NUREG/IA-0012

International Agreement Report

RELAP/MOD2 Calculations of OECD-LOFT Test LP-SB-01

Prepared by
P.C. Hall, G. Brown

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Office of Nuclear Regulatory Research
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Prepared as part of
The Agreement on Research Participation and Technical Exchange
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NOTICE

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Abstract:

To assist CEGB in assessing the capabilities and status of RELAP5/MOD2, the code has been used to simulate SBLOCA test LP-SB-01 carried out in the LOFT experimental reactor under the OECD LOFT programme. This test simulated a 1.0% hot leg break in a PWR, with early tripping of the primary coolant circulating pumps. This report compares the results of the RELAP5/MOD2 analysis with experimental measurements.

Comparison of the present calculation with earlier RELAP5/MOD1 calculations shows that significant improvements have been made. Most notably, the horizontal stratification model in MOD2 was found to enable improved calculation of fluid density close to the break in this test. In addition mass conservation errors, numerical stability and the computer run time were all greatly improved, compared with an earlier CEGB analysis using MOD1.

The major difference between the RELAP5/MOD2 results and the experimental data is in the critical discharge flow rate. It is concluded that the error arises from thermal disequilibrium effects in the discharge nozzle which are not modelled in the code. However, the discrepancies are not considered unduly significant for safety analysis of small break loss of coolant accidents in nuclear power plants, since in this application such effects would normally be allowed for by performing sensitivity studies to break size, orientation, etc.

Executive Summary:

The RELAP5/MOD2 transient thermal-hydraulics computer code is being used by CEGB for calculation of small break loss of coolant accident (LOCA) sequences for Sizewell 'B'. To assist CEGB in assessing the capabilities and status of this code, it has been used to simulate SBLOCA test LP-SB-01 carried out in the LOFT experimental reactor under the OECD LOFT programme. This test simulated a 1.0% hot leg break in a PWR, with early tripping of the primary coolant circulating pumps. This report compares the results of the RELAP5/MOD2 analysis with experimental measurements.

RELAP5/MOD2 was developed from RELAP5/MOD1 and contains more sophisticated hydraulic models and constitutive relationships. Comparison of the present calculation with earlier MOD1 calculations shows that significant improvements have been made. Most notably, the horizontal stratification model in MOD2 was found to enable improved calculation of the effects of flow stratification in the hot leg on the fluid density close to the break in this test. In addition mass conservation errors, numerical stability and the computer run time were all greatly improved, compared with an earlier CEGB analysis using MOD1.

Overall agreement with the experimental data was found to be reasonably good, though the following two deficiencies were encountered:

(a) Systematic underprediction of critical discharge flow rates by about 30% at the low quality conditions which occurred in the early part of this test. The errors have been attributed to thermal disequilibrium effects in the discharge nozzle which cannot be modelled by RELAP5. However, the discrepancies are not considered unduly significant for reactor loss-of-coolant accident analyses, since in this application such effects would normally be allowed for by performing sensitivity studies to break size, orientation, etc.,

(b) activation of the RELAP5/MOD2 vertical stratification model in the upper plenum has been found to lead to the erroneous calculation of sudden draining of the hot legs. The current basis for general application of this model appears questionable.

CONTENTS

1. INTRODUCTION

The RELAP5/MOD2 code [11] is in use by CEGB for calculating small-break LOCA (SBLOCA) sequences for Sizewell 'B'. RELAP5/MOD2 uses a six-equation two fluid model to describe two-phase flow in the reactor primary and secondary systems. It supersedes the RELAP5/MOD1 code, which employed a five-equation two-phase flow model (one phase constrained to thermal equilibrium) and used less sophisticated models for flow regime transitions and interphase interaction terms.

To assist in assessing the capabilities and status of RELAP5/MOD2, the code has been used to simulate SBLOCA test LP-SB-01 carried out in the LOFT experimental reactor under the OECD LOFT programme.

LOFT test LP-SB-01 simulated a 1% hot leg break in a Pressurized Water Reactor (PWR) with an early trip of the primary circulating pumps. The test is described in detail in refs. [1], [2]and [3].

The present report describes this analysis. Comparisons are given with earlier simulations carried out with RELAP5/MOD1 described in refs. [2], [4] and [5]. The effect of modelling changes introduced into the MOD2 code version are highlighted.

2. CODE VERSION AND INPUT MODEL

The code used for this calculation was RELAP5/MOD2 Cycle 36.02. This code version included several error corrections implemented by UKAEA, Winfrith, including a correction to enable the junction horizontal stratification model to be utilized at cross flow junctions; and correction of Cray conversion errors.

The input data was based on that used in ref. [6] for the analysis of LOFT cold leg break test LP-SB-03. Changes were introduced to describe the revised break location, to model the emergency cooling system and improve the representation of the inactive loop. The noding diagram is shown in Figure 1. The model consisted of 120 Volumes, 126 junctions and 125 heat structures. A significant difference between the RELAP5/MOD2 model and the RELAP5/MOD1 model used for the analyses in refs. [2], [4] and [5] is that in the present case junctions between the hot leg and the break line, and between the hot and cold legs and the vessel, were modelled using cross flow junctions. This meant that new hydrodynamic volumes were required in the hot leg and in the vessel upper plenum and upper downcomer.

A microfiche listing of the code input and output has been filed under Safety Technology Section in Microfiche Archive at Barnwood.

3. INITIAL AND BOUNDARY CONDITIONS

To establish the required steady state, a pseudo-transient calculation was run until the problem time reached 91.2s, at which the code indicated a satisfactory steady state. Parameters controlled to achieve the desired steady state were steam and feed flow, and the pump speed. A dummy time dependent volume was attached to the top of the pressurizer to maintain the desired steady primary pressure. Figures 2, 3 and 4 show the separator void fraction, the flows into and out of the SG separator, the pressurizer pressure and surge line flow during the steady state run. These variables are sensitive indicators, and demonstrate that a very satisfactory steady state was achieved.

The RELAP5 calculated steady state initial conditions are compared with experimental values for ref. [2] in Table 1. These can all be seen to be in agreement, except for the steam generator (SG) secondary side level, which had to be set artificially high in order to eliminate periodic emptying and filling of the separator volume. This modification was considered acceptable since in test LP-SB-01 the SG secondary plays only a minor role in the overall primary system energy removal.

Boundary conditions used in the test were obtained from the EG&G data package, ref [3]. This did not include auxiliary feed-water flow-rate. Appropriate data were deduced from the observed rate of change of liquid level in the SG. A fixed value of 0.28 L/s, for the period 64.5s to 1864.8s was used in the calculation.

Ref. [1] stated that the steam bypass valve was opened once, early in the test. Based on examination of the experimental secondary pressure and discussions with INEL staff the bypass valve was modelled as being opened when secondary pressure exceeded 6.5MPa and latched closed when the pressure fell below 6.5MPa. The area of the valve was taken as $3.2\ 10^{-4}\ m^2$, in line with the RELAP5 input dataset given in ref. [7].

Combined fission and decay power was inserted in the code as a table based on that used in ref. [5]. For times greater than 250s, values were taken from ref. [13].

4. COMPARISON OF RELAP5/MOD2 RESULTS WITH EXPERIMENTAL DATA

4.1 DESCRIPTION OF TEST

The sequence of events in the test is given in Table 2.

The transient is briefly described as follows. The primary coolant pumps were tripped at t = 24.6s, and pump run-down was complete at t = 43s. Two-phase natural circulation flow was maintained up to approximately 500s, at which time the system entered a reflux condensation mode and the SG U-tubes, cold leg and hot leg piping successively drained. The break line attached to the hot leg uncovered at t = 715s, approximately the same time as the cold leg became empty. Reflux condensation in the SGs terminated at about t = 1100s.

The system inventory continued to fall until about 2000s when the pressure reached a level at which the high pressure injection (HPI) flow balanced the break flow. Thereafter the system inventory rose slowly. The test was terminated when the primary pressure reached 2.5MPa. No core dry-out was observed at any time.

4.2 RELAP5 RESULTS

(i) Initial Calculation

In the first calculation attempted, the break nozzle was modelled using liquid (CD1) and two-phase (CD2) discharge miltipliers of 0.93 and 0.81 respectively, as in previous LOFT test analyses [5], [6]. The calculated break flow-rate is compared with the measured value in Fig. 5. It is seen that there is a systematic underprediction of flow-rate of 30% in the period before nozzle uncovering at 715s. During this period the quality in the break line is in the region 0-0.4%.

Similar discrepancies in flow-rate were found in the RELAP5/MOD1 calculations in refs. [2], [4] and [5]. Refs. [2] and [5] attributed the errors to the inability of RELAP5/MOD1 to correctly calculate the quality of fluid entering the break line from the hot leg, since no account was taken for the effect on the discharge quality of flow stratification in the hot leg. RELAP5/MOD2 has a special model designed to correct the break flow quality for the effects of flow stratification in an upstream volume and this model was utilized in the present calculation. Fig. 6 shows the predicted fluid density in the break line. Comparison with Fig. 7 shows that the calculated break line density is correctly predicted to be higher than that in the hot leg, as a result of flow stratification in the hot leg. This shows that the RELAP5/MOD2 flow stratification model is working correctly. The implication is, therefore, that the error in the discharge flow-rate is not attributable to an error in the calculated discharge quality, as was postulated in refs. [2] and [5].

It is believed that the more probable explanation for the error in the predicted break flow-rates is the occurrence of thermal-disequilibrium in the discharge nozzle, as was postulated in ref. [1]. The RELAP5 critical flow model approximates to a thermal equilibrium expansion in the nozzle. Fig. 8 compares RELAP5/MOD2 predictions of critical flow-rate with calculations of the simple isentropic homogeneous thermal equilibrium critical flow model (HEM), taken from ref. [8]. Calculations are for a 12.7mm diameter nozzle discharging from a reservoir at 68.9 bars. It is seen that the RELAP5 prediction is very close to the HEM. In the quality range 0.2-5% results are about 10% below the HEM.

The Henry-Fauske [9] critical flow model is frequently applied in the analysis of nozzles and short tubes, where thermal-disequilibrium effects are important. Predictions of the Henry-Fauske model for the conditions of test LP-SB-01 are shown in fig. 5, taken from ref. [1]. It is seen that this model does indeed give a good prediction of the break flow-rate during the period of low-quality discharge in test LP-SB-01.

It remains to be established if disequilibrium effects were likely to have occurred for the particular nozzle geometry and range of qualities encountered in test LP-SB-01. To see if this was the case, we examine the data of Sozzi and Sutherland [10] who measured steam-water critical flow-rates in nozzles with the same length and diameter characteristics as the LOFT nozzle [see fig. 9]. Test results are shown as the curves in the figure. It is seen that for the range of stagnation qualities of present interest, $X_0 = 0.0 - 0.004$, thermal disequilibrium effects are likely to give rise to departures from the HEM of about +40% for a nozzle of the length and diameter used in test LP-SB-01.

The above observations suggest that the break flow-rate discrepancies in LP-SB-01 are probably due to the fact that the RELAP5 critical flow model is inappropriate for the particular nozzle geometry and range of discharge qualities encountered in the period from 50s to 715s of this test.

For the present calculation it is accepted that the RELAP5/MOD2 critical flow model underpredicts the data as a result of disequilibrium effects, possibly by as much as 50%. So as to establish a suitable boundary condition against which to assess the performance of the balance of the code against this test, a second calculation was performed in which the two-phase discharge multiplier CD2 was set to 1.18 (to fit the low quality discharge data for LP-SB-01). When the void fraction in the break line reached a value of 40%, the value of the two-phase flow discharge coefficient (CD2) was reset to the value of 0.81 as used in previous calculations. At this stage, it was judged that disequilibrium effects would be relatively insignificant, (extrapolating the data of Sozzi & Sutherland). This second calculation (termed the reference calculation) is discussed in the rest of this report.

(ii) Reference Calculation

The reference calculation was run from t=0 to 2000s, after which time HPI flow exceeded break flow and little of interest occurred in the transient.

(a) Break Flow-Rate

The break flow and primary system inventory are shown in figures 10 and 11. The agreement is good although this is to a large extent due to the choice of a value of the two-phase multiplier, CD2 = 1.18 for the low quality discharge period of the test.

(b) Primary and Secondary Pressures

Figure 12 shows calculated and measured primary pressure. The good agreement indicates that the discharge quality and mass flow rate are accurately calculated by RELAP5/MOD2.

Also shown in figure 12 are measured and calculated secondary pressure transients. There is a systematic overestimate of secondary pressure of 0.25-0.5MPa corresponding to errors in saturation temperature of 2.5 to 6K. This may arise from a tendency to overestimate heat transfer, leading to the need for a smaller primary to secondary temperature difference to drive the heat fluxes necessary to satisfy the primary energy balance. Other possible explanations are errors in modelling heat losses, or steam leakage via the main steam control valve. In view of the small part played by the SGs in this test, this error was not investigated in detail.

(c) Loop Flow-Rates and Densities

Figures 13 and 14 show the density in the hot leg and break line. In the period prior to break uncovery (t<715s), stratification effects cause the density in the break line to be higher than that in the hot leg. The horizontal stratification model in RELAP5/MOD2 captures this effect well. After break uncovery, the experimental data shows that the density in the break line falls below that in the hot leg. Again RELAP5/MOD2 calculates the correct trend.

Figures 13 and 15 show significant errors in the calculated values of the density in the hot and cold legs. The discrepancies in the period before 700s appear to stem from differences in the calculated natural circulation behaviour and subsequent draining of the SG tubes. In the calculation, natural circulation was predicted to cease at about 270s. This is the point in figure 16, where the calculated cold leg vapour velocity falls sharply. At the same time, calculated velocity in the hot leg (close to the vessel) fell rapidly (figure 17), as the SG heat removal mechanism switched from natural circulation to reflux condensation. Measured velocities shown in figures 16-17 indicate that natural circulation actually ceased at about 500s. (Note that the absolute values of the measured velocities are less than the measurement uncertainty, and can therefore be regarded as indicative only). It is clear that these discrepancies in calculated natural circulation behaviour contributed to the errors in calculated density in the hot leg and to the erroneous prediction that the cold leg drains suddenly (see fig. 15).

Figure 18 illustrates that the code correctly predicted the pump suction to remain full of water at all times.

Fig. 13 shows that the draining of the active loop hot leg which began at 700s was reasonably well calculated up to 1050s, when the calculation indicated sudden emptying. Sudden draining was also calculated in the upper plenum volume (252) and the inactive loop hot leg. Simultaneously, water was calculated to appear in the cold leg, (figure 15) and the calculated void fraction fell in the core outlet volumes. This movement of water from the hot legs to the cold legs is believed to result from the triggering of the RELAP5/MOD2 vertical stratification model, which is designed to sharpen the void fraction gradient in a stack of vertical volumes. The vertical stratification model is initiated when the difference in void fraction in volumes above and below a given volume exceeds 0.5. Figure 19 shows that this condition was satisfied in volume 250 at 1080s. The primary effect of invoking this model was to reduce suddenly the interphase drag forces in the junction between volumes 250 and 252, causing the draining of volume 252 and the consequential draining of both hot legs, which are connected to volume 252.

It is clear from these results that the vertical stratification model can produce unphysical draining of the loop pipework. Ref. 11 suggests that the model was developed to model pressurizers where the geometry is much simpler than in the vessel inlet and outlet plena. The current basis for general application of the vertical stratification model therefore appears questionable.

(d) CPU Time and General Code Performance

The calculations presented here were run on a Cray -1 computer at a CPU/real time ratio of 1.16. The maximum and minimum time steps were 0.1s and 10^{-7}s, with the code selecting the maximum time step continuously from t = 70s onwards. The code was found to be robust in that no failures were encountered, other than those arising from Cray conversion errors.

5. DISCUSSION AND COMPARISON WITH PREVIOUS ANALYSES

It is useful to highlight the major differences between the present calculation and the analyses of LP-SB-01 reported previously in refs. [2] and [5] using RELAP5/MOD1. The main points are as follows:-

(a) Effect of Stratification on the Break Flow-Rates

The RELAP5/MOD2 analyses in refs. [2] and [5] highlighted the difficulty of correctly calculating the break line density in the period when stratified flow existed in the active loop hot leg, to which the break line is connected. As described above, the present calculation indicates that this problem has been successfully resolved in RELAP5/MOD2.

(b) Critical Flow Model

Significant errors occurred in the calculated break flow-rate in the low quality discharge phase prior to break line uncovering at 700s (see figure 5). Similar errors were found in the RELAP5/MOD1 analysis in [2], [4] and [5]. As discussed in section 4, these errors are almost certainly due to the effects of thermal-disequilibrium of the critical flow-rate in the nozzle. RELAP5/MOD2 includes a model, based on the work of Alamgir and L__nhard [14] designed to take account of the effect of nucleation delay on the choked flow of subcooled liquid. This model is extended into the low quality region in order to smooth the calculated critical flow at the transition from subcooled to saturated upstream conditions. However, it does not appear to have had any significant effect in the analysis reported here. In any case, the implementation of the model is in a very simplified and approximate form, and would not be expected to provide accurate calcuations of the effects of detailed changes in the geometry of discharge nozzles on critical discharge flow rates. The magnitude of these thermal-disequilibrium effects depends strongly on the geometry of the break nozzle and the thermodynamic conditions.

For reactor analysis it is probably not worthwhile to try to develop a model detailed enough to describe these trends, for incorporation into RELAP5/MOD2. This is because in reactor safety analysis it is possible to allow for potential departures from thermal equilibrium behaviour by performing sensitivity studies with respect to break size and the magnitude of the break discharge coefficients.

(c) Flow Regime Calculation

In the RELAP5/MOD 1 analysis in ref. [5] it was noted that the transition to the stratified flow regime in the hot leg occurred at about 550s; experimental measurements indicated partial stratification at about 50s representing a significant error. The new flow regime maps included in RELAP5/MOD2 led to the prediction of stratified flow in the hot leg at 220s. The prediction of lower (i.e. closer to measured) steam and water velocities in the present calculation may also have been a contributory factor in this improvement.

(d) Stability and Mass Conservation

In the RELAP5/MOD1 calculation in ref. [5] mass conservation errors of about 700kg were observed, mostly arising in the SG secondary side during injection of auxiliary feed-water. The maximum mass conservation error in the present calculation was 1kg, which is negligible.
In ref. [5] it was also reported that RELAP5/MOD1 produced non-physical spikes of steam temperature in steam filled volumes. No evidence of anomalies of this kind was seen in the present analysis.

(e) CPU Time

RELAP5/MOD2 appears to run much faster than the MOD1. The RELAP5/MOD1 calculation in ref. [5] was executed on a Cyber 176 at a CPU/real time ratio of 34.2. As noted above the present calculation was executed on a Cray-1 at a CPU/real time ratio of 1.16. The same maximum and minimum time steps (0.1s and 10^{-7}s) were used in both analyses. The different machines used make exact comparisons difficult, but extensive studies by Kmetyk et al. [12] using RELAP5/MOD1 suggest that the Cray-1 is 1.5 to 2 times faster than the Cyber. This implies that in the simulation of test LP-SB-01, RELAP5/MOD2 ran faster than RELAP5/MOD1 by a factor of between 15 and 20.

6. CONCLUSIONS

This report has described the results of a RELAP5/MOD2 calculation of LOFT test LP-SB-01 which simulated a 1% hot leg loss of coolant accident in a PWR.

Overall agreement with experimental data was reasonable and the code performed better than RELAP5/MOD1 which has been used previously to simulate this experiment. In particular the difficulty of accounting for the effect of flow stratification in the hot leg on the density in pipe leading to the break orifice, encountered by previous workers, has been overcome in RELAP5/MOD2. Furthermore, MOD2 was found to run between 15 and 20 times faster than MOD1, and to be virtually free of numerical instabilities.

The principal deficiencies encountered were as follows:

(a) errors were seen in the calculation of critical discharge flow rates at the low quality conditions which occurred in the early part of this test. The errors have been attributed to thermal disequilibrium effects in the discharge nozzle which cannot be modelled by RELAP5. However, the discrepancies are not considered unduly significant for reactor loss-of-coolant accident analyses, since in this application such effects would normally be allowed for by performing sensitivity studies to break size, orientation, etc.,

(b) activation of the RELAP5/MOD2 vertical stratification model in the upper plenum has been found to lead to the erroneous calculation of sudden draining of the hot legs. The current basis for general application of this model appears questionable.

7. References

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TABLE 1

INITIAL CONDITIONS FOR EXPERIMENT LP-SB-01

Parameter	Measured	Calculated
Primary Coolant System		
Core T (K)	18.5±1.7	19.57
Hot leg pressure (MPa)	15.00±0.08	15.099
Cold leg temperature (K)	557.2±1.5	558.36
Mass flow-rate (kg/s)	483.1±3.2	483.1
Reactor Vessel		
Power level (MW)	48.8±1.2	48.8
Steam Generator Secondary Side		
Pressure (MPa)	5.53 ±0.05	5.546
Mass flow-rate (kg/s)	25.79±0.77	25.5
Liquid level (m)	3.12.±0.01	3.699
Pressurizer		
Liquid volume (m^3)	0.625±0.001	0.5905
Water temperature (K)	615.8±8.2	615.6
Pressure (MPa)	15.06±0.11	15.06
Emergency Core Cooling System		
BWST temperature (K)	304±7	304

TABLE 2

SEQUENCE OF EVENTS FOR EXPERIMENT LP-SB-1

Event	Experiment	Calculation
Small break valve opened	0.0	0.0
Reactor Scrammed	1.4 ± 0.05	2.5
MSCV started to close	3.4 ± 0.2	2.5
MSCV fully closed	15.4 ± 0.2	19.0
Primary coolant pumps tripped	24.6 ± 0.2	24.1
Steam bypass valve opened	not known	26.0
HPIS flow initiated	41.4 ± 0.2	45.4
Steam bypass valve closed	not known	50.0
Subcooled blowdown ended	57.5 ± 0.2	49.7
Auxiliary feed-water initiated	63.4 ± 0.2	64.5
Break started to uncover	715 ± 3	615
Primary system pressure becomes less than secondary system pressure	1077 ± 10	833
Auxiliary feed-water shut off	1864.8 ± 0.8	1864.8

LIST OF FIGURES

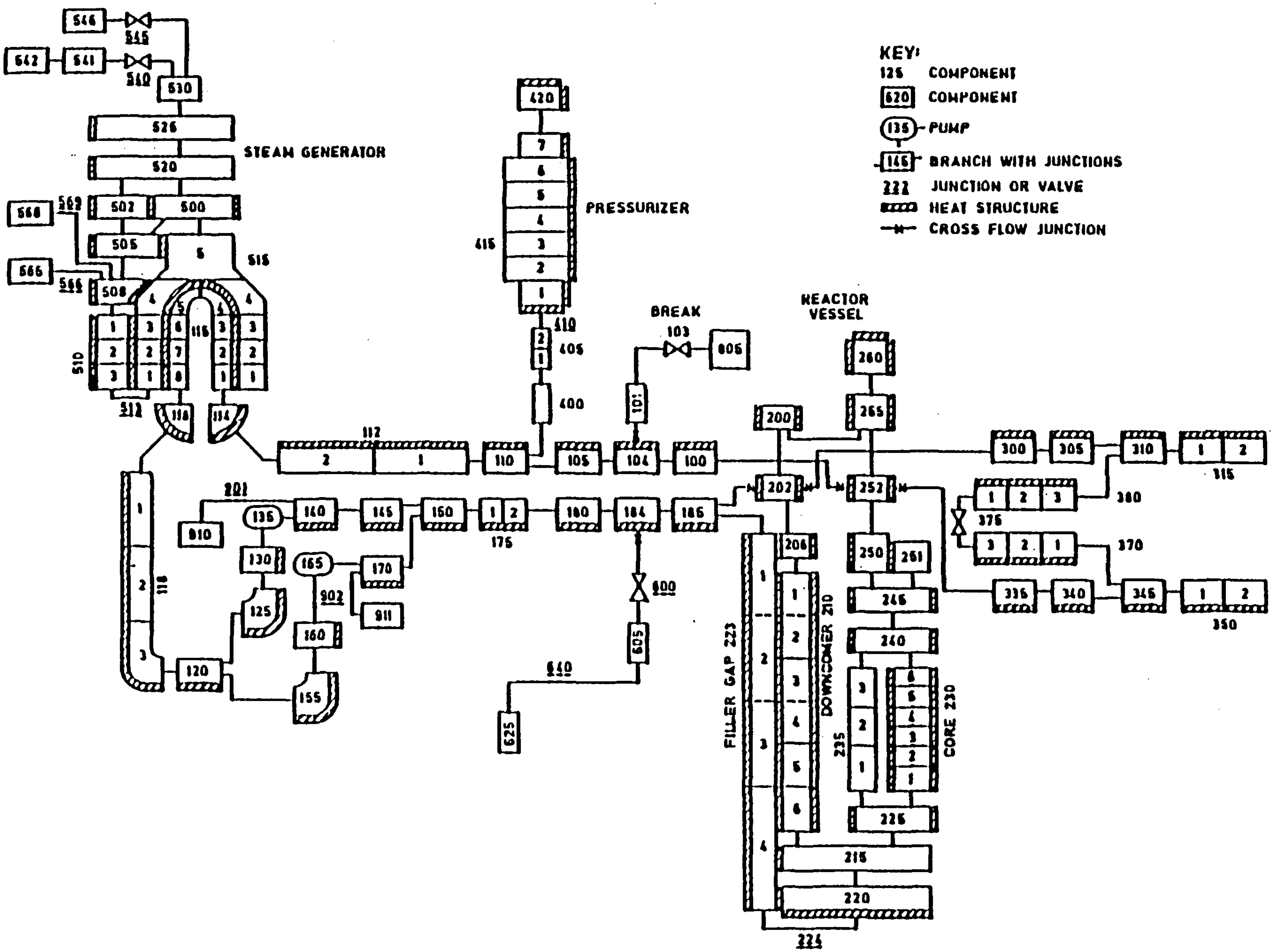


FIG. 1 RELAP 5 NODING DIAGRAM FOR LOFT LP-SB-1 CALCULATION

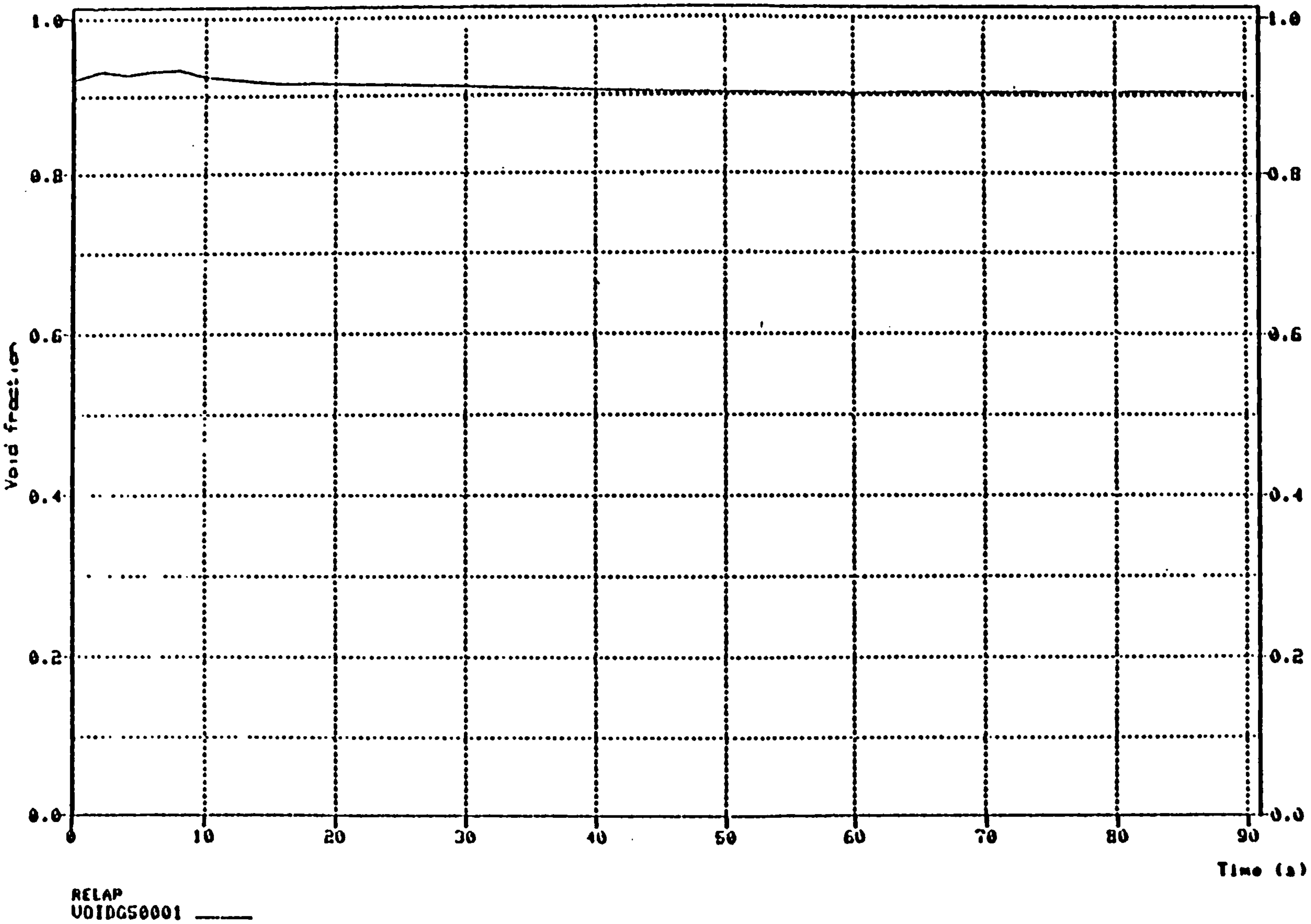


FIGURE 2 Separator void fraction. (Steady state)

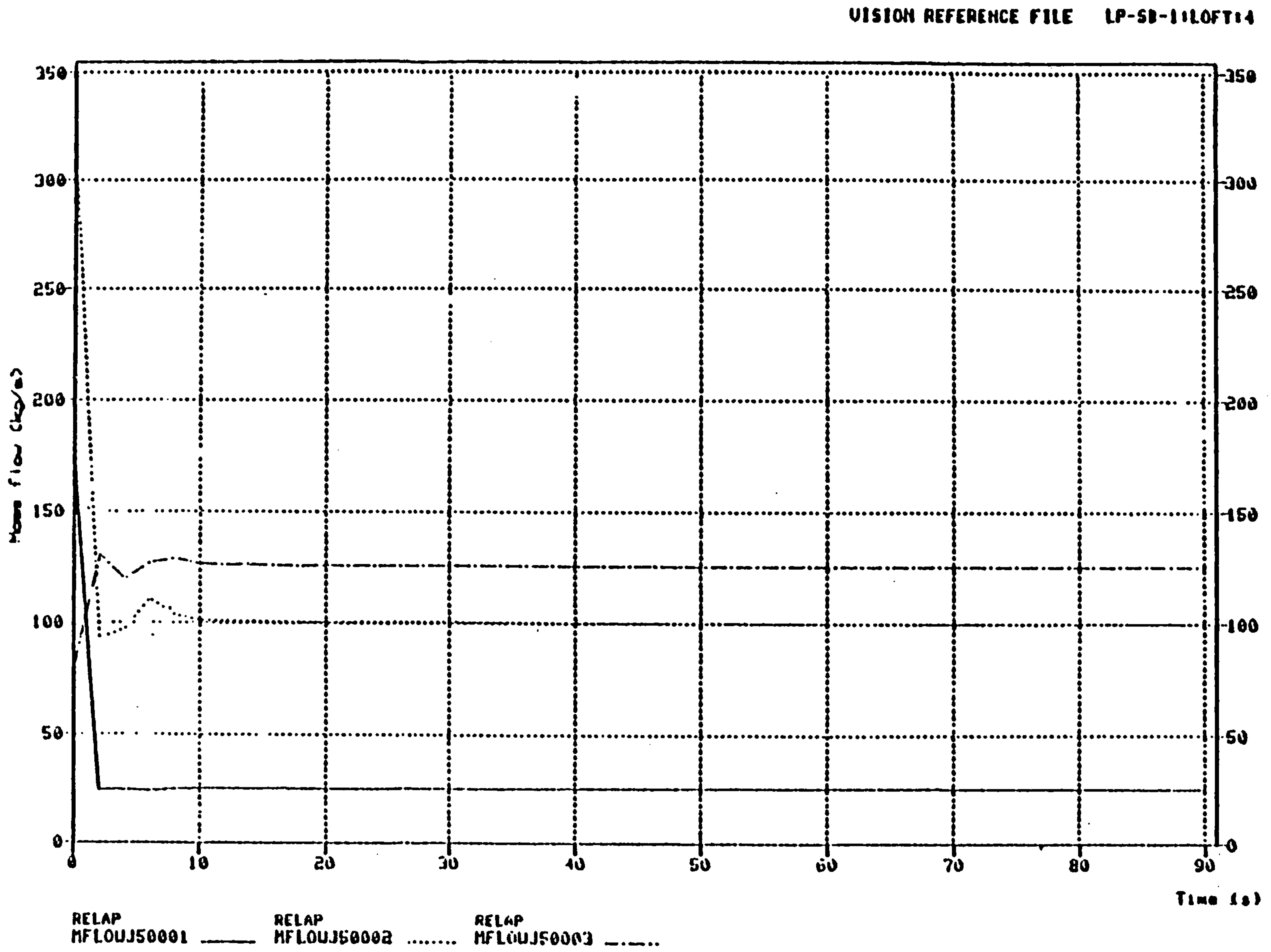


FIGURE 3 SG separator mass flows. (Steady state)

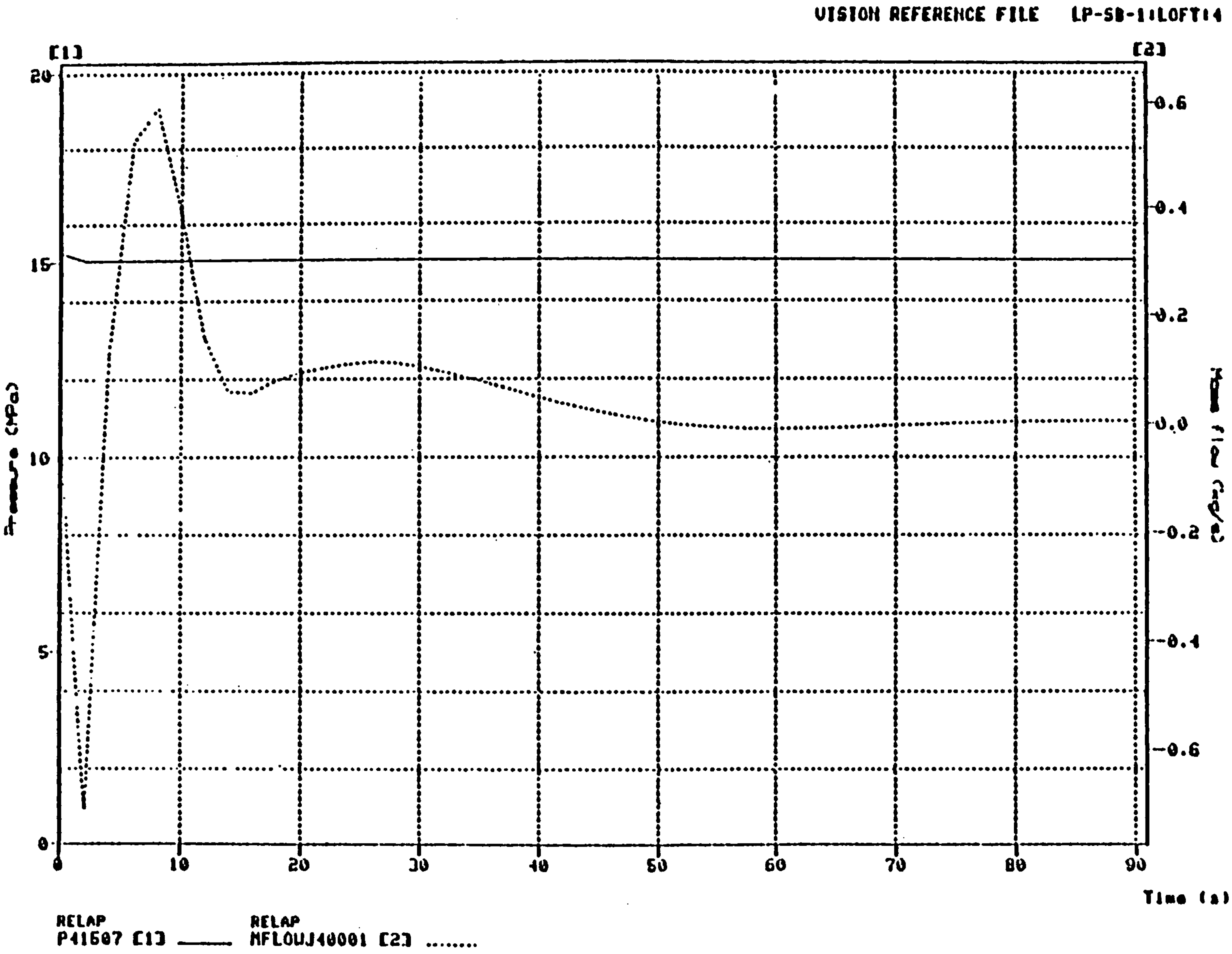


FIGURE 4 Pressuriser pressure and surge line flow. (Steady state)

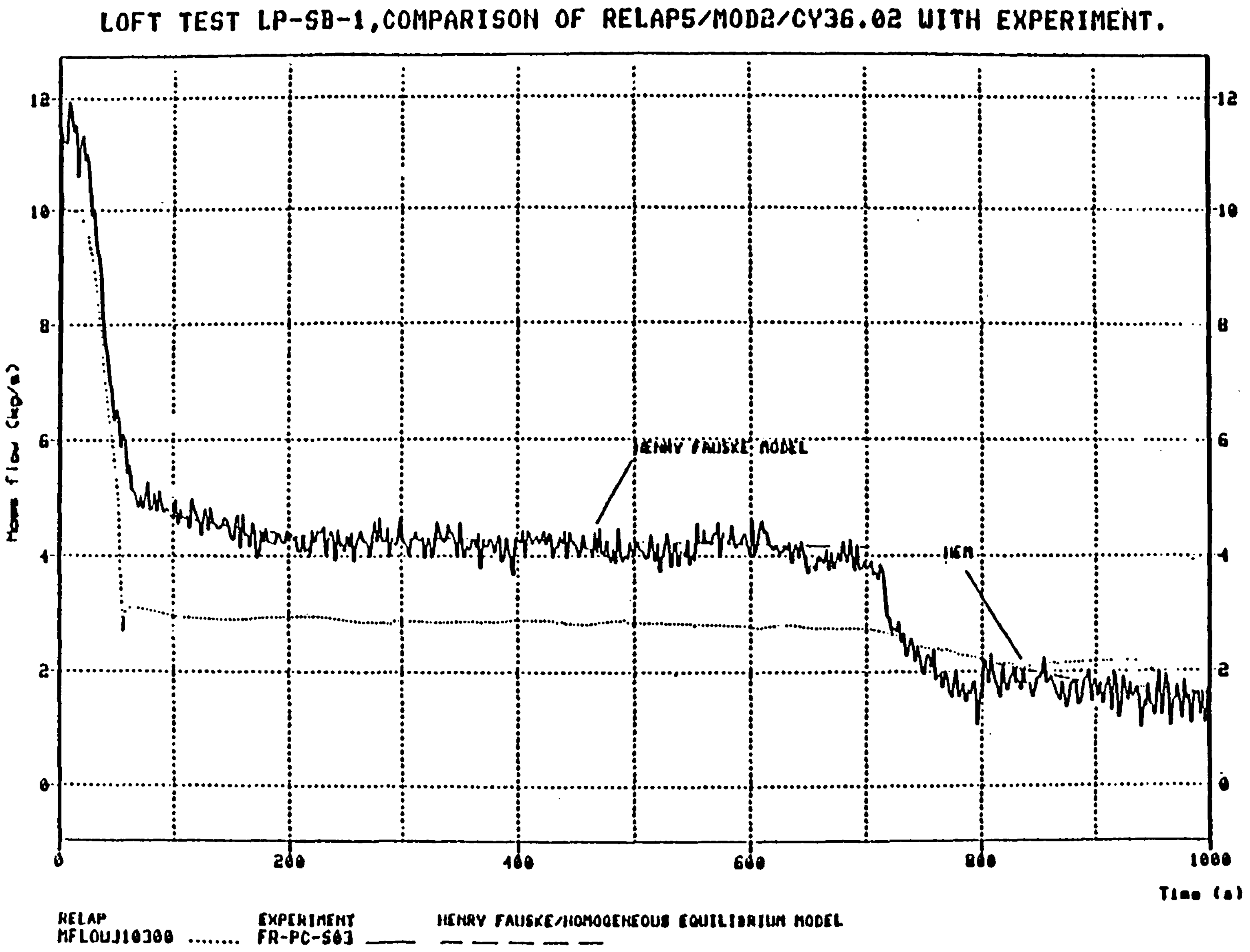


FIGURE 5 Break flow - preliminary calculation.

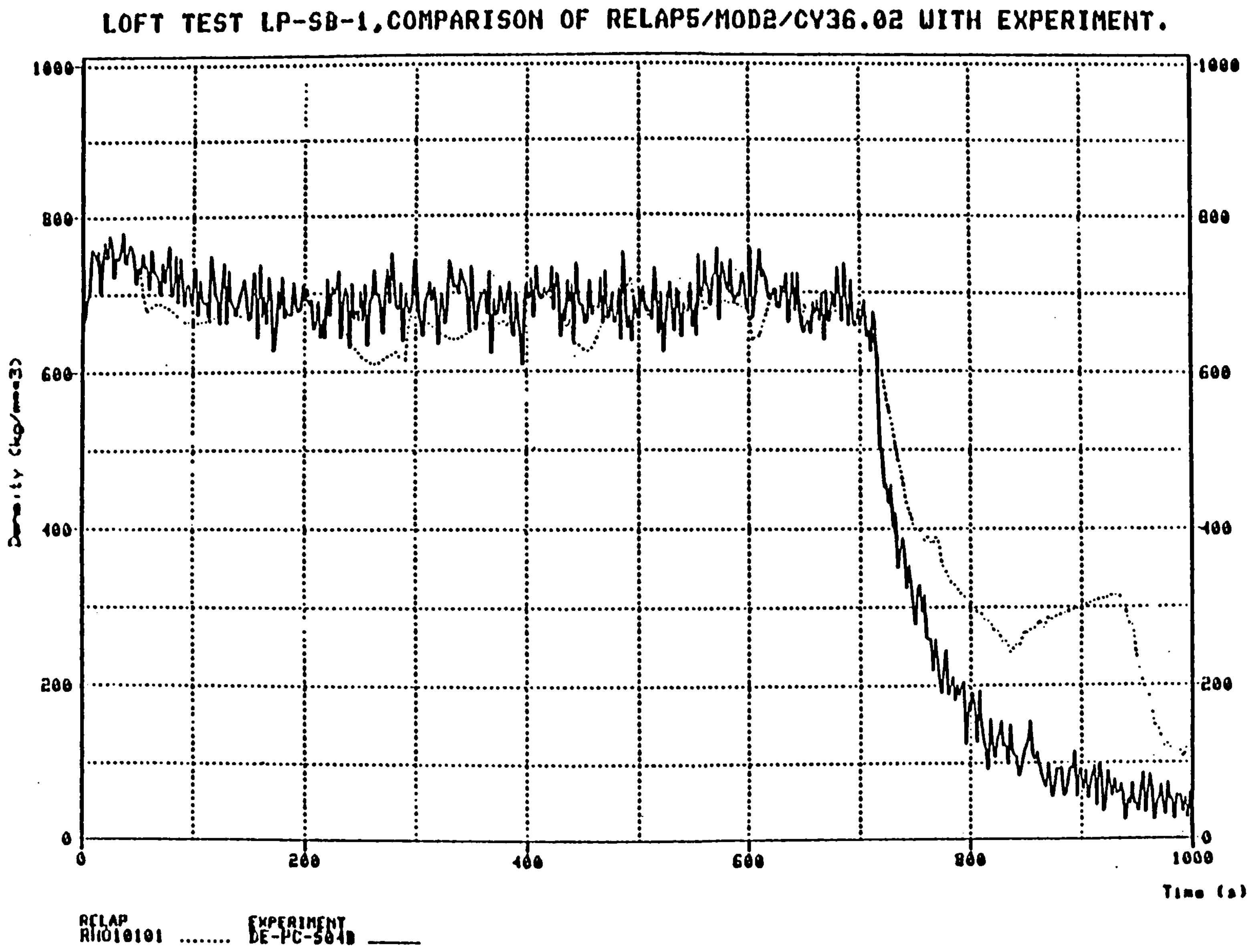


FIGURE 6 Break upstream density - preliminary calculation.

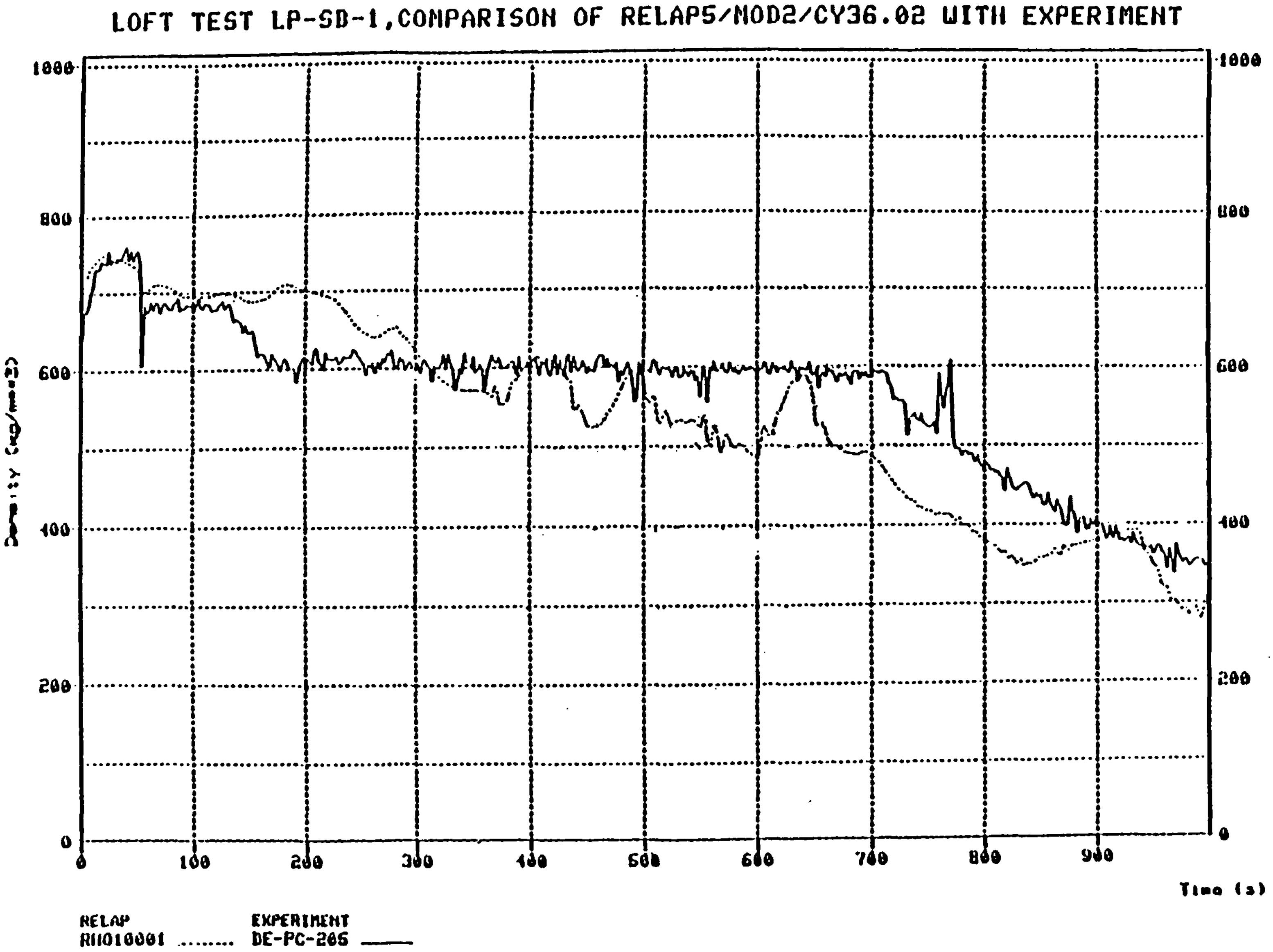


FIGURE 7 Hot leg density - preliminary calculation.

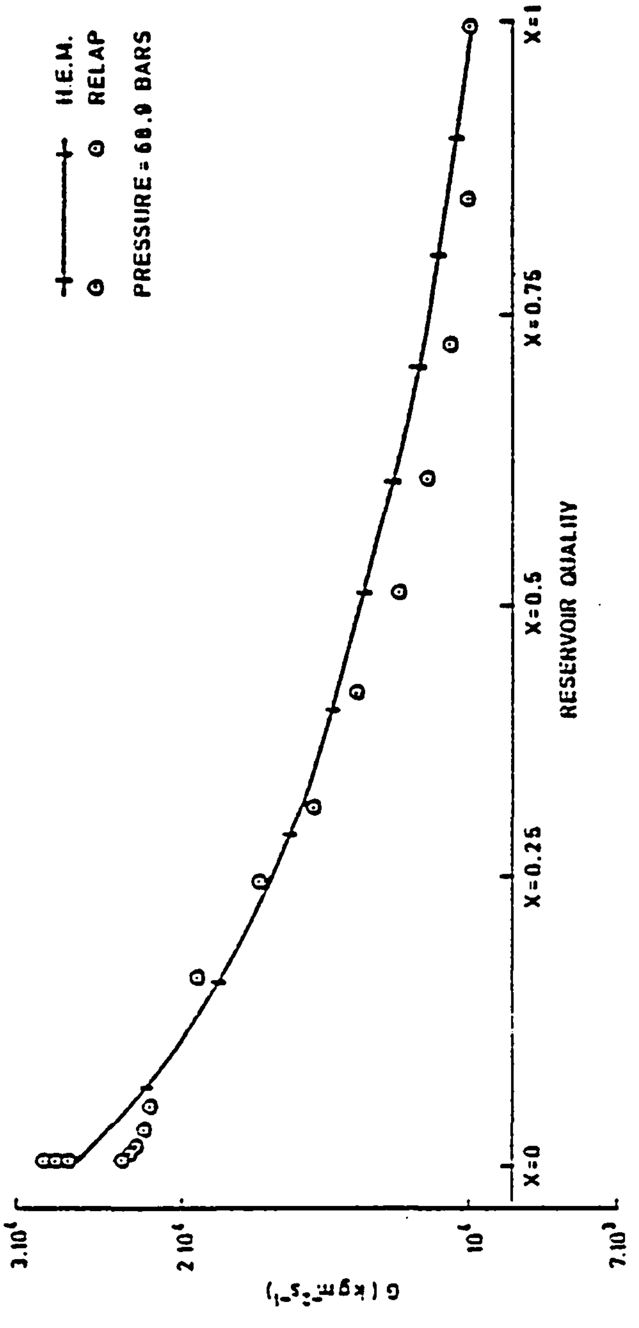
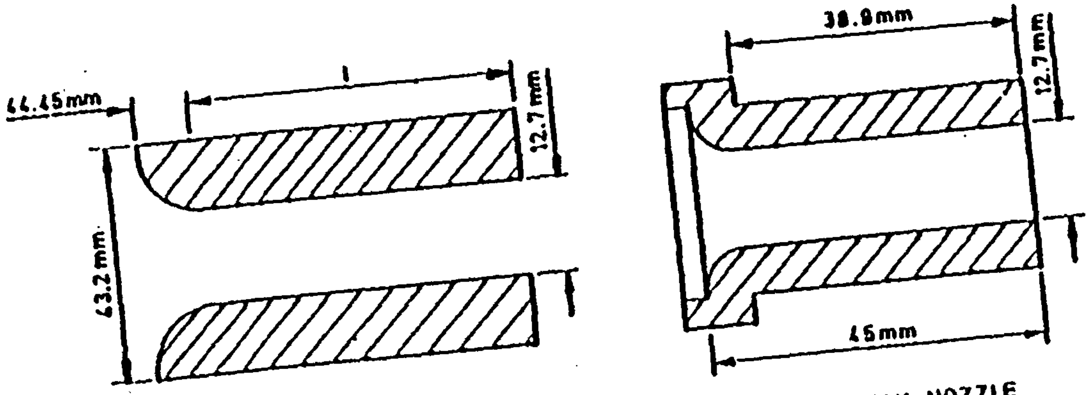


FIGURE 8 COMPARISON OF CRITICAL FLOWRATE CALCULATED USING THE HOMOGENEOUS EQUILIBRIUM MODEL AND RELAP5/MOD2



SOZZI AND SUTHERLAND BREAK NOZZLE

LOFT BREAK NOZZLE

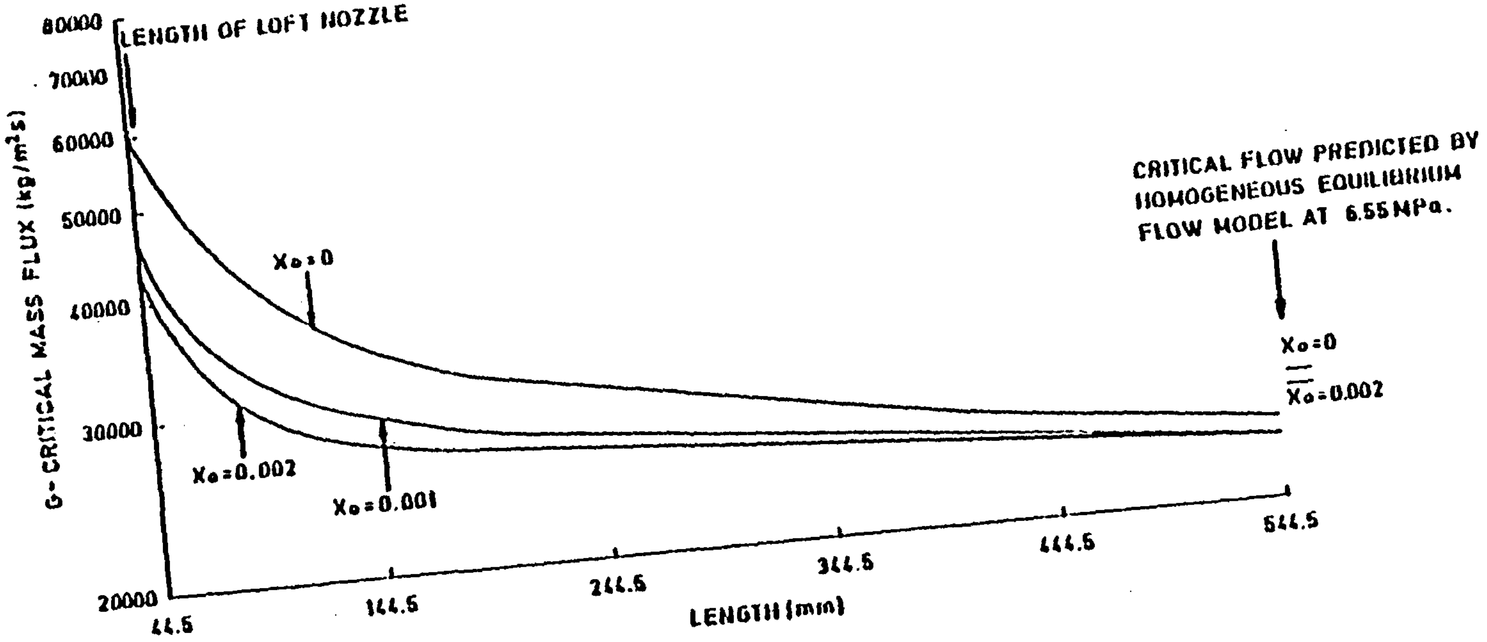


FIGURE 9 SELECTED DATA OF SOZZI AND SUTHERLAND (10) AT 6.55 MPa

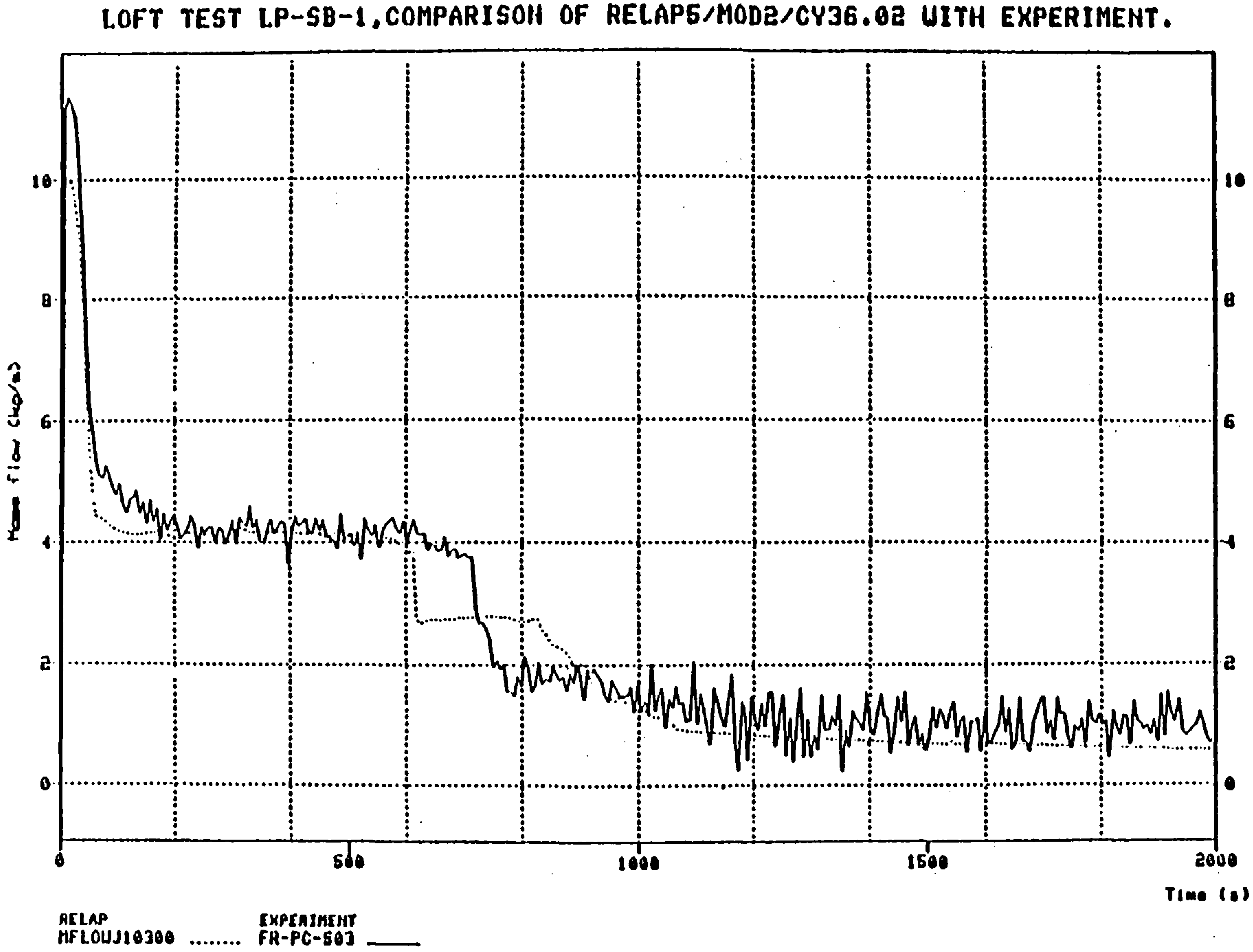


FIGURE 10 Break flow.

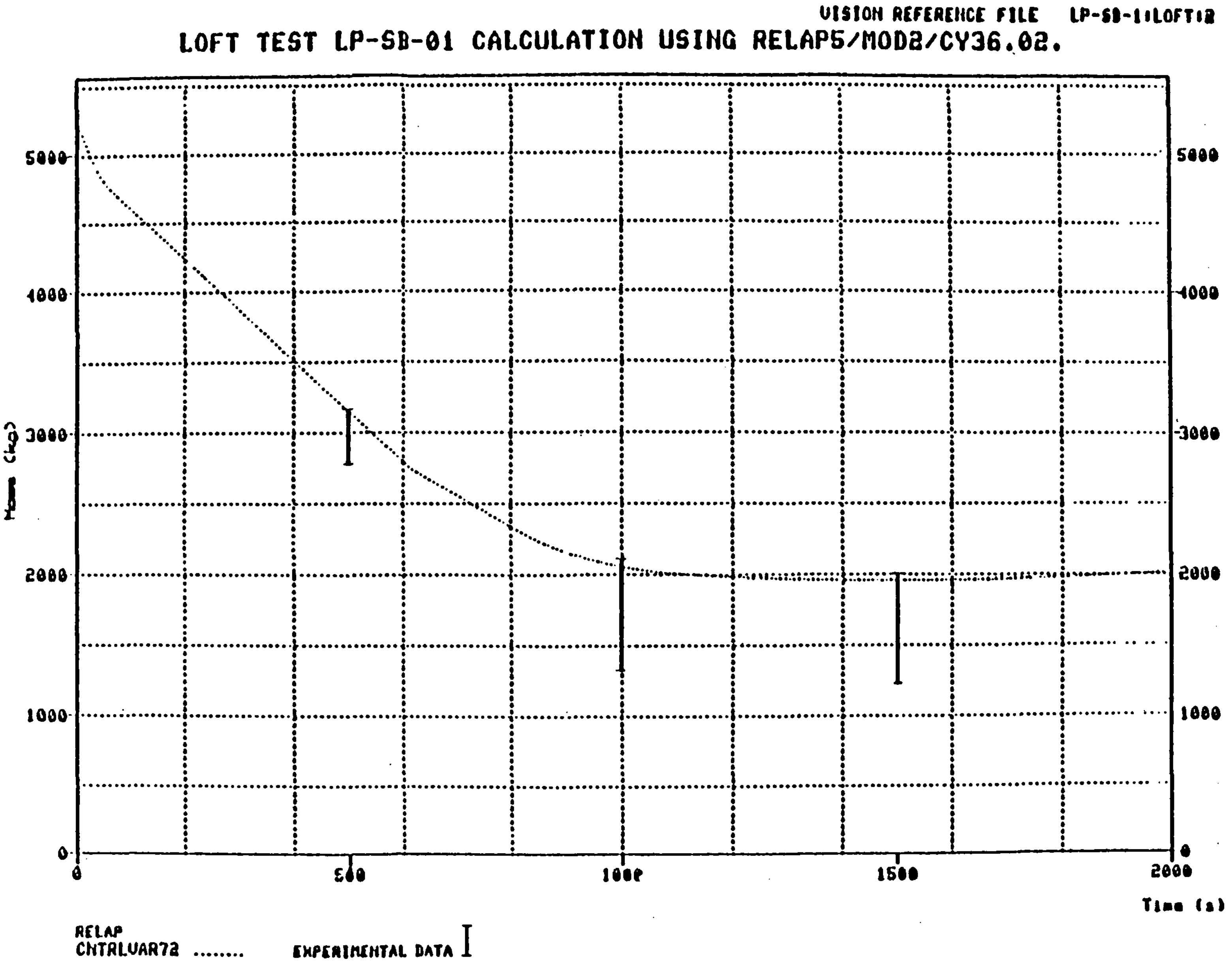


FIGURE 11 Primary system inventory.

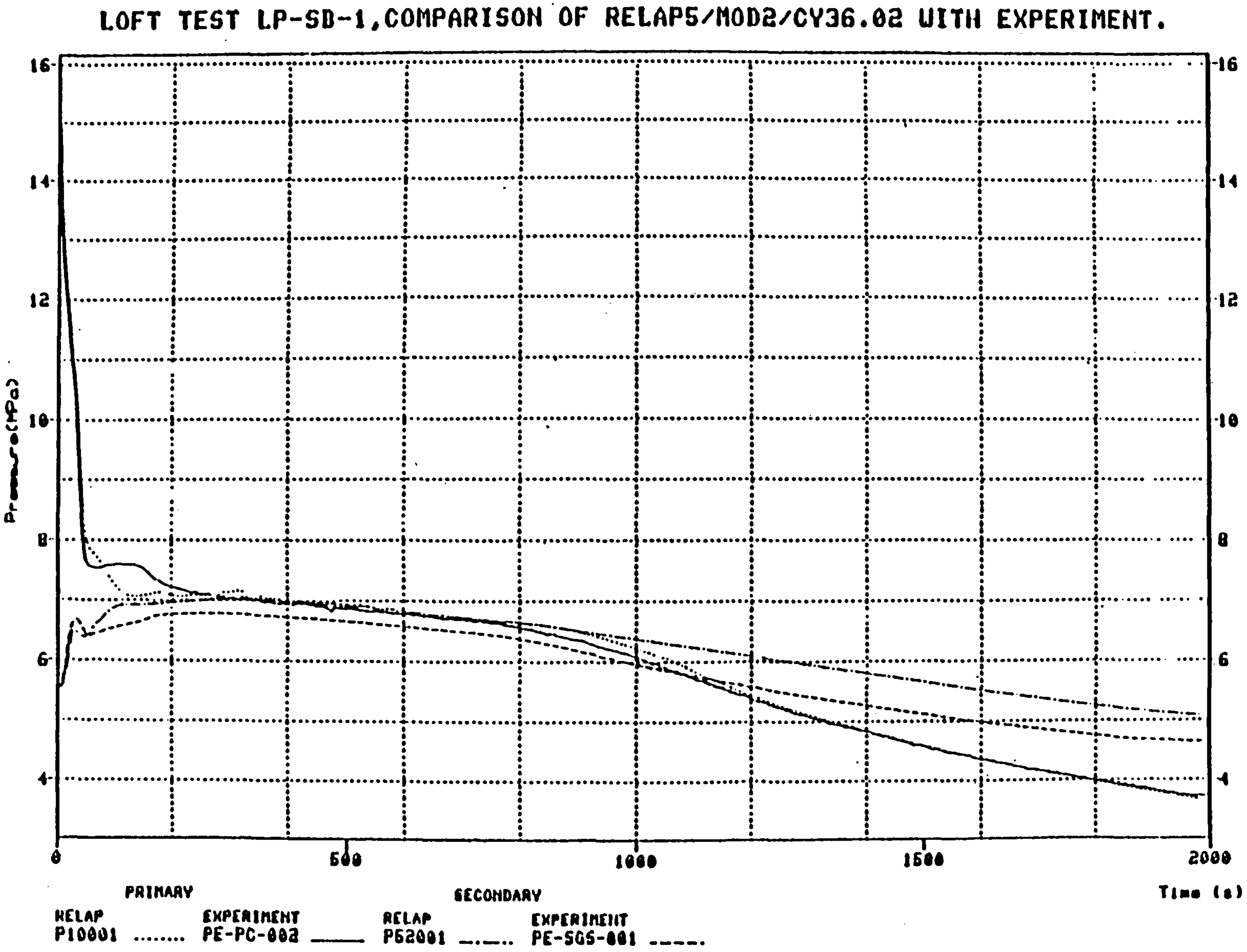
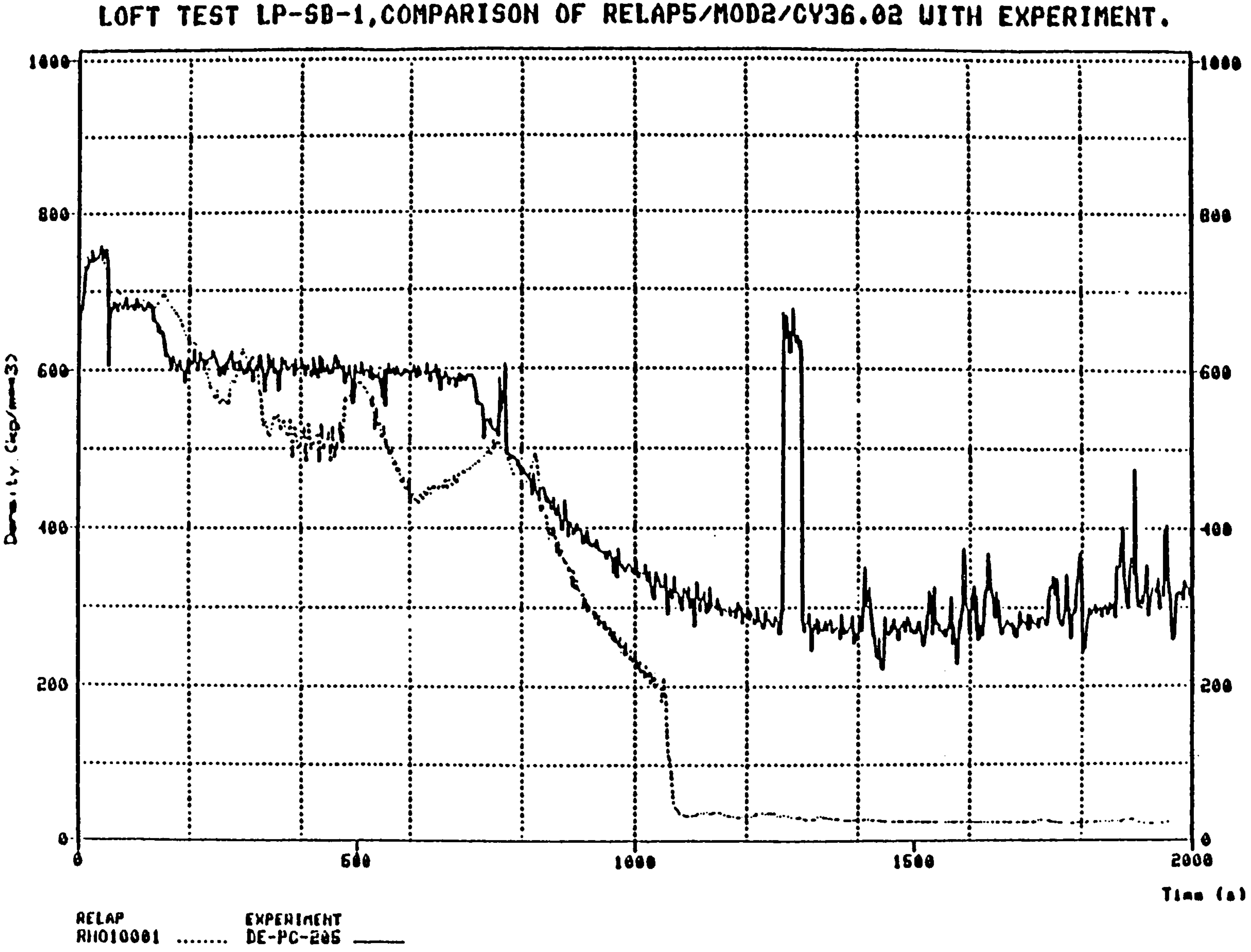


FIGURE 12. Primary and secondary pressure.



LOFT TEST LP-SB-1,COMPARISON OF RELAP5/MOD2/CY36.02 WITH EXPERIMENT.

FIGURE 13 Hot leg density.

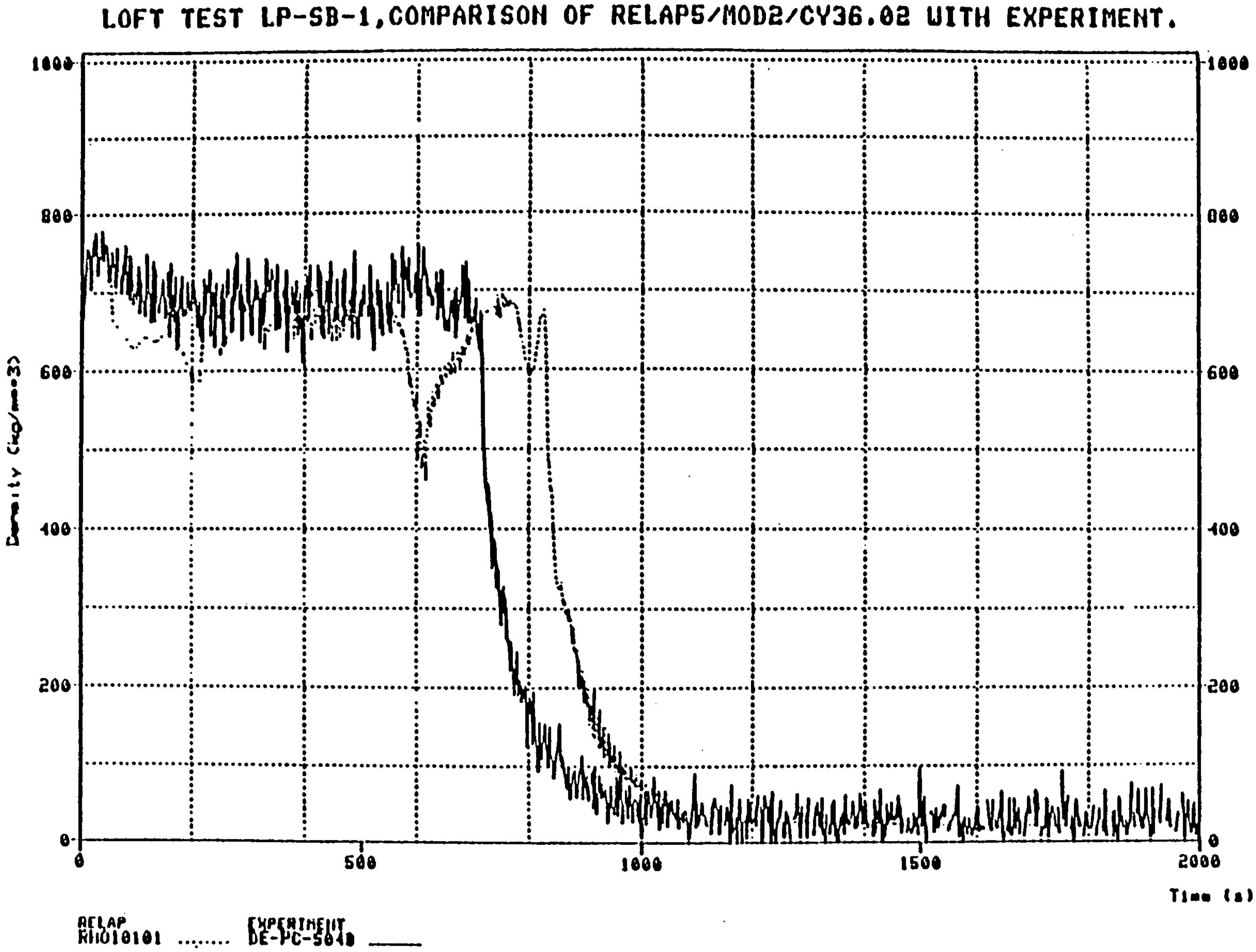


FIGURE 14 Break upstream density.

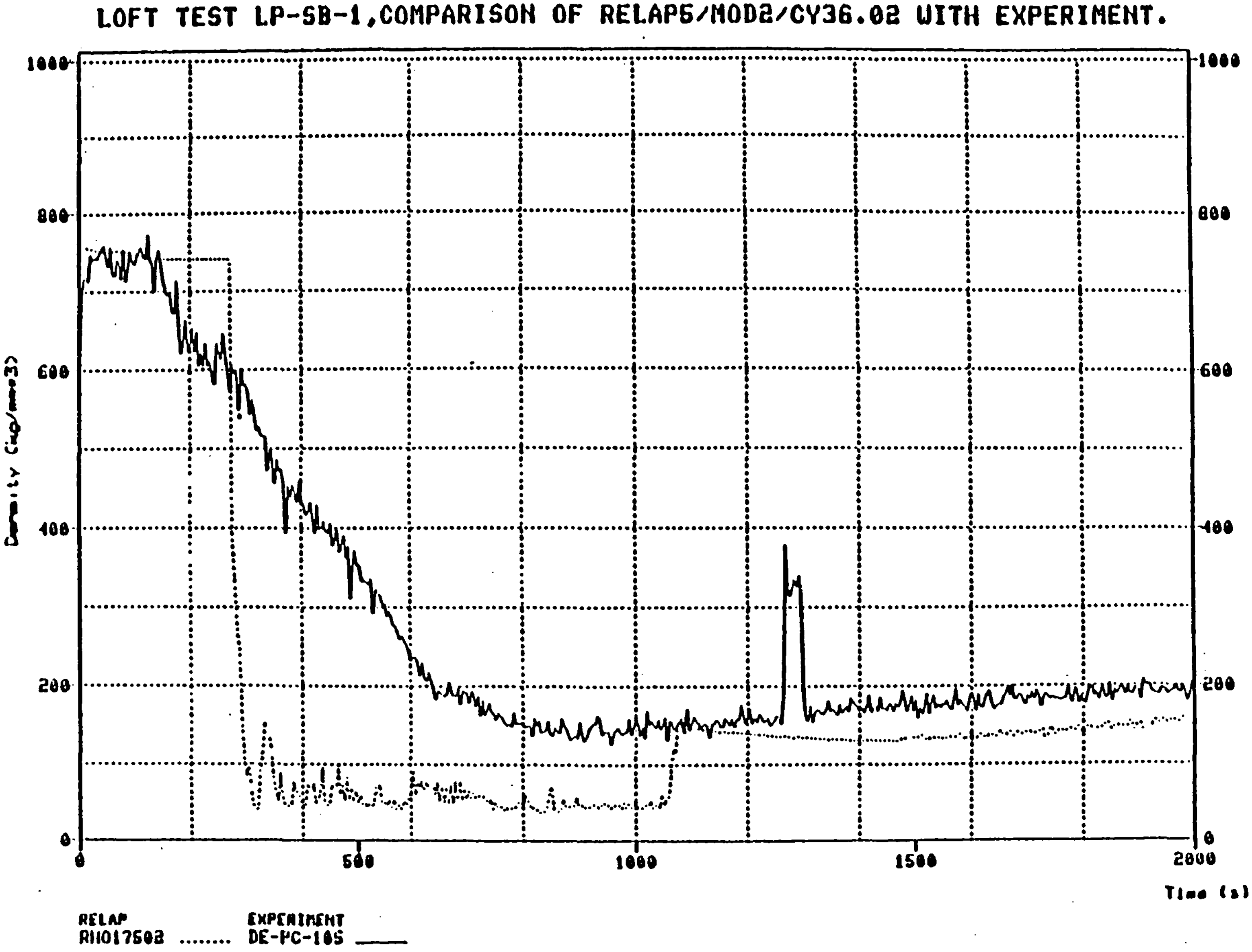


FIGURE 15 Cold leg density.

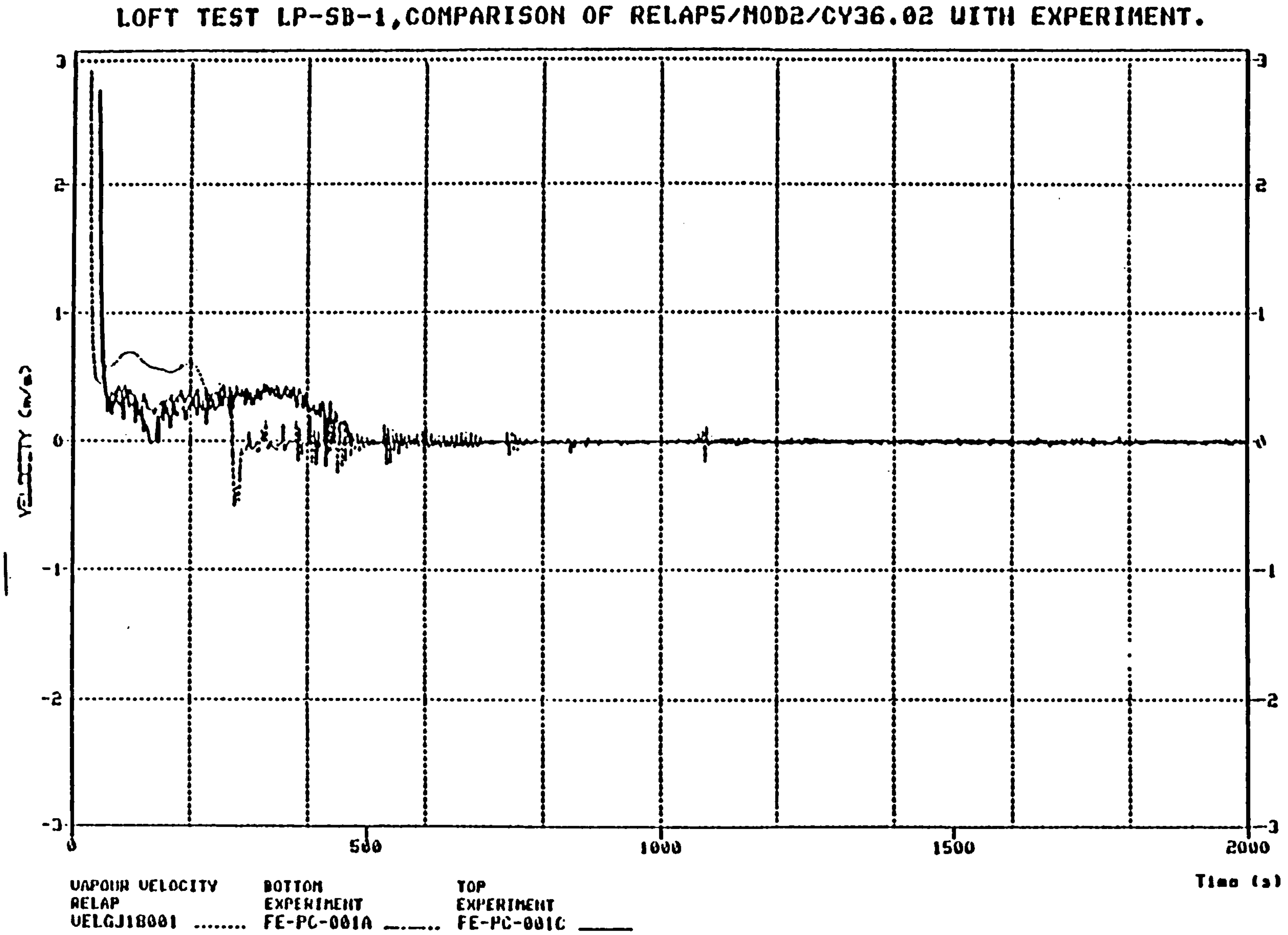


FIGURE 16 Cold leg fluid velocities.

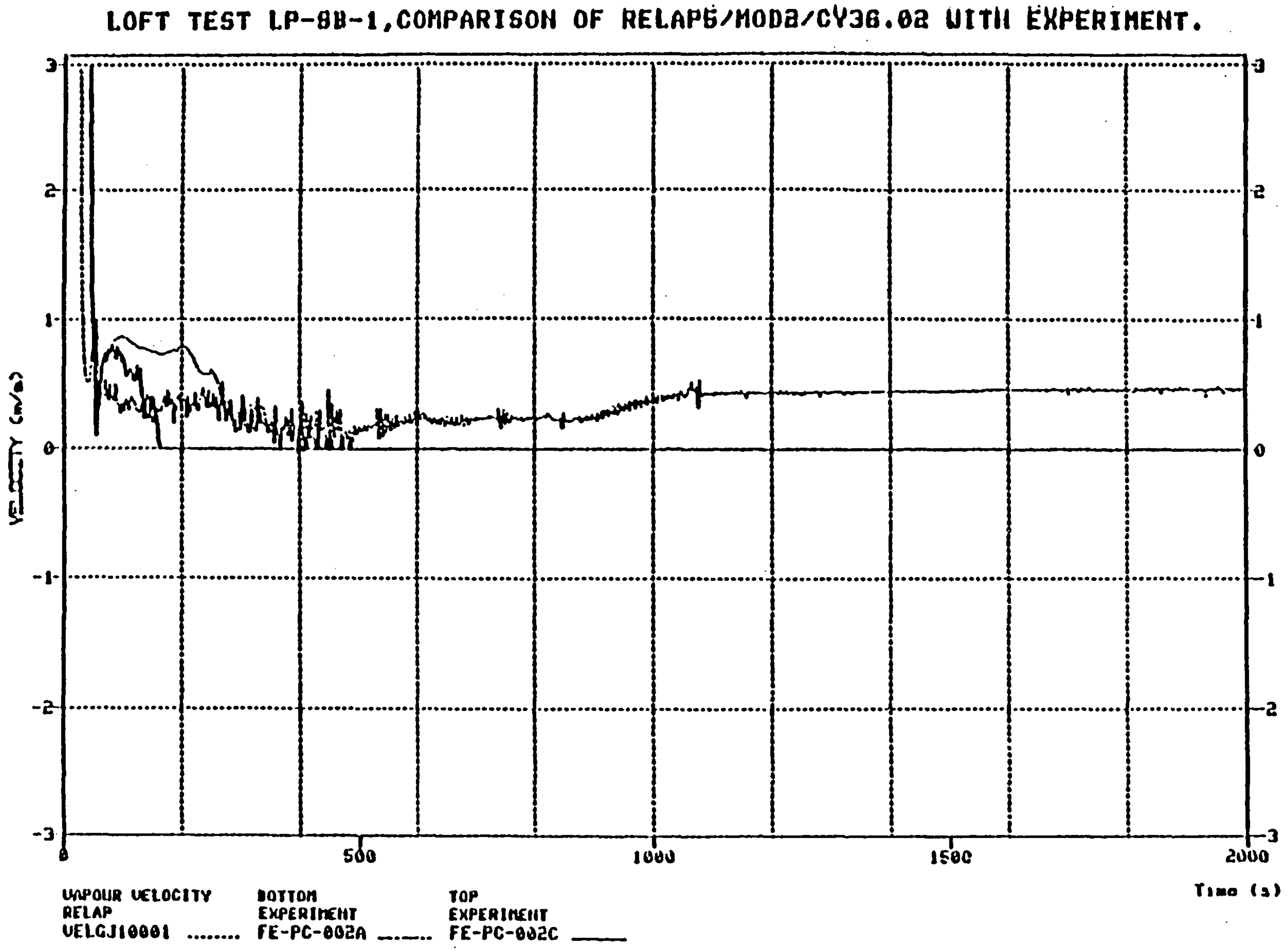


FIGURE 17 Hot leg fluid velocities.

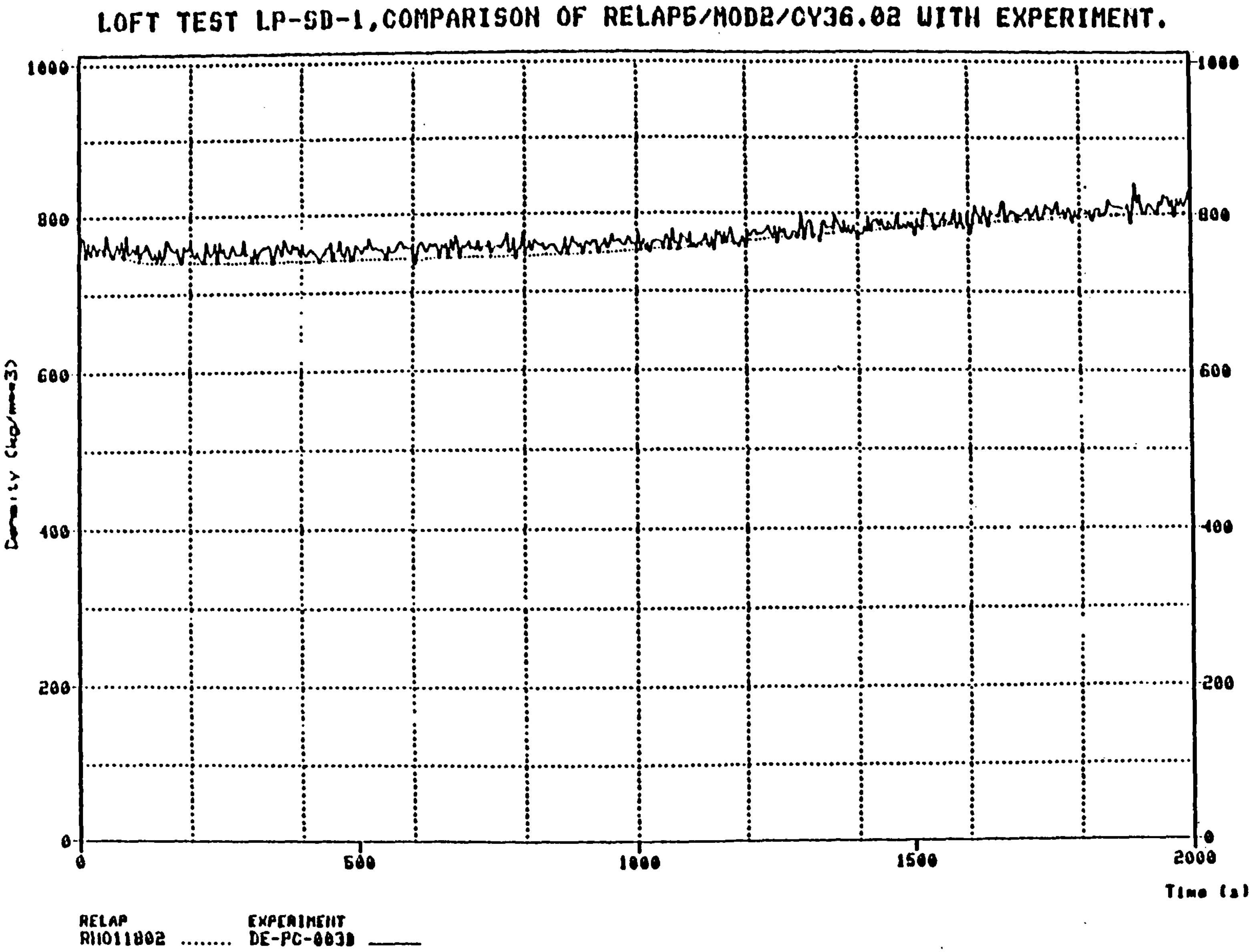


FIGURE 18 Loop seal density.

VISION REFERENCE FILE LP-SB-1:LOFT1B

LOFT TEST LP-SB-1 CALCULATION USING RELAP5/MOD2/CY36.02

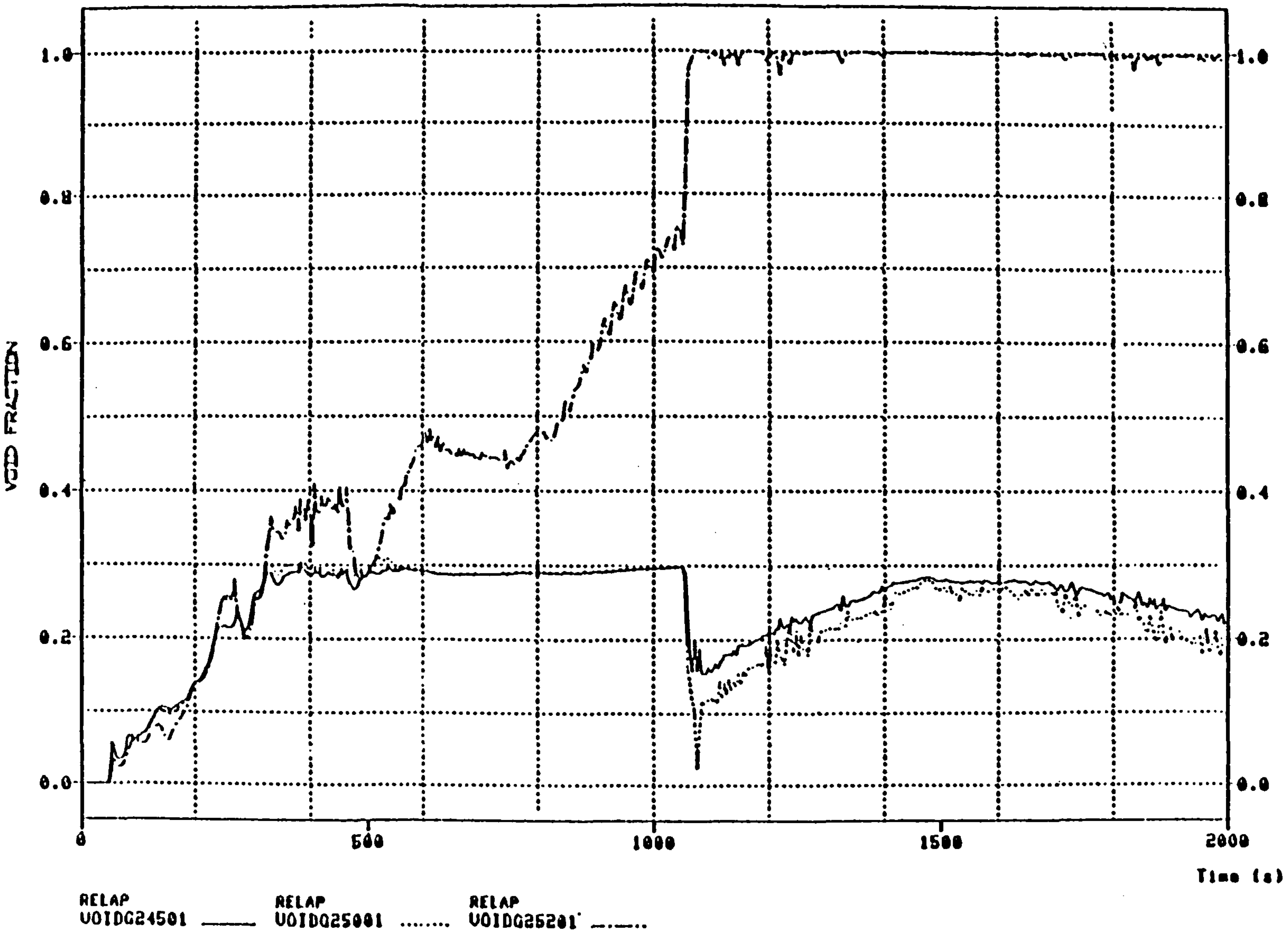


FIGURE 18 Upper plenum void fractions.

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To assist CEGB in assessing the capabilities and status of RELAP5/MOD2, the code has been used to simulate SBLOCA test LP-SB-01 carried out in the LOFT experimental reactor under the OECD LOFT programe. This test simulated a 1.0% hot leg break in a PWR, with early tripping of the primary coolant circulating pumps. This report compares the results of the RELAP5/MOD2 analysis with experimental measurements

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