced in a similar scenario for PWR plant. The analysis will also form the UK submission for the International Standard Problem 38 being hosted by AEA Technology at Winfrith.

CONTENTS

1. Introduction 1

2. Rig configuration 2

3. RELAP5 model 3

4. Initial conditions 3

5. The transient and RELAP5 calculation comparison 4

  5.1 Phase 1 (Os - 2670s) 4
    5.1.1 Pressure response 4
    5.1.2 Flow in control rod guide tubes 5
    5.1.3 Core bypass recirculation 5
    5.1.4 Hot leg 1 conditions 6
  5.2 Phase 2 (2670s to 5660s) 7
  5.3 Phase 3 (t=5660s to 9044s) 7
  5.4 Mass error 8

6. Implications for large PWR plant 8

7. Conclusions 9

Acknowledgement 10

References 11

LIST OF FIGURES

Fig. 1. Schematic diagram of rig circuits
Fig. 2. Primary cooling system - Plan view
Fig. 3. Primary cooling system - Elevations
Fig. 4. Pressure vessel - General view
Fig. 5. Pressuriser manway configuration
Fig. 6. SG1 outlet plenum manway configuration
Fig. 7. Identification of transducers in the vessel
Fig. 8. Identification of transducers in the loops
Fig. 9. RELAP5 noding scheme for BETHSY integral facility
Fig. 10. RELAP5 noding for BETHSY vessel
Fig. 11. RELAP5 noding for BETHSY loop 1
Fig. 12. RELAP5 noding for BETHSY loops 2 & 3
Fig. 13a. Hot leg 1 void fraction (0.0 to 4000s)
Fig. 13b. Hot leg 1 void fraction
Fig. 14. DP in surge line
Fig. 15. DP in pressuriser
Fig. 16. DP in hot leg 1 vertical section
Fig. 17. DP in SG 1 inlet plenum
Fig. 18. DP in SG 1 tubes
Fig. 19. Upper plenum pressure
Fig. 20. DP in intermediate leg 1 - pump side
Fig. 21. Total mass flow through upper head - downcomer link
Fig. 22. Steam mass flow through upper head - downcomer link
Fig. 23. Flow through core bypass
Fig. 24. Core inlet temperature
Fig. 25. Liquid fractions in hot leg 1 volumes
Fig. 26. Integrated mass flows near surge line
Fig. 27. Integrated mass flows in hot leg 1
Fig. 28. Pressuriser manway discharge rate
Fig. 29. SG outlet plenum manway mass discharge
Fig. 30. DPs in intermediate leg 1
Fig. 31. Gravity feed mass flow rate
Fig. 32. DP in core
Fig. 33. Primary circuit mass
Fig. 34. Peak clad temperature
Fig. 35. Mass error(1), cpu time (2), & relative mass error (3)
Fig. 36. Primary circuit mass with mass error correction

1. Introduction

A safety issue of primary concern is the management of PWR plant following the loss of the Residual Heat Removal System (RHRS), particularly if the primary circuit is open and partially drained. The system pressure will be low, typically < 3 bars, and core power will be about 0.5% of its nominal value. The analysis of such situations has not hitherto received as much detailed attention as other transients. Following an incident at the PWR plant at Vogtle in 1990 the USNRC commissioned studies by INEL[1 & 2] to investigate the key phenomena involved in this type of event. Subsequent PSA, both in France and the USA, highlighted the importance of cold shut down scenarios as a contributor to core melt frequency. The scenario is also important in considering plant management during refuelling and maintenance.

There is a series of BETHSY Tests (6.9a-d) which is directly related to this issue. The BETHSY test rig [3] is a 1/100 scale, 3-loop integral facility at Grenoble, France, and has the capability for tests relevant to a wide range of LOCA and non-LOCA transients starting from both full power and shutdown conditions. Figure 1 shows a schematic diagram of the rig circuits. The data for Tests 6.9a, c and d are available to the AEA Technology through membership of the BETHSY Club.

The overall purpose of BETHSY Test 6.9c [4] was to study the accident transient following the loss of the Residual Heat Removal System during mid-loop operation with the primary circuit open at the pressuriser and steam generator outlet plenum manways. This is a more severe condition than Test 6.9a[5], analysed previously, where only the pressuriser manway is open and contrasts with Test 6.9d[6] where there were only very small vents open. There is a significant loss of primary mass inventory in Test 6.9c which results in core uncovery and heat-up. These are arrested by an emergency water supply to the primary circuit driven by gravity alone.

The aims of the test (as specified by CEN, Grenoble) are to study:

a) the entrainment and temporary retention of water in the pressuriser caused by the steam flow escaping via the pressuriser manway,

b) the sensitivity of the entrainment phenomenon to steam velocity in the hot legs,

c) the level swell in the upper head,

d) the expulsion of water through the steam generator manway,

e) the level of pressurisation, which could jeopardise the effectiveness of the gravity feed,

f) the re-flooding and re-filling of the core from the gravity (and, if necessary, forced) emergency core cooling water injection.

For the analysis the underlying objectives of this work are:

- To assess the potential of RELAP5/MOD3 [7] in:
  a. addressing the key safety issues associated with accidents at shutdown,
  b. predicting the effects of possible accident management procedures.
- To provide a UK submission to ISP38 to benefit from the comparison of results with those of other participants.
- To provide UK input to the BETHSY club and to take full advantage of the benefits of the BETHSY club membership.
- To provide RELAP5/MOD3 assessment required as part of the UK commitments to the CAMP agreement.

This particular programme of work includes:

1. an analysis of the test procedures and the overall course of the transient;
2. an assessment of RELAP5/MOD3 models for mid-loop operation at low pressure;
3. an assessment of the implications for PWR plant accident analysis.

This report describes the analysis of the transient with RELAP5/MOD3.2, the latest release version. The calculation will form the basis of the submission to ISP38. Previously, in the interim report [8] on this work, the transient had been calculated with the development version MOD3.1.2. Although it was found that there were differences in the results in detail, broadly the two calculations were very similar. It was, however, necessary to incorporate some changes in the noding for RELAP5/MOD3.2 so a direct comparison was not practical.

The calculation with the new code version will be acceptable as a CAMP in-kind contribution. Furthermore, it is expected that the majority of participants to ISP38 will be using RELAP5/MOD3.2 so the comparison will be more meaningful.

The rig configuration is described in Section 2 and the RELAP5 model changes for this test are outlined in section 3. The initial conditions for the test are explained in section 4. The transient is described in section 5 together with a discussion on the performance of RELAP5 in modelling the test. The implications for PWR plant are highlighted in section 6 and finally, in section 7, conclusions are drawn based on the analysis of the test.

2. Rig Configuration

A schematic diagram of the BETHSY rig circuits is shown in figure 1 and their plan and elevation are shown in figures 2 and 3 with a more detailed diagram of the vessel in 4.

The basic configuration for this test can be summarised as follows.

The manway openings were represented by calibrated orifices with fast acting valves downstream. The pressuriser manway was connected to the top of the pressuriser. The steam generator outlet plenum manway was connected to a branch in intermediate leg 1 just below the SG outlet plenum and 720 mm above the hot leg axis. The details of the manways are shown in figures 5 & 6.

The pressuriser was connected to loop 1.

All the steam generators were drained down and isolated.

For reference, the positions and the identification of the primary circuit instruments are shown in figures 7 and 8. The identifications are on all the graphs showing the experimental results.

3. RELAP5 model

The same basic nodalisation scheme, figures 9 to 12 , as used for the calculation of Test 6.9a was employed in this calculation. The changes to the deck were relatively few and will be described here.

The SG manway was represented by a horizontal pipe and orifice at the correct level in the SG side of the intermediate leg. The discharge coefficient of the orifice was set in agreement with the test report [4]. This was also done for the pressuriser manway. The gravity feed was represented by a time dependant junction with the pressure characteristic taken from the test report.

The number of hydraulic cells in the core has been chosen to match the heater rod structures. All except the end nodes are 0.26m high. A reasonably fine noding was recommended at the recent CAMP meeting [9] for this type of transient.

4. Initial Conditions

The test represented a reactor in a shut down condition with the loops filled to the mid-loop level. In BETHSY, this means that at the start the hot legs were half full of water, but the cold legs, being at a lower elevation, were completely full. For this test there was only water vapour in the parts of the circuit above the liquid level. The pressure was close to atmospheric and the core power off.

The heat losses (primary and secondary) were balanced by the rig trace heating. The trace heating on the primary circuit was maintained constant throughout the transient. The secondary side trace heating was controlled to maintain a constant wall temperature of 105°C for the lower part of the SG riser throughout the transient.

The primary circuit temperatures were very near to saturation except in the cold leg where the temperature was about 10 °C subcooled due to the effect of the pump cooling and the instrumented section where there was no trace heating. During the drain down phase of the experiment (not modelled) cold water from the pump seal/bearing cooling tended to be drawn along the cold legs.

For the calculation the initial conditions were set by starting with the primary circuit full and draining it down to mid loop level. It was necessary to provide a temporary cold feed to the cold legs just before the transient was started in order to establish the lower temperatures observed there.

5. The Transient and RELAP5 calculation.

The test was started by opening the manway isolation valves and increasing the core power to 138kW which represents about 0.5% of nominal reactor power.

The overall course of the transient can be separated into three relatively distinct phases:

- in the first phase (0-2670 s) the two phase level in the vessel remained close to the level of the hot leg axis;
- in the second phase (2670-5660 s) the mixture level fell below the hot leg nozzle and started to uncover the core until the gravity feed was triggered;
- in the third phase (5660-9044 s) the core refilled under the action of the gravity feed until the mixture reached the hot leg nozzles again.

These phases will now be described individually and compared with the calculated results.

5.1 Phase 1 (0s - 2670s)

As the liquid was close to the saturation pressure at the start of the test, the increase of core power and the opening of the manways led to rapid boiling and the entrainment of water into hot leg 1, thence in to the surge line and pressuriser. Two phase mixture was also entrained into the vertical sections of the hot legs and into the up-flow side of the SG1 u-tubes, (figures 16 to 18).

5.1.1 Pressure response

By comparing the calculation with the experimental data, figure 13a & b, it is clear that the void fraction in hot leg 1 is well matched. The entrainment in the surge line (as reflected in the DP measurements), figure 14, and the pressuriser, figure 15 are also well matched. After the start of the transient, less water is entrained into the pressuriser surge line from the hot leg. This allowed the water to drain down from the pressuriser into the surge line. It appears that only a limited amount of water (possibly none) escapes from the surge line before it is driven back up into the pressuriser again. The cycle is repeated three times before the pressure falls. This complicated behaviour is reproduced quite well by the code but an extra cycle arises and the pressure fall is delayed.

The mixture also flows up into the SG inlet plenum and the SG1 tubes (up-side) only. The amount of water present in the vertical portion of the hot leg is in good agreement with the experiment, figure 16, but the liquid held-up in the SG inlet plenum is low, figure 17. Initially the hold-up in the SG1 tubes (up-side) is slightly high, but the peak is correctly predicted, figure 18. There is, however, late emptying of these components (figs 16,17,18)

The liquid entrainment in the pressuriser and surge line noted above leads to a rise in the upper plenum pressure during phase 1 of the transient. This is evident in figure 19 and it is seen that the calculation closely matches the initial pressure peak. As a consequence of the pressure rise, water is driven towards the SG manway from the cold legs. The DP measurement in the SG side of the loop seal is shown in figure 20. It is seen that the DP rise reaches 3.0×10^4Pa, the pressure required for liquid to flow out of the manway, but only for a short time (~200s) compared with 1000s in the test. It will be seen later, however, that the calculated flow through the manway over this short period is about the same as that over the longer period in the experiment.

In both the calculation and the test, the system pressure rise is not sufficient to cause the loop seal to clear in loop 1. The calculation, however, comes nearer to a clearance. After 2000s, when the pressure falls and the water redistributes itself, the intact loops refill completely but the loop seal only partially refills because more water had been ejected through the SG manway. There is sufficient water left, however, to provide a seal and prevent steam reaching the SG manway via the cold leg.

5.1.2 Flow in control rod guide tubes.

Some of the vapour generated in the core escapes up the control rod guide tube and down the upper head - downcomer link where it condenses in the downcomer inlet and cold legs which are emptying. This vapour flow is important as it reduces the rate of energy discharge from the primary circuit. The experimental results indicate that the flow is only steam. The calculation over-estimates the mass flow, figure 21, due to the presence of some water being carried over but the mass flow of the steam only is well predicted, figure 22. At its peak this flow represents about 25% of the vapour being generated in the core.

5.1.3 Core bypass recirculation

A further feature of this part of the transient is the core recirculation which occurs around the core and the core bypass. The flow is downwards in the core bypass and leads to subcooled water reaching the bottom of the core. There is a resultant effect on the core void fraction profile and the vapour generation. The flow is not measured in the rig but the estimated magnitude is 5 kg/s. Figure 23 shows that the calculation predicts about half this value (downwards flow is shown as positive). Prediction of the flow in the bypass is not straightforward because of the presence of formers maintaining the shape of the core shroud, which protrude into the core bypass gap. The discrepancy, however, is not fully understood. But, as the calculated flow at 2.5 kg/s is significantly greater than the steam boil-off rate of ~0.07 kg/s most of the water entering the core will be recirculated from the core bypass rather than drawn in from the lower plenum. Thus core inlet temperature will still be largely determined by the core bypass temperature. It can be seen, figure 24, that this is essentially correct: the main difference between the two curves occurs when the calculated pressure is higher than in the test.

5.1.4 Hot leg 1 conditions

The predicted conditions in the hot leg 1 have received some attention. Almost entirely throughout the transient horizontal stratified flow is calculated and this agrees with the interpretation of the gamma-densitometer beam traces from the test. Significant wave formation is not expected as the vapour flow is about 1/3 of the Kelvin - Helmholtz criterion for sustained wave production. The void fraction in hot leg 1 is well predicted although it remains at about 0.8 for about 1000s longer than in the test and doesn't empty completely as the experimental data appear to show.

Figure 25 shows the liquid fractions at each of the calculation volumes along the horizontal section of hot leg 1, with the bottom curve representing the volume nearest to the vessel. The average liquid fraction here is significantly lower than at the far end of the hot leg where it is almost entirely above 0.5. Liquid surges emanating from the vessel (indicated by peaks in the curves) *appear*[1] to be carried along the length of the hot leg. But surges which appear to come from the far end of the hot leg are not generally seen as significant increases in the liquid fraction close to the vessel. This suggests that there is a tendency for liquid from the steam generator tubes and inlet plenum to be entrained into the surge line as it flows back along the hot leg.

In figure 26 curves 1, 2 & 3 show the calculated integrated junction mass flows at the junctions before, after and at the surge line respectively. (Note: the vertical scale does not give a true value but the trends in the curves are correct and can be observed more easily). In curve 3 there are three short periods of a steep increase in the curve when a significant amount of water is entrained into the surge line. The first period is around 100s into the transient and is a result of the initial level swell as the liquid in the vessel boils. Subsequently there continues to be a flow along the hot leg, but there is no corresponding liquid entrainment into the surge line as the liquid fraction is too low. From around 750s water flows back from the steam generator for a short time but then there is a reversal of the flow and quite a sudden increase in the liquid fraction. This increase gives rise to a significant water entrainment into the surge line. Near 2000s there is a reversed flow along the hot leg and again further entrainment into the surge line.

An indication of the liquid entrainment into and out of hot leg 1 can be seen in figure 27. Plotted together for comparison are the integrated value of the liquid mass entrained into the

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[1] The full resolution of these points is not possible at the plotting frequency of these graphs.

hot leg nozzle, (curve 1), the pressuriser surge line (curve 2), the right angle bend at the end of the hot leg (curve 3) and the SG tube plate (curve 4). There is a significant entrainment into the hot leg nozzle, the surge line and the vertical part of hot leg 1 over the first 100s. but there is a delay of about 600s, while the SG inlet plenum is filling, before the liquid is entrained into the SG tubes. The reversed flow around 2000s (noted above) is seen to come from the emptying of the SG tubes and follows a reduction of entrainment into the hot leg.

5.2 Phase 2 (2670s to 5660s)

Throughout this phase the system pressure remains close to 1.02 bars because the pressuriser is empty. The core starts to uncover at about 3433s. There is no steam flow through the upper head bypass at this time. 30% of the vapour escapes through the pressuriser manway and 70% through the SG manway, via the SG tubes. Figures 28 & 29 show the calculation to be in good agreement during this phase.

From figure 30 it is seen that there is a slightly greater pressure at the pump side of the intermediate leg than at the SG side, which is a measure of the pressure loss experienced by the steam as it flows from the core to the SG manway. The difference is correctly reflected in the calculation, although the levels are lower because more of the loop seal liquid has been ejected. The result is taken as confirmation that the friction loss in the pathway from the upper plenum to the SG manway via the steam generator is correct.

At 5660s the core cladding temperature reaches 250 °C in the upper level of the core. At this temperature the gravity feed is triggered. The time is about 150s late in the calculation, figure 31. The collapsed level at this time, as indicated by the DP measurement is low by about 0.1m (figure 32), despite the fact that initially there is a significant under-prediction of the level. The actual mixture level is about 2 m above the bottom of the heated length.

5.3 Phase 3 (t=5660s to 9044s)

Since the system pressure is low the initial gravity feed is about at its maximum (0.125 kg/s) and this is approximately twice the estimated rate of boil off in the core. Thus there is sufficient flow to refill the core and primary circuit, figure 33.

The injection is into cold leg 3 and this causes condensation to occur in the region of the downcomer inlet. The flow in the upper head - downcomer link then becomes re-established in the test and the value is well matched in the calculation. There is not a sustained reduction of the flow in the pressuriser manway as occurs in the test. The effect is, however, evident in the SG manway discharge. The condensation does, however, help to maintain a low pressure level (~0.97 bar) in the cold leg and so the gravity feed is sustained. The core becomes re-covered by 6805s.

The maximum temperature reached by the heater rods was 305 °C, but this is over-predicted by 15 °C in the calculation, figure 34. The first peak in the calculation curve is at a level of 2.7m above the start of the heated length. The second peak is at 3.6m and this is also the level of the experimental curve.

In the calculation the temperatures at all the three upper zones i.e. >2.7m are similar whereas the experimental data show a peak of 450K at 2.7m rising to 575K at 3.6m.

Finally, the test was terminated when the hot leg void fraction was about 0.8 at 9044s. The calculation was extended to 10000s but the primary inventory, see figure 33, was not recovered.

5.4 Mass error

A matter of concern with RELAP5 calculations at low pressure has been the occurrence of mass error. The mass error is known to be sensitive to pressure, time step, and, as identified recently by PSI [10], the bubbly/slug interfacial shear package.

For the calculation presented here the run statistics are shown in figure 35. The mass error (curve 2) increases most rapidly during the first phase of the transient and after 6000 s. At its peak the mass error is about 20% of the primary mass inventory. If the mass error is added to the primary inventory then an almost perfect match to the experimental data results is obtained, figure 36. This confirms that the mass error is a ‘mass loss’. Inspection of the output file shows that the cells which have had the largest error are widely distributed around the circuit. The cell which recorded the largest mass error most frequently was in the intermediate leg for loop 2[2].

6. Relevance to large commercial PWR plants

It is noted that the BETHSY facility is a scaled (~1% by volume) representation of a 3 loop PWR. In constructing the facility some design compromises are inevitable which preclude an absolutely precise comparison with PWR plant. Further there are design differences between individual plant and the rig (the pressuriser surge line is one example)

The implications for the management of a shut down event of the scenario analysed here has been discussed in previous reports ([11] & [12]) on the tests in this series. With the analysis made here more information is now available about the transient. The conclusions drawn in those reports, however, are still valid. It was that "the broad characteristics of the transient would be present in a similar scenario for the plant. There are, however, design characteristics which would probably result in a higher pressure level in the plant and possibly a less effective gravity feed."

It can now be seen that with the SG manway open the pressure rise in the primary circuit will be limited. Higher pressure may result from (say) an alternative siting of the pressuriser surge

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[2] A calculation with a more recent development version of RELAP5, i.e. MOD3.2.1.2, shows the mass error reduced to ~5% of the primary mass inventory.

line junction (e.g. at the bottom of the hot leg) since more water will be forced up into the pressuriser line. The peak pressure reached may well be higher but this will mean that the loop seal in the leg with the open SG manway will clear and open up another route for steam to escape from the primary circuit. There will thus be three paths by which vapour can escape from the circuit but the actual balance of flows will depend on the flow losses in each. The important point is that the pressure should not rise very high and so an effective gravity replenishment of the primary circuit inventory should be assured if no power was available to drive a forced feed.

Further design differences concerns the bend at the end of the hot leg which may be inclined at less than the 90° of the BETHSY rig. The differences will be manifest in two ways. For the steam flow there will be less loss at the bend. The amount will depend on the radius but must inevitably reduce the losses in the steam path to the SG manway compared to the 90° bend. For small pipes reference [13] suggests that there is no effect of pipe inclination on the onset of flooding although there are observed differences in flow patterns. It is reported in [14] that the Wallis correlation is not applicable for large pipe diameters. Although the CCFL model was activated at the bend for this analysis, the output from the calculation shows that the conditions did not arise for it to be applied. It is therefore unlikely to affect the response of the plant significantly.

7. Conclusions.

1. From the study of the experimental data it can be confirmed that the aims of the test were satisfied and good information is provided on the phenomena that were involved. The measurements are of the same high quality that has been evident in the analysis of previous tests.

2. The full transient has been calculated with the latest release version of the code, RELAP5/MOD3.2. No code failures were encountered.

3. The main phenomena in the test are correctly represented in the calculation. The primary pressure peak is well matched although the reduction in pressure is delayed. This appears to be due to water draining from the steam generator tubes and then being entrained up into the surge line. It is not possible to determine whether this effect occurred in the test.

4. The mass error remains less than 10% of the primary mass for the early part of the transient until the gravity injection phase when it rises to a peak of 20%. The underprediction of the primary mass is almost precisely accounted for by the mass error.

5. The clad temperature rise is initially delayed but then is slightly more rapid than in the test. The gravity feed start is delayed by 300s but is still able to arrest the rise in temperature. The peak temperature is overestimated by 15 °C.

6. In considering the implications for PWR plant it is anticipated that the course of the

transient will be similar. Higher pressures may occur due to differences in detail design but the effects will be limited since only a small increase in pressure is necessary to clear the loop seal and provide a further route for steam escape.

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References

[1] *Consequences of the Loss of the Residual Heat Removal Systems in Pressurised Water Reactors.* L W Ward et al NUREG/CR-5820 May 1992

[2] *Thermal Hydraulic Processes During Reduced Inventory Operation with Loss of Residual Heat Removal.* S A Naff et al. NUREG/CR-5855

[3] *BETHSY General Description.* CEN Note SETH/LES/90-97 April 1990

[4] *BETHSY - Test 6.9c: Loss of Residual Heat Removal System during Mid-loop Operation. Pressuriser and steam generator outlet plenum manways open. Test Report.* G Lavialle CEN Note STR/LES/92-110. December 1993.

[5] *BETHSY - Test 6.9a: Loss of Residual Heat Removal System during Mid-loop Operation. Pressuriser Manway Open. Test Report.* G Lavialle. CEN Note STR/LES/92-111. December 1992.

[6] *BETHSY - Test 6.9d: Loss of Residual Heat Removal System during Mid-loop Operation. Primary system partly open. Test Report.* B Noel CEN Note STR/LES/93-140. August 1993.

[7] *RELAP5/MOD3 Code Manual. Volumes I to VI.* The RELAP5 code development team NUREG/CR-5535 June 1995.

[8] *RELAP5/MOD3 Analysis of BETHSY Test 6.9c Loss of Residual Heat Removal System Pressuriser and Steam Generator Outlet Plenum Manways Open. Draft report.* G R Kimber AEA/16423592/001. November 1995

[9] *RELAP5 . G Johnsen.* Presentation at the CAMP meeting. Pennsylvania State University. October 1995

[10] *Effect of wet wall interfacial shear correlations on the mass error of RELAP5/MOD3.1* G Th Analytis, Transaction ANS Winter Meeting San Francisco. October 1995.

[11] *RELAP5/MOD3 Analysis of BETHSY Test 6.9a Loss of Residual Heat Removal System Pressuriser Manway Open.* G R Kimber AEA RS 5644 March 1994

[12] *RELAP5/MOD3 Analysis of BETHSY Test 6.9d Loss of Residual Heat Removal System Primary System Partly Open.* G R Kimber AEA/CS/16401552/002 March 1995

[13] *Countercurrent flow limitation in inclined channels with bends.* S M Ghiaasiaan et al. Nuclear Engineering and Design 152 (1994) 379-388.

[14] *The CCFL option in the Sizewell Project version of RELAP5/MOD2.* M J Dillistone,W M Bryce. AEEW-M2574 1989.

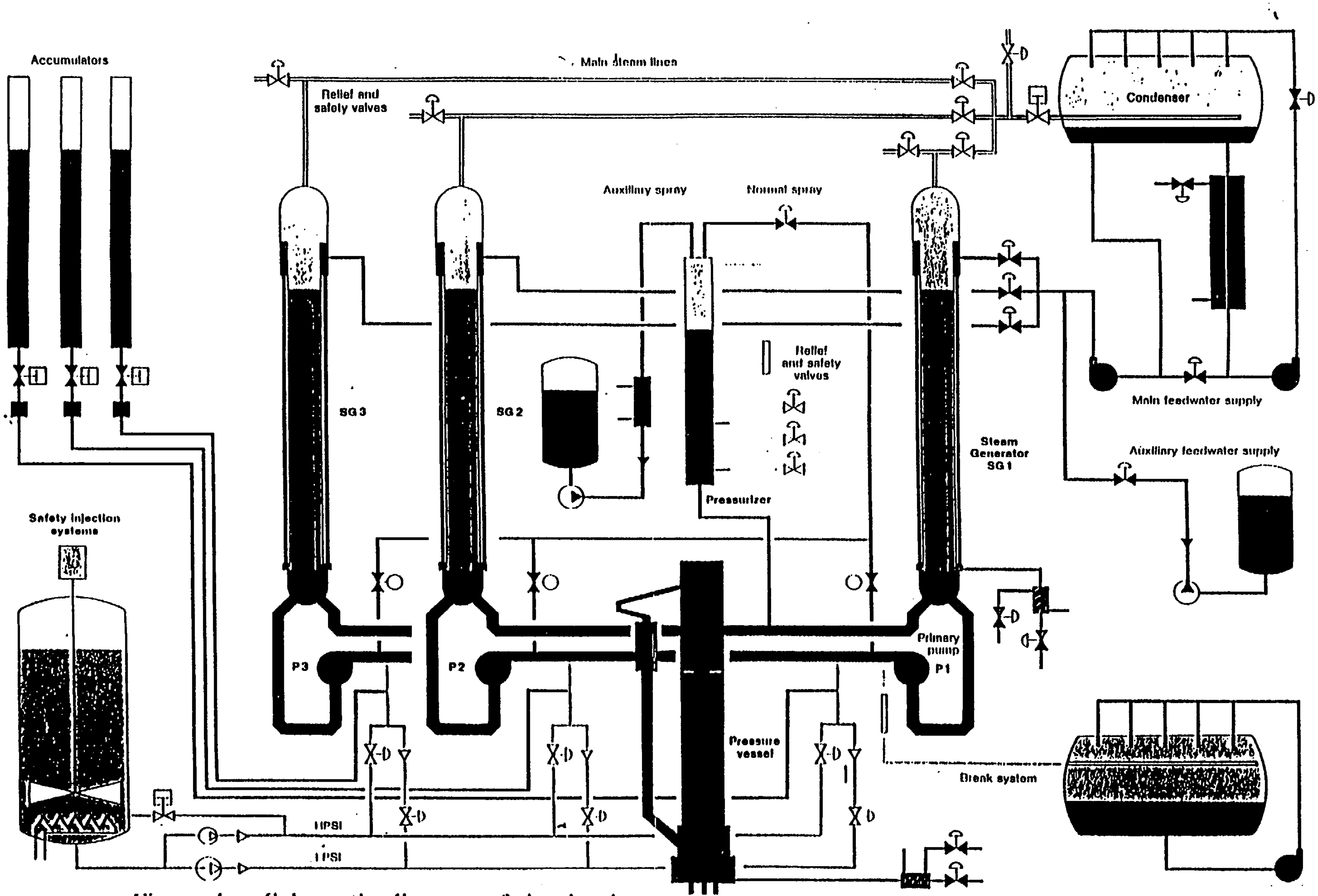


Figure 1 Schematic diagram of rig circuits

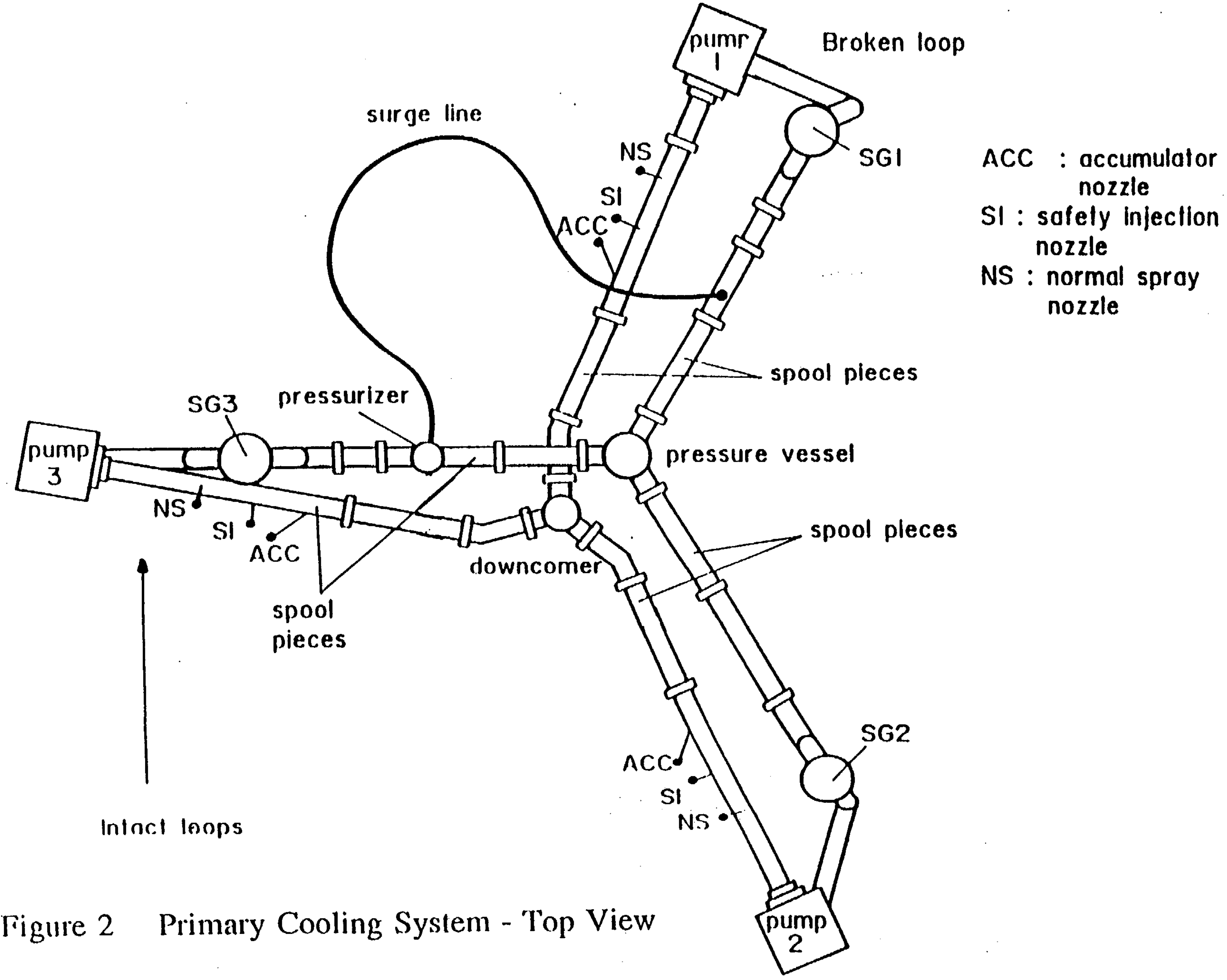


Figure 2 Primary Cooling System - Top View

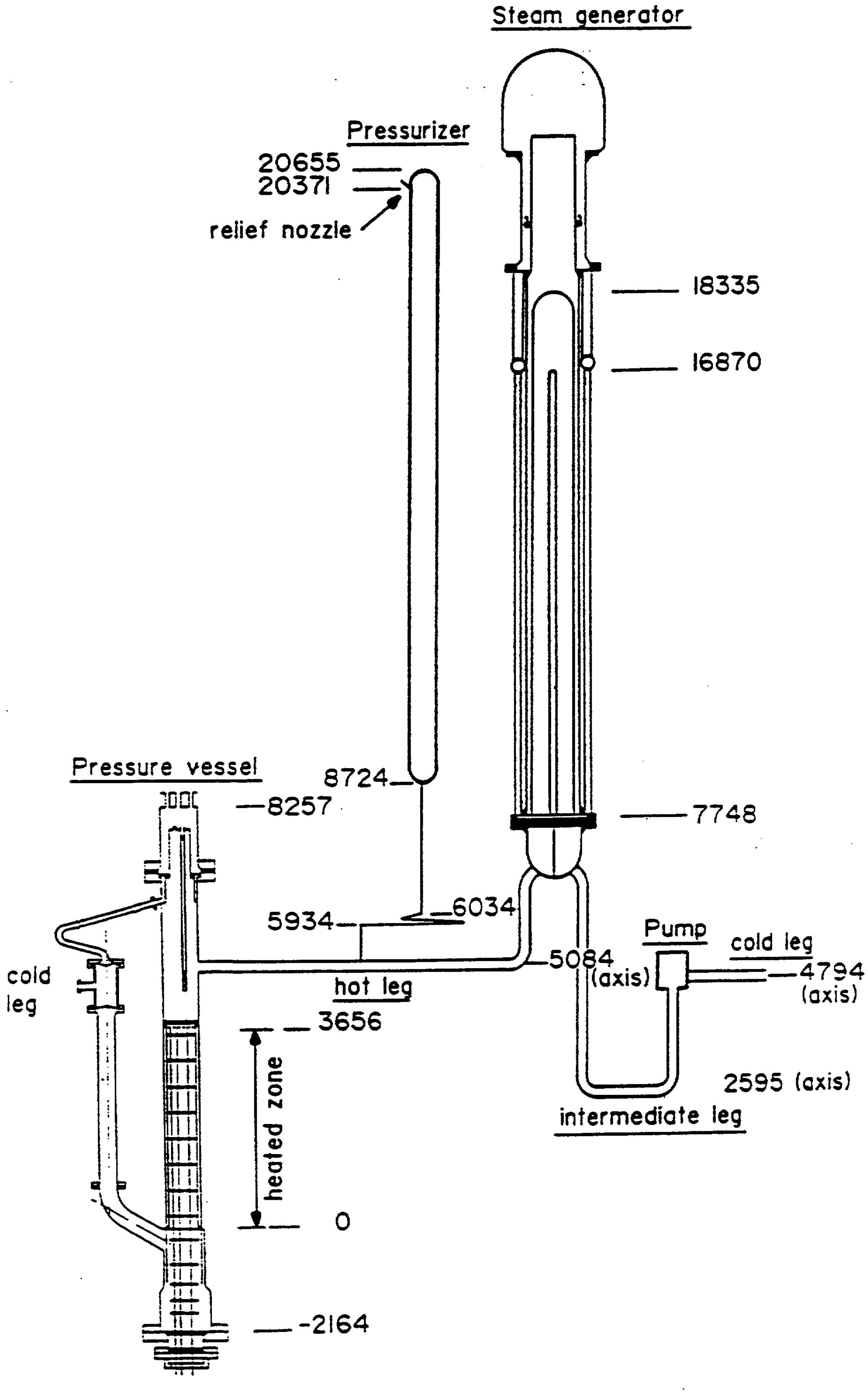


Figure 3 Primary Cooling System - Elevations

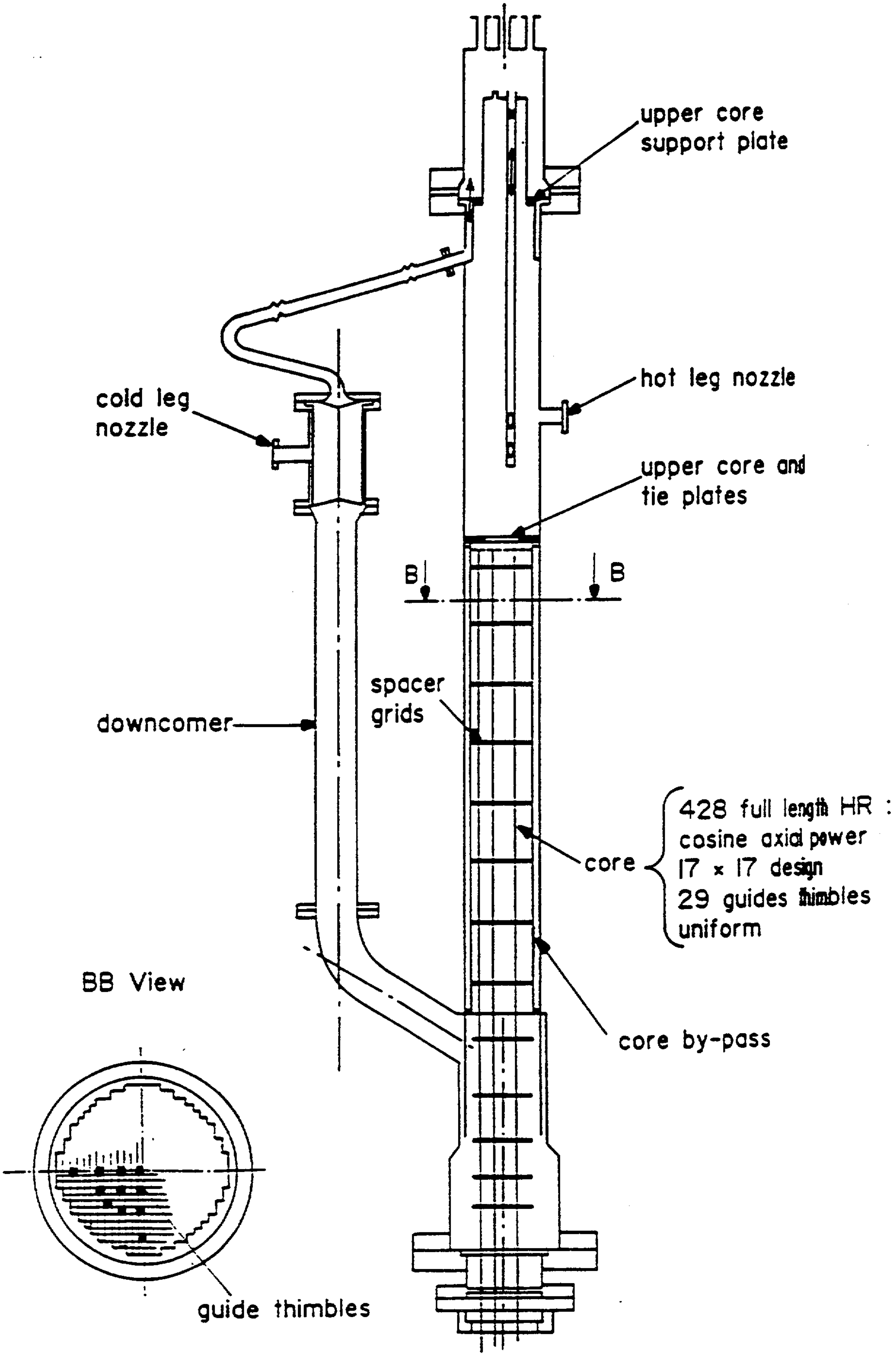


Figure 4 Pressure vessel - General view

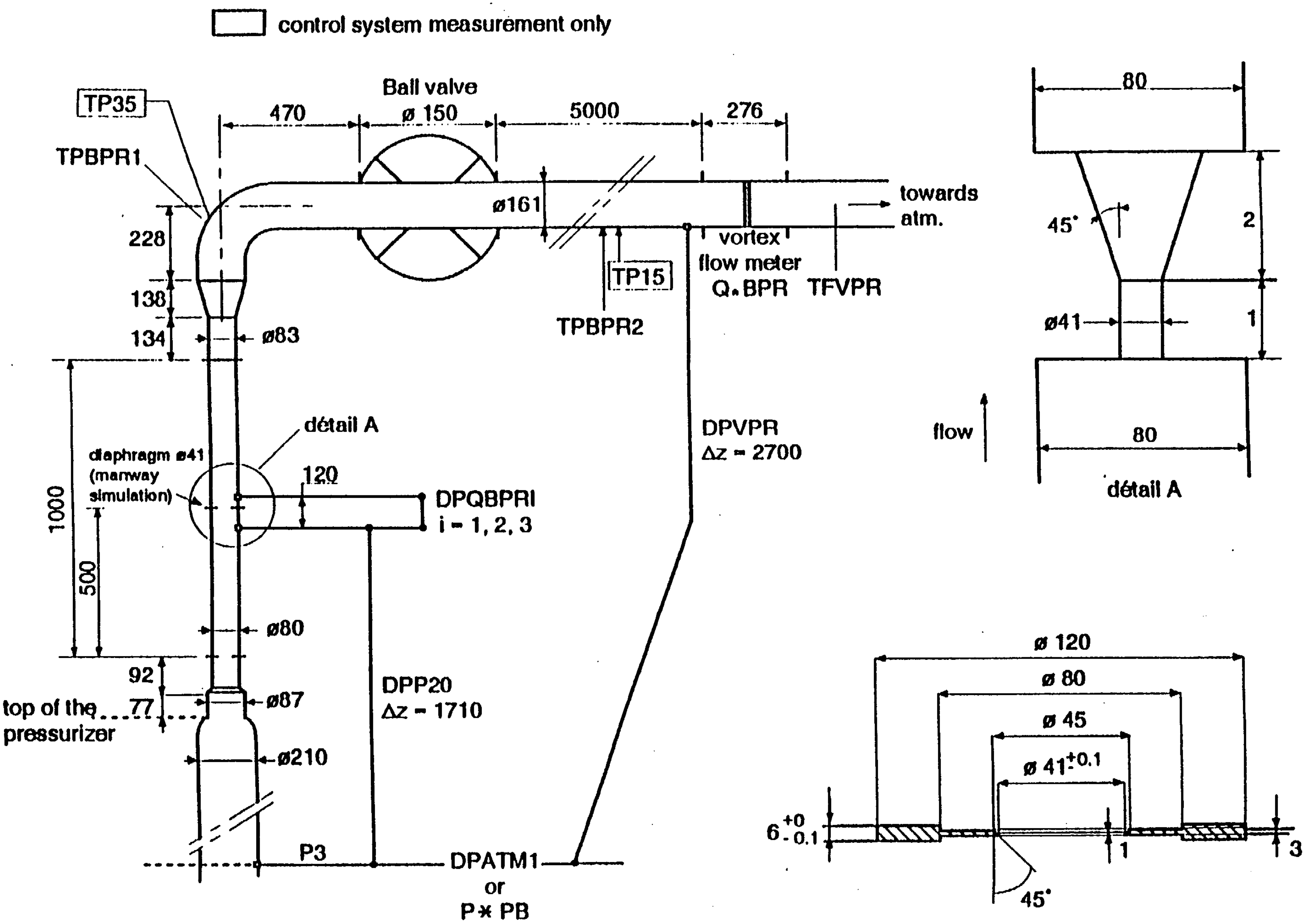


Figure 5 Loss of R.H.R.S - Pressuriser Manway Arrangement.

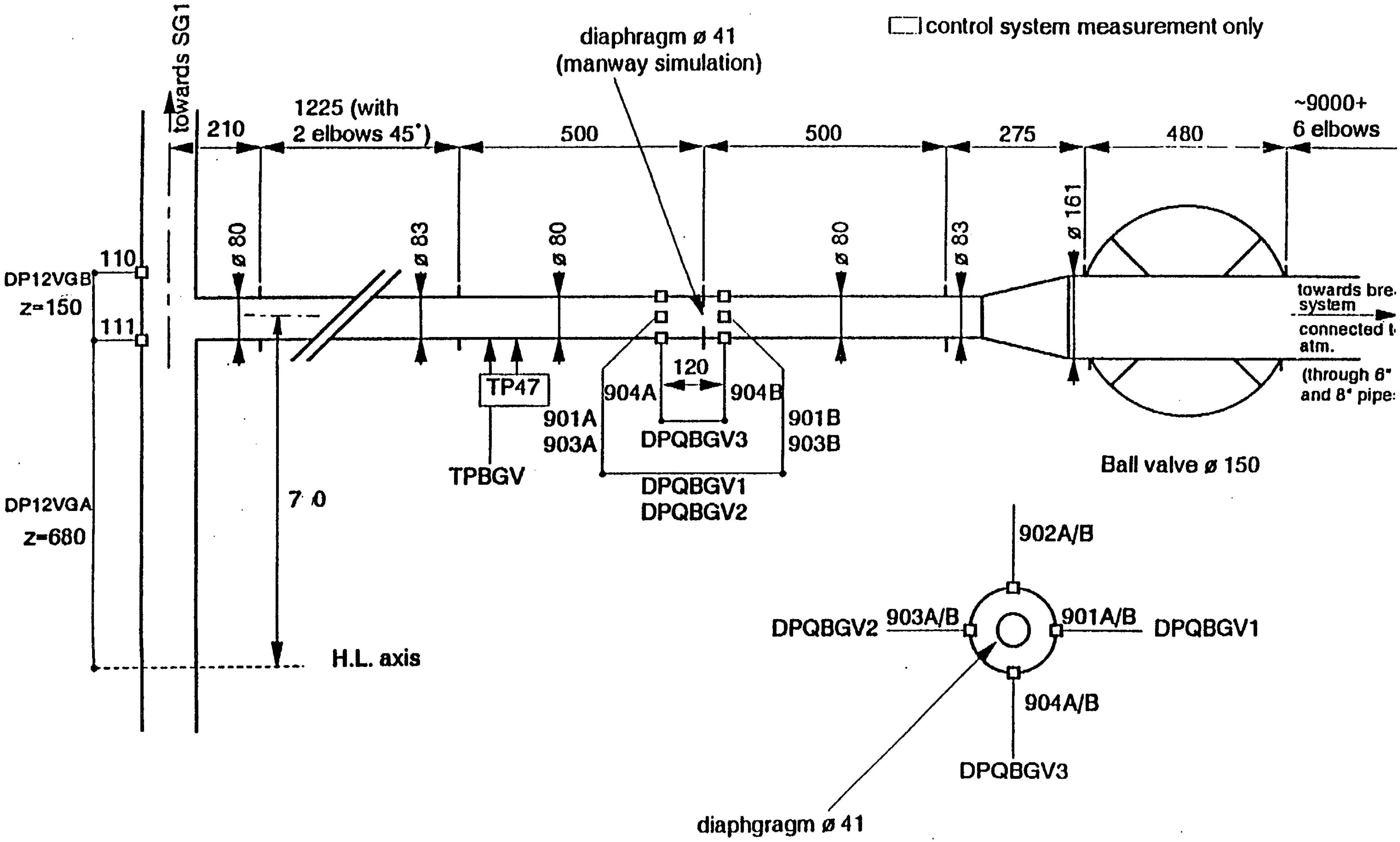
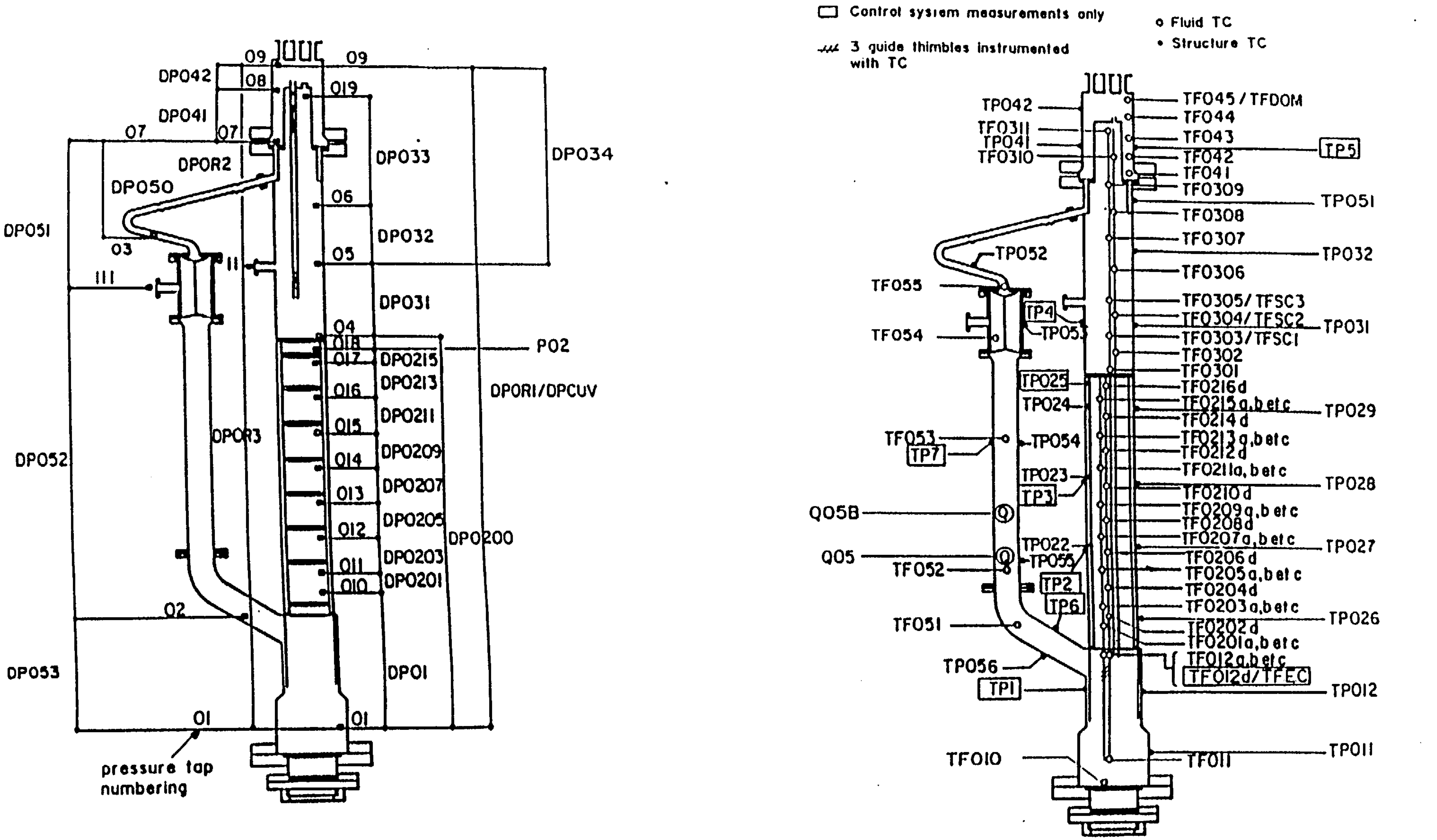


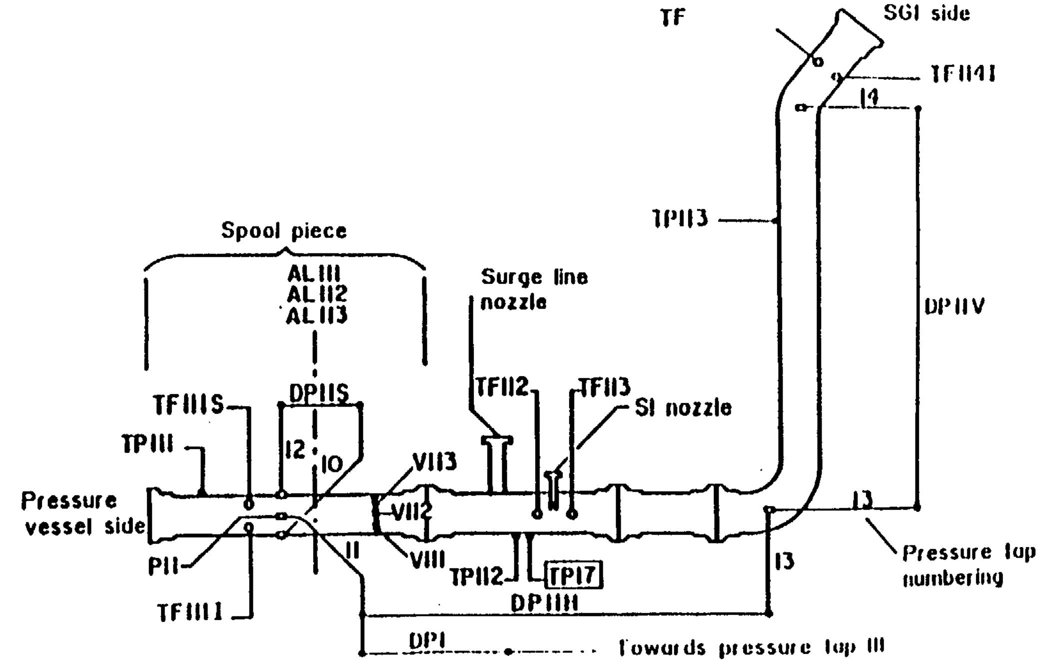
Figure 6. SG1 outlet plenum manway configuration



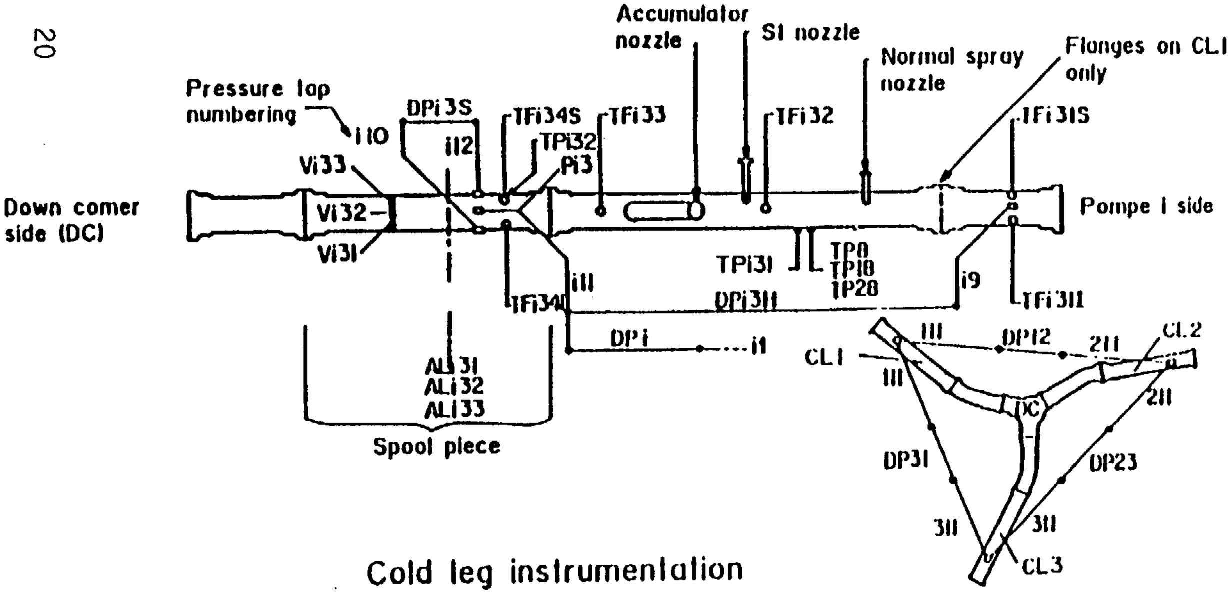
Pressure vessel. Gauge and differential pressure measurements

Pressure vessel. Temperature (except HR cladding) and flow rate measurements

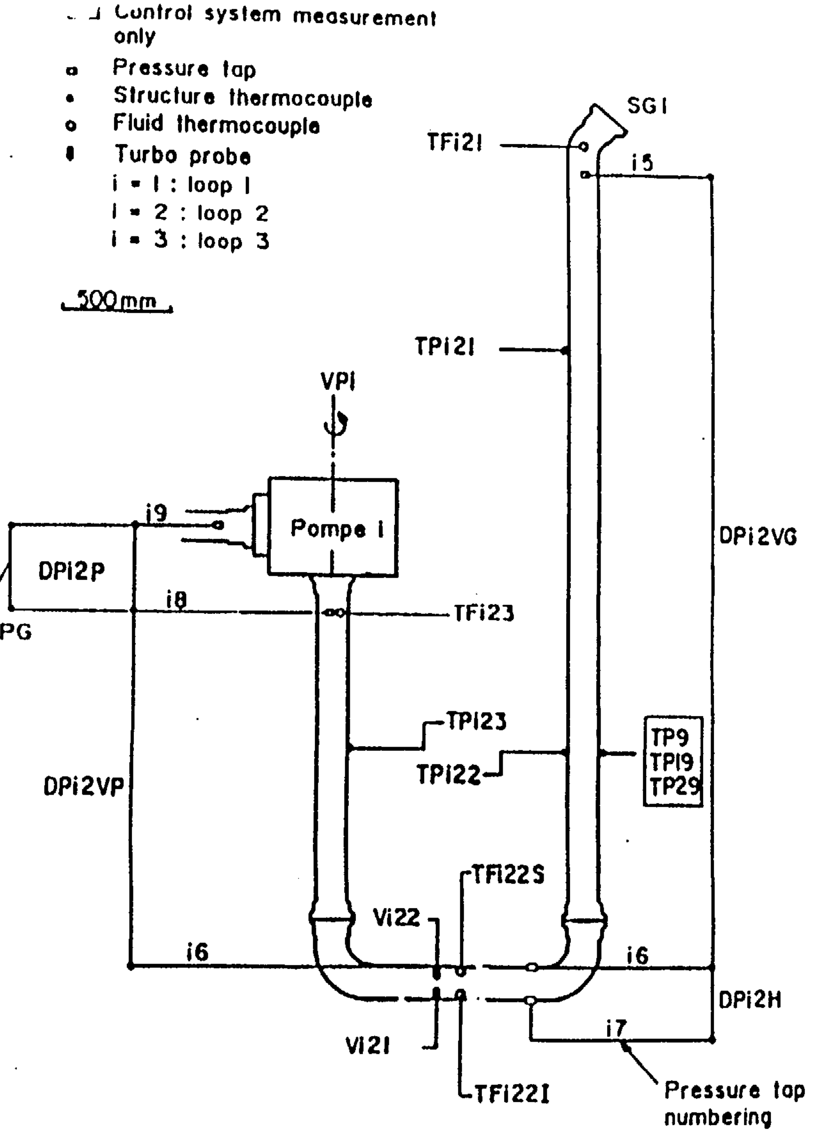
Figure 7. Identification of transducers in the vessel



Hot leg n°I instrumentation



Cold leg instrumentation



Cross over leg instrumentation

Figure 8. Identification of transducers in the loops

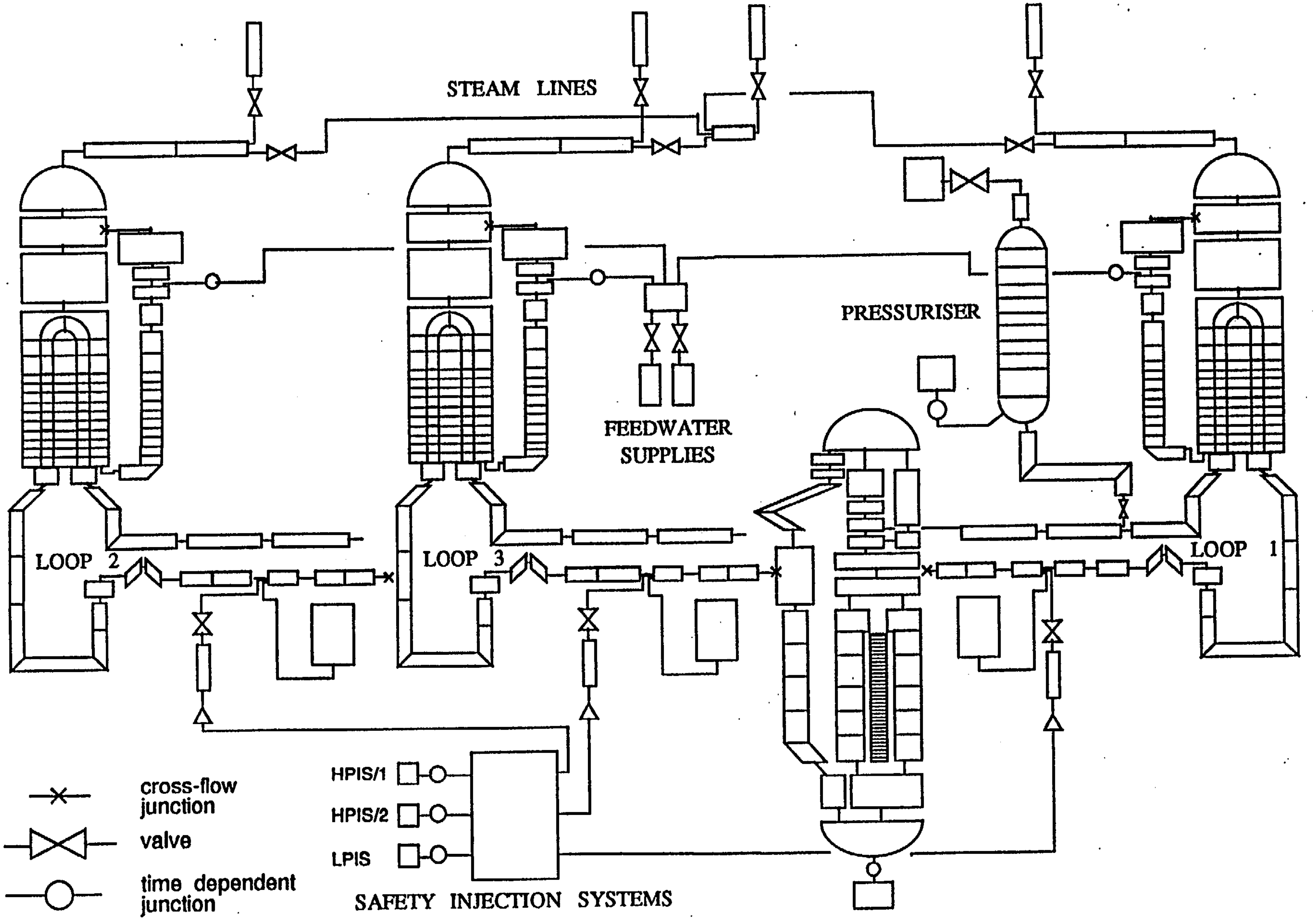


Figure 9. RELAP5 noding scheme for BETHSY integral facility

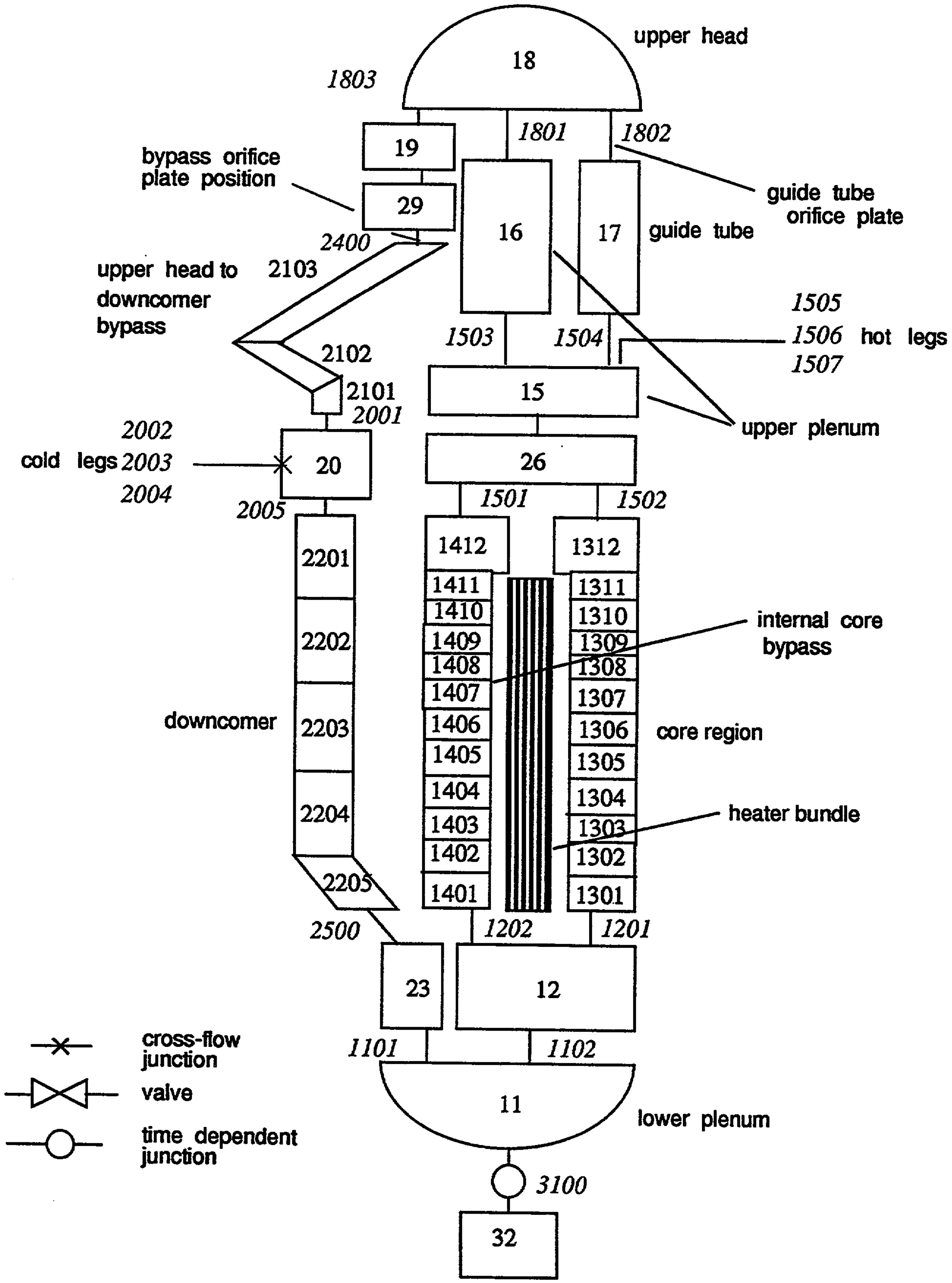


FIG 10 RELAP5 NODING FOR BETHSY VESSEL

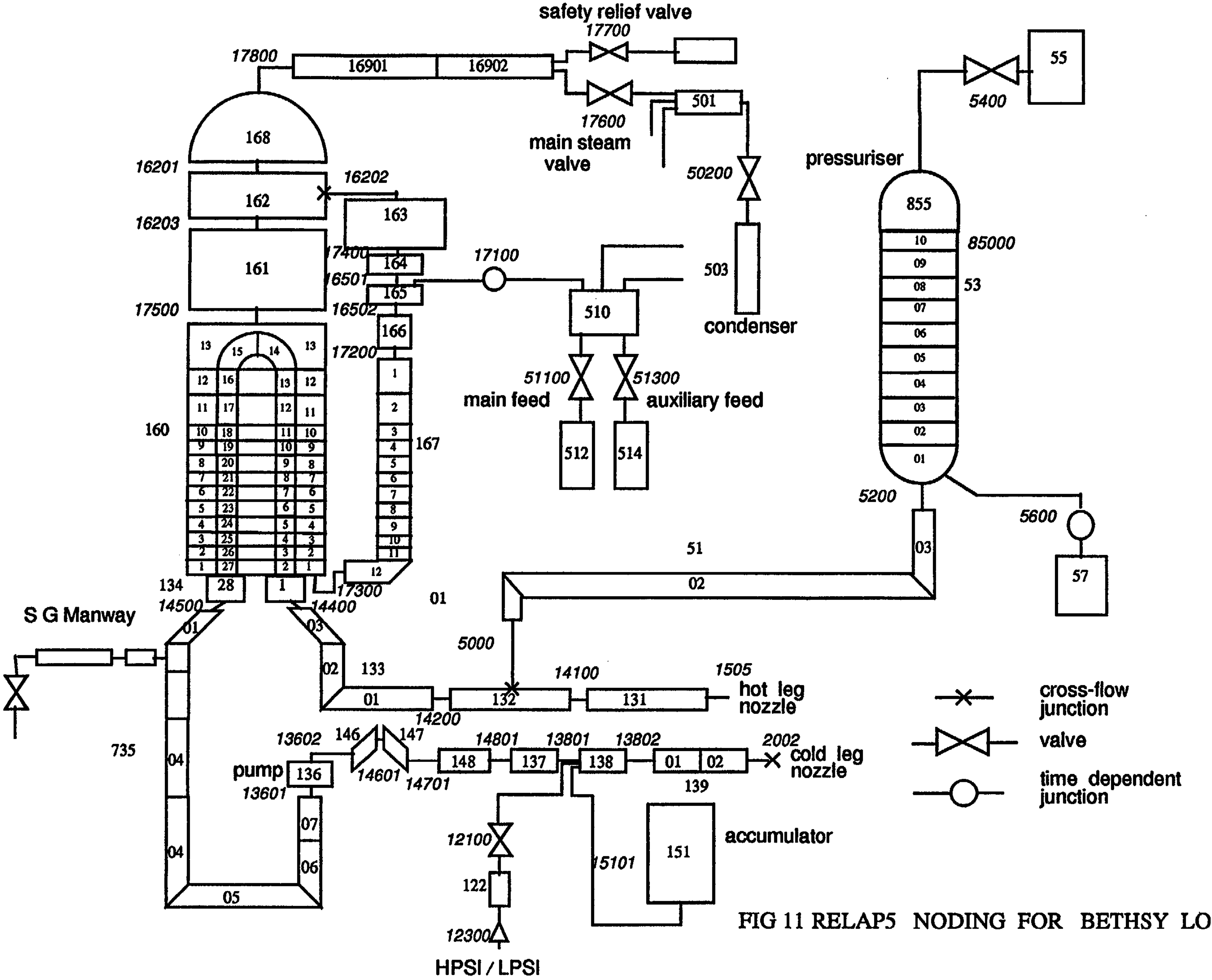


FIG 11 RELAP5 NODING FOR BETHSY LOOP 1

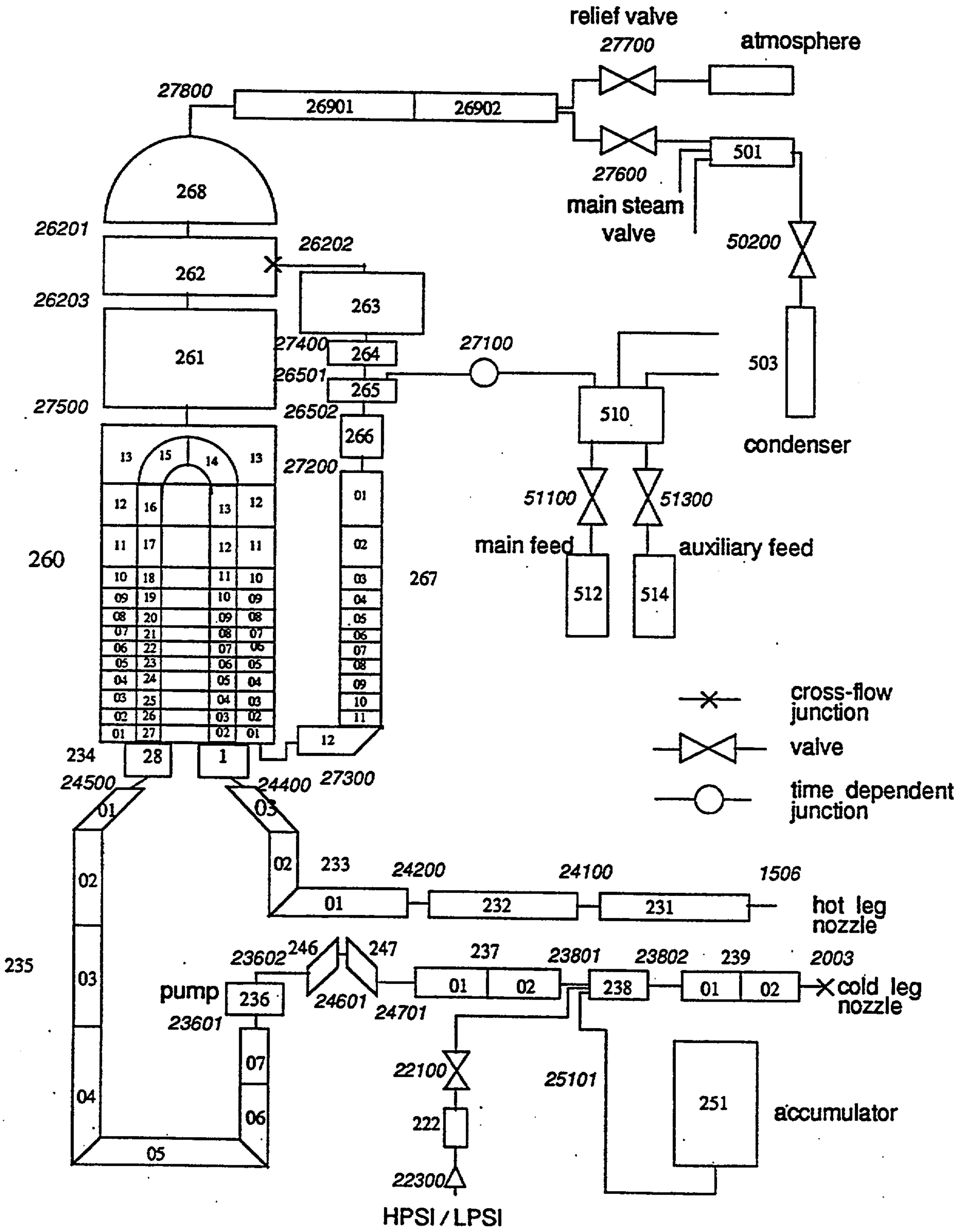


Figure 12. RELAP5 noding for BETHSY loops 2 & 3

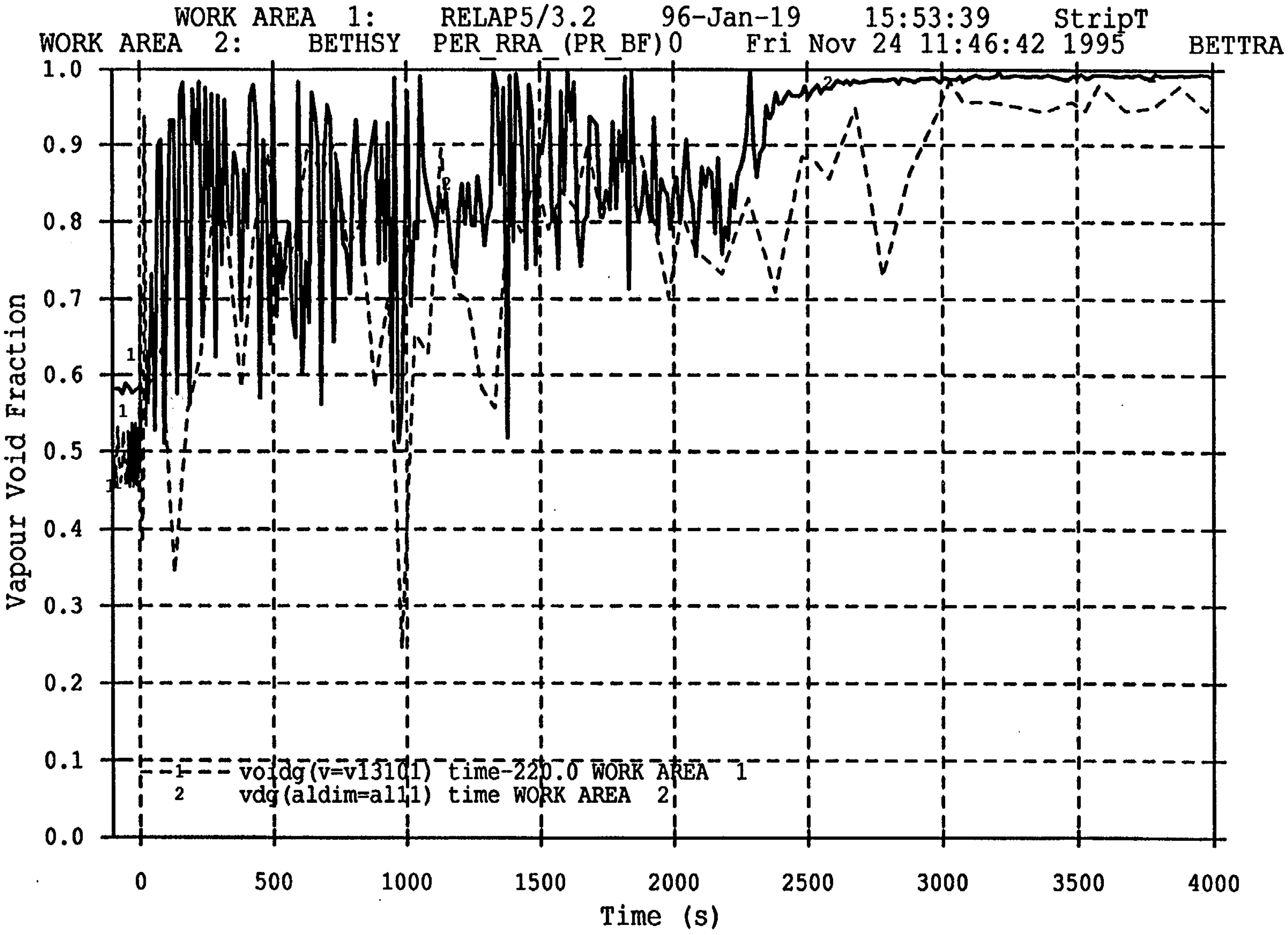


Fig. 13a. Hot leg 1 void fraction (0.0 to 4000s)

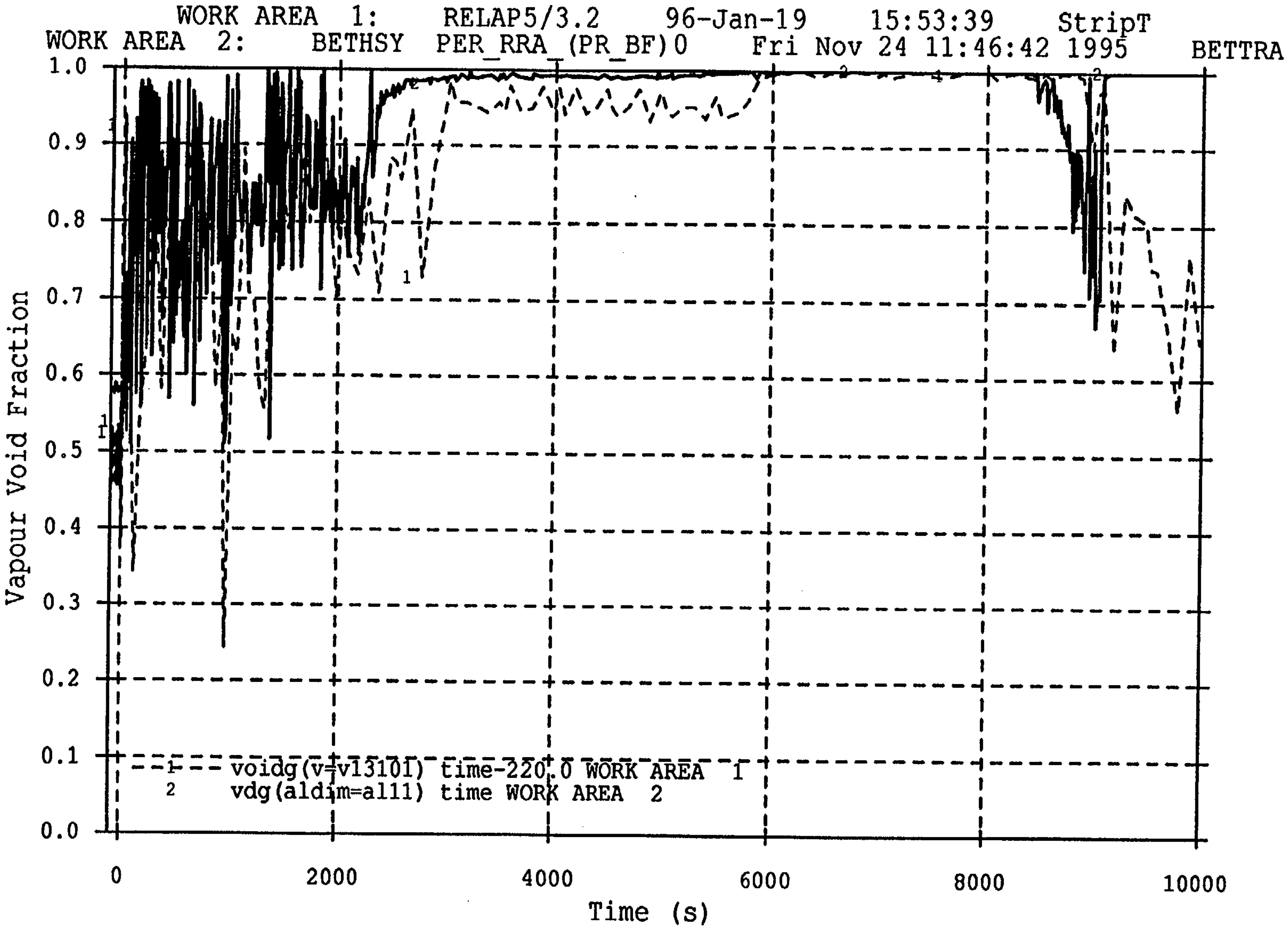


Fig. 13b. Hot leg 1 void fraction

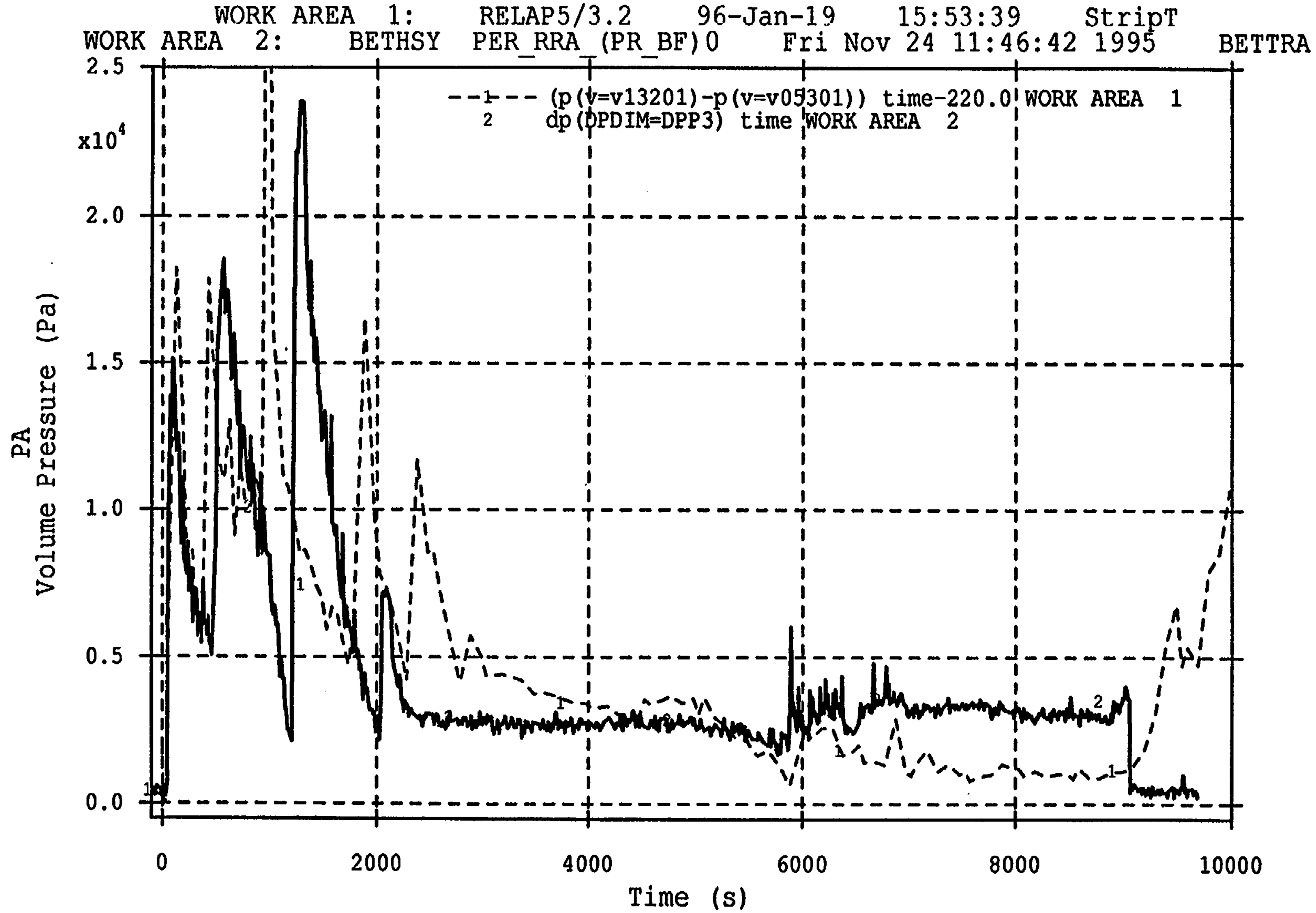


Fig. 14. DP in surge line

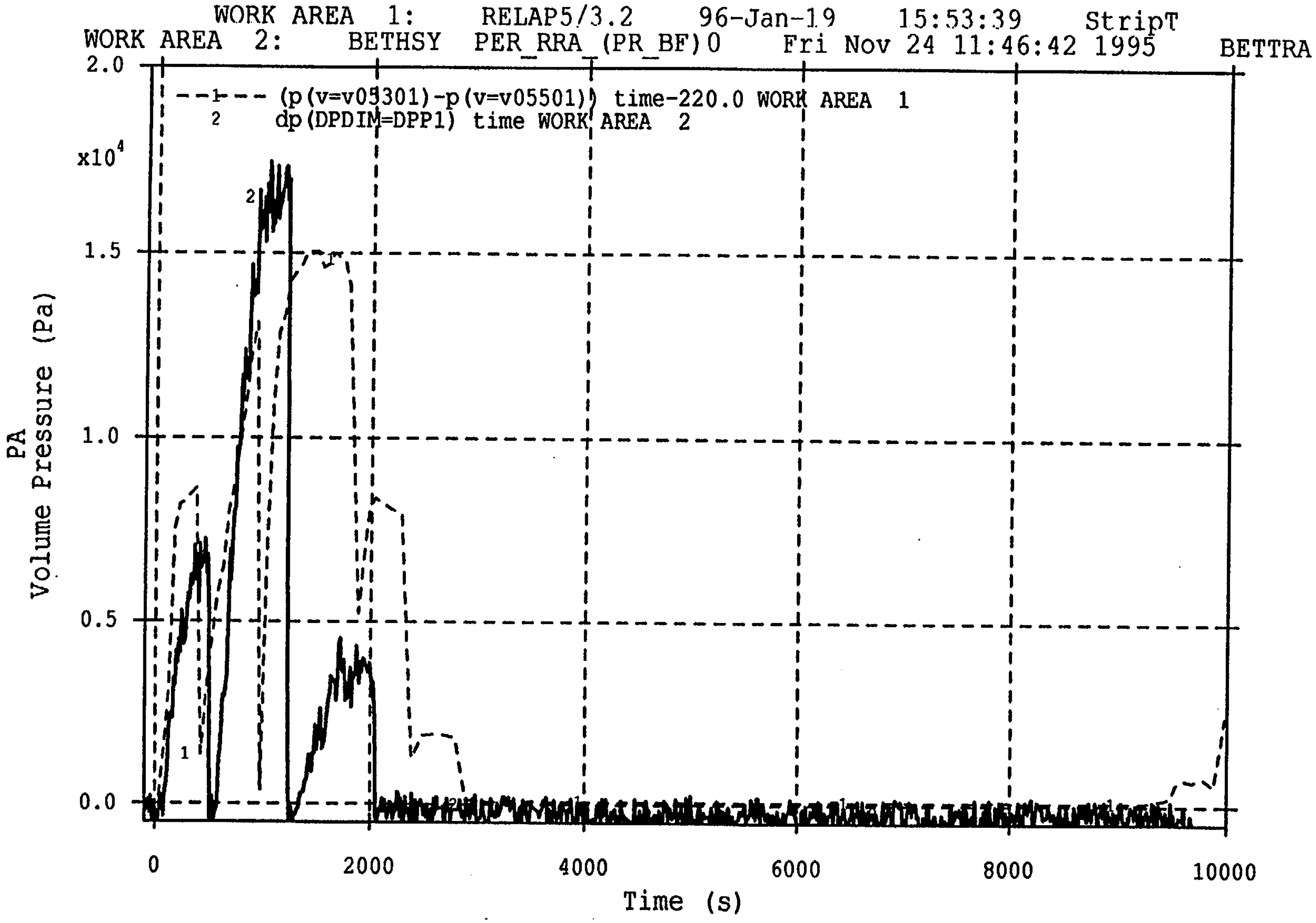


Fig. 15. DP in pressuriser

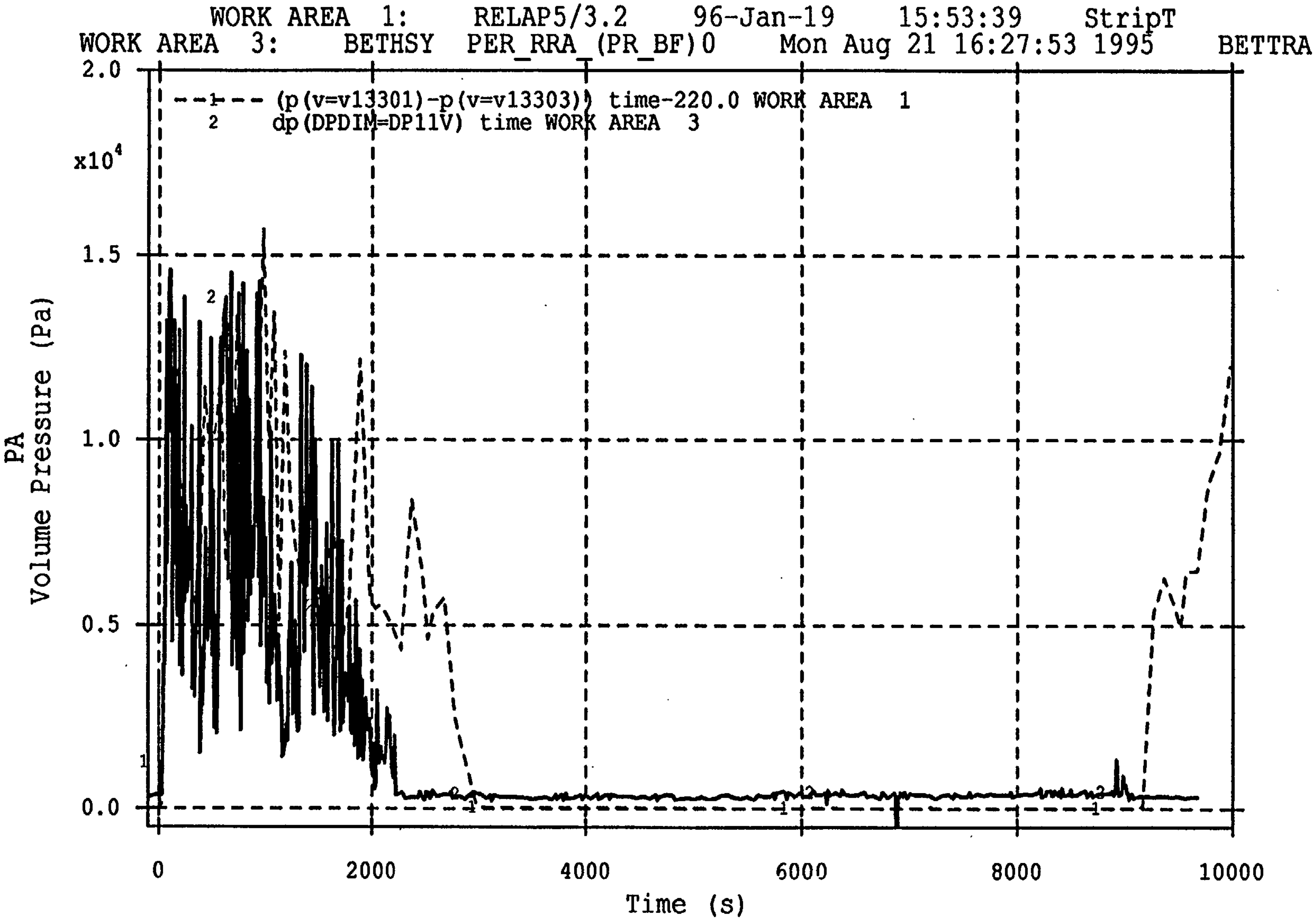


Fig. 16. DP in hot leg 1 vertical section

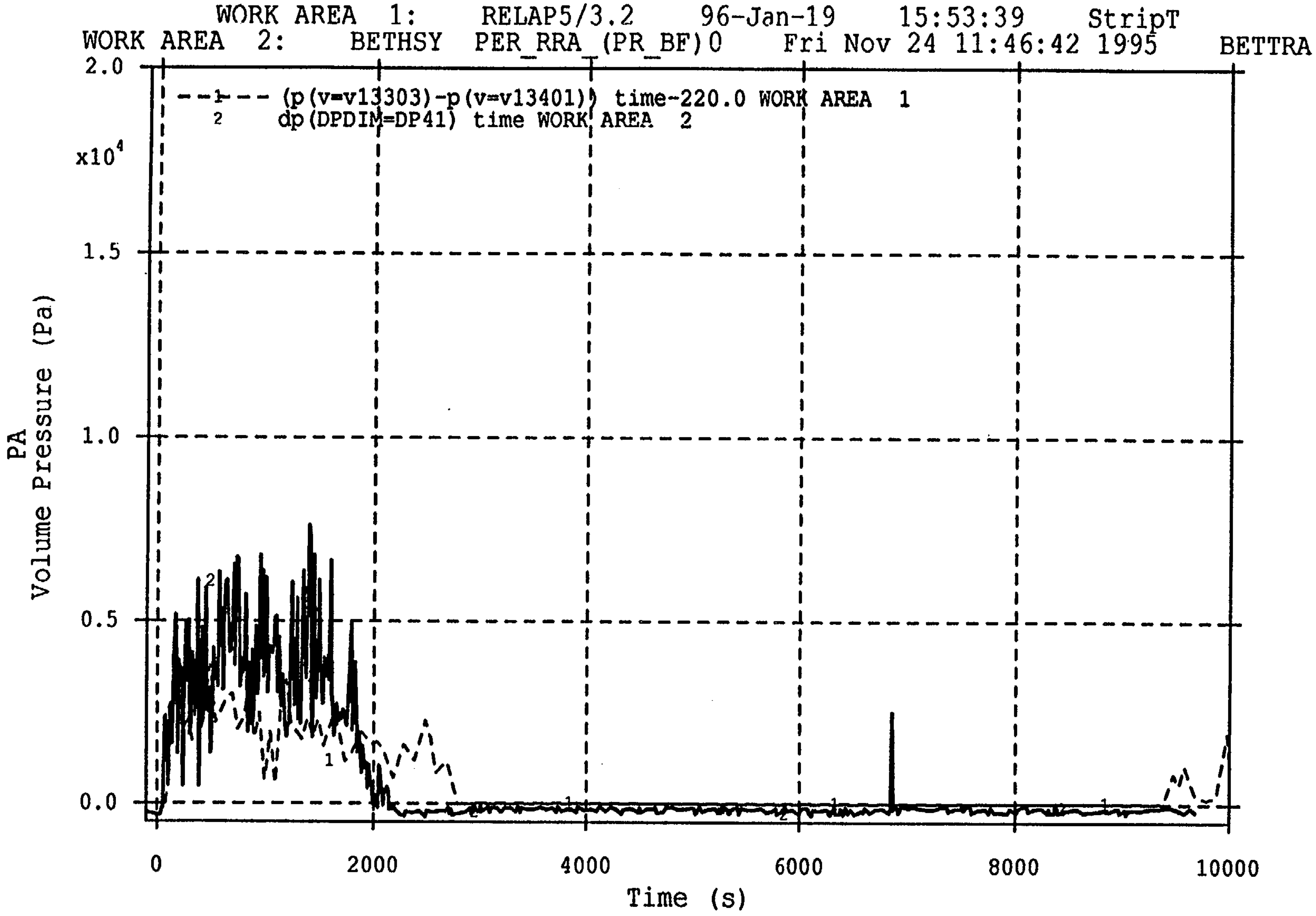


Fig. 17. DP in SG 1 inlet plenum

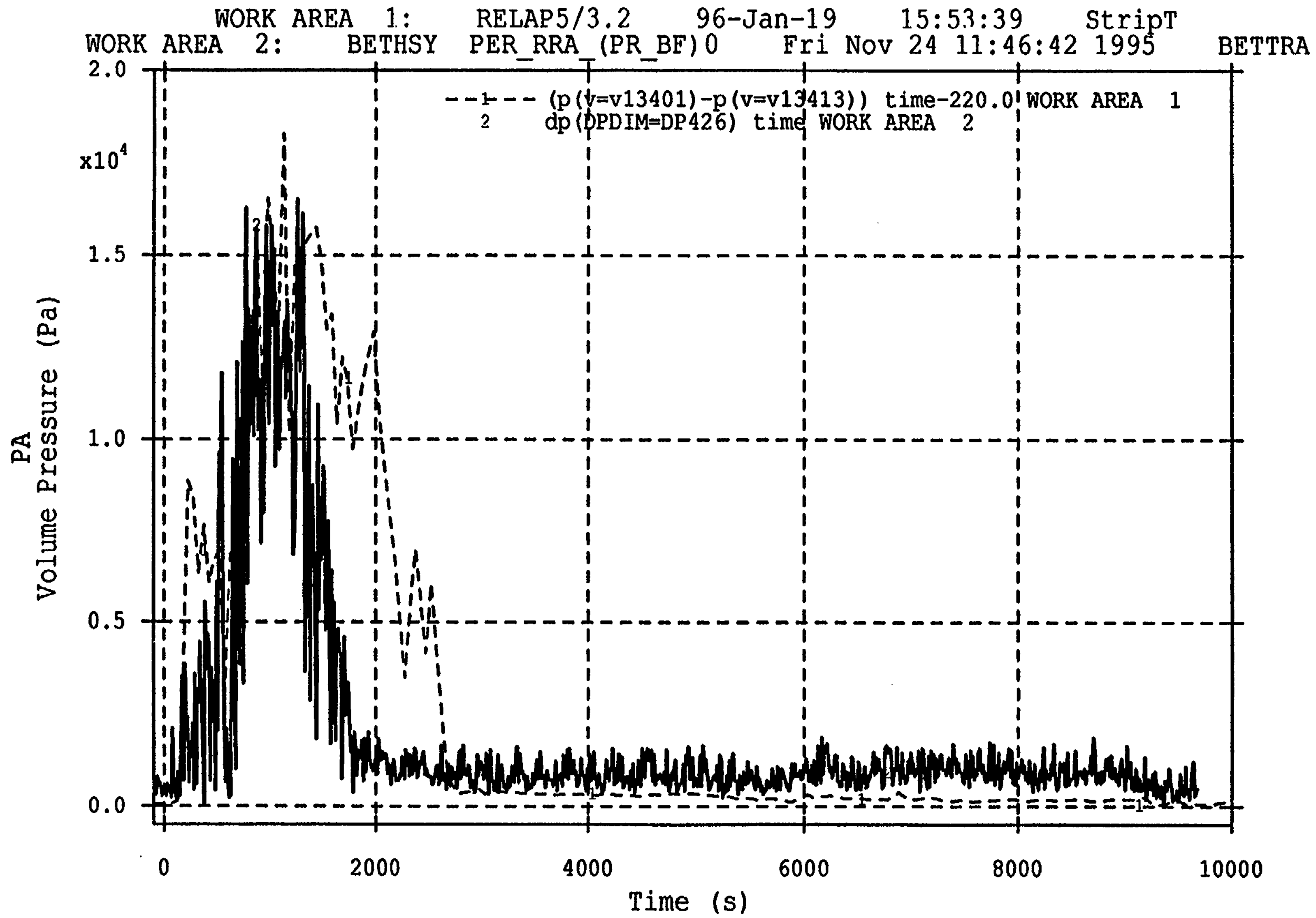


Fig. 18. DP in SG 1 tubes

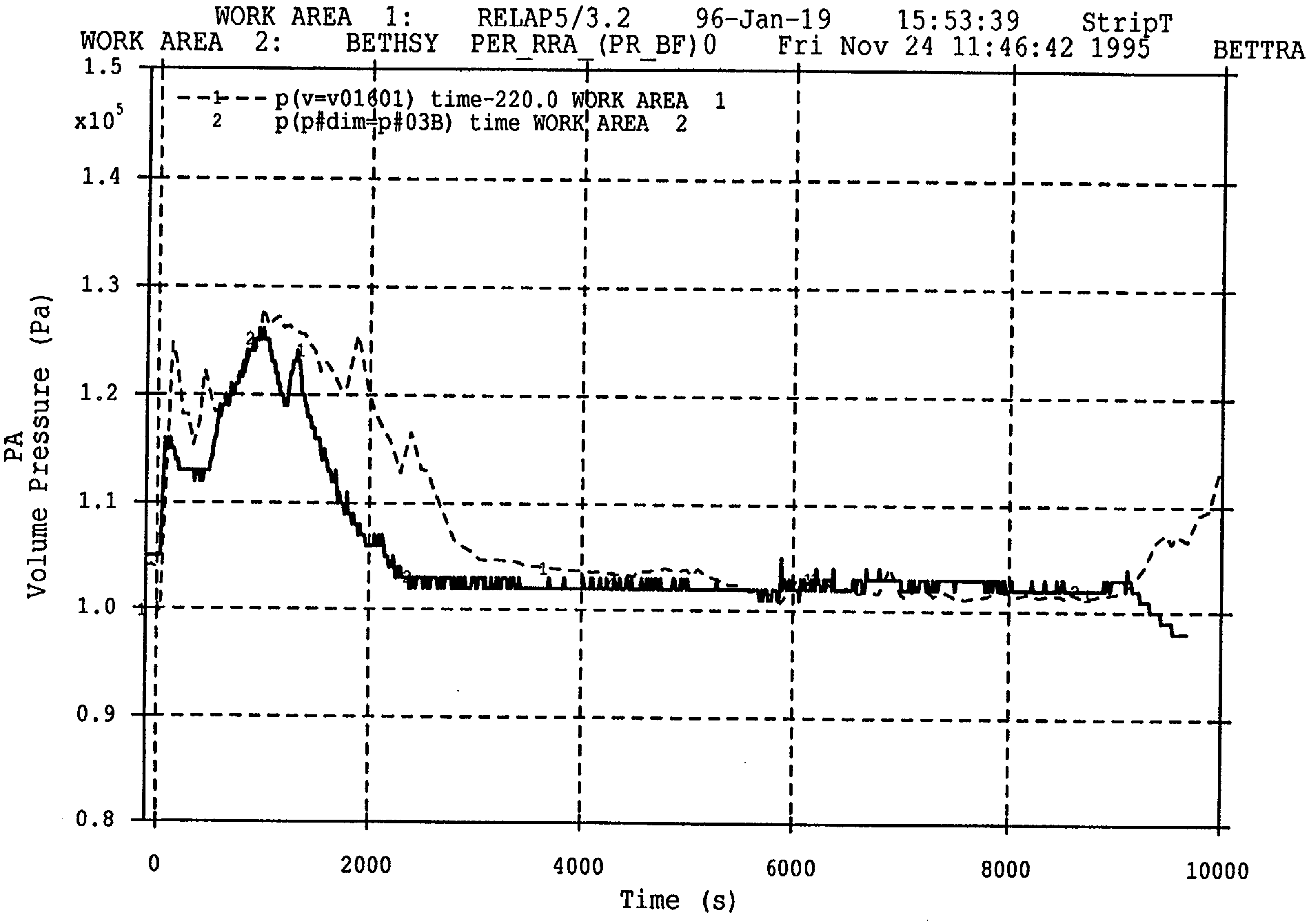


Fig. 19. Upper plenum pressure

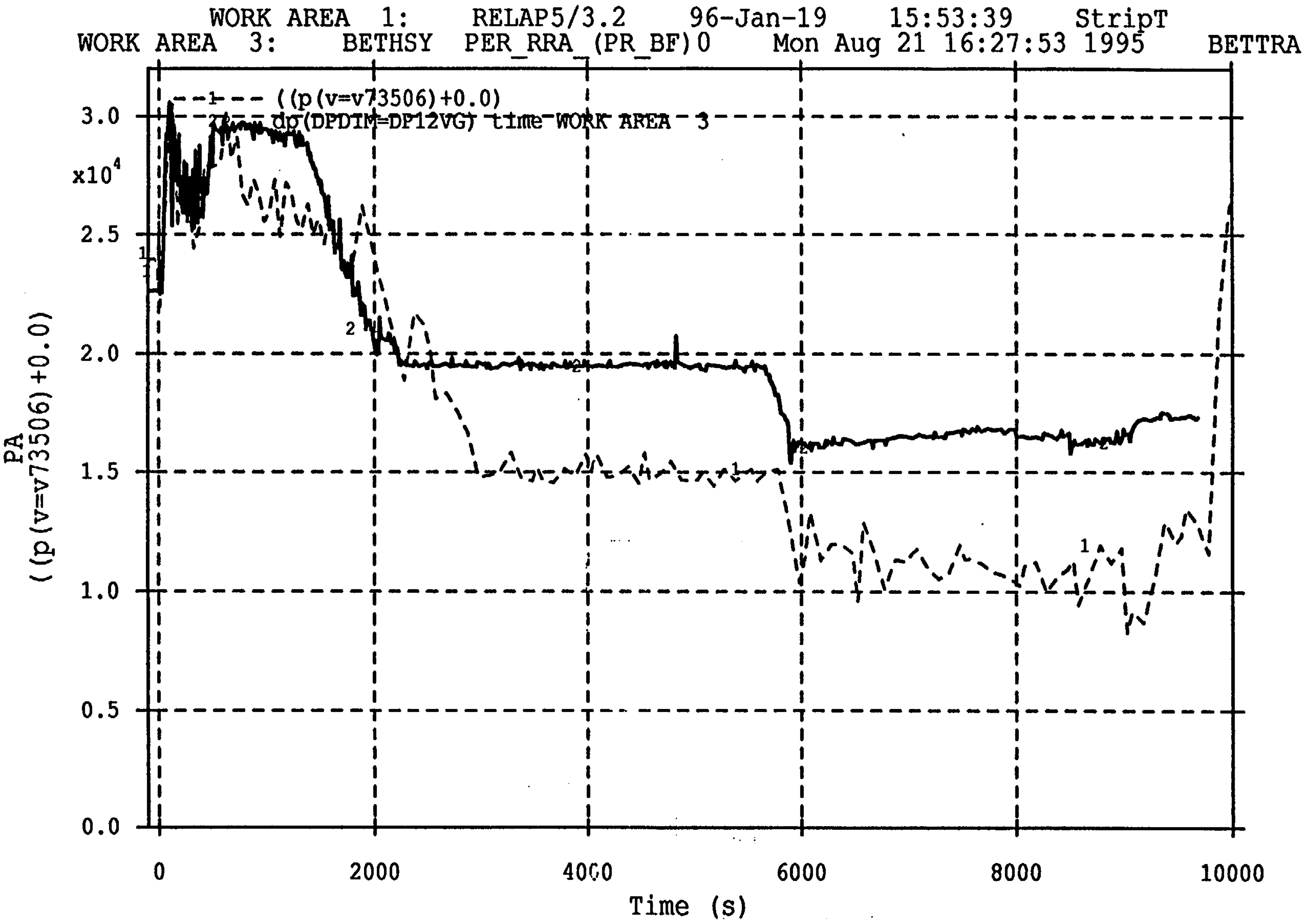


Fig. 20. DP in intermediate leg 1 - pump side

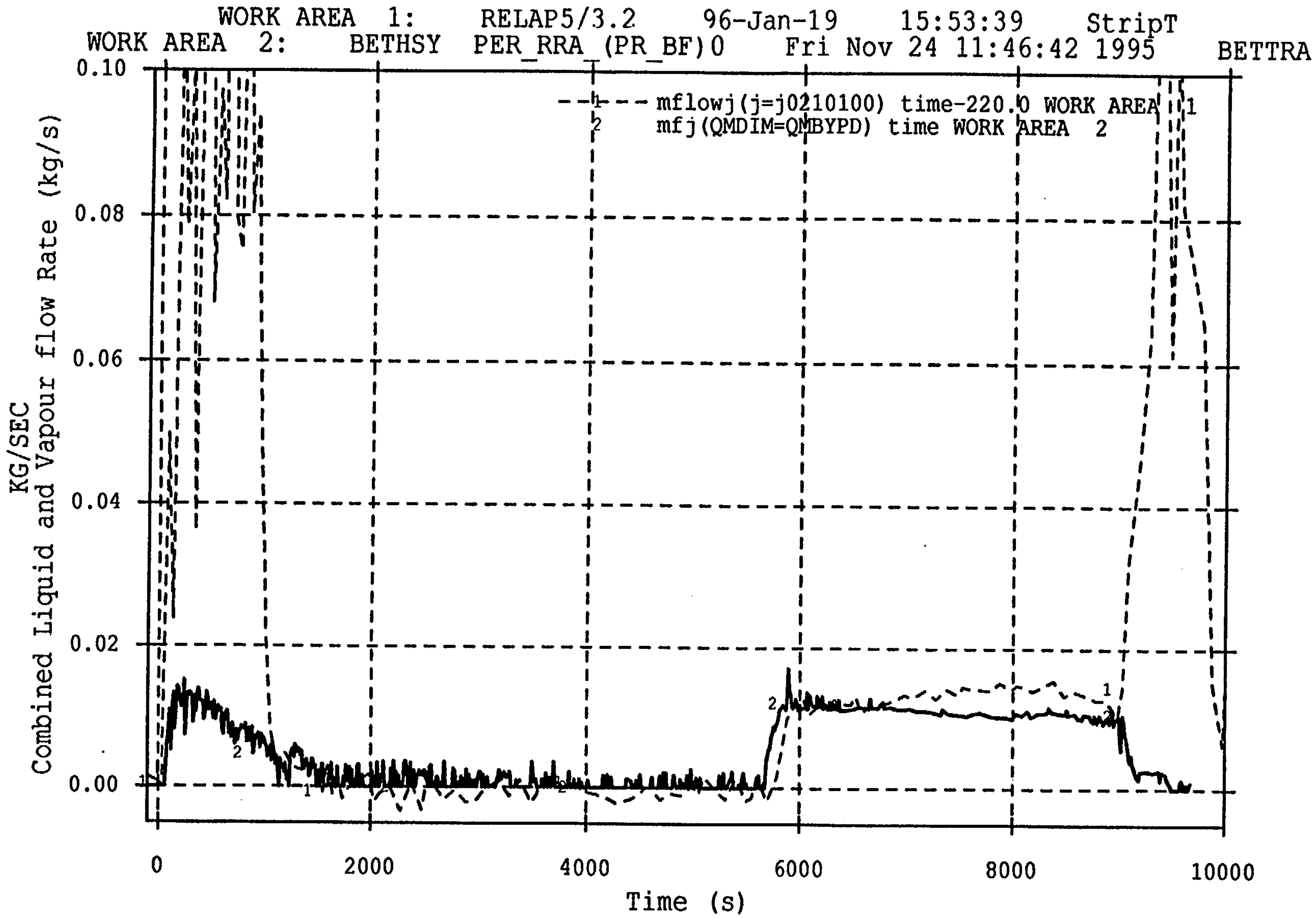


Fig. 21. Total mass flow through upper head - downcomer link

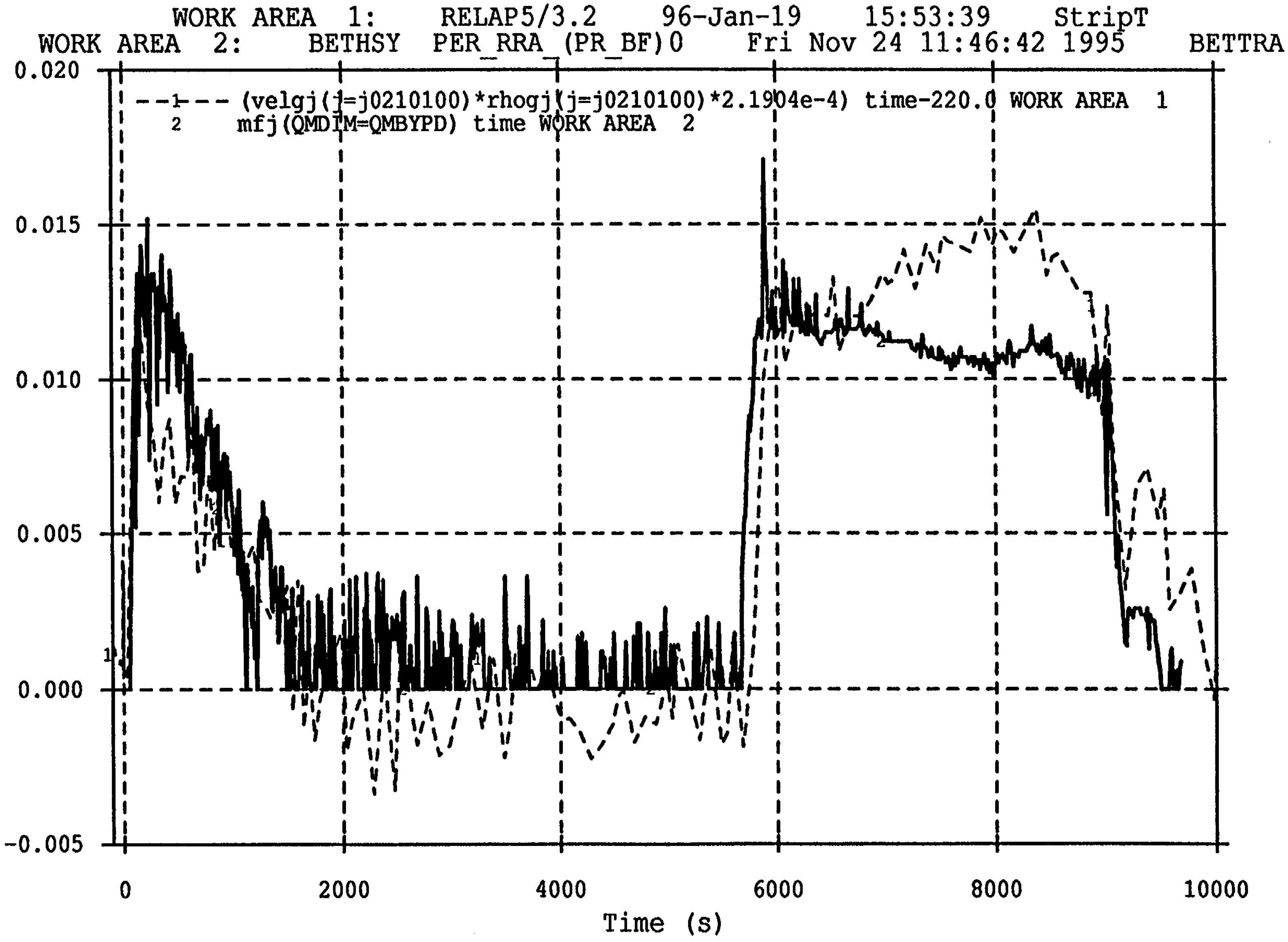


Fig. 22. Steam mass flow through upper head - downcomer link

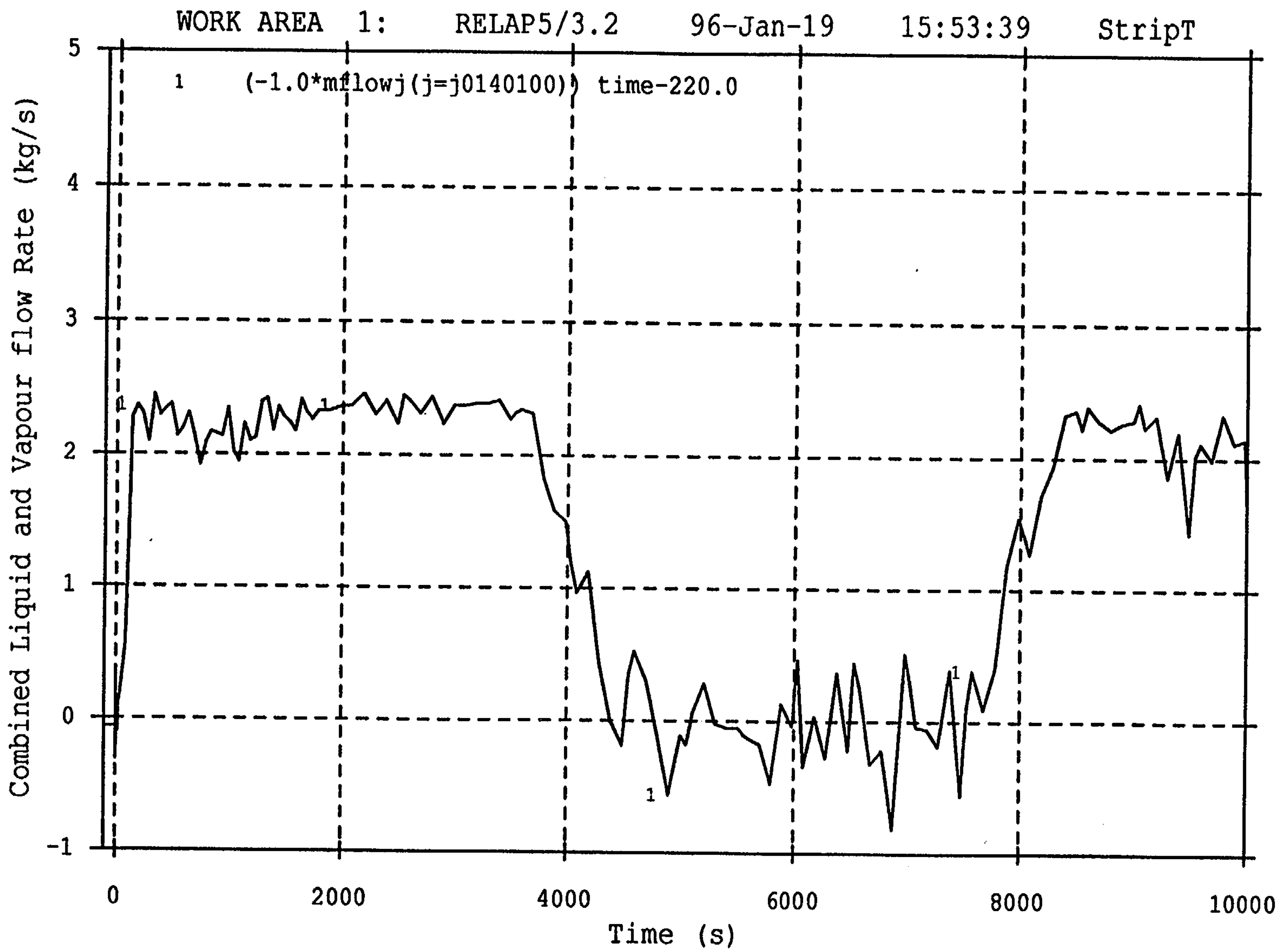


Fig. 23. Flow through core bypass

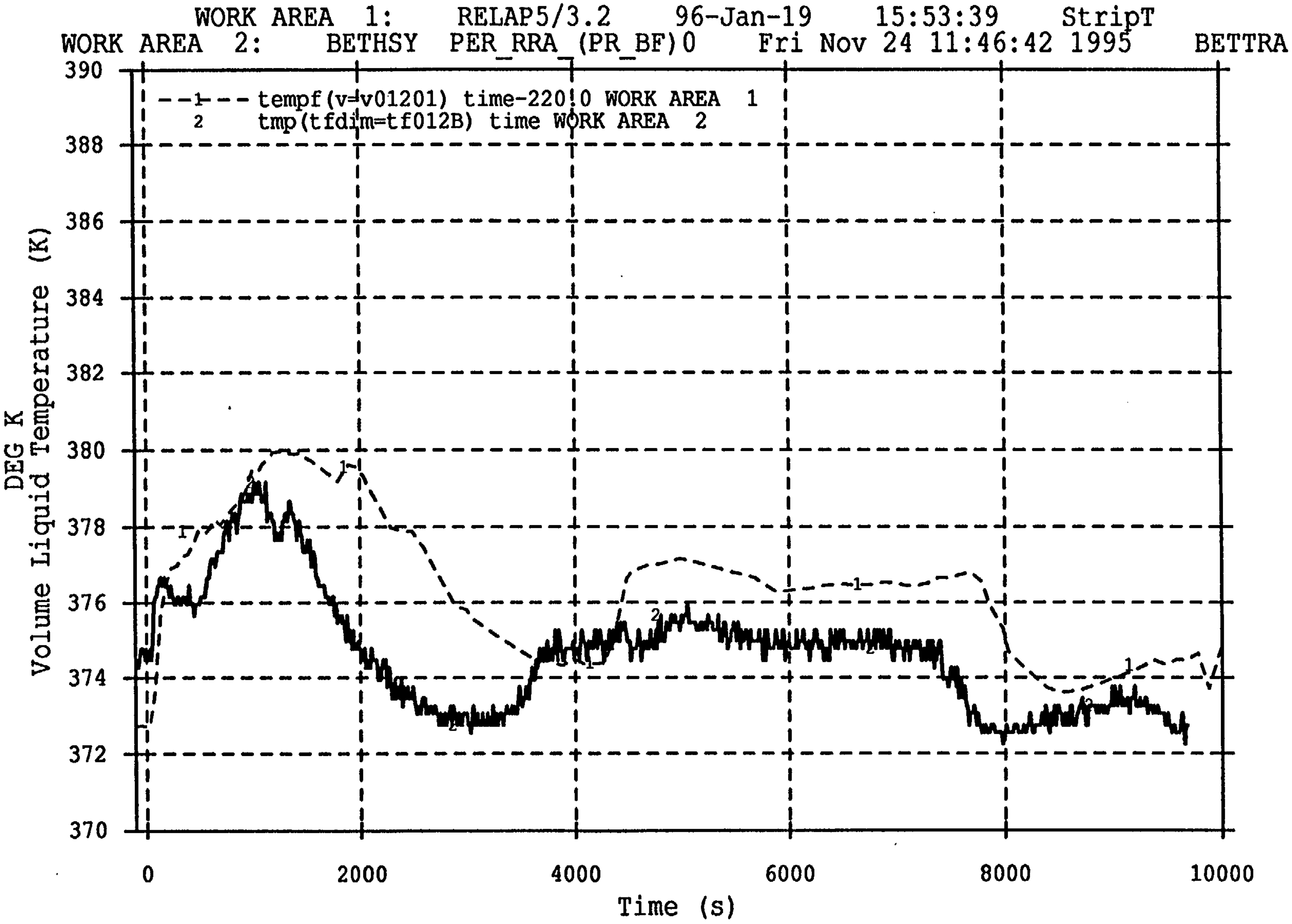


Fig. 24. Core inlet temperature

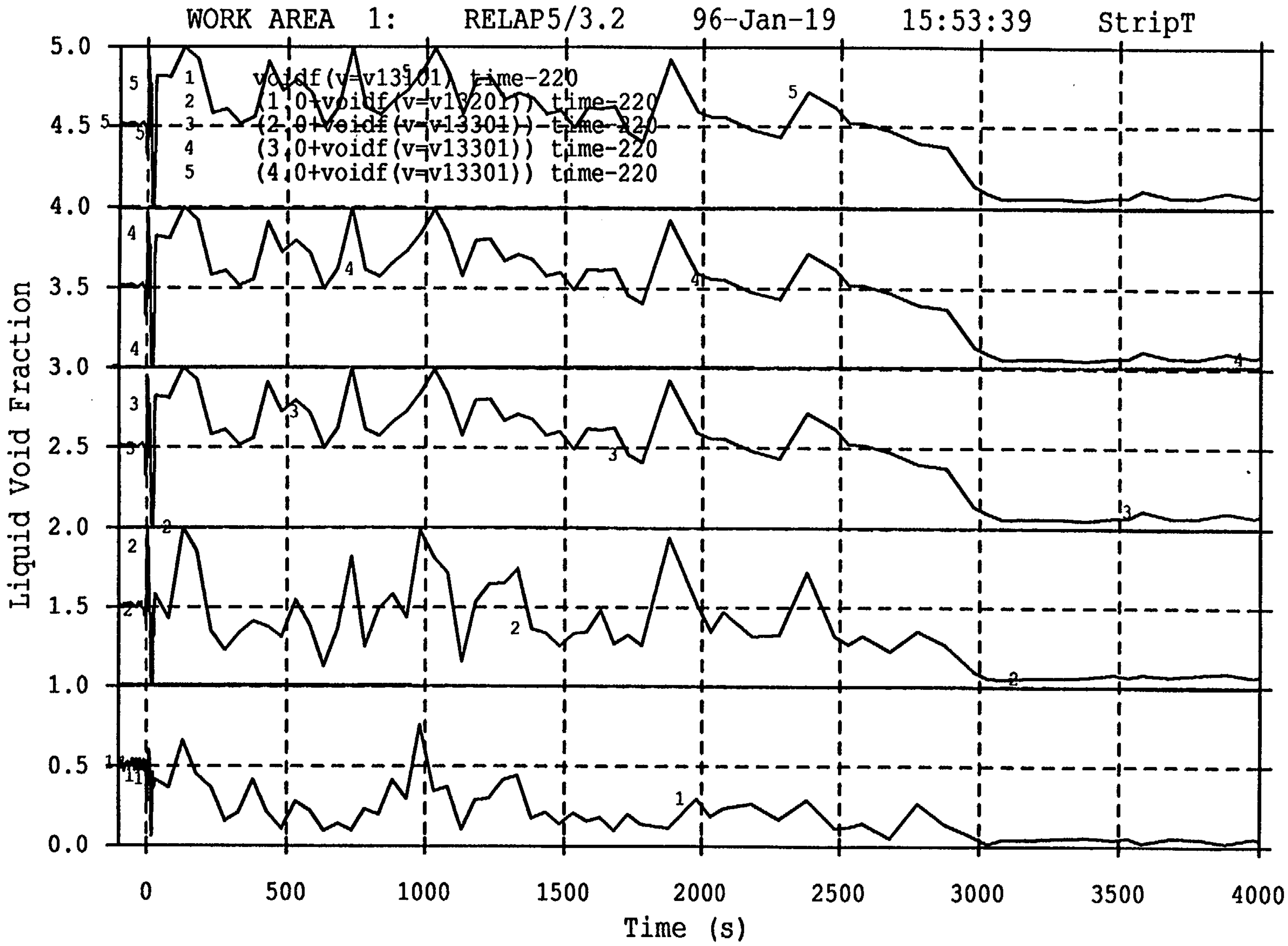


Fig. 25. Liquid fractions in hot leg 1 volumes

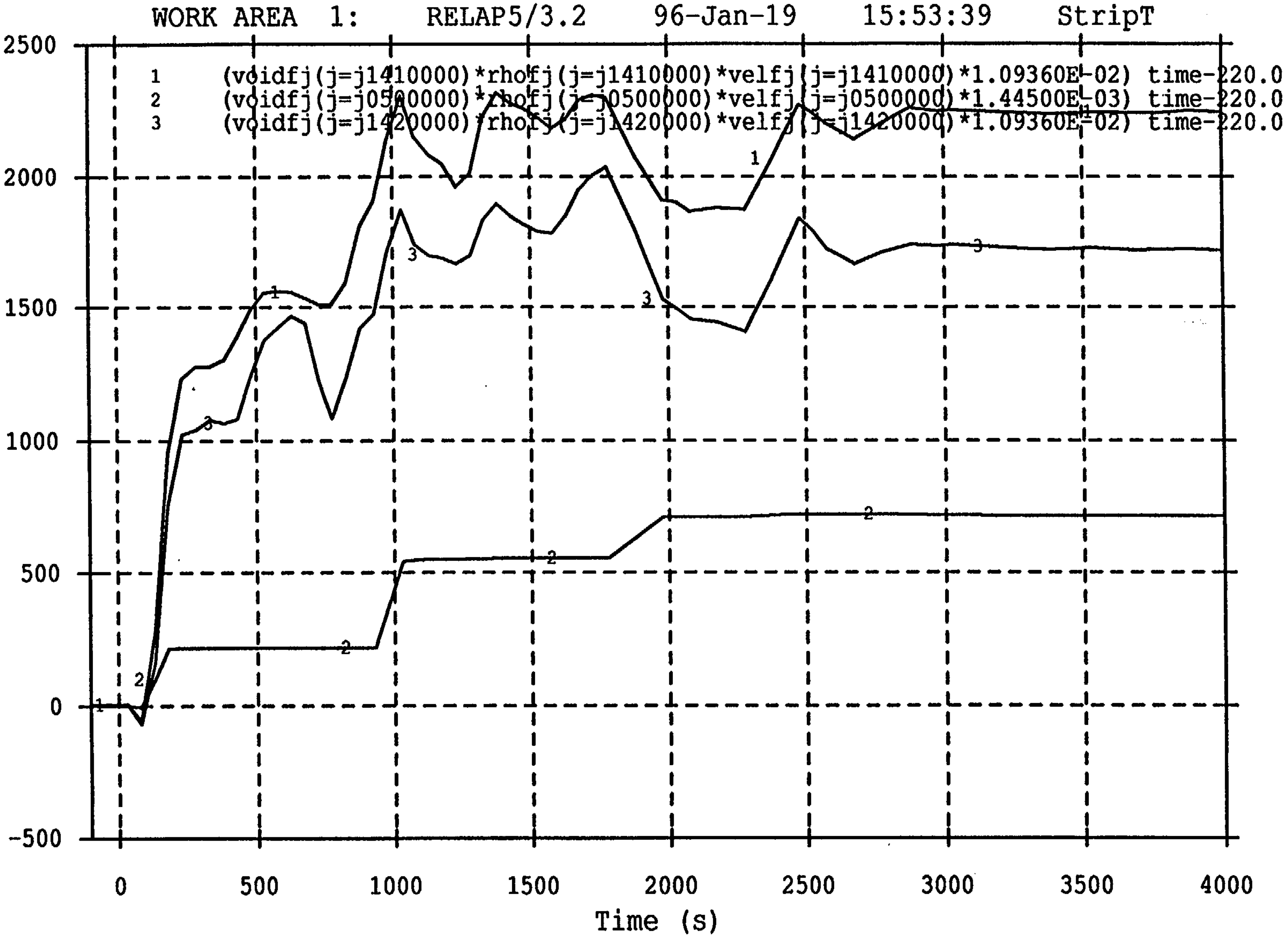


Fig. 26. Integrated mass flows near surge line

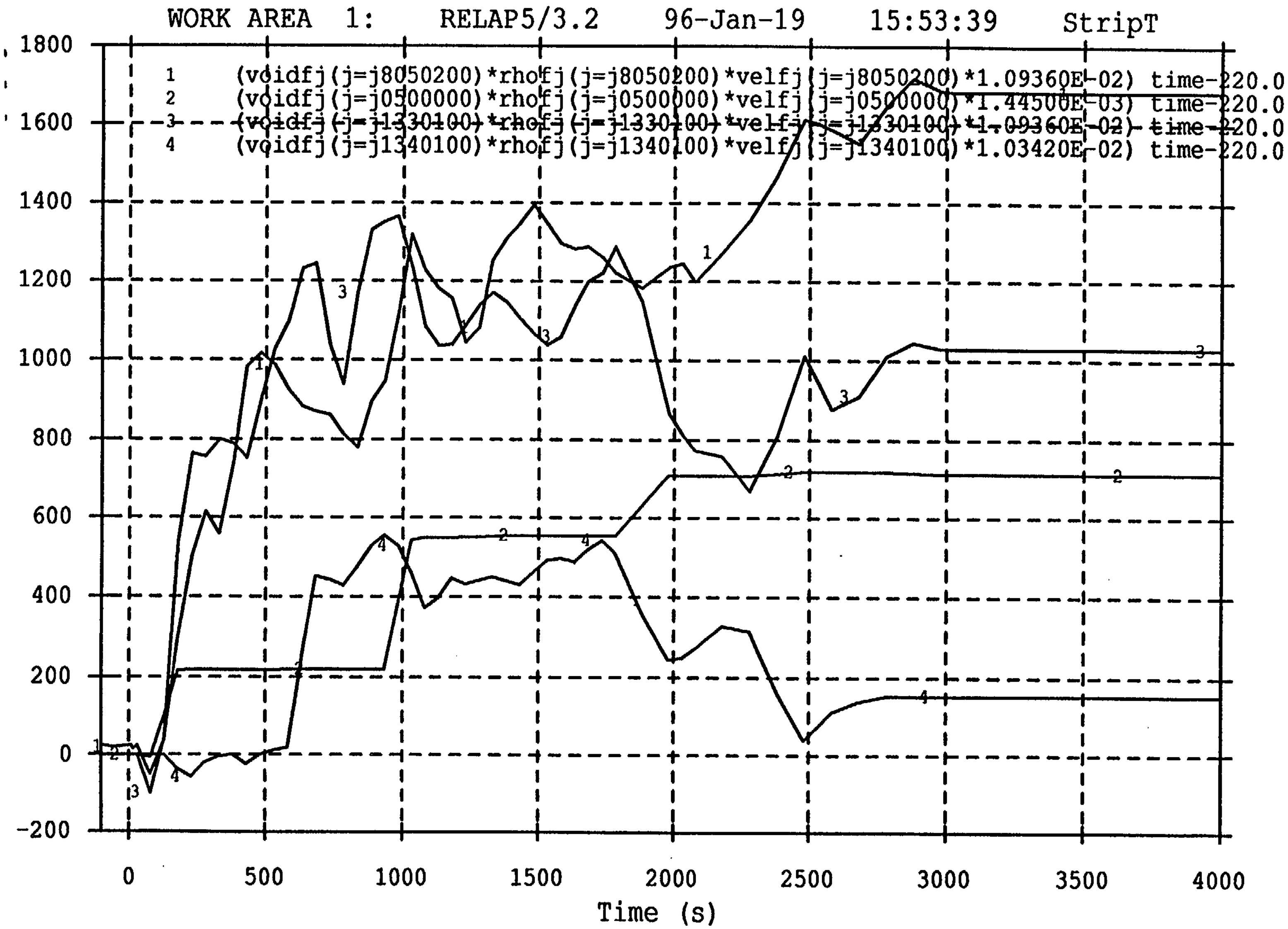


Fig. 27. Integrated mass flows in hot leg 1

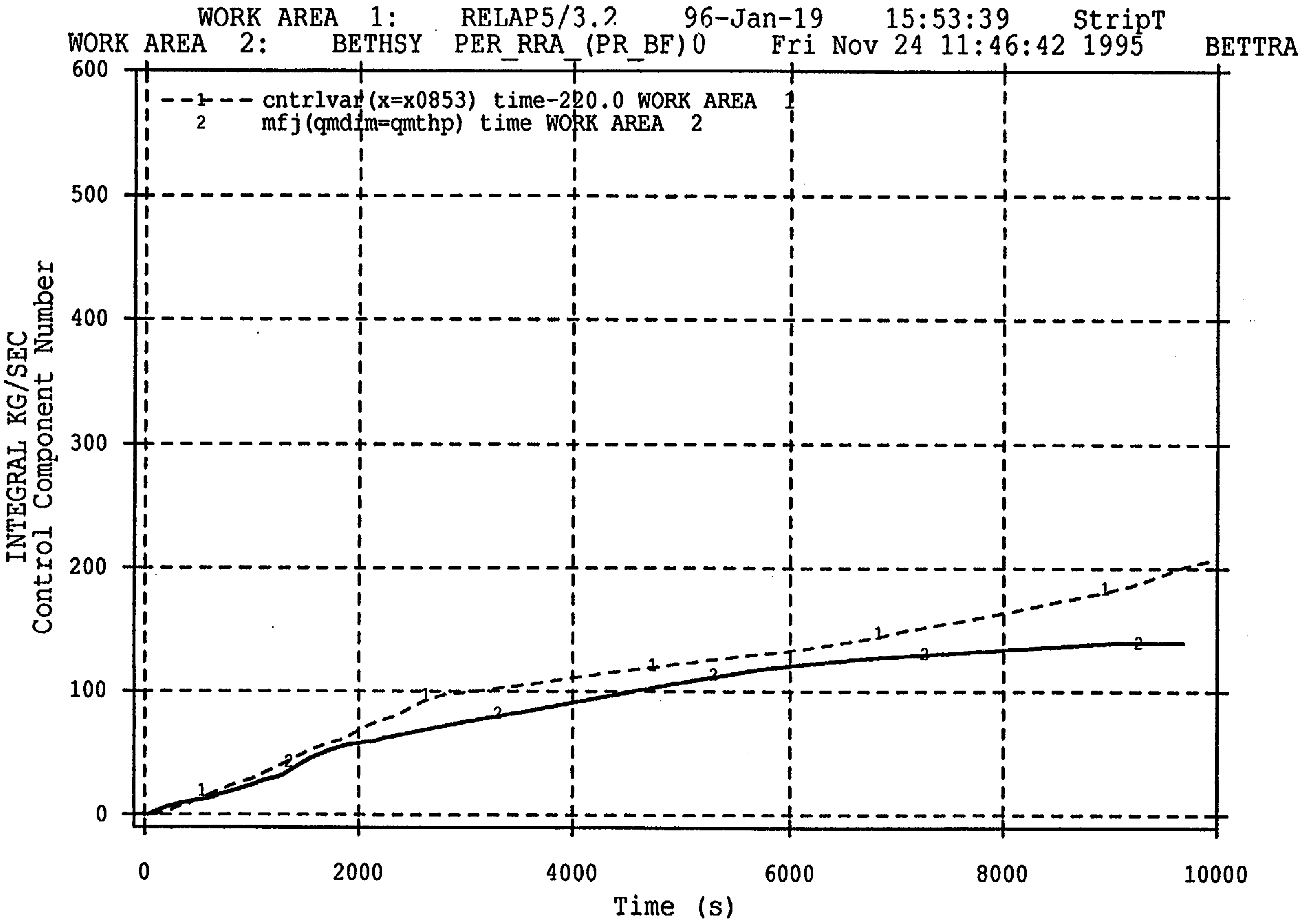


Fig. 28. Pressuriser manway discharge rate

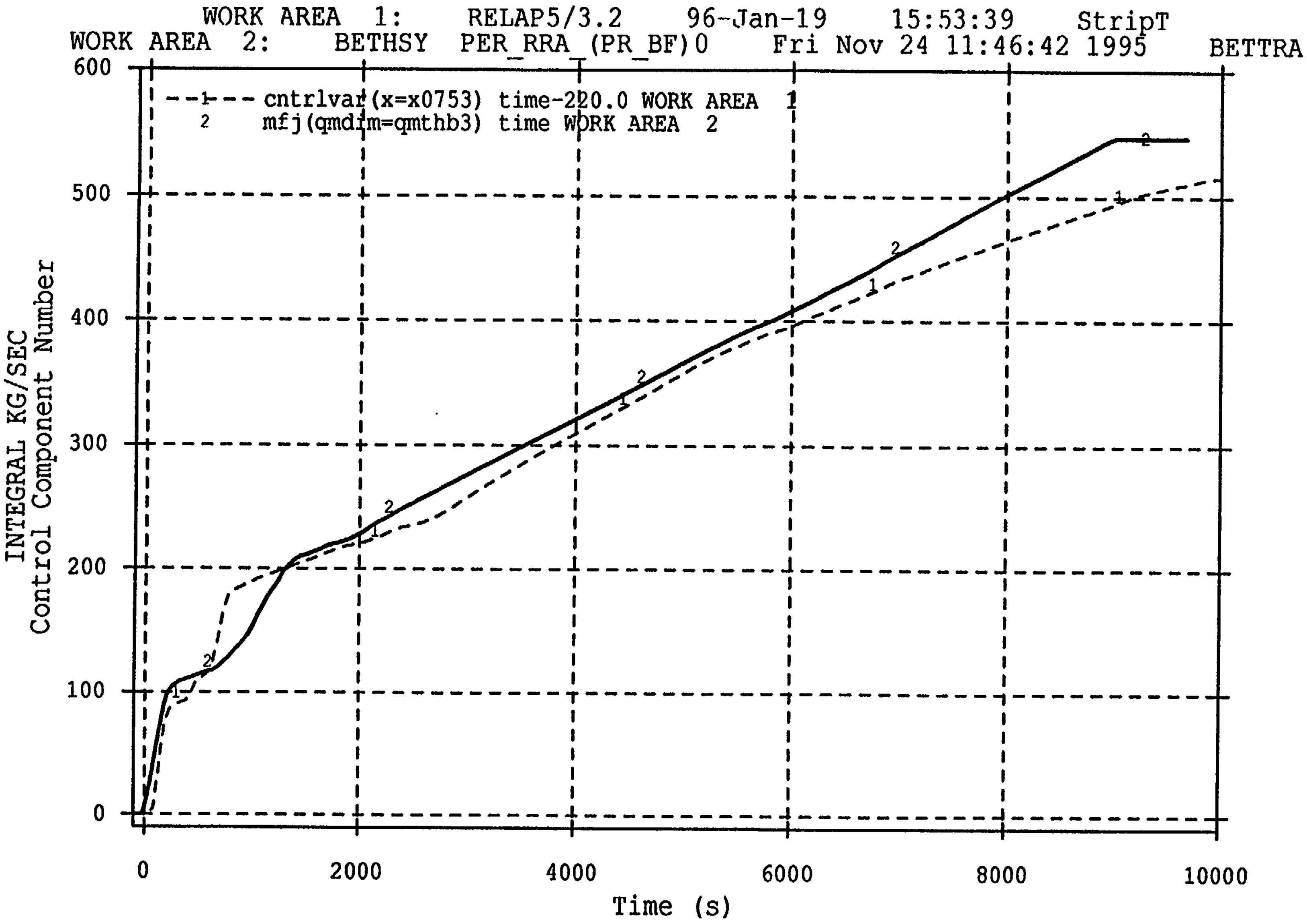


Fig. 29. SG outlet plenum manway mass discharge

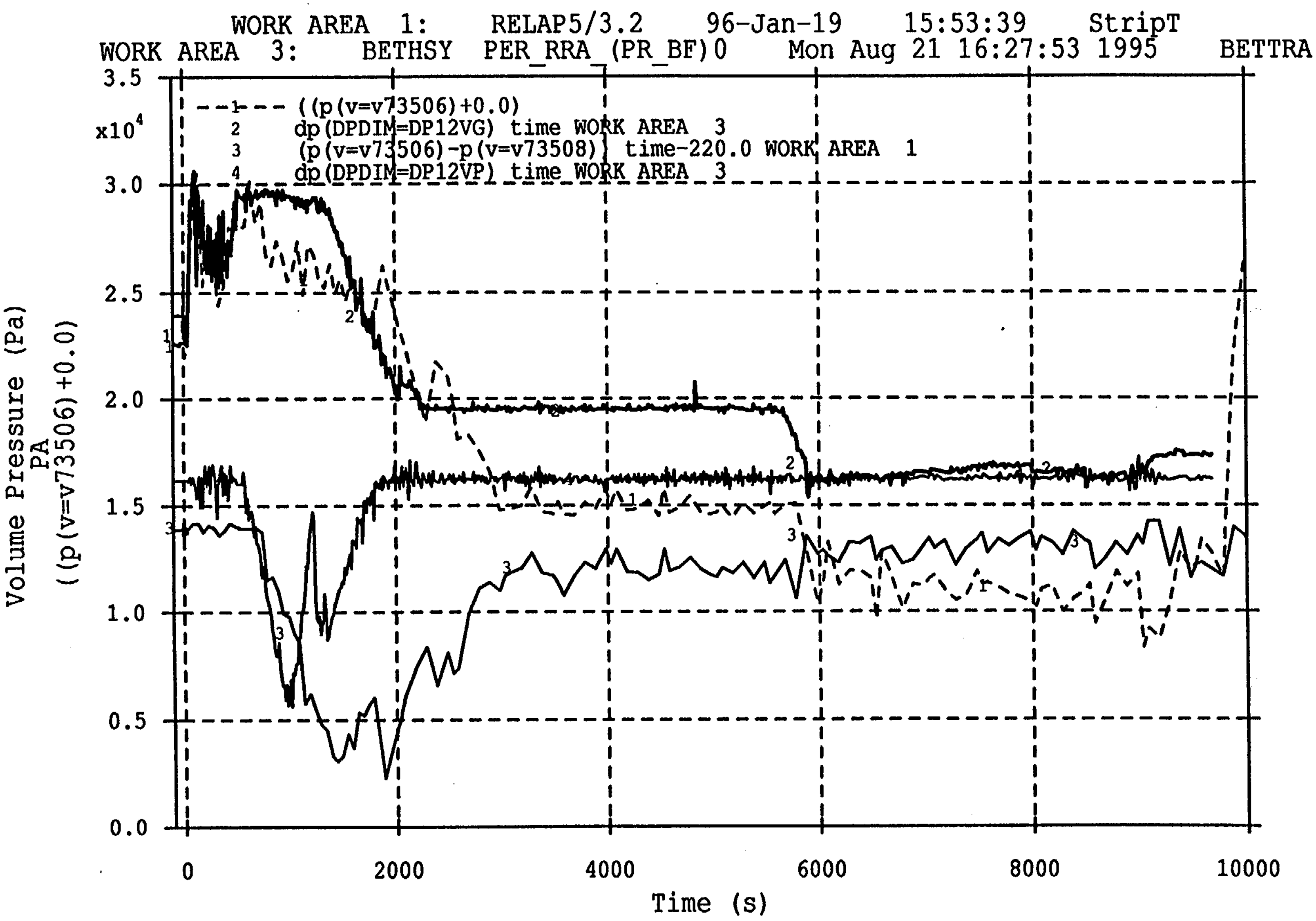


Fig. 30. DPs in intermediate leg 1: S G Side (DP12VG) & Pump Side (DP12VP)

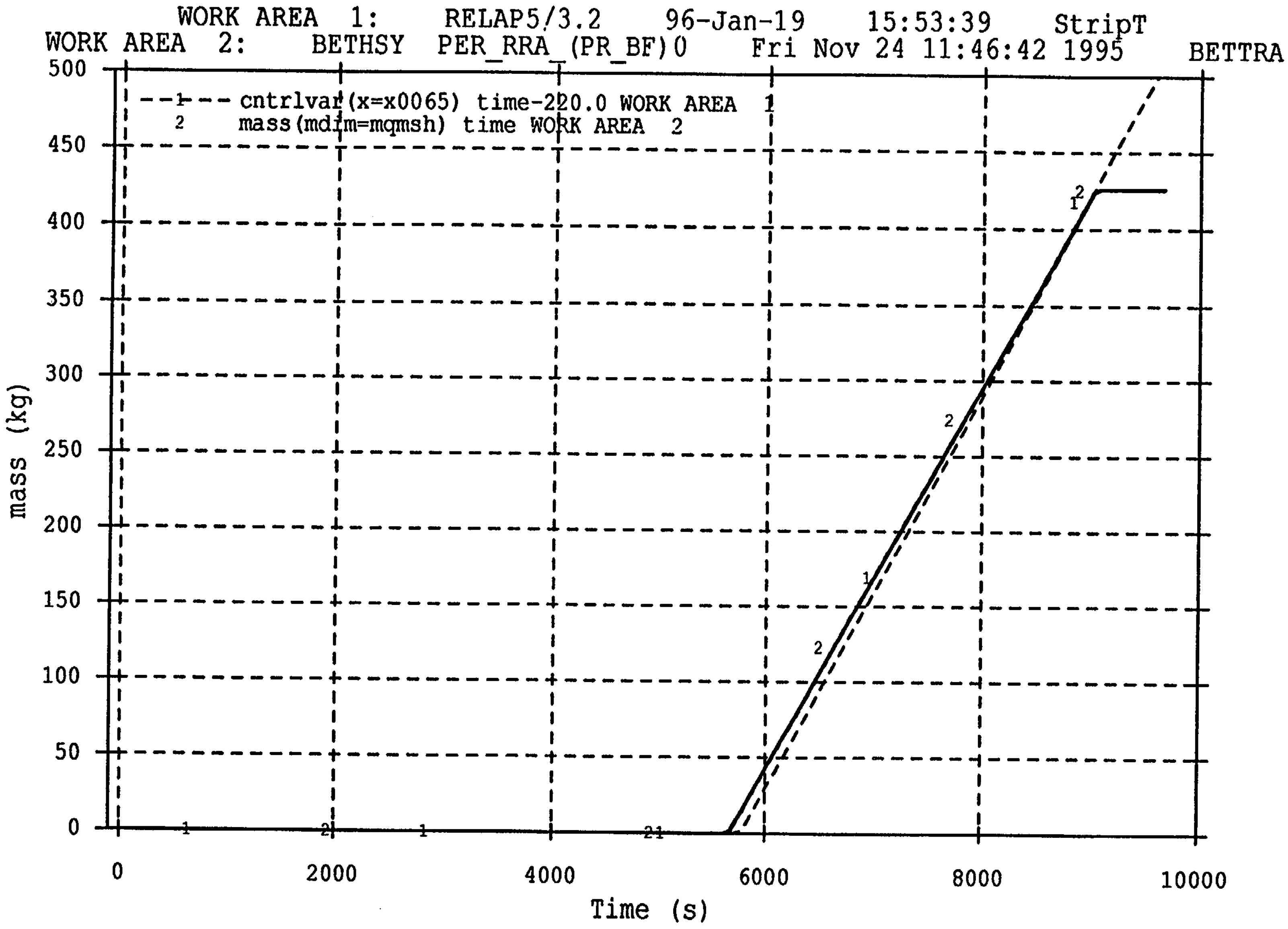


Fig. 31. Gravity feed mass flow rate

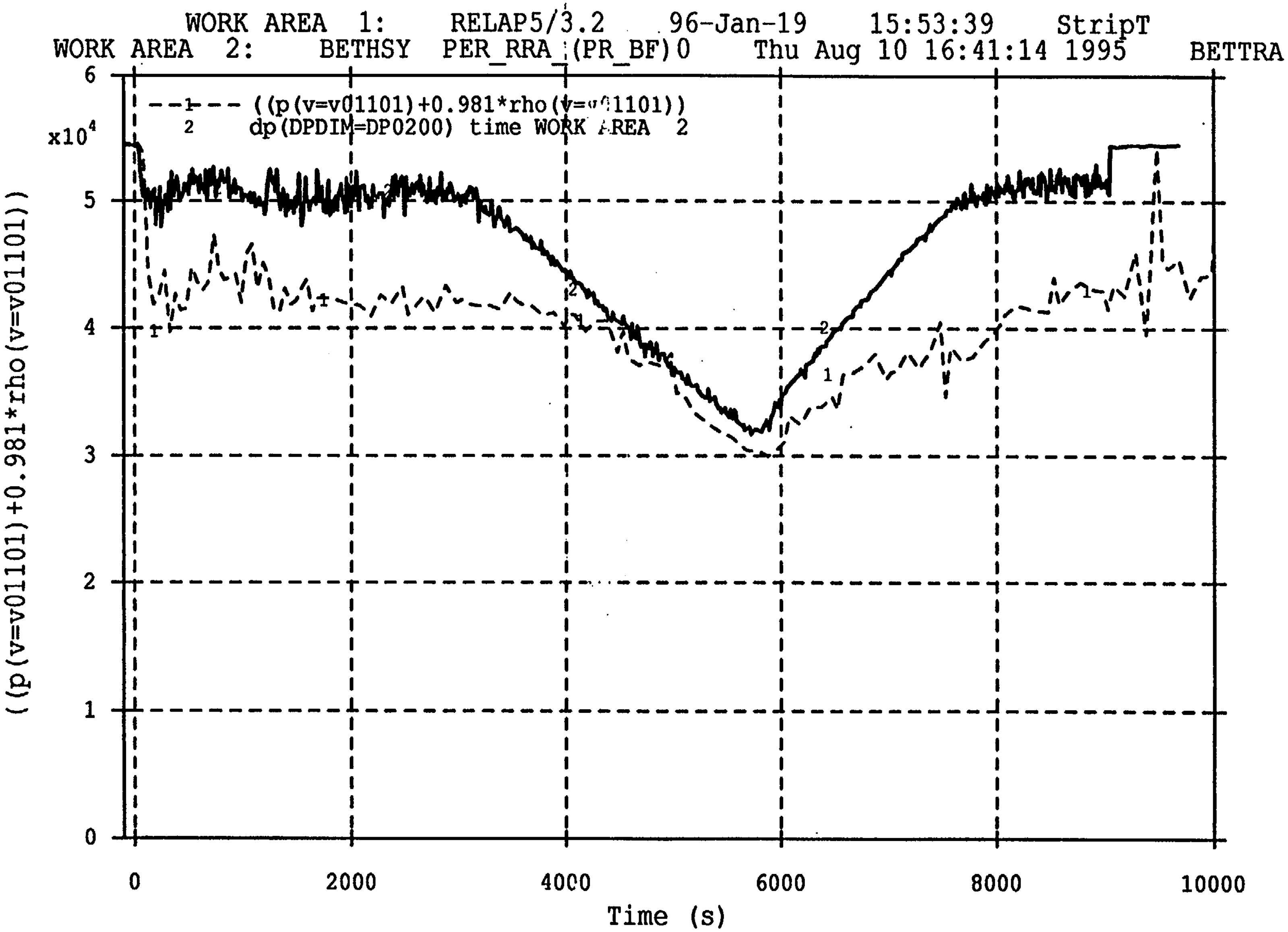


Fig. 32. DP in core

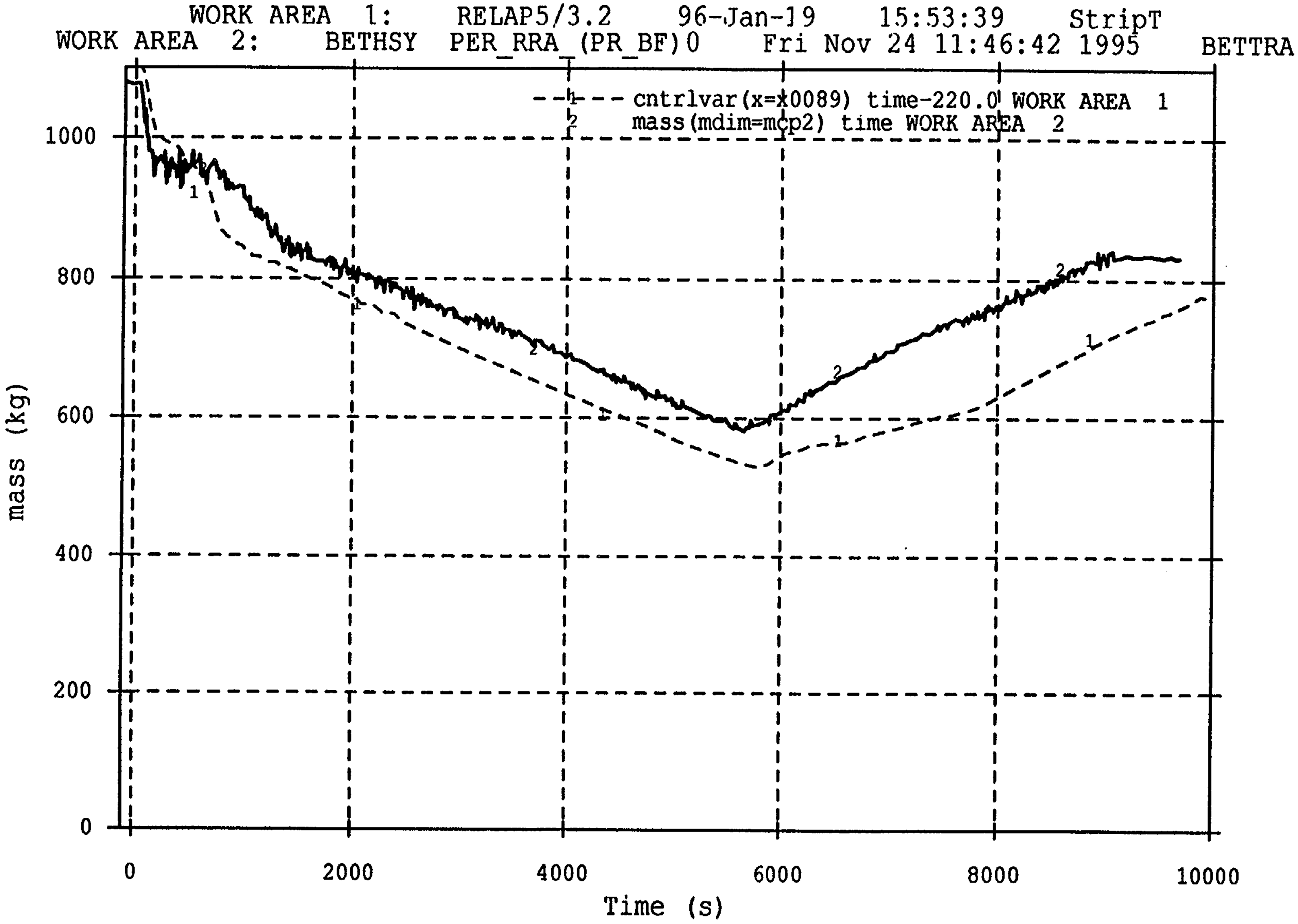


Fig. 33. Primary circuit mass

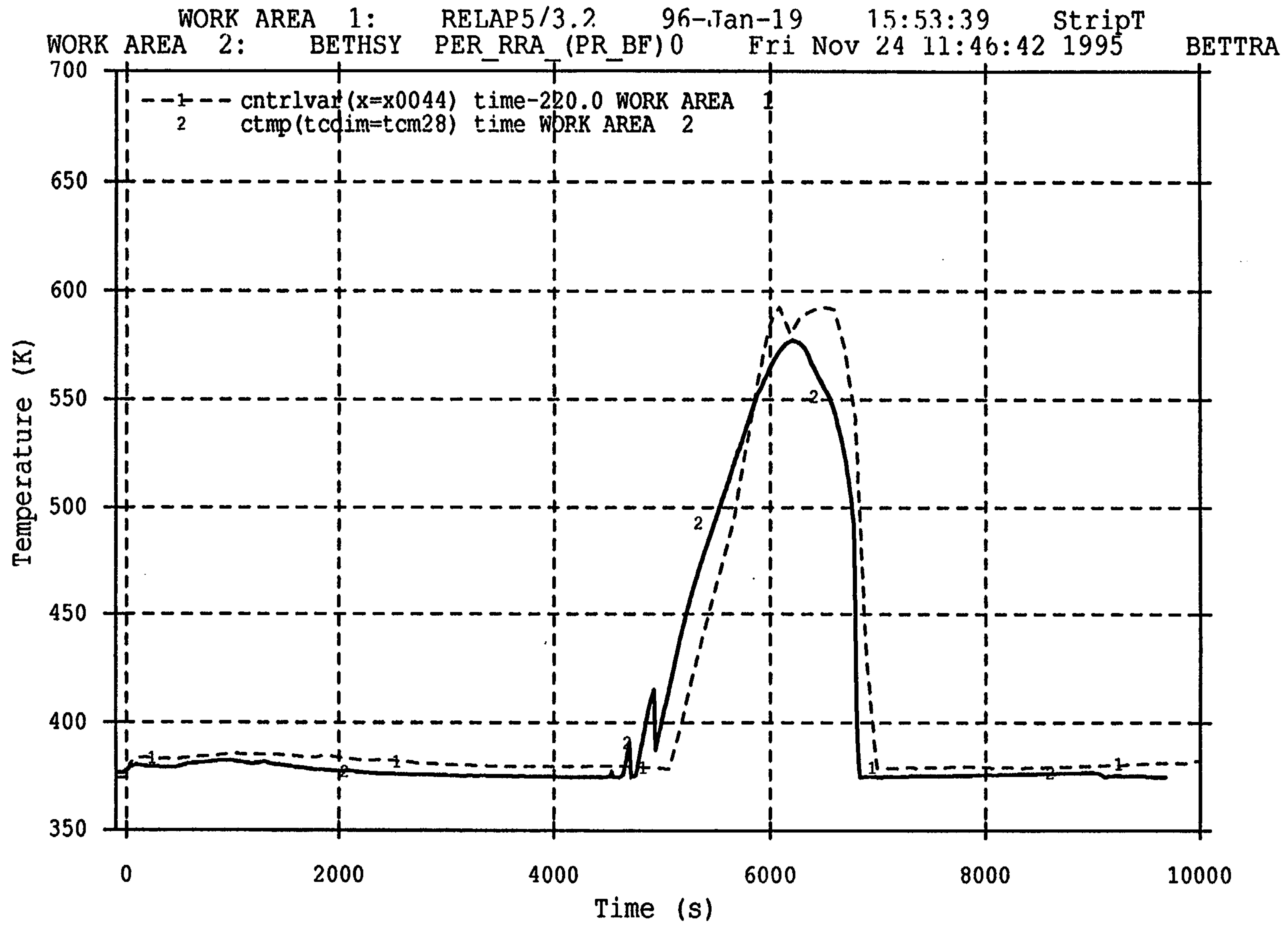


Fig. 34. Peak clad temperature

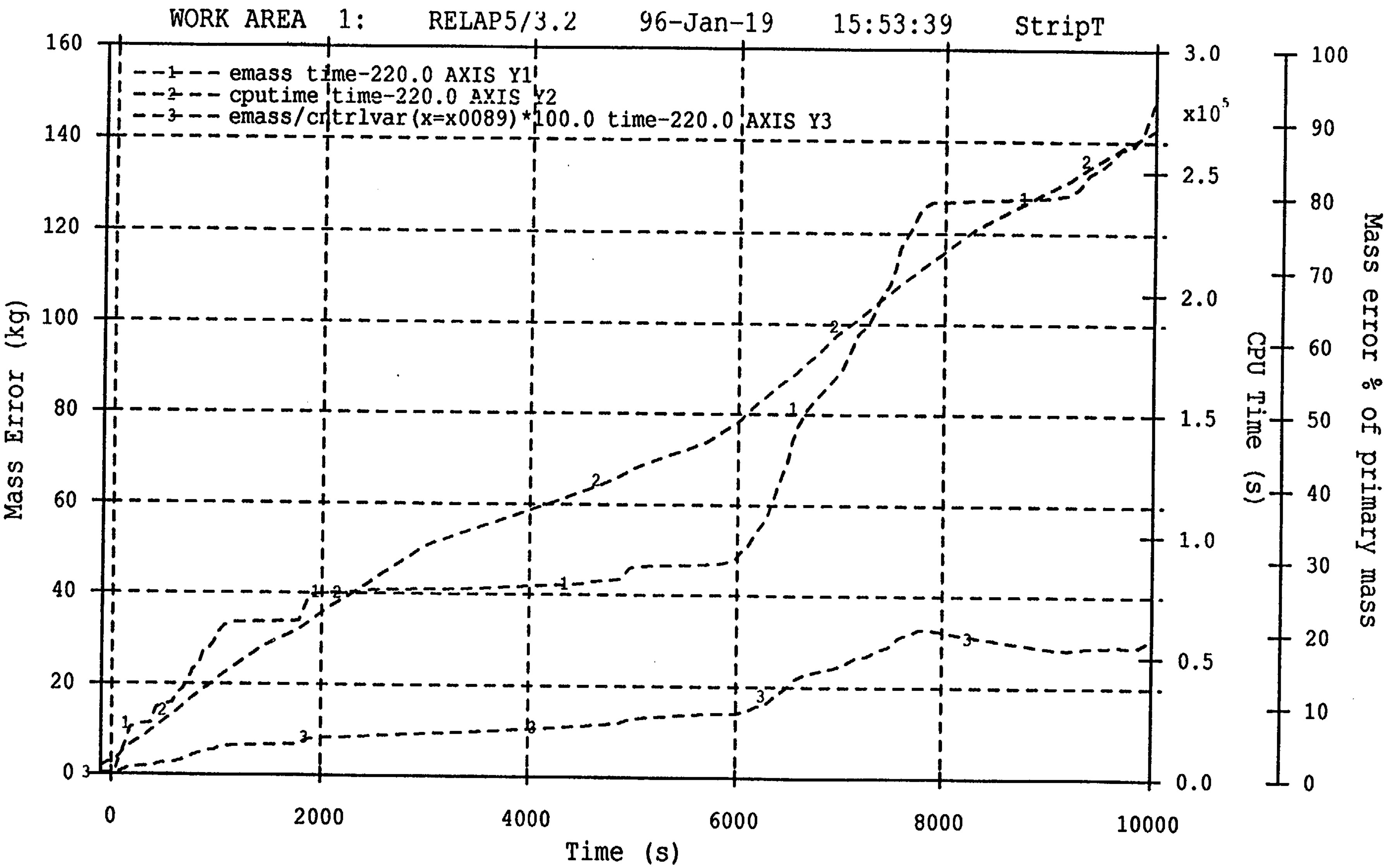


Fig. 35. Mass error(1), cpu time (2), & relative mass error (3)

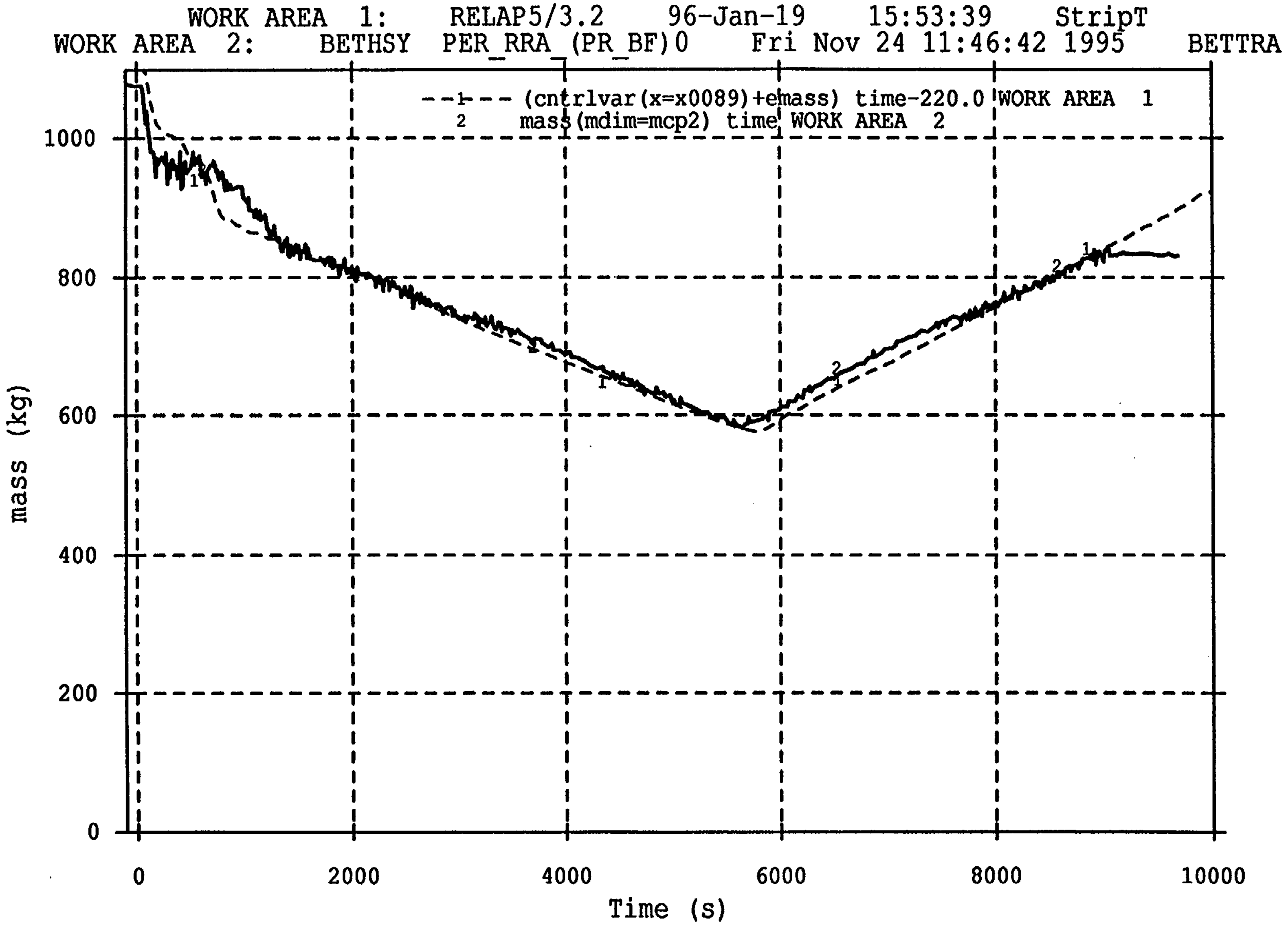


Fig. 36. Primary circuit mass with mass error correction

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

Accidents associated with a loss of the Residual Heat Removal System (RHRS) during PWR shutdown operation have received attention in recent years. Typically such events occur at low pressure and low core power. A series of tests, 6-9a-d, has been performed in the BETHSY Integral Test Facility at Grenoble, France to address the safety issues posed in this type of accident. The data from Tests 6.9a, c&d are available to the AEA Technology through its membership of the BETHSY Club. Tests 6.9a & d have been analyzed in previous years. Test 6.9c, the subject of this report differs from previous tests as it simulates plant conditions following a loss of RHRS when the primary circuit is open in two places; one at the pressuriser manway and the other at the steam generator outlet plenum. There is thus the potential for a large inventory loss from the primary circuit and a deep core uncovery. This did in fact occur. The analysis of this test is directly relevant to PWR thermal hydraulics safety issues associated with loss of RHRS.

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RELAP5/MOD3 ANALYSIS OF BETHSY TEST 6.9C: LOSS OF RHRS: SG MANWAY OPEN

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WASHINGTON, D.C. 20555-0001

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