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RELAP5/MOD3.2 Post Test Calculation of the PKL-Experiment PKLIII-B4.3

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Table of Contents

Abstract

The PKL III test facility (Primär-Kreis-Lauf) simulates a typical 1300 MWe Pressurized Water Reactor of Siemens/KWU. In test B4.3, the influence of non-condensables on heat transfer in the steam generators during reflux condenser conditions was investigated.

This report presents the results of a post-test analysis of PKL III-B4.3 using RELAP5/Mod 3.2. A description of the input model is given, and the correspondence of measured and calculated results is discussed.

The results of the calculation show differences in the distribution of nitrogen in the primary system compared to the experiment. When nitrogen was injected into the hot leg of the primary system, the heat transfer in the affected steam generator decreased. In contrast to the experiment RELAP calculated that the volumes in the adjacent steam generator did not get the full amount of nitrogen and that nitrogen was transported from the steam generators to other locations during the course of the transient. Thus the heat transfer in these steam generators later increased in contradiction to the measured values.

In the steam generator tubes, RELAP calculated that the nitrogen accumulates in the descending part as predicted in the experiment. For the ascending U-tubes RELAP predicted that the nitrogen was transported to the loop seal, which was not seen in the experiment.

Fluctuations occured during the course of the RELAP5/Mod 3.2 analysis of the PKLIII B4.3 experiment. This phenomenon may be the main reason, that RELAP calculates the transport of nitrogen from the steam generators into the system and predicts finally a homogeneous distribution of nitrogen in the primary system.

The analysis performs an inkind contribution to the CAMP contract.

Abbreviations

ACCU	accumulator
ARV	Abblaseregelventil (relief valve)
ASC.	ascending (U-tubes)
Byp.	bypass
CAMP	Code Assessment and Maintenance Program
CCFL	counter current flow limitation
CL	cold leg, collapsed level
CV, CNTRLVAR	control variable
DC	downcomer
DE	Dampferzeuger (SG)
Depress., dp	depressurization
DESC.	descending (U-tubes)
DH	Druckhalter (pressurizer)
Diff.	difference
Exp.	experiment
HKPM, RCP	Hauptkühlmittelpumpe (reactor coolant pump)
HL	hot leg
Int., Integr.	integrated
L	loop
LOCA	loss of coolant accident
LPL	lower plenum
MFLOWJ	junction mass flow
N	nitrogen
PKL, PCL	Primärkreislauf, Primary Coolant Loop
Press., P	pressure
Primary-S.	primary side
PWR	pressurized water reactor
R	RELAP
RDB, RPV	Reaktordruckbehälter, reactor pressure vessel
SATTEMP	saturation temperature
SATT-Pr.	saturation temperature primary side
SATT-Sec.	saturation temperature secondary side
SBB	Stabbündelbehälter (rod bundle vessel)
SBLOCA	small break LOCA
Secondary-S.	secondary side
SG	steam generator
SPW	Speisewasser (feedwater)
SV	Sicherheitsventil (safety valve)
TEMP	temperature
UPL	upper plenum
U-tubes	tubes with ∩-profile for SGs

1 Introduction

The PKL III test facility simulates a typical 4 loop 1300 MWe pressurized water reactor of Siemens/KWU design. Within the PKL III-B4 test series, three tests have been performed to investigate the influence of non-condensables in the primary system on steam generator heat transfer.

In Test B4.1 the primary inventory was 100 % and thus the influence of non-condensables on single-phase natural circulation was investigated. In Test B4.2 the primary inventory was reduced to 85% which generated two-phase natural circulation. In test B4.3, by a further reduction of the inventory to 35% the influence of non-condensables on reflux-condenser conditions was investigated.

In this report a post-test analysis of PKL III-B4.3 using RELAP5/Mod 3.2 is presented. A description of the input model is given, and the correspondence of measured and calculated results is discussed.

The purpose of this analysis is to serve as a contribution to the verification of RELAP5/Mod 3.2's ability to handle a non-condensable component in the gaseous phase properly.

2 Description of the PKL Test Facility

The PKL III test facility simulates a typical 1300 MWe pressurized water reactor of Siemens/KWU of a volume/power scale of 1:145 (Fig. 2.1). All elevations correspond to real plant dimensions. It is a large scale facility with four primary loops, which are arranged symmetrically around the pressure vessel. Each of the four loops contains a main coolant pump and a fully scaled steam generator with prototypical tubing and tube sheet. The core is simulated by a bundle of 314 electrically heated rods, with a total power of 2.5 MW, corresponding to 10% of the scaled nominal power. The primary pressure is limited to 4.5 MPa. Regarding the limited pressure of the PKL III test facility the scaling of the experiments falls into three general categories:

The first category of experiments provides an insight into special physical phenomena, such as CCFL or the influence of nitrogen, which are expected to take place in PWR's at pressures below 4.5 MPa. The second category concerns experiments "entering" a PWR-transient at a pressure level of 45 bar. The conditions in PKL at the start of such a test are set up using code-calculations for the PWR, an example being small break LOCAs, where the important phenomena occur at pressures below 50 bar. The third category covers scenarios where phenomena occurring at high pressures in PWR's can be simulated at pressures below 50 bar in PKL, with the results being extrapolated to the original pressure (with the help of codes or comparisons with experimental results from full-pressure test facilities).

The test facility is equipped with all important safety and auxiliary systems, e.g. volume control system, high and low pressure injection system, accumulators and residual heat removal system. In correspondence to KWU-type plants, four independent high and low pressure injection systems which are connected to both the hot and cold legs are simulated.

The arrangement of the test facility is shown in Fig 2.1,

The steam generators of the test facility are equipped with U-tubes. Each SG has 27 heat exchanger tubes in accordance to the 1:145 scale. The tubes are arranged to assemblies with 7 different lengths. The peak elevations of the longest and shortest tube correspond to the plant dimensions. Two replacement bodies are inserted in the secondary side to achieve the volume scale. A cross-sectional view is given by Fig. 2.2.

At least 3 U-tubes in each SG are equipped with thermocouples for the measurement of primary side fluid temperature at different axial positions. The axial location of these thermocouples is shown in Fig. 2.3.

Within the test facility there are more than 1300 locations for measurement instrumentation. This provides extensive information necessary for the understanding of all relevant thermal hydraulic phenomena.

3 Description of Experiment PKLIII B4.3

3.1 Objectives of Test PKLIII B4.3

Beginning by January 1989 the test series IIIB was initiated at the PKL test facility. Focused on accident-management procedures the majorities of tests were performed in order to investigate phenomena occurring during primary side and secondary side feed and bleed procedures. Within PKL III B4 three tests have been performed to investigate plant performance with presence of non-condensables in the primary system.

The investigation of the influence of non-condensables on plant performance was considered to be meaningful, because accident scenarios exist where nitrogen or hydrogen accumulates in the steam generators and reduces heat transfer to the secondary side. Nitrogen may be expelled by the accumulators in the cause of an postulated Large Break Loss-of-Coolant Accident. It is dissolved in the primary system coolant, in the liquid of the refueling storage tank, and accumulator liquid, or may be already present in the system during refueling. And hydrogen generated by metal-water reaction at the fuel cladding may accumulate in the steam generators during post-design accident scenarios.

In the test series primary pressure (1 MPa) and power generation rate (2 %) have been kept constant whereas primary side inventory was different in each test. In Test B4.1 the primary inventory was 100 % and thus the influence of non-condensables on single-phase natural circulation was investigated. In Test B4.2 the primary inventory was set to 85% which generated two-phase natural circulation. And in Test B4.3, by a further reduction of the inventory down to 35% the influence of non-condensables on reflux-condenser conditions was investigated.

Descriptions of the PKL test facility and of experiment PKL III B4.3 is given in reference /1/ through /3/

3.2 Initial and Boundary Conditions of the Test B4.3

The test was initiated by a conditioning phase where the primary inventory has been already reduced, but no nitrogen was injected.

The reflux condenser conditions resulted in an accumulation of liquid inventory in the hot legs and in the inlet regions of the SG tubes. In the hot leg a collapsed level of 1.2 m was observed. The collapsed levels in the tubes were 1.5 m. The swell level in the vessel was below the inlet junctions of the loop pipings. The loop seals were filled with water.

With the secondary side pressure (and saturation temperature) given, the primary side pressure is a system response. The primary side pressure is established to generate the temperature difference, which is necessary for stationary heat removal. In the experiment under consideration the temperature difference was 6 K.

Based on a secondary side energy balance it can be concluded, that about 460 kW are transferred to the secondary side. Consequently, the primary side heat losses are about 60 kW. On the secondary side there is a heat loss of approximately 10 kW per SG.

The major parameters of the stationary conditions in the primary system are summarized in Table 3.1, the secondary side conditions are summarized in Table 3.2.

Primary Inventory	35 %
Power	2 % (520 kW)
Primary Pressure	1.0 MPa
Core Outlet Temperature	453 K / 180 °C (saturated)
Main Coolant Pumps	not operating
Pressurizer	isolated
Primary/Secondary Side Temperature Difference	6 K

Tab. 3.1: Primary System Initial Conditions

Collapsed Level in SG Downcomer	12 m
Steam Line Pressure LBA 10-40	0.87 MPa
Steam Line Temperature	447 K / 174 °C
Feed Water Mass Flow LAB 10-40	0.05 kg/s / loop

Tab. 3.2: Secondary System Initial Conditions

3.3 Sequence of Events

Test PKLIII B4.3 investigates the system's response to a succession of nitrogen injections periods into the primary system at various injection ports. In the course of the test the secondary pressure was reduced occasionally in order to compensate the influence of nitrogen on heat removal in the steam generators.

The sequence of nitrogen injection periods and secondary side pressure operations is given in Table 3.3:

Time	**Event**
0 - 3600 s (10990 - 14590 s)	1. period of nitrogen injection 0.25 Nm^3, 3600 s, HL 10
4870 - 6310 s (15860 - 17300 s)	2. period of nitrogen injection 0.1 Nm^3, 1440 s, CL 30
6400 - 10000 s (17390 - 20990 s)	0.25 Nm^3, 3600 s, CL 30
10880 - 11180 s (21870 - 22170 s)	3. period of nitrogen injection 0.25 Nm^3, 300 s, HL 20
14295 - 14595 s (25285 - 25585 s)	4. period of nitrogen injection 0.25 Nm^3, 300 s, CL 40
14735 s (25725 s)	reduction of secondary pressure to .80 MPa
16000 - 19600 s (26990 - 30590 s)	5. period of nitrogen injection 1.5 Nm^3, 3600 s, HL 10
(21430 s)	reduction of secondary pressure to 0.55 MPa
22840 - 26440 s (33830 - 37430 s)	6. period of nitrogen injection 1.5 Nm^3, 3600 s, CL 30
27340 s (38330 s)	reduction of secondary pressure to 0.37 MPa
(38990 s)	End of Test

Tab. 3.3: Nitrogen Injection Periods and Secondary Side Pressure Settings

The amount of nitrogen which is injected in each of the first four periods corresponds to the amount which is dissolved in the accumulator liquid. During each the fifth and sixth period of injection the full depletion of a accumulator gaseous inventory was simulated.

3.4 Phenomenological Analysis of Test Results

This chapter analyses the phenomena which occurred during the test and describes

- the effect on heat transfer in the steam generator during reflux condenser mode if nitrogen is present in the primary system,
- the overall distribution of nitrogen in the primary system depending on the location of an injection
- and the dependence on the primary to secondary side pressure and temperature difference.

A detailed description of the test results will be given later in this report in conjunction with comparison to calculational results.

The reflux condenser mode is characterized by counter-current flow of liquid and steam in the hot leg. If nitrogen is injected into the primary system, it is transported by convection (diffusion is not effective). At locations of lower temperature, such as the steam generator or reactor coolant pump, steam is condensed and nitrogen is subsequently accumulated. The quality of nitrogen is increased until the partial pressure of steam and its saturation temperature corresponds to the saturation pressure of the local temperature (e.g. secondary side). These conditions represent a thermal equilibrium, and no heat transfer or condensation occurs in such a passive area.

The transition from an active heat transfer area to a passive heat transfer area is accelerated by the phenomenon that the inert gas is accumulated at the condensation film on the cooling surface. The density of the inert gas in this boundary layer is higher than in the center of the steam flow. For this reason the partial pressure and the temperature of the steam in the nitrogen enriched layer is lower than the average steam temperature and partial pressure in the steam flow. After the termination of the condensation the layer of accumulated inert gas is dispersed by diffusion.

The distribution of nitrogen in the primary system depends on the location of injection. If a moderate amount of nitrogen is injected into a hot leg of the loop of the test facility, it is transported to the adjacent steam generator where an accumulation at the location of condensation takes place. A "region of inertness" or passive area is established. It proceeds from the SG outlet chambers and depending on the amount of nitrogen injected, can occupy the whole steam generator. If the hot leg is completely filled, nitrogen flows to the upper plenum and into the other hot legs. However under these conditions no permanent accumulation of nitrogen was observed in the upper plenum. The distribution of nitrogen does not depend significantly on the injection rate but only on the total amount of injected nitrogen.

If a moderate amount (0.25 Nm^3 in 1h) of nitrogen is injected into the cold leg, under reflux condenser conditions it is accumulated in the adjacent pump, as heat losses dominate in this component and steam is accordingly condensed. If more nitrogen is injected or if the injection rate is high, nitrogen is transported via the bypass from the downcomer into the upper plenum and finally into the steam generators.

The influence of nitrogen on heat transfer in the SG tubes can be compensated by lowering the secondary pressure or increasing the primary pressure. The resulting increase of temperature difference between primary and secondary side has a direct impact on heat transfer. In addition the partial pressure of steam is diminished via the accumulation of nitrogen. Therefore the concentration of nitrogen can be higher. By an increase of primary pressure the region of inertness is compressed and establishes thus a additional partial recovery of the heat transfer.

4. Results of RELAP5/Mod 3.2 Analysis

4.1 Description of RELAP5/Mod 3.2

The Mod3.2 version of RELAP5 has been developed within the Code Applications and Maintenance Program (CAMP).

The code development has benefitted from extensive application and comparison to experimental data in test facilities such as LOFT, PBF, Semiscale and NRU.

RELAP5 is a highly generic code, that can be used in both nuclear and non-nuclear systems involving mixtures of steam, water, non-condensables, and nonvolatile solute.

A description of RELAP5/Mod3 is given in reference /4/.

4.2 Description of Input Model

The nodalization scheme is shown in fig. 4.1.

The core area is represented by a single axial flow channel with 8 hydraulic volumes in the heated region. The fuel rod simulators are represented by 3 heat structures (HST-10421, HST-10422 and HST-10423) with different power generation rates given by General Tables 801-803. In the test facility the downcomer consists of two pipes. In the RELAP input they are modeled as a single pipe.

Though being rather coarse, the modeling of the test vessel corresponds to the requirements of Test PKLIII B4.3, as the phenomena under consideration occur in the SGs and the loops, and as no core uncovery occurs during the course of the experiment.

Each loop is modeled separately. The hot leg is represented by 13 hydraulic volumes. Three types of SG tubes with different lengths are modeled (18, 20, 22 volumes). The loop piping between SG and pump is represented by 16 volumes, piping between pump and vessel by 5 volumes. The modeling of the piping and the steam generators is sufficiently fine to allow an adequate representation of thermal-hydraulic phenomena relevant in the test under consideration.

The pumps are represented by pump components; homologic data are used, which have been determined for the LOBI test facility. The cooling of the pumps is considered.

The noding of the steam generator secondary side has 16 axial nodes in the riser and 13 axial nodes in the downcomer.

The nitrogen injection is simulated at the hot and cold injection port of the emergency core cooling system. To consider the flow direction of these nozzles towards the RPV, the injection junctions are connected to the outlet of the volumes in the hot legs and to the inlet in the volumes of the cold legs.

The input deck includes a variety of control variables (cv). The following table comprises control variables which are of particular interest for test PKL III B4.3.

Total power	cv 7900
Drained mass of primary system	cv 7500
SG collapsed levels	cvs 2103, 2203, 2303, 2403
Smoothed levels in the SGs, calculated by a Lag component with a Lag time of 30 s	cvs 2110, 2210, 2310, 2410
Sum of the heat transfer in the short, medium and long SG tubes of all SGs	cvs 7175, 7275, 7375, 7475
Smoothed heat transfer in the SGs, calculated by a Lag component with a Lag time of 50 s	cvs 7176, 7276, 7376, 7476

4.3 Calculational Procedures and Boundary Conditions

The post test calculation was started to reach steady-state conditions with a significantly reduced primary inventory. A calculation was made to meet the initial and boundary conditions. During the calculation 1491 kg of liquid inventory was drained from the primary system and the inventories in the SGs were adjusted by controlling feed water flow and secondary pressure. The calculation for steady state was stopped after 5000 s. At that time the thermal-hydraulic conditions have been almost stationary.

As a boundary condition during the transient nitrogen was injected into hot legs 10 and 30 and cold legs 20 and 40. These injection rates are shown in Fig. 4.2 and 4.3.

As the heat transfer in the SG depends on the pressure difference and is merely independent from the absolute pressure, during the calculations the secondary side pressure was used in correspondence to the experiment as a calculational boundary condition. The development of the secondary side pressure is shown in Fig. 4.4.

Additional to these presumptions the input was fitted out with control variables to get the nitrogen accumulation and nitrogen flow in the primary system. Together with the heat transfer to the secondary side the results of the RELAP5/Mod3.2 analysis were assessed against the experimental results.

4.4 General System Response

The overall system response to nitrogen injection is depicted in Fig. 4.5 through Fig. 4.7.

At first the measured system behavior is discussed.

Fig 4.5 shows the pressure history of primary and secondary side. The pressure increase following the 1. period of nitrogen injection into HL10 (0 - 3600 s) is very moderate. The 2. period of injection into CL30 (4870 - 10000 s) has no effect on primary system pressure. The pressure increase during the 3. injection period into HL20 (10880-11180 s) is more pronounced than in period 1. At the end of injection period 4 the secondary side pressure is reduced for the first time and generates a simultaneous decrease of the primary side pressure. The subsequent injection period 5 with large amounts of nitrogen results in an continuous increase of primary pressure which was compensated at the end of this injection period by a further adjustment of the secondary side pressure.

The pressure difference between the primary and secondary side results in a difference of the corresponding saturation temperatures, which determines the overall heat transfer. The history of calculated and measured temperatures and temperature difference is shown in Fig. 4.6 and 4.7. The initial temperature difference before nitrogen injection calculated by RELAP5/Mod3.2 is 4 K compared to 6 K in the experiment. The temperature decrease on the secondary side shown in the experiment during the first period is to be explained by a local effect (plume of cold water at the thermocouple).

The temperature difference which is formed at the end of each injection period is summarized in the following table:

	Experiment		RELAP	
	pre pressure reduction	post pressure reduction	pre pressure reduction	post pressure reduction
Initial Condition	6 K	*	4 K	*
1. Period (HL 10)	6 K	*	5 K	*
2. Period (CL 30)	6.5 K	*	5 K	*
3. Period (HL 20)	8 K	*	7 K	*
4. Period (CL 40)	8 K	9 K	7 K	8 K
5. Period (HL 10)	19 K	23 K	18 K	25 K
6. Period (CL 30)	27 K	30 K	30 K	42 K

* no pressure reduction performed

Tab. 4.1: Measured and Calculated Temperature Differences between Primary and Secondary System in Test PKL III B4.3

For the temperature differences shown in table 4, the primary temperature is taken from the upper plenum as calculated and measured, respectively , and the secondary temperature (for the calculation the same as for the experiment) Fig. 4.6) corresponds to the secondary saturation pressure.

Injections of small amounts of nitrogen into a cold leg do not affect heat transfer to secondary side. For the 5th (hot leg injection) and 6th (cold leg injection) injection periods, heat removal was too small to generate a stationary condition. This non-equilibrium resulted into an almost constant pressure increase. At the end of each of both periods, secondary side pressure has been reduced in the experiment. The first temperature difference corresponds to secondary side pressure before reduction, the second temperature difference is the respective value after pressure reduction. As primary side pressure follows the secondary side pressure, the reduction of pressure in the primary system results into an extension of the volume of inertness (passive area) in the steam generators. Therefore the temperature difference between both systems is expected to be higher with a lower pressure level.

In the following the RELAP5 results are compared to the measured values.

During steady state (before injection of N into the system) RELAP5 shows a lower (50%) temperature difference between primary and secondary side (Fig. 4.7, 4K calculated by RELAP5, 6K measured), although the total heat transferred to the secondary side is calculated to be lower in RELAP5 than in the experiment

(440 kW vs. 460 kW). This indicates a small overestimation of heat losses on the primary side in the RELAP5 model.

For the first period (nitrogen injection of 0,25m^3 in 1 hr into HL10) RELAP5 calculates a small response of the system behavior (ΔT increase by 1K to 5K); the measured system response cannot be clearly interpretated, because of the shown anomalies (Fig. 4.6) but indicates almost no increase of the primary temperatures. The RELAP5 results (ΔT increase) show that the decrease of heat transfer in SG 10, because of nitrogen injection, cannot be compensated completely by the remaining SGs (as in the experiment).

Both the experiment and RELAP5 show almost no influence of the nitrogen injection of 0,25m^2 N in 1 hr into CL30 on the system behavior during the 2nd period.

In the 3rd period (0,25m^3 N in 5min into HL 20) RELAP5 shows a similar system response to the nitrogen injection as measured (1,5K vs 2K).

In the 4th period with 0,25m^3 nitrogen injection in 5min into CL40 both RELAP5 and the experiment show no system response. Experiment and RELAP5 define an increase of 1K of the primary temperature after the depressurization.

During the 5th and 6th period of nitrogen injection, RELAP5 and the experiment show a continuous increase of primary pressure and consequently an increase of the temperature difference primary to secondary side, which are terminated by the secondary side depressurization.

4.5 Steam Generator Heat Transfer as a Function of Nitrogen Distribution in the Primary System

The distribution of nitrogen and its influence on steam generator heat transfer was analyzed. The heat transfer in the SG depends on the distribution of nitrogen in the U-tubes.

In the RELAP5/Mod 3.2 calculation, the nitrogen accumulations in all relevant components can be shown using control variables. These control variables serve as a basis to analyse the nitrogen transport. The calculated nitrogen distribution is depicted in Fig. 4.12 through 4.37 in comparison to the experimental values. The nitrogen mass distribution of the experiment shown in the figures is estimated from the test report description. Additional the heat transfer of the individual SGs can be derived from the live steam flows, hence these values are proportional to the heat transfer, when the level in the SG secondary side is kept constant by the feedwater injection (see Fig. 4.38). The heat transfer in the SGs of the calculation was derived directly via the heat flux parameters of the U-tubes (see Fig. 4.39).

Consequently the calculated heat transfer of each SG can be compared with the experiment. (Figures 4.40 through 4.43), based on the nominal heat transfer rate in one SG of about 115 kW. When the heat transfer declines in a SG by accumulation of nitrogen, the inertness is compensated by the increase of the steam temperature in the primary system, which leads to a better heat transfer in the SGs which are free from nitrogen.

Fig. 4.37 confirms a good agreement of the integral nitrogen inventory in the system between experiment and calculation and the correctness of the boundary conditions. Differences between calculated and measured heat transfer can be explained via the calculated differences in nitrogen distribution.

1st Nitrogen Injection of 0,25m^3 into the Hot Leg of Loop 10 in 1hr

The experiment shows the following: During the 1st nitrogen injection period (Fig. 4.2) the heat transfer in SG 10 decreased (Fig 4.40) from the initial value to 20kW. The development of a passive area in the SG10 can be seen in Fig. 4.8 and 4.9. The total mass of 0,3kg N injected is accumulated in HL10 and in SG10 (Fig. 4.12 to 4.13). To preserve the total heat removal the heat transfer in the other SGs increased (see Fig. 4.41 to 4.43) without a pressure and temperature increase in the primary system (Figs 4.5, 4.6).

RELAP5 shows the following: The heat transfer in SG10 decreased from 110kW to less than 10kW at 1200 sec (Fig. 4.40). This loss of total heat transfer of about 100kW (compared to approx. 40kW in the test) cannot be compensated by the 3 other SGs without a small temperature and pressure increase at the primary side (Figs 4.5, 4.6). The evaluation of the nitrogen distribution shows that less N is accumulated in SG10 compared to the experiment (Fig. 4.13). The increase of pressure in the upper plenum and at the SG outlet leads to oscillatory loop seal clearing (Fig. 4.44) and consequently to the N transport to the RCP (Fig. 4.15, 4.16).

2nd Nitrogen Injection of 0,25 m^3 into the Cold Leg of Loop 30 in 1hr

The experiment shows no significant change of heat transfer in all 4 SGs (Figs 4.40 to 4.43) during the N injection. The nitrogen injected is accumulated in the DC only (Fig. 4.36).

The RELAP5 calculation shows also no significant change in overall heat transfer. SG10 recovers slightly around 8000 sec to about 40kW heat transfer (Fig. 4.40). The nitrogen distribution calculated differs from the experimental results. RELAP5 calculates a nitrogen flow to the UPL and closure head (Fig. 4.36), which is an indication of an underestimation of condensation in the pump region, resulting in positive pressure difference CL to UPL and closure head.

3rd Nitrogen Injection of 0,25m^3 into the Hot Leg of Loop 20 in 5 min

The experiment shows a significant decrease of heat transfer in SG20 to 60kW (down from 140kW) (Fig. 4.41). This decrease is compensated by a permanent increase of heat transfer in SG30 from 160kW to about 230kW (Fig. 4.42). Beside short peaks, SG10 and SG40 remain unaffected. The nitrogen accumulates primarily in the SG20 and partly in the loop between SG20 outlet and loop seal.

The RELAP5 calculation shows a much stronger decrease of heat transfer down to 0 in SG20 with a continuous recoverment thereafter (Fig. 4.41). SG30 and SG40 show an increase from 140kW to 160kW and a continuous decrease thereafter. SG10 shows a permanent increase of heat transfer from 40kW to 130kW (no increase in the test). Fig. 4.23 shows that not all injected nitrogen is calculated to accumulate in the SG20, it partly flows towards the UPL. The amount of nitrogen in SG20 decreases continuously (Fig. 4.20), thereby causing an increase of heat transfer (Fig. 4.41).

4th Nitrogen Injection of 0,25m^3 into the Cold Leg of Loop 40 in 5 min

The experiment shows no significant change of heat transfer in any of the 4 SGs before the depressurization (Figs 4.40 to 4.43). The secondary pressure decrease leads to a temporary peak of heat transfer in all 4 SGs. The nitrogen is accumulated in DC region only.

The RELAP5 calculation shows also no significant response of the system till the depressurization. Only SG20 shows a significant reaction during the depressurization. The nitrogen is calculated to accumulate first primarily in the DC and partly in the UPL. Thereafter it is redistributed from the DC region into UPL and the rest of the primary system (Fig. 4.36).

5th Nitrogen Injection of 1,5m^3 into the Hot Leg of Loop 10 in 1hr

The experiment shows no overall change in heat transfer during the injection period (Figs 4.41 to 4.43). SG30 shows a decrease and a consecutive increase, whereas SG40 shows in the same time period an increase and a decrease of heat transfer. The actual decrease of heat transfer by condensation in the U-tubes is compensated by a continuous increase of primary pressure and corresponding saturation temperature (Fig. 4.5). The nitrogen accumulates in all 4 SGs in parallel (Figs 4.13, 4.20, 4.27, 4.32). The pressure reduction creates similar reactions like in period 4.

RELAP5 calculates a similar overall system response regarding the total heat transfer and pressure increase in the primary system (Fig. 4.5 and 4.40 to 4.43). SG10 looses completely its heat transfer capacity during the injection. SG20 reaches full capacity (up to 160kW) again and SG30 and SG40 increase also their heat transfer by 20kW. The nitrogen is calculated to increase in all 4 SGs similar to the experiment.

6^{h} Nitrogen Injection of 1,5m^{3} into the Cold Leg of Loop 30 in 1 hr

The test shows a strong decrease of heat transfer in SG30 at 2400 sec down to about 80kW. The other 3 SGs raise their heat transfer. The actual decrease in the condensation rate in the SG U-tubes is compensated by a continuous increase of primary pressure and corresponding saturation temperature. The nitrogen is accumulated in all 4 SGs in parallel (Figs 4.13, 4.20, 4.27, 4.32).

The RELAP5 calculation shows a comparable result regarding the primary pressure response (Fig. 4.5). SG20 and SG30 have a higher calculated heat transfer compared to the test, whereas SG40 has a lower calculated value. The nitrogen is calculated to increase in SG20, 30 and 40 but remains nearly constant in SG10.

Conclusion

In this chapter we have discussed the nitrogen distribution in the PCL and the influence on the heat transfer in the SGs during the 6 nitrogen injection periods.

Comparing the nitrogen distribution in the system between the experiment and the RELAP calculation significant differences were shown in the results. In the RELAP calculation, the nitrogen was accumulated at the measured locations but to a different amount. The U-tubes of the SGs were calculated to receive enough inert gas to influence the heat transfer as predicted in the experiment.

The overall heat transfer response is predicted by RELAP5 in a similar way compared to the test. But differences are shown in the distribution of the heat transfer among the SGs. In the experiment the heat transfer differs from 60 kW to about 250 kW (Fig. 4.38), while in the RELAP calculation the heat transfer rate is at a uniform level near 150 kW, but for the SGs with passive areas (Fig. 4.39).

4.6 Propagation of Nitrogen Concentration in the Steam Generator U-Tubes

Based on the evaluation of the experiment for reflux condenser operation with a hot injection of nitrogen, in the course of this test a front of high nitrogen concentration is formed in the SGs, which moves through the SG from the outlet chamber to the inlet chamber. An indication for this movement is the measurement of fluid temperatures in the SG tubes (see Figs 4.8 to 4.11), because steam temperature in this region decreases according to the partial pressure. In the evaluation the presence of nitrogen in the U-tubes of the SGs has been verified in this manner.

As described in chapter 4.5 the heat transfer in SG 10 and SG 20 did not exactly correspond with the prediction of the experiment. These SGs were effected by hot leg nitrogen injection during the periods 1 and 3. In the experiment they showed a constant heat transfer of about 10 kW resp. 60 kW after the 3rd injection period (Figs 4.40, 4.41). In the RELAP analysis, SG 10 was activated again when nitrogen was injected into the hot leg of loop 20 and the heat transfer in SG 20 collapsed totally. Later on, in SG 20 the heat transfer increased continuously to about 150 kW after the termination of the 3rd nitrogen injection.

This calculated increase of the heat transfer in the RELAP5/Mod 3.2 analysis is not shown in the experiment and should be analysed closer. As the phenomena in each U-tube are similar, only results of the longest tube of SG 10 and 20 are presented here.

When condensation takes place in the U-tubes, heat is transferred to the secondary side. Another criterion for heat transfer is the temperature difference between the steam in the U-tubes and the secondary side of a SG. In figures 4.8 through 4.11 steam temperatures and secondary side temperatures are depicted for the ascending and descending U-tubes. The temperature differences confirm the heat transfer shown by the steam condensation in the figures 4.49 and 4.50. Furthermore the temperature differences between the saturation temperatures and the steam temperatures in figures 4.8 through 4.11 indicate the presence of nitrogen in the U-tubes as predicted in the experiment.

Figures 4.49 and 4.50 of the RELAP calculation show the generation of condensate in the respective SG for the ascending and descending U-tubes. As predicted in the test, the condensate generation in the descending part decreased earlier than in the ascending tubes, caused by concentration of nitrogen during condensation of steam and by the flow of nitrogen from the ascending part to the descending part together with steam.

At 1000 s, generation of condensate in the descending U-tubes of the SG 10 (Fig. 4.49) has been stopped totally by reaching a saturated state of the mixture.

At 4000 s in SG 10 the nitrogen inventory in the descending part decreased while it was constant in the ascending tubes (RELAP calculation, Fig 4.17). The reason for this behavior shows the integral nitrogen flow at the inlet and outlet of pipe 320 (RELAP calculation, Fig. 4.18). Nitrogen that flowed to the loop seal (RELAP calculation, Fig. 4.14) has been withdrawn from the ascending U-tubes. The same behavior of the RELAP calculation showed SG 20 at 11500 s (Figs 4.24, 4.25).

Therefore the heat transfer behavior calculated by RELAP5 of SG10 and SG20 after nitrogen injection into their corresponding hot legs can be explained by the nitrogen transport out of the SG U-tubes into SG outlet and the adjacent loop.

In the experiment the nitrogen obviously remains in the U-tubes of the affected SG (see Figs 4.13, 4.14 and 4.20, 4.21).

5 Conclusions

The PKL III test facility simulates a typical 1300 MWe pressurized water reactor of Siemens/KWU design. In Test B4.3, the influence of non-condensables on reflux-condenser conditions was investigated.

This report presents a post-test analysis of PKL III B4.3 using RELAP5/Mod 3.2. A description of the input model is given, and the correspondence of measured and calculated results is discussed.

The main findings of the comparison of RELAP5/Mod 3.2 results with the PKLIII B4.3 experiment are as follows:

The general system response (pressure, temperature) of nitrogen injection in the primary system is calculated by RELAP5/Mod3.2 quite well. In a detailed evaluation RELAP5 calculates a non conservative behavior of heat transfer for small nitrogen injections effecting a particular SG. This statement can be concluded from the course of the heat transfers in the SGs 10 and 20 (see chapter 4.5 and 4.6).Thus a too large calculated heat removal from the primary system underestimates the effect of nitrogen on the emergency core cooling in loss of coolant accidents. When the steam flow of the reflux condenser operation is terminated in a SG caused by inertness, less nitrogen of the injection is transported to the SG U-tubes. For this reason first a smaller nitrogen inventory in the U-tubes of a SG has been calculated to accumulate as predicted in the experiment and later on the nitrogen has been calculated to leave the SG (chapter 4.6).

Looking at the figures of the transient, it is shown that RELAP calculates small fluctuations which transport nitrogen in the system without physical background. In a long term behavior, because of this numerical instability RELAP will predict a homogenous distribution of the nitrogen in the primary system.

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/3/ B. Schoen, P. Weber
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/4/ Idaho National Engineering Laboratory
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NUREG/CR-5535 INEL-95/0174 Vol. I - VII

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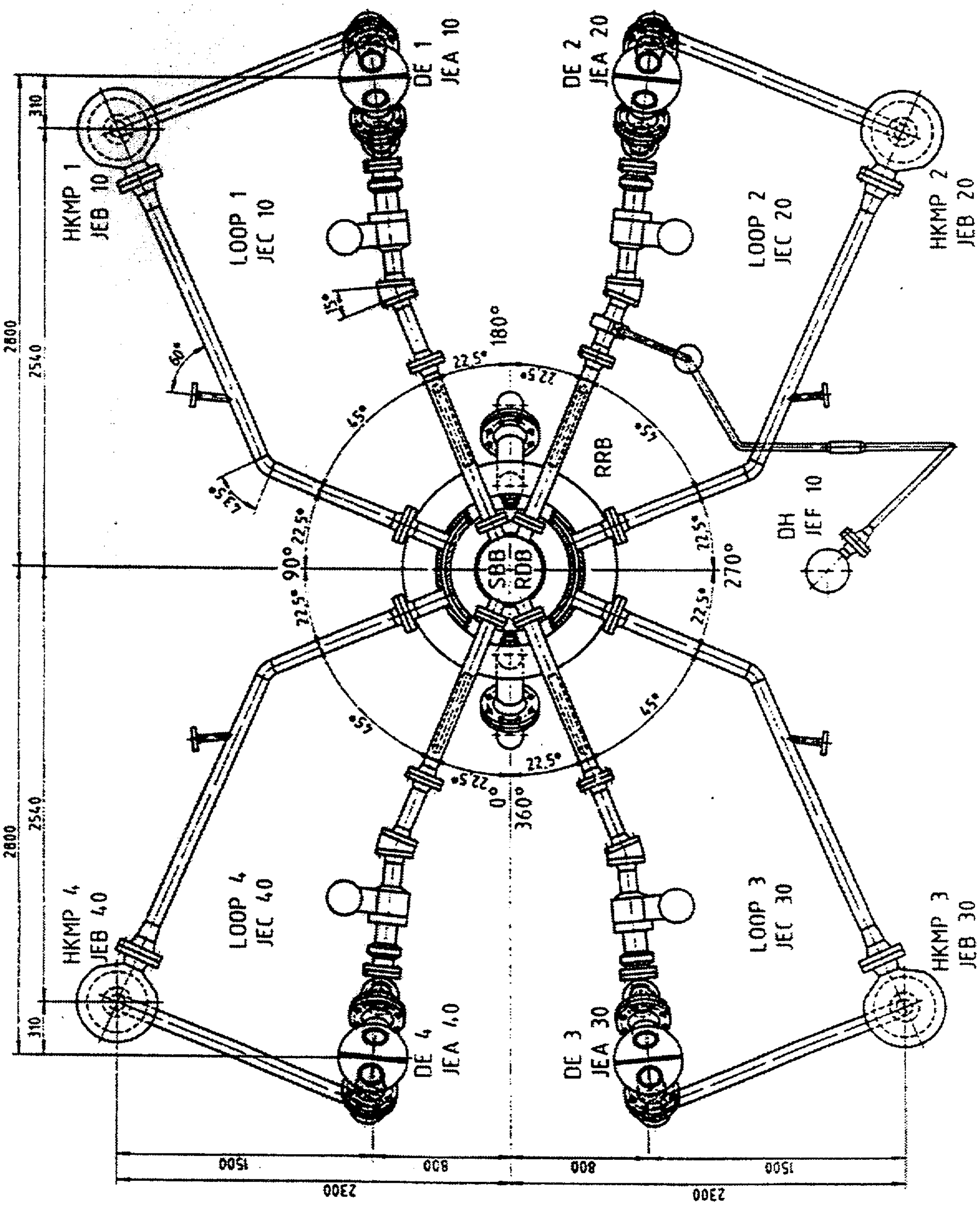
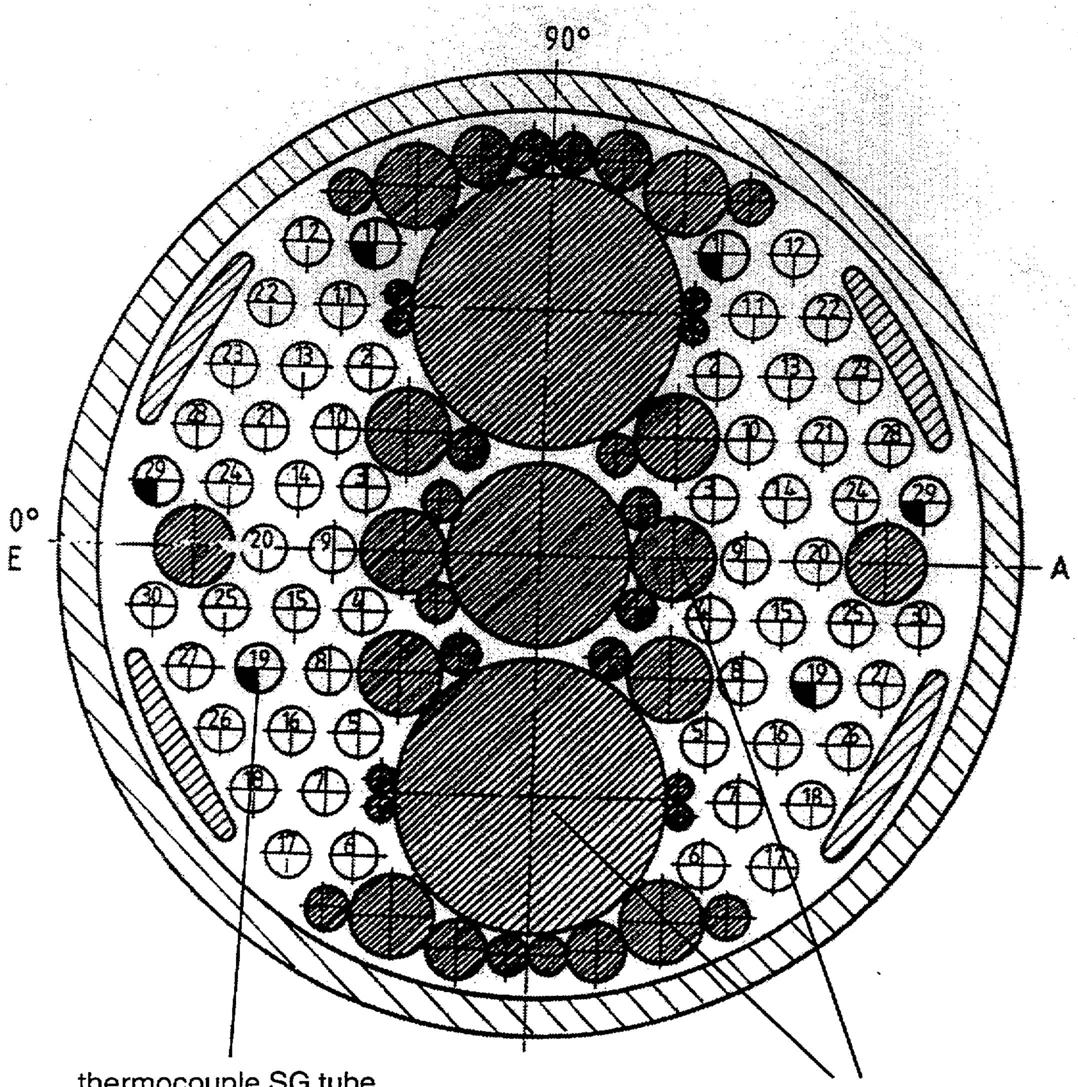


Abb. 2.1: View of PKLIII Test Facility



thermocouple SG tube

replacement bodies

Fig. 2.2: Cross-Sectional View of a PKL III Steam Generator

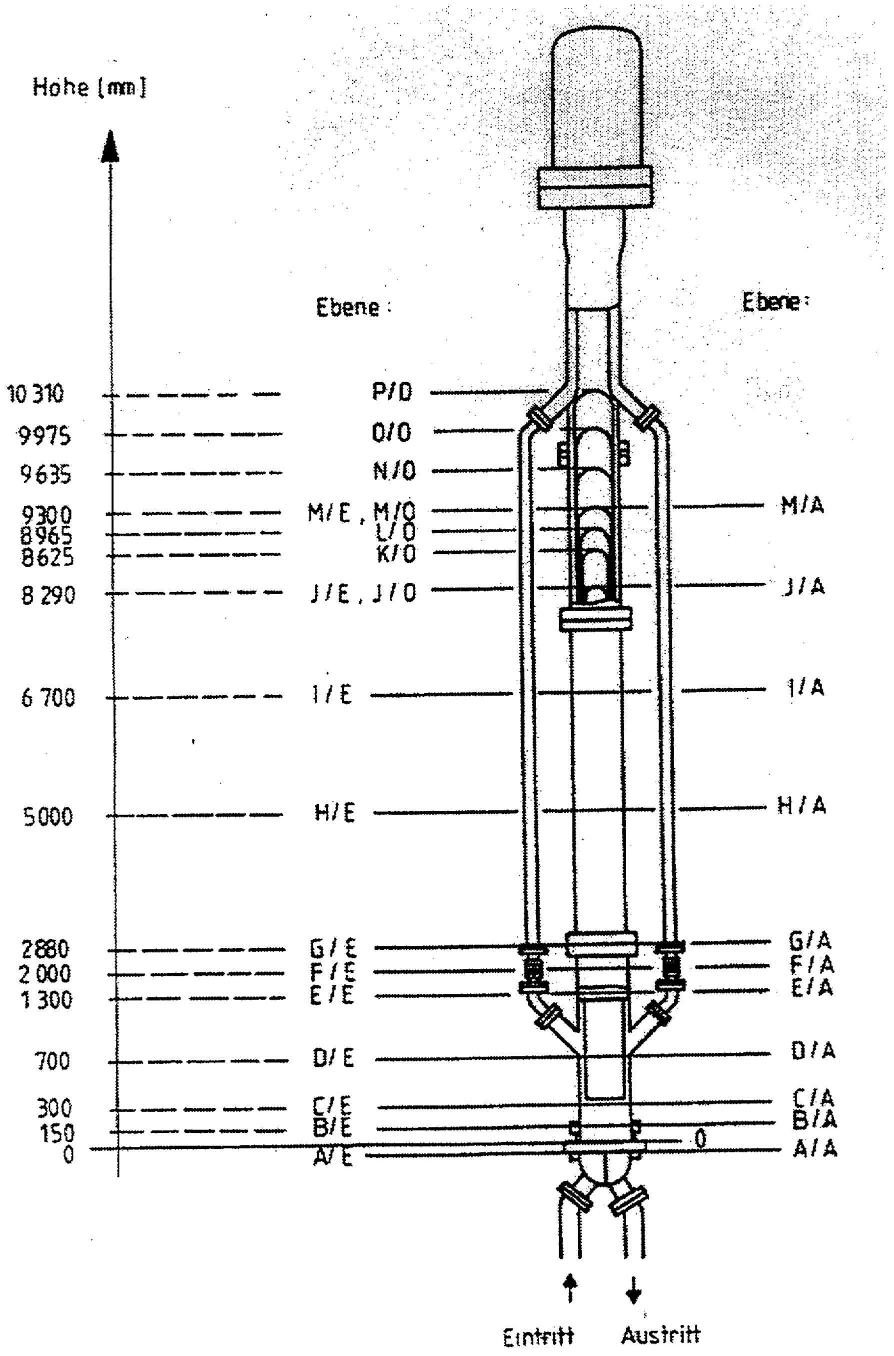


Fig. 2.3 : Axial Locations of Thermocouples in SG tubes

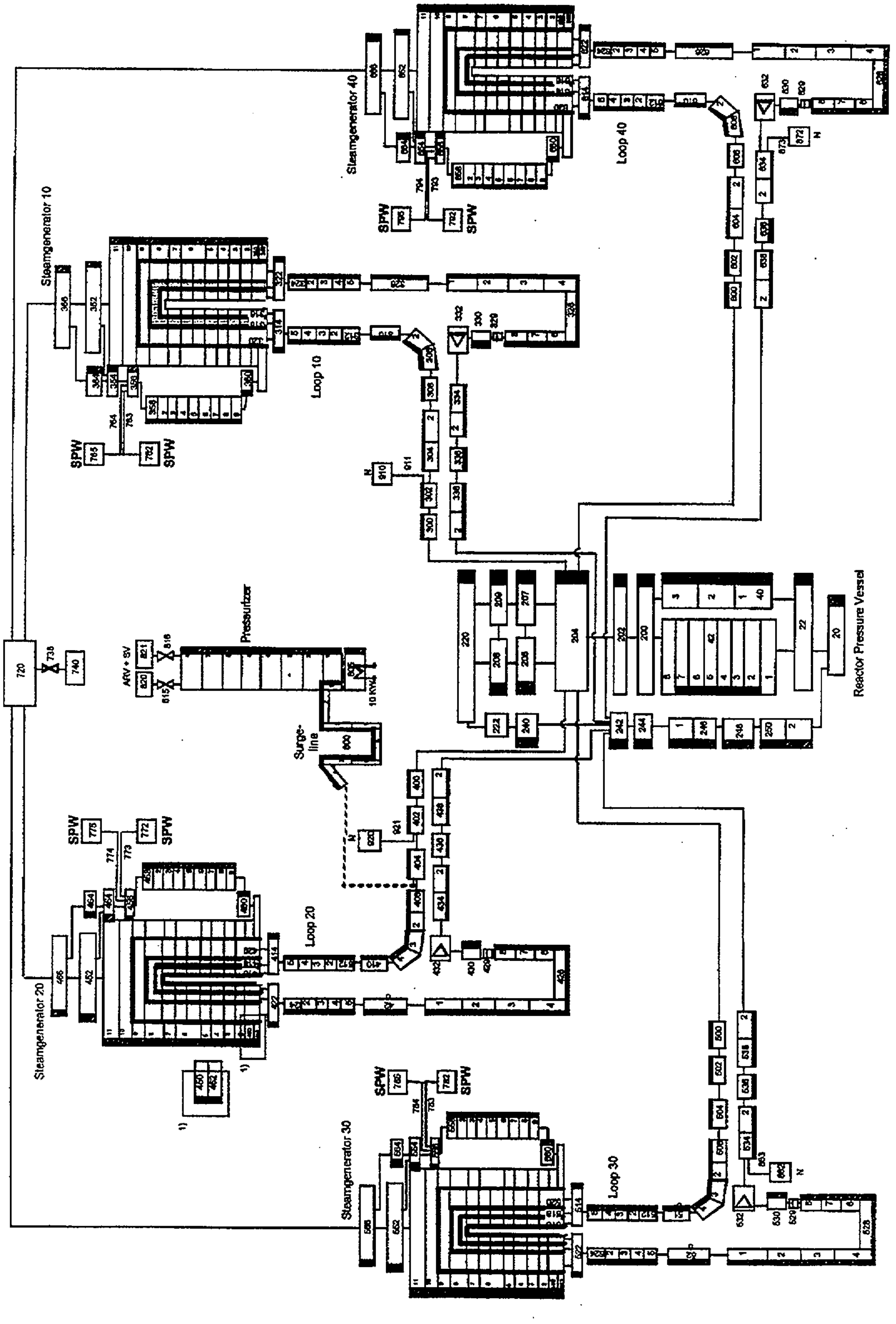


Fig. 4.1 :Nodalization of the PKL III Test Facility with Respect to the B 4.3 Experiment

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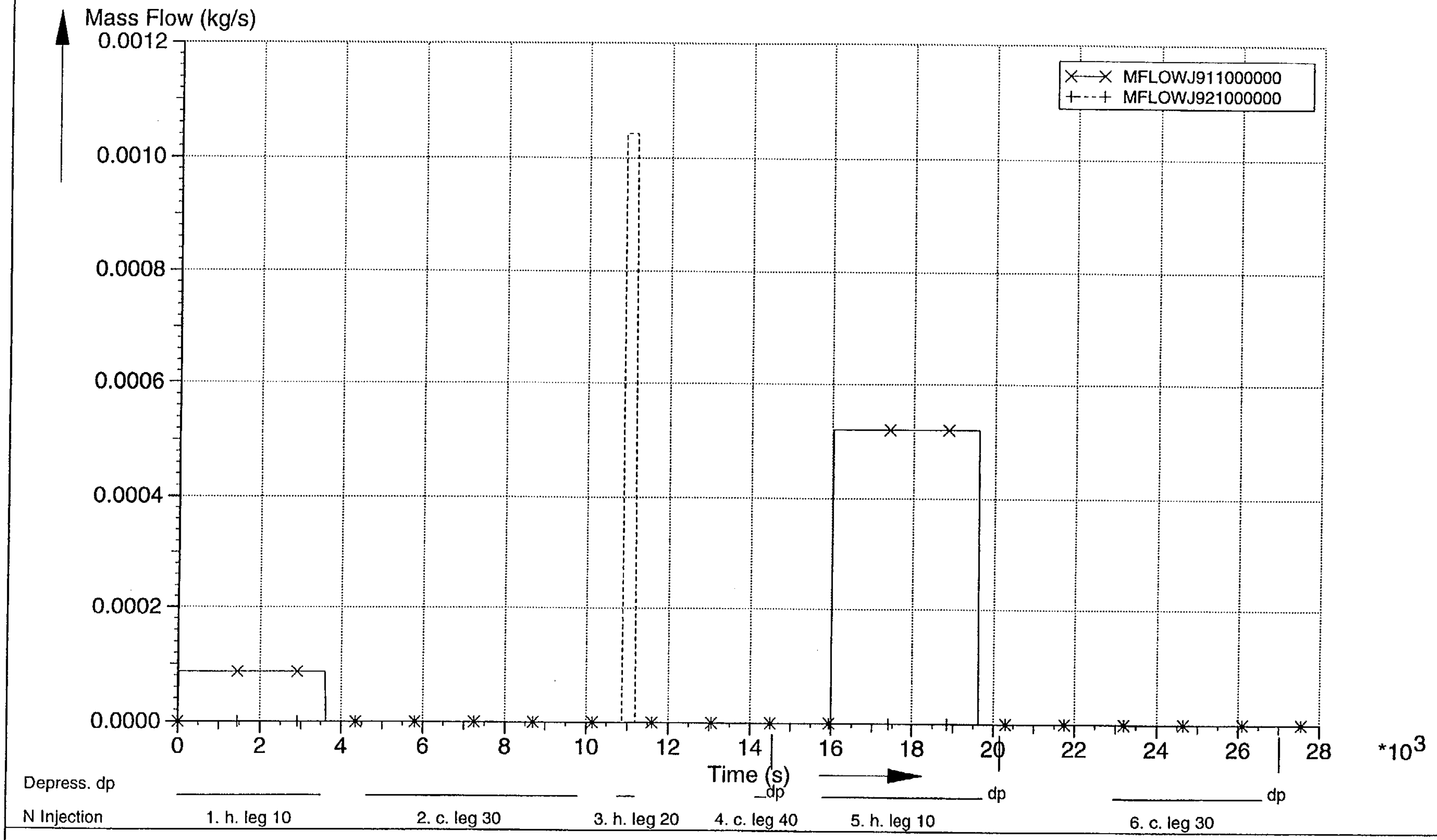

Comparison of Experiment and Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.2: Nitrogen Injection Rate into Hot Legs 10(X) and 20(- -)

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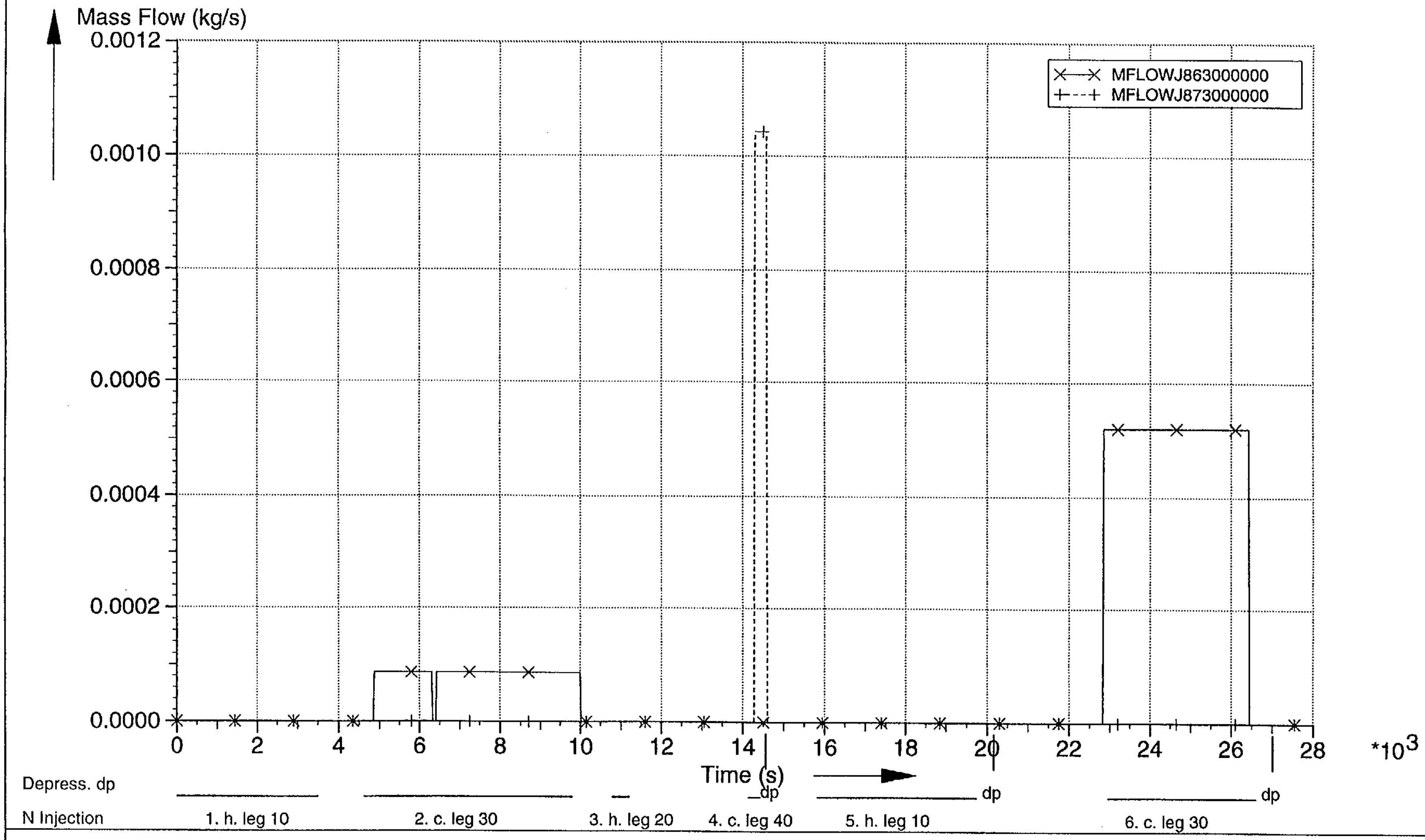

Comparison of Experiment and Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.3: Nitrogen Injection Rate into Cold Legs 30(X) and 40(- -)

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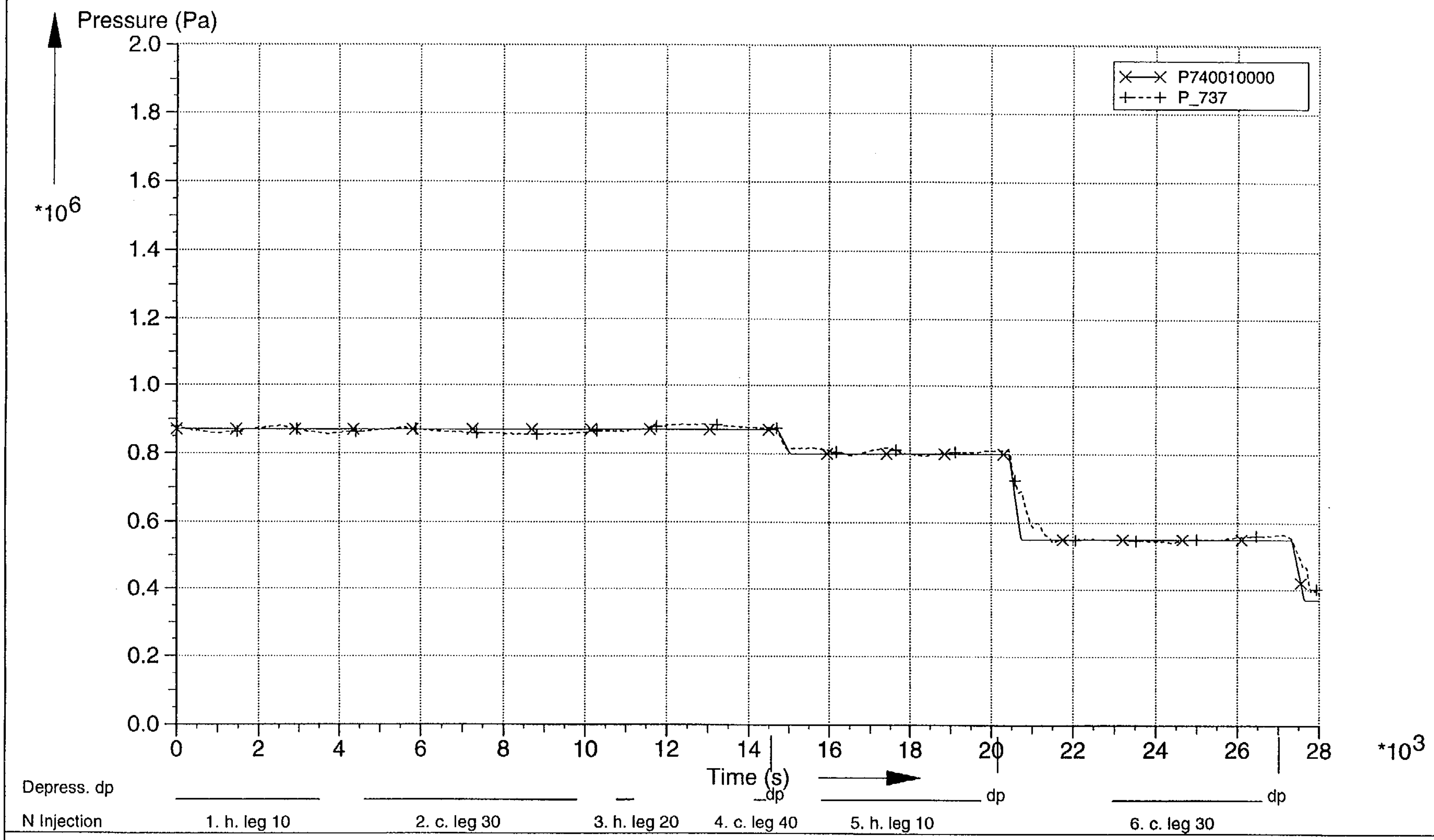

Comparison of Experiment and Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.4: Secondary System Pressure RELAP(X), Experiment(+)

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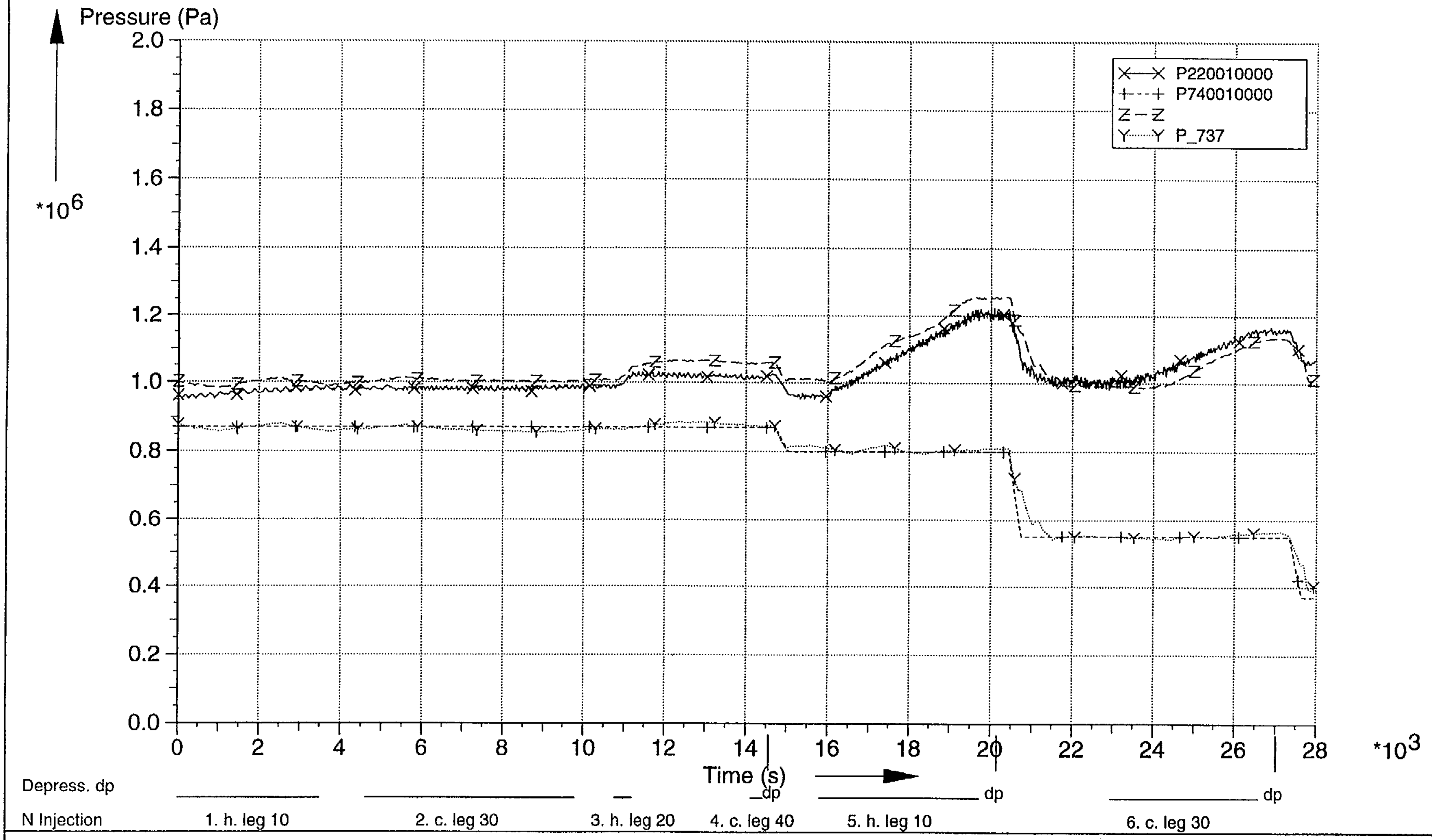

Comparison of Experiment and Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.5: Primary Pressure R(X), Exp.(Z), Secondary Press. R(+), Exp.(Y)

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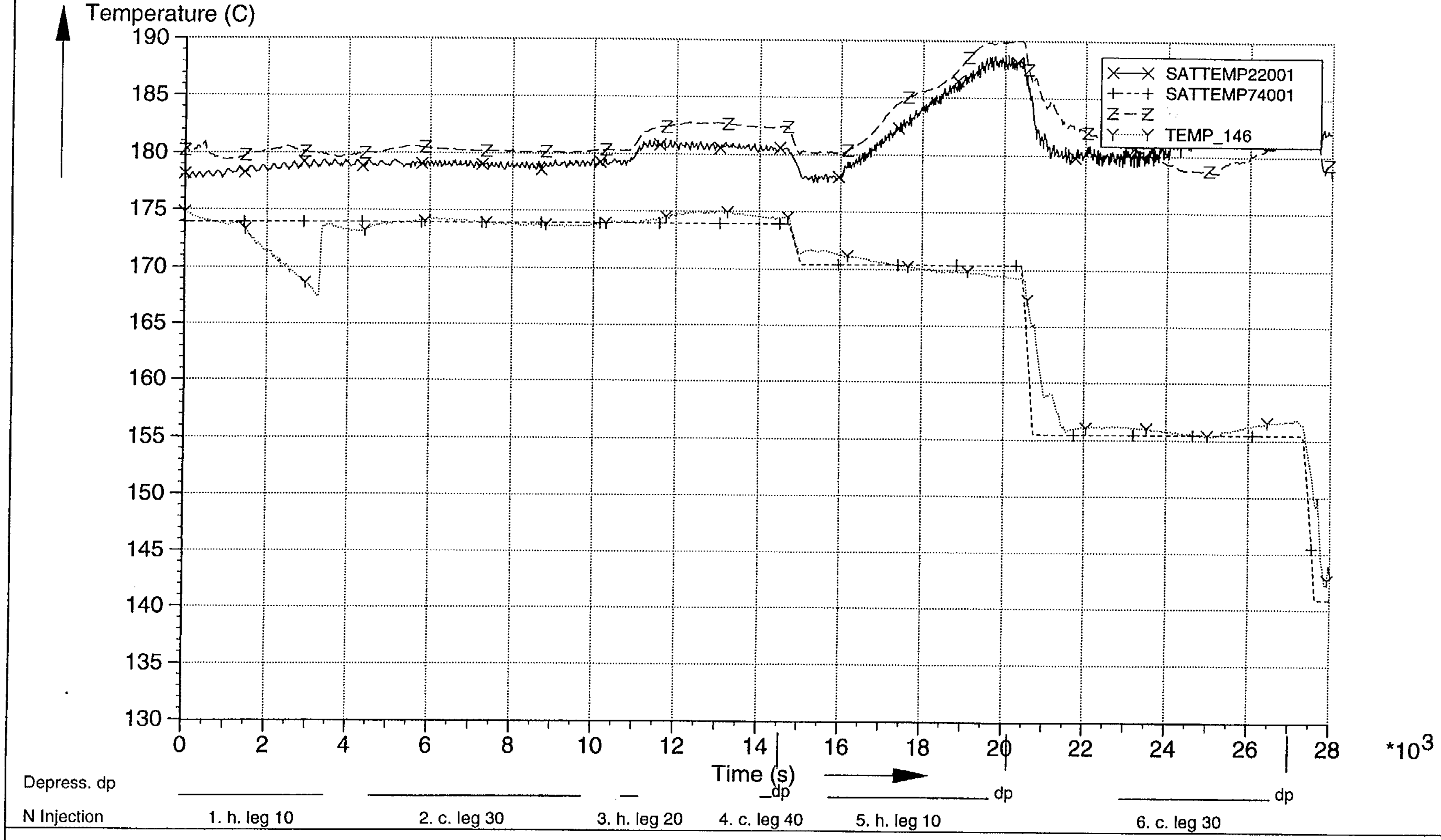

Comparison of Experiment and Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.6: Primary Temperature R(X), Exp.(Z), Second. Temp. R(+), Exp.(Y)

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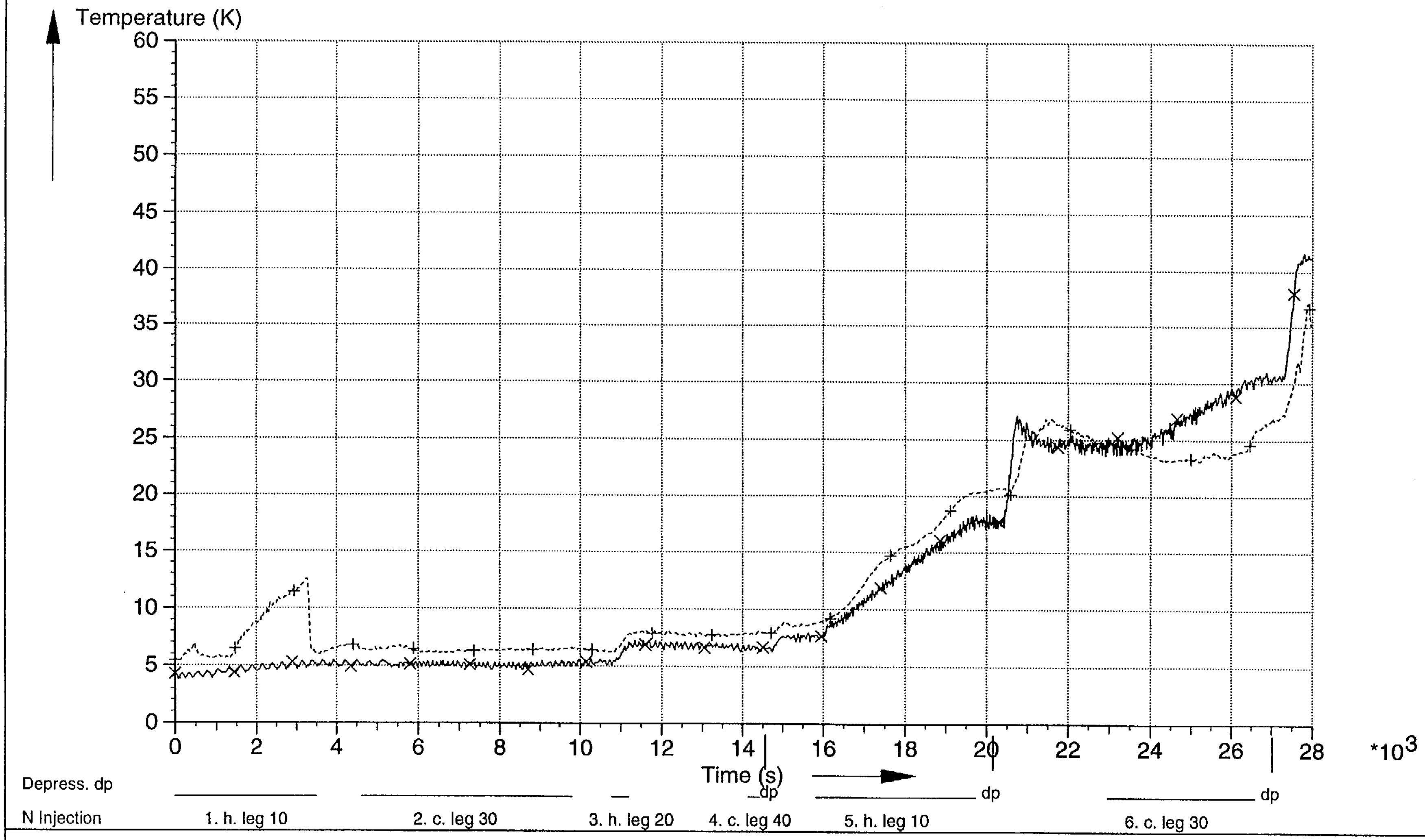

Comparison of Experiment and Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.7: Temperature Diff. Primary-S. - Secondary-S. R(X), Exp.(+)

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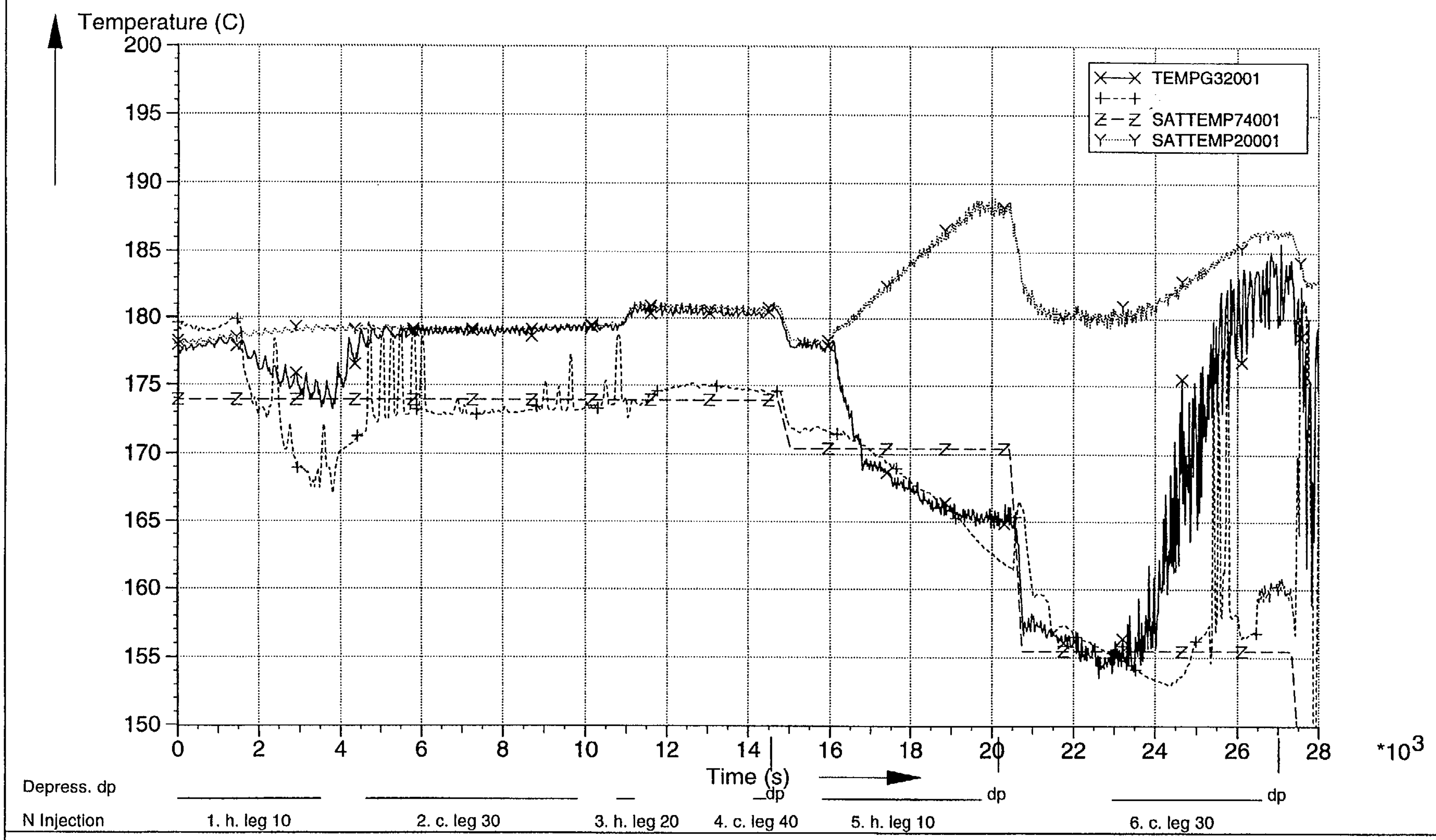
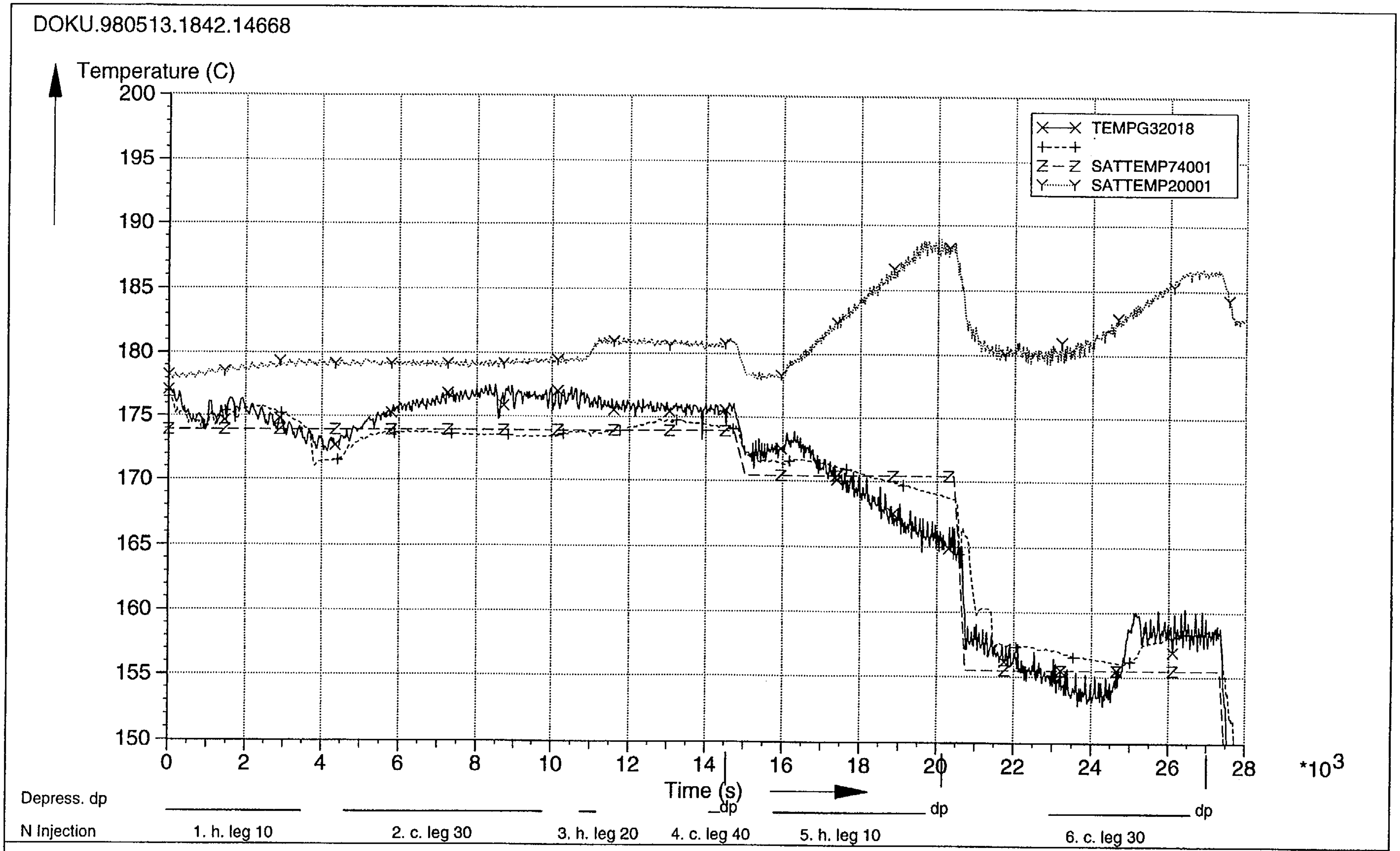


Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.8: SG 10 Asc. U-Tubes R(X), Exp.(+), Satt-sec(Z), Satt-pr(Y)



Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.9: SG 10 Desc. U-Tubes R(X), Exp.(+), Satt-sec(Z), Satt-pr(Y)

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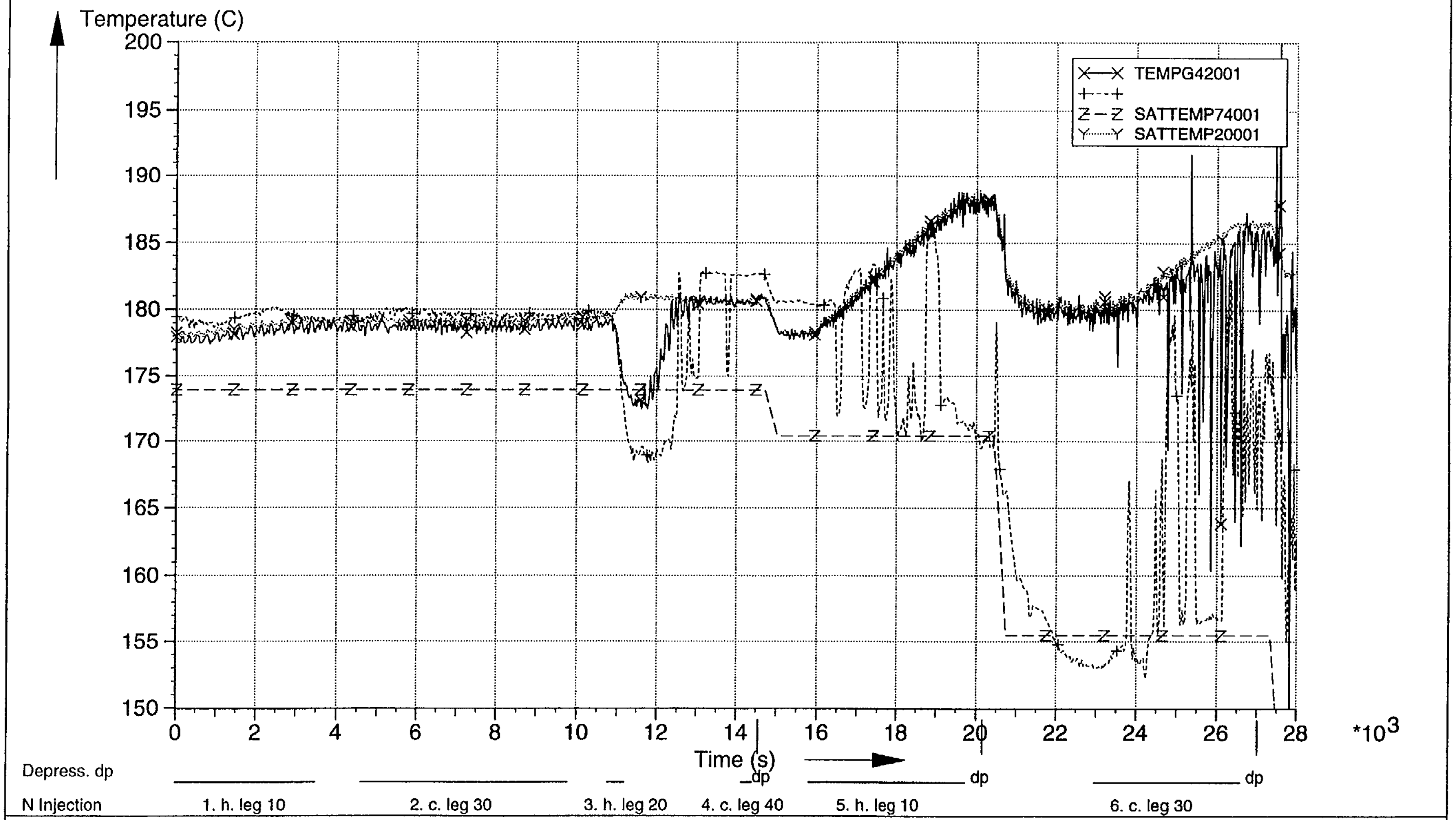

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.10: SG 20 Asc. U-Tubes R(X), Exp.(+), Satt-sec(Z), Satt-pr(Y)

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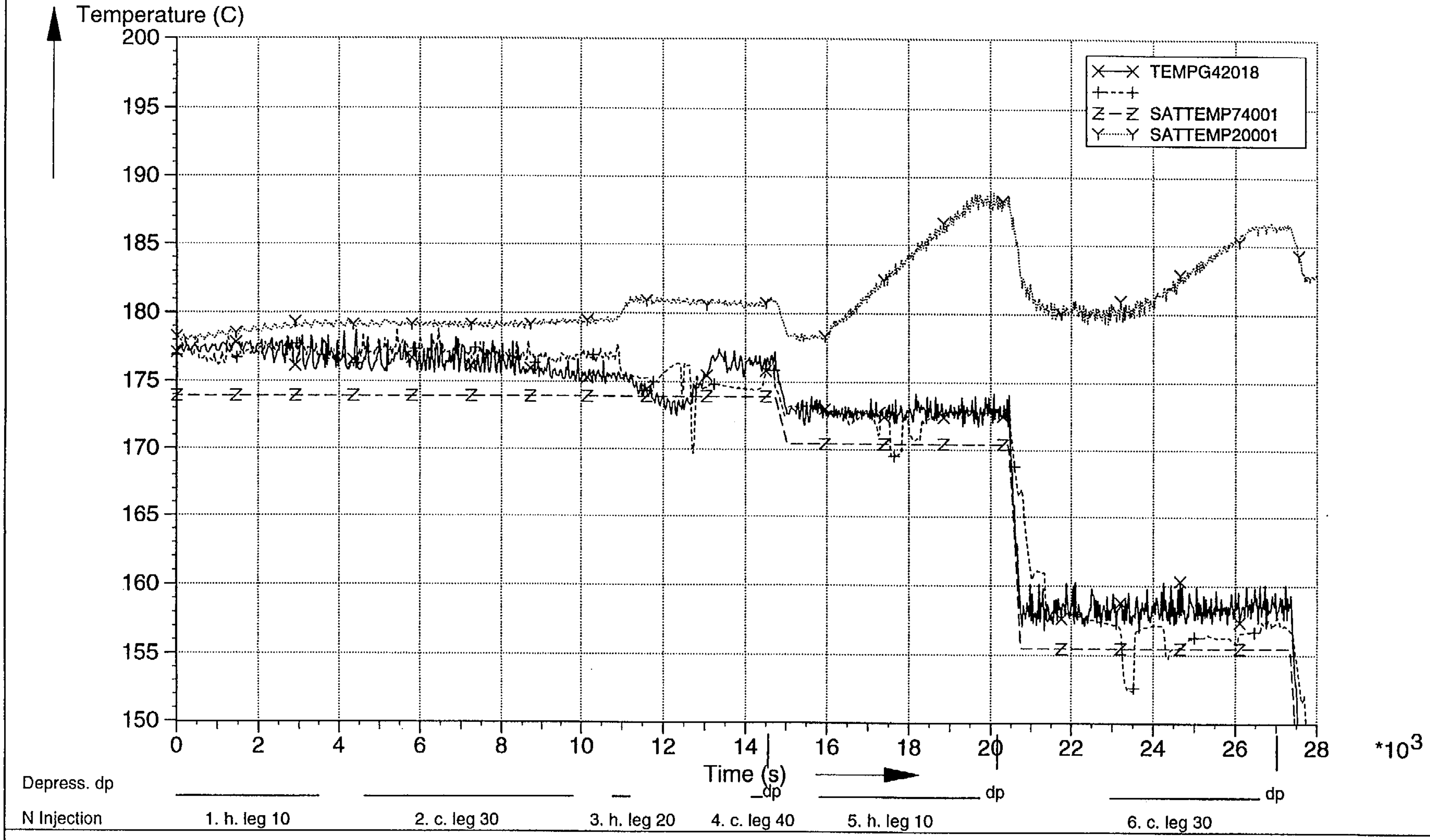

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.11: SG 20 Desc. U-Tubes R(X), Exp.(+), Satt-sec(Z), Satt-pr(Y)

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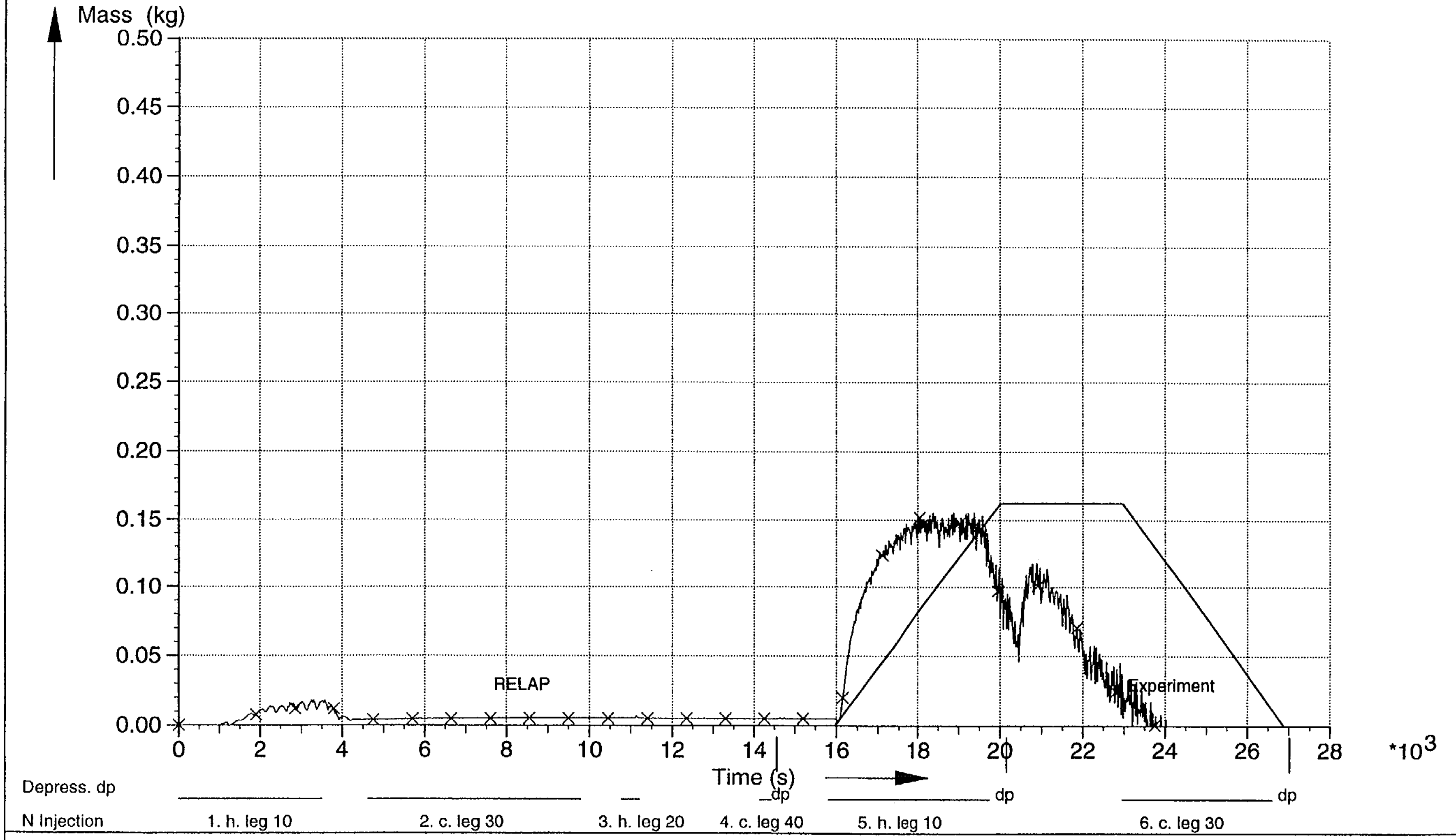
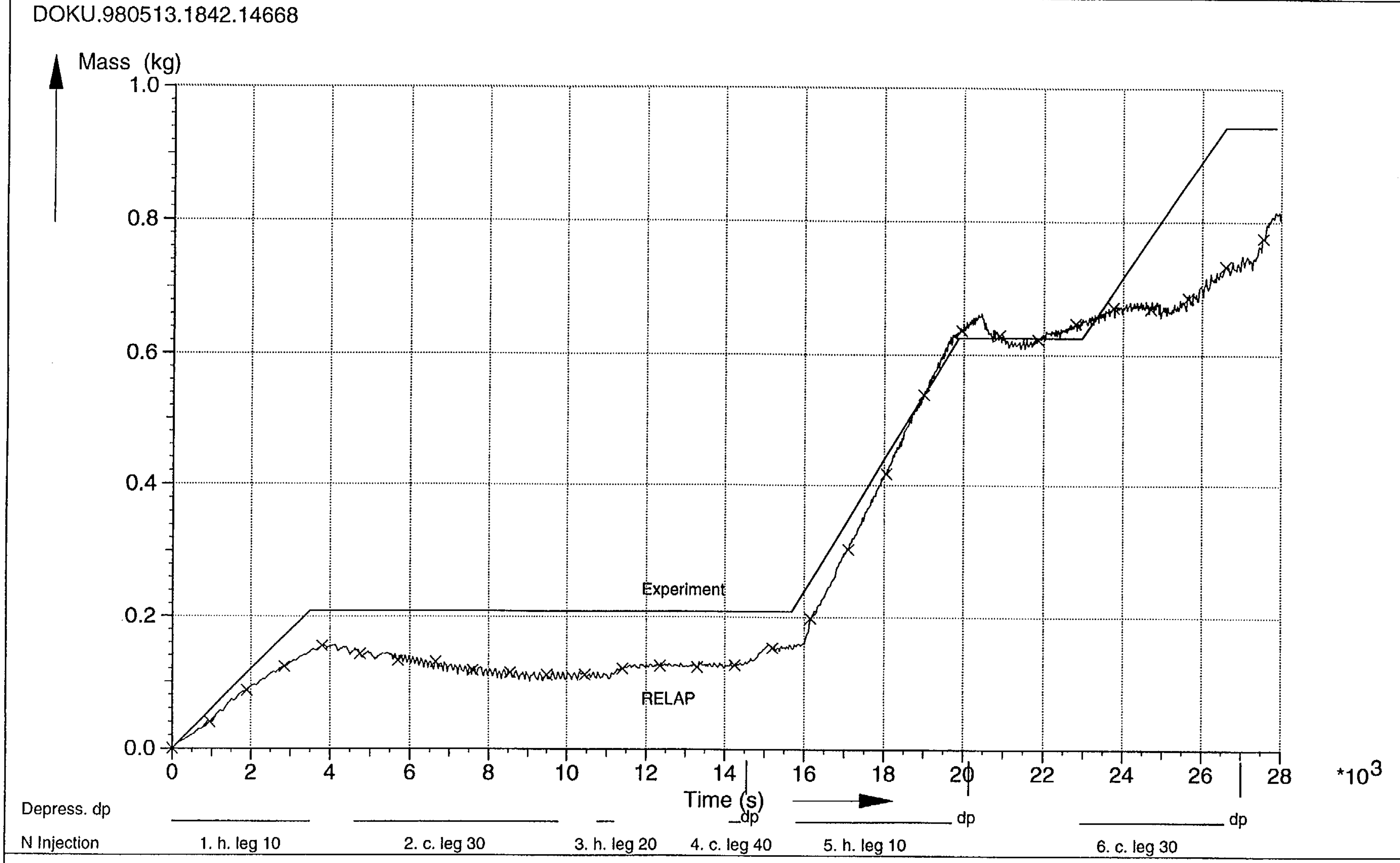


Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.12: Nitrogen Mass Loop 10 Hot Leg + SG Inlet



Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.13: Nitrogen Mass Loop 10 SG U-Tubes

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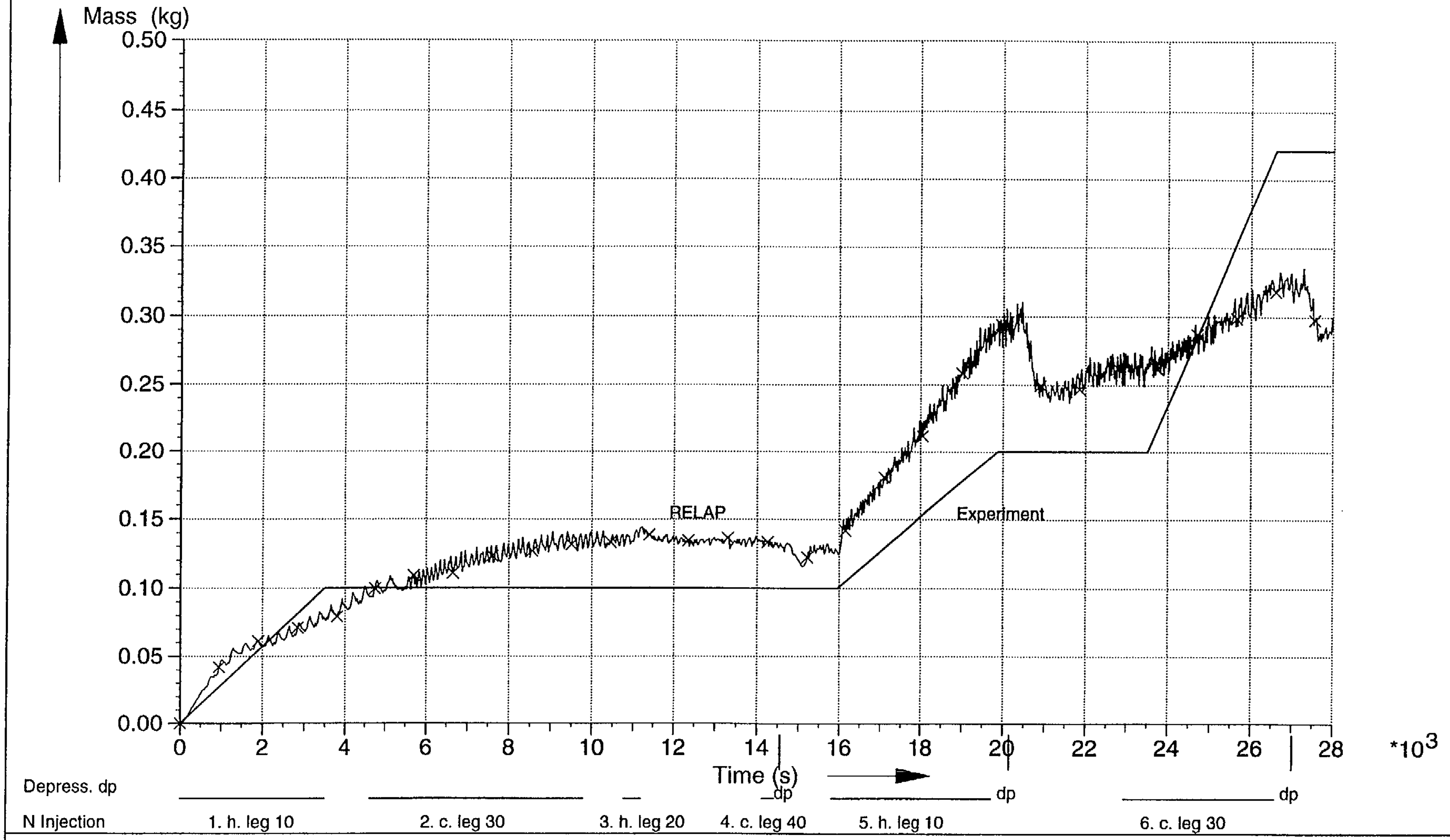

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.14: N Mass SG 10 Outlet to half Loop Seal

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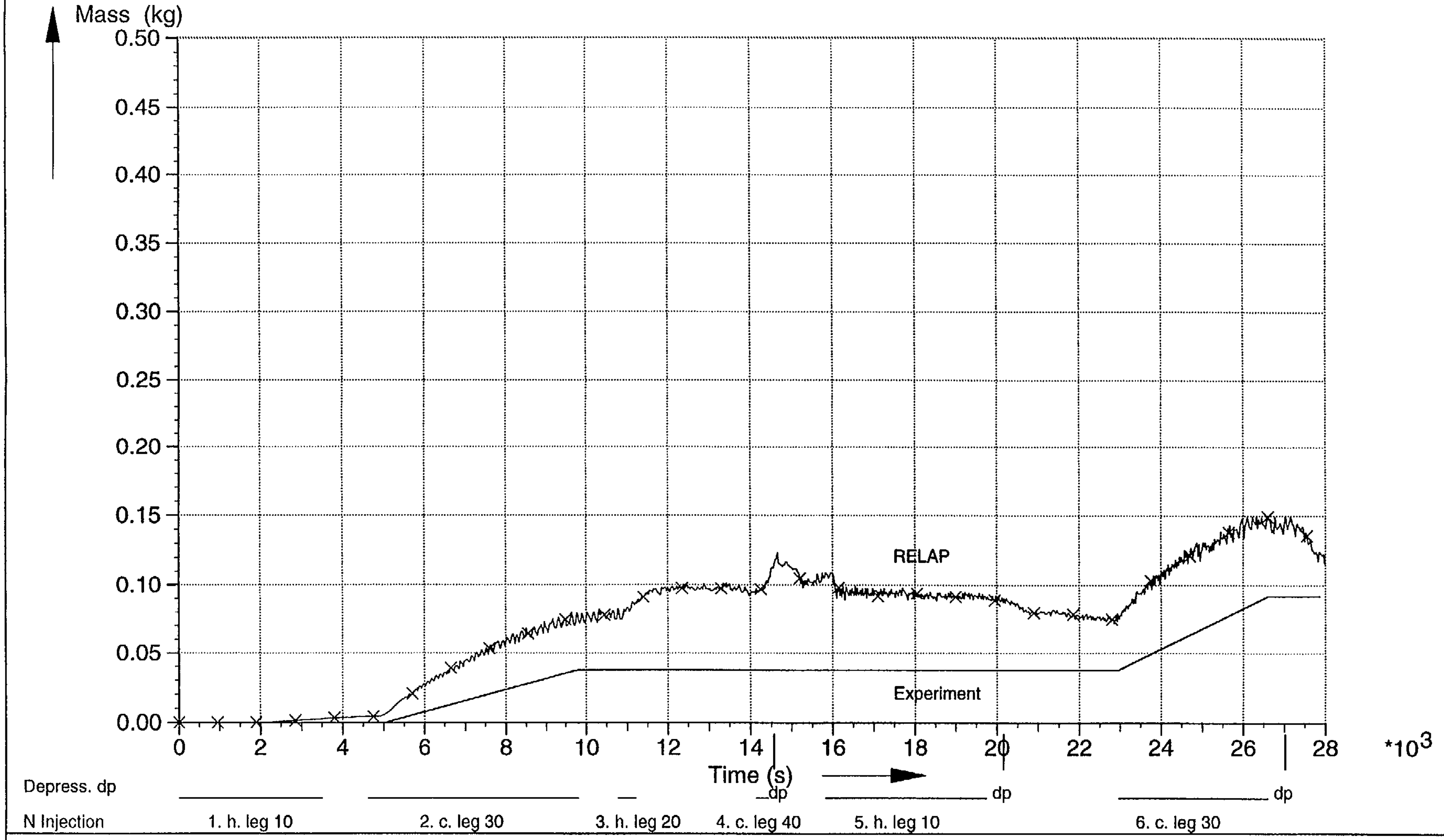

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.15: N Mass Loop 10 half Loop Seal to RPV Inlet

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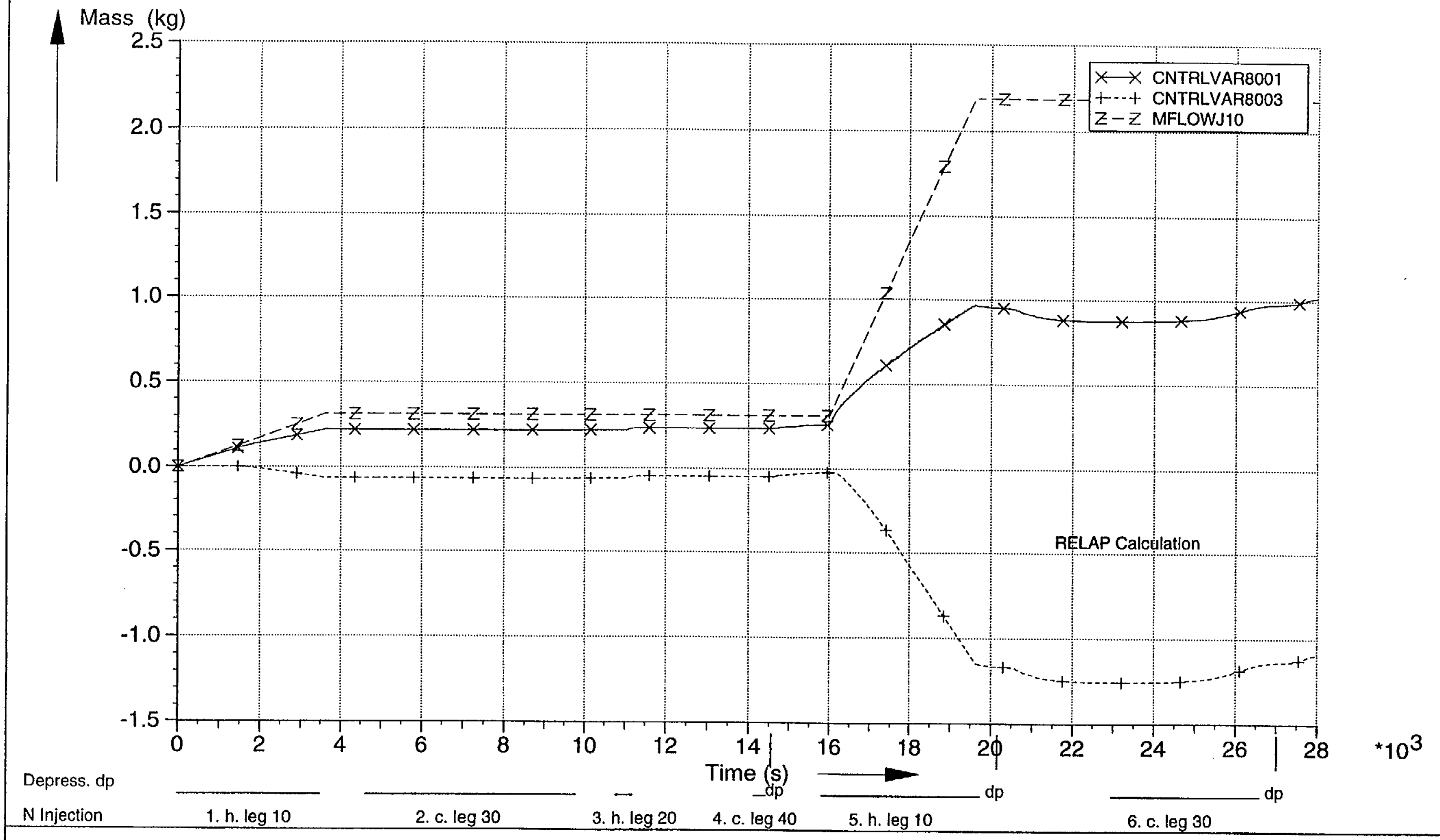

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.16: Int. N Injection L. 10 Hot Leg(Z), SG-Side(X), RPV-Side(+)

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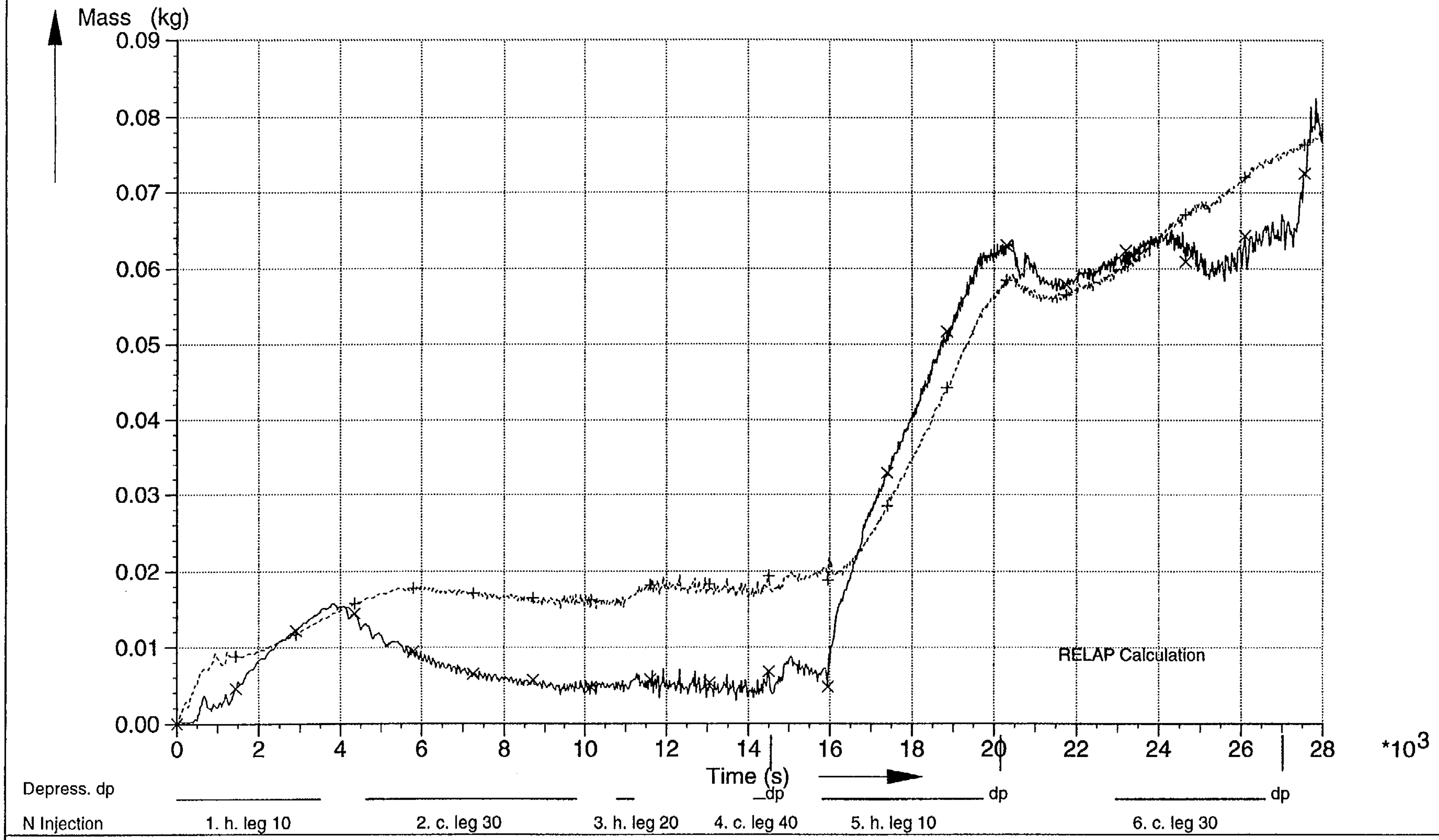

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.17: N Mass SG 10, Pipe 320 Ascending(X), Descending(+) U-Tubes

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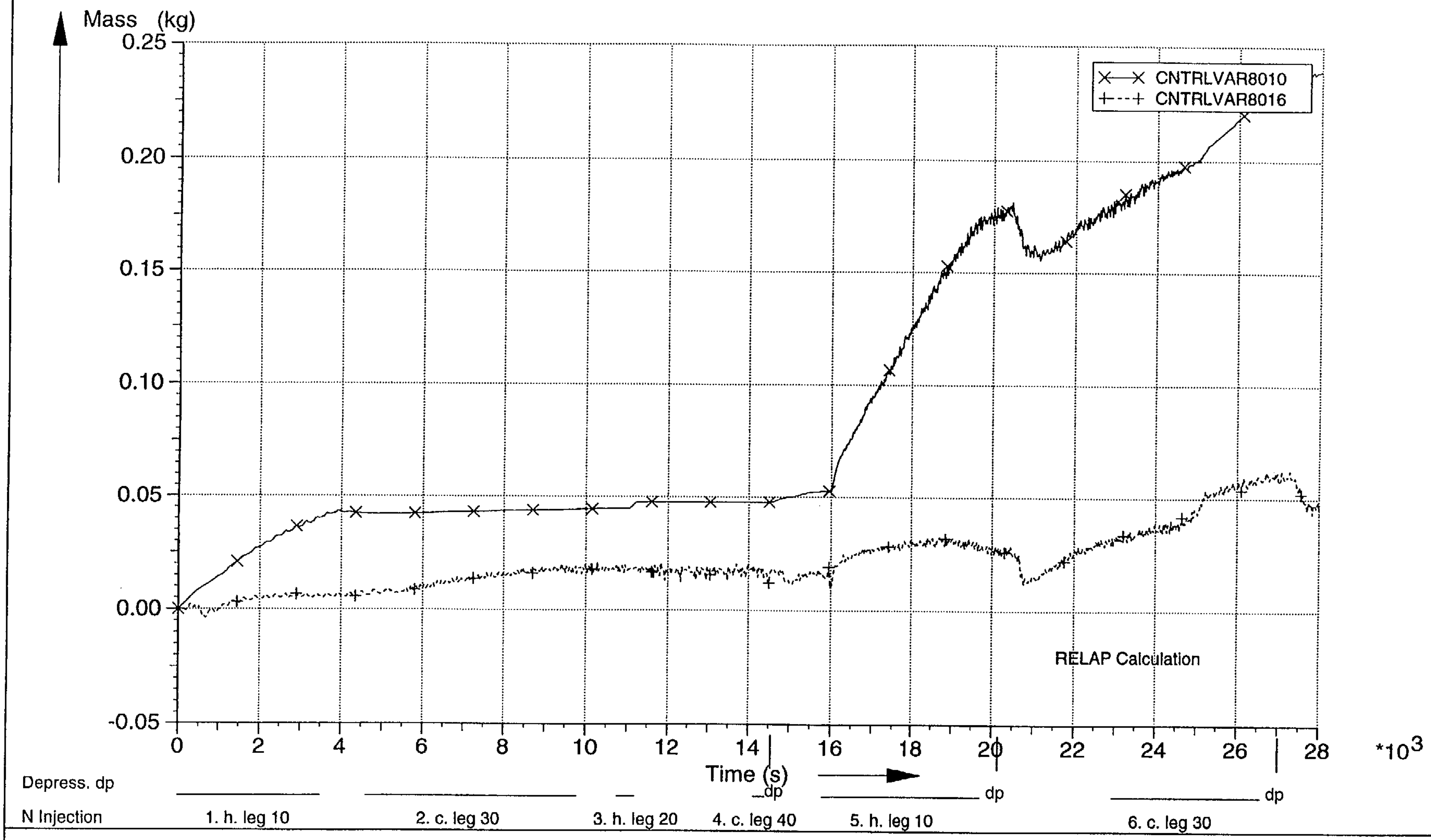

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.18: Integr. N Mass Flow SG 10, Pipe 320 Inlet(X), Outlet(+)

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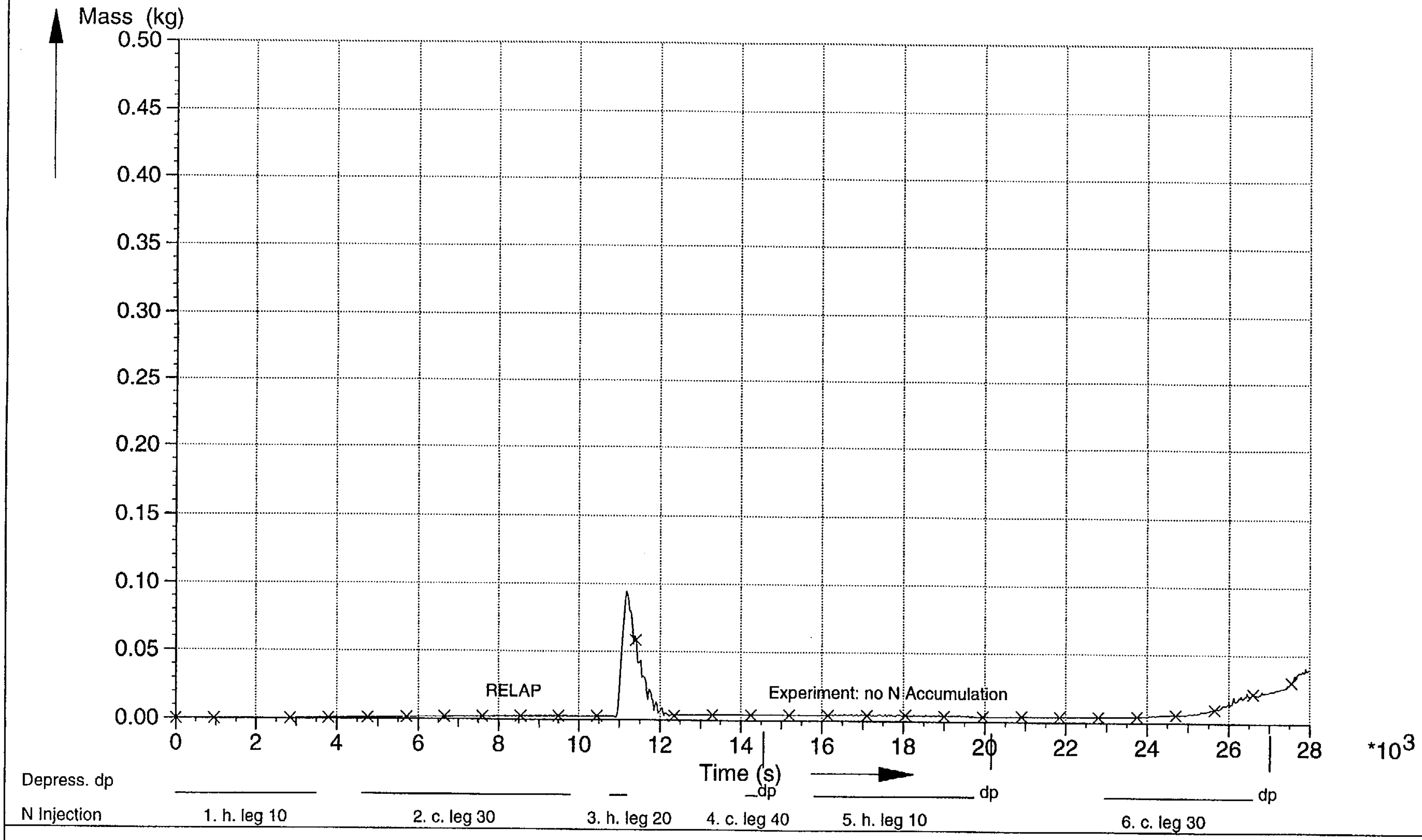

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.19: Nitrogen Mass Loop 20 Hot Leg + SG Inlet

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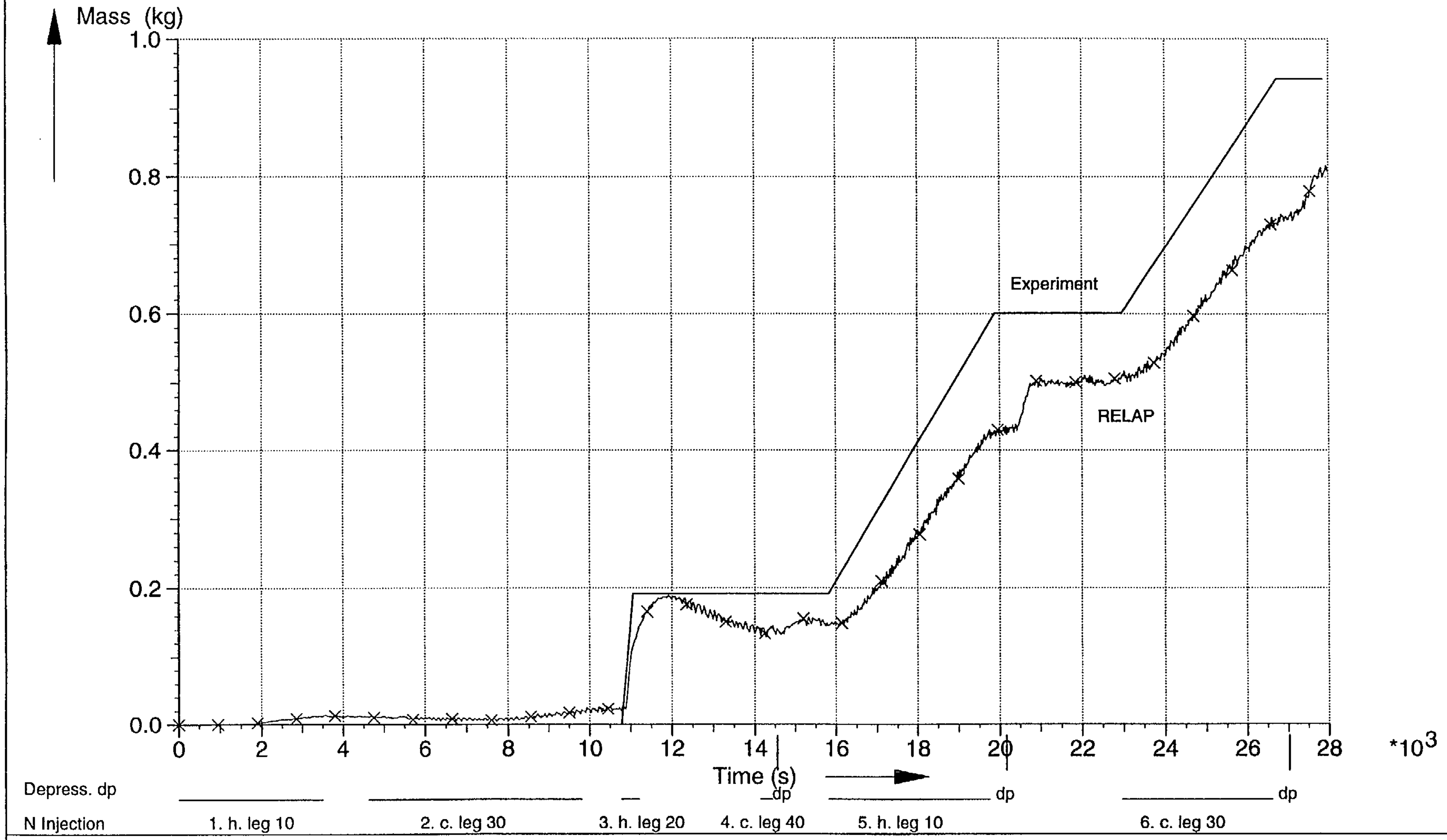

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.20: Nitrogen Mass Loop 20 SG U-Tubes

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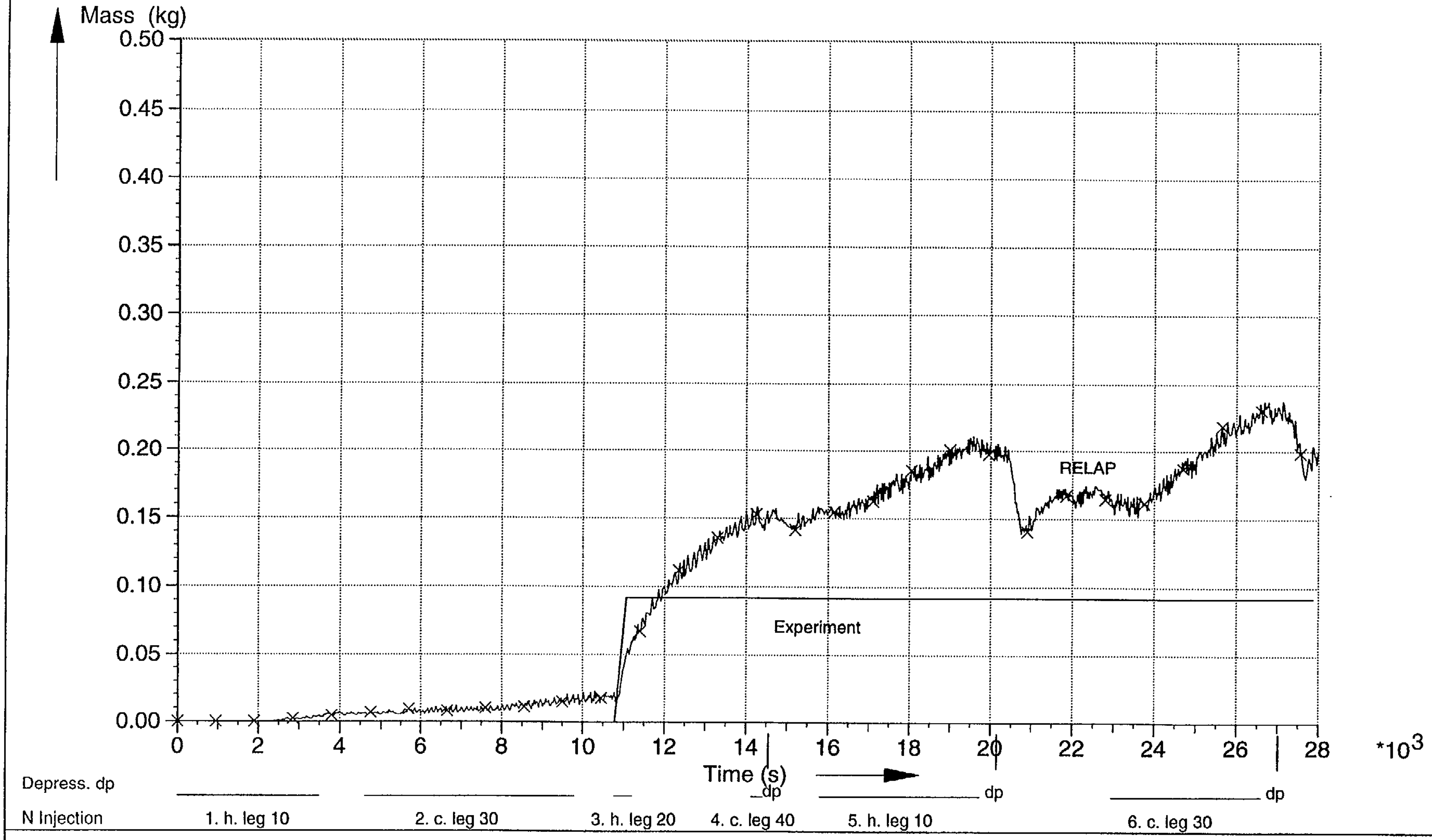

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.21: N Mass SG 20 Outlet to half Loop Seal

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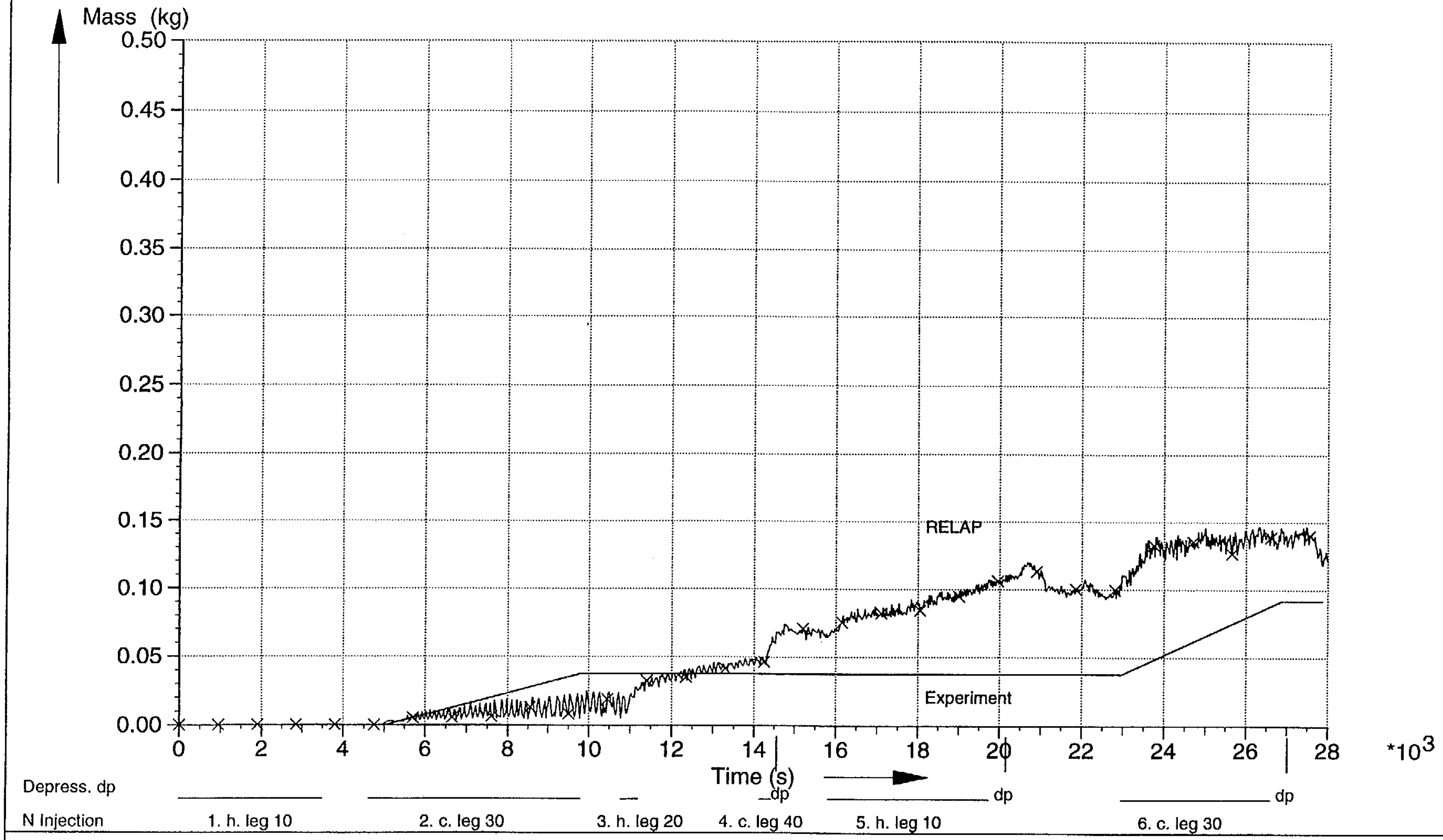

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.22: N Mass Loop 20 half Loop Seal to RPV Inlet

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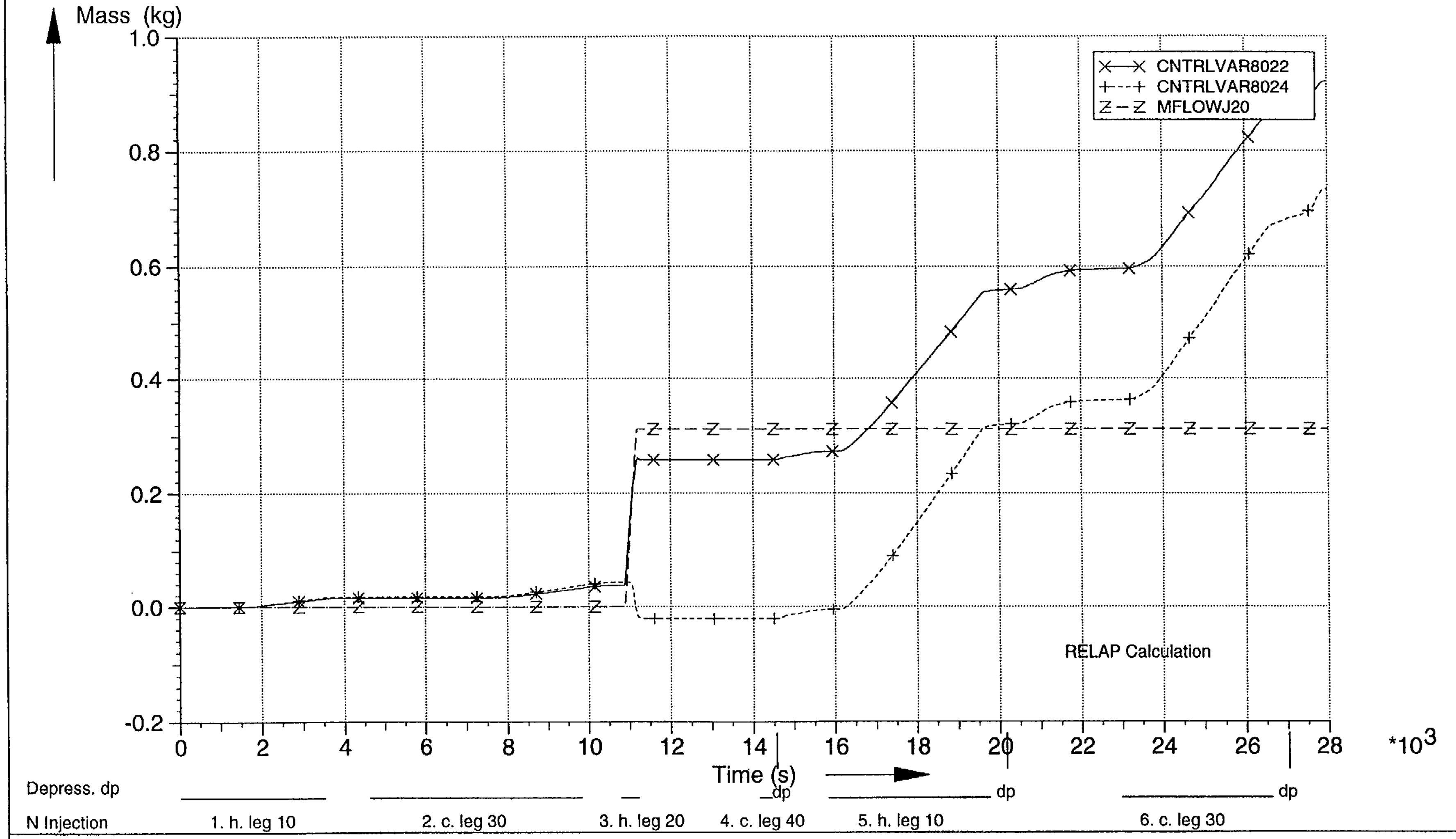

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.23: Int. N2 Injection L. 20 Hot Leg(Z), SG-Side(X), RPV-Side(+)

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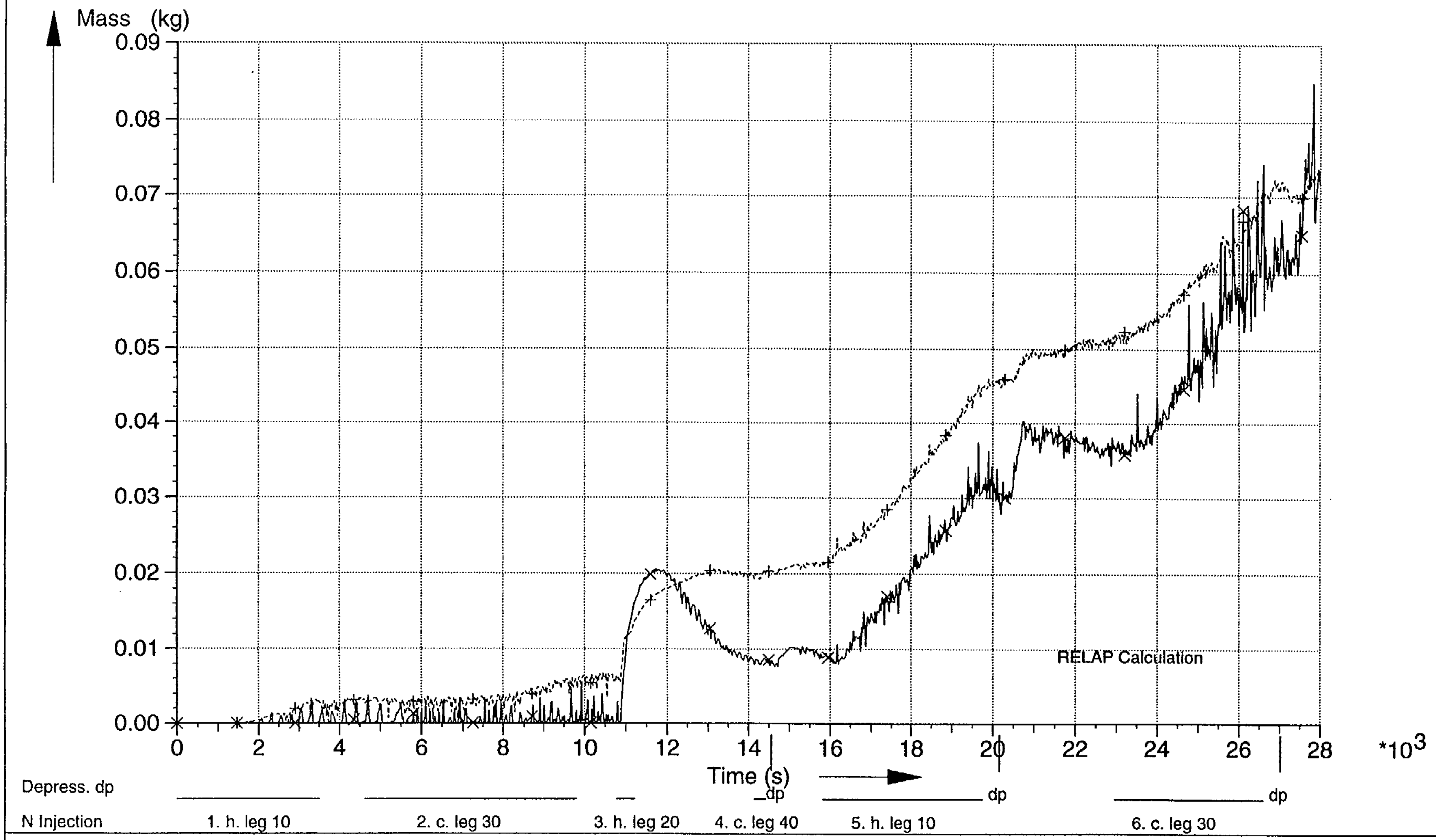

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.24: N Mass SG 20, Pipe 420 Ascending(X), Descending(+) U-Tubes

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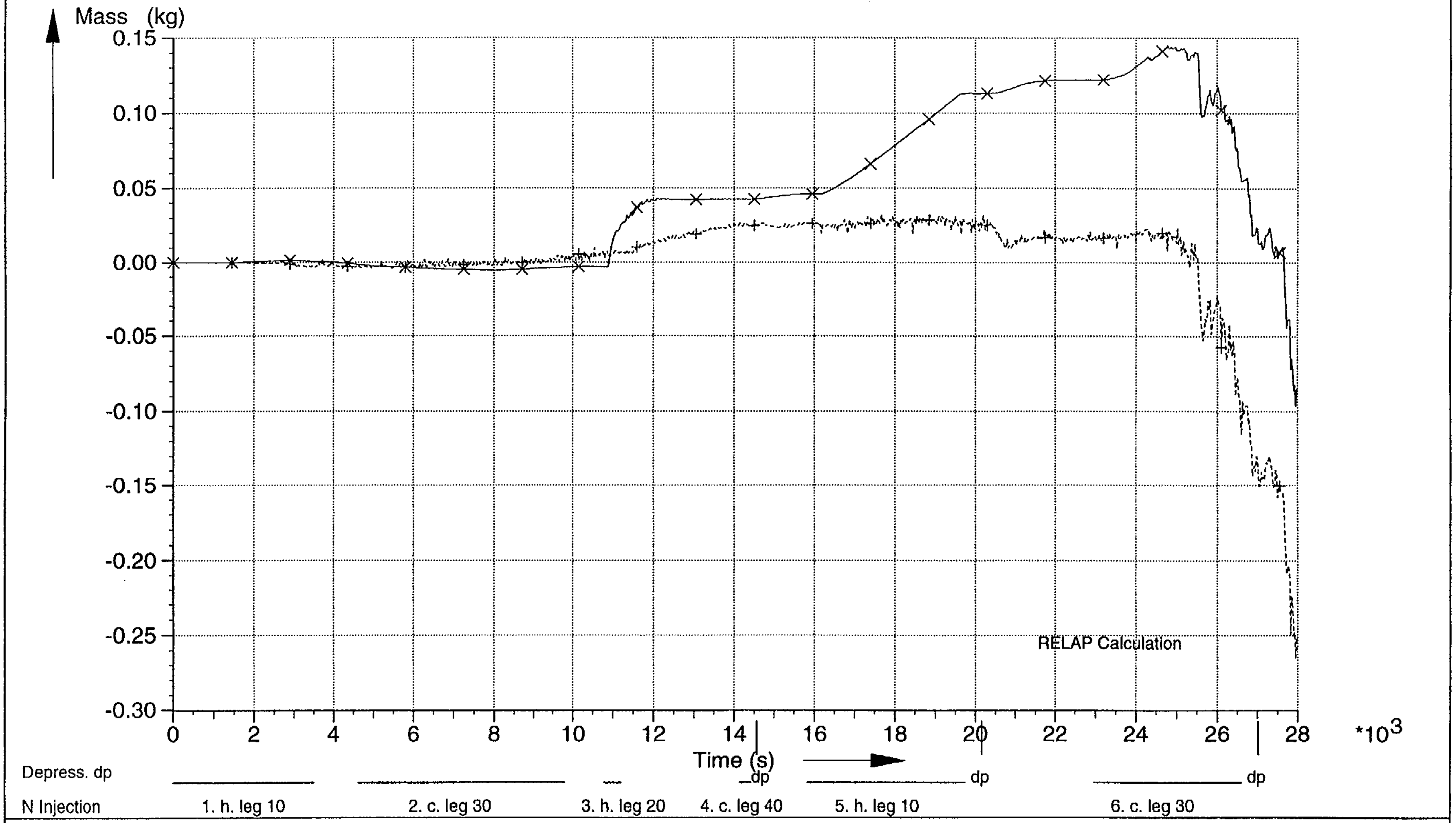
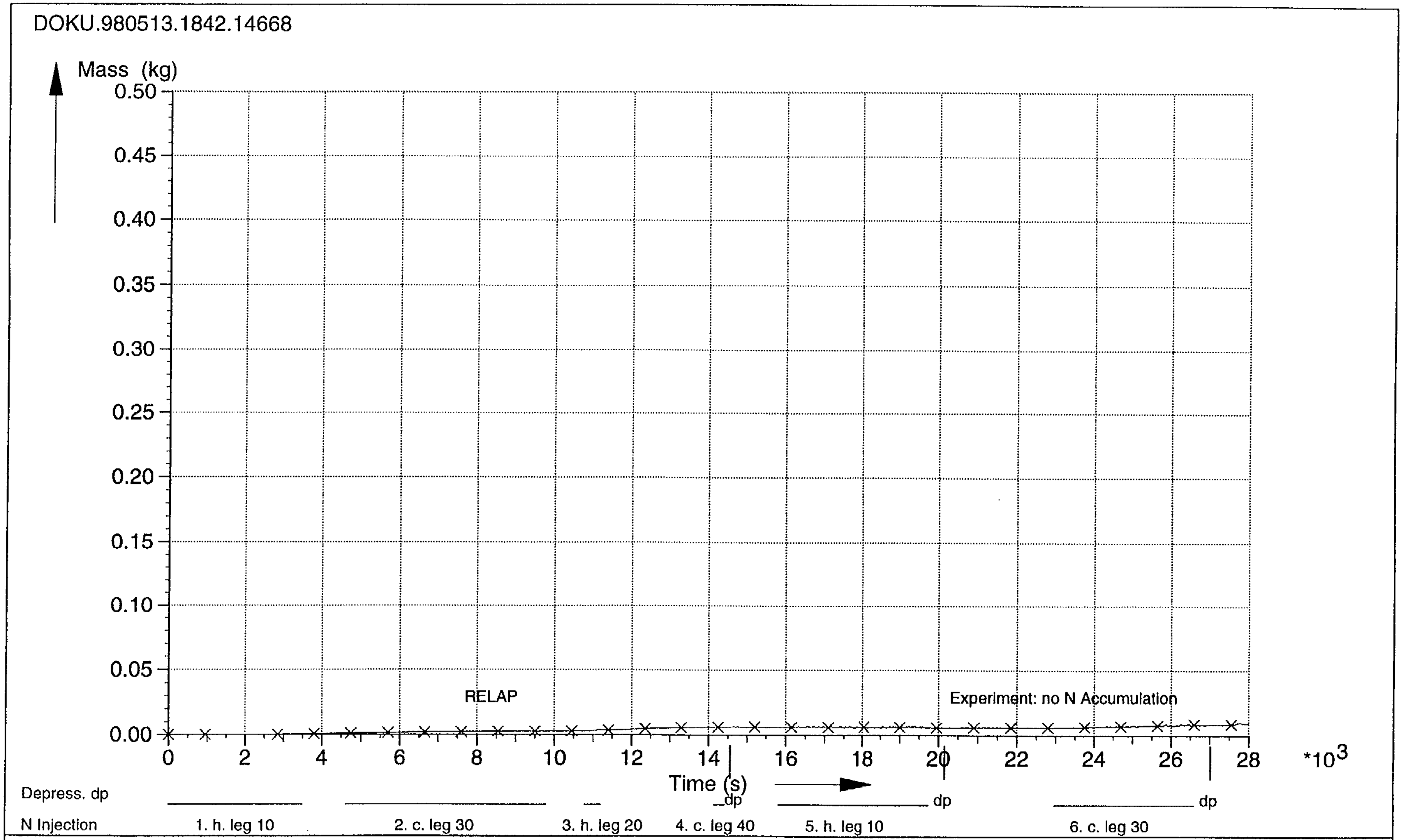


Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.25: Integr. N Mass Flow SG 20, Pipe 420 Inlet(X), Outlet(+)



Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.26: Nitrogen Mass Loop 30 Hot Leg + SG Inlet

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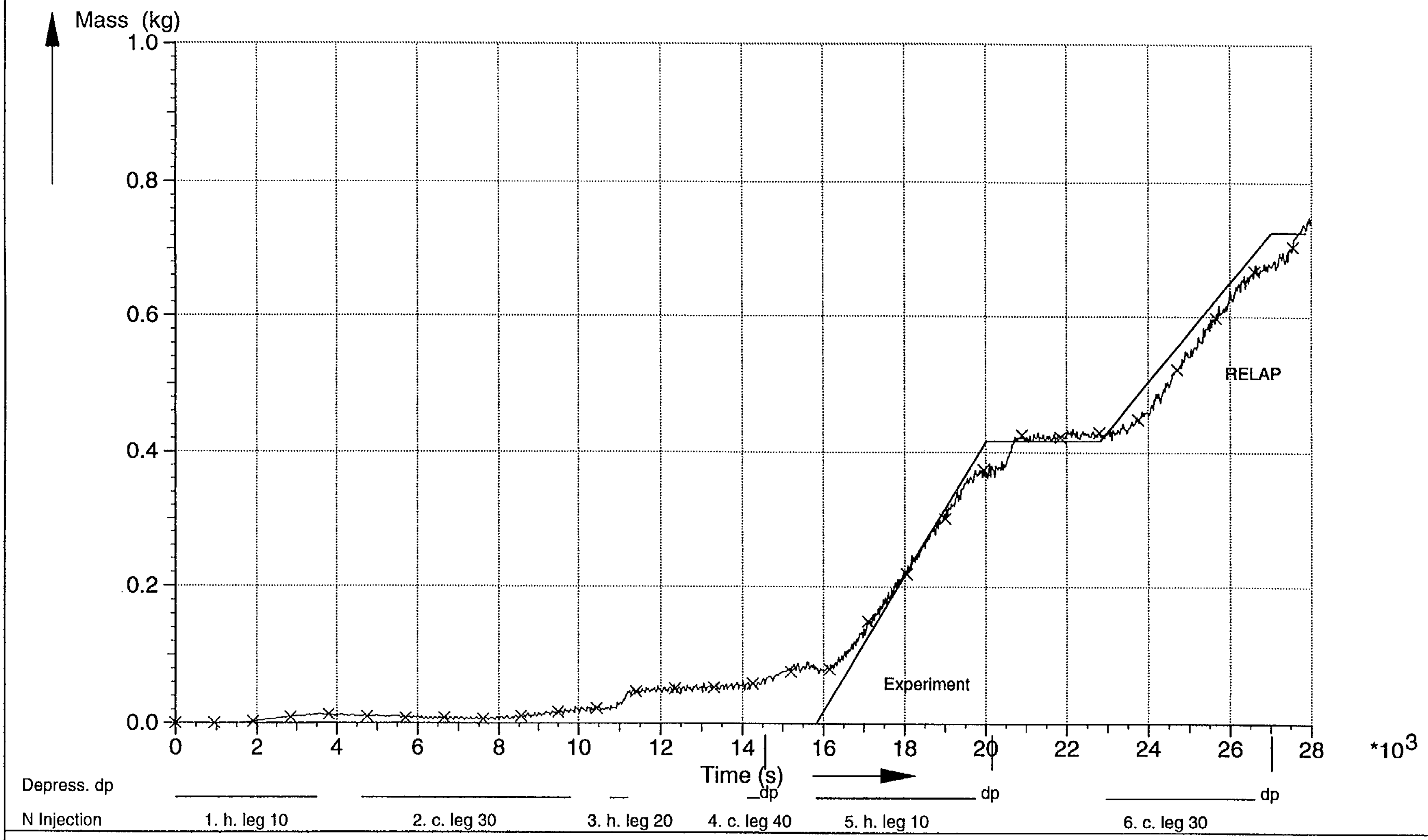

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.27: N Mass Loop 30 SG U-Tubes

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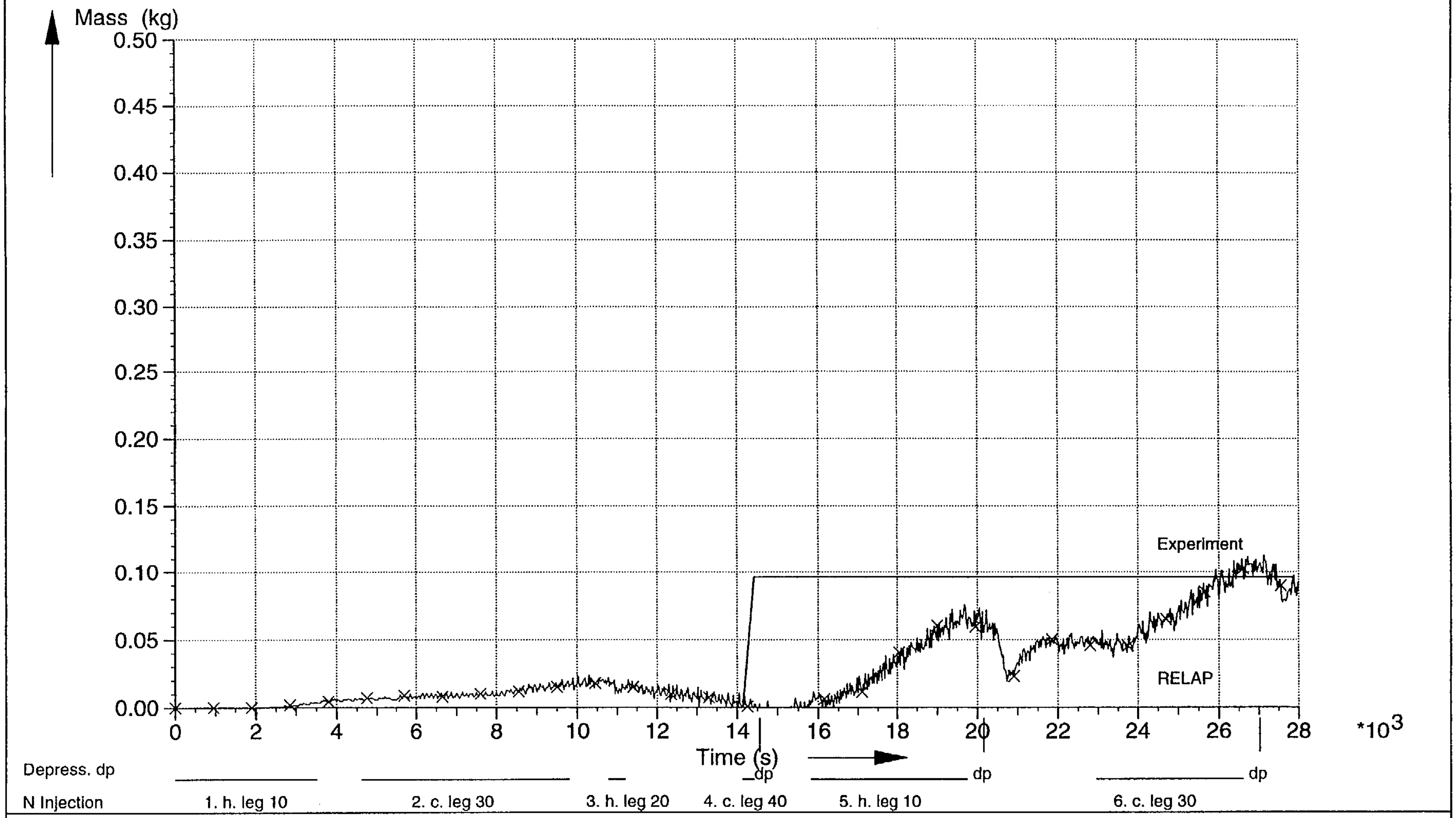

Comparison of Experiment und Analysis PKL III B 4.3
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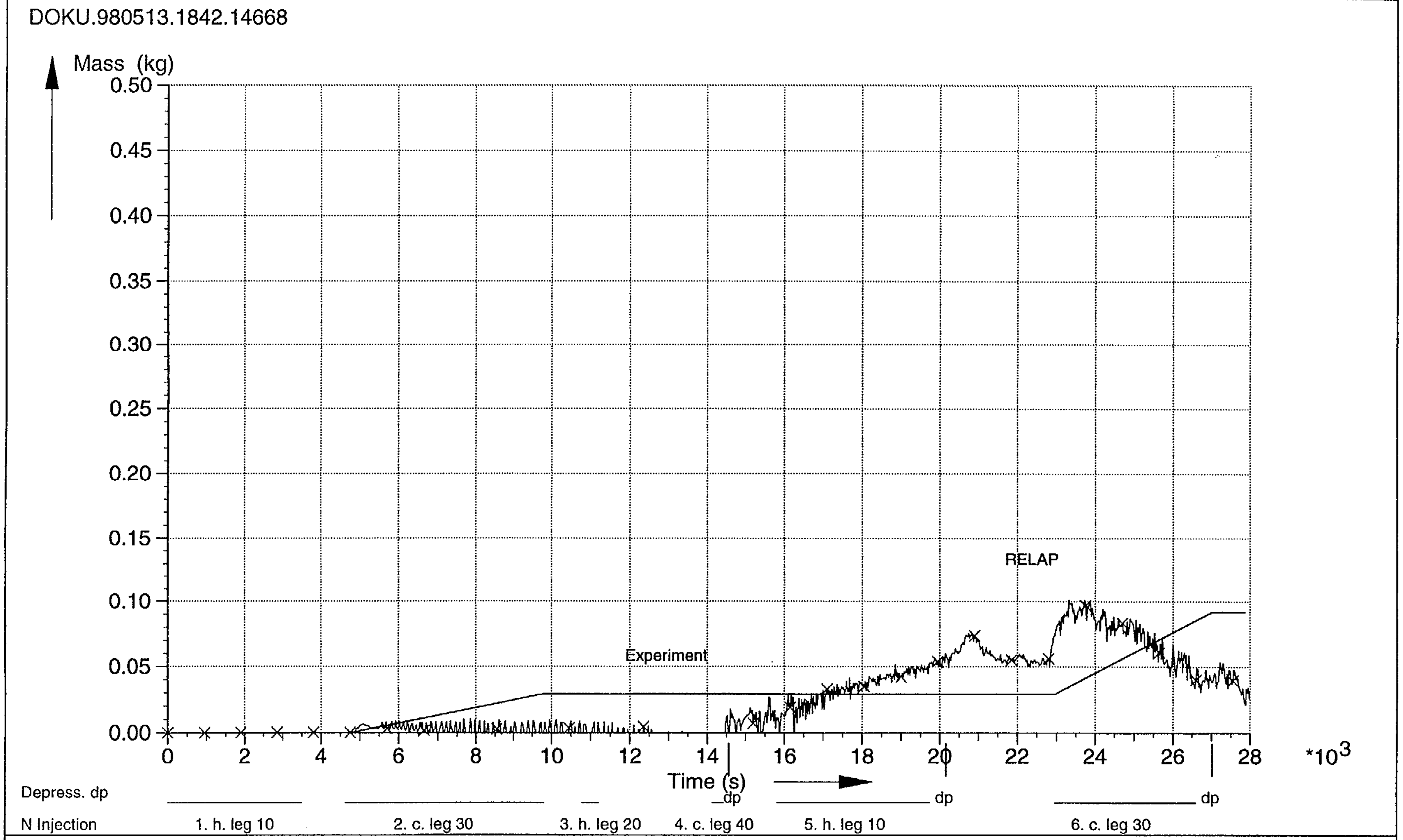
Fig. 4.28: N Mass SG 30 Outlet to half Loop Seal



Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.29: N Mass Loop 30 half Loop Seal to RPV Inlet

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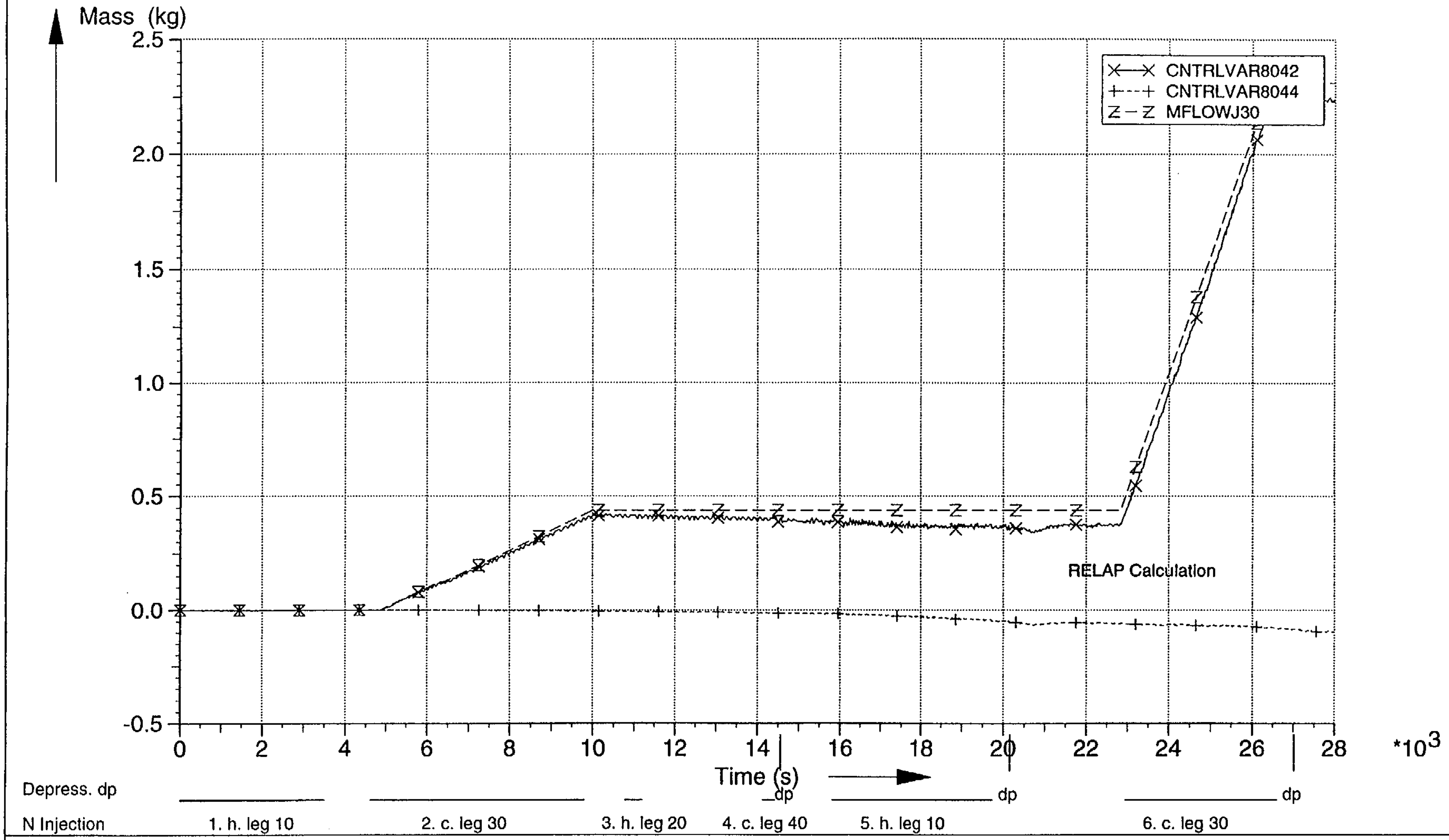

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.30: Int. N Injection L. 30 Cold Leg(Z), RPV-Side(X), SG-Side(+)

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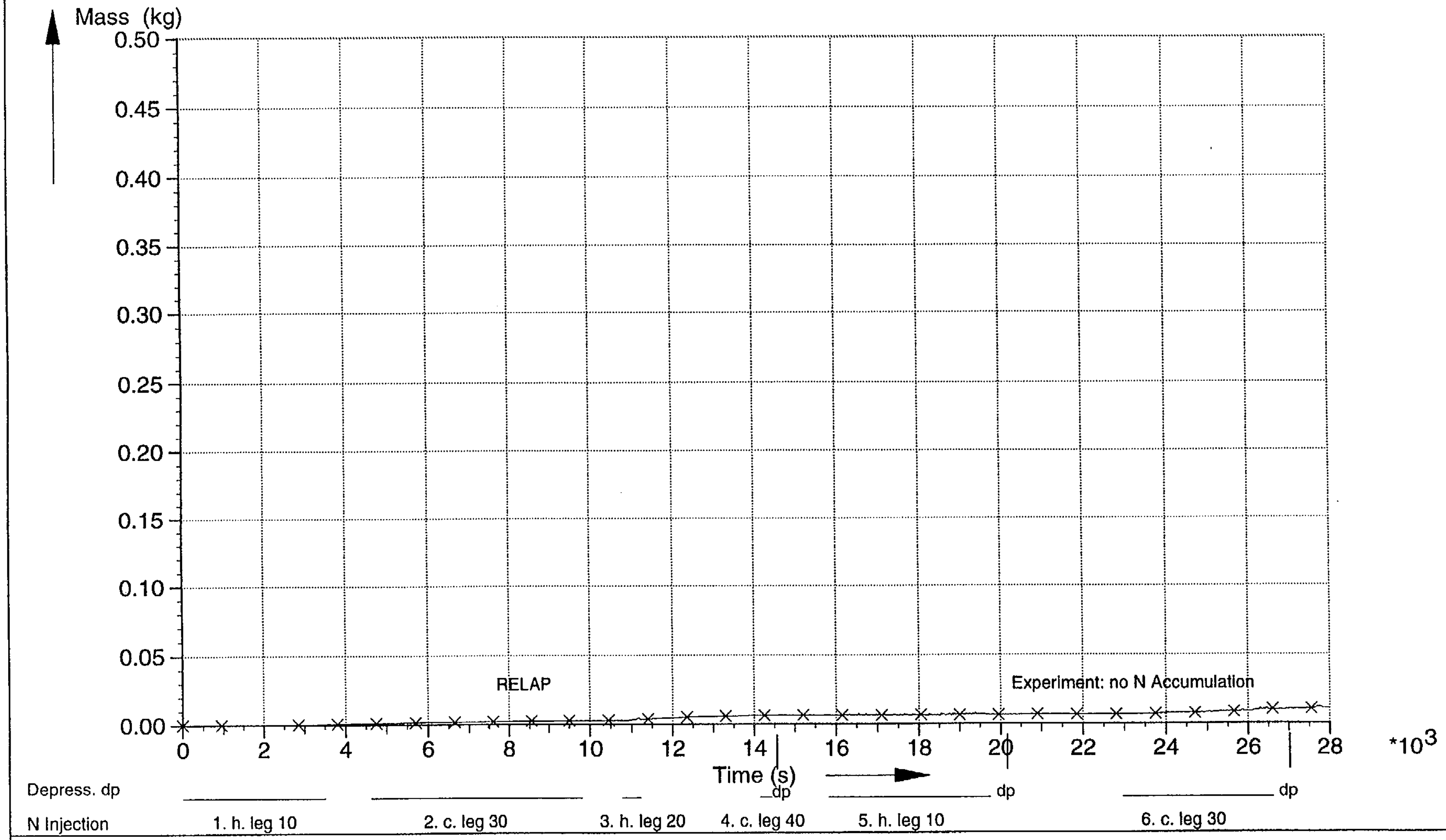

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.31: Nitrogen Mass Loop 40 Hot Leg + SG Inlet

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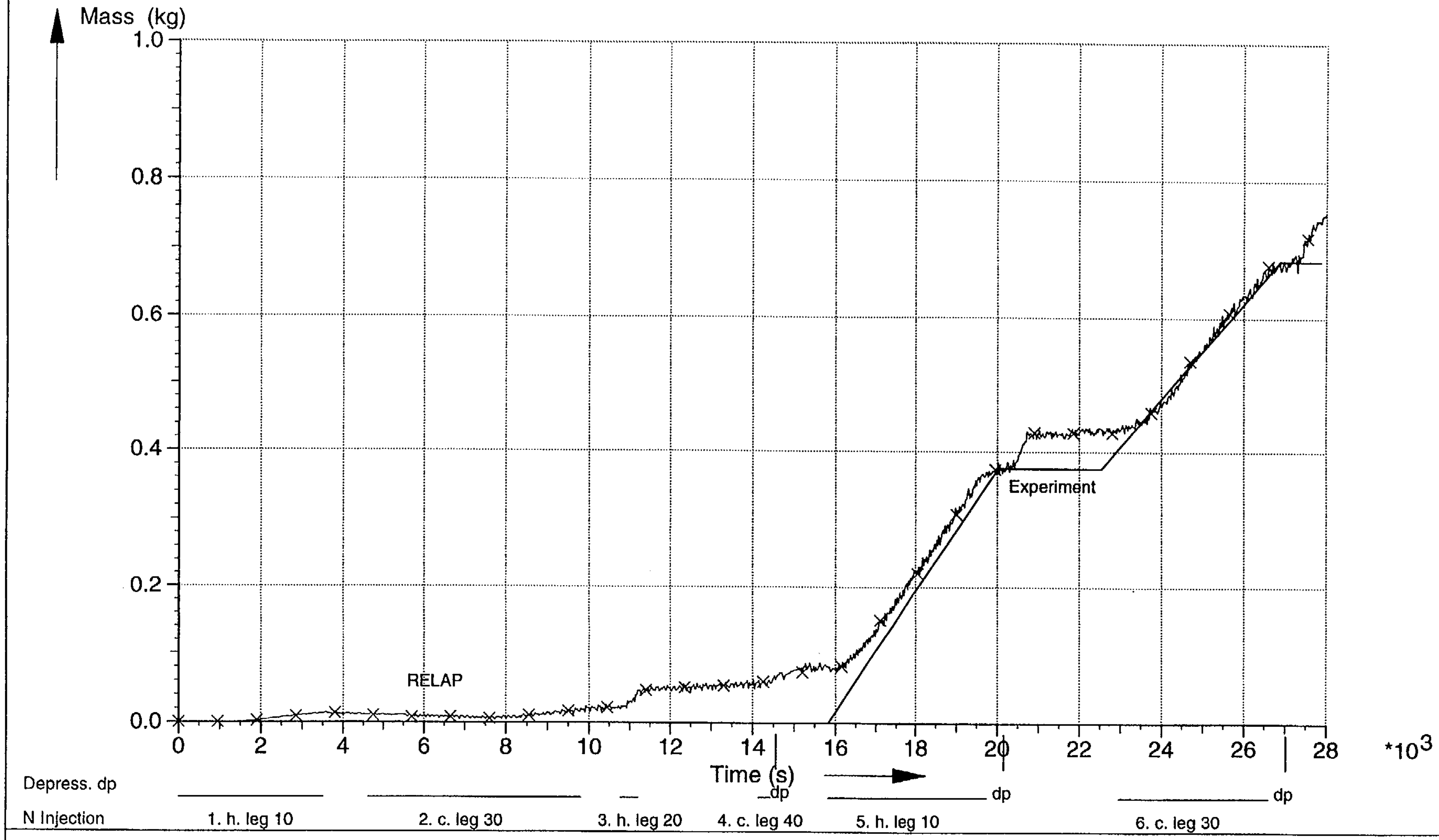

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.32: Nitrogen Mass Loop 40 SG U-Tubes

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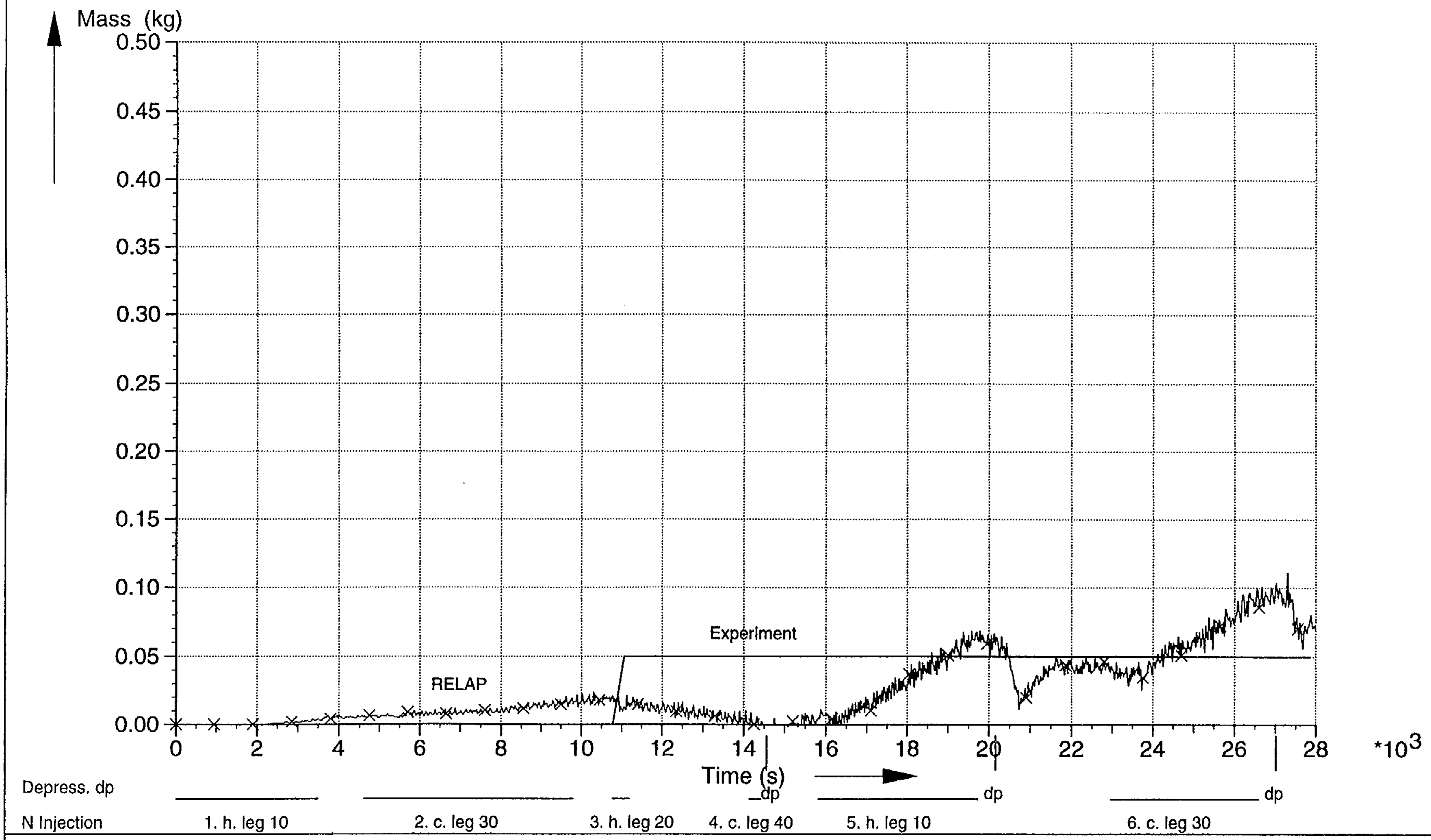

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.33: N Mass SG 40 Outlet to half Loop Seal

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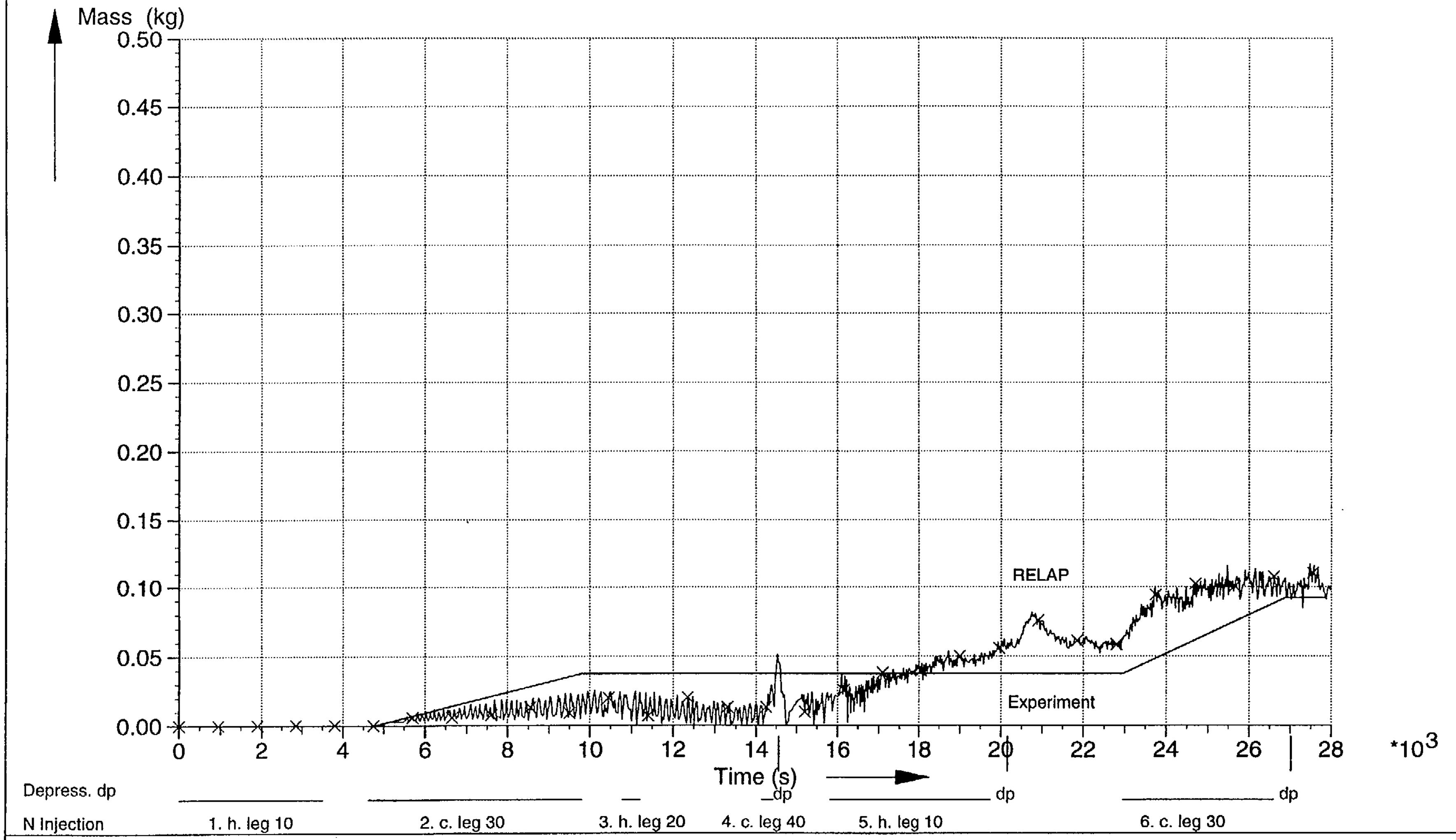

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.34: N Mass Loop 40 half Loop Seal to RPV Inlet

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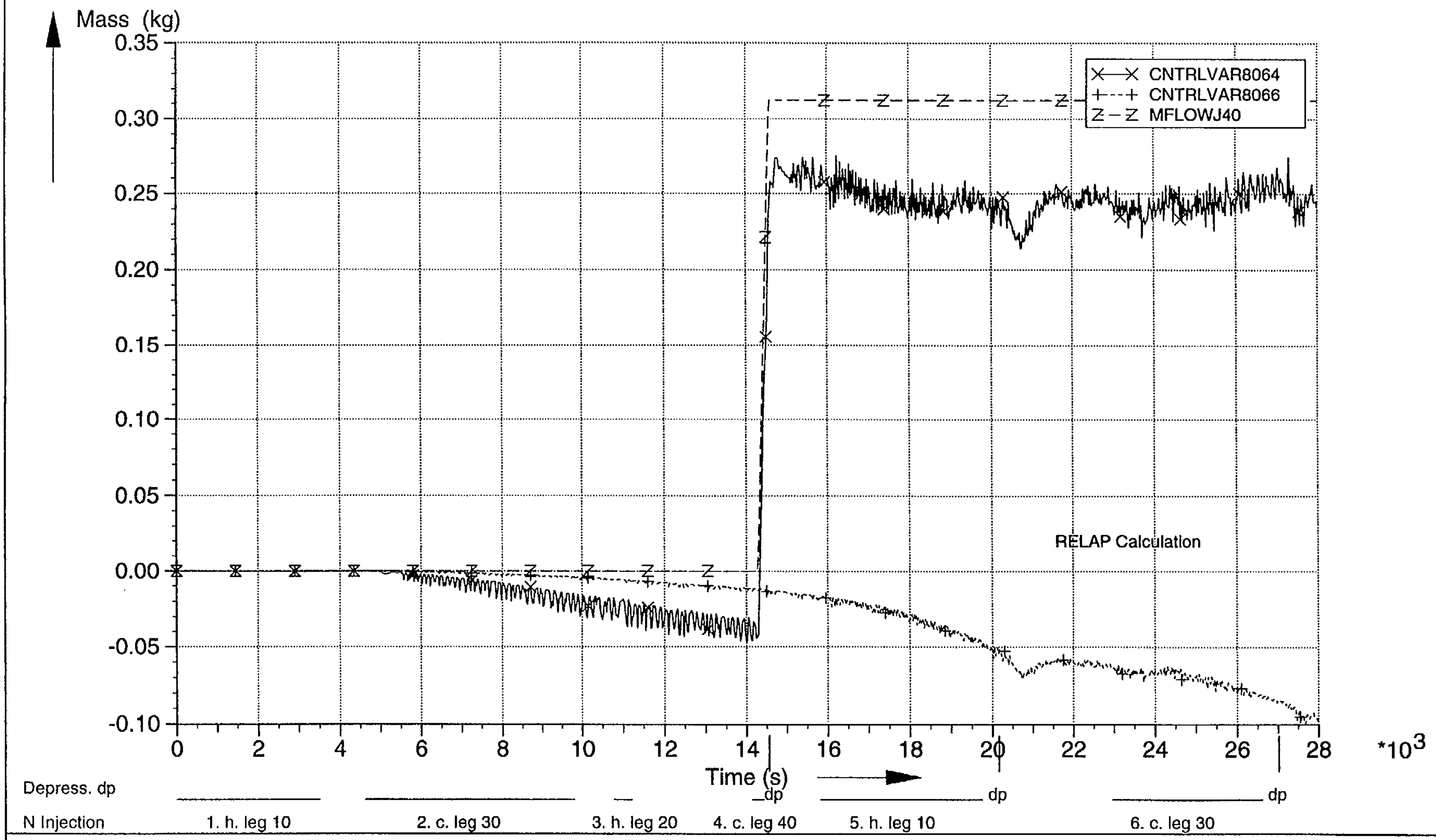

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.35: Int. N Injection L. 40 Cold Leg(Z), RPV-Side(X), SG-Side(+)

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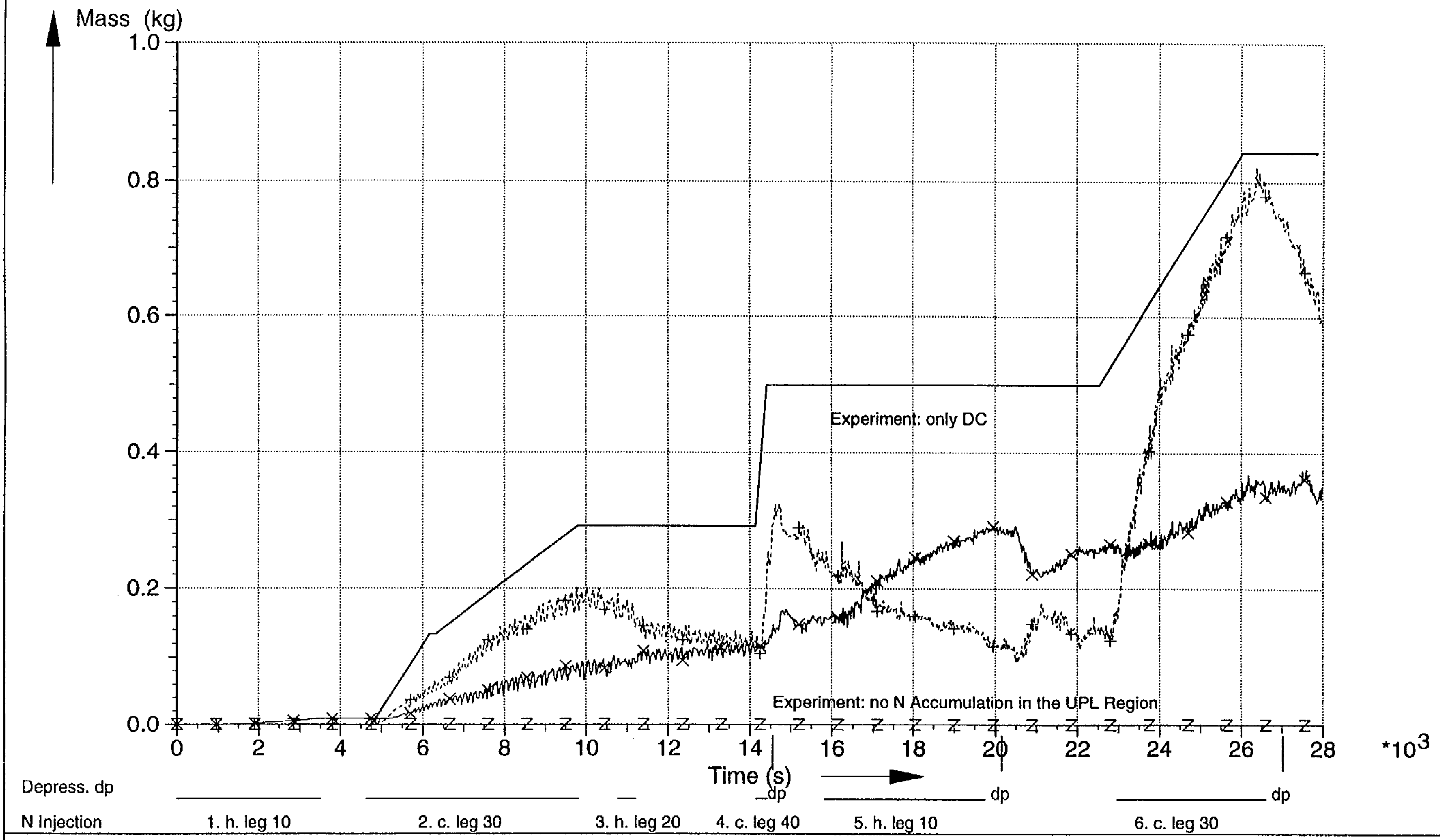

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.36: N Mass Closure Head and UPL(X), DC(+), LPL Core and Byp.(Z)

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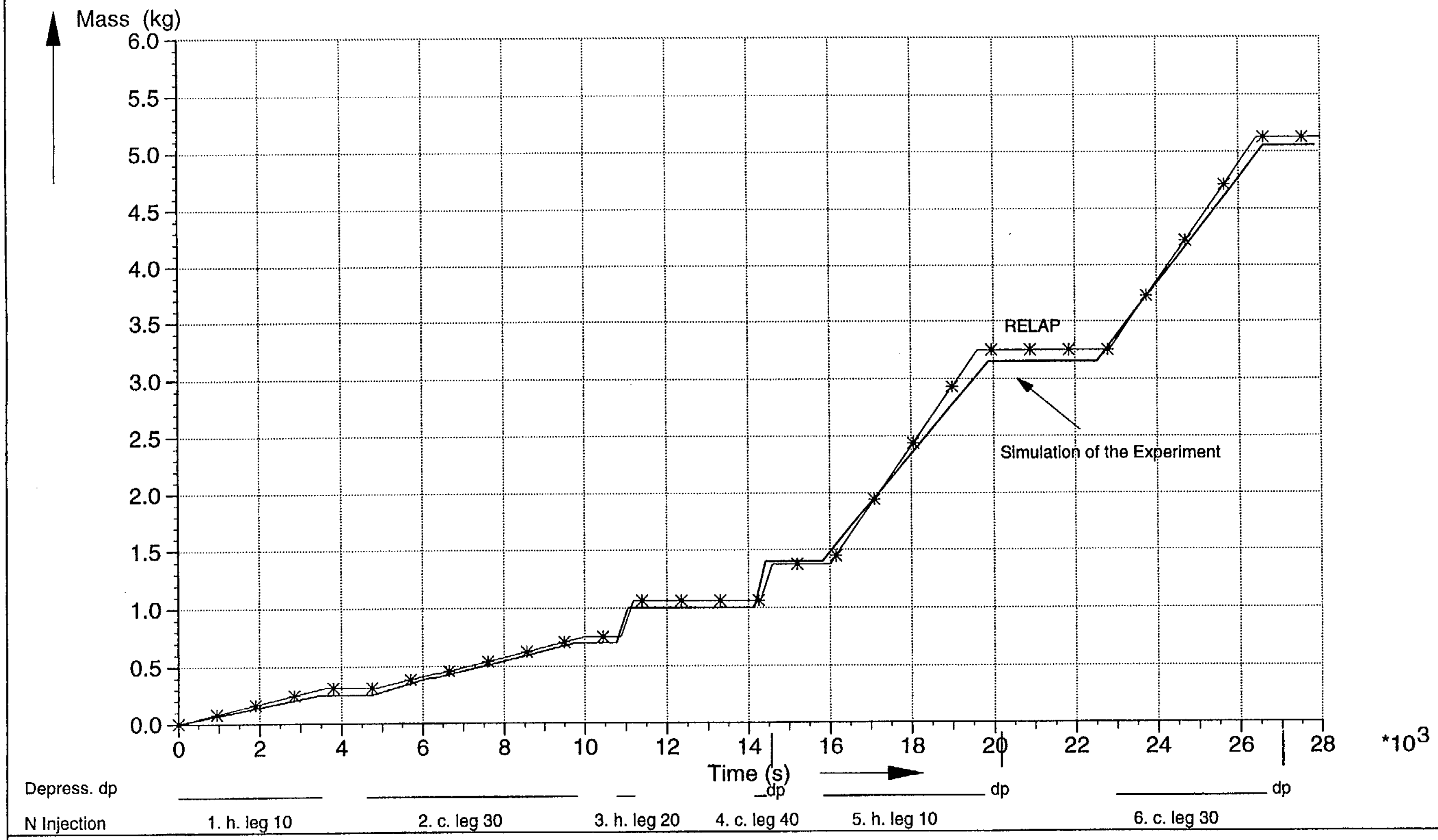

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.37: N Mass Primary System RELAP(X), Injected N Mass(+)

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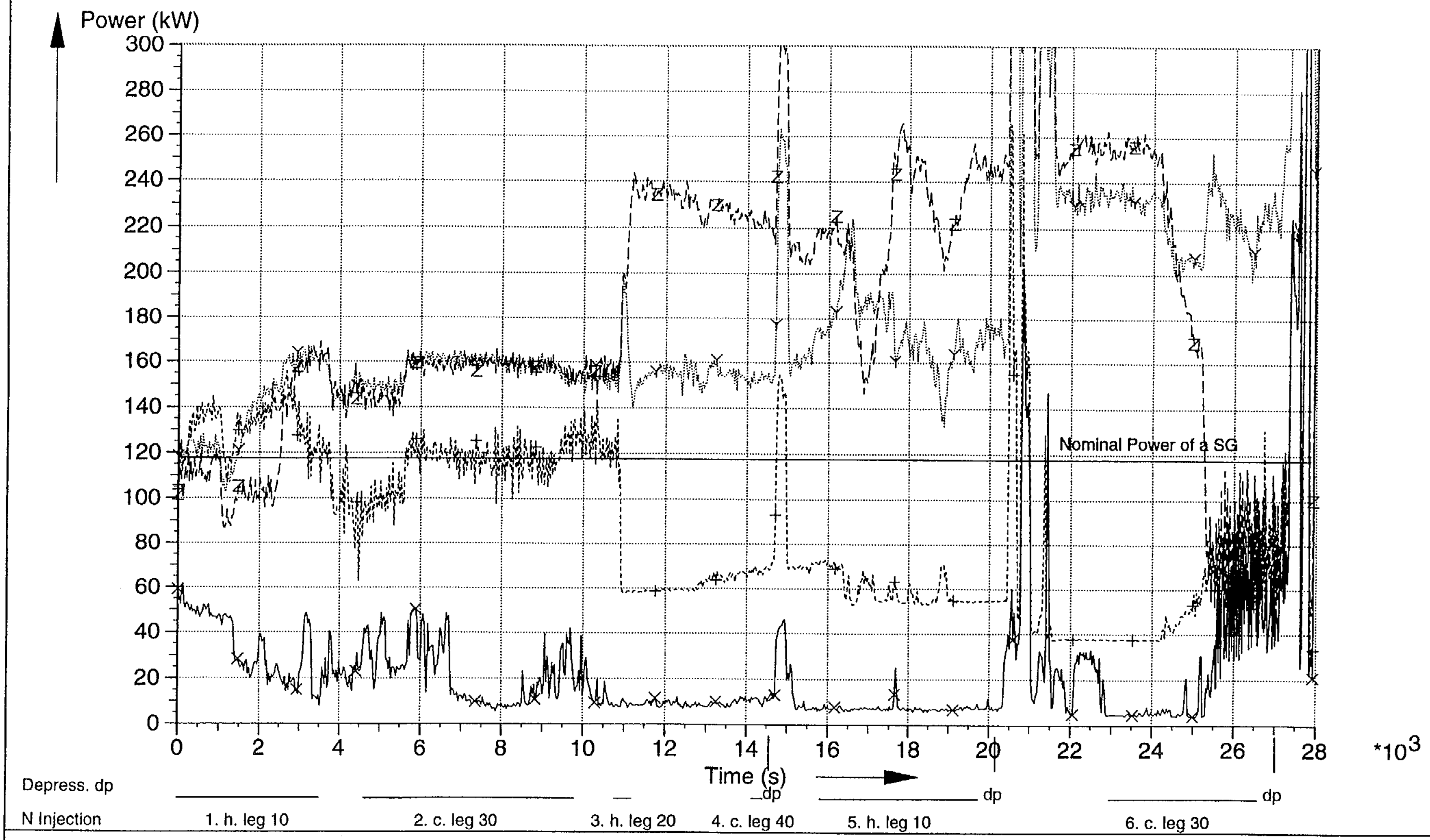

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/M0d3.2
Fig. 4.38: Heat Transfer Experiment SGs 10(X), 20(+), 30(Z), 40(Y)

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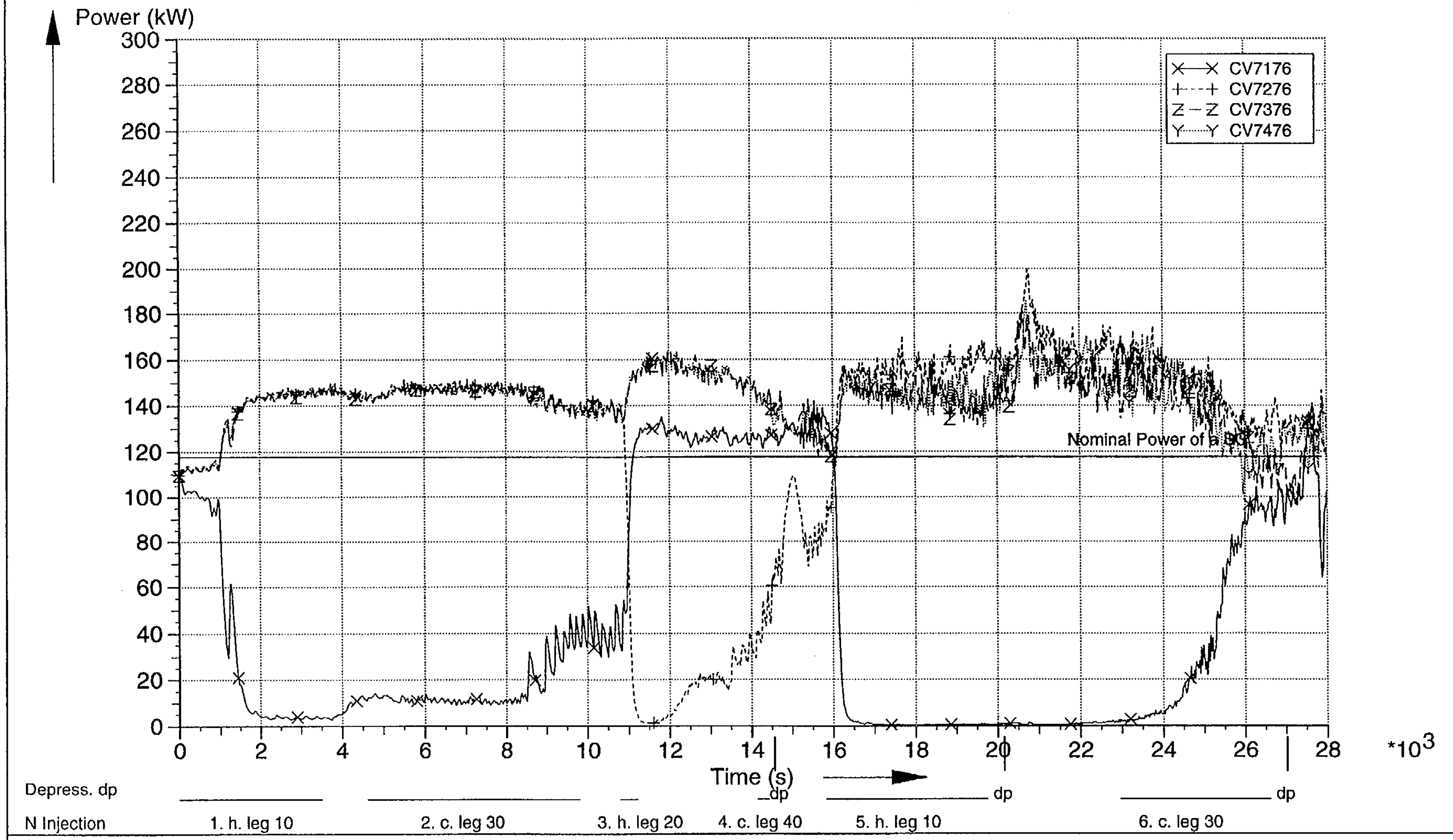

Comparison of Experiment and Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.39: Heat Transfer RELAP (smoothed) SG 10(X), 20(+), 30(Z), 40(Y)

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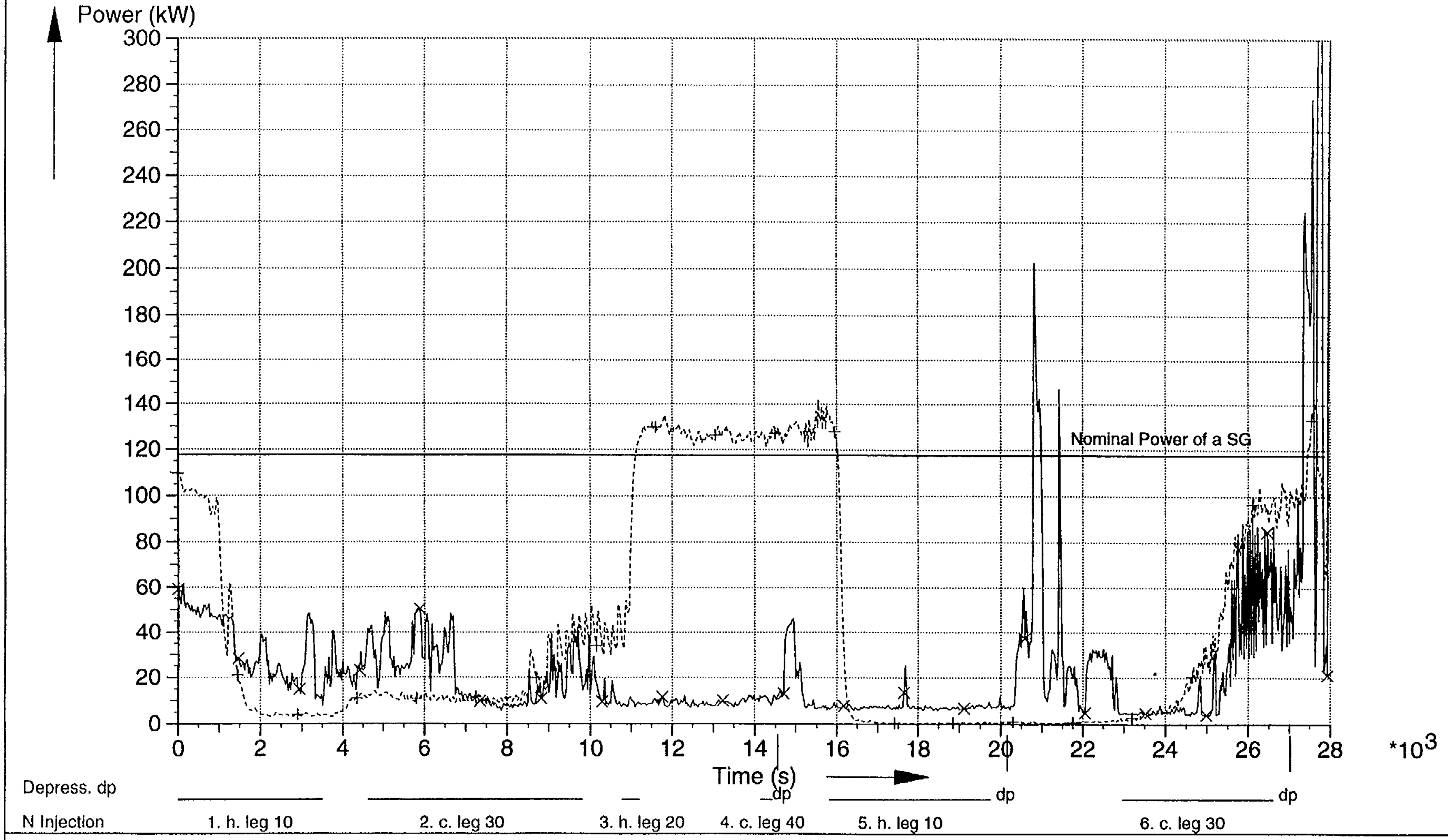

Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/M0d3.2
Fig. 4.40: Heat Transfer SG 10 Experiment(X), RELAP(+)

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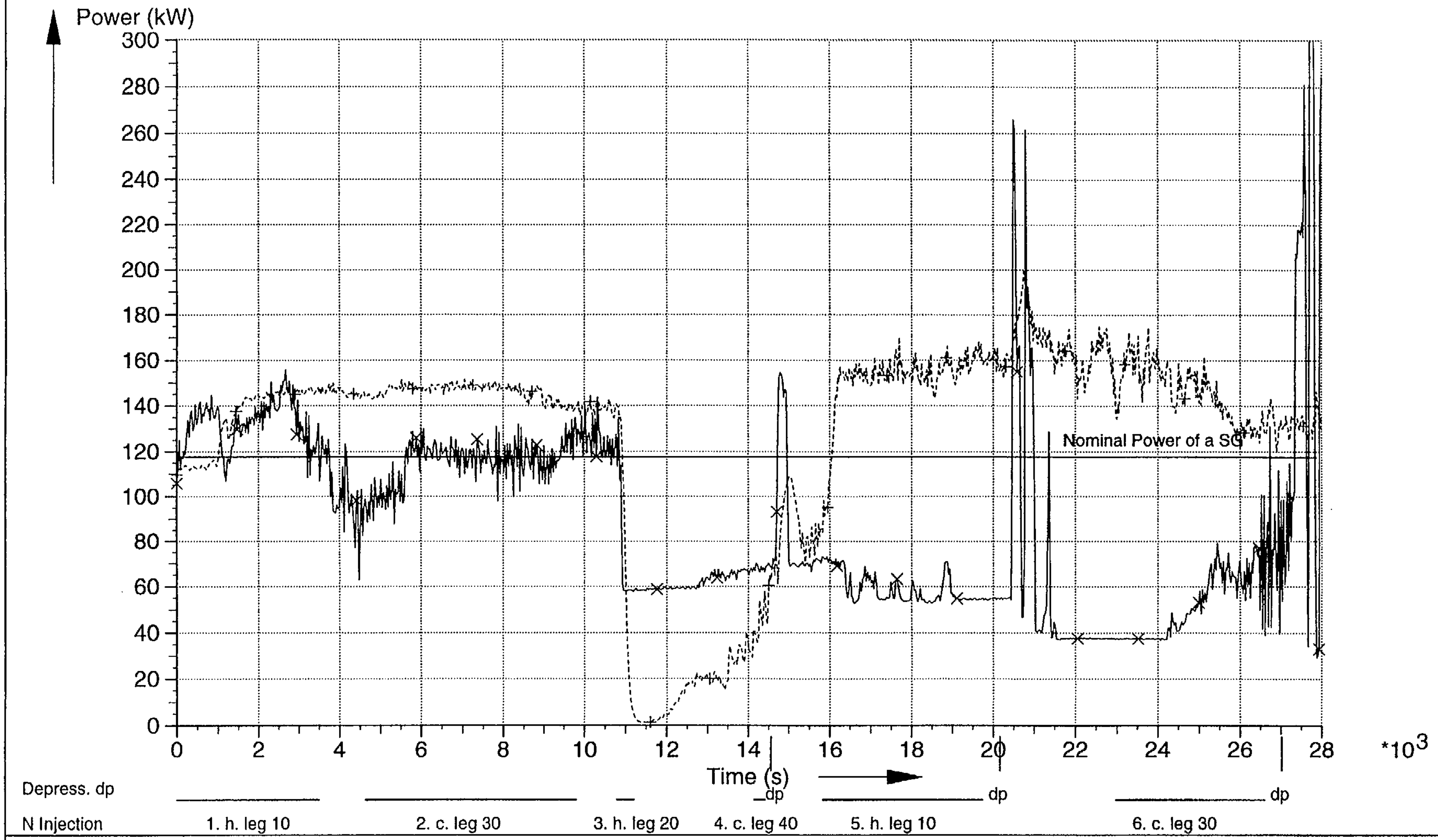

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/M0d3.2

Fig. 4.41: Heat Transfer SG 20 Experiment(X), RELAP(+)

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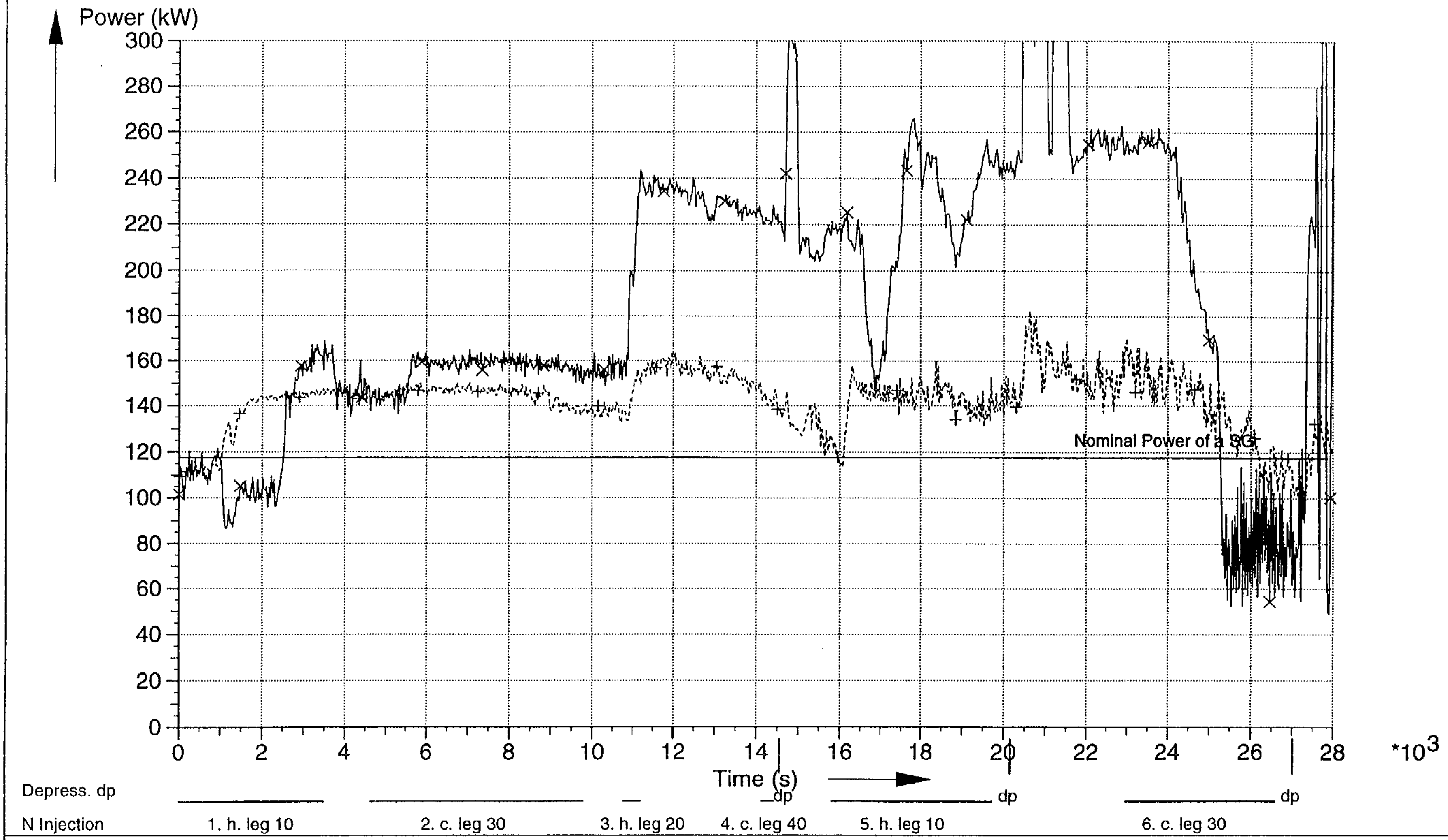

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/M0d3.2

Fig. 4.42: Heat Transfer SG 30 Experiment(X), RELAP(+)

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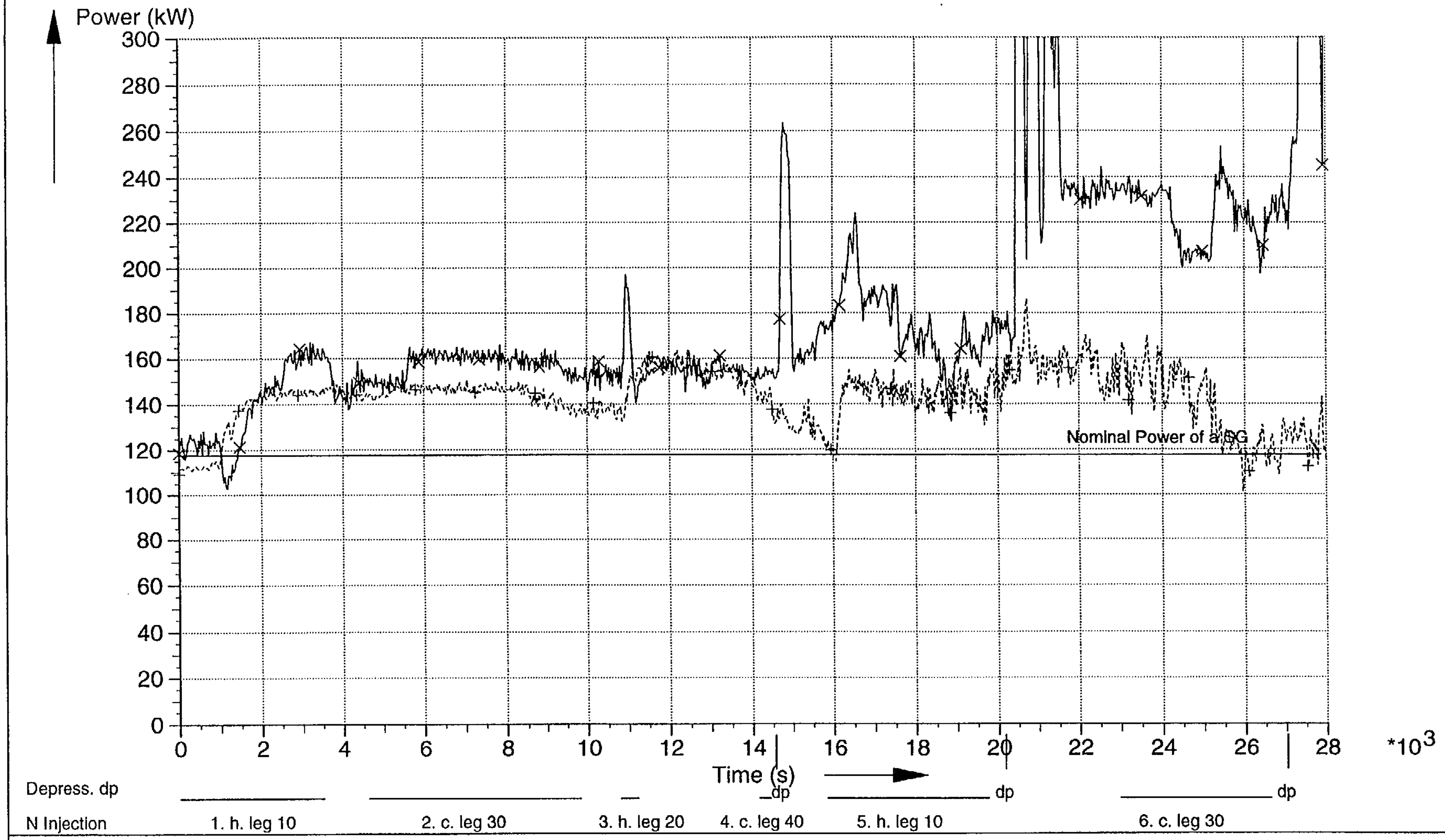

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/M0d3.2

Fig. 4.43: Heat Transfer SG 40 Experiment(X), RELAP(+)

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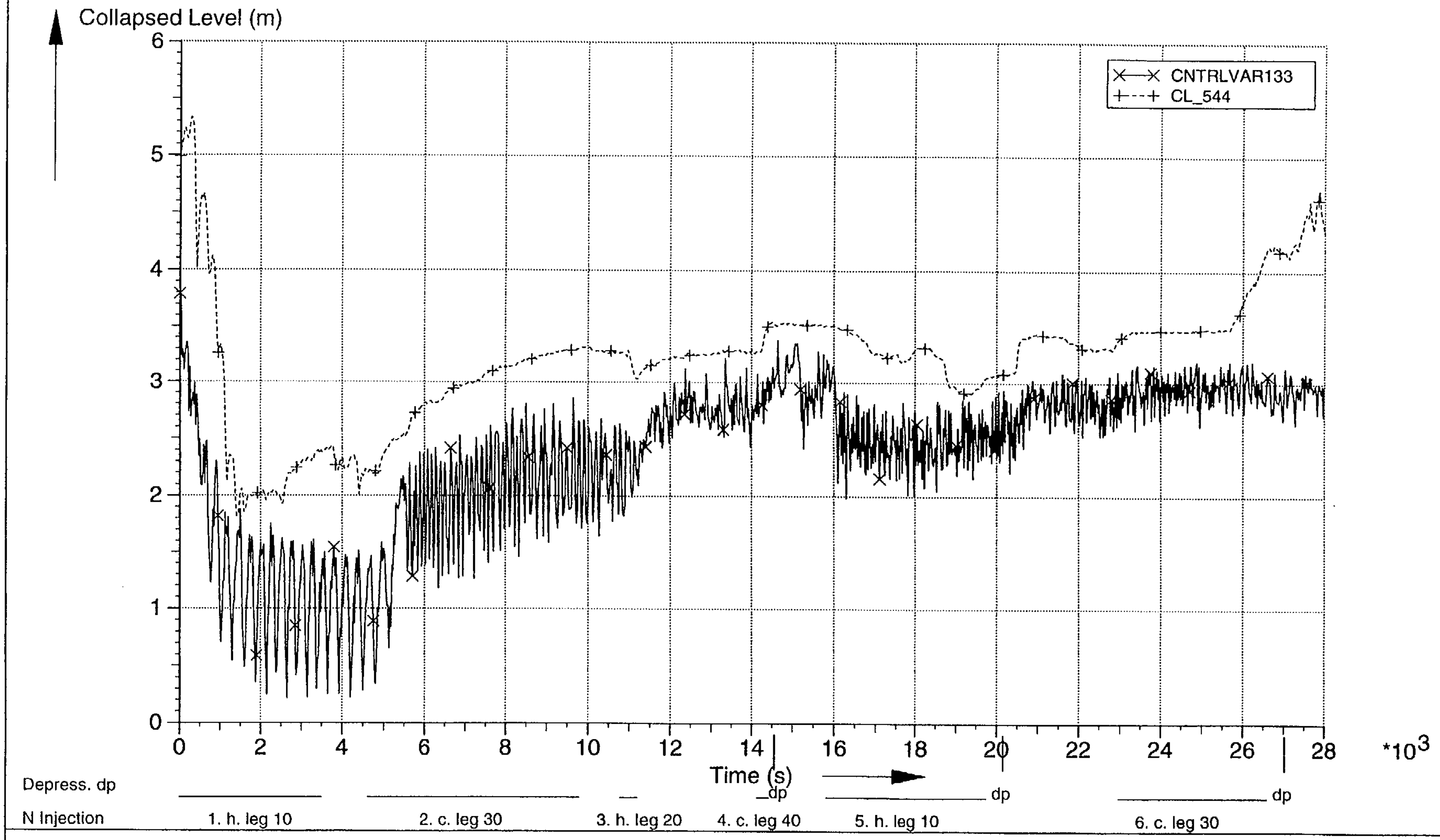
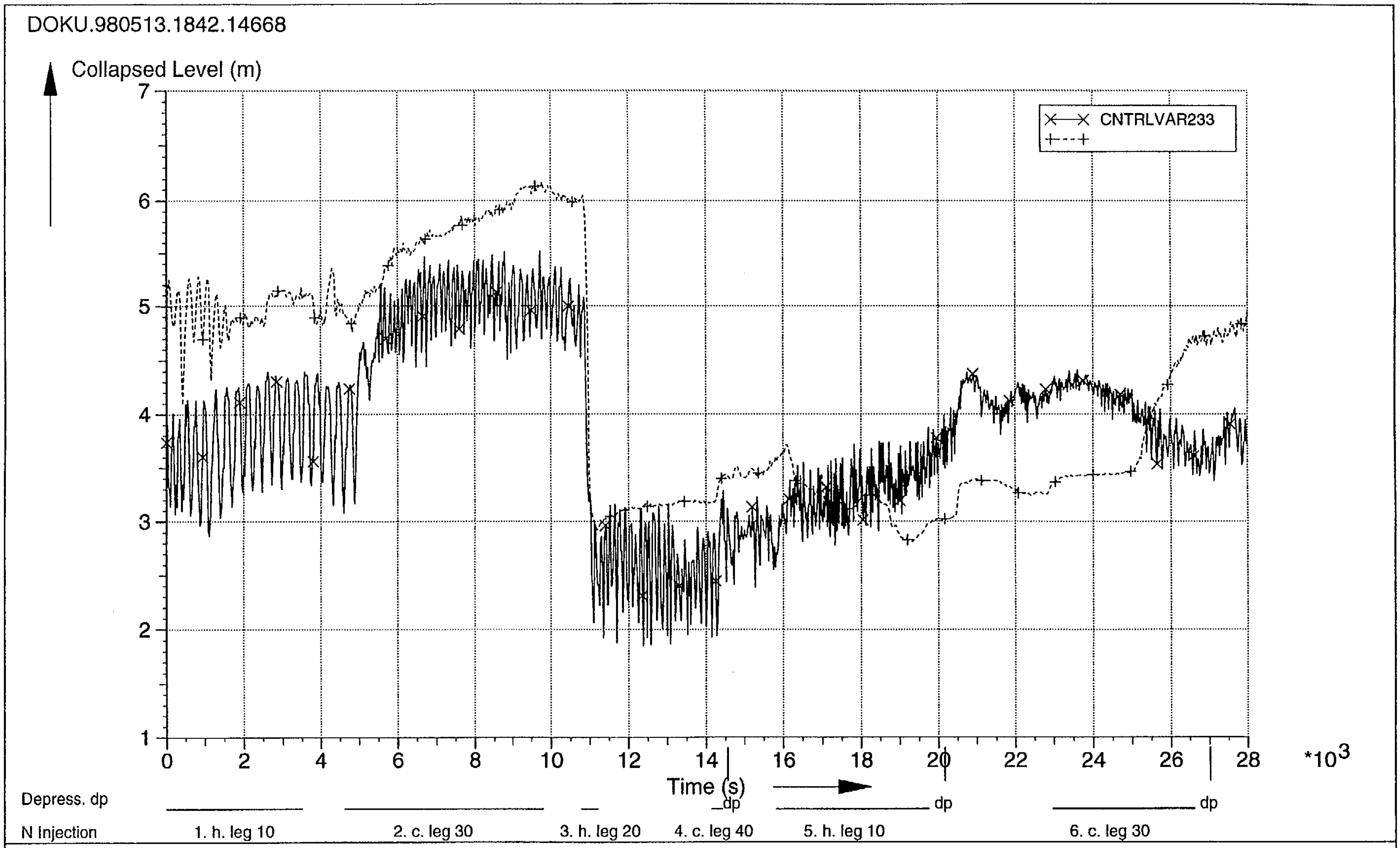


Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.44: CL Loop-Seal 10 SG-Side RELAP(X), Experiment(+)



Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.45: CL Loop-Seal 20 SG-Side RELAP(X), Experiment(+)

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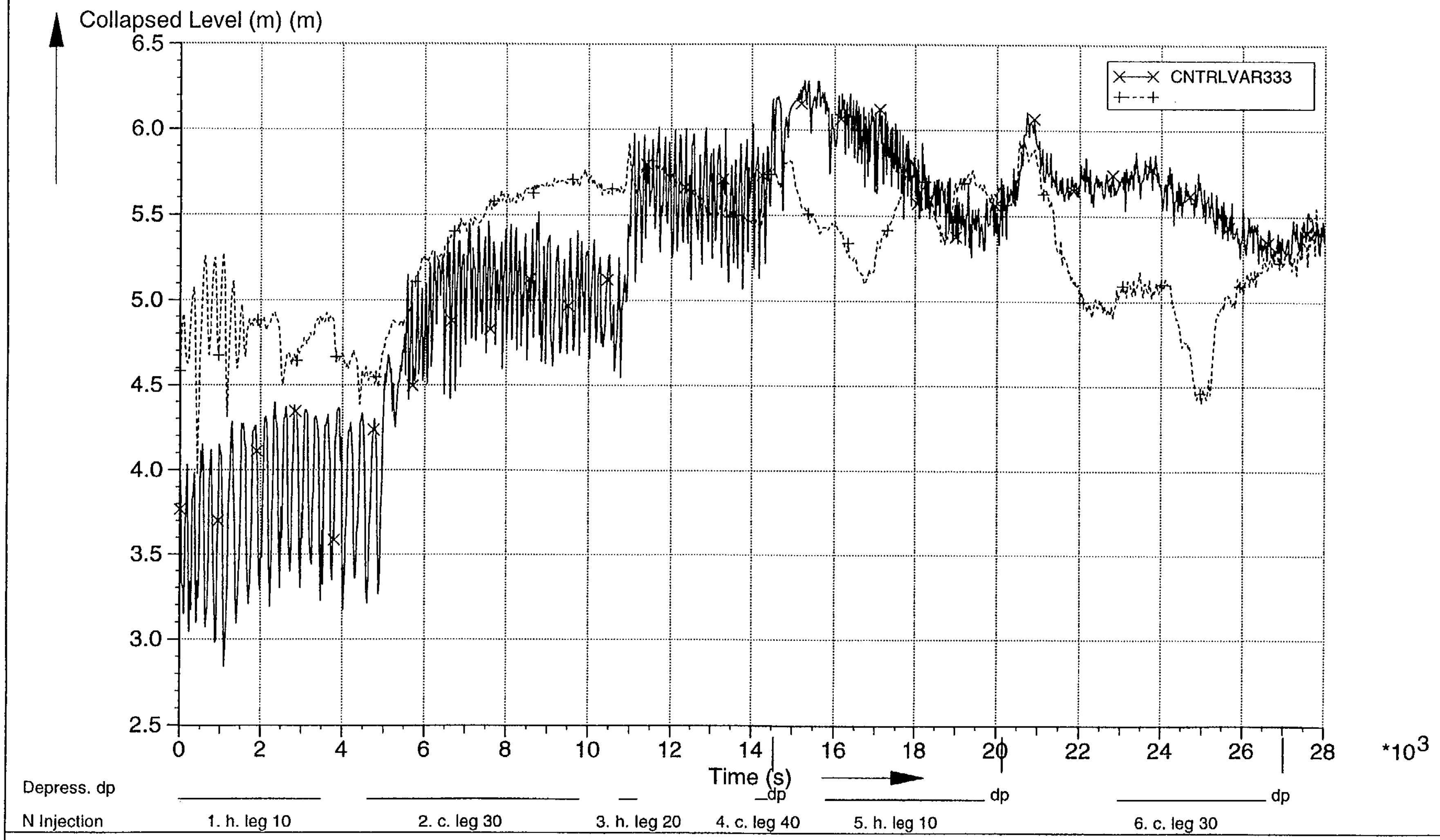
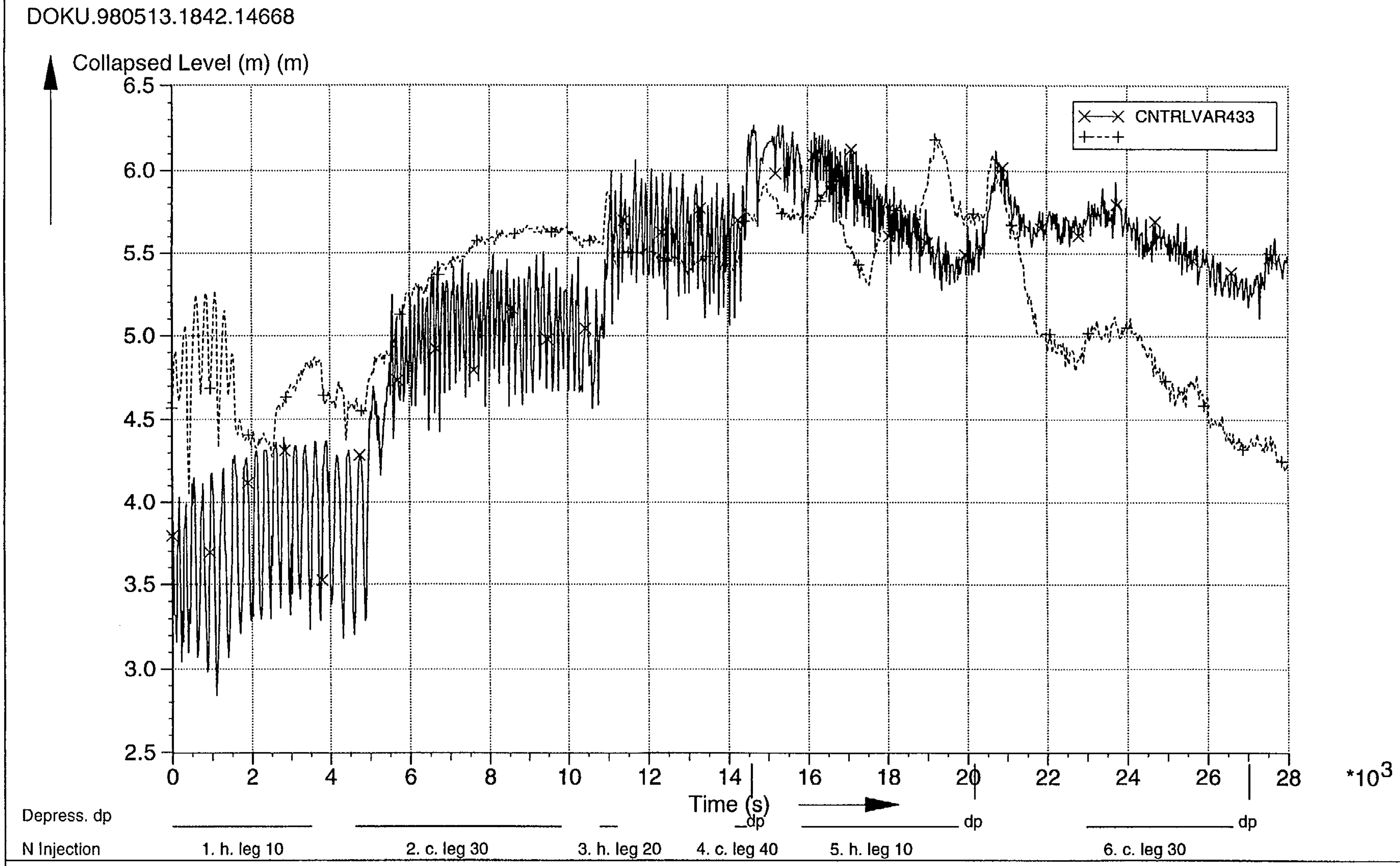


Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.46: CL Loop-Seal 30 SG-Side RELAP(X), Experiment(+)



Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.47: CL Loop-Seal 40 SG-Side RELAP(X), Experiment(+)

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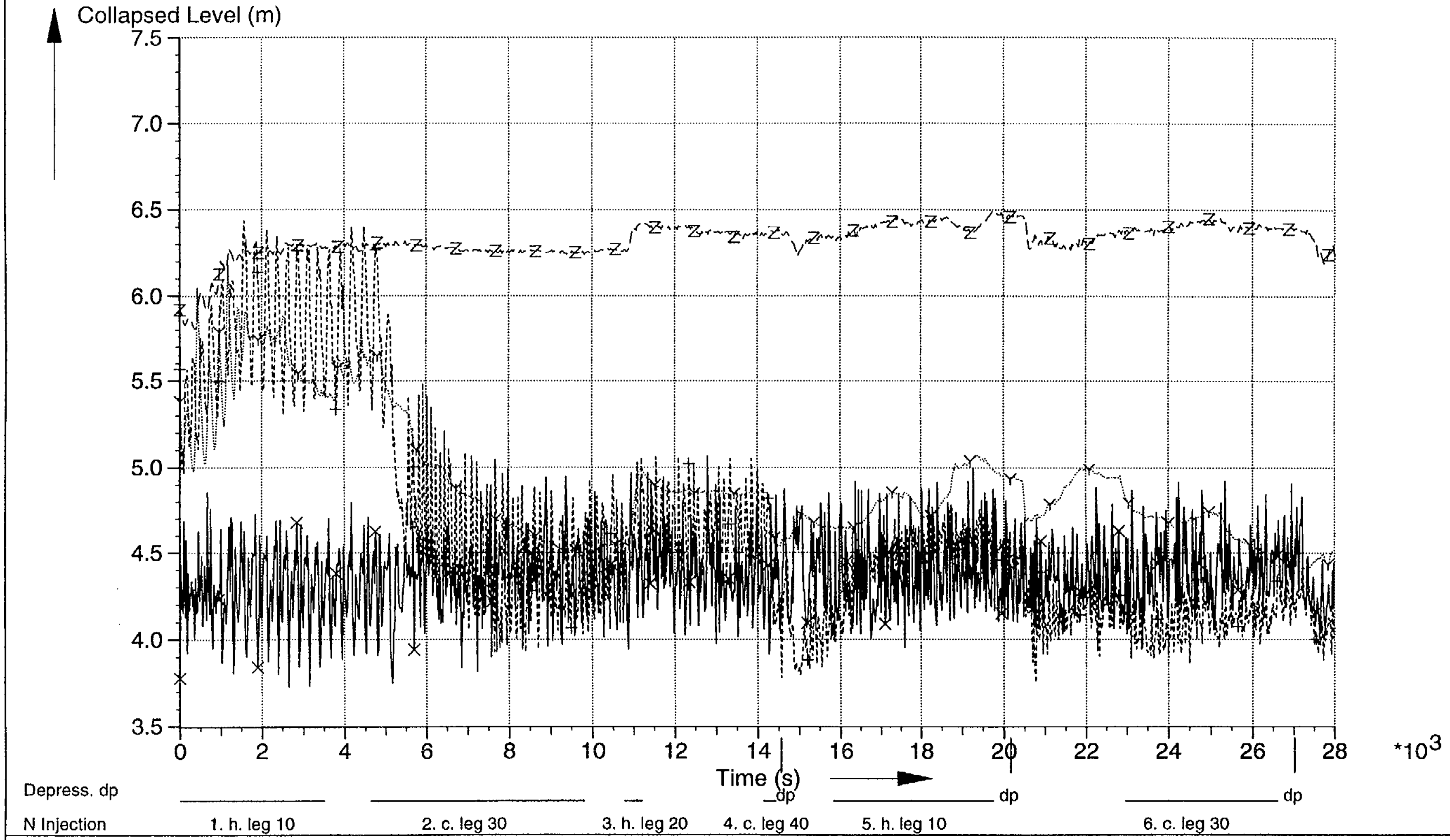
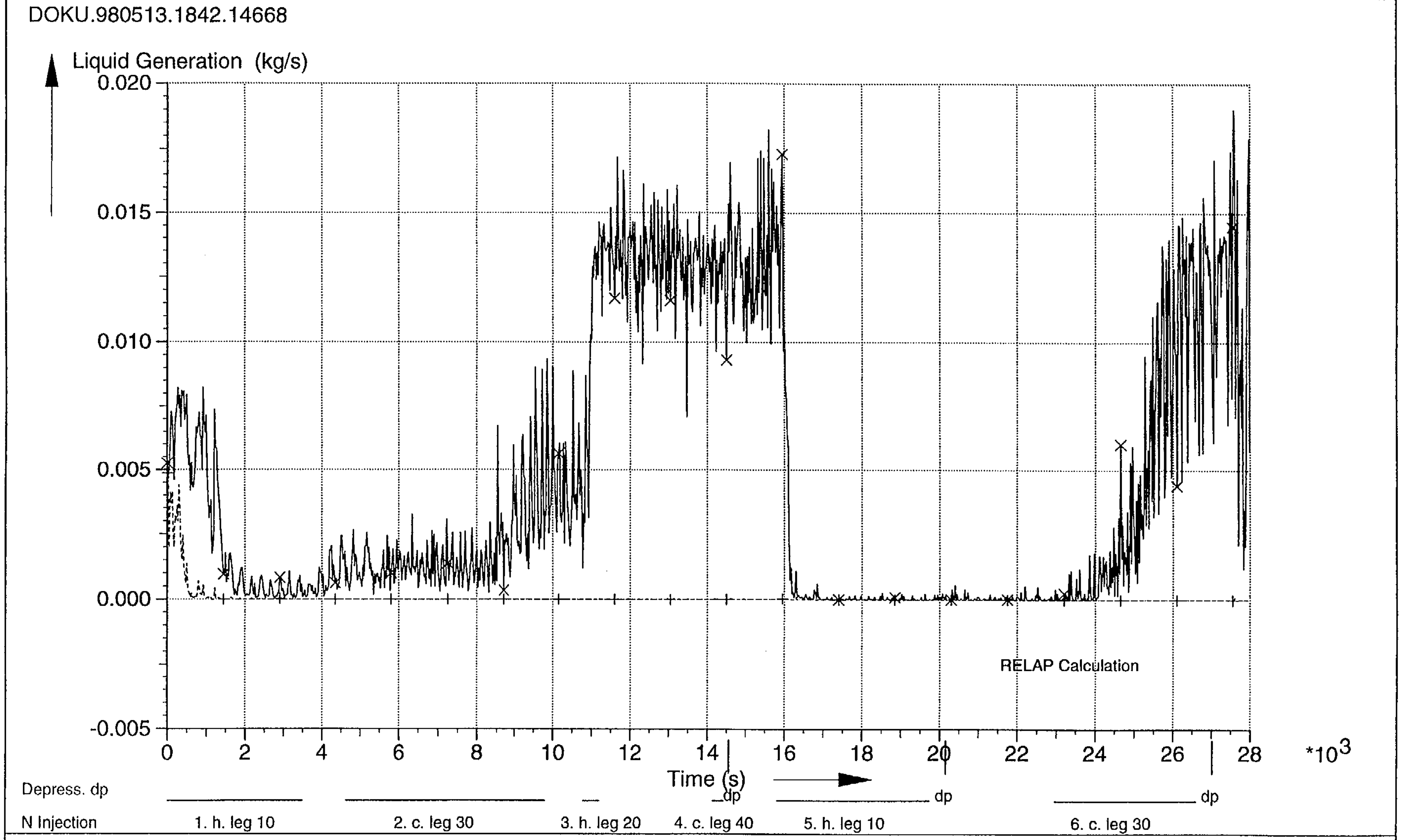


Comparison of Experiment und Analysis PKL III B 4.3
Data b4_3 -- RELAP5/Mod3.2
Fig. 4.48: RPV RELAP Core(X), DC(+); Experiment Core(Z), DC(Y)



Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.49: Condensate SG 10, Pipe 320 Ascending(X), Descending(+) U-Tube

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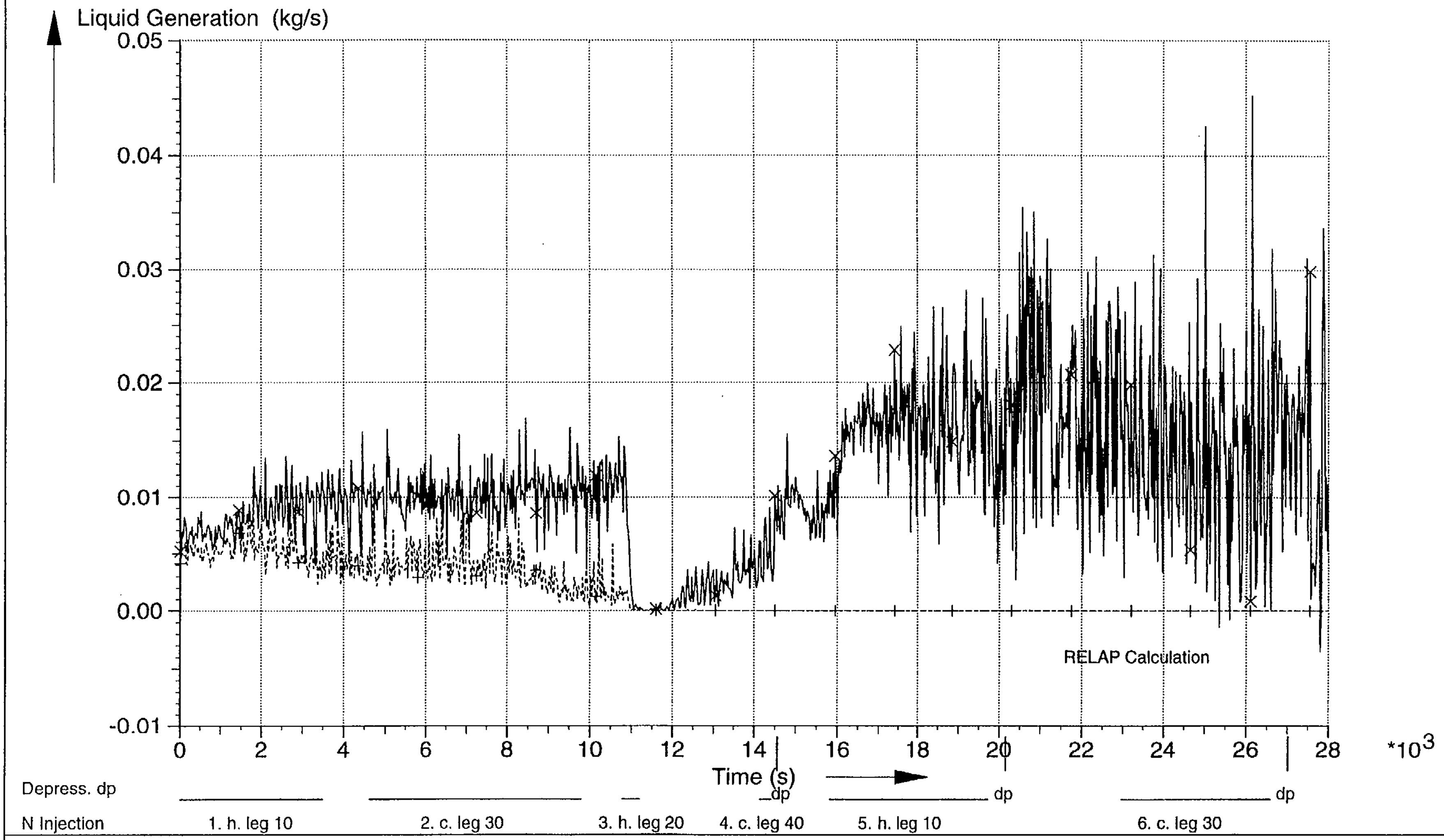

Comparison of Experiment und Analysis PKL III B 4.3

Data b4_3 -- RELAP5/Mod3.2

Fig. 4.50: Condensate SG 20, Pipe 420 Ascending(X), Descending(+) U-Tube

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

The PKL III test facility (Primar-Kreis-Lauf) simulates a typical 1300 MWe Pressurized Water Reactor of Siemens/KWU. In test B4.3, the influence of non-condensables on heat transfer in the steam generators during reflux condenser conditions was investigated. This report presents the results of a post-test analysis of PKL III-B4.3 using RELAP5/MOD 3.2. A description of the input model is given, and the correspondence of measured and calculated results is discussed.. The results of the calculation show differences in the distribution of nitrogen in the primary system compared to the experiment. When nitrogen was injected into the hot leg of the primary system, the heat transfer in the affected steam generator decreased. In contrast to the experiment RELAP calculated that the volumes in the adjacent steam generator did not get the full amount of nitrogen and that nitrogen was transported from the steam generators to other locations during the course of the transient. Thus, the heat transfer in these steam generators later increased in contradiction to the measured values. In the steam generator tubes, RELAP calculated that the nitrogen accumulated in the descending part as predicted in the experiment. For the ascending U-tubes RELAP predicted that the nitrogen was transported to the loop seal, which was not seen in the experiment. Fluctuations occurred during the course of the RELAP5/MOD 3.2 analysis of the PKLIII B4.3 experiment. This phenomenon may be the main reason, that RELAP calculates the transport of nitrogen from the steam generators into the system and predicts finally a homogeneous distribution of nitrogen in the primary system. The analysis performs an in kind contribution to the CAMP contract.

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

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RELAP5/MOD3.2

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