NUREG/IA-0074
ICSP-LP-SB-1-R

International Agreement Report

RELAP5/MOD2 Post-Test Calculation of the OECD LOFT Experiment LP-SB-1

Prepared by
J. Perez, R. Mendizabal

Consejo de Seguaridad Nuclear
Justo Dorado, 44
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Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
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April 1992

Prepared as part of
The Agreement on Research Participation and Technical Exchange
under the International Thermal-Hydraulic Code Assessment
and Application Program (ICAP)

Published by
U.S. Nuclear Regulatory Commission

Available from

Superintendent of Documents
U.S. Government Printing Office
P.O. Box 37082
Washington, D.C. 20013-7082

and

National Technical Information Service
Springfield, VA 22161

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ABSTRACT

This document presents the analysis of the OECD LOFT LP-SB-1 experiment performed by the Consejo de Seguridad Nuclear of Spain working group making use of RELAP5/MOD2 in the frame of the Spanish LOFT Project.

LP-SB-1 experiment studies the effect of an early pump trip in a small break LOCA scenario with a 3 inches equivalent diameter break in the hot leg of a commercial PWR.

CONTENTS

PAGE

SECTION 1.INTRODUCTION 1

2.DESCRIPTION OF THE LOFT INSTALLATION 1

3.RELAP5/MOD2 MODEL OF LOFT FACILITY 2

4.EXPERIMENT LP-SB-1 2

- 4.1Steady state calculation 3
- 4.2Transient boundary condition 3
  - 4.2.1Decay heat data 3
  - 4.2.2Pumps injection flow 3
  - 4.2.3Auxiliary feedwater flow 3
  - 4.2.4High pressure injection system 3
  - 4.2.5Secondary side steam control valve 3
  - 4.2.6Operational set-points 3

5.POST TEST CALCULATIONS 3

- 5.1Preliminary calculation (RUN A) 4
  - 5.1.1Code performance 4
  - 5.1.2Chronology of events 4
  - 5.1.3Secondary side pressure 4
  - 5.1.4Primary side pressure 4
  - 5.1.5Temperatures 5
  - 5.1.6Density distribution 5
  - 5.1.7Break line density and break massflow rate 5
  - 5.1.8Primary system mass inventory 5
- 5.2Base calculation (RUN B) 6
  - 5.2.1 Code performance 6
  - 5.2.2Chronology of events 6
  - 5.2.3Secondary side pressure 7
  - 5.2.4Primary side pressure 7
  - 5.2.5Temperatures 7
  - 5.2.6Density distribution 7
  - 5.2.7Break line density and break massflow rate 8
  - 5.2.8Primary system mass inventory 8
- 5.3Selected items 9
  - 5.3.1 Loop flow and natural circulation 9
  - 5.3.2 Hot leg flow stratification 9

6.CONCLUSIONS 11

7.REFERENCES 12

TABLES 13

FIGURES 16

APPENDIX I -DISKETTE CONTAINING THE RELAP5/MOD2 INPUT DECKS FOR LP-SB-1 70

APPENDIX II -TAITEL-DUKLER CRITERION FOR HORIZONTAL FLOW STRATIFICATION 71

APPENDIX III-HORIZONTAL STRATIFICATION ENTRAINMENT MODEL IN RELAP5/MOD2 72

TABLES

PAGE

1. INITIAL CONDITIONS FOR EXPERIMENT LP-SB-1 13
2. OPERATIONAL SETPOINTS FOR EXPERIMENT LP-SB-1 14
3. LP-SB-1 CHRONOLOGY OF EVENTS 15

FIGURES

PAGE

1. LOFT PIPING SCHEMATIC 16
2. AXONOMETRIC PROJECTION OF THE LOFT SYSTEM CONFIGURATION FOR EXPERIMENT LP-SB-1 AND LP-SB-2 17
3. RELAP5 NODING DIAGRAM FOR LOFT LP-SB-1 CALCULATION (RUN A) 18
4. RELAP5 NODING DIAGRAM FOR LOFT LP-SB-1 CALCULATION (RUN B) 19
5. STEADY STATE CALCULATION - PRIMARY PRESSURE 20
6. STEADY STATE CALCULATION - S.G. & PZR LEVELS 21
7. STEADY STATE CALCULATION - RECIRCULATION RATIO 22
8. STEADY STATE CALCULATION - SURGE LINE MASS FLOW 23
9. C.P.U. TIME - RUN A 24
10. SECONDARY SIDE PRESSURE - RUN A 25
11. MAIN STEAM CONTROL VALVE STEM POSITION 26
12. PRIMARY SIDE PRESSURE - RUN A 27
13. HOT LEG TEMPERATURE - RUN A 28
14. COLD LEG TEMPERATURE - RUN A 29
15. HPIS MASS FLOW RATE - RUN A 30
16. COLD LEG DENSITY - RUN A 31
17. COLD LEG FLUID VELOCITY - RUN A 32
18. HOT LEG DENSITY - RUN A 33
19. S.G. U-TUBES LEVEL - RUN A 34
20. BREAK LINE DENSITY - RUN5 A 35
21. HOT LEG AND BREAK LINE DENSITIES - RUN A 36
22. BREAK MASS FLOW RATE - RUN A 37
23. BREAK VELOCITY - RUN A 38
24. PRIMARY SYSTEM MASS INVENTORY - RUN A 39
25. C.P.U. TIME - RUN B 40
26. TIME STEP - RUN B 41
27. BREAK LINE VELOCITY - RUN B 42
28. PRIMARY SIDE PRESSURE - RUN B 43
29. HOT LEG TEMPERATURE - RUN B 44
30. PZR TEMPERATURE - RUN B 45
31. COLD LEG LIQUID TEMPERATURE - RUN B 46
32. COLD LEG VAPOR TEMPERATURE - RUN B 47
33. S.G. PLENA TEMPERATURE - RUN B 48
34. HOT LEG DENSITY - RUN B 49
35. LOOP SEAL DENSITY - RUN B 50
36. HOT LEG & BREAK LINE VOID FRACTION - RUN B 51
37. S.G. U-TUBES COLAPSED WATER LEVEL - RUN B 52
38. BRU7EAK MASS FLOW RATE - RUN B 53
39. FLOW REGIME NUMBER IN THE BREAK LINE - RUN B 54
39.(bis) FLOW REGIME NUMBER DIFF. IN THE BREAK LINE - RUN B 55
40. PRIMARY SIDE MASS INVENTORY - RUN B 56
41. S.G. PLENA VOID FRACTION - RUN B 57
42. CORE VOID FRACTIONS - RUN B 58
43. HOT LEG FLUID VELOCITY - RUN B 59
44. EXPERIMENTAL MASS FLOW RATE BREAK LOCATION - SG. 60
45. COLD LEG LEVEL - RUN B 61
46. HOT LEG FLUID VELOCITY - RUN B 62
47. U-TUBES FLUID VELOCITY - RUN B 63
48. PCS - SG TUBES HEAT TRANSFER COEFFICIENT - RUN B 64
49. FLOW REGIME NUMBER IN HOT LEG - RUN B 65
50. TAITEL-DUKLER LIMIT VELOCITY - RUN B 66
51. DIFFERENCE $|V_g|-V_{gl}$ IN HOT LEG - RUN B 67
52. DIFFERENCE $|V_g|-V_{gl}$ IN HOT LEG - TIME STEP=0.01s. 68
53. FLOW REGIME NUMBER IN HOT LEG - TIME STEP= 0.01 s. 69

EXECUTIVE SUMMARY

Experiment LP-SB-1 was conducted on June 23, 1983 in the LOFT facility at the Idaho National Engineering Laboratory.

The LP-SB-1 experiment simulated a 7.6 cm (3 inch) equivalent diameter break in a hot leg pipe of a PWR plant. Experiment LP-SB-1 addresses the analysis of a small break loss of coolant accident with the break at the midplane of the intact loop hot leg. LP-SB-1 was one of a pair of experiments aimed a<t addressing the effects of early and delayed pump trip on system behaviour. The primary coolant pumps were tripped early in experiment LP-SB-1.

The main objective of this calculation was to assess the code in the challenging conditions of a small break scenario.

Our aim was to simulate the major physical phenomena of the transient that took place until the beginning of the plant recovery.

The code used to simulate the LP-SB-1 experiment was RELAP5/MOD2 Cycle 36.04 installed on a CYBER 810.

The input data was based on that used in pretest calculations. Basically we have introduced the following changes:

(i)Use of an ideal steam separator.

(ii)Adjustment of the heat transfer from primary to secondary through an adjustment of the hydraulic diameter in the secondary side.

(iii)A change of the nodalization in the upper part of the vessel by introducing crossflow junctions in the connections of the nozzles.

(iv)Introduction of crossflow junctions in the connections between the break line and the surge line with the hot leg. The Fig 3 shows the final nodalization of the preliminary calculation (RUN A).

A second calculation (called "Base Calculation") was run with the following modifications in the input deck:

(v)HPIS piping was supressed and the injection was modelled by a TMDPJUN, in order to avoid the big amplitude flow oscillations found in RUN A.

(vi)The junction between the hot leg and the break line was defined as normal junction to make operative the offtake model under stratified flow conditions.

(vii)The break line was splitted in two volumes. The node close to the break nozzle was made short (0.5 m), trying to eliminate the stepwise behaviour of the break mass flow.

The preliminary calculation revealed discrepancies with the experimental results. The most significant ones were:

-The very poor prediction of the break mass flow rate and the break line density. That did not show at all the break uncovery. The HZFLOW subroutine that accounts for offtake model in a crossflow junction under stratified flow conditions was not active in our code version.

-The strange, stepwise evolution of the break mass flow rate, due to the occurrence of large differences for the phase velocities (slip) in the break. This deficiency has been identified by JRC-ISPRA as caused by the RELAP5/MOD2 interphase drag model.

-Strong instabilities of the HPIS mass flow rate, due to the entrance of vapor in the ECCS line from the cold leg.

The base calculation was performed using a normal junction in the break tee and splitting the break line in two nodes, a small one close to the break nozzle trying to improve the break flow behaviour. The comparison with experimental results suggest the following comments:

-The offtake model in the break tee was active in this run. However the splitting of the break line produced strong instabilities in the break flow.

-The two-phase natural circulation finished in the experiment at ~500 sec., and reflux condensation around 600 sec. later. In the simulation this happened at ~700 and ~1200 sec respectively.

-In LP-SB-1, the intact loop hot leg flow stratified at ~50 sec.. In the simulation, the code detected stratified flow regime in ILHL at ~320 sec..

The major conclusions are:

i)The code could not account for the liquid entrainment and vapor pull-through in the break tee modelled as a crossflow junction.

ii)It is necessary to improve the RELAP5/MOD2 choked flow model to avoid large instabilities in the break phase velocities and thermal disequilibrium effects.

iii)The Taitel-Dukler model is unable to describe properly horizontal flow stratification in the LP-SB-1 experiment.

iv)Natural circulation was correctly reproduced by the code.

FOREWORD

This report represents one of the assessment/application calculations submitted in fulfilment of the bilateral - agreement for cooperation in thermalhydraulic activities between the Consejo de Seguridad Nuclear of Spain (CSN) and the United States Nuclear Regulatoy Commission (US-NRC) in - the form of Spanish contribution to the International Code Assessment and Applications Program (ICAP) of the US-NRC whose main purpose is the validation of the TRAC and RELAP system codes.

The Consejo de Seguridad Nuclear has promoted a coordinated - Spanish Nuclear Industry effort (ICAP-SPAIN) aiming to - satisfy the requirements of this agreement and to improve the quality of the technical support groups at the Spanish - Utilities, Spanish Research Establishments, Regulatory Staff and Engineering Companies, for safety purposes.

This ICAP-SPAIN national program includes agreements between CSN and each of the following organizations:

- Unidad Eléctrica (UNESA)
- Unión Iberoamericana de Tecnología Eléctrica (UITESA)
- Empresa Nacional del Uranio (ENUSA)
- TECNATOM
- LOFT-ESPAÑA

The program is executed by 12 working groups and a generic code review group and is coordinated by the "Comité de Coordinación". This committee has approved the distribution of this document - for ICAP purposes.

ACKNOWLEDGEMENTS

Great appreciation is expressed to Mr. A. López Lechas for his help in the understanding of RELAP5/MOD1 at the preliminary steps of this work.

1. INTRODUCTION

Thermal-hydraulic research has required close interaction between experimental and analytical work. A number of separate-effect experiments have been performed to help in the validation of best estimate computer codes. Analogously the overall results of code calculations are assessed using data from integral test facilities. The analyses show that the codes generally provide accurate calculations of the Loss of Coolant Accident (LOCA). Areas where model's improvements are needed have also been identified by these tests. In particular the Loss of Fluid Test (LOFT) facility was adapted to study some small breaks. The motivation of one of these is explained hereafter.

An analysis performed after TMI showed that one of the key factors in the core damage was the tripping of the primary circuit pumps. The USNRC requested the reactor vendors to carry out an analysis of this problem. The conflict between the results of these investigations led to a recommendation to carry out experiments on this program in order to clarify the criteria for pump trip. The experiments LP-SB-1 and LP-SB-2 modelled small breaks in the hot leg. They differ in time of pump trip which is early in the former and delayed in the later of these tests. In this paper the results obtained in a post test analysis of the experiment LP-SB-1 by the CSN working group, part of the Spanish LOFT project are set down. The calculations with RELAP5/MOD2 Cycle 36.04 were carried out on a CYBER 810 in Madrid.

2. DESCRIPTION OF THE LOFT INSTALLATION

The experimental LOFT installation simulates a four loop 1000 MW commercial PWR. It has a thermal power of 50 MW. The installation consists of a vessel scaled 1/47 in volume, an intact circuit with an active steam generator, a pressurizer, two pumps in parallel and a broken leg, connected by recirculation lines to the intact circuit in order to maintain a temperature of this broken circuit near to that of the coolant at core inlet at the beginning of the experiment.More detailed information on the LOFT system configuration is provided in Reference 1.

A LOFT piping schematic with instrumentation for experiment LP-SB-1 and LP-SB-2, and an axonometric projection of the LOFT system configuration are shown respectively in Figures 1 and 2.

3. RELAP5/MOD2 MODEL OF LOFT FACILITY

The code used for this calculation was RELAP5/MOD2 Cycle 36.04.

The input data was based on that used in pretest calculations. Basically we have introduced the following changes:

(i) Use of an ideal steam separator.

(ii) Adjustment of the heat transfer from primary to secondary through variation of the hydraulic diameter in the secondary side.

(iii) A change of the nodalization in the upper part of the vessel by introducing crossflow junctions in the connections of the nozzles [10].

(iv) Introduction of crossflow junctions in the connections between the break line and the surge line with the hot leg [10]. The Fig 3 shows the nodalization of the preliminary calculation (RUN A).

A second calculation (called "Base Calculation", RUN B) was run with the following modifications in the input deck:

i) HPIS piping was suppressed and the injection was modelled by a TMDPJUN, in order to avoid the big flow oscillation found in RUN A.

ii) The junction between the hot leg and the break line was defined as normal junction to make operative the offtake model under stratified flow conditions.

iii) The break line was splitted in two volumes. The node close to the break nozzle was made short (0.5 m), trying to eliminate the stepwise behaviour of the break mass flow.

Figure 4 shows the final nodalization.

4. EXPERIMENT LP-SB-1

Experiment LP-SB-1 was conducted on June 23, 1983 in the LOFT facility at th0e Idaho National Engineering Laboratory.

The LP-SB-1 experiment simulated a 7.6 cm (3 inch.) equivalent diameter break in the midplane of the hot leg pipe of a PWR plant. LP-SB-1 was one of a pair of experiments aimed to address the effects of early and delayed pump trip on system behaviour. The primary coolant pumps were tripped early in experiment LP-SB-1.

A detailed description of the experiment is found in Reference 2.

4.1 Steady state calculations

To accelerate the achievement of steady-state conditions the following variables were controlled.

(i) Liquid level in the "downcomer" of the steam generator.
(ii) Primary mass flow.

In addition the upper part of the pressurizer was connected to a dummy volume to maintain the desired pressure in the primary side.

Under these situation the code achieved steady-state conditions in 100 secs. Then a calculation without controls for 25 secs was carried out to demonstrate that a true steady state had been reached. These stationary state conditions are compared with the initial conditions of the plant in Table 1. The Figures 5 - 8 show significant parameters during the null transient (RUN A).

4.2 Transient boundary conditions

4.2.1 Decay Heat Data

Reactor power after scram was specified by means of a table. During the first 2 seconds of the transient, data were taken from the RELAP5/MOD1 input deck used for the pretest prediction of LP-SB-1 (3). After that, data contained in Reference 4 were used until the end of the transient.

4.2.2 Pumps injection flow

The pumps injection flow was simulated assuming a constant flow of 0.0475 l/s, to each pump (2,5).

4.2.3 Auxiliary Feedwater Flow

An auxiliary feedwater flow of 0.5 l/s (5) was manually initiated at 63.4 seconds and turned off at 1864.8 seconds.

4.2.4 High Pressure Injection System

The HPIS was initiated in experiment LP-SB-1 when the intact loop hot leg pressure had fallen to 8.24 MPa (2).

4.2.5 Secondary Side Steam Control Valve

Descriptive data of the steam bypass valve were not available. Its function was assumed by the steam control valve. After 80 seconds it was latched closed to a flow area of 0.0925% of its fully opened value, throughout the transient.

4.2.6 Operational set-points

The operational set-points measured during the experiment, and those used in the RELAP5/MOD2 calculation are given in table 2.

5. POST TEST CALCULATIONS

A preliminary calculation (RUN A) was carried out which led to some important conclusions. To confirm these a number of detailed modifications were incorporated and used for a second calculation (RUN B)

5.1 Preliminary calculation (RUN A)

The calculation was run for 2200 secs. This was considered to be sufficient to obtain the most significant data. Table 3 shows the event chronology.

5.1.1 Code Performance

Two thousand seconds of transient required about 100,000 cpu seconds (Fig. 9). This corresponds to a cpu/real time ratio of about 45. The user-specified minimum allowable time step throughout the calculation was 10-7 seconds and the maximun time step was set to 0.1 seconds.

During the first 27 seconds the code reduced the time step to 0.025 seconds. Afterwards and throughout the whole transient the step was the specified 0.1 seconds.

The model consisted of 122 hydrodinamic volumes, 128 junctions and 124 heat structures.

The grid time for this run was 34.6 ms per volume per advancement.

In a restart at 700 sec. with new control variables the c.p.u. time variable was reset to zero by the code (Fig. 9). There is not any reference at this behaviour in the code manual.

5.1.2 Chronology of events

The predicted timing of significant events is compared with measurements during the LP-SB-1 transient in Table 3.

5.1.3 Secondary side pressure

The isolation of the main feed water and the closure of the steam control valve produced an increase on the secondary side pressure. In our simulation the rate of pressurisation was overpredicted (Fig. 10). Consequently the steam bypass valve started to open in advance of the experiment (Fig. 11).

The energy removal from the steam generator was through the steam valve leakage (around 3 x 10-2 kg/sec. from 500 seconds on) and heat losses through the shell. The minimum flow area of the main steam valve was restricted to 0.0925% of its fully-open value.

5.1.4 Primary side pressure

The primary pressure was in agreement with the experiment during the subcooled blowdown (Fig. 12). The rate of depressurisation was approximately well predicted. However, the simulation did not account for the increase in the rate of depressurisation due to the break uncovery. The result was that primary pressure was overpredicted from 1200 seconds on.

5.1.5. Temperatures

The measured and calculated fluid temperatures are shown in Figures 13 and 14 for the hot and cold leg, respectively.

The hot leg temperature, following the pressure trend, was overpredicted from 1200 seconds onwards.

Cold leg intact loop temperature is in good agreement with the experiment until ~400 seconds. At this time the cold leg suddenly emptied through the vessel downcomer in coincidence with the end of natural circulation (Fig. 17). Following this, the big oscillations of HPIS flow rate (Fig. 15) produced analogous spikes in liquid temperature (Fig. 14).

The reactor vessel plena temperatures were overpredicted beyond 1000 seconds of transient.

5.1.6 Density distribution

The calculated cold leg mixture density is that of the liquid until -400 seconds (Fig. 16), when the pipe empties. The experimental density decreases less rapidly.

The hot leg density follows the experimental trend until -750 sec. After that the calculated density shows two big peaks. This is due to the steam generator tubes depletion (fig. 18, 19).

5.1.7 Break line density and break mass flow rate

The break line density before the time of measured break uncovery (-700 sec.) was underpredicted (Fig. 20). In fact the calculated hot leg and break line densities were nearly equal (Fig. 21). This shows that the offtake model with stratified flow conditions in the main pipe does not work in our RELAP5/MOD2 version, when the crossflow option is used. An obvious consequence is that the simulation does not account for the break uncovery and overpredicts density after -700 sec.

Analogously the break mass flow rate was underpredicted before and overpredicted after the measured break uncovery time (Fig. 22).

The strange step-wise evolution of the calculated break mass flow rate is due to the occurrence of large differences between the phase velocities (slip) (Fig. 23).

5.1.8 Primary system mass inventory

The calculated HPIS plus pumps injection mass flow rates became equal to the break mass flow rate (and so the inventory was minimum) at around 2200 sec.. This minimum inventory was in good agreement with the measured data (Fig. 24).

5.2 Base calculation (RUN B)

This calculation was run for 2500 secs. The grid time in this case was 46.9 ms. per volume per advancement.

5.2.1. Code Performance

The c.p.u. time spent by the code [Fig. 25] was similar to RUN A until around 1400 seconds. After that, the code ran slowlier (Fig. 26) because of the high velocity in the small node close to the break nozzle.(Fig. 27).

In this run the model consisted of 117 hydrodinamic volumes, 123 junctions and 122 heat structures.

5.2.2. Chronology of events.

The predicted timing of significant events is compared with measurements during the LP-SB-1 transient in Table 3.

The opening of the valve in the ILHL break line was the beginning of the transient.

The reactor scram occured 0.65 seconds later than in the experiment. The timing of the initial events was predicted, by the RELAP5/MOD2 calculation, to within ~1 second.

Two seconds after the reactor scram, closure of steam control valve w as initiated. Isolation of the main feedwater took ~3 seconds.

The main steam control valve was fully closed at 17 seconds, 2.6 seconds later than in the experiment. It is known (Ref. 7) that the steam flow bypass valve was open at around 30 seconds when the secondary side pressure exceeded ~6.7 MPa. To account for this fact, in our calculation the main valve was let to reopen.

The primary coolant pumps trip occured at 26.8 sec. in the calculation. The HPIS initiated at 44 sec., 3 seconds later than in the experiment.

The coast down of both pumps was completed at 48 seconds.

The break line reached saturated conditions at 76 seconds. This marks the end of subcooled blowdown.

The auxiliary feedwater was initiated at 62.05 seconds and turned off at 1862.05 seconds.

In the experiment, the break line was uncovered at 715 sec. That did not appear in the simulation. Until this time the break mass flow rate was underpredicted and after that it was overpredicted.

Around 1650 seconds the primary coolant system pressure fell bellow the secondary system pressure (1077 seconds in the experiment).

The minimun primary mass inventory was estimated to be reached at between 1800 and 2200 seconds in the experiment. That happened in the simulation at 2050 seconds (when the HPIS+pump injection mass flow rates exceeded the break mass flow rate).

The experiment finished at 3668 seconds.

Up to 50 seconds the chronology of events improved in this calculation. The break uncovery was poorly predicted because of the depletion of the S.G. U-tubes as it is explained later.

5.2.3. Secondary side pressure

The general behaviour is similar to that of RUN A.

5.2.4. Primary side pressure.

The primary pressure was well predicted until around 700 seconds. After that it was overpredicted, though the code detected the break uncovery at about 1400 seconds (Fig. 28).

5.2.5. Temperatures.

The hot leg temperature was closer to the experimental one than in RUN A (Fig. 29).

The pressurizer temperature history shows (Fig. 30) a sharp initial decrease. After the emptying of the component, around 33 seconds, the steam became superheated and its temperature began to increase. That is due to the radiative heat transfer from the pressurizer wall.

Cold leg liquid temperature was right until 400 seconds (leg depletion). Afterwards it showed spikes due to HPIS injection and level oscillations (Fig. 31). From 400 seconds on the vapor temperature was in agreement with the data (Fig. 32 bis).

Steam generator plena temperatures are showed in Figure 33. There are not big discrepancies between simulated and measured values until their depletion . Hot wall radiation and thermal conduction from the wall to the thermocouples seem to have distorted the measurement beyond 1100 seconds, Ref. 2.

5.2.6. Density distribution.

The cold leg density is similar to RUN A until 1400 seconds. After that there is a slight increase in density, in coincidence with the beginning of a circulation loop between the vessel downcomer and the vessel filler gap.

The hot leg density follows, again, the experimental trend, until the SG tubes depletion.

The subsequent density peaks are clearly smaller than in RUN A (Fig. 34). Also, the density does not fall, after 1500 sec, so rapidly as in RUN A.

The agreement between the experimental and calculated loop seal densities is very good (Fig.35).

5.2.7. Break line density and break mass flow rate.

The offtake model with stratified flow conditions and normal junction option was active during RUN B. Now the break line void fraction has a logical behaviour versus that of the hot leg (Fig. 36). In spite of this, the calculated break line density is quite different from the measured one, between 700 and 1600 sec. . This is another effect of the SG tubes water depletion (Fig. 37).

The break mass flow rate was again underpredicted before the measured break uncovery time (Fig. 38). Now the simulation shows the break uncovery, but much later than in the experiment (1400 sec.).

The break mass flow step-wise evolution in RUN A is in RUN B replaced by strong instabilities, likely due to unsimultaneous switching between flow regimes in the adjacent volumes of the break piping (Fig. 39 and 39-bis). Perhaps a time step reduction should eliminate some of these instabilities.

In both calculations, the code detected choked flow conditions in the break as soon as it opened.

5.2.8. Primary system mass inventory.

Figure 40 compares the measured and calculated primary system mass inventory. Although not accurately known from the experimental data minimum primary mass inventory was estimated to have occurred at between 1800 and 2200 seconds.

An obvious consequence of the break mass flow underprediction is the overprediction up to 20 % of the mass inventory during 1500 seconds.

Around 800 seconds began the S.G. tubes depletion (Fig. 37). This process culminated with the S.G. plena emptying between 1300 seconds (cold side) and 1400 seconds (hot side) (Fig. 41).

The slow fall of the tubes liquid rised the hot leg level above the break line. This delayed the final break uncovery until 1650 seconds in RUN A and 1400 seconds in RUN B.

Calculated core void fractions (Fig.42) reveal that the core was not uncovered, as observed in the experiment.

5.3 Selected items

5.3.1 Loop flow and natural circulation

In LP-SB-1 experiment, natural circulation was the only means for energy transfer between the core and the steam generator.

The measured velocities (Fig. 43) indicate that natural circulation was established after the pumps coastdown (~50 sec.). At about 500 sec., the turbine meters showed zero velocity.

Figure 44 [2] indicates that break mass flow rate became larger than thIGe hot leg mass flow rate at about 400 sec., and this suggests some flow from the S.G. to the break after this time. This may be due to the blockage by vapor of the top of the U-tubes, and the resultant liquid draining from them.

The measured S.G. plena temperatures (Fig. 33) suggest that the thermocouples remained wet until -1100 sec. because of liquid draining and from possible reflux condensate.

So, it appears that two-phase natural circulation finished at -500 sec., due mainly to flow blocking through the U-tubes.

After this time, the system entered a reflux condensation mode, and the U-tubes, cold leg and hot leg piping successively drained. This cooling mode in the S.G. finished at about 1100 sec., when the secondary pressure became equal to primary pressure.

In our base calculation, the cold leg suddenly emptied at - 400 sec., and the circulation ceased at about 700 sec. (Figures 45 and 46). Inmediatly, the liquid velocity in the U-tubes indicated that the system entered the reflux condenKIsation mode (Fig. 47). The primary coolant-tubes heat transfer coefficient consistently increased (Fig. 48). At about 1200 sec. the U-tubes emptied (Fig. 37).

When the onset of reflux condensation was detected by the code the primary coolant mass inventory was of 65% , very close to the actual inventory of 60%. These values are in the typical range encountered for experiments in several facilities (Semiscale, PKL, LSTF,...) [9].

5.3.2 Hot leg flow stratification.

In LP-SB-1, the intact loop hot leg fJlow stratified at -50 sec. (Fig. 34)[2].

In our RUN B simulation, the code detected stratified flow regime in ILHL at -320 sec.

The criterion defining horizontally stratified regime in RELAP5/MOD2 is that developed by Taitel and Dukler.[8]. It states that the flow is horizontally stratified when the vapor velocity satisfies the condition that:

$$|Vg|<Vgl$$

where

$$V_{gl}=\frac{1}{2}\left(\frac{(\rho_f-\rho_g)g\alpha_g A}{\rho_g D\sin\vartheta}\right)^{\frac{1}{2}}(1-\cos\vartheta)$$

The angle ϑ is related to the liquid level h and the vapor fraction by:

$$h=\frac{D(1+\cos\vartheta)}{2}$$

$$\pi\alpha_g=\vartheta-\sin\vartheta\cos\vartheta$$

In Figure 43 we see the comparison between measured and calculated hot leg fluid velocities. It is surprising to observe that, during a short time around 50 sec., the calculated vapor velocity became very small, and even negative. However, the code did not predict any change to stratified flow regime during that lapse (Fig. 49).

Figure 50 shows the comparison between the calculated vapor velocity and the Taitel-Dukler limit velocity [1] for RUN B. As expected, the limit velocity is higher than the vapor velocity from 320 sec. on. Around 50 sec., Vgl is very small. Figure 51 plots the difference |Vg|-Vgl and shows that the code never detected negative values of this magnitude.

We repeated the first 500 sec. of transient with a time step of 0.01 sec. (rather than 0.1 sec.). Now, the above difference became negative during a few seconds, and,consistently, the code detected stratified flow conditions (Fig. 52 and 53).

So, the code did not notice the change on flow regime because the time step was too long.

In conclusion, the code predicted well a minimum of fluid velocities at around 50 sec., and so, the onset of horizontal stratified flow in hot leg. After that, natural circulation established, and experimental and calculated velocities increased. The simulated flow changed back from stratified to bubbly, but the actual one did not.

Keeping in mind that hot leg density and velocity are reasonably reproduced by the code, it is obvious that Taitel-Dukler model is unable to describe properly flow stratification in LP-SB-1.

6. CONCLUSIONS

The major conclusions are:

i) The code could not account for the liquid entrainment and vapor pull-through in the break tee modelled as a crossflow junction.

ii) It is necessary to improve the RELAP5/MOD2 choked flow model to avoid large instabilities in the break phase velocities and thermal disequilibrium effects.

iii) The Taitel-Dukler model is unable to describe properly horizontal flow stratification in the LP-SPB-1 experiment.

iv) Natural circulation was correctly reproduced by the code.

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2 MODRO, S M et al. "Experiment Analysis and Summary Report on OECD LOFT Nuclear Experiments LP-SB-1 and LP-SB-2". OECD LOFT T-3205, May 1984.

3 CHEN, T H. MODRO, S M. "Best Estimate Prediction for OECD LOFT Experiment LP-SB-1", OECD LOFT T-3203, May 1983.

4 McPHERSON, G D. "Decay Heat Data for OECD LOFT Experiments", October 19E85 (Letter to OECD LOFT Programme Review Group Members).

5 MODRO, S M. CHEN, T H. "OECD LOFT Proyect Experiment Especification Document. Hot Leg Small Break Experiments LP-SB-1 and LP-SB-2" OECD LOFT T-3201, April 1983.

6 PELAYO, F. "TRAC-PF1/MOD1 Post-test calculations of the OECD LOFT Experiment LP-SB-2" CSN/SEP/PROG/18/87. AEEW-R 2202, April 1987.

7 ALLEN, E.J. "TRAC-PF1/MOD1 Post-test calculation of the OECD LOFT Experiement LP-SB-1" AEEW-R 2254. August 1987.

8 RANSOM, V.H., et al. "RELAP5/MOD2 CODE MANUAL". NUREG/CR-4312.

9 "Compendium of ECCS Research for Realistic LOCA Analysis". NUREG-1230.

10 HALL, P.C. , BROWN, G. "RELAP5/MOD2 Calculations of the OECD LOFT test LP-SB-01". CEGB. GD/PE-N/544. November 1986.

TABLE 1

INITIAL CONDITIONS FOR EXPERIMENT LP-SB-1

	MEASURED	PREDICTED (RUN A)
PRIMARY COOLANT SYSTEM		
Core T (K)	18.5 ± 1.7	18.7
Hot leg pressure	15.00 ± 0.08	15.04
Cold leg temperature (K)	557.2 ± 1.5	558.1
Mass flow rate (kgs-1)	483.1 ± 3.2	484.0
REACTOR VESSEL		
Power level (MW)	48.8 ± 1.2	48.8
STEAM GENERATOR SECONDARY SIDE		
Liquid level (m)	3.12 ± 0.01	3.116
Water temperature (K)	535.2 ± 3.6	526.5
Pressure (MPa)	5.53 ± 0.05	5.54
Mass flow rate (kgs-1)	25.79 ± 0.77	26.
PRESSURIZER		
Liquid volume (m3)	0.625 ± 0.001	0.598
Steam volume (m3)	0.377 ± 0.001	0.403
Water temperature (K)	615.8 ± 8.2	615.1
Pressure (MPa)	15.06 ± 0.11	15.0
Liquid level (m)	1.072 ± 0.002	1.126
BROKEN LOOP		
Cold leg temperature (K)	555.7 ± 6.3	558.02

TABLE 2

OPERATIONAL SETPOINTS FOR EXPERIMENT LP-SB-1

Action	Reference	Measured Setpoint
Small-break valve Opened	Time	0.
Reactor scrammed	ILHL Pressure (MPa)	14.57± 0.03
Main feedwater Shut off	ILHL Pressure (MPa)	14.57± 0.03
Main steam control valve started to close	Time after reactor scram (seconds)	2.± 0.2
Primary coolant pumps tripped	ILHL Pressure (MPa)	11.12± 0.03
HPIS Flow) initiated	ILHL Pressure (MPa)	8.24± 0.03
Auxiliary feed-water initiated	Time after reactor scram (seconds)	62.± 0.2
Auxiliary feed-water terminated	Time after reactor scram (seconds)	1864.2± 0.8

TABLE 3

LP-SB-1 CHRONOLOGY OF EVENTS

EVENT	PLANT	RUN A	RUN B
Small-break valve opened	0.0	0.0	0.0
Reactor scramed	1.4	2.05	1.9
Main feedwater shut off	1.4	2.05	1.9
Main steam control valve started to close	3.4	4.1	3.95
Main feedwater isolated	3.8	5.	4.3
Main steam control valve fully closed	15.	4 17.	13.95
Primary coolant pumps tripped	24.6	26.85	25.9
Pressurizer liquid level below indicating range	34.6	33.	32.
HPIS flow initiated	41.4	44.	48.
Primary coolant pump 1 coastdown completed	42.6	48.	49.
Primary coolant pump 2 coastdown completed	43.0	48.	49.
Subcooled blowdown ended	57.5	76.	55.
Auxiliary feedwater initiated	63.4	62.05	64.
Break started to uncover	715.	1050.* 1650.*	880.* 1440.
Primary system pressure becomes less than secondary system pressure	1077.		1450.
Auxiliary feedwater shut off	1864.8		1865.4
HPIS + pump injection flow rate exceeded break flow rate			
HPIS flow rate exceeded break flow rate	1998.0		

---

* Collapsed level under the HL pipe midplane

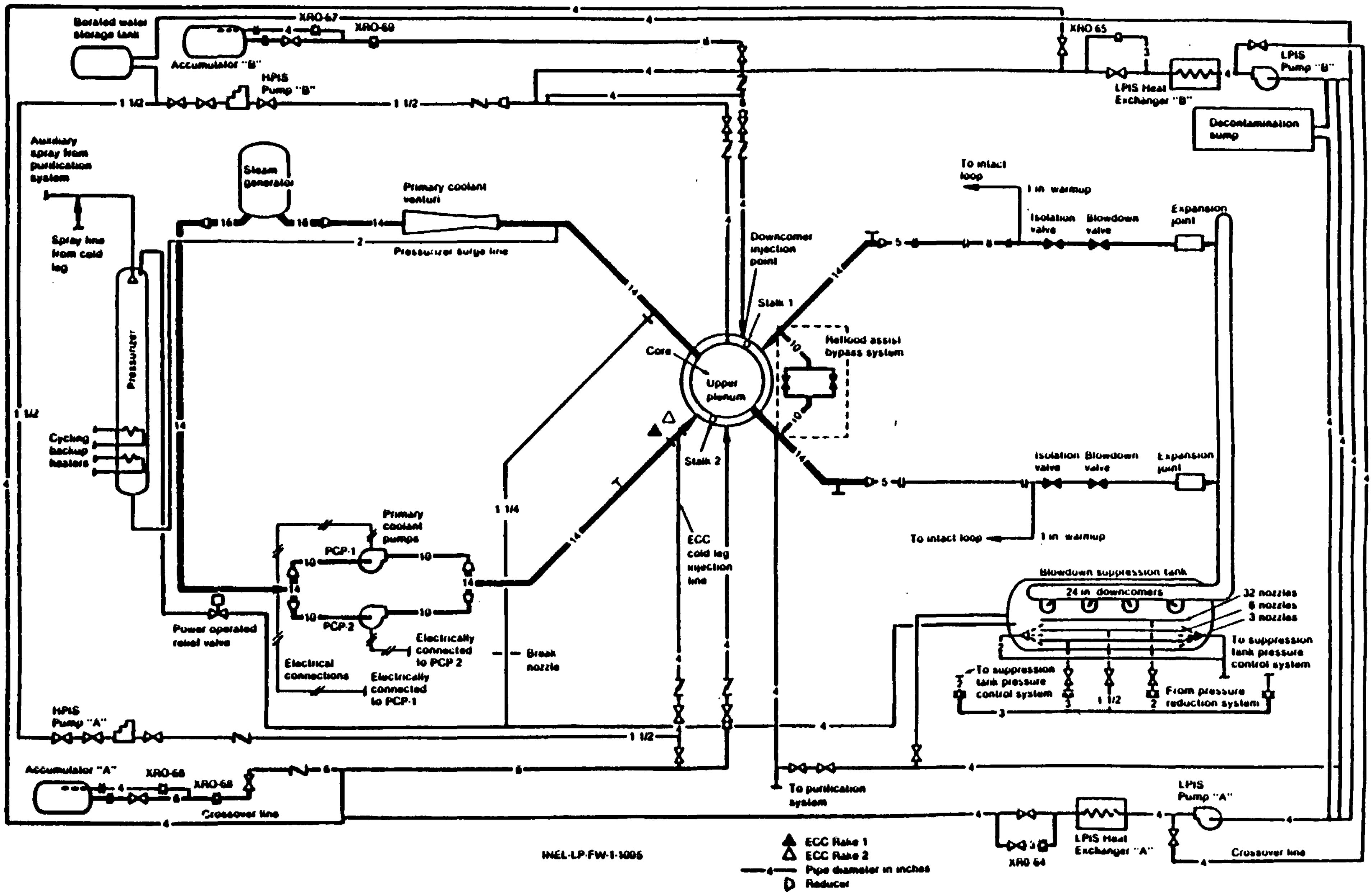


Figure 1. LOFT piping schematic.

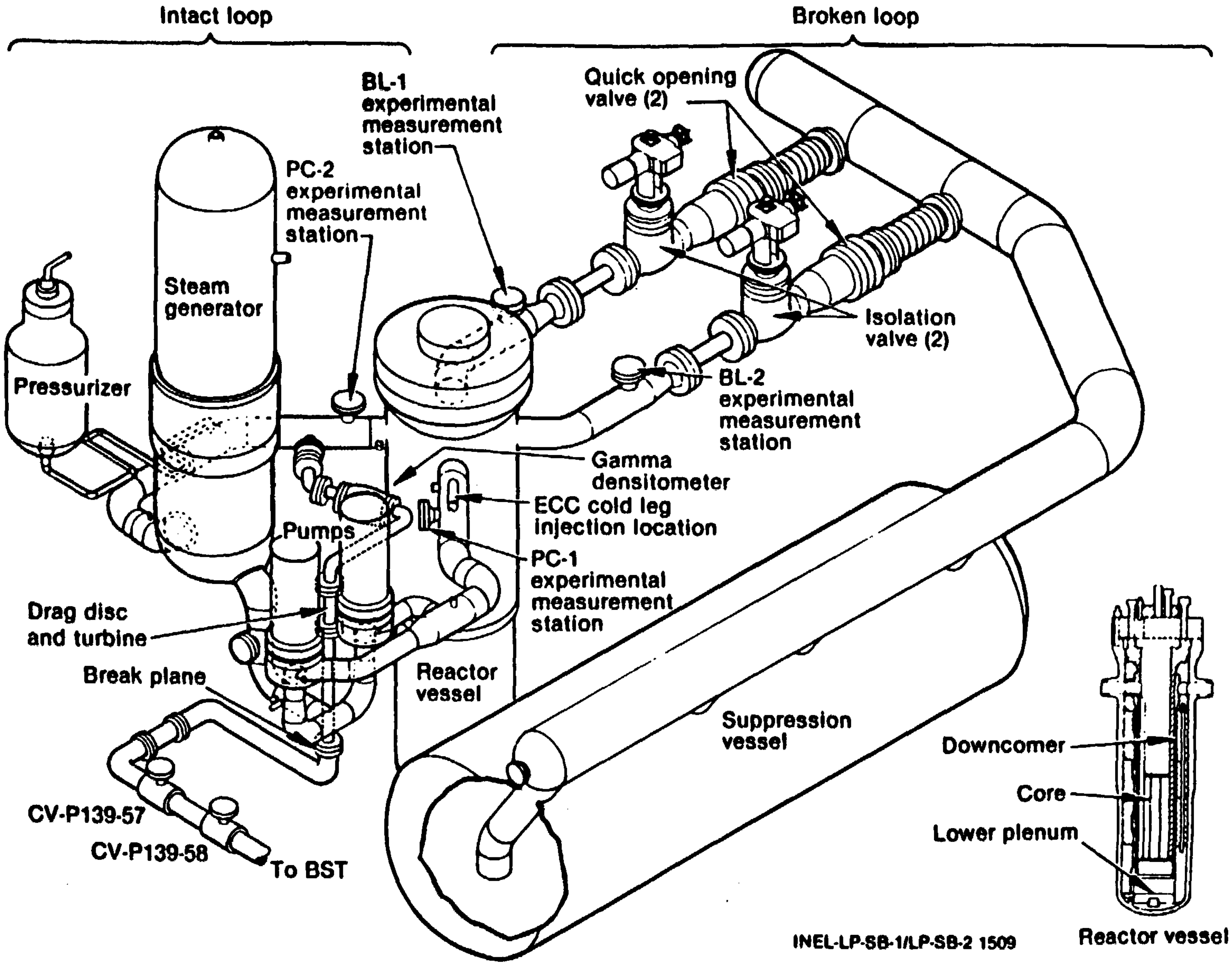


Figure 2. Axonometric projection of the LOFT system configuration for Experiments LP-SB-1 and LP-SB-2.

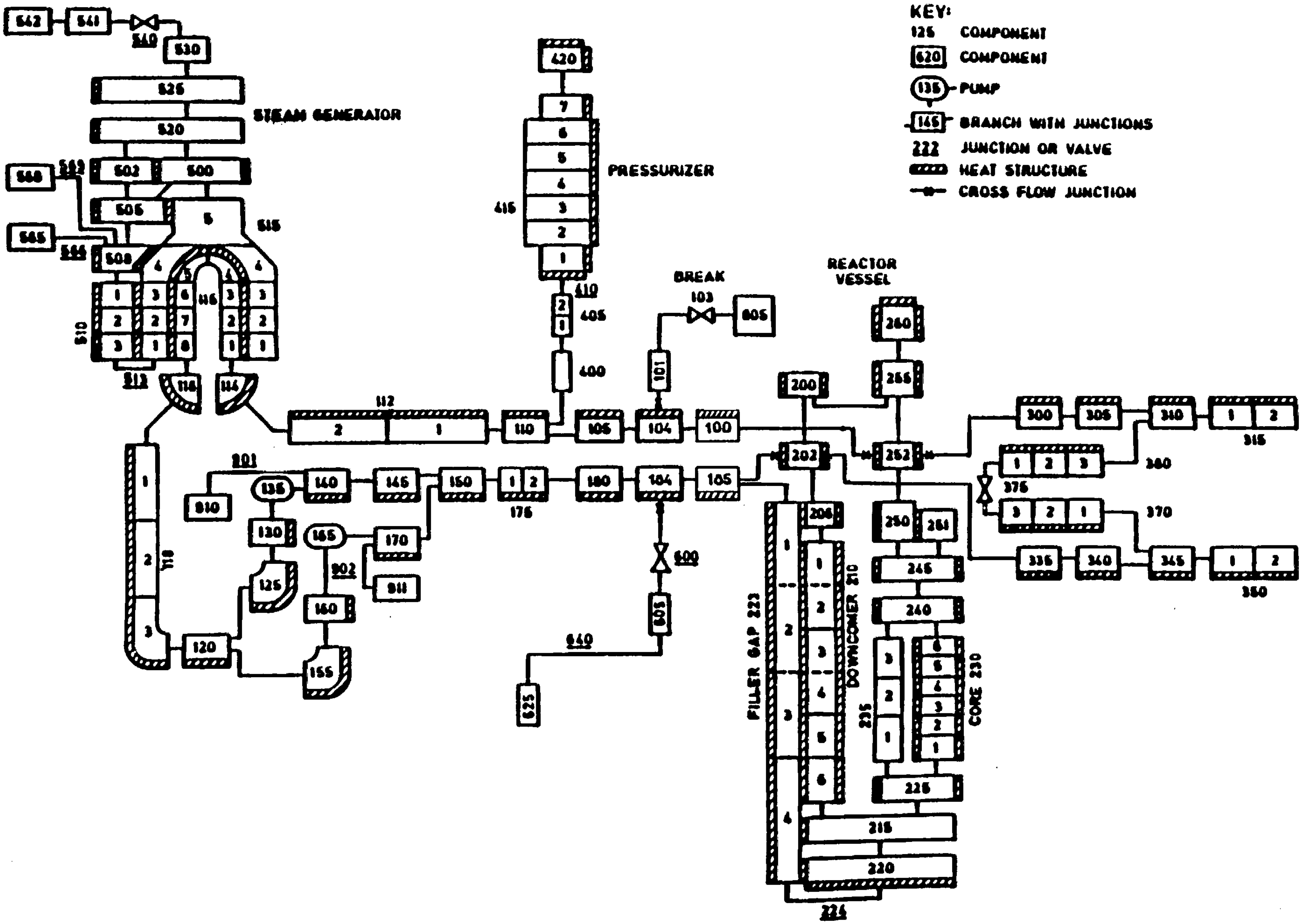


FIG.3 RELAP 5 NODING DIAGRAM FOR LOFT LP-SB-1 CALCULATION (RUN A)

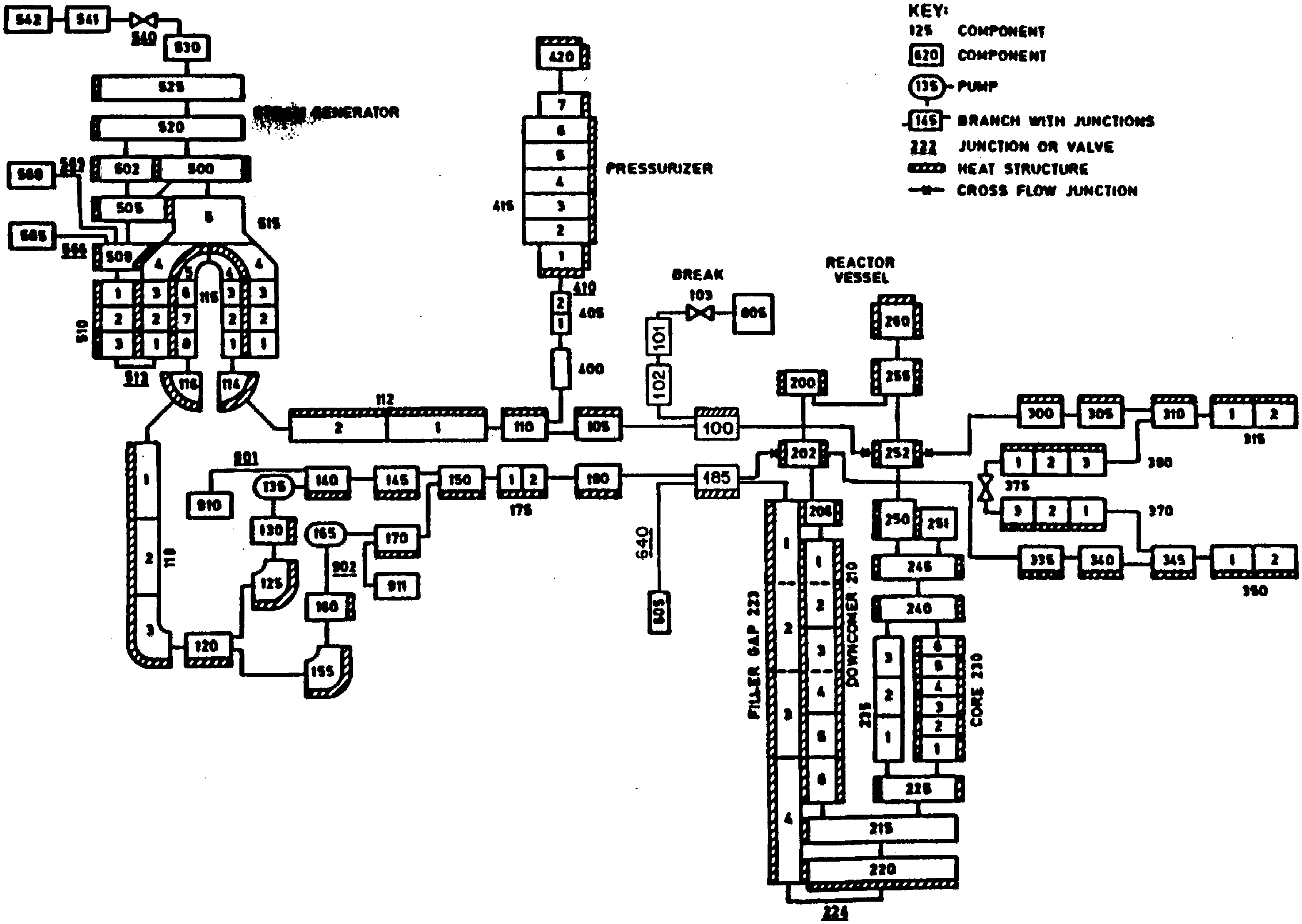
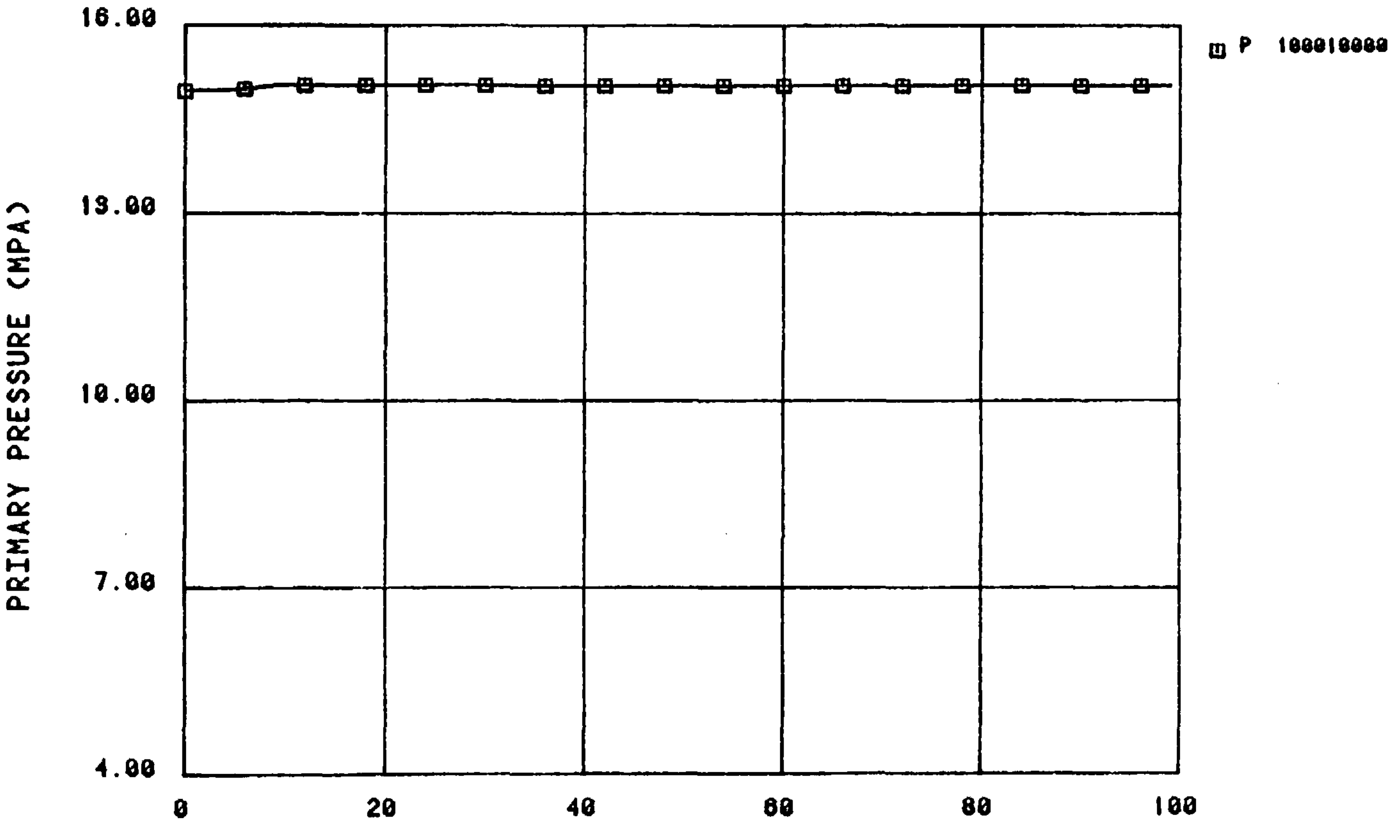
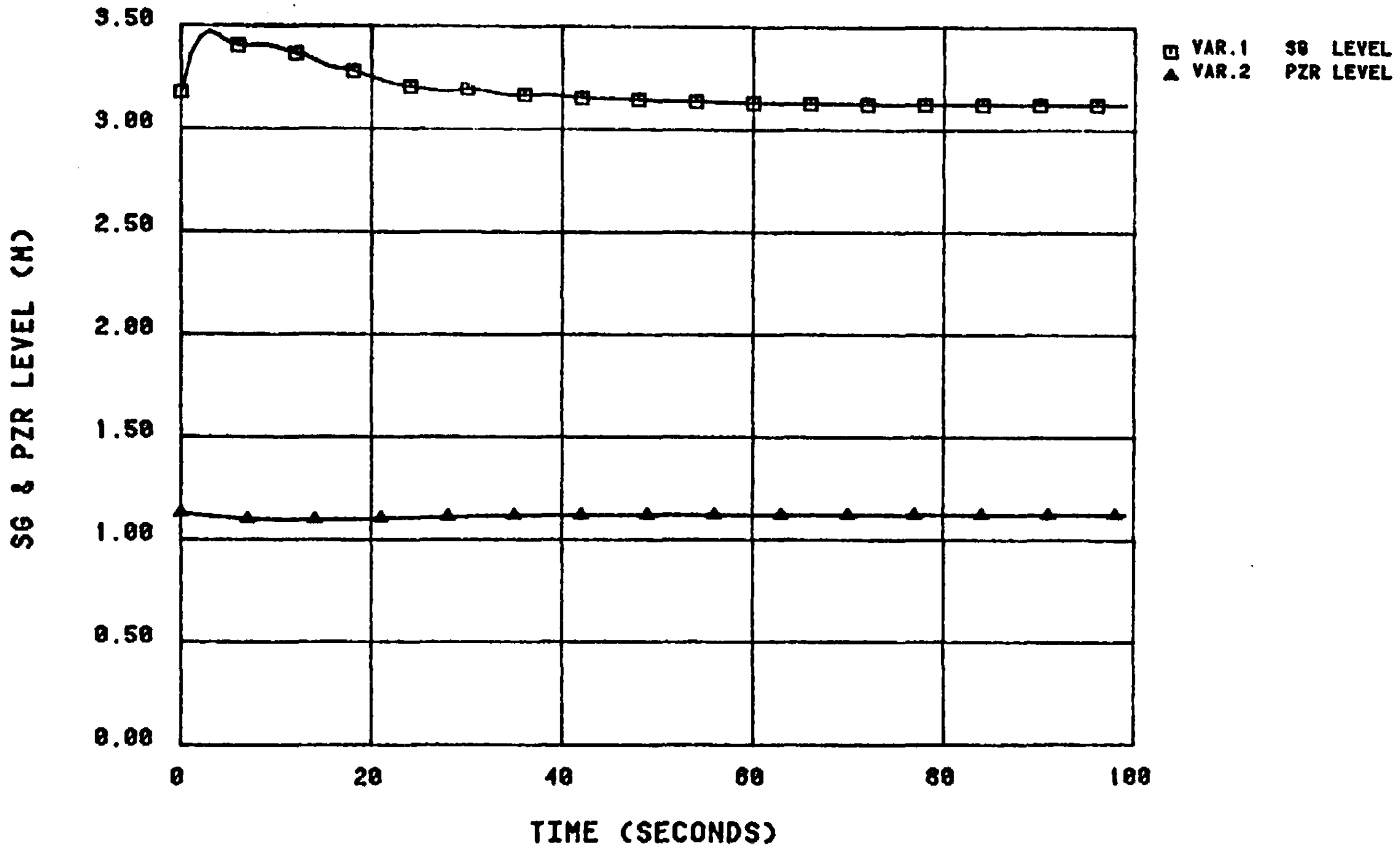


FIG.4 RELAP 5 NODING DIAGRAM FOR LOFT LP-SB-1 CALCULATION (RUN B)



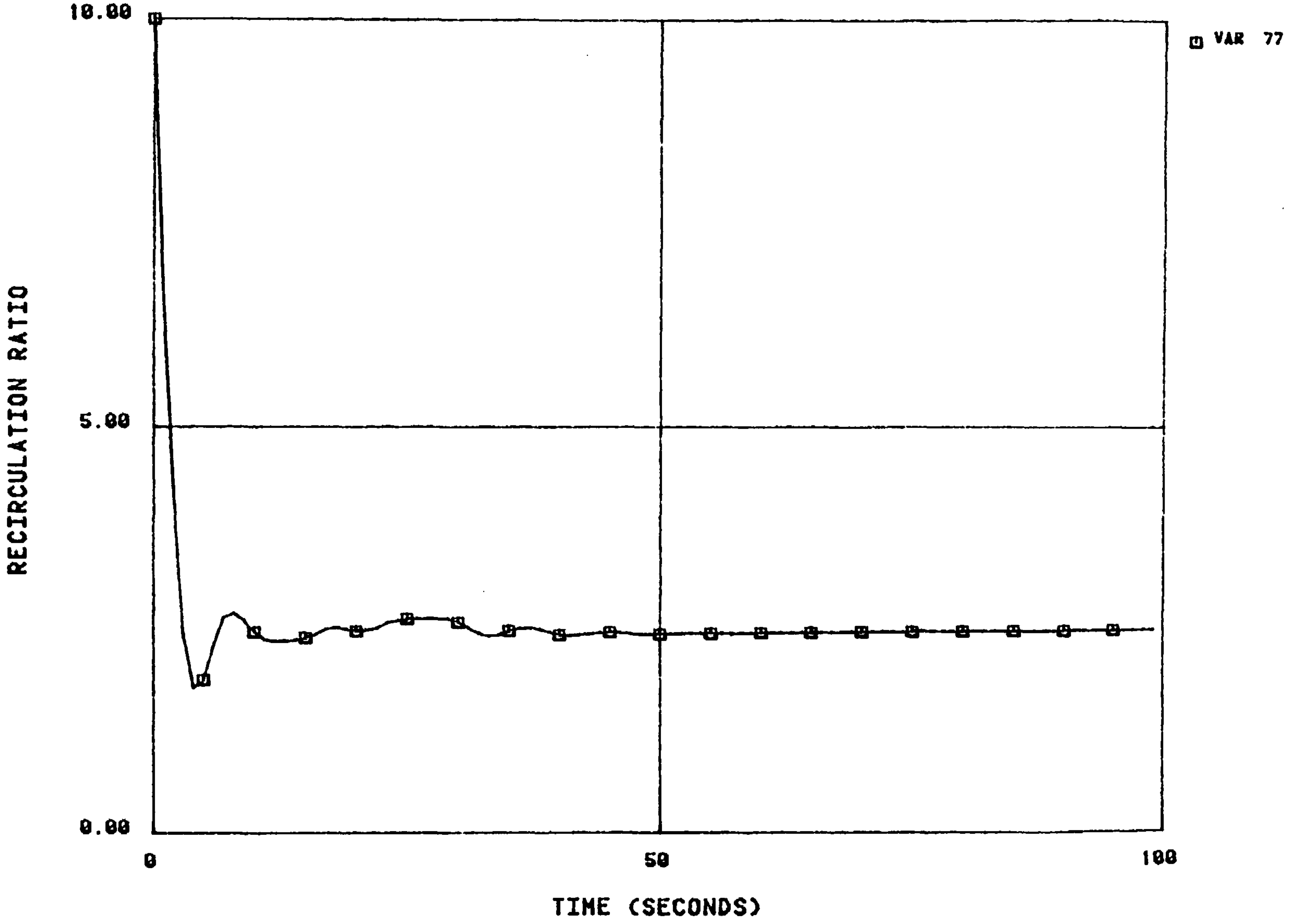
LP-SB-1 STEADY STATE. RUN A

FIG. 5



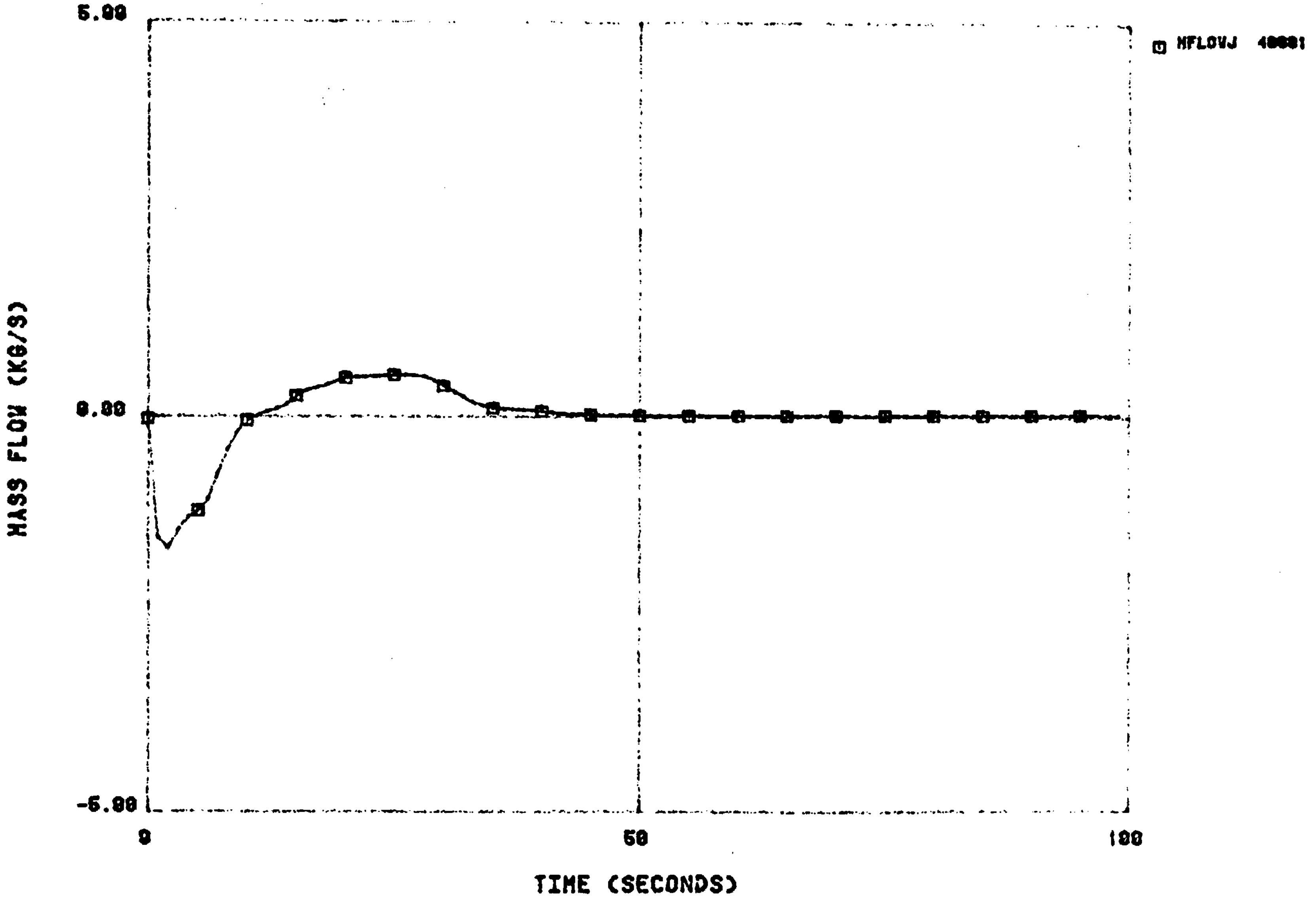
LP-SB-1 STEADY STATE. RUN A

FIG.6



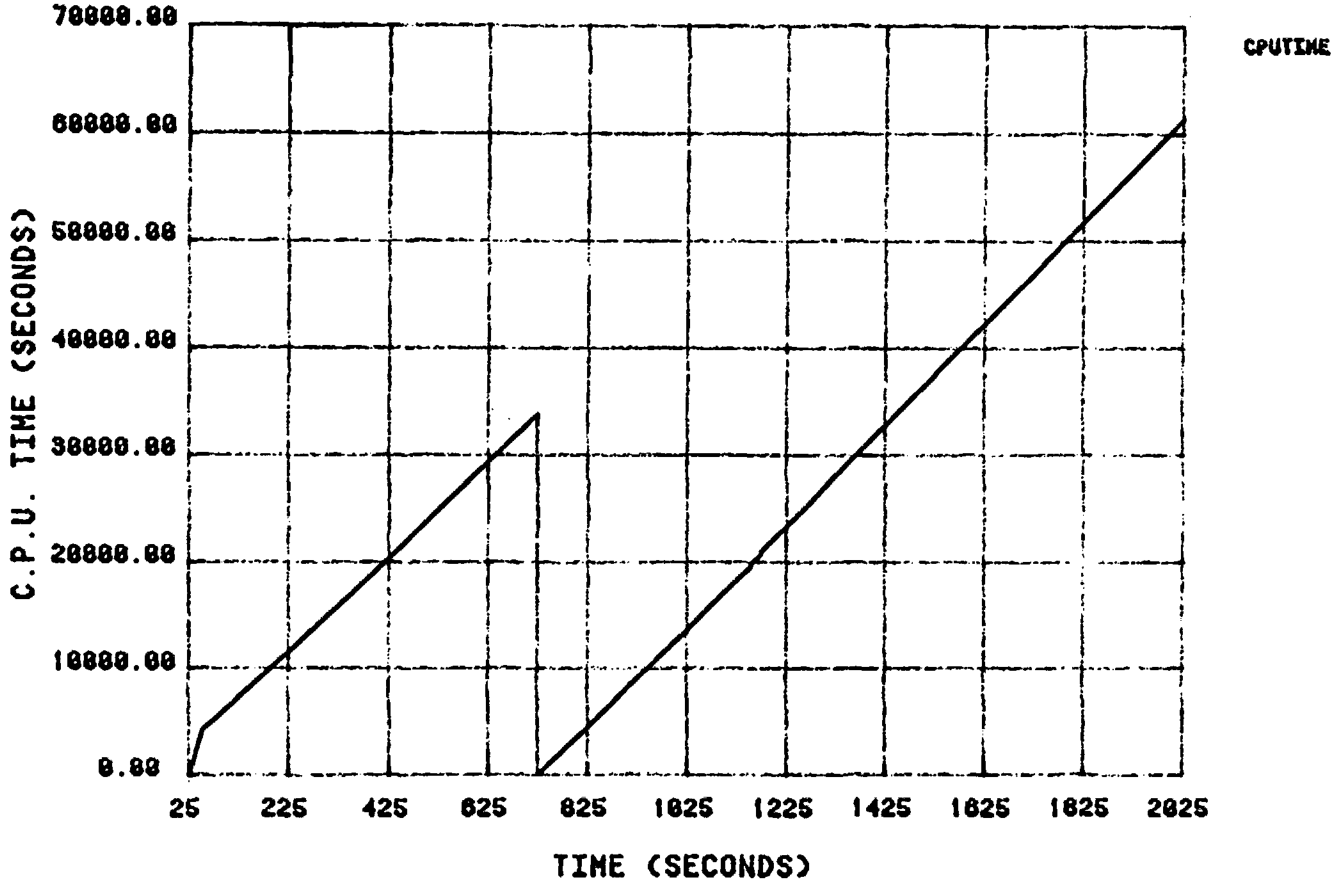
LP-SB-1 STEADY STATE. RUN A.

FIG. 7



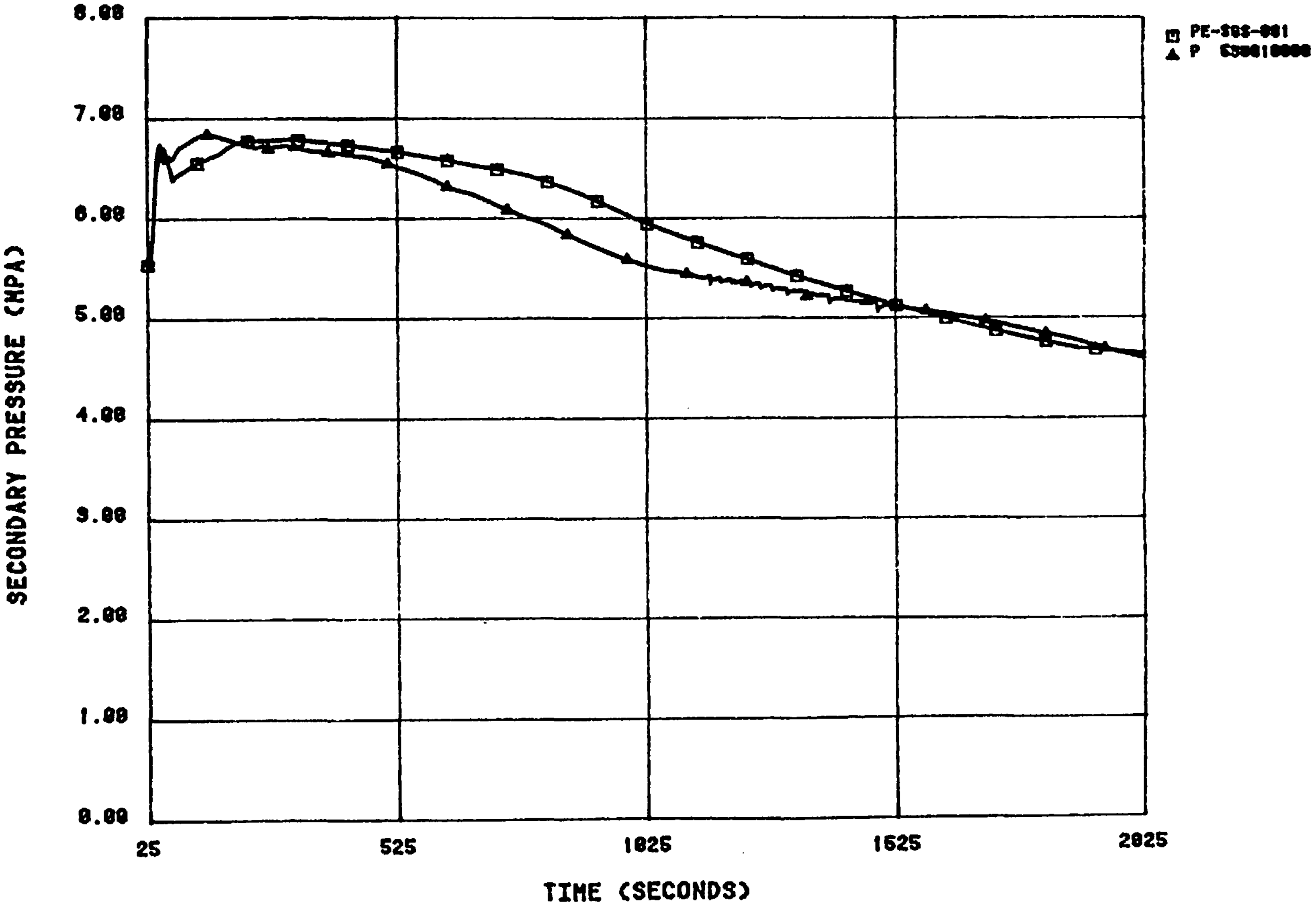
LP-SB-1 STEADY STATE. RUN A.

FIG. 8



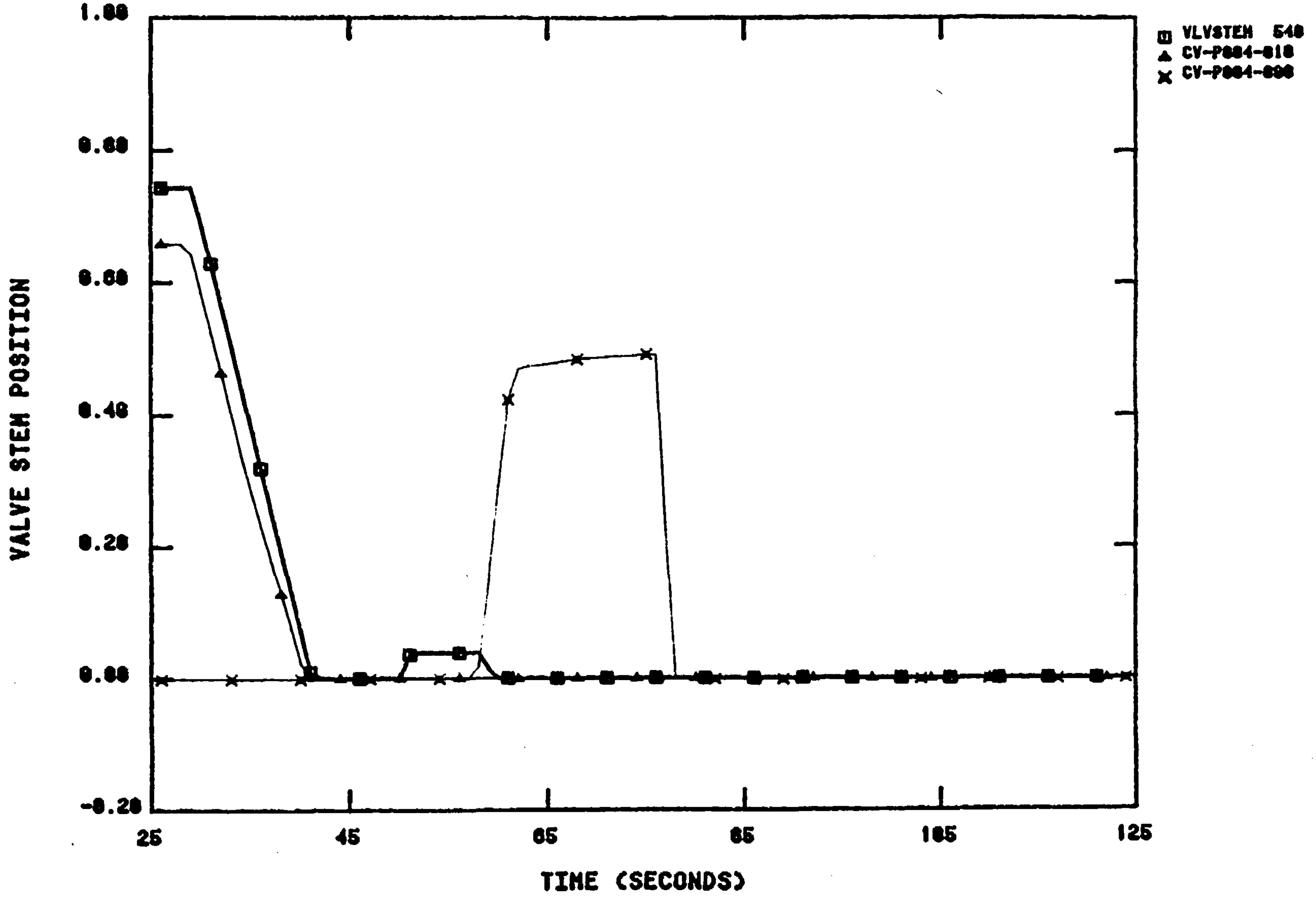
LP-SB-1. RUN A

FIG. 9



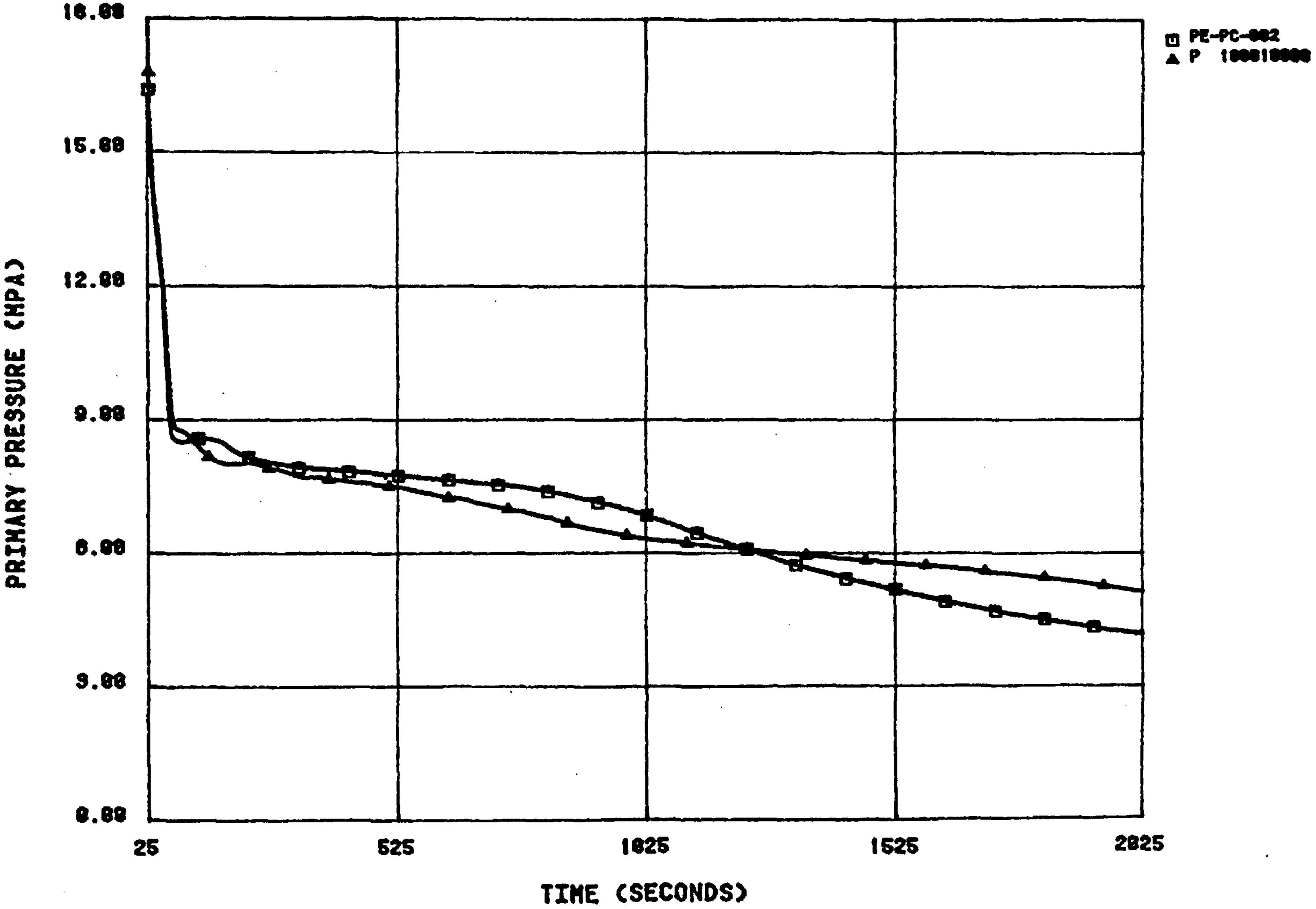
LP-SB-1. RUN A

FIG. 10



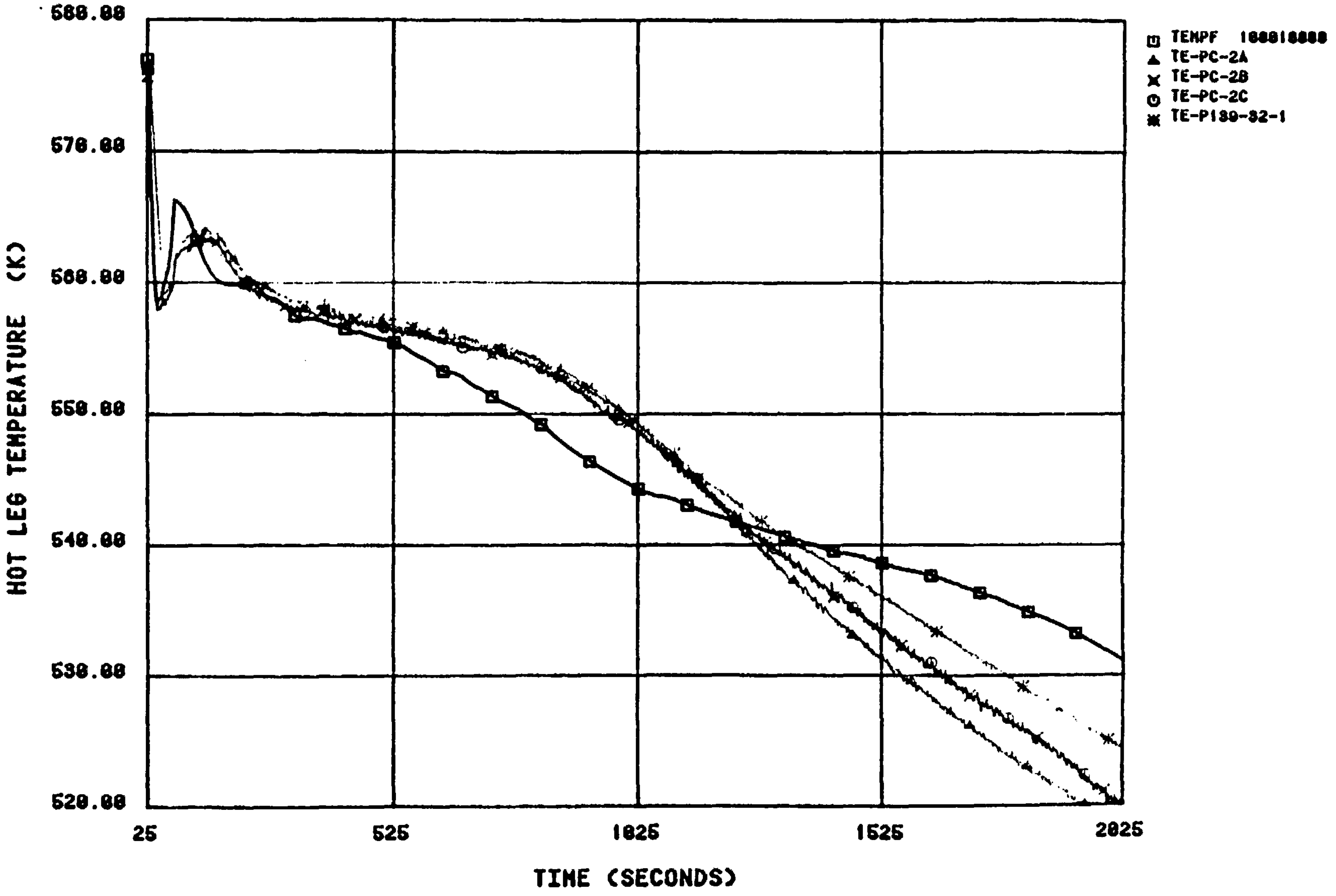
LP-SB-1. RUN A

FIG. 11



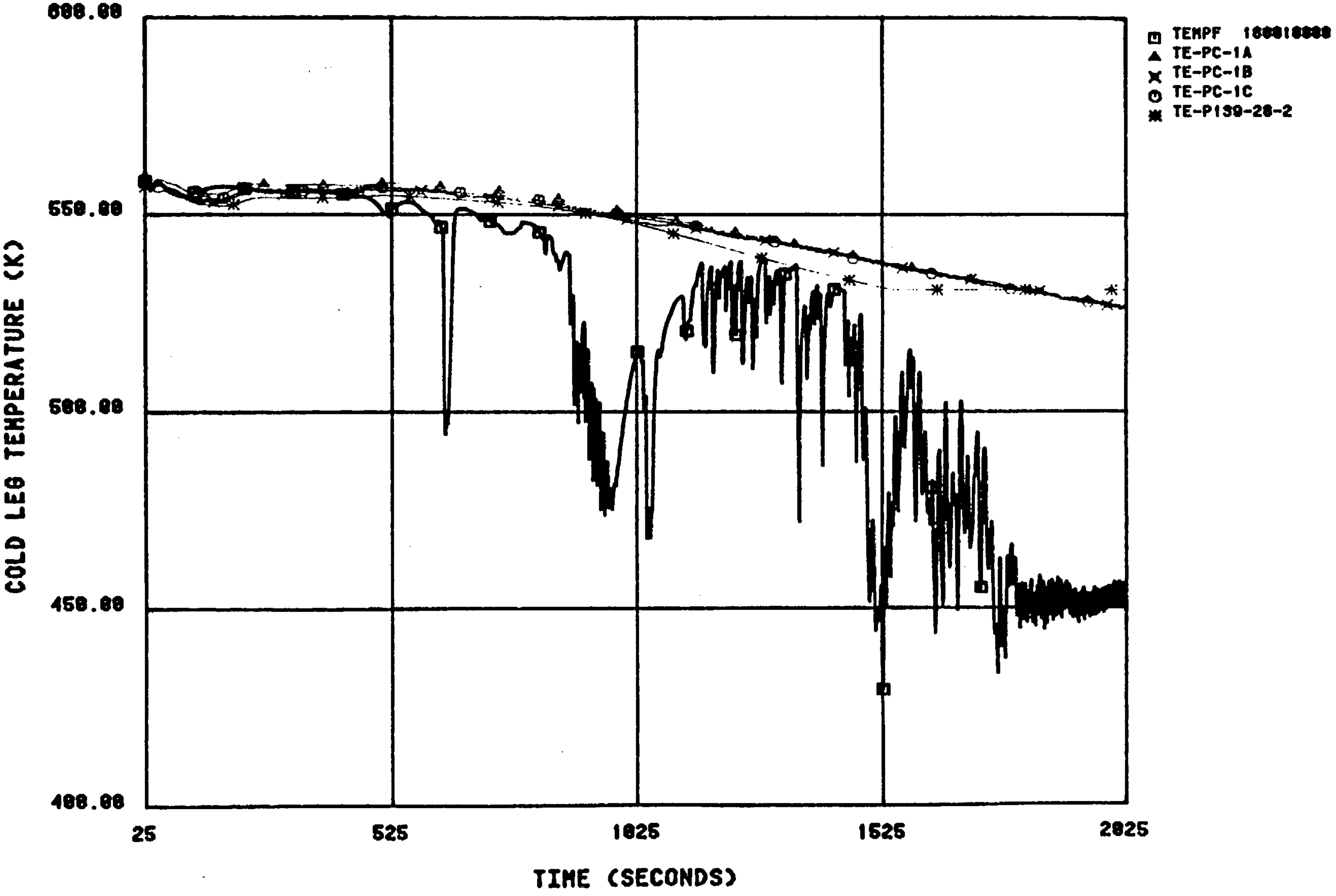
LP-SB-1. RUN A

FIG. 12



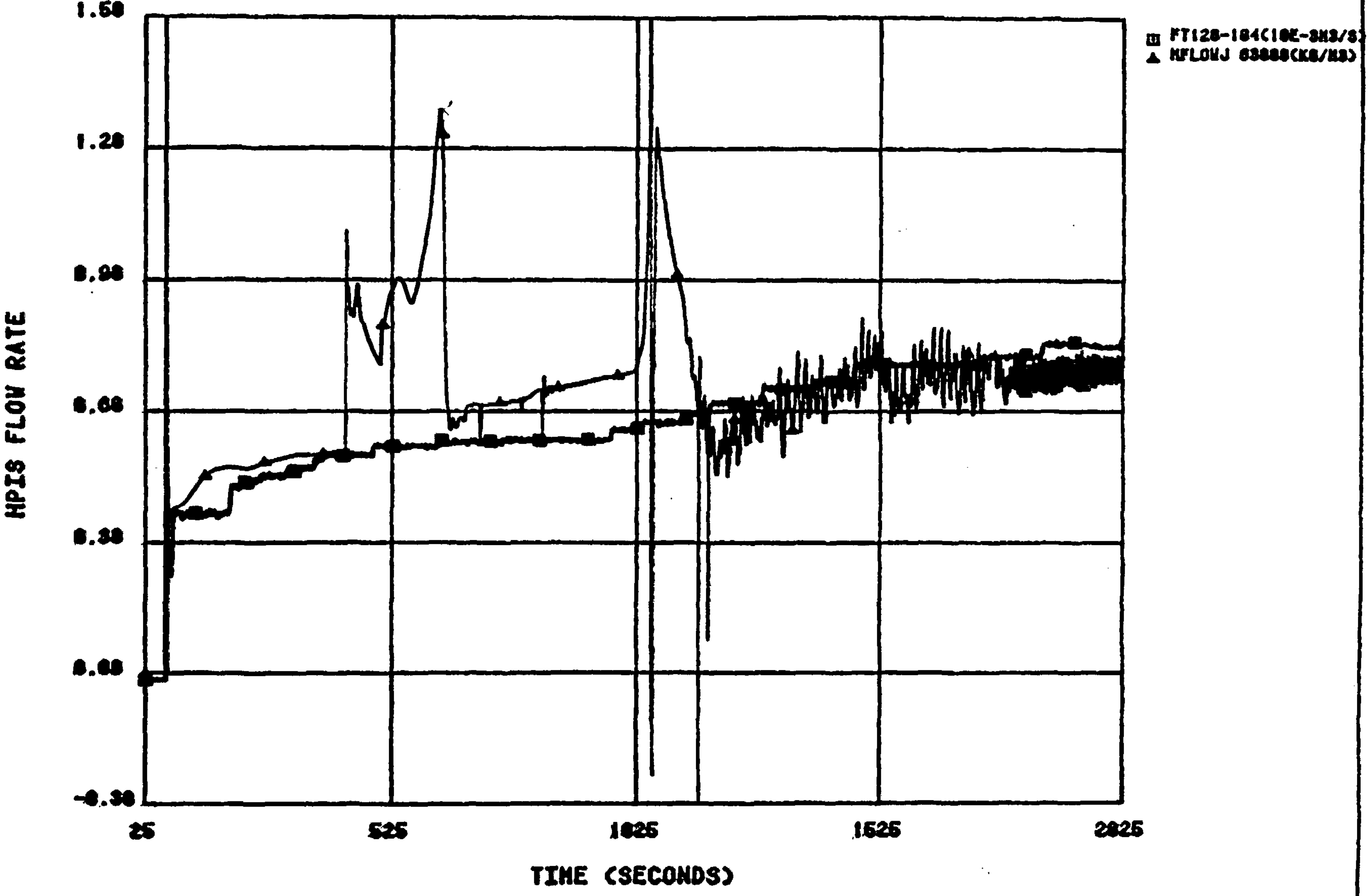
LP-SB-1. RUN A

FIG. 13



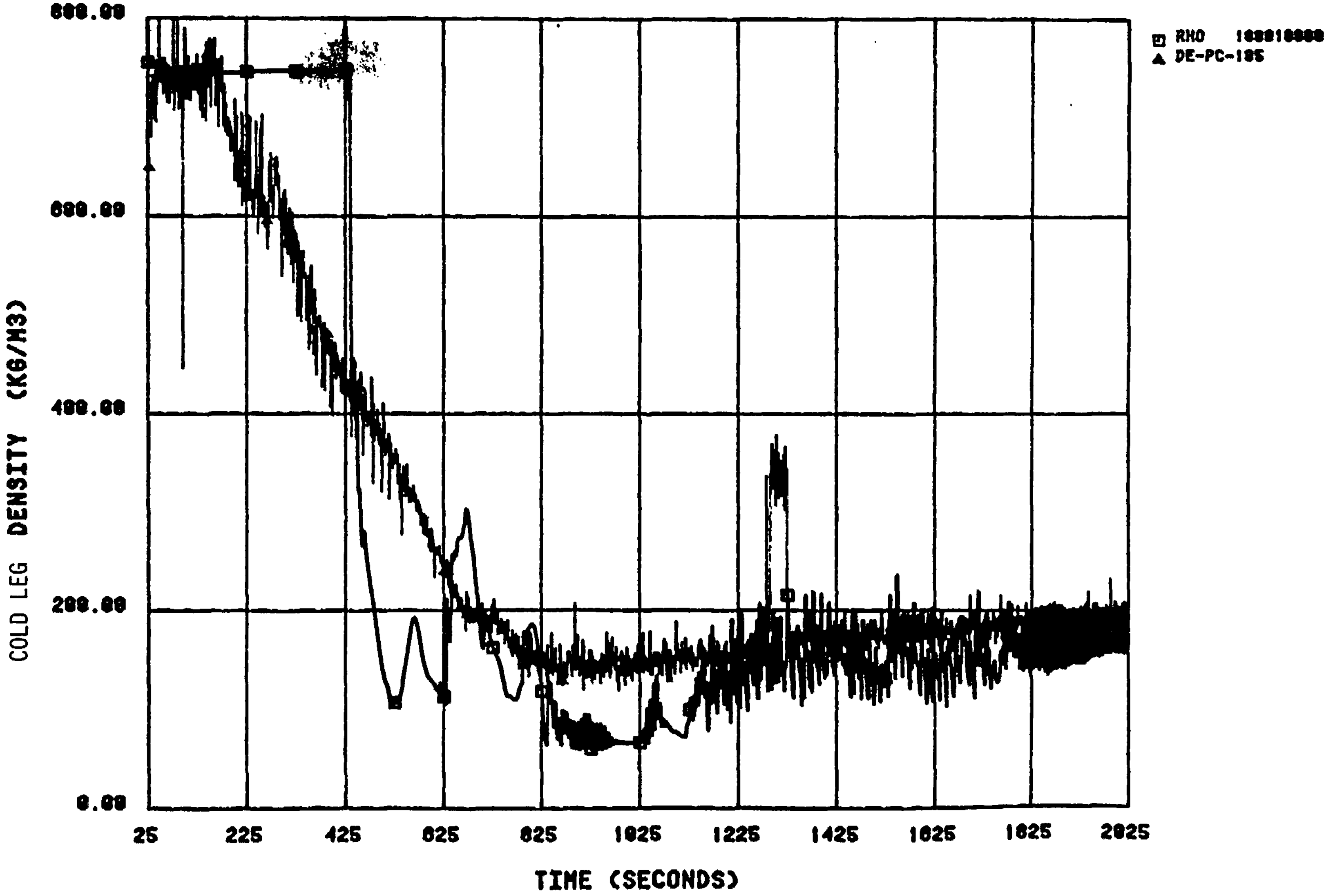
LP-SB-1. RUN A

FIG.14



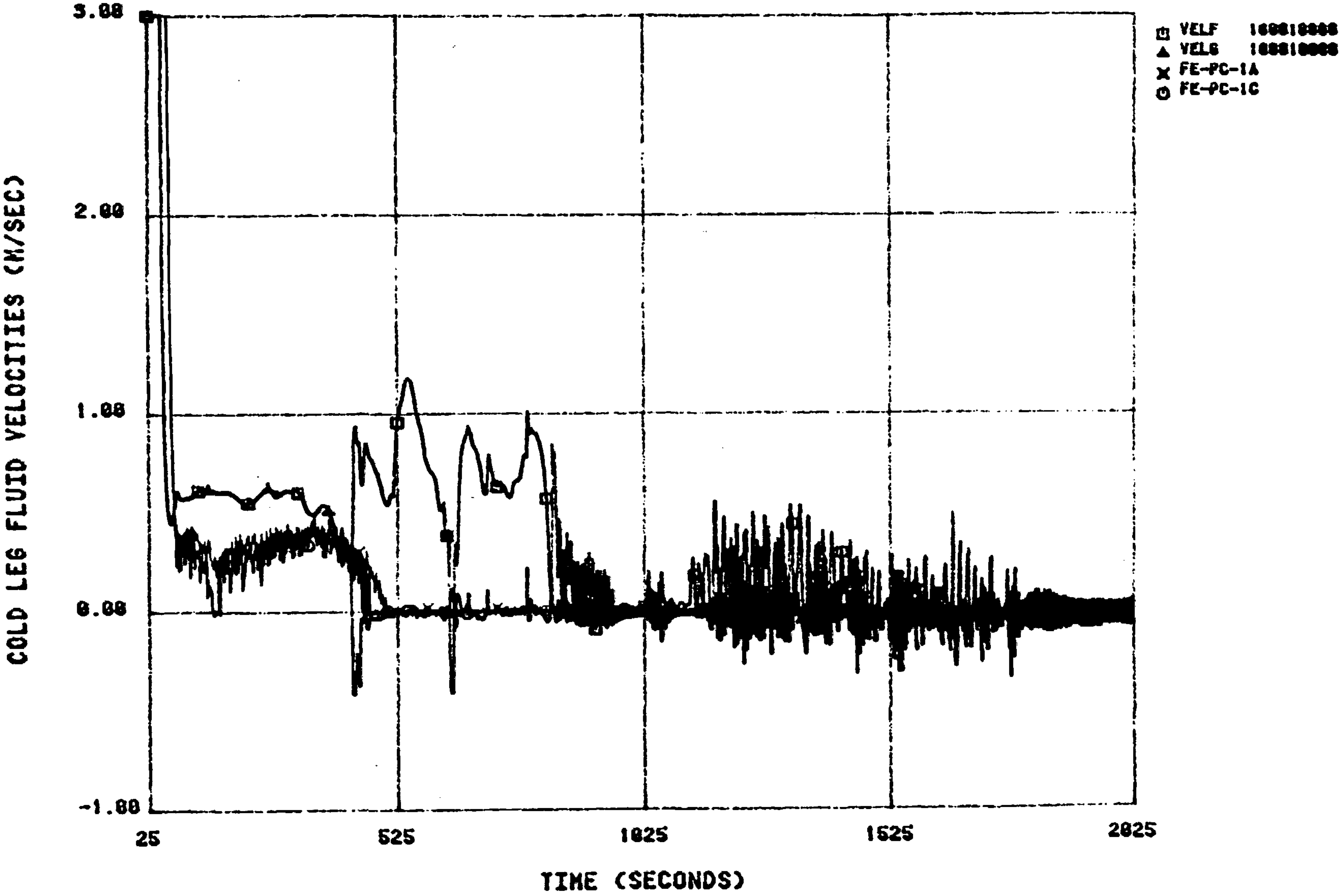
LP-SB-1. RUN A

FIG. 15



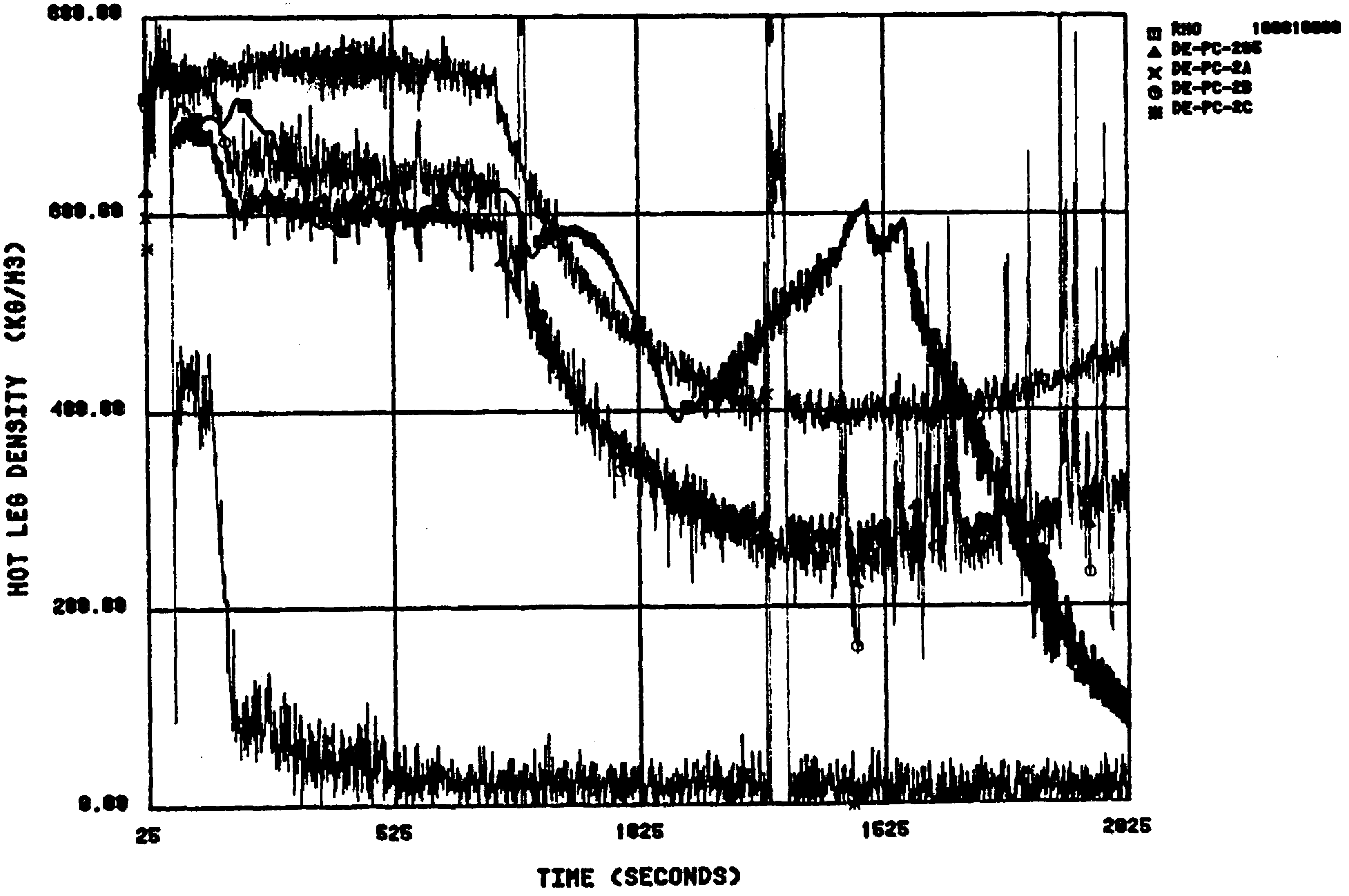
LP-SB-1. RUN A

FIG. 16



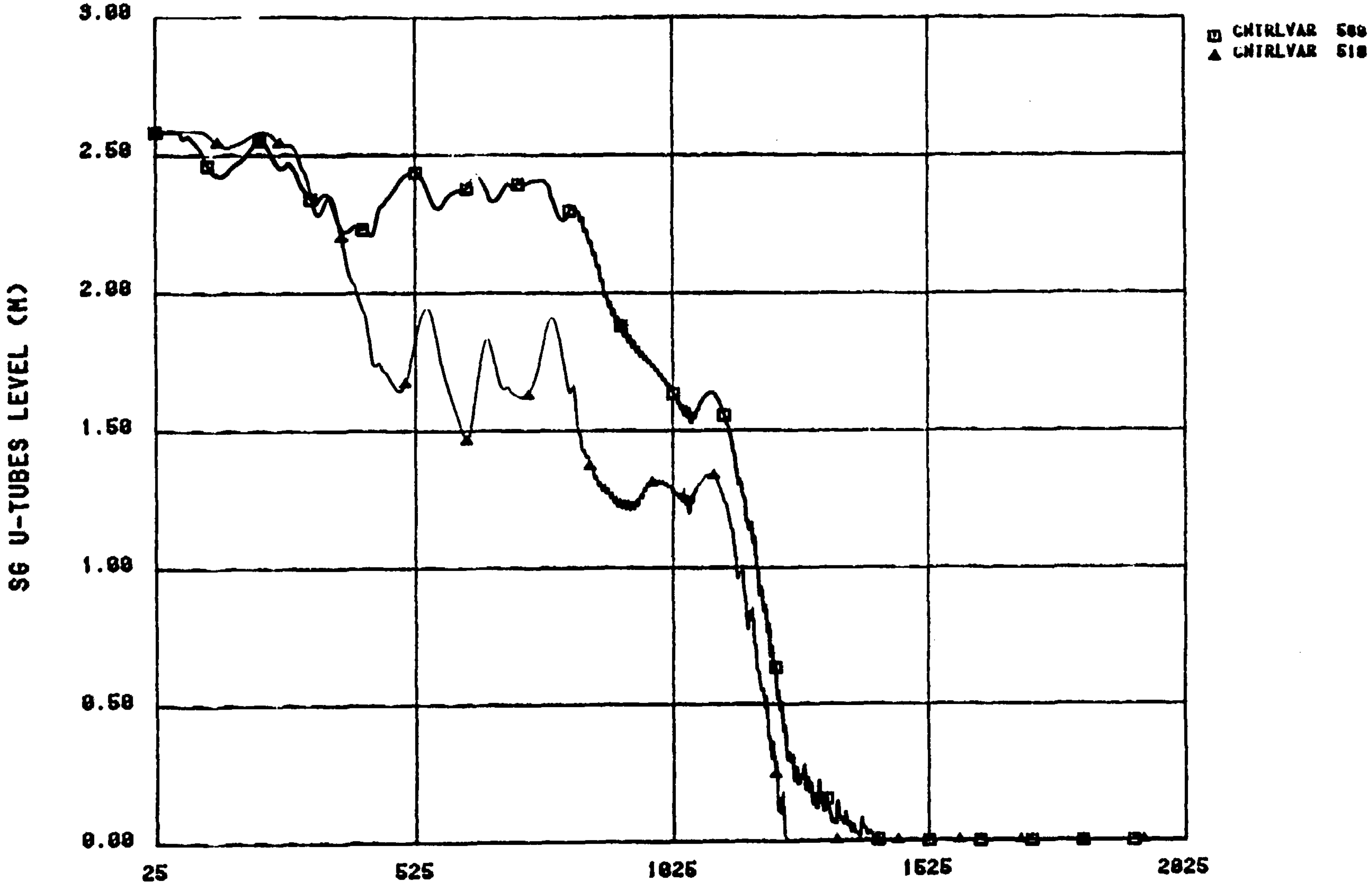
LP-SB-1. RUN A

FIG. 17



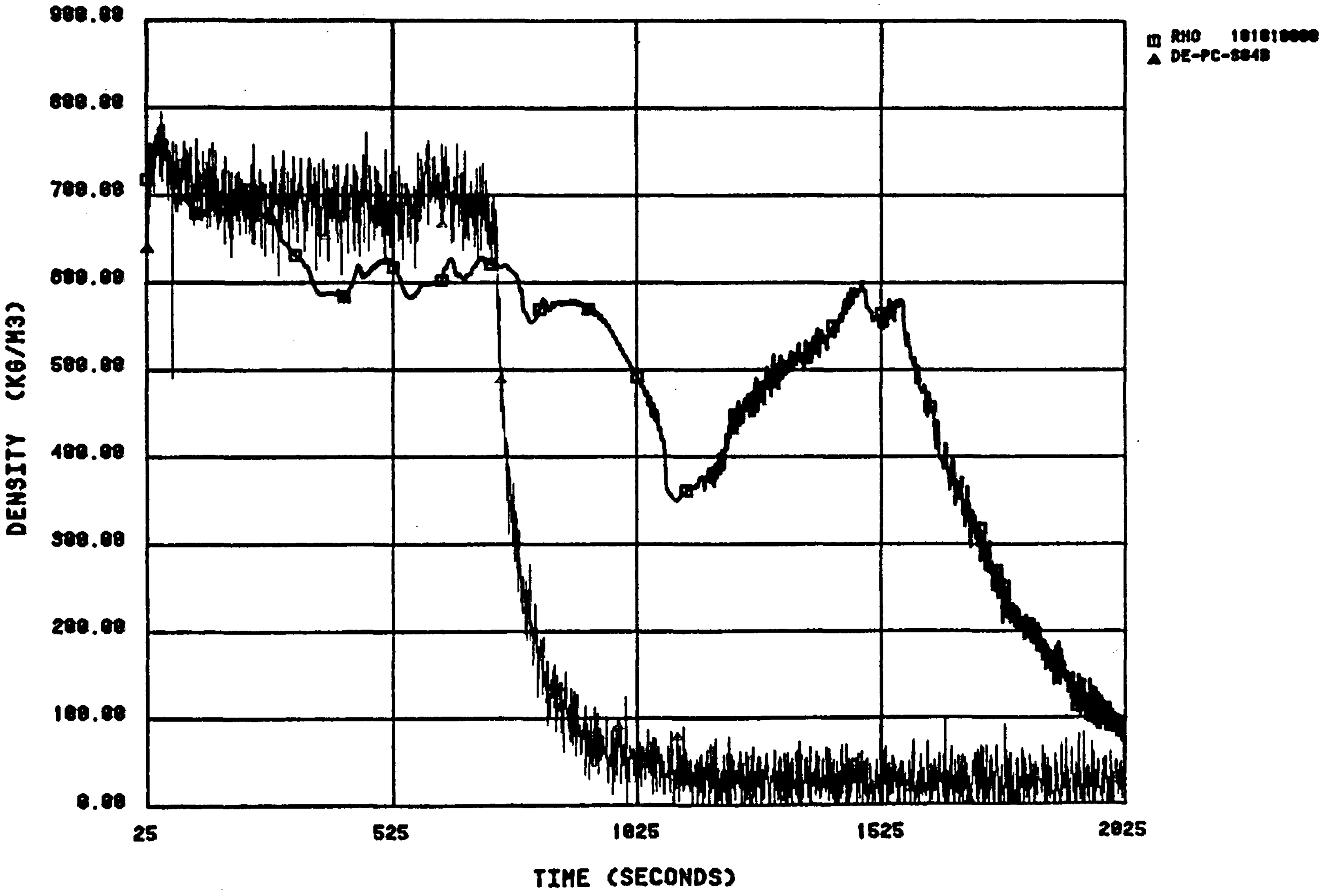
LP-SB-1. RUN A

FIG. 18



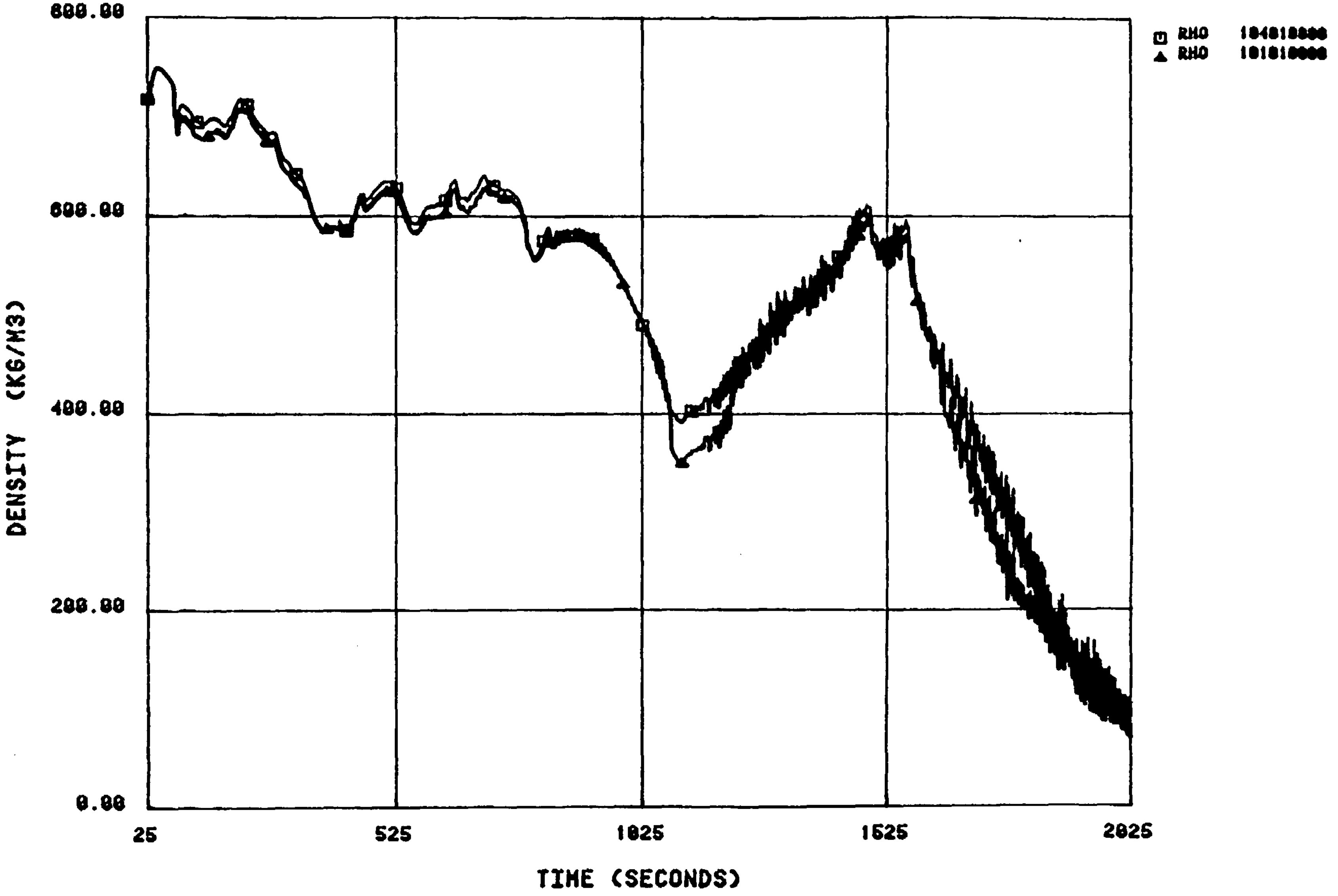
LP-SB-1. RUN A

FIG. 19



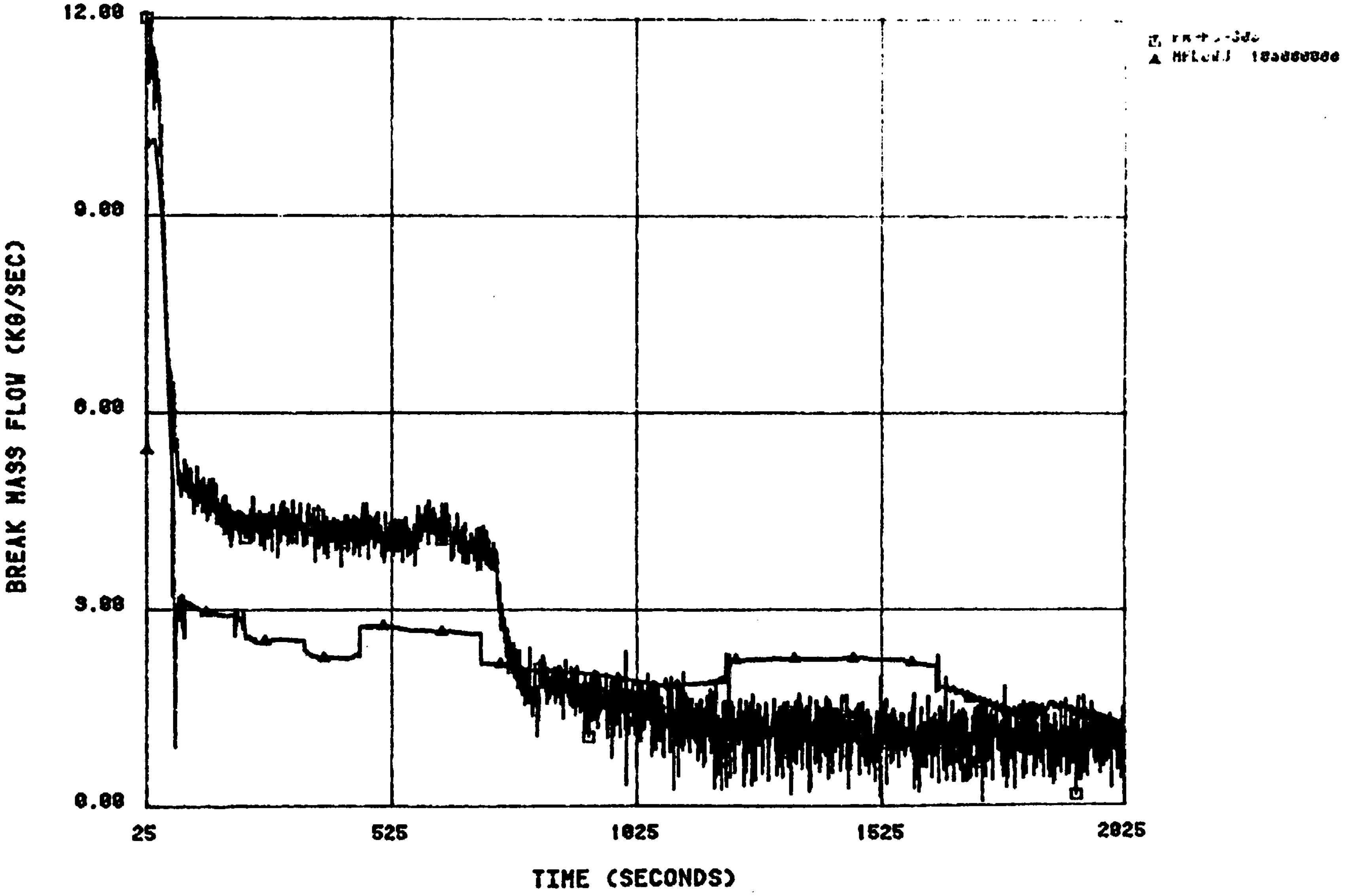
LP-SB-1. RUN A

FIG. 20



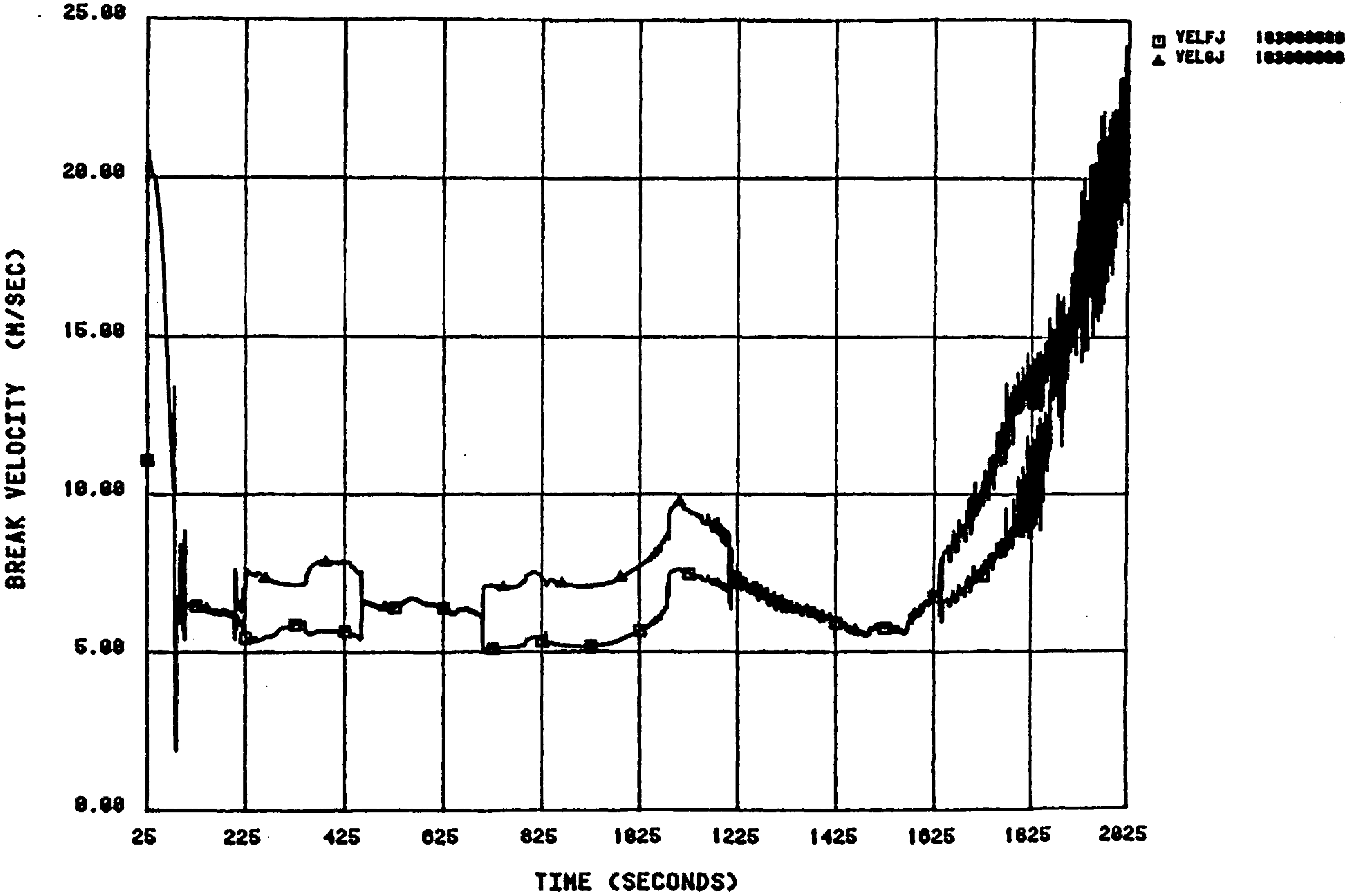
LP-SB-1. RUN A

FIG. 21



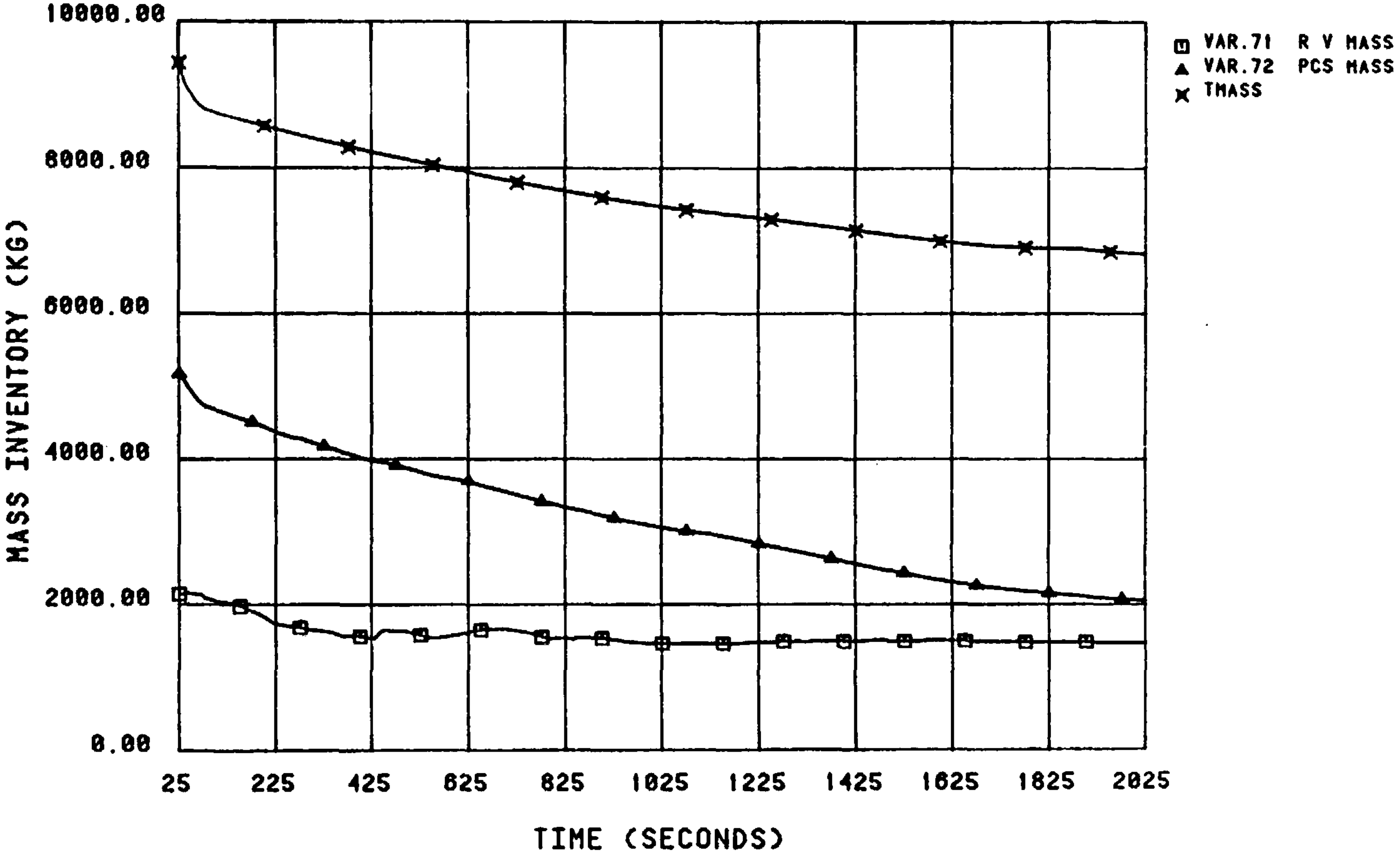
LP-SB-1. RUN A

FIG.22



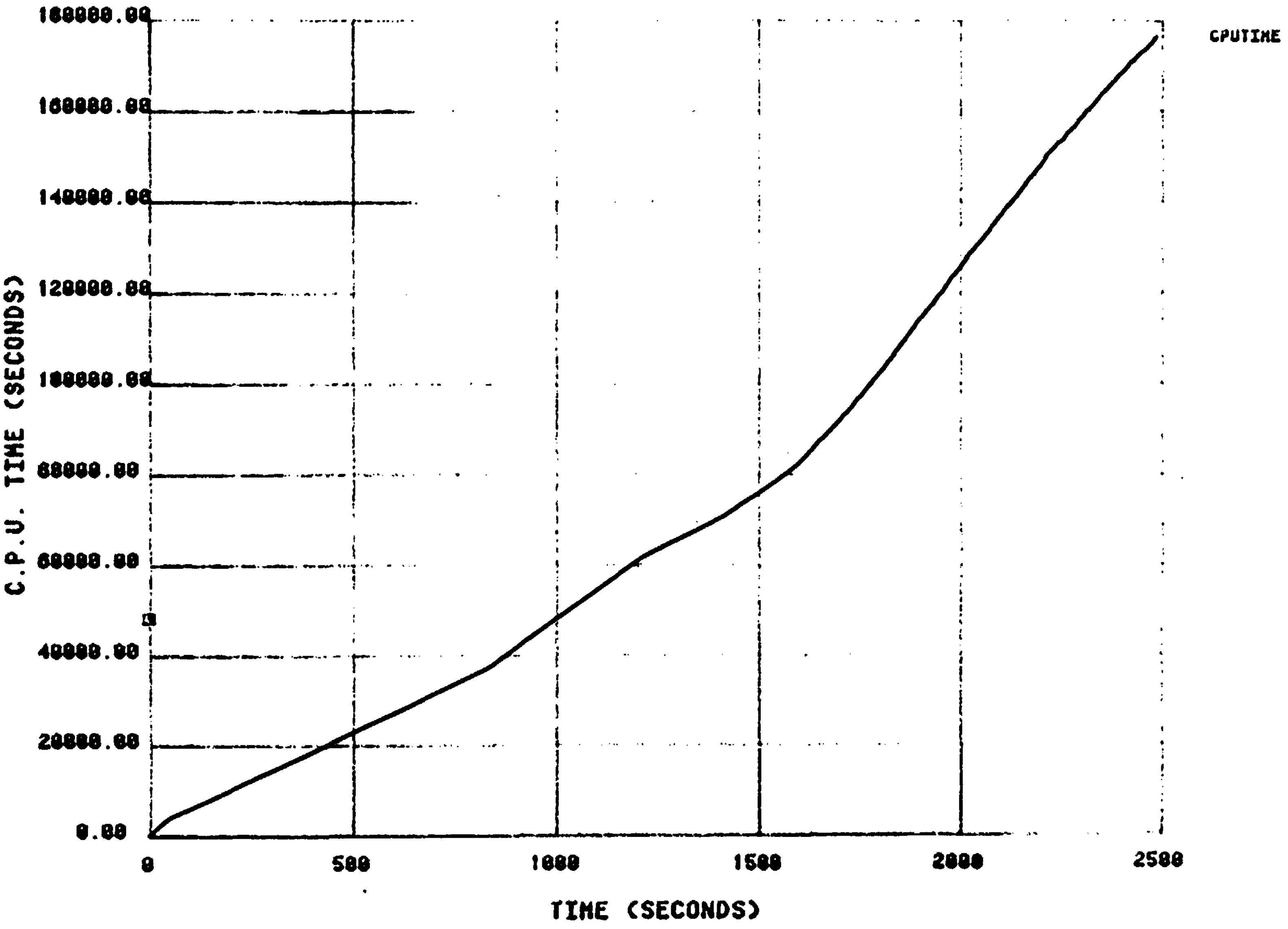
LP-SB-1. RUN A

FIG. 23



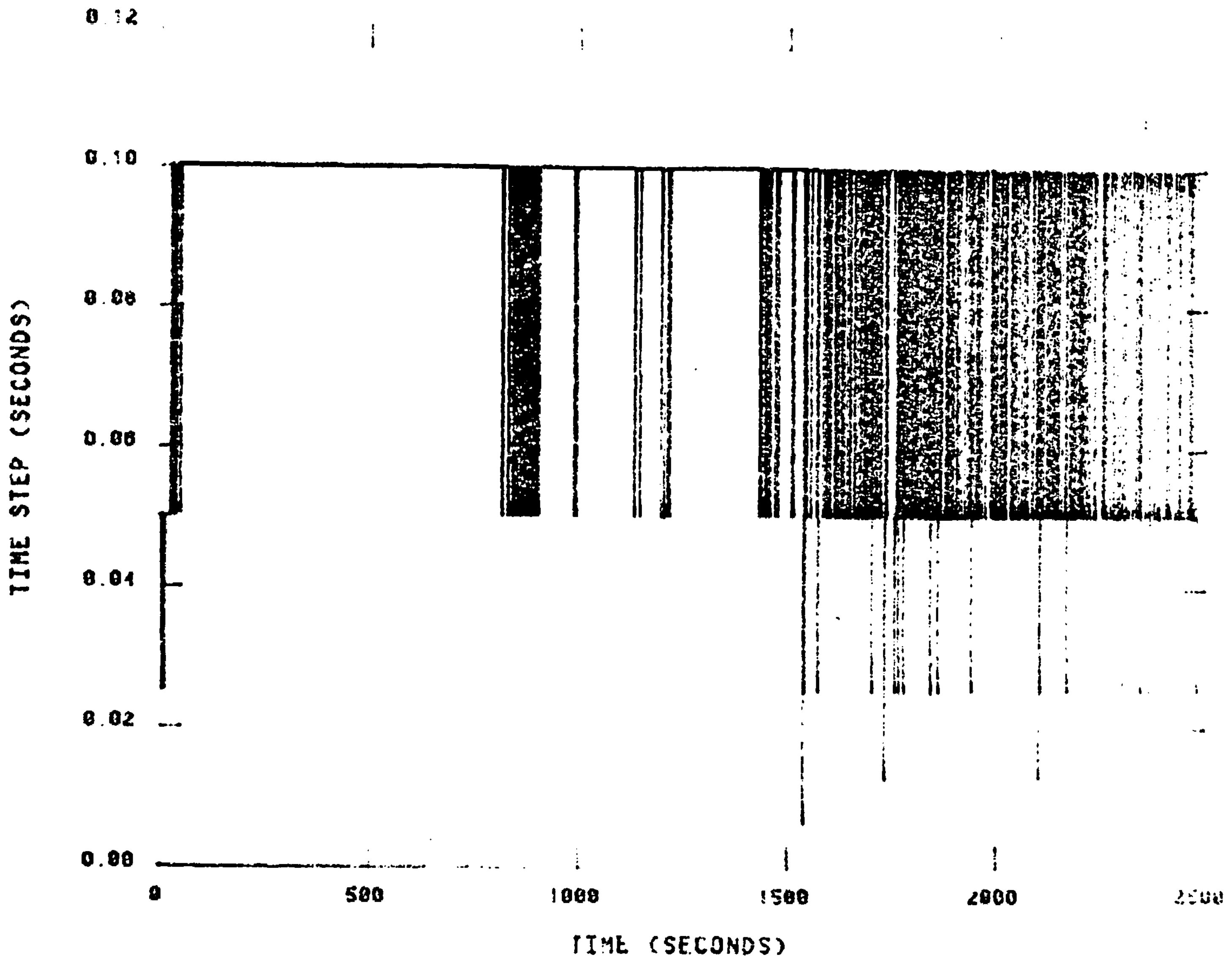
LP-SB-1. RUN A

FIG. 24



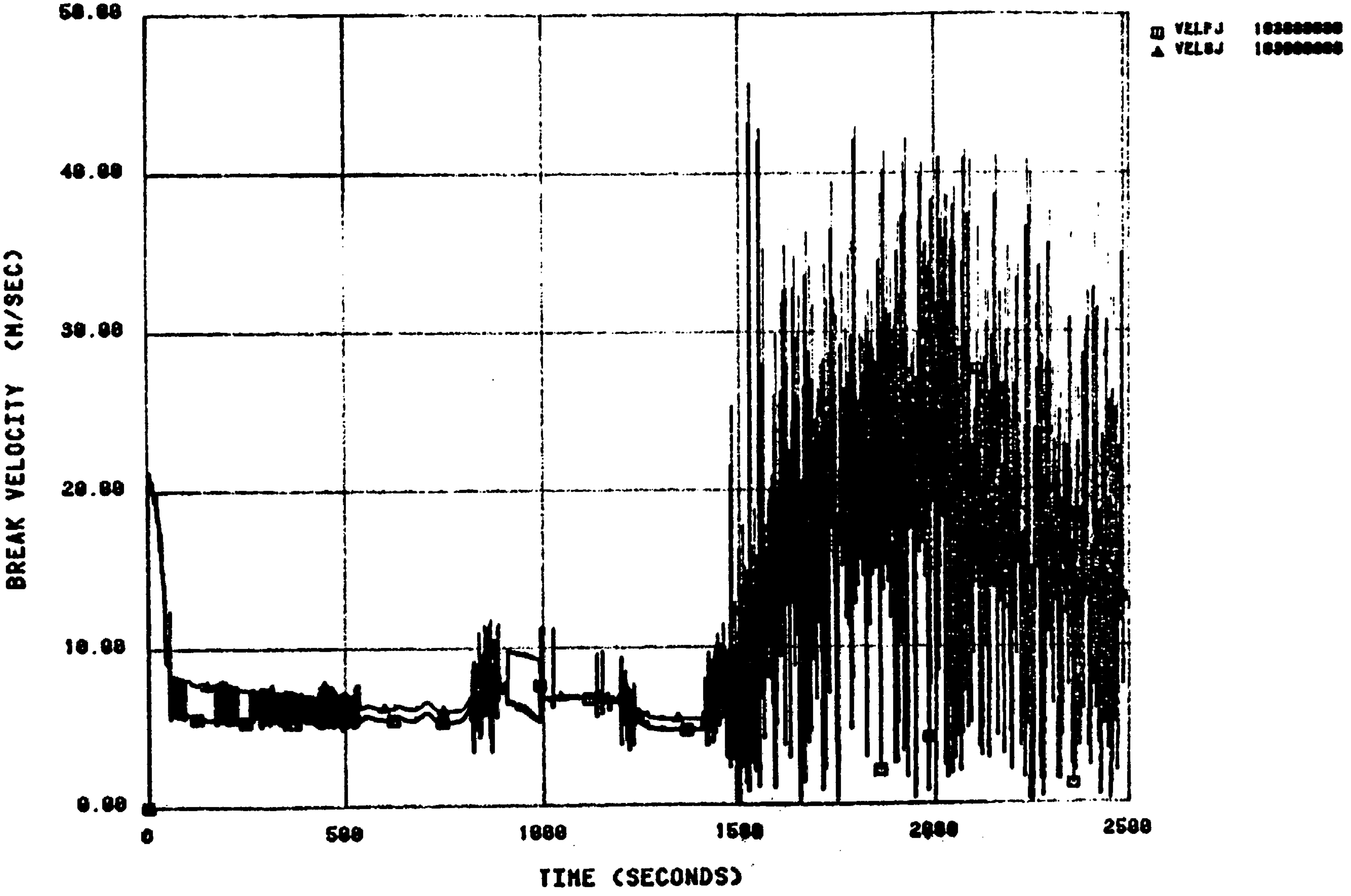
LP-SB-1. RUN B

FIG. 25



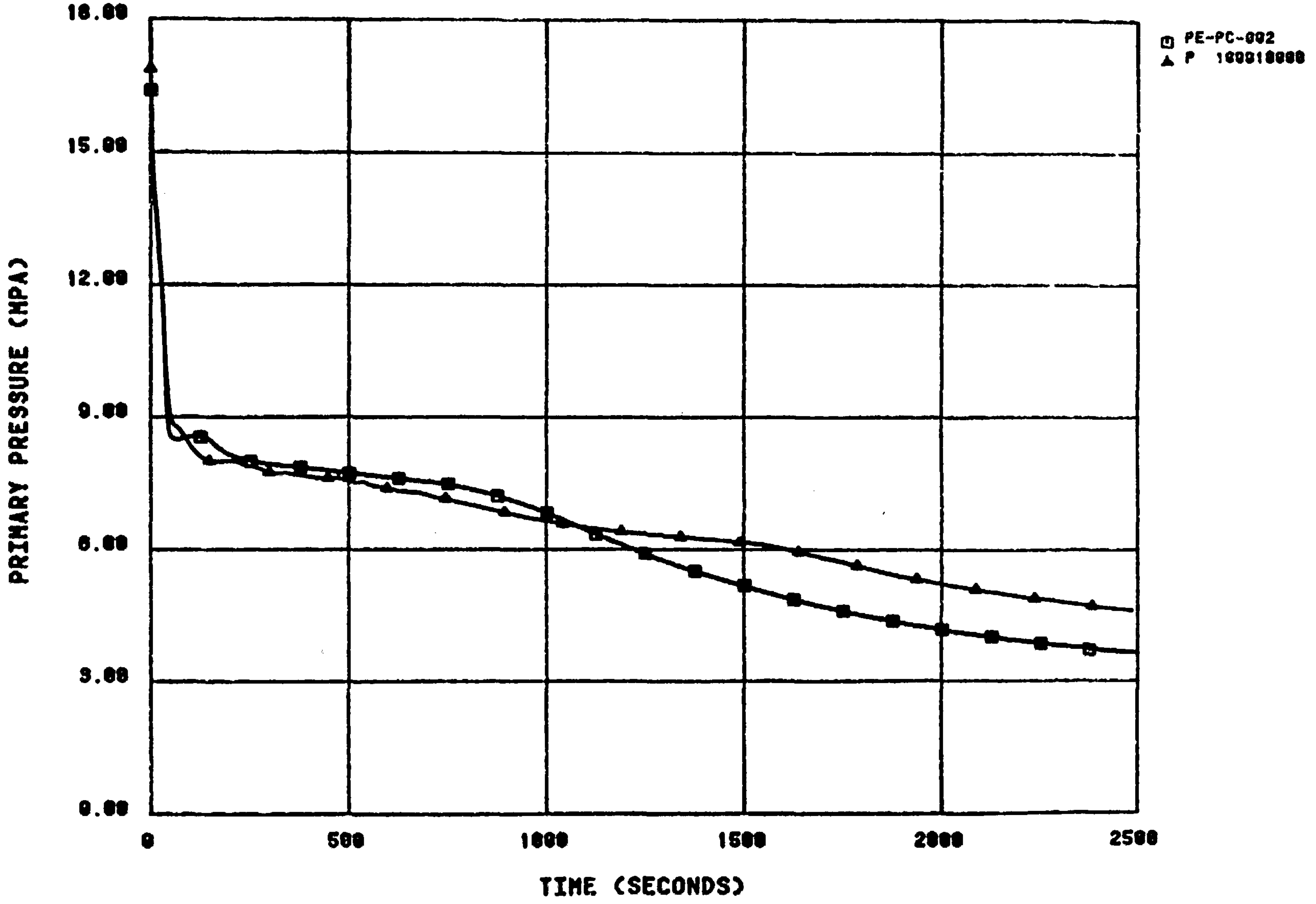
LP-SB-1 RUN B

FIG.26



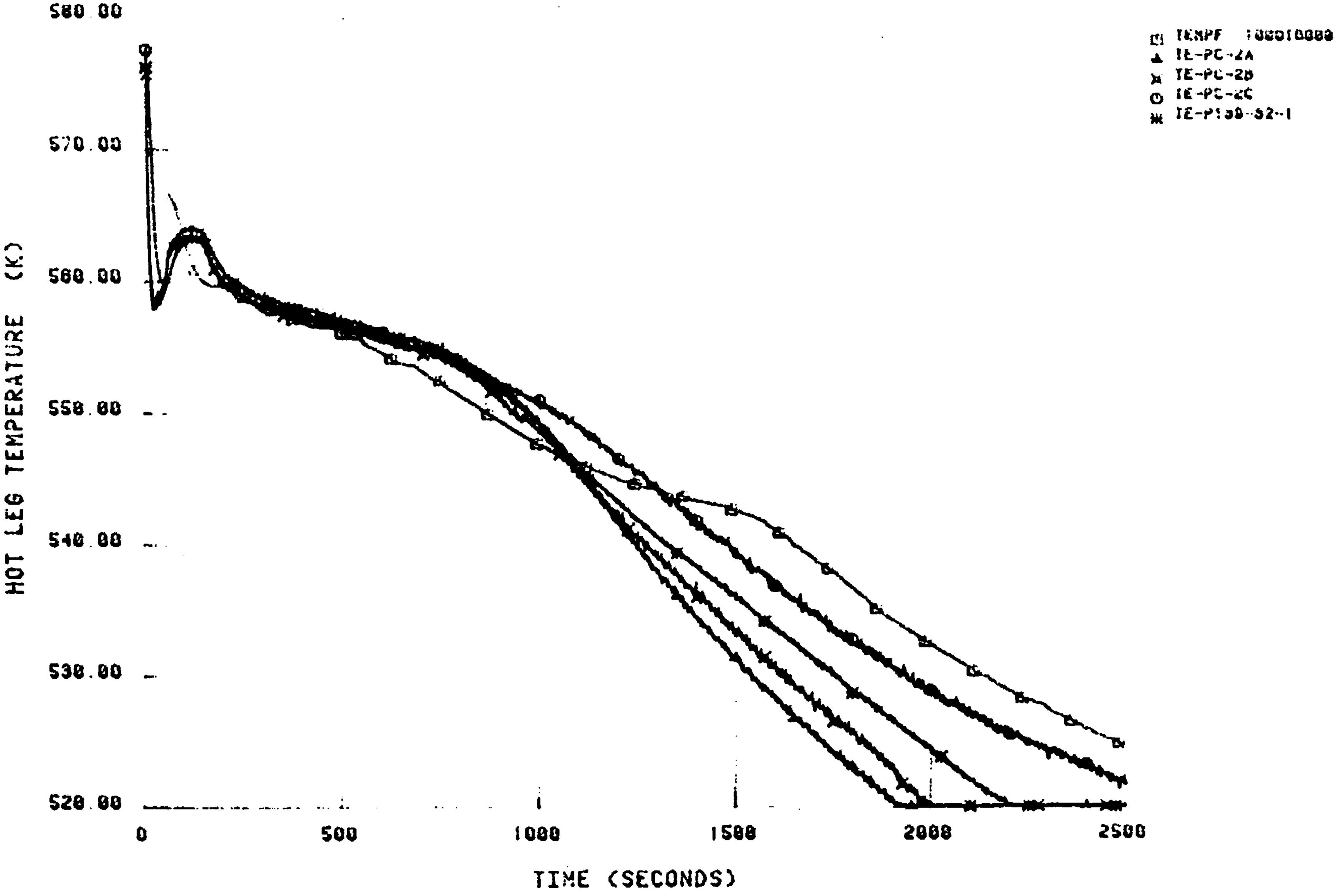
LP-SB-1. RUN B

FIG. 27



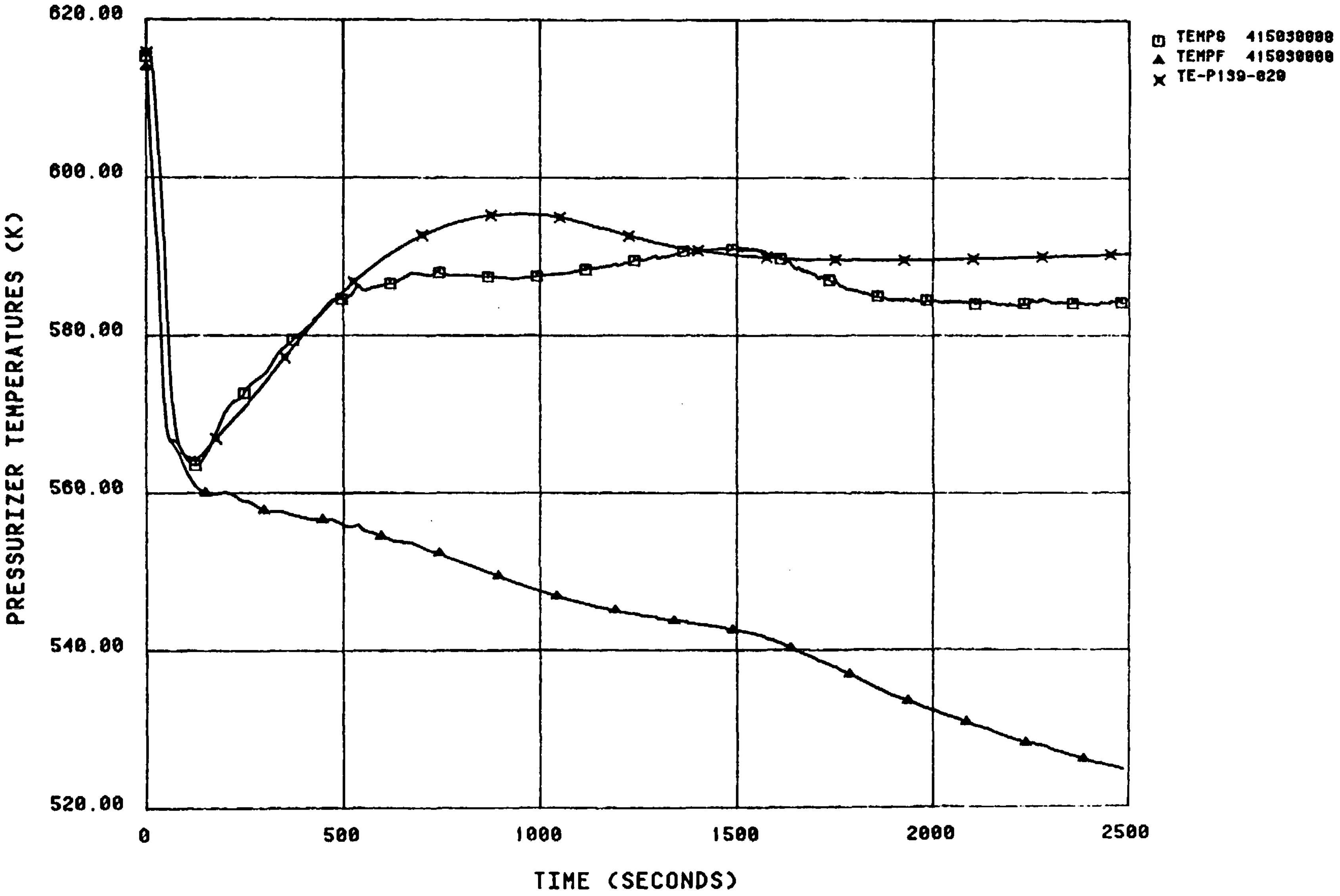
LP-SB-1. RUN B

FIG. 28



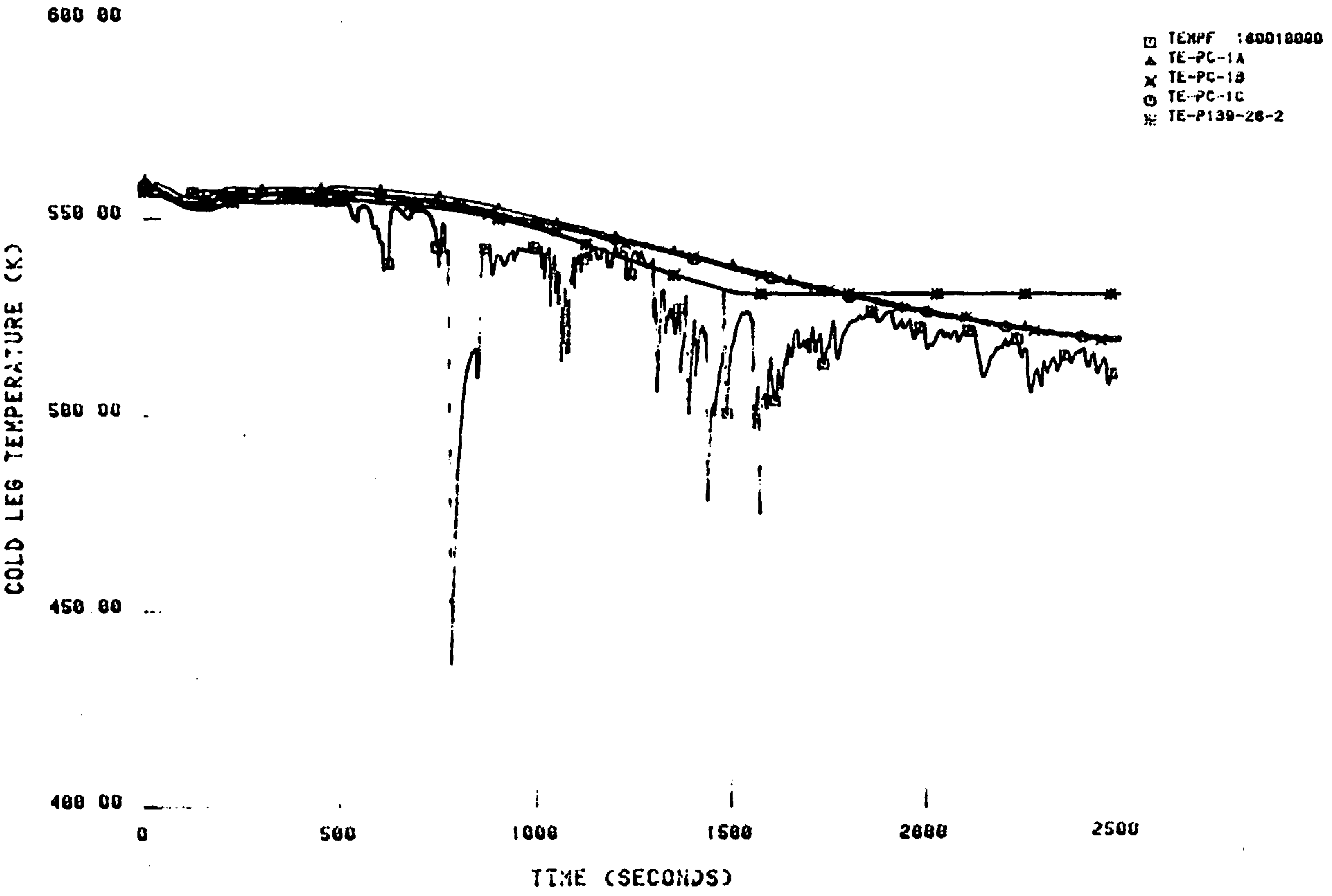
LP-SB-1. RUN B

FIG. 29



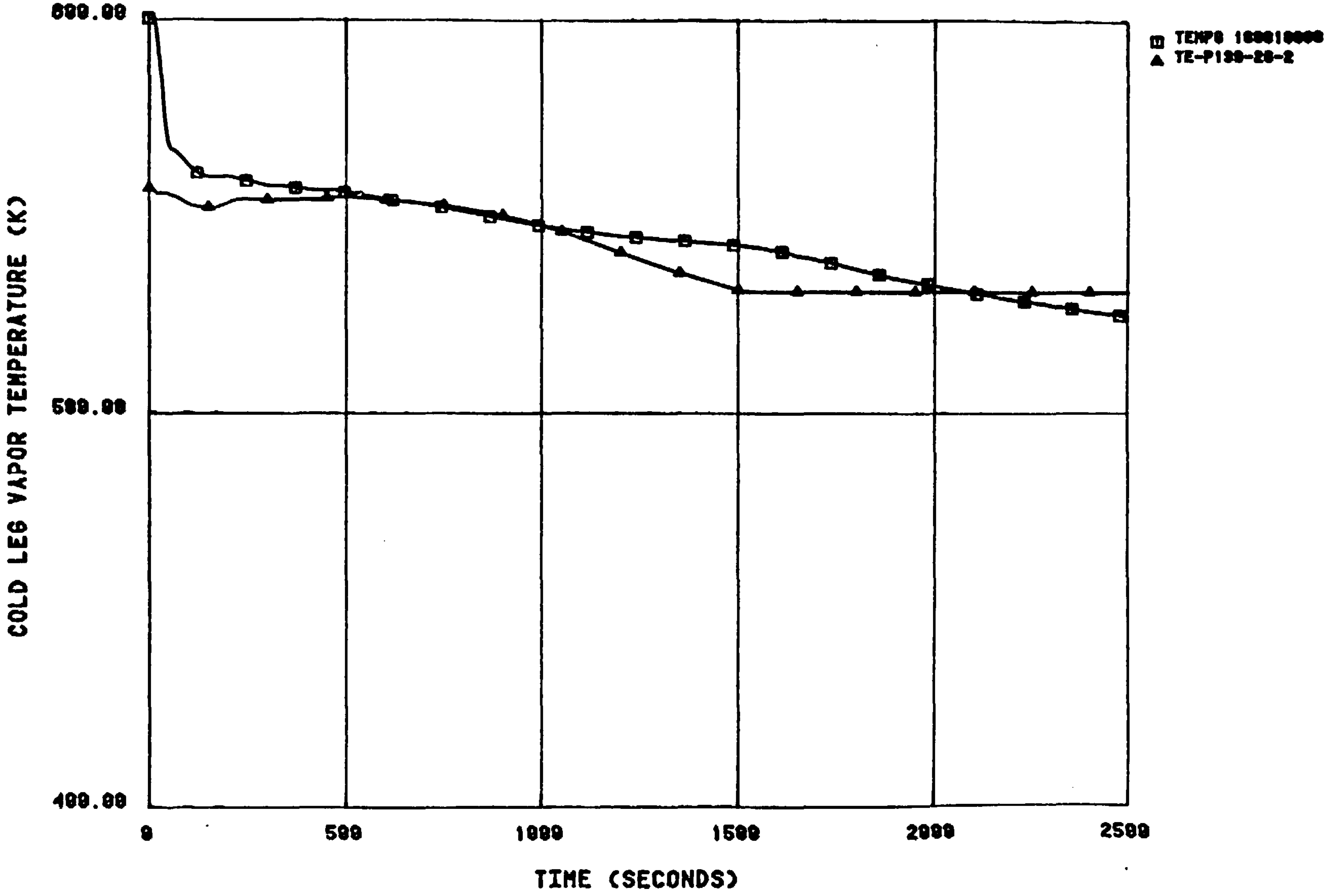
LP-SB-1. RUN B

FIG. 30



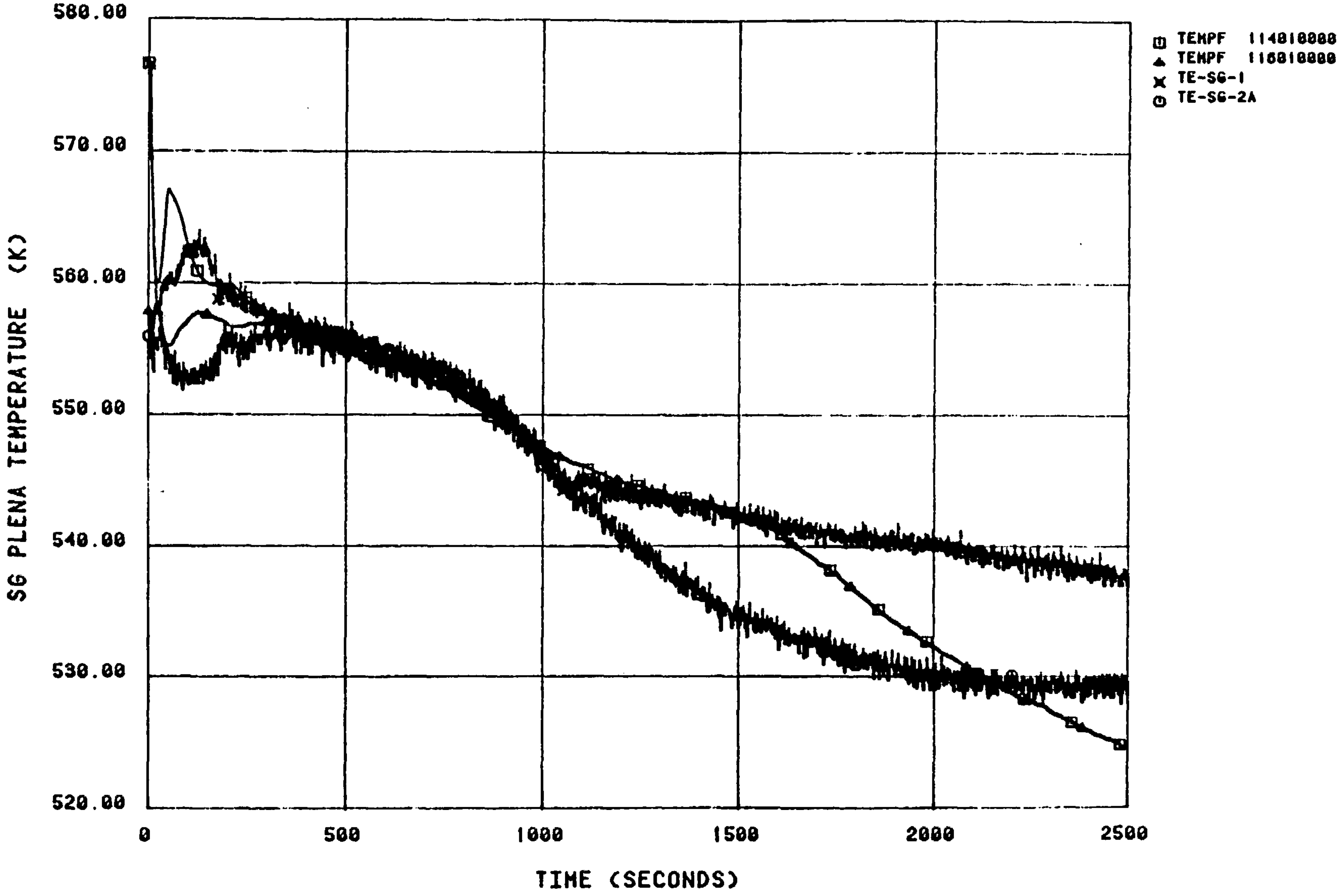
LP-SB-1, RUN B

FIG. 31



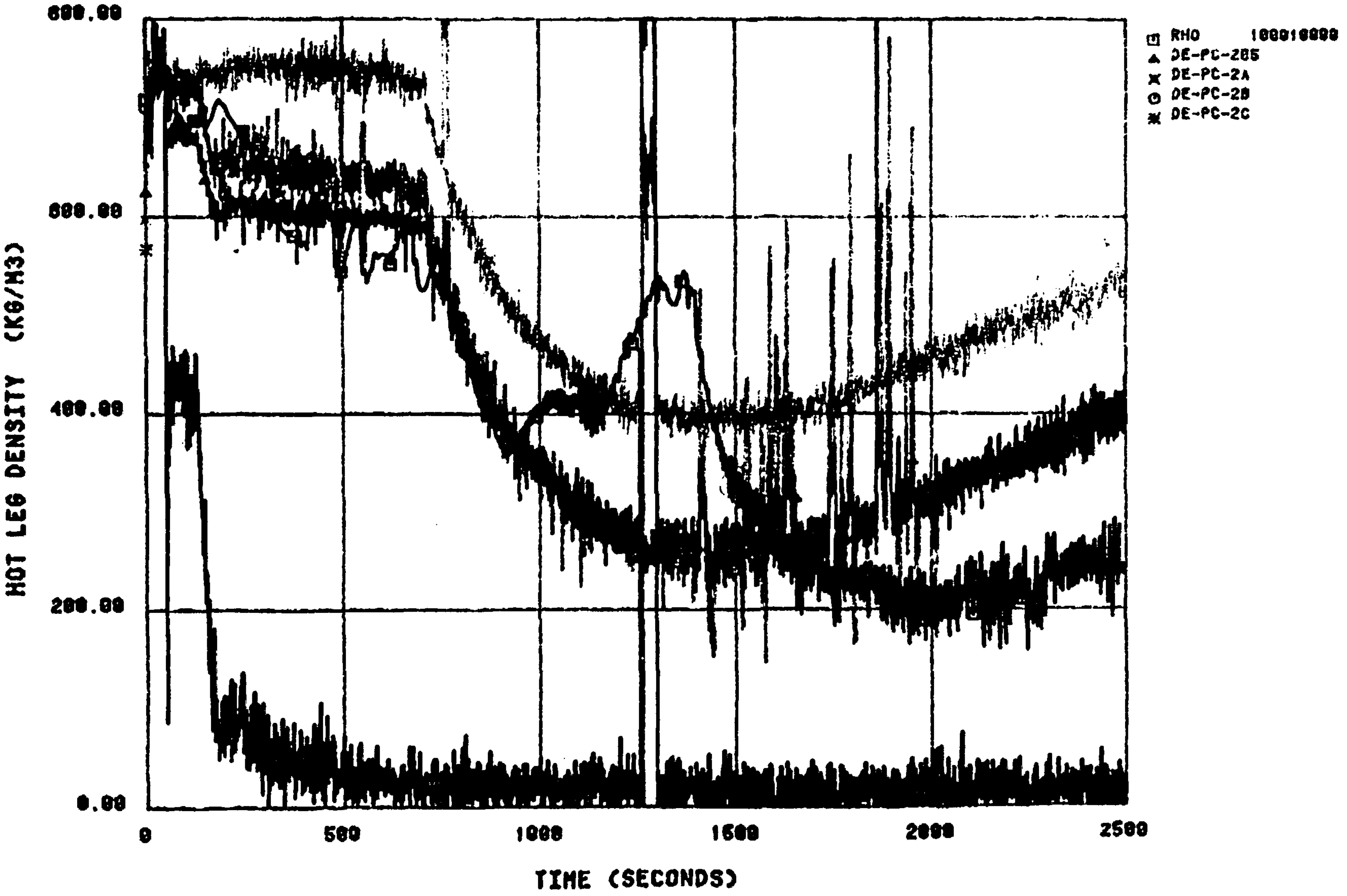
LP-SB-1. RUN B

FIG. 32



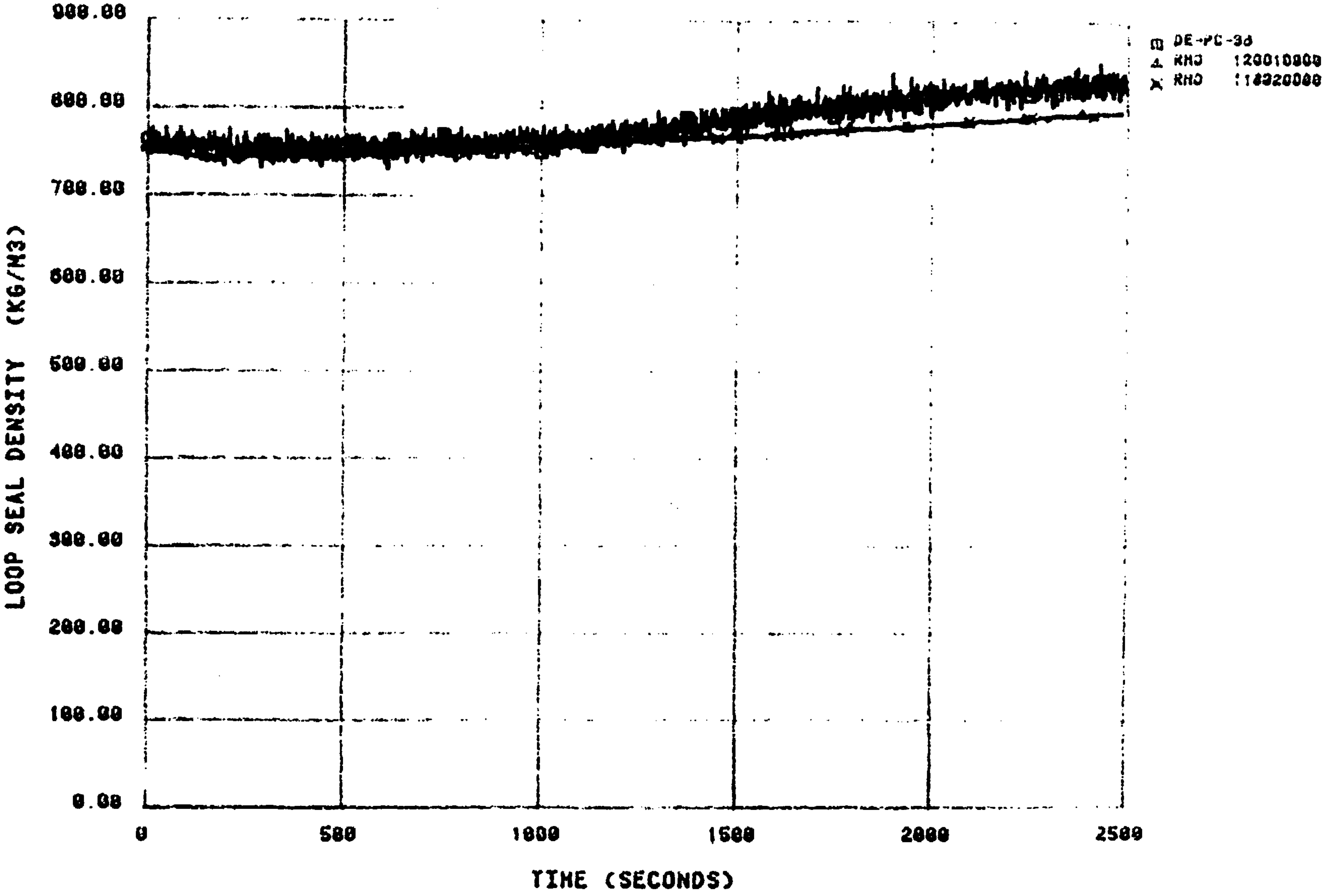
LP-SB-1. RUN B

FIG.33



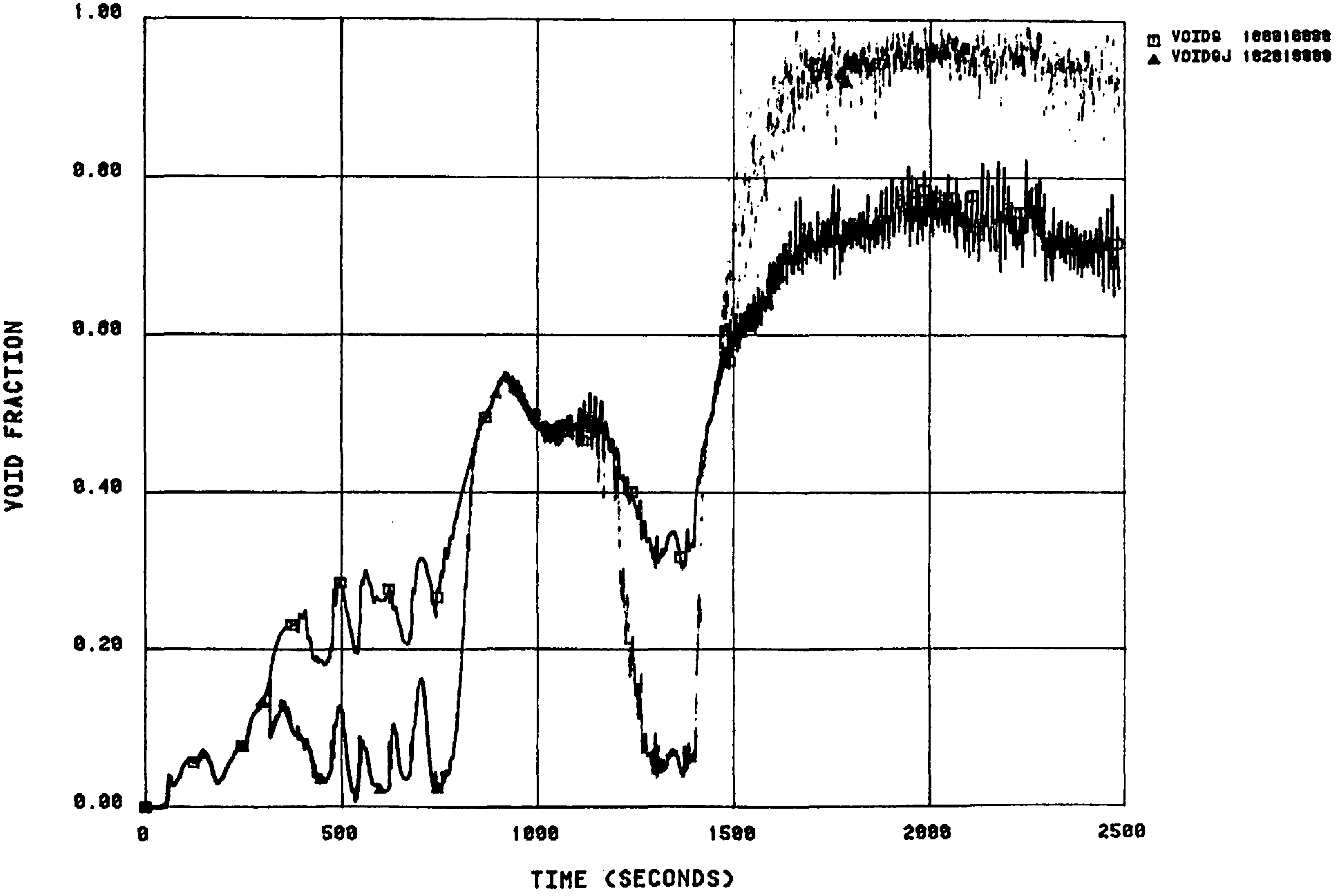
LP-SB-1. RUN B

FIG. 34



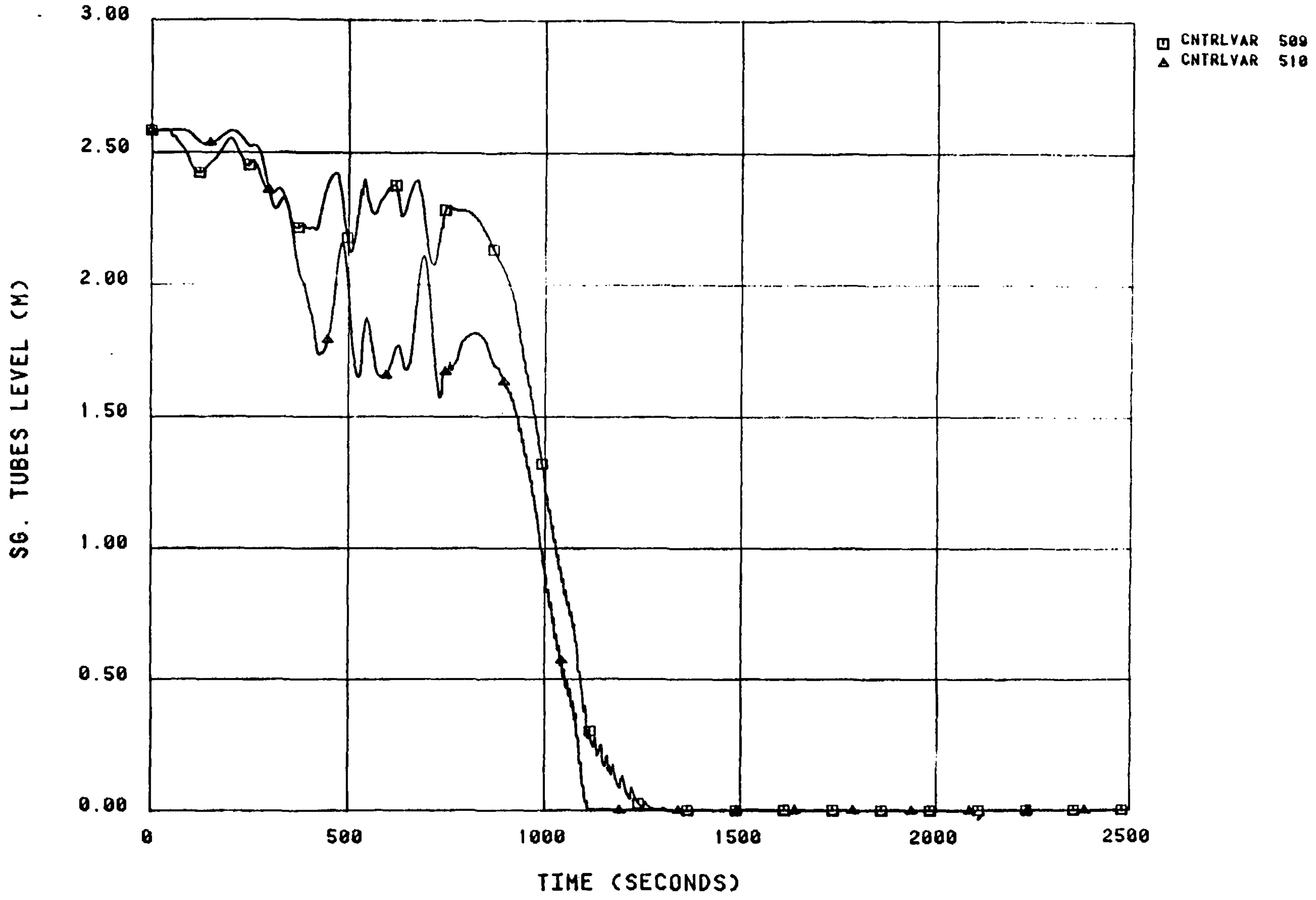
LP-SB-1. RUN B

FIG. 35



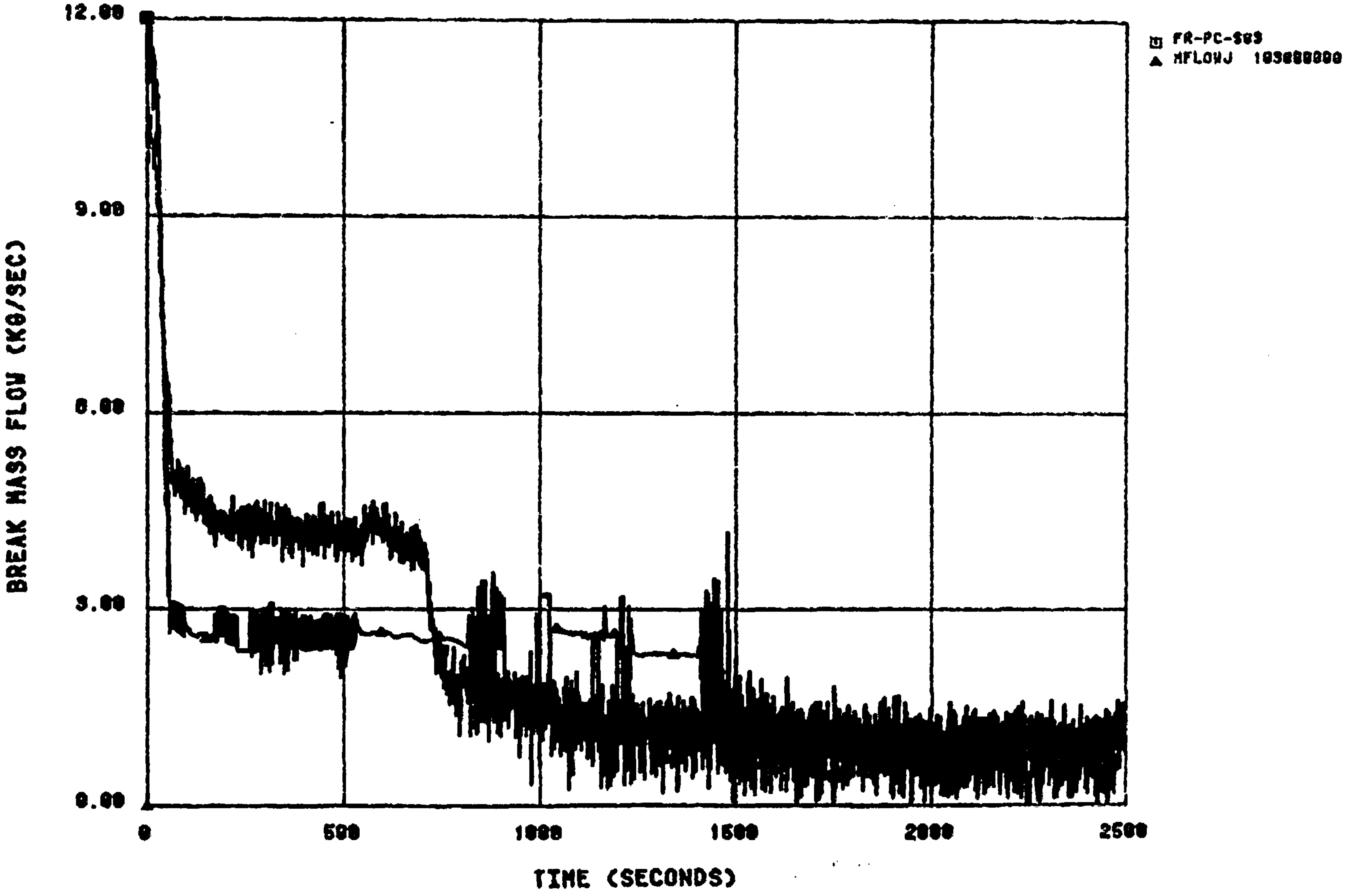
LP-SB-1. RUN B

FIG. 36



LP-SB-1. RUN B

FIG.37



LP-SB-1. RUN B

FIG.38

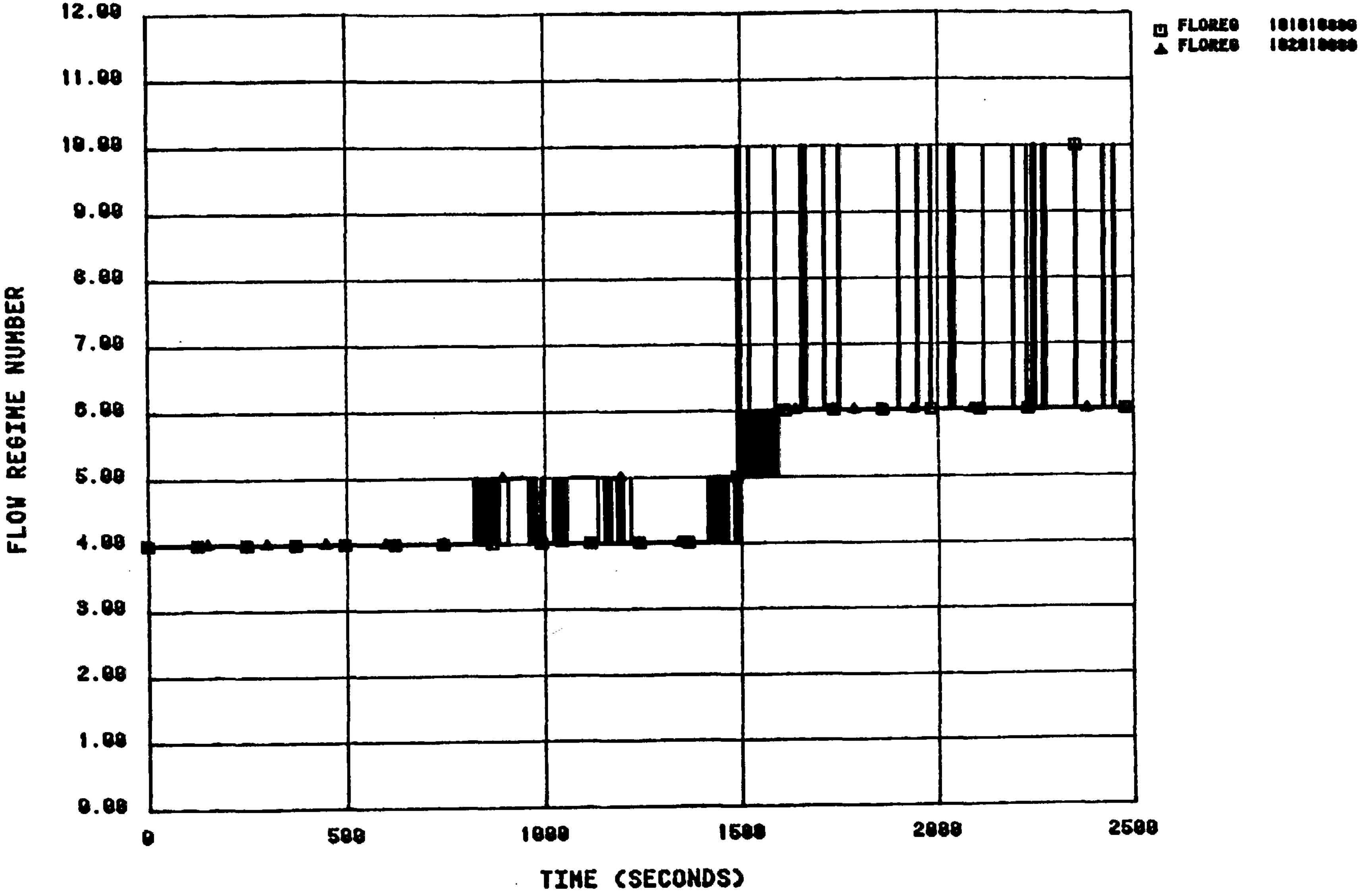


FIG. 39

LP-SB-1. RUN B

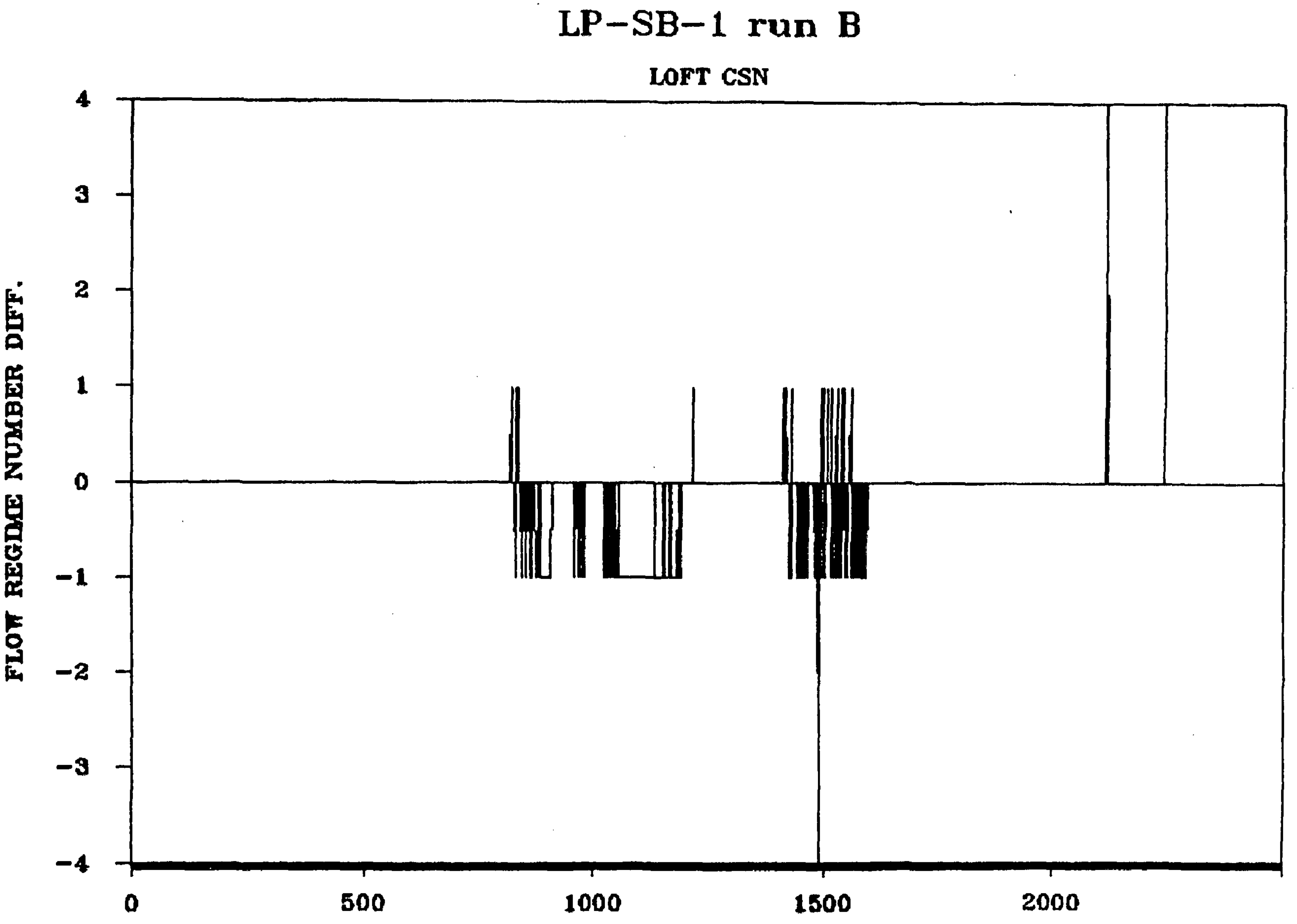
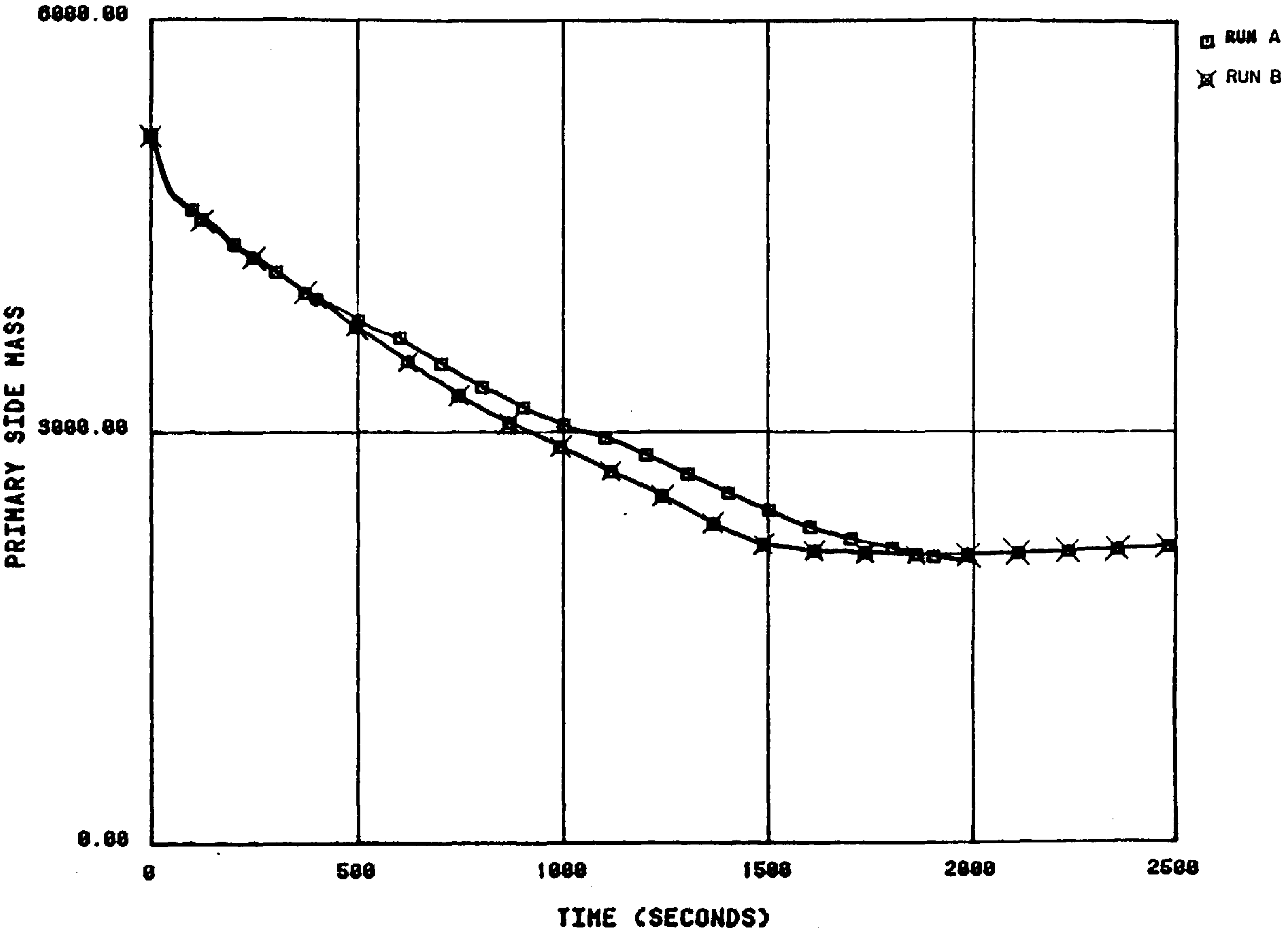
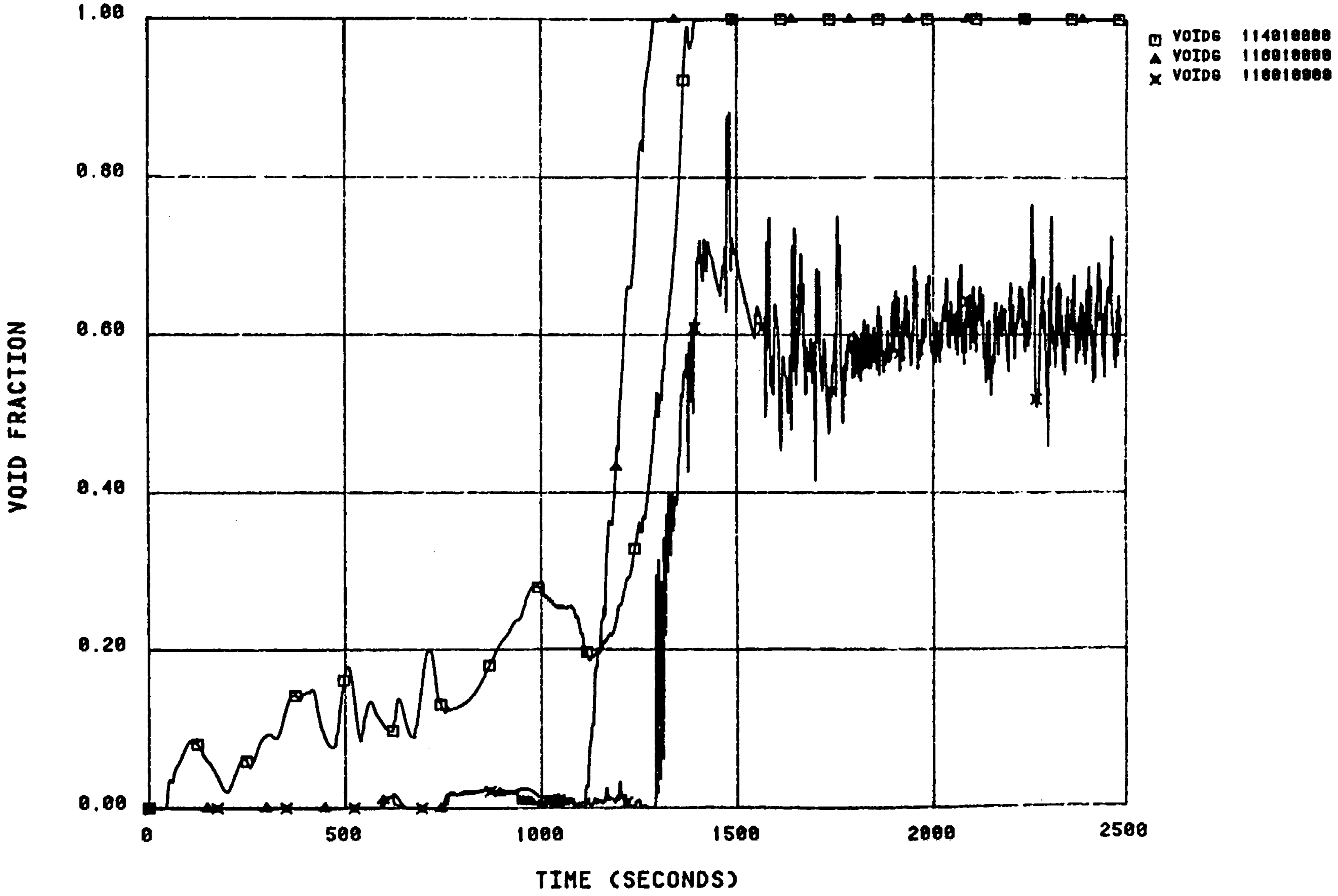

LP-SB-1 run B
LOFT CSN
FLOW REGIME NUMBER DIFF.
4
3
2
1
0
-1
-2
-3
-4
0
500
1000
1500
2000
TIME (SECONDS)

FIG. 39 (BIS)


6000.00
3000.00
0.00
PRIMARY SIDE MASS
0
500
1000
1500
2000
2500
TIME (SECONDS)
RUN A
RUN B

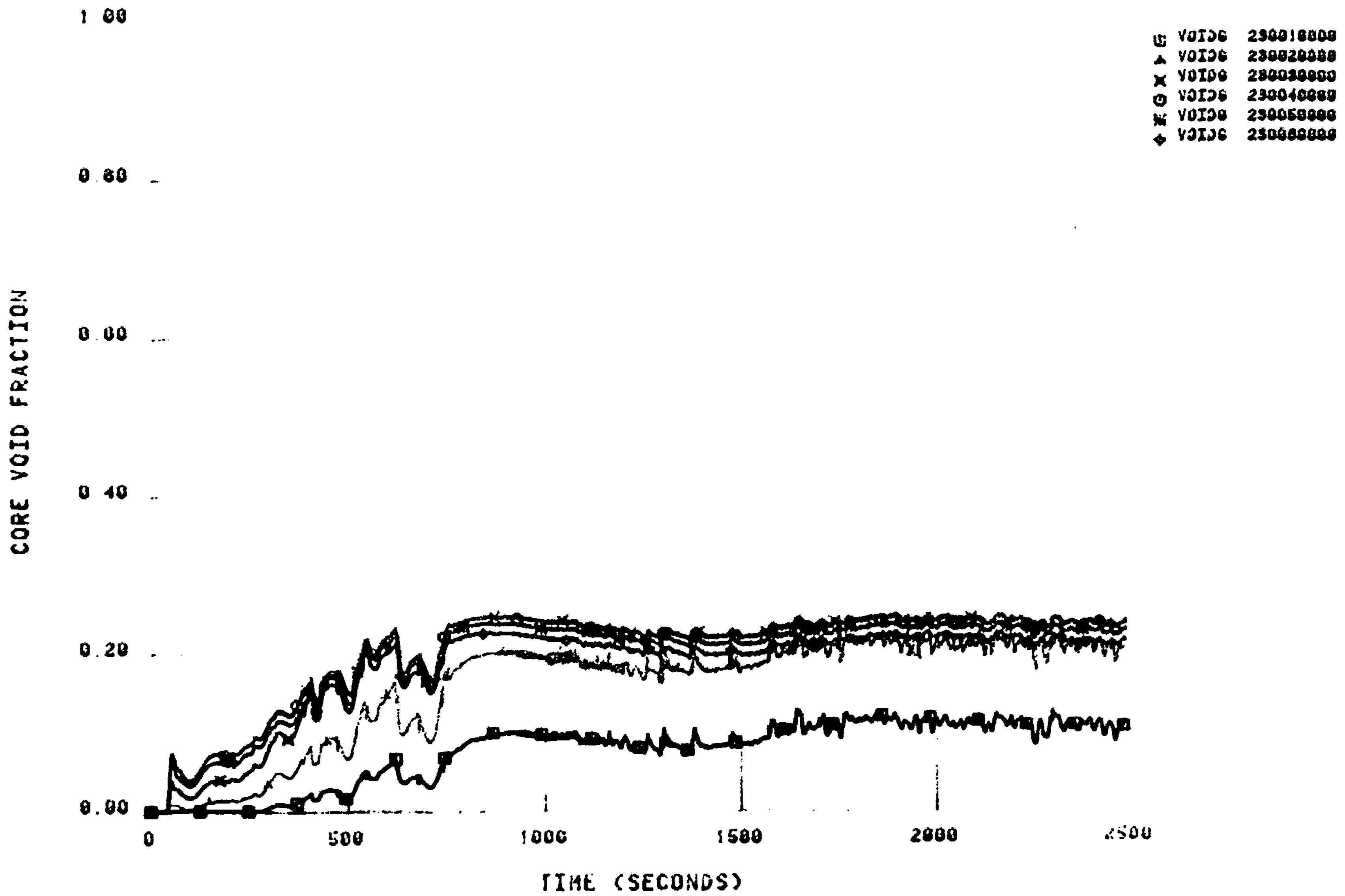
LP-SB-1.

FIG. 40



LP-SB-1. RUN B

FIG. 41



LP-SB-1 RUN B

FIG. 42

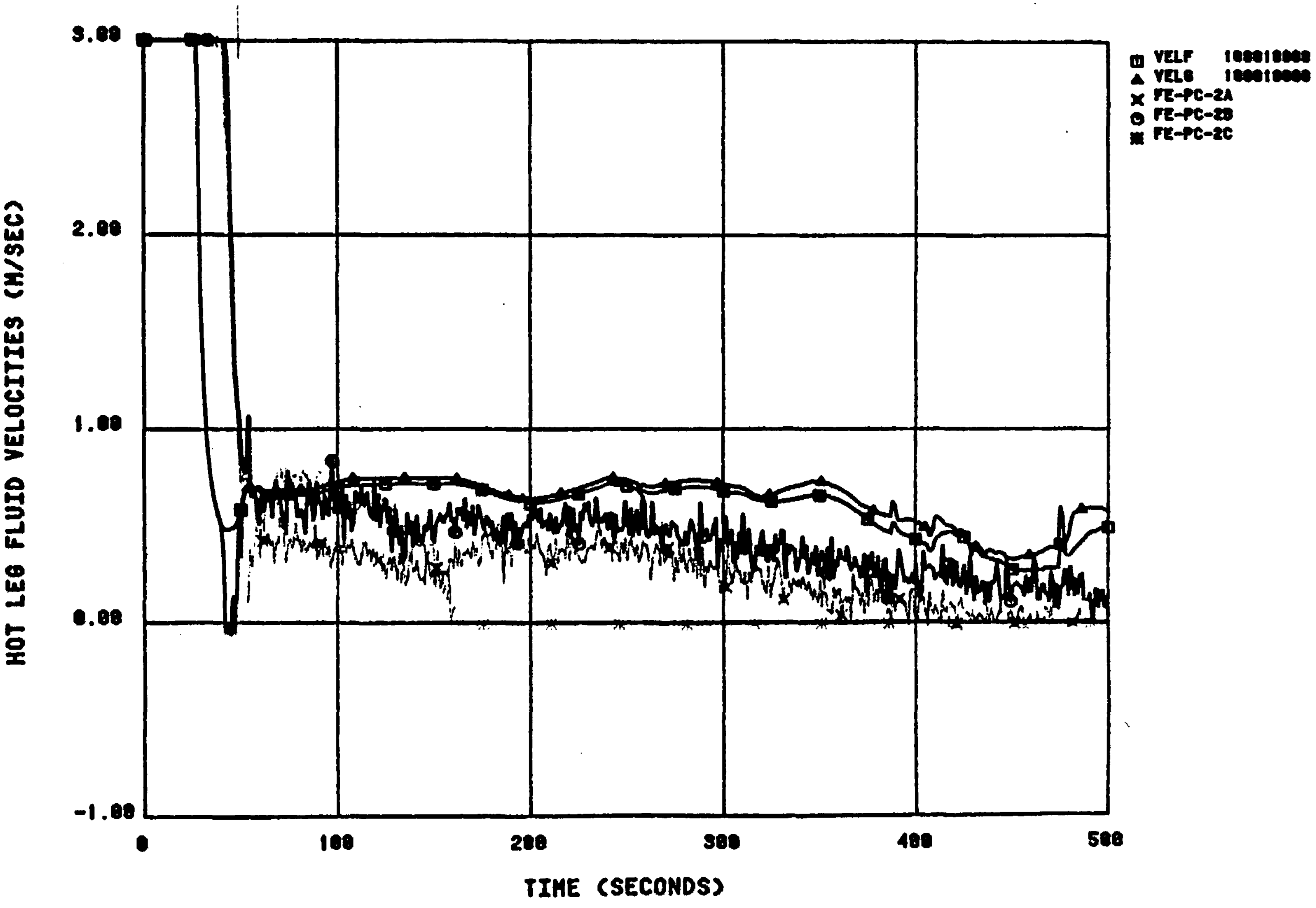


FIG.43

LP-SB-1. RUN B

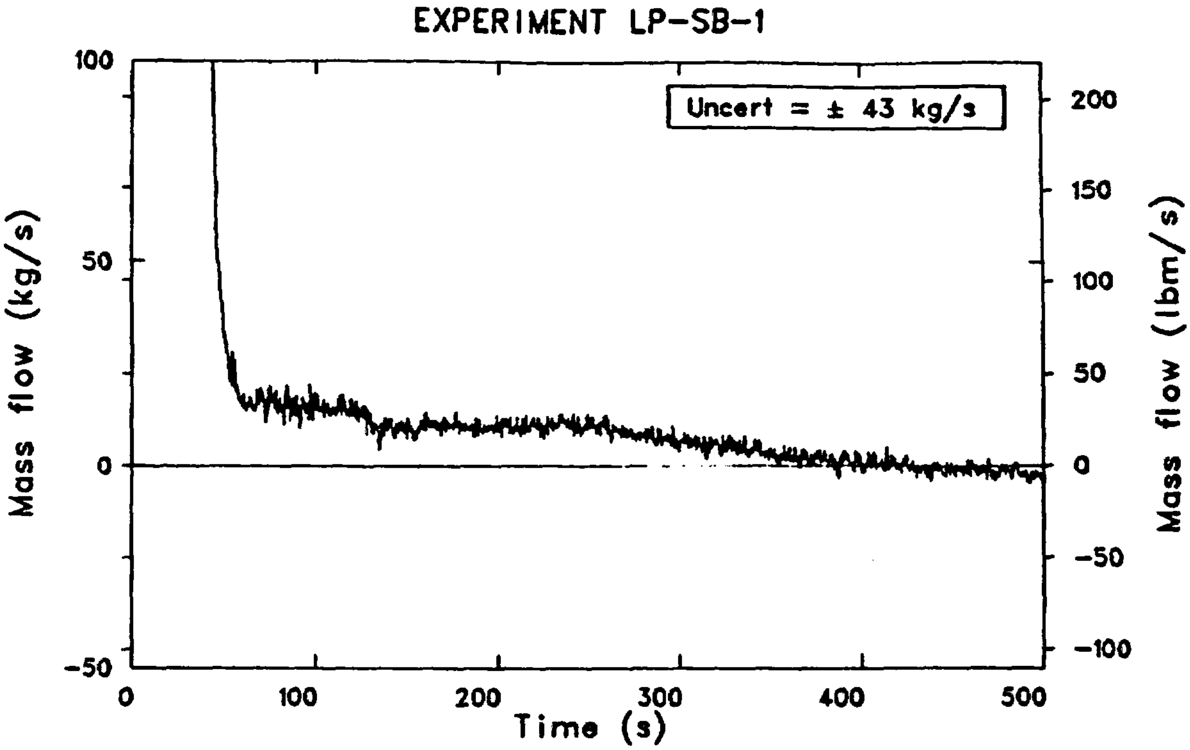
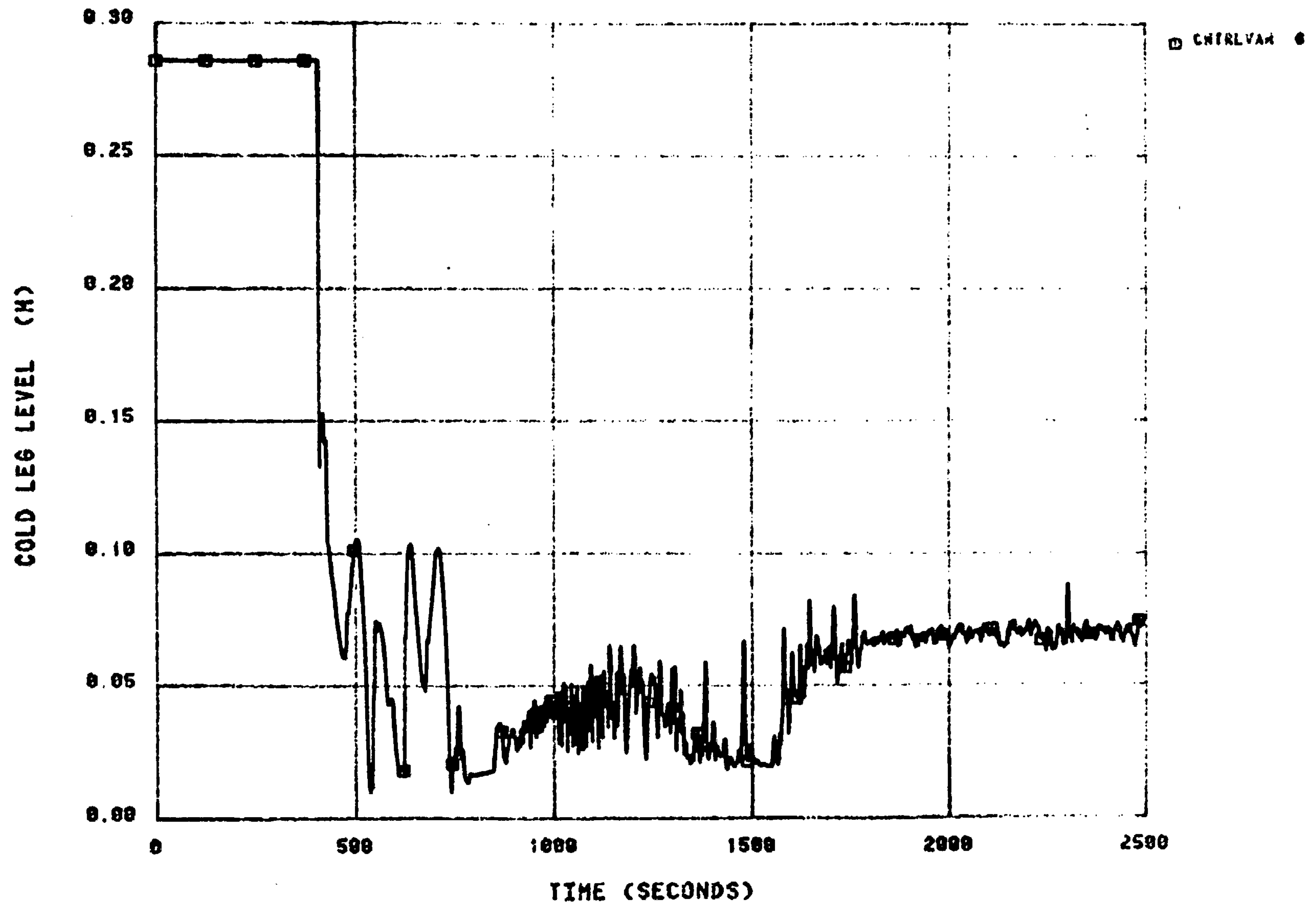
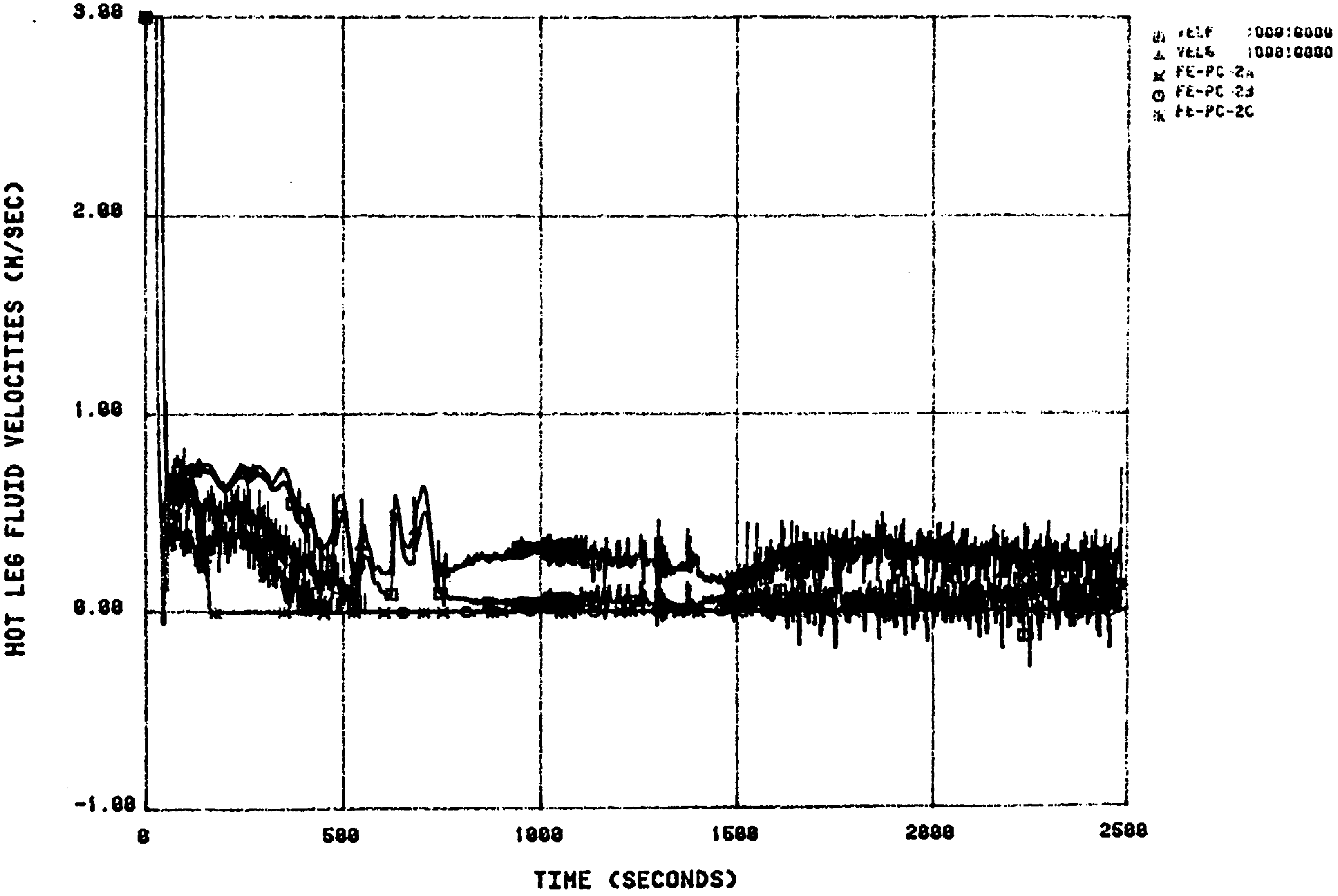

EXPERIMENT LP-SB-1
Uncert = ± 43 kg/s
Mass flow (kg/s)
100
50
0
-50
Mass flow (lbm/s)
200
150
100
50
0
-50
-100
Time (s)
0
100
200
300
400
500

FIG. 44



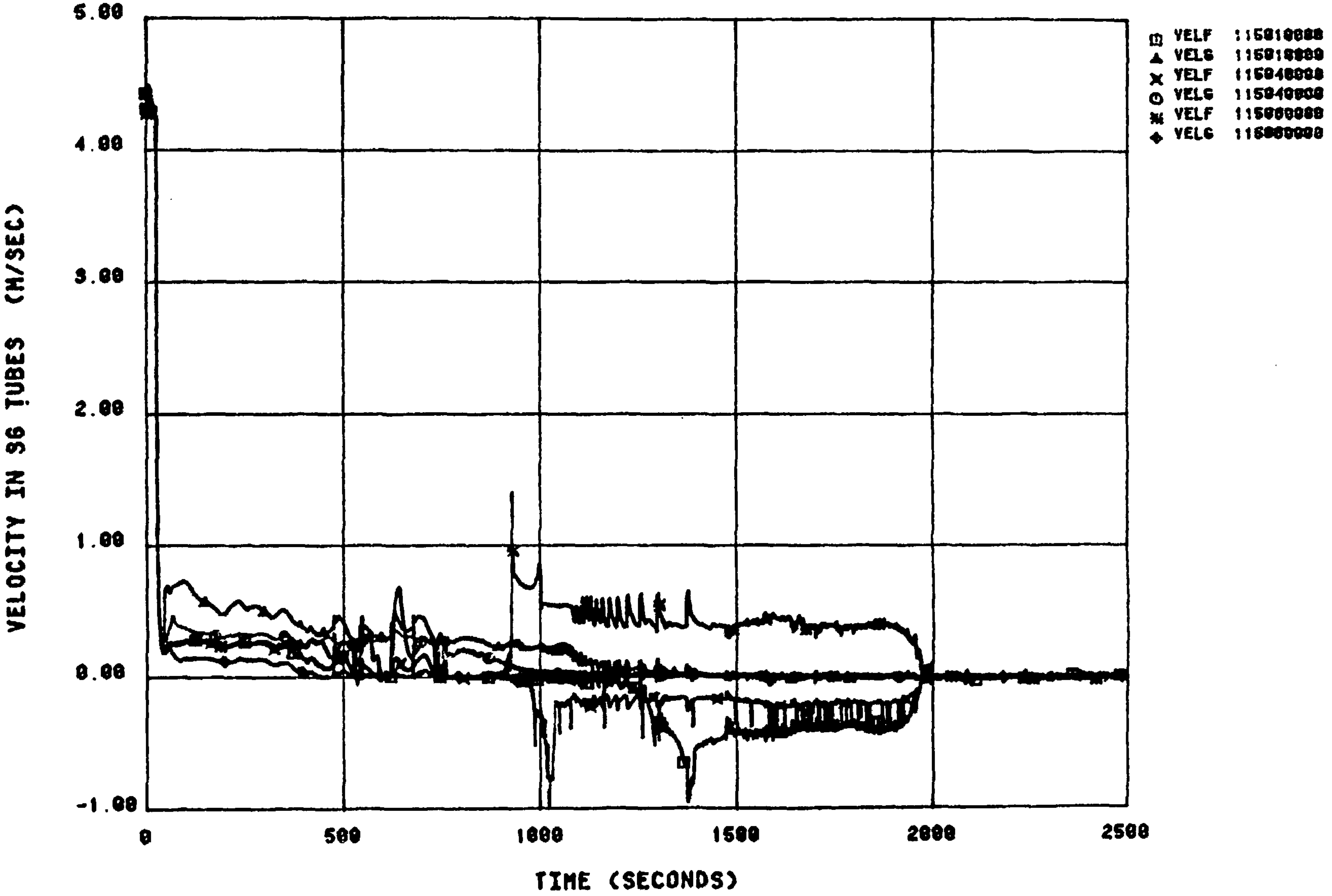
LP-SB-1. RUN B

FIG.45



LP-SB-1. RUN B

FIG.46



LP-SB-1. RUN B

FIG. 47

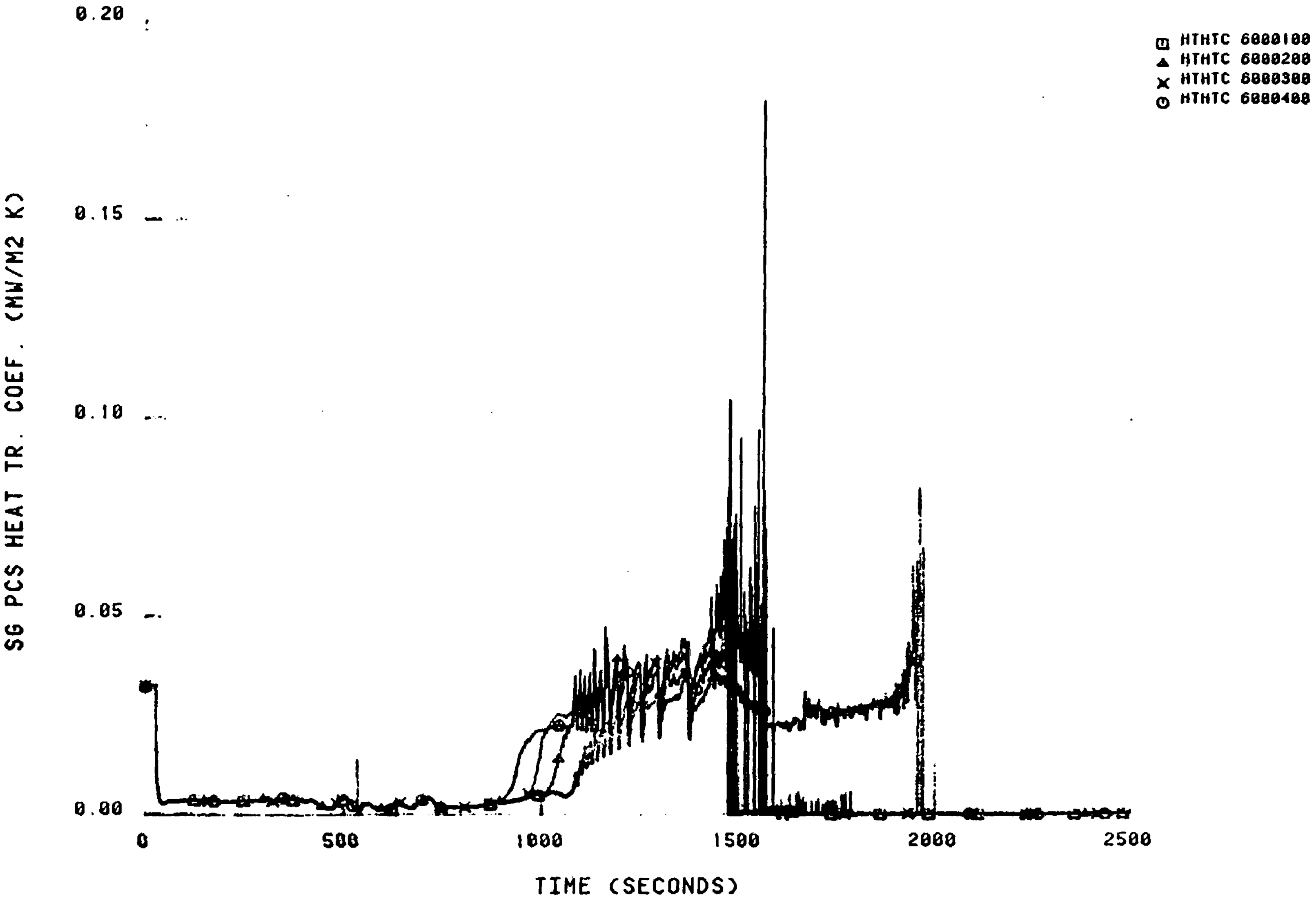


FIG.48

LP-SB-1. RUN B

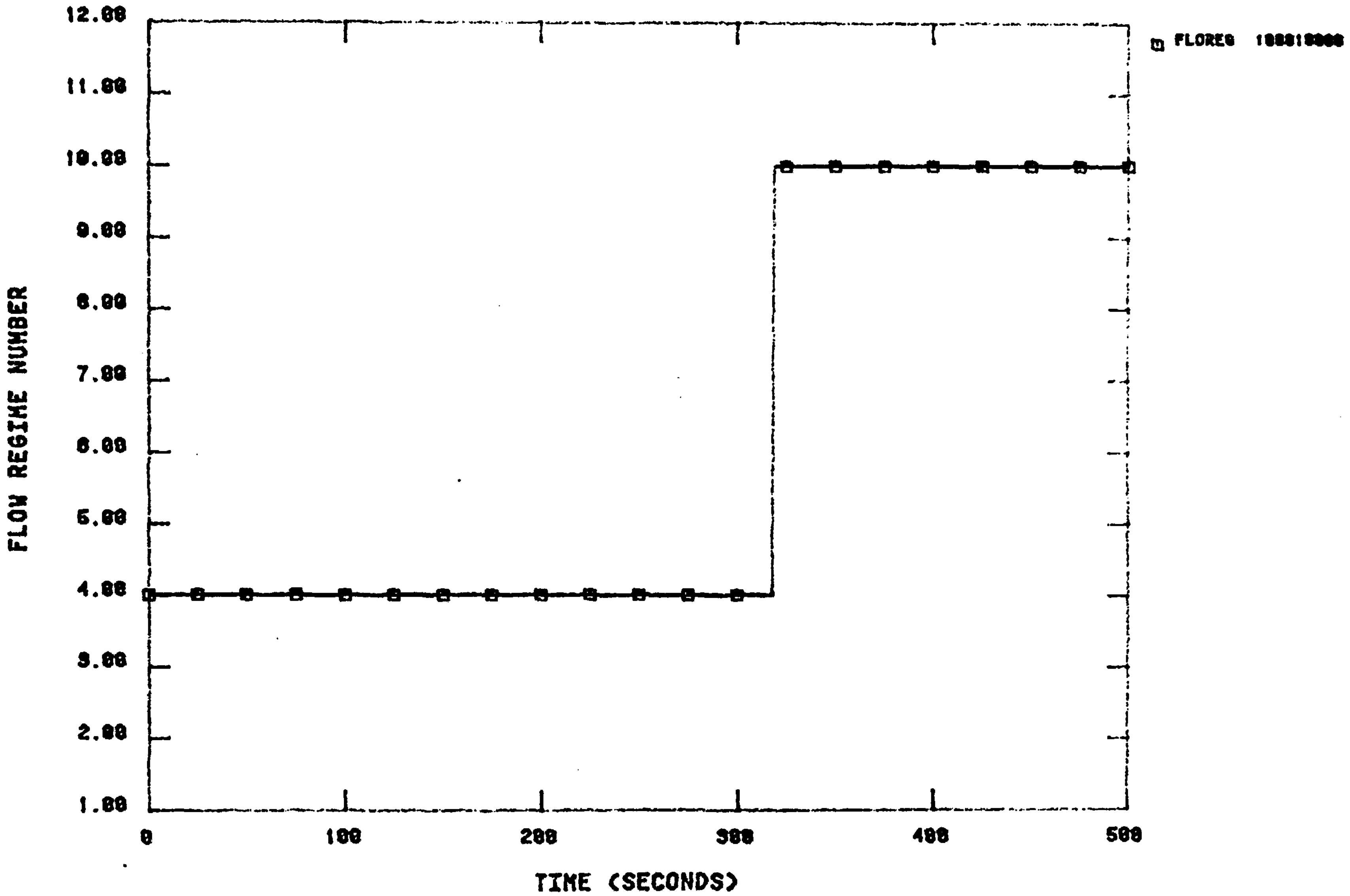
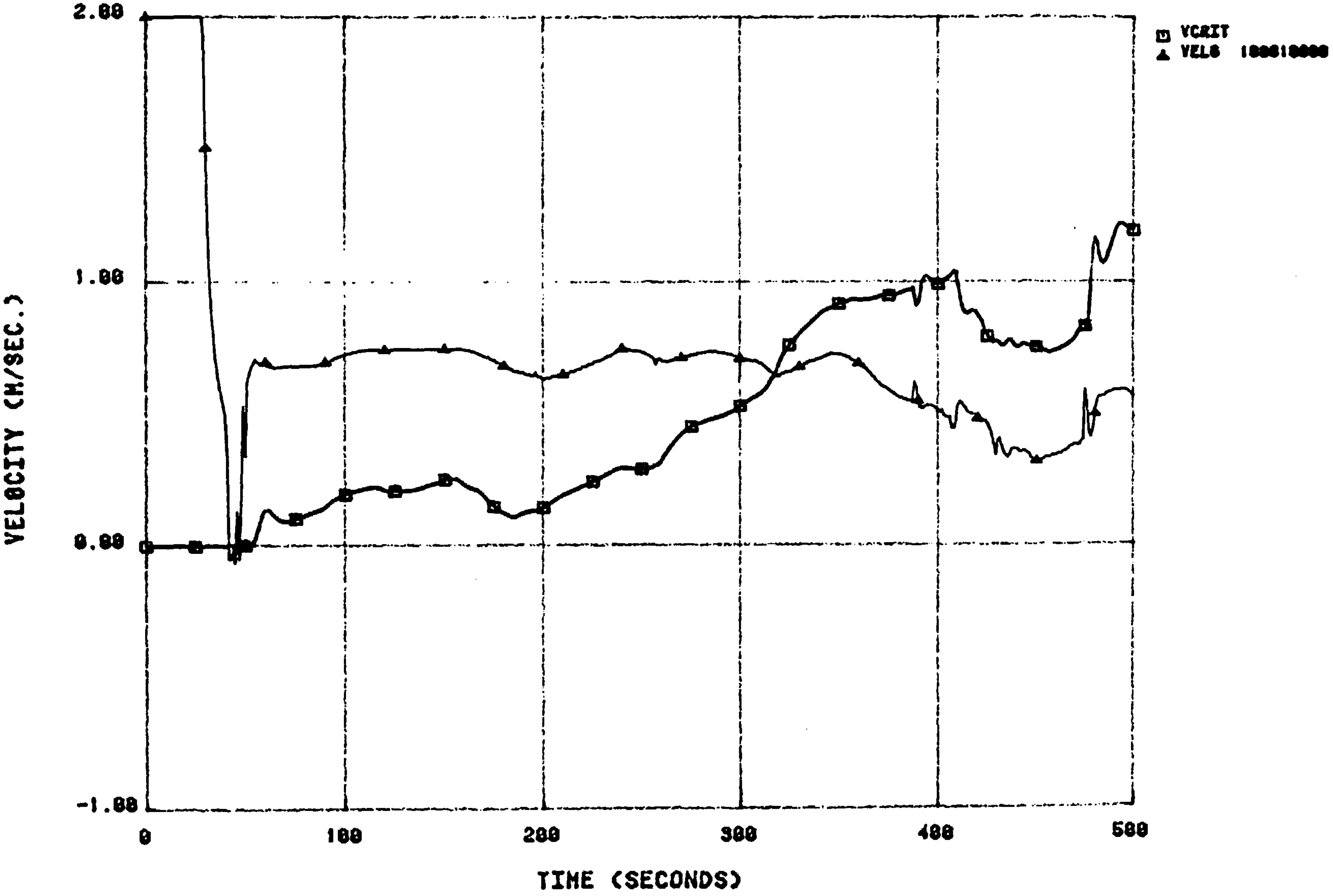

FLOW REGIME NUMBER
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0
100
200
300
400
500
TIME (SECONDS)
FLOREG 100010000

FIG.49

LP-SB-1.


VCRIT
VELS 100010000
VELOCITY (M/SEC.)
2.00
1.00
0.00
-1.00
0
100
200
300
400
500
TIME (SECONDS)

LP-SB-1.

FIG.50

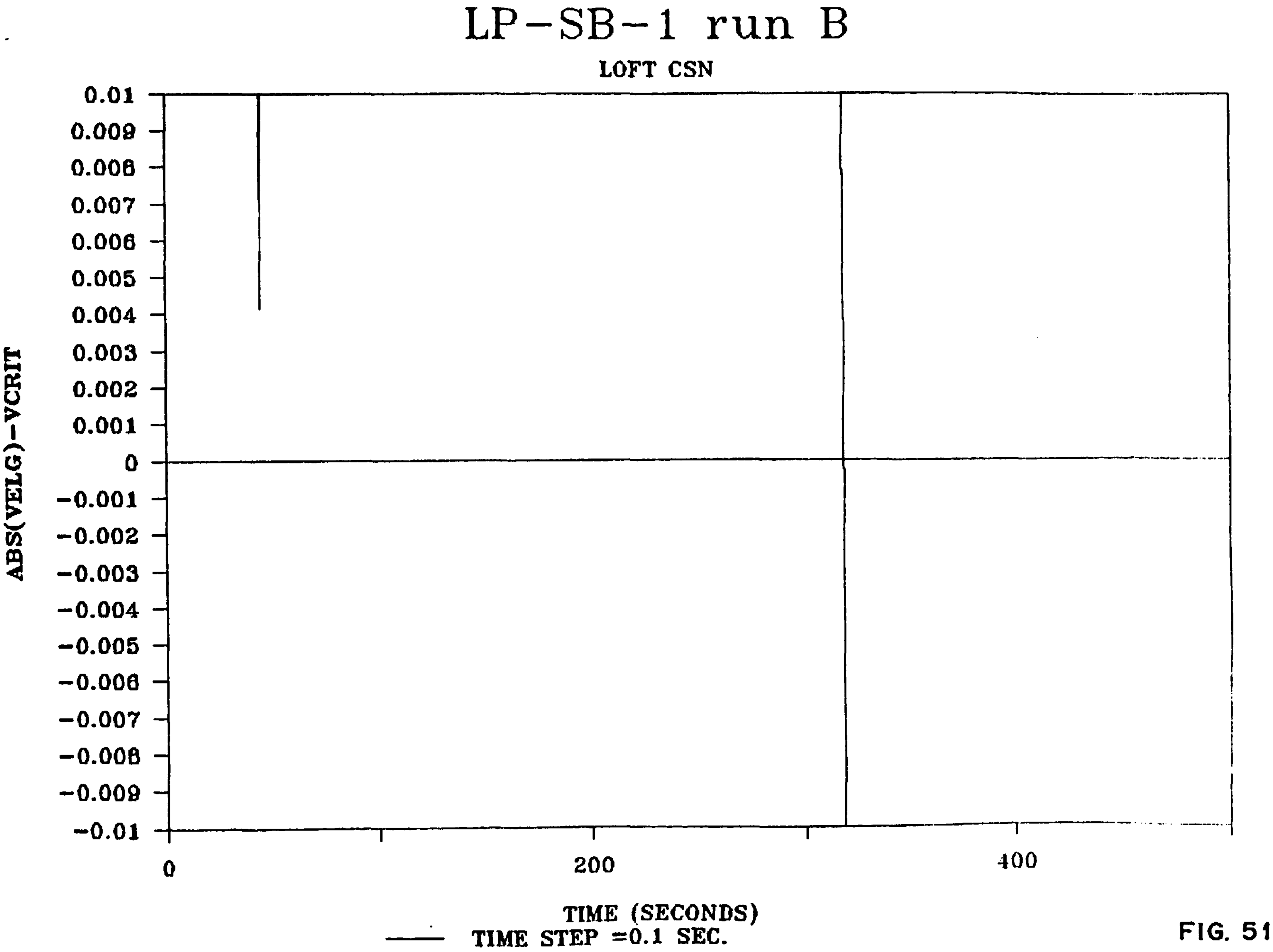

LP-SB-1 run B
LOFT CSN
ABS(VELG)-VCRIT
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
-0.007
-0.008
-0.009
-0.01
0
200
400
TIME (SECONDS)
TIME STEP =0.1 SEC.

FIG. 51

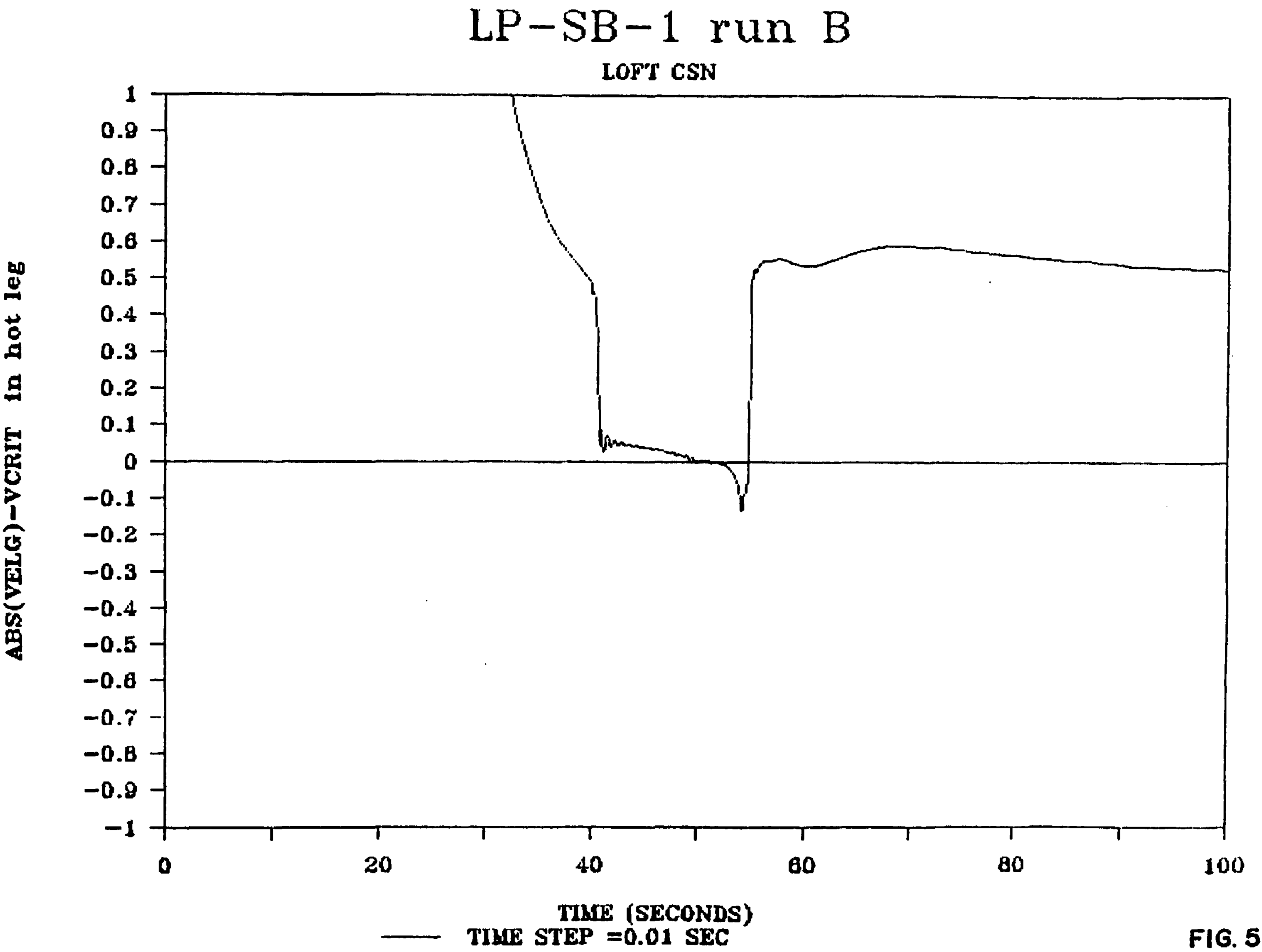

LP-SB-1 run B
LOFT CSN
ABS(VELG)-VCRIT in hot leg
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
20
40
60
80
100
TIME (SECONDS)
TIME STEP =0.01 SEC

FIG. 52

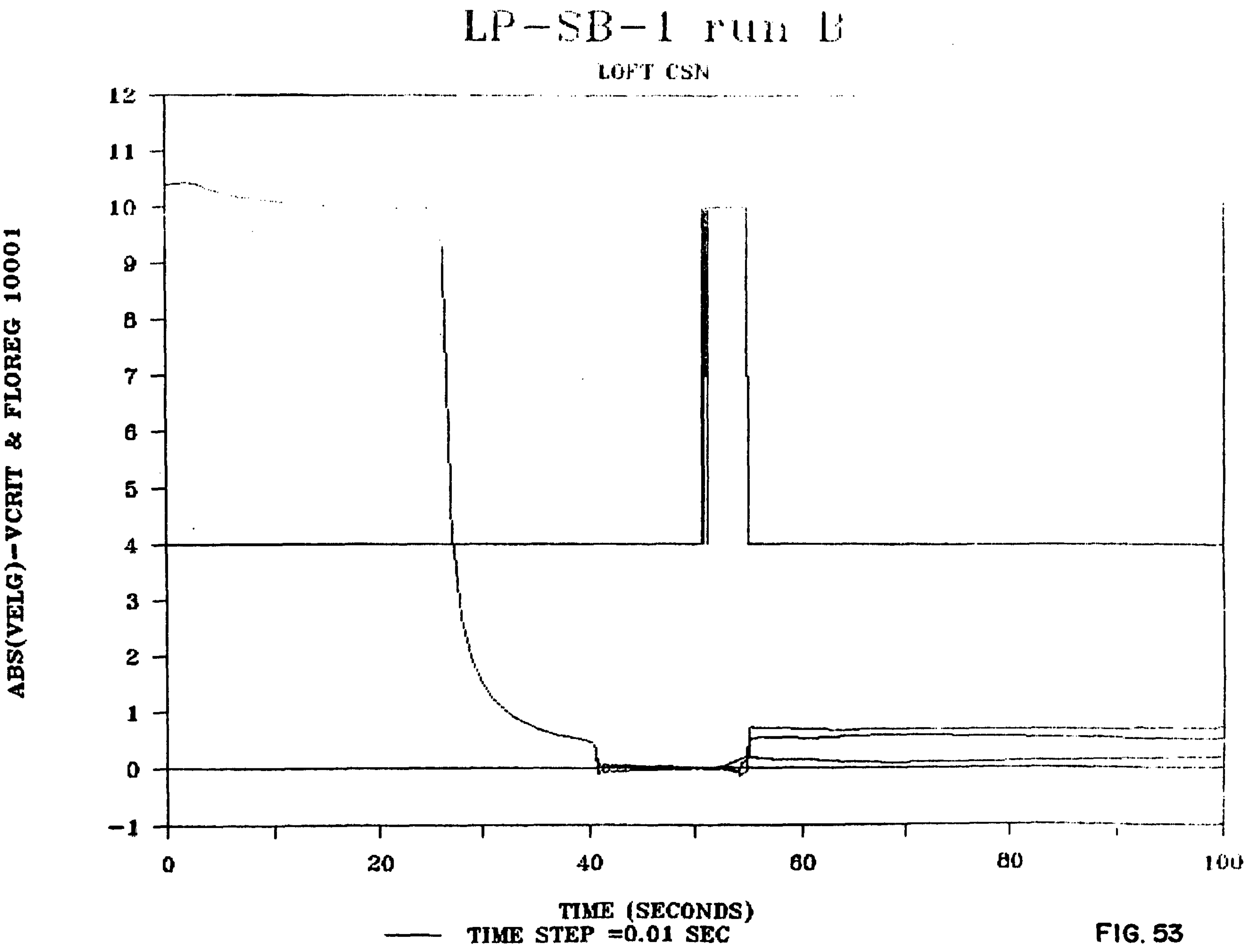

LP-SB-1 run B
LOFT CSN
ABS(VELG)-VCRIT & FLOREG 10001
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
0
20
40
60
80
100
TIME (SECONDS)
TIME STEP =0.01 SEC

FIG. 53

APPENDIX I

DISKETTE CONTAINING THE RELAP5/MOD2 INPUT DECK FOR LP-SB-1

APPENDIX II

TAITEL-DUKLER CRITERION FOR HORIZONTAL FLOW STRATIFICATION

RELAP5/MOD2 employs a criterion developed by Taitel and Dukler to define horizontally stratified flow regime. It applies to hydrodynamic volumes with an inclination angle $\leq 15^{o}$.

Taitel and Dukler proposed that the transition from stratified horizontal to nonstratified flow regimes occurs as a result of the instability of a solitary wave on the liquid layer. They derived this condition of instability as :

$$|v_g| > v_{gl}$$

where

$$v_{gl} = C \left[\frac{(\rho_f - \rho_g) g \alpha A}{\rho_g D \sin\vartheta} \right]^{\frac{1}{2}}$$

and

$$C = \frac{1}{2} (1 - \cos\vartheta)$$

ρ_f and ρ_g are liquid and vapor densities, respectively. g is the acceleration of gravity. A and D are, respectively, the cross section area and the diameter of the horizontal volume.

The angle ϑ is related to the liquid level, h, and the void fraction α, by the relationships (Fig. 54)

$$h = \frac{D}{2} (1 + \cos\vartheta)$$

$$\alpha\pi = \vartheta - \sin\vartheta\cos\vartheta$$

If the horizontal stratification condition

$$|v_g| < v_{gl}$$

is met, then the flow field undergoes a transition to horizontally stratified. If it is not met, the flow field undesgoes a transition to the bubbly, slug, or annular mist flow regime.

APPENDIX III

HORIZONTAL STRATIFICATION ENTRAINMENT MODEL IN RELAP5/MOD2

Under stratified conditions in horizontal components, the void fraction of flow through a junction may be different from the upstream volume void fraction [8]. Consequently, the regular donoring scheme for junction void fraction is no longer appropriate because vapor may be pulled through the junction and liquid may also be entrained and pulled through the junction. The correlations describing the onset of vapor pull through and liquid entrainment for a centrally oriented junction are given hereafter. The incipient liquid entrainment is determined by the criterion that

$$V_g \geq V_{ge}$$

where V_g is the vapor velocity in the junction, and

$$V_{ge} = 3.25 \left(\frac{\frac{D}{2} - h}{d} \right)^2 \left[\frac{g(\rho_f - \rho_g)(\frac{D}{2} - h)}{\rho_g} \right]^{1/2}$$

ρ_f and ρ_g are liquid and vapor densities, respectively. g is the acceleration of gravity. D and d are, respectively, the horizontal volume and junction diameters. h is the liquid level in the volume.

The condition for the onset of vapor pull-through is determined by

$$V_f > V_{fp}$$

where V_f is the liquid velocity in the junction, and

$$V_{fp} = 3.25 \left(\frac{h - \frac{D}{2}}{d} \right)^{5/2} \left[\frac{g(\rho_f - \rho_g)\, d}{\rho_f} \right]^{1/2}$$

For liquid entrainment, the junction liquid fraction, α_{fj}, is related to the donor volume liquid fraction, α_{fk}, by the expression

$$\alpha_{fj} = \alpha_{fk}\left[1 - \exp\left(-C_1 V_g/V_{ge} - 10V_g^2/V_{gl}^2\right)\right]$$

where V_{gl} is the Taitel-Dukler limit velocity (Appendix II). For vapor pull-through, the junction void fraction is given by

$$\alpha_{gj} = \alpha_{gk}\left[1 - \exp\left(-C_2 V_f/V_{fp} - 10V_g^2/V_{gl}^2\right)\right]$$

The constants C_1 and C_2 are obtained by comparisons of code calculations with experimental data. Currently, C_1 and C_2 are both equal to 1.

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

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC. Add Vol., Supp., Rev., and Addendum Numbers, If any.)
NUREG/IA-0074
ICSP-LP-SB-1-R

2. TITLE AND SUBTITLE
RELAP5/MOD2 Post-Test Calculation of the OECD
LOFT Experiment LP-SB-1

3. DATE REPORT PUBLISHED

MONTH	YEAR
April	1992

4. FIN OR GRANT NUMBER
A4682

5. AUTHOR(S)
J. Perez, R. Mendizabal

6. TYPE OF REPORT
Technical

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION — NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*
Consejo de Seguaridad Nuclear
Justo Dorado, 44
28040 Madrid, Spain

9. SPONSORING ORGANIZATION — NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

This document presents the analysis of the OECD LOFT LP-SB-1 Experiment performed by the Consejo de Seguridad Nuclear of Spain working group making use of RELAP5/MOD2 in the frame of the Spanish LOFT Project. LP-SB-1 experiment studies the effect of an early pump trip in a small break LOCA scenario with a 3-inch equivalent diameter break in the hot leg of a commercial PWR.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*
ICAP, RELAP5/MOD2, Post-Test, Calculation, OECD, Loft Experiment, LP-SB-1

13. AVAILABILITY STATEMENT
Unlimited

14. SECURITY CLASSIFICATION
(This Page)
Unclassified
(This Report)
Unclassified

15. NUMBER OF PAGES

16. PRICE

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

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

120555063572 4 1AN1CI
US NRC-RES
DIV OF SYSTEMS PESEARCH
BRANCH CHIEF
REACTOR & PLANT SYSTEMS BR
NL/N-353
WASHINGTON DC 20555