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Study of the Late Phase of Core Degradation during Reflooding by Safety Injection System for VVER1000 with ASTECv2 Computer Code

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Abstract**—**This paper presents the modeling approach in SBO sequence for VVER 1000 reactors and describes the reactor core behavior at late in-vessel phase in case of late reflooding by HPIS and gives preliminary results for the ASTECv2 validation. The work is focused on investigation of plant behavior during total loss of power and the operator actions. The main goal of these analyses is to assess the phenomena arising during the Station blackout (SBO) followed by primary side high pressure injection system (HPIS) reflooding of already damaged reactor core at very late "in-vessel" phase. The purpose of the analyses is to define how the later HPIS switching on can delay the time of vessel failure or possibly avoid vessel failure. The times for HPP injection were chosen based on previously performed investigations.

Keywords**—**VVER, operator action validation, reflooding of overheated reactor core, ASTEC computer code.

I. INTRODUCTION

THE presented analyses are based on the integral code ASTEC jointly developed by IRSN and GRS. ASTEC (Accident Source Term Evaluation Code) aims at the calculation of entire sequences of severe accidents in light water reactors from the initiating event up to the possible release of fission products into the environment, thereby covering most important in- and ex-vessel phenomena.

The sequence simulates plant behavior mainly after beginning of heat up of reactor core, which is coming due to selected initiating events for analyzed transient. The purpose of these analyses is to analyze the reactor core behavior parameters and to estimate the operator time available for performing actions. Consequently calculations have been done without and with operator actions selected based on severe accident management strategies considered in Kozloduy nuclear power plant (KNPP).

The paper shows results for possible preservation of the reactor core from further damage during a severe accident and assesses the likelihood of additional generation of hydrogen as a result of reflooding of the super-heated core.

The selected reference nuclear power plant for this analysis is Units 5 and 6 of Kozloduy NPP equipped with VVER - 1000 reactors Model V320. The layout of the reactor vessel, pressurizer, steam generators (SG), hydroaccumulators (HA), main coolant pumps (MCP), primary circuit, and other important equipment for safety operation of VVER 1000 is presented in Fig. 1. This type of reactor is a pressurized water reactor with 3000 MW thermal power and 1000 MW electric power. All VVER reactors are equipped with horizontal steam generators, whose behavior is very different in comparison to western types of vertical steam generators. The Steam Generators have a very important role for the safety and reliability of VVER nuclear power plants.

The four primary coolant loops of VVER 1000/V320 reactor are modeled by one single loop and one lumped loop representing the other three loops. Each loop consists of hot and cooled legs, MCP and a horizontal steam generator. The SGs are fed by feedwater systems.

II. BRIEF DESCRIPTION OF ASTEC INPUT MODEL FOR VVER – 1000 REACTOR

The ASTEC code has been used for the simulation of the above-described initiating event. The ASTEC computer code is composed of a system of modules whose aim is to predict the behavior of a water cooled nuclear power plant during a severe accident. Each module is in charge of a part of the reactor or the simulation of a particular physical phenomenon.

The input model for VVER-1000/V320 reactor has been used for ASTEC v2 calculations [1], [3]. The nodalization scheme of the ASTEC input model - reactor vessel and primary circuit is presented on Fig. 2. Initiating event SBO has been chosen. Loss of all AC and DC power at the beginning of transient has been simulated as well.

The ASTEC input file includes modules: CESAR, ICARE, SOPHAEROS and CPA.

All ASTEC modules have been used in a "coupled mode". No other modules are involved as the study is specific to the in-vessel phase of the accident.

The CESAR module simulates the thermal-hydraulics in the primary and secondary sides and in the reactor vessel up to the start of core uncovery.

The reactor vessel structures are modeled with the ICARE module which includes reactor core, baffle, the cylindrical part of the barrel, vessel cylindrical part, fuel assembly supports and vessel lower head. ICARE models the in-vessel degradation phenomena for both earlier and late degradation phases. It also simulates the release of core structural materials, including control rods. The SOPHAEROS module

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simulates the fission products (FPs) and structural materials transport phenomena through the circuit. The CPA module allows the simulation of all relevant processes in the containments of reactors.

The ASTEC model of VVER-1000 reactor includes the major components of the primary and secondary sides, as well as the necessary safety injection systems. One of the primary loops has been modeled as a single loop by 7 volumes and 8 junctions representing hot leg, SG hot collector, SG tubes, SG cold collector, cold leg (presented by three parts) and a main coolant pump (MCP). The other three primary loops are modeled as one lumped loop. Pressurizer with 3 relief valves and surge line has been modeled.

The reactor core has been divided in axial and radial direction (10 axial nodes and five rings in radial direction, including baffle and barrel). The pressurizer has been represented by one total volume of 79 m^3 water and steam. The secondary circuit is modeled by defining the SG1&SG2 volumes, which is connected to the corresponding steam header volumes. Two accumulators have been represented by ACCU1&2 volumes and connected to the upper plenum. The other two accumulators have been connected to the downcomer and they are represented by ACCU3&4 volumes.

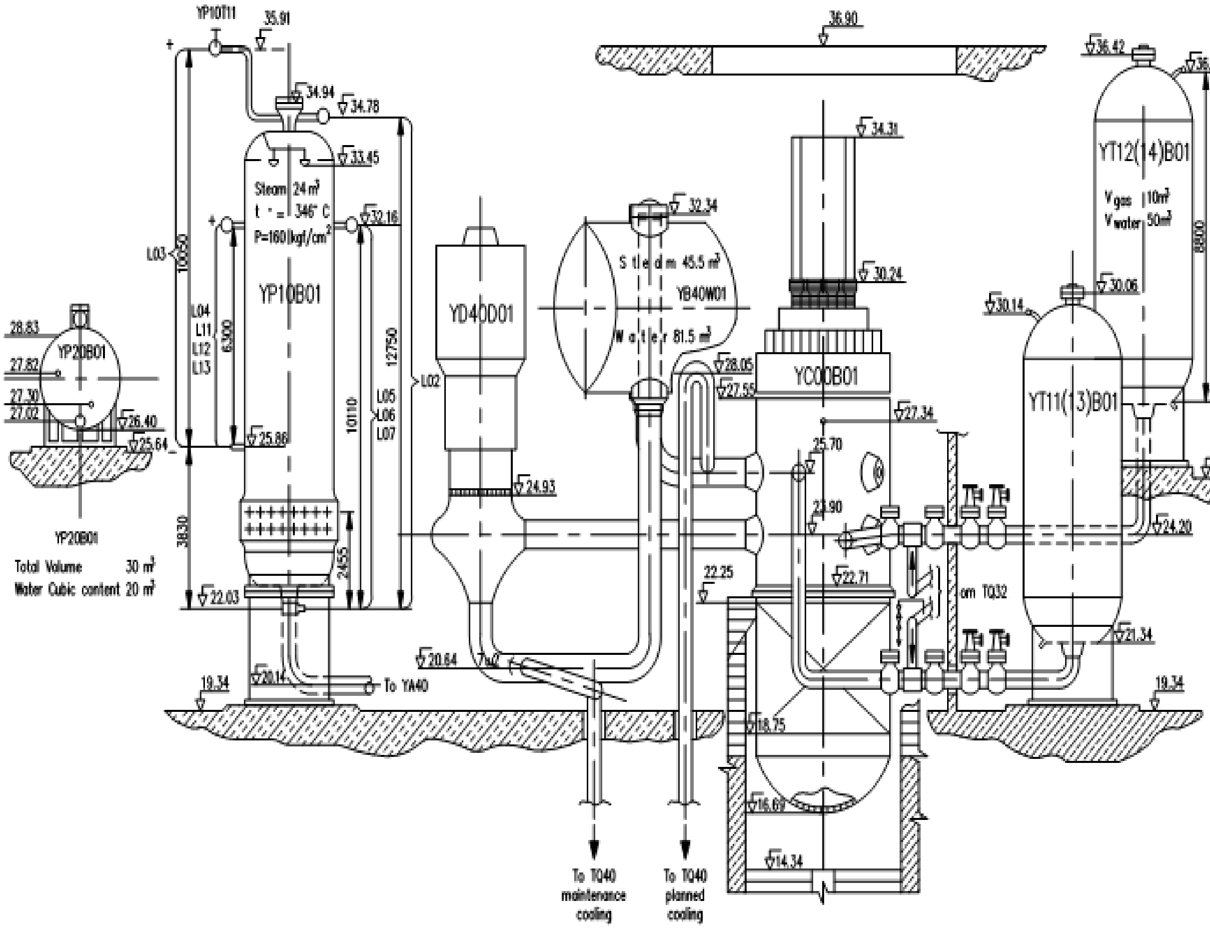

Fig. 1 Layout of main equipment of primary circuit of VVER 1000

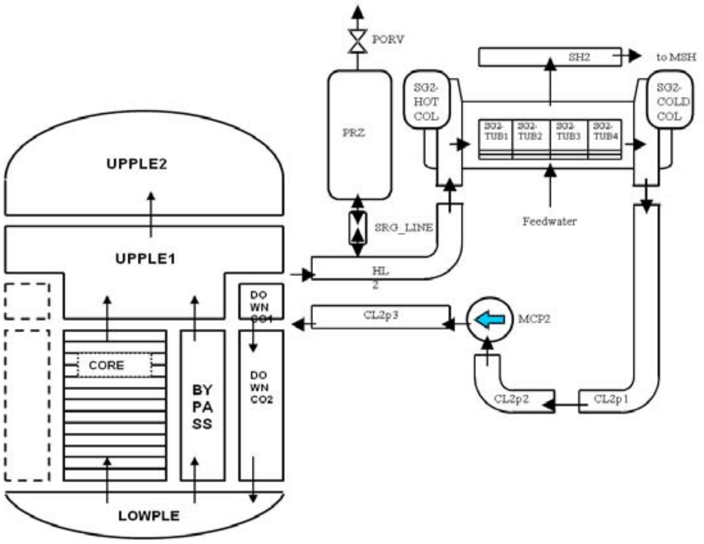

Fig. 2 Nodalization scheme of ASTEC input model - Reactor vessel and primary circuit

The main initial conditions are presented in Table I, where ASTEC v2 calculated values are compared with plant design values.

TABLE I
INITIAL PLANT CONDITIONS

Parameters	Plant Design	ASTEC v2
Core power, MW	3000	3000
Primary pressure, MPa	15.7	15.7
Average coolant temperature at reactor outlet, K	593.15	593.55
Maximum coolant temperature at reactor inlet, ^{K}	563.0	563.35
Mass flow rate through one loop, kg/s	4400.0	4363.1
Pressure in SG, MPa	6.27	6.418
Pressure in main steam header (MSH), MPa	6.08	6.38
Steam mass flow rate through SG steam line, kg/s	408	409.6

Decay power corresponds to the end of life.

There is one safety system available. In the analysis is used only one high pressure pump - TQ13. The other pumps of this safety system are not used – TQ11 – spray pump and TQ12 – low pressure pump.

The signal for initiation of operator actions is the time based on previous calculations. After reaching 14000 sec 16000 sec and 17000 sec the operator starts to inject water in the cold leg with one HPP (TQ13). Two additional calculations are performed with injection of water with an HPP at different times: 16000 sec and 17000 sec.

III. INVESTIGATED SCENARIO

- Initiation of SBO event;
- Hydro-accumulators assumed to fail;
- After opening of Pressurizer SV at its set point stuck in open position;
- Failure of BRU-As;
- Failure of all LPPs and two of HPPs after DG is available;
- Dryout of SGs at natural circulation by SG SVs;
- Failure of EFW pumps after DG is available;
- MCPs seal leakages are not taken into account;
- One HPP is available.

Four calculations have been performed with the following conditions:

Base case:

1. Without operator actions

Operator action case:

2. Operator starts to inject with one HPP in cold leg at 14 000 sec;
3. Operator starts to inject with one HPP in cold leg at 16 000 sec;
4. Operator starts to inject with one HPP in cold leg at 17 000 sec.

IV. MAIN OUTCOMES FROM CODE APPLICATION ON ANALYTICAL VALIDATION OF OPERATOR ACTIONS

The sequences of the investigated scenario are presented in Table II.

The sequence of the main events during a SBO without hydro accumulator's intervention and with actuation of HPIS is presented in Table II. The calculations represent switching on one HPP at a different stage during the accident. All calculations have been performed with integral computer code ASTECv2 [2], [4]-[6].

TABLE II
SEQUENCE OF MAIN EVENTS

No	Events	SBO HPIS starts at 14000 s	SBO HPIS starts at 16000 s	SBO HPIS starts at 17000 s	SBO without HPIS
		Time, s			
1	Reactor scram	0.0	0.0	0.0	0.0
2	MCPs are switched off	1.62	1.62	1.62	1.62
3	Turbine stop valves (TSVs) are closed	6.25	6.25	6.25	6.25
4	Start of ICARE – automatic start	7776.2	7776.6	7776.6	7776.6
5	Start of structural material release	7815.1	7815.1	7815.1	7815.1
6	Beginning of oxidation	7953.6	7953.6	7953.6	7953.6
7	First cladding creep rupture	9022.6	9022.6	9022.6	9022.6
8	Start of FPs release from fuel pallets	9023.6	9023.6	9023.6	9023.6
9	First material slump in lower plenum	10152.9	10152.9	10152.9	10152.9
10	First total core uncovery	10980.9	10980.9	10980.9	10980.9
11	Melting pool formation in the core	11839.8	11839.8	11839.8	11839.8
12	First slump of corium with FPs in lower plenum	-	15563.6	15563.6	15563.6
13	Start of one HPP to inject in primary side	14000.0	16000.0	17000.0	-
14	Lower head vessel failure	-	18852.5	18203.2	18206.4

A comparison is made between main events during SBO in VVER 1000 with consequent later HPIS switching on (after melting pool formation in the core). Table II presents how ASTECv2 predicts a core degradation behaviour and consequent vessel failure in case of different times of HPIS system actuation.

The performed analysis covers SBO sequence with simultaneous loss of EFWS and spray system due to failure of DGs. Availability of hydro-accumulators (HAs) is not considered for this study. Integral code ASTECv2 (jointly developed by IRSN, France and GRS, Germany) is used for analyzing the transients. As mentioned above one HPP starts to inject at different times during the accident. It should be said that the investigation is limited to the in-vessel phase.

After SBO initiation all MCPs stop. FW delivery to all SG is also terminated due to loss of electricity supply. After a while a natural circulation is established. The core decay heat is transferred to the secondary side and removed via ‘steam dump to atmosphere’ (BRU-As). The role of BRU-As is to keeps the secondary pressure at approximately 6.7 MPa (68 kg/cm2) and opens and closes after reaching pressure thresholds. As a result deviations could clearly be seen until 6000 sec in secondary pressure curves in Figs. 2-5. Secondary pressure behavior influences primary pressure behavior and the same oscillations in the primary pressure curve could be observed at the beginning of the accident.

As seen from the figure, due to SGs depletion and the loss of natural circulation primary temperature and respectively pressure continue to increase and at approximately 6000s pressure reaches threshold for PRZ safety valve opening. The PRZ relief valve SEMPELL opens after reaching pressure value 18.52/18.56 MPa. It has been assumed that after PRZ safety valves open they failed and stuck in open position. It causes primary mass inventory depletion. Water level in the reactor vessel decreases and at 10980.9 sec is observed total core uncovery. This causes core overheating and consequent core degradation into the lower plenum. As seen from the results, after start of one HPP at 14000 sec it is possible to prevent a corium slump with FP, which is observed in all three calculations at 15563.6 sec. Later activation of HPIS - 16000 sec and 17000 sec could not prevent a reactor vessel failure.

The behavior of most important parameters is given in Figs. 3-34.

Primary pressure and temperature behaviour is given in Figs. 3-10. The results show pressure and temperature jump after one HPP actuation due to abnormal water vaporization. More interesting is what can be observed in the calculation, where one HPP starts to inject at 14000 sec. The core heat removing via PRZ safety valves causes primary temperatures and pressure decrease. The oscillations appear due to the intensity of the vaporization.

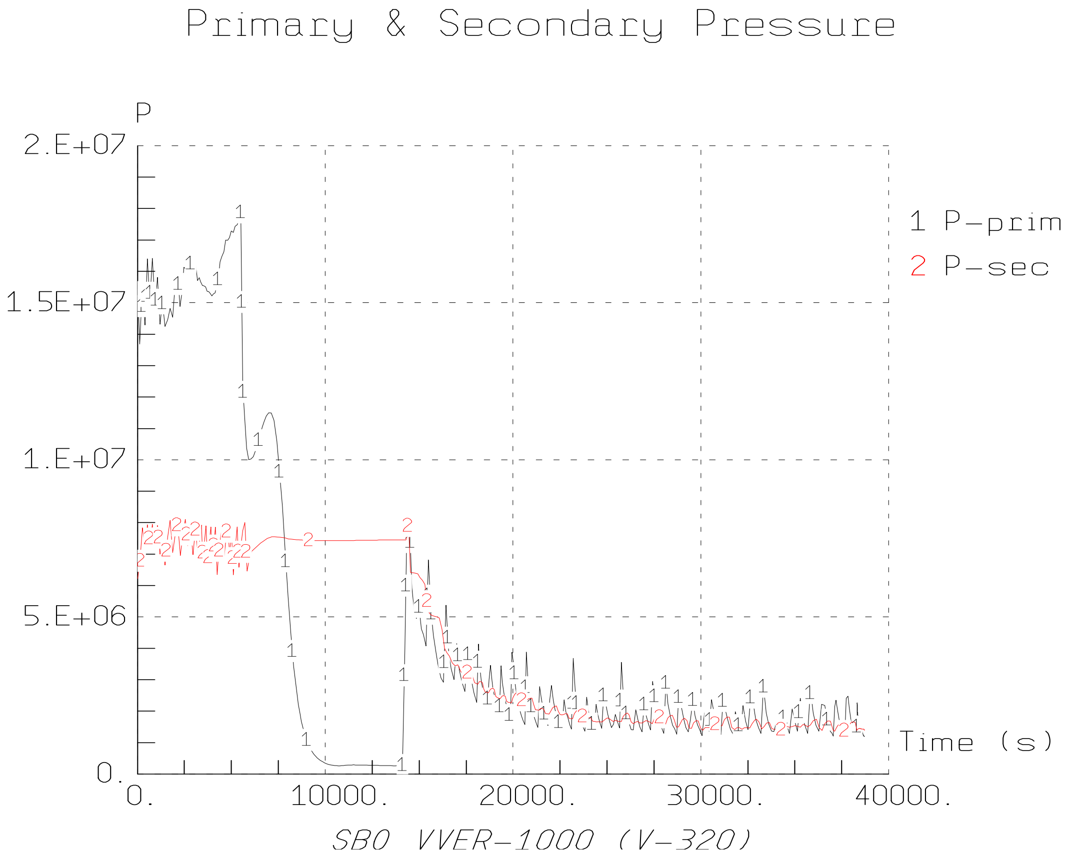

Fig. 3 ASTECv2 SBO with actuation one HPP at 14000s; Primary and Secondary Pressure

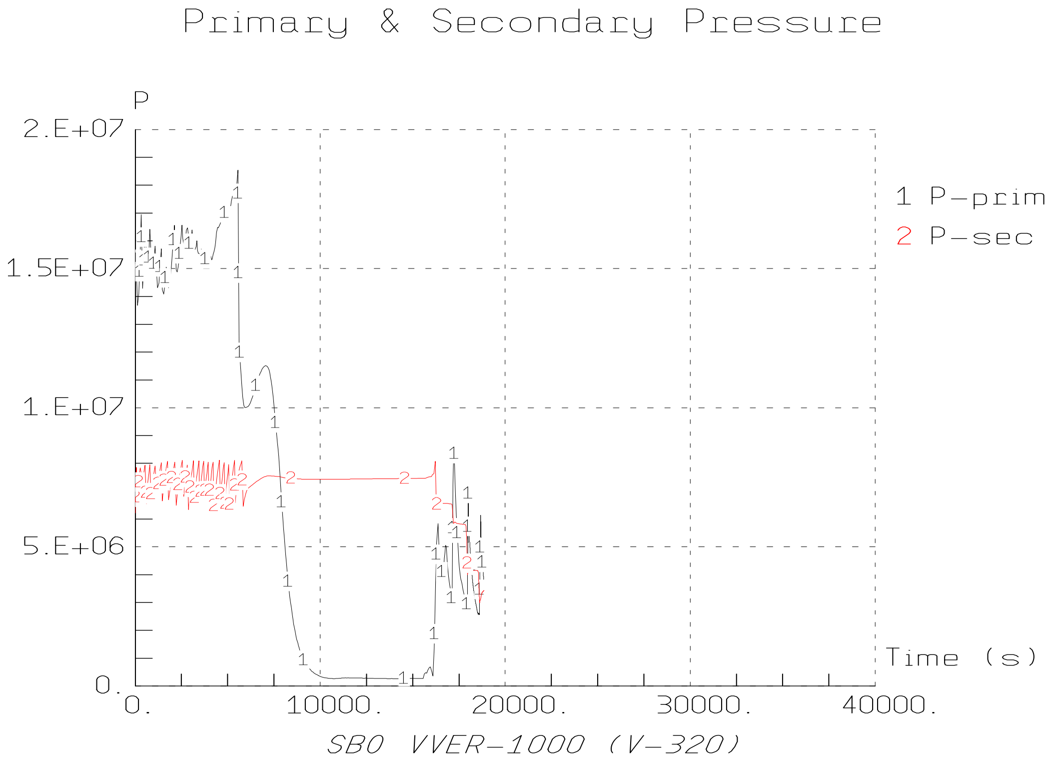

Fig. 4 ASTECv2 SBO with actuation one HPP at 16000s; Primary and Secondary Pressure

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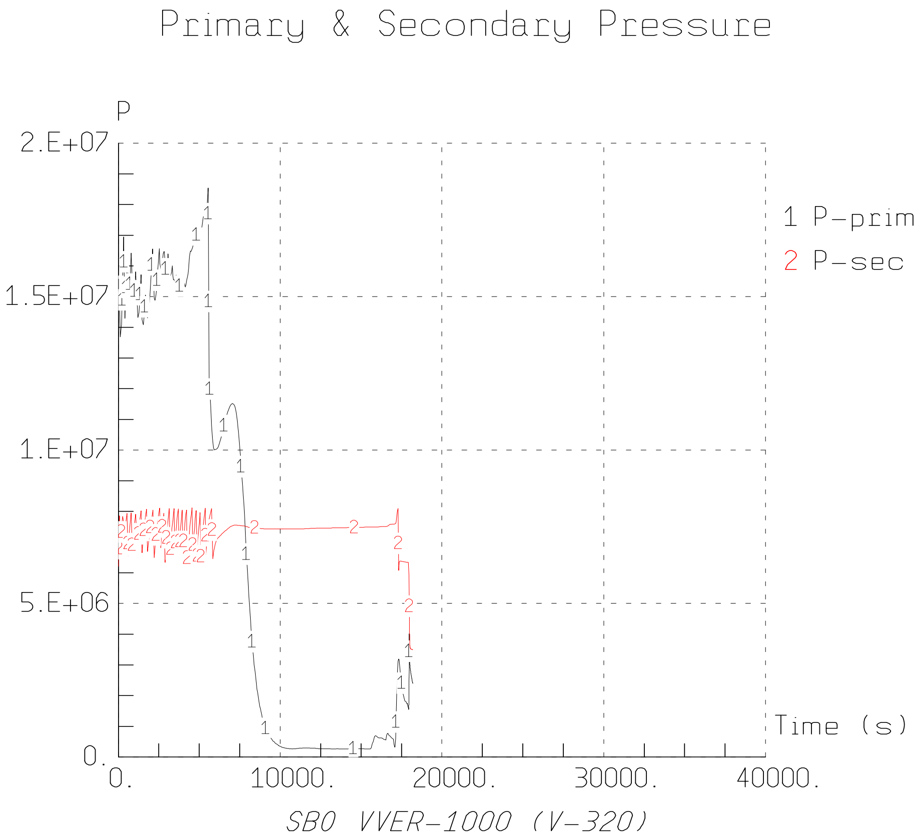

Fig. 5 ASTECv2 SBO with actuation one HPP at 17000s; Primary and Secondary Pressure

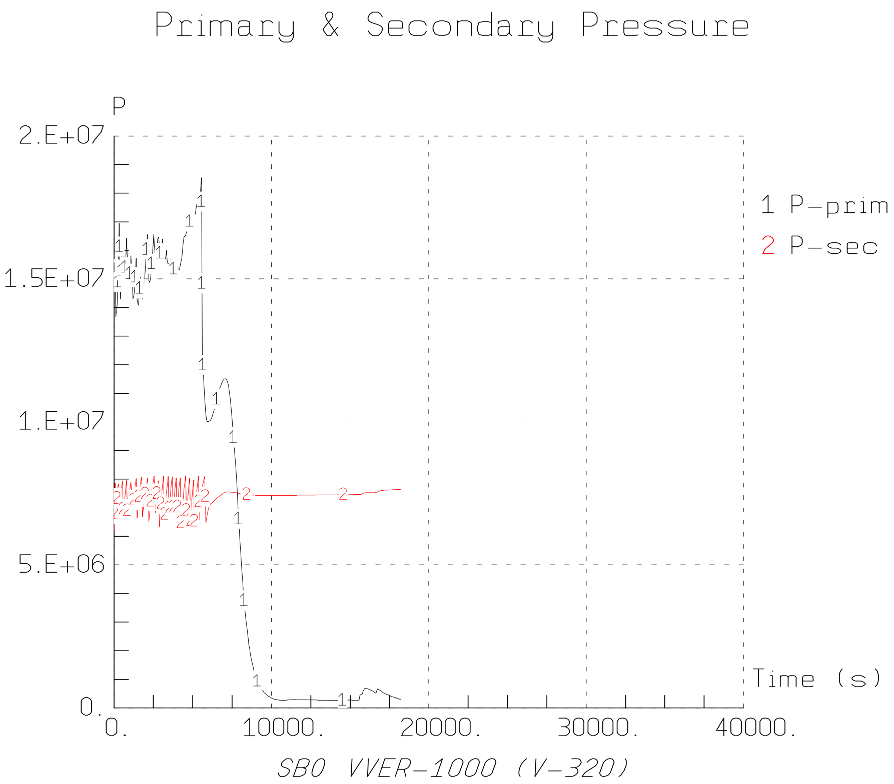

Fig. 6 ASTECv2 SBO without HPIS actuation; Primary and Secondary Pressure

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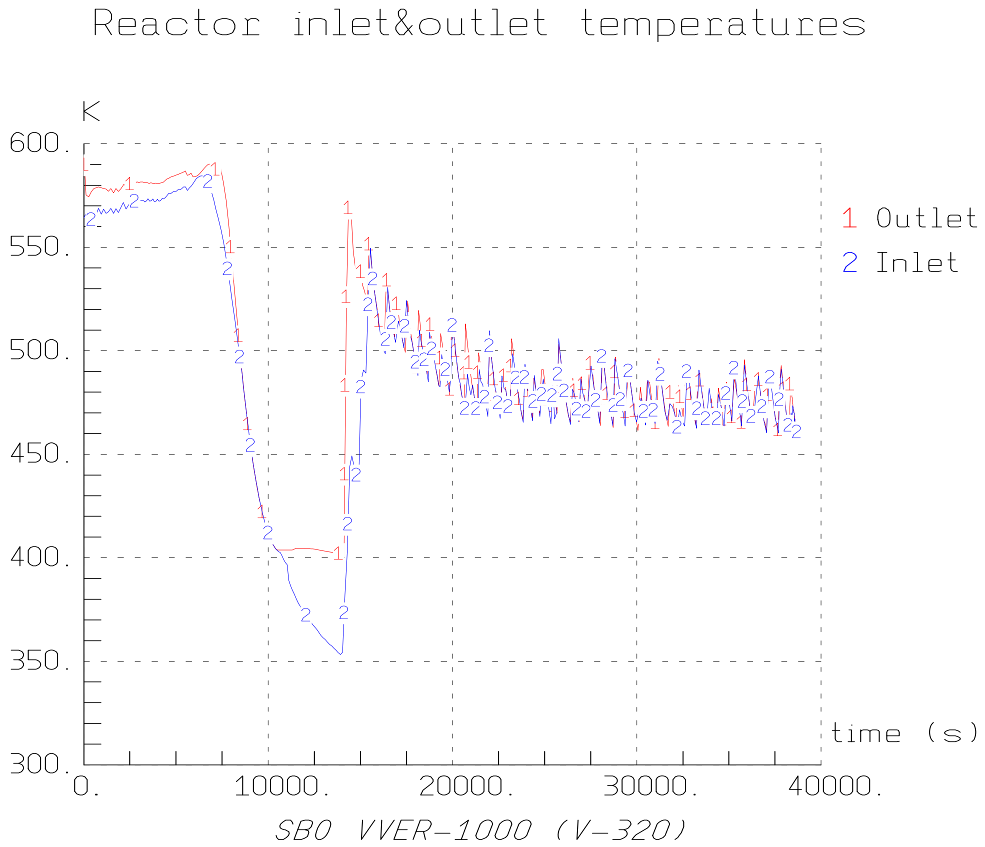

Fig. 7 ASTECv2 SBO with actuation one HPP at 14000s; Reactor Inlet & Outlet Temperatures

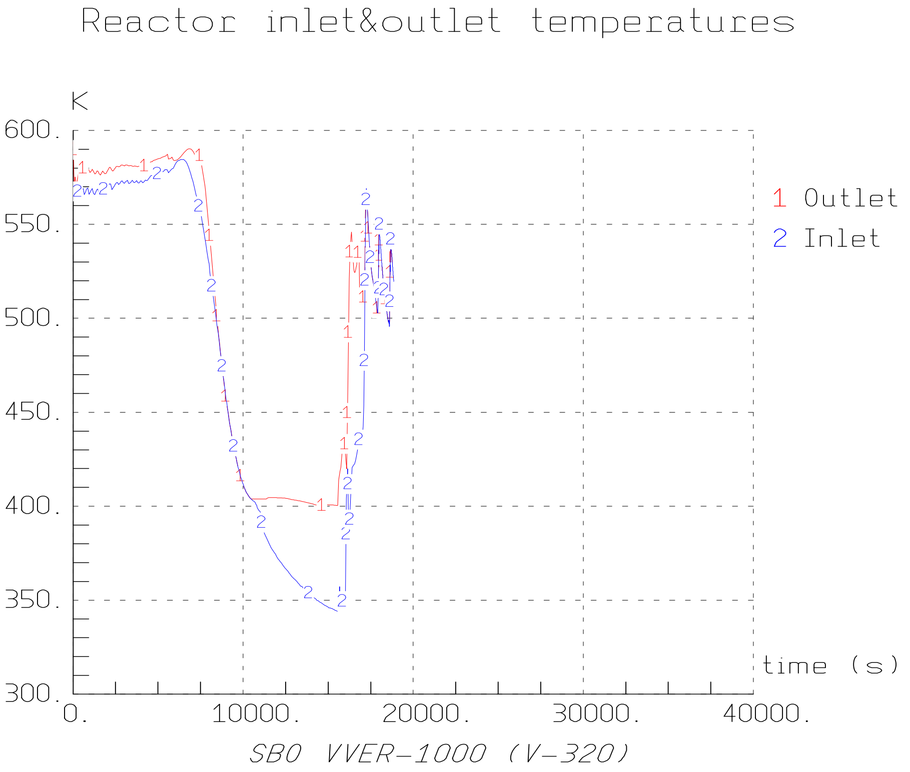

Fig. 8 ASTECv2 SBO with actuation one HPP at 16000s; Reactor Inlet & Outlet Temperatures

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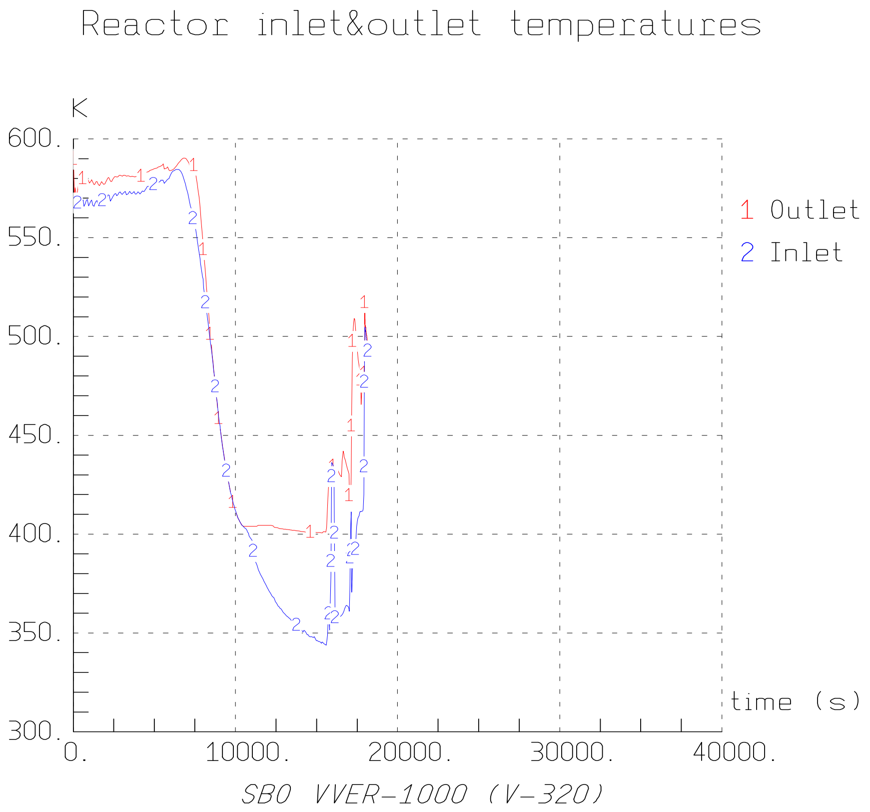

Fig. 9 ASTECv2 SBO with actuation one HPP at 17000s; Reactor Inlet & Outlet Temperatures

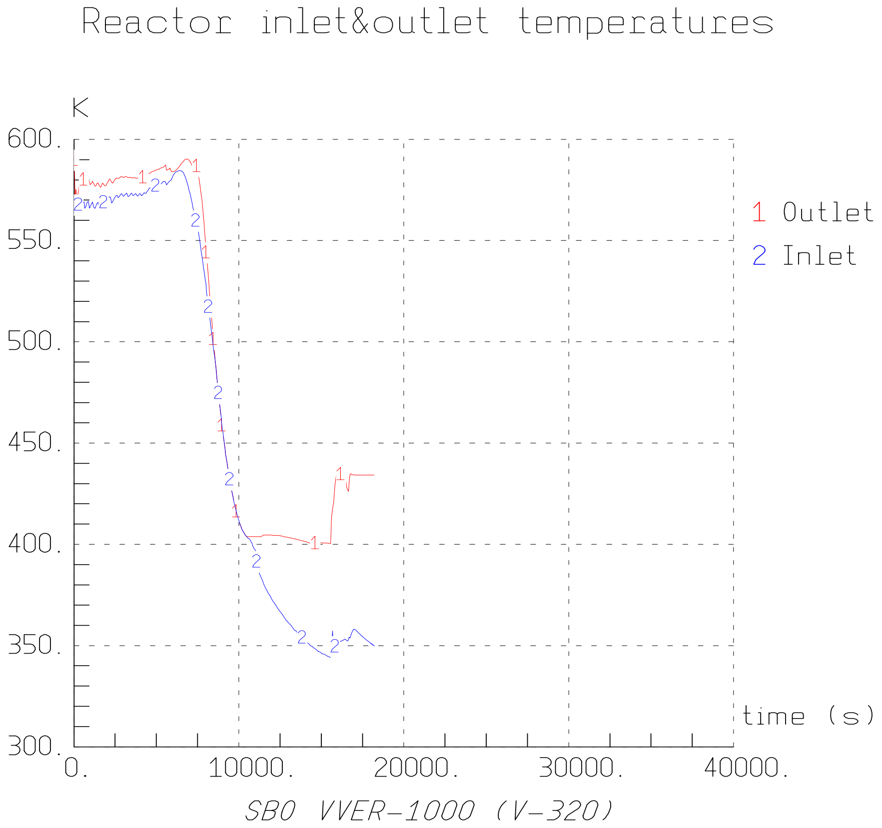

Fig. 10 ASTECv2 SBO without HPIS actuation; Reactor Inlet & Outlet Temperatures

The same temperature and pressure oscillations could be seen in Figs. 4, 5, 8 and 9 after 16000 sec and 17000 sec, when HPP start to inject. The deviations are observed up to the time of vessel failure.

The behavior of the primary mass of water and steam is presented in Figs. 11-14. It could be seen that after PRZ safety valves open at approximately 5500 sec the water mass inventory starts to decrease and in 7600 sec the primary side is almost completely discharged. Due to the rapid drop of primary pressure at the same time are reached conditions for saturation and the steam mass slowly increases. HPIS actuation indicates water mass increase in primary side respectively at 14000 sec, 16000 sec and 17000 sec (Figs. 11-13).

The oscillations observed at primary mass of water and steam behaviour influence pressure and temperature behaviour at the same time.

Pressurizer water mass and flow rate through PRZ relief valve in the fourth calculations are presented in Figs. 15-18. After open of SEMPELL at nearly 5500 sec primary mass inventory and respectively water mass in PRZ start to decrease.

Simultaneously due to the pressure drop, a steam bubble generates at the top of pressurizer. It causes a small peak in the pressure at approximately 6000 sec – 6500 sec and deviations in pressurizer water mass curves at the same time. After that water mass in PRZ decreases rapidly and at 7500 sec it is completely discharged. The maximum flow rate of 140 kg/s has been reached at around 7000 sec.

The injection of one HPP, which starts consequently at 14000 sec, 16000 sec and 17000 sec, is presented in Figs. 19-21. Fig. 22 shows simulation results without HPIS actuation.

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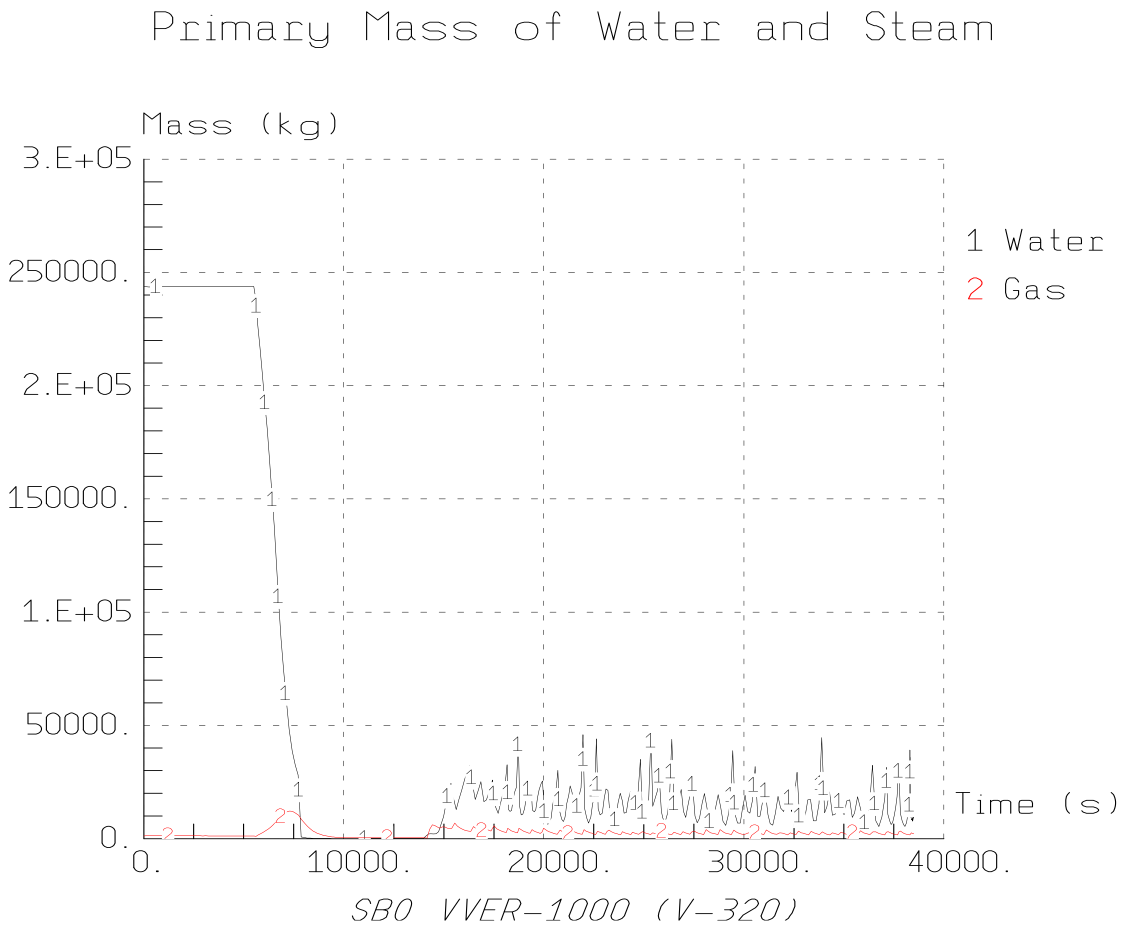

Fig. 11 ASTECv2 SBO with actuation one HPP at 14000s; Primary Mass of Water and Steam

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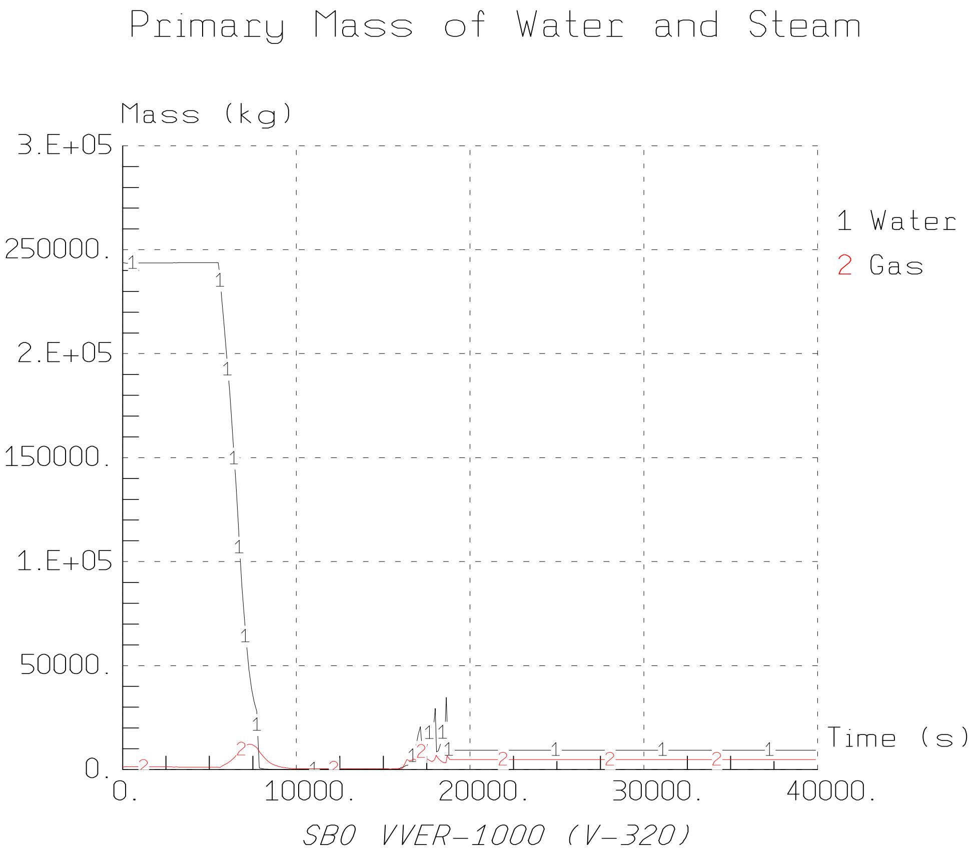

Fig. 12 ASTECv2 SBO with actuation one HPP at 16000s; Primary Mass of Water and Steam

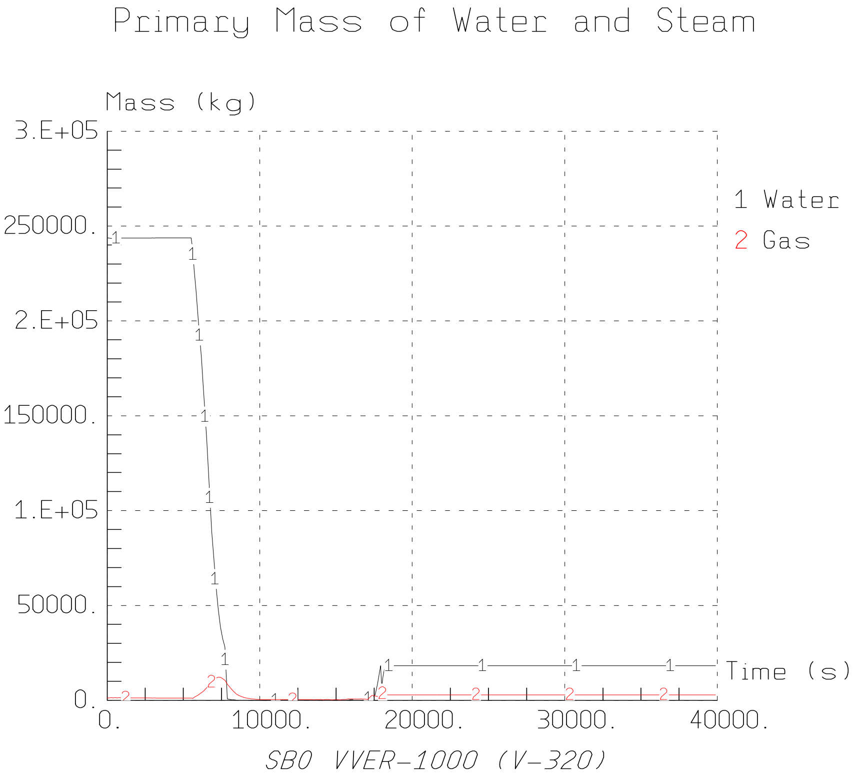

Fig. 13 ASTECv2 SBO with actuation one HPP at 17000s; Primary Mass of Water and Steam

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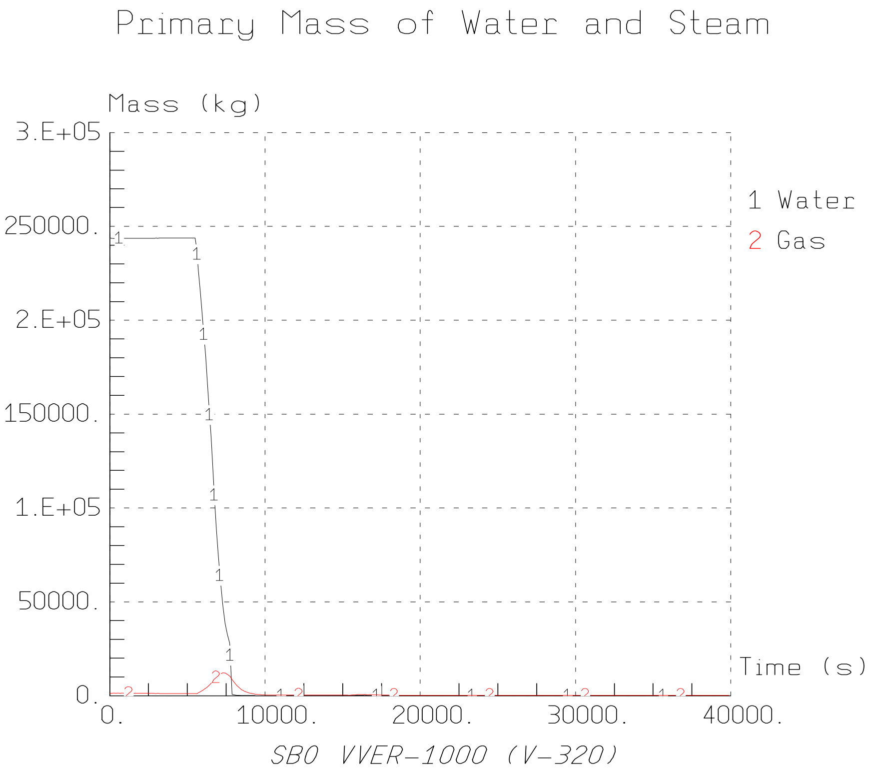

Fig. 14 ASTECv2 SBO without HPIS actuation; Primary Mass of Water and Steam

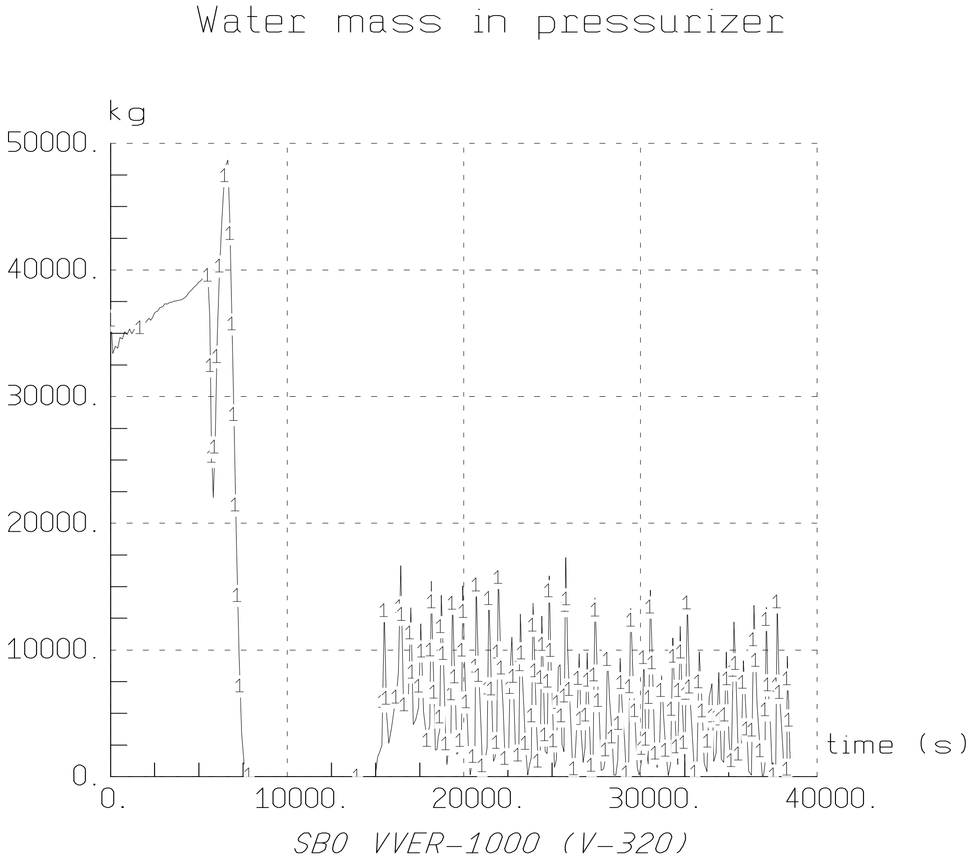

Fig. 15 ASTECv2 SBO with actuation one HPP at 14000s; Water Mass in Pressurize

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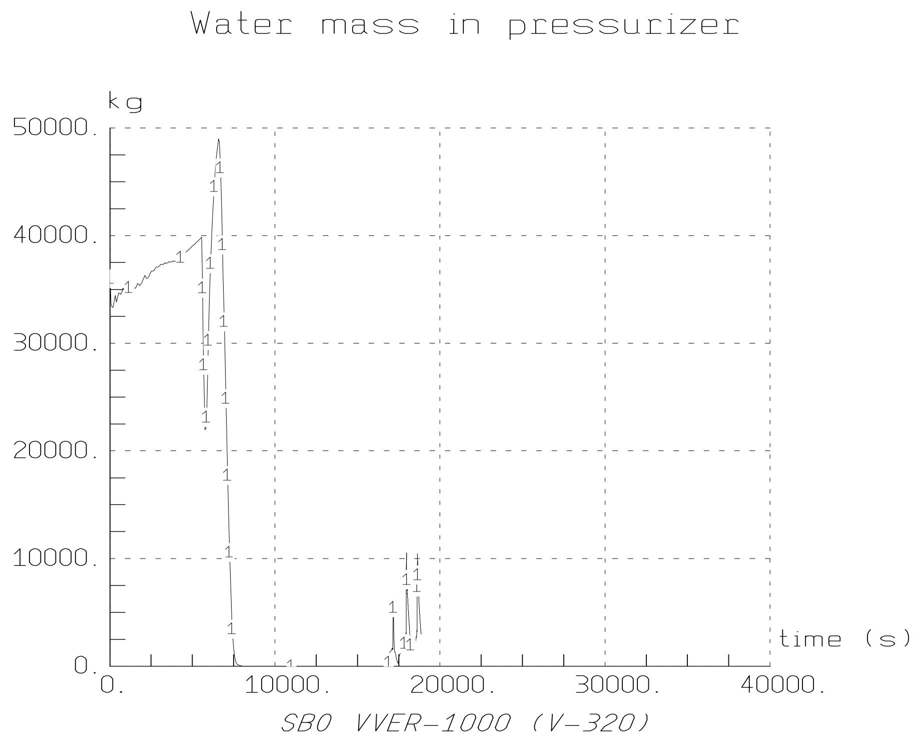

Fig. 16 ASTECv2 SBO with actuation one HPP at 16000s; Water Mass in Pressurizer

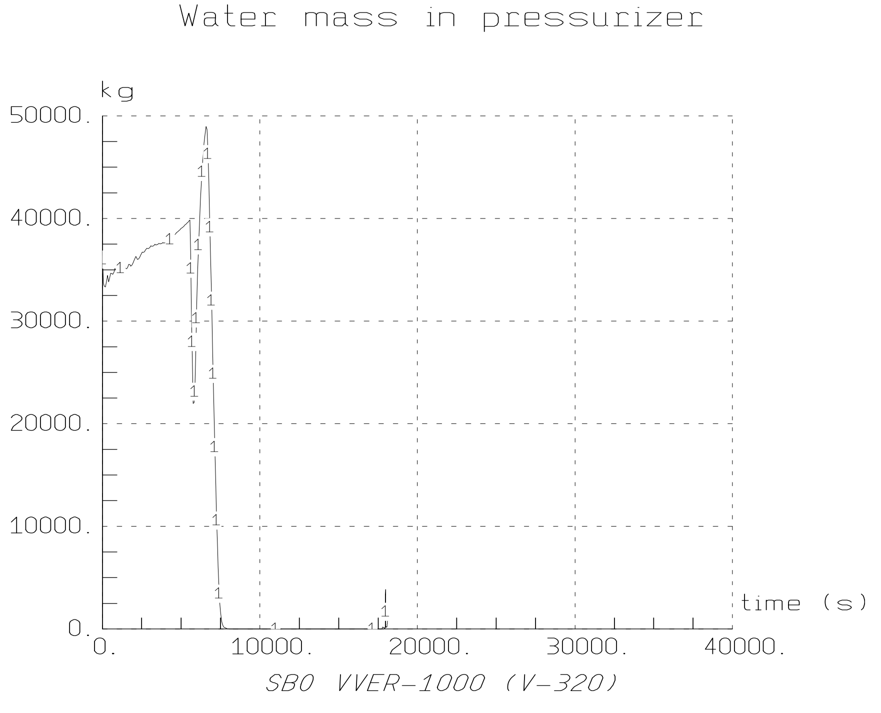

Fig. 17 ASTECv2 SBO with actuation one HPP at 17000s; Water Mass in Pressurizer

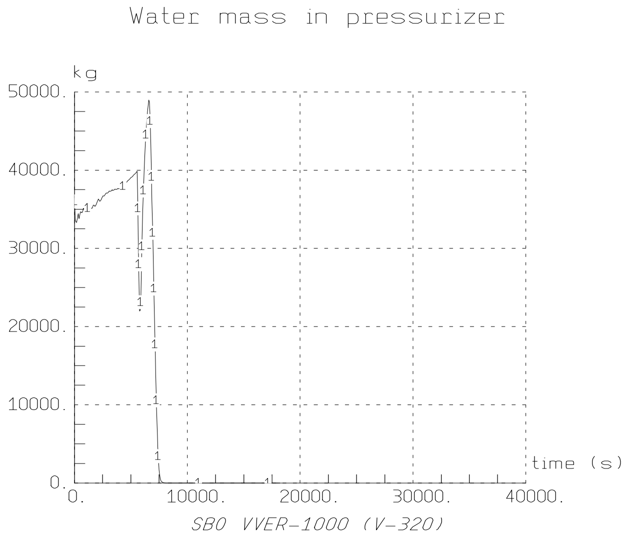

Fig. 18 ASTECv2 SBO without HPIS actuation; Water Mass in Pressurizer

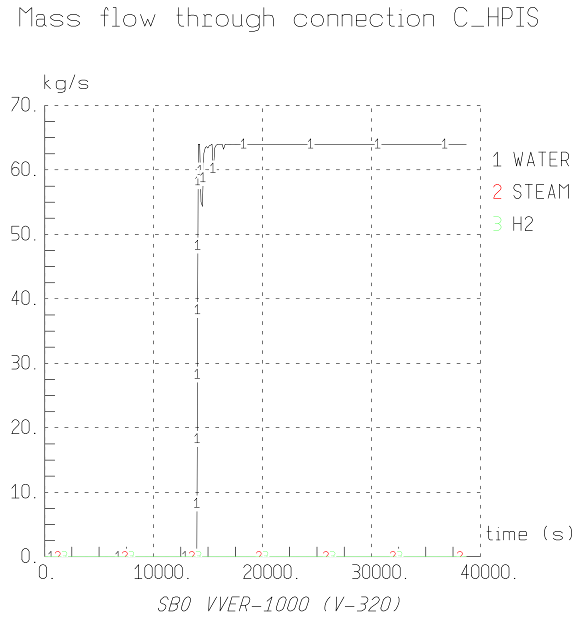

Fig. 19 ASTECv2 SBO with actuation one HPP at 14000s; Mass Flow Rate through a connection between HPIS

The first H2 production could be observed with the start of ICARE module due to the beginning of the oxidation of fuel claddings. During the core degradation the fission products are released from the fuel pellets and transported with the steam and non-condensable gases.

In Fig. 23, ASTECv2 predicts peak in H2 production after HPP injection due to abnormal steam generation promoting cladding oxidation. Total H2 mass reaches approximately 122 kg at 14000 sec. In Figs. 23-25 first corium slump with FP causes an increase in H2 production at around 15000 sec.

The calculations indicate first material slump of nearly 1.5 tons in lower plenum at 10152.9 sec. The first slump with FP of nearly 39 tons appears at 15563.6 sec in Figs. 28-30. The maximal corium mass and the time of vessel failure could be clearly seen from the figures above. In Figs. 29, 30 corium mass increases to almost 60 tons before vessel failure occurs.

Corium temperatures in the lower plenum are shown in Figs. 31-34. The maximal temperature of 1750 K in Fig. 31 is reached at the time of first corium slump 10152.6 sec. Due to the second corium slump with FP, temperatures in Figs. 32-34 jumps and reach values greater than 3200 K. In Fig. 31 the lower amount of corium results in considerably lower temperatures. This allows MAGMA temperature to be reduced to 500 K by Injection of just one HPP. Actually this is a premise for vessel failure not to occur.

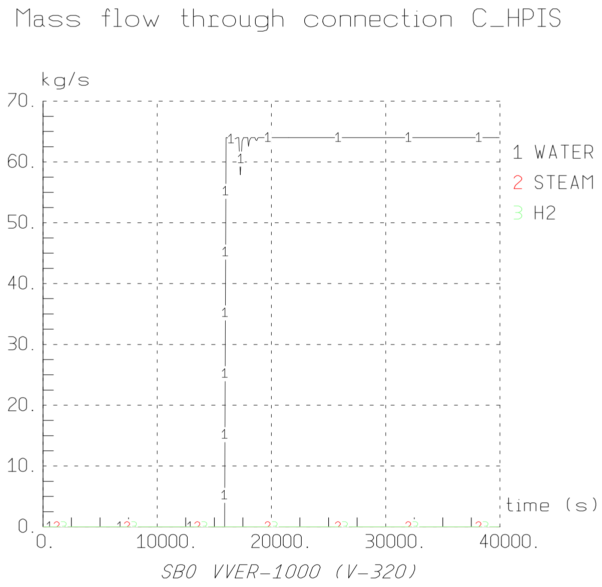

Fig. 20 ASTECv2 SBO with actuation one HPP at 16000s; Mass Flow Rate through a connection between HPIS

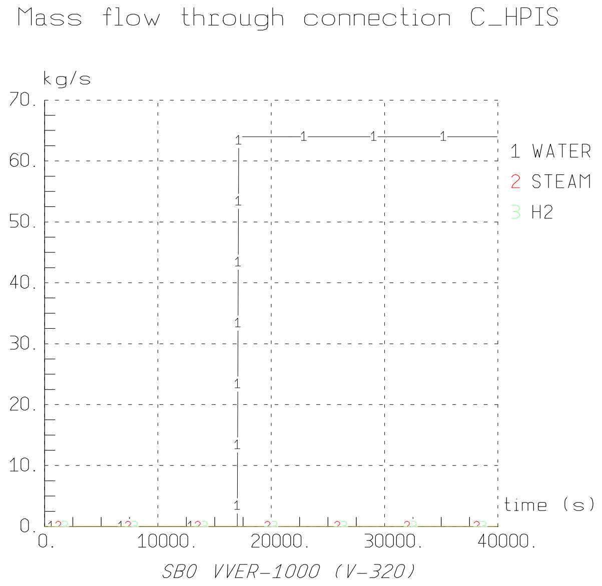

Fig. 21 ASTECv2 SBO with actuation one HPP at 17000s; Mass Flow Rate through a connection between HPIS

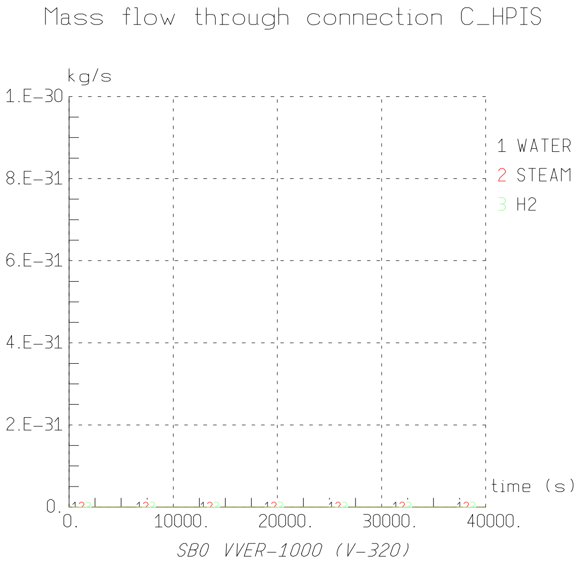

Fig. 22 ASTECv2 SBO without HPIS at actuation; Mass Flow Rate through a connection between HPIS

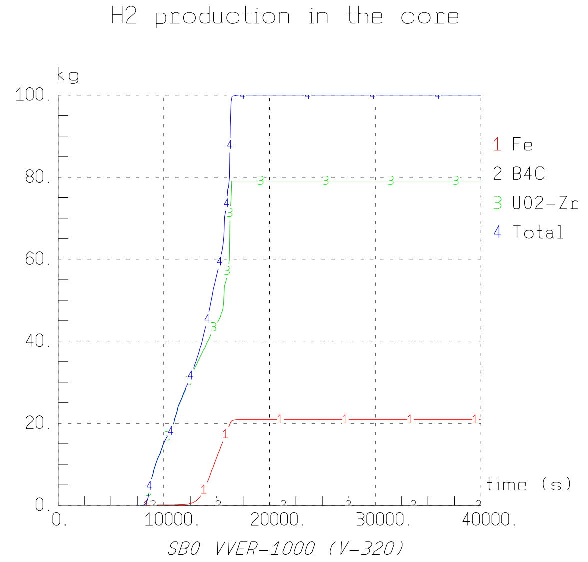

Fig. 24 ASTECv2 SBO with actuation one HPP at 16000s; Hydrogen production

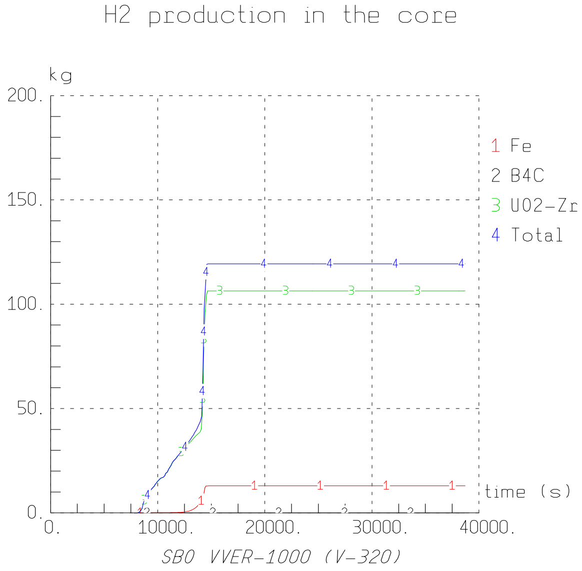

Fig. 23 ASTECv2 SBO with actuation one HPP at 14000s; Hydrogen production

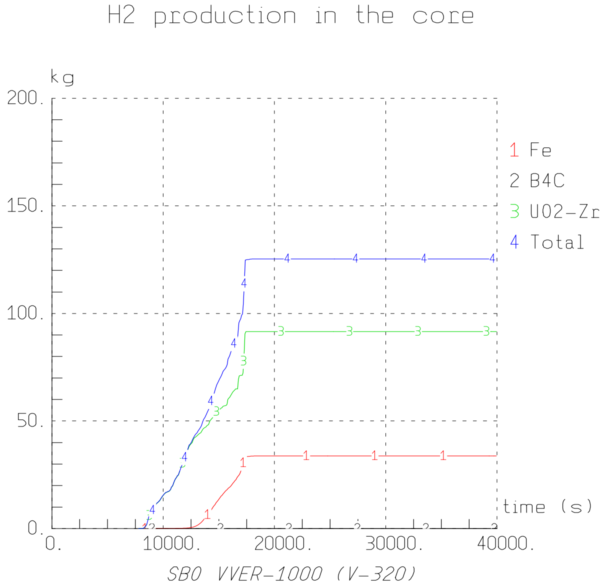

Fig. 25 ASTECv2 SBO with actuation one HPP at 17000s; Hydrogen production

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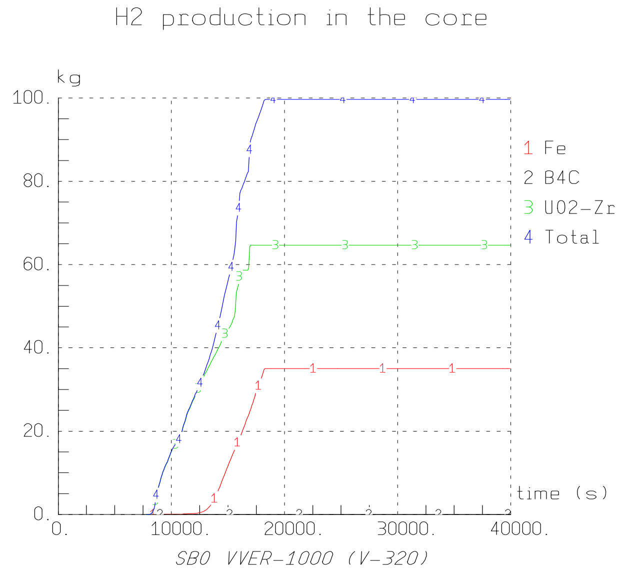

Fig. 26 ASTECv2 SBO without HPIS actuation; Hydrogen production

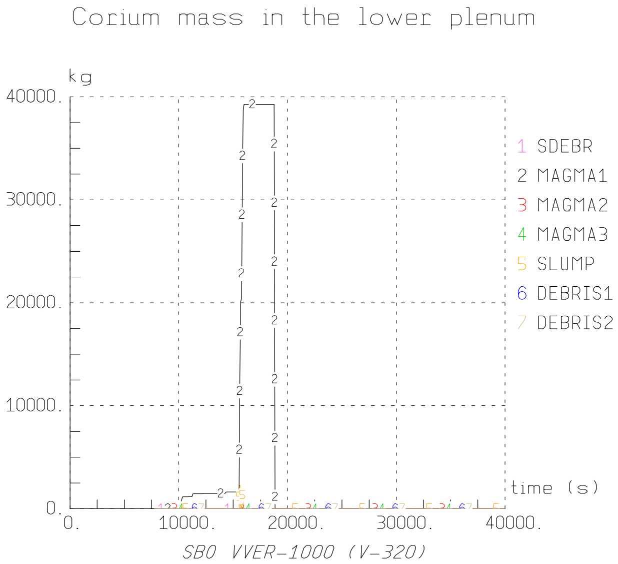

Fig. 28 ASTECv2 SBO with actuation one HPP at 16000s; Corium Mass in the Lower Plenum

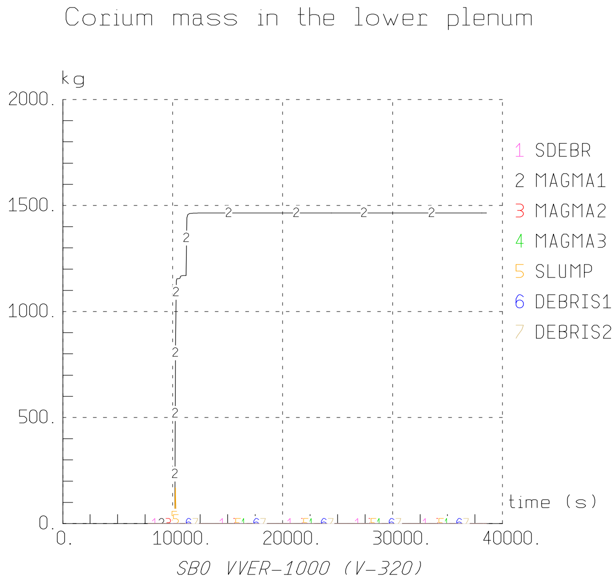

Fig. 27 ASTECv2 SBO with actuation one HPP at 14000s; Corium Mass in the Lower Plenum

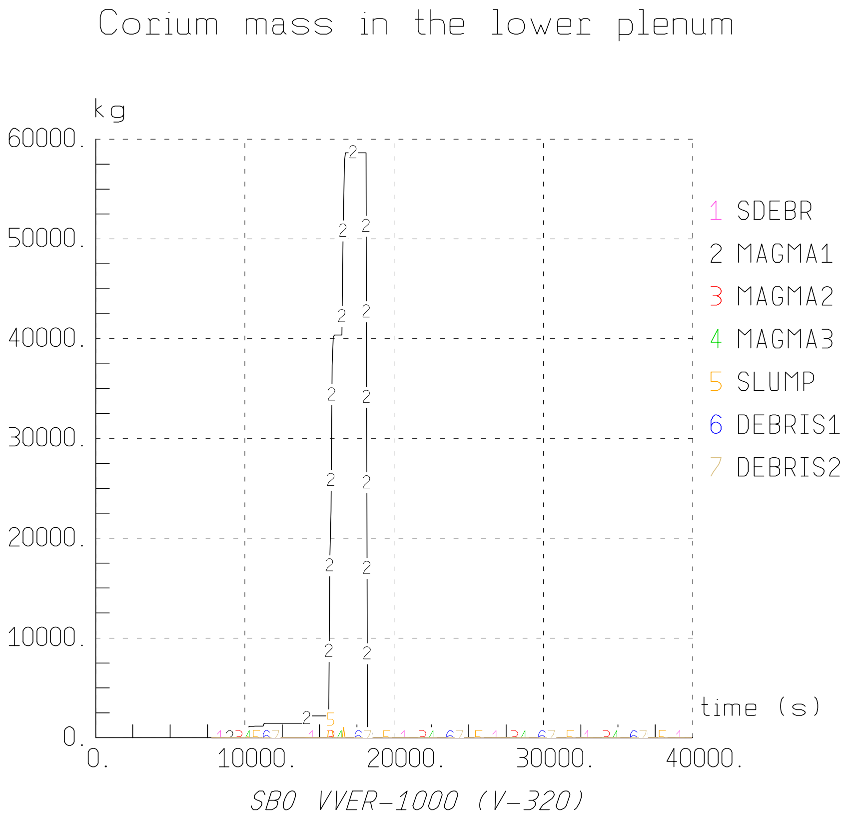

Fig. 29 ASTECv2 SBO with actuation one HPP at 17000s; Corium Mass in the Lower Plenum

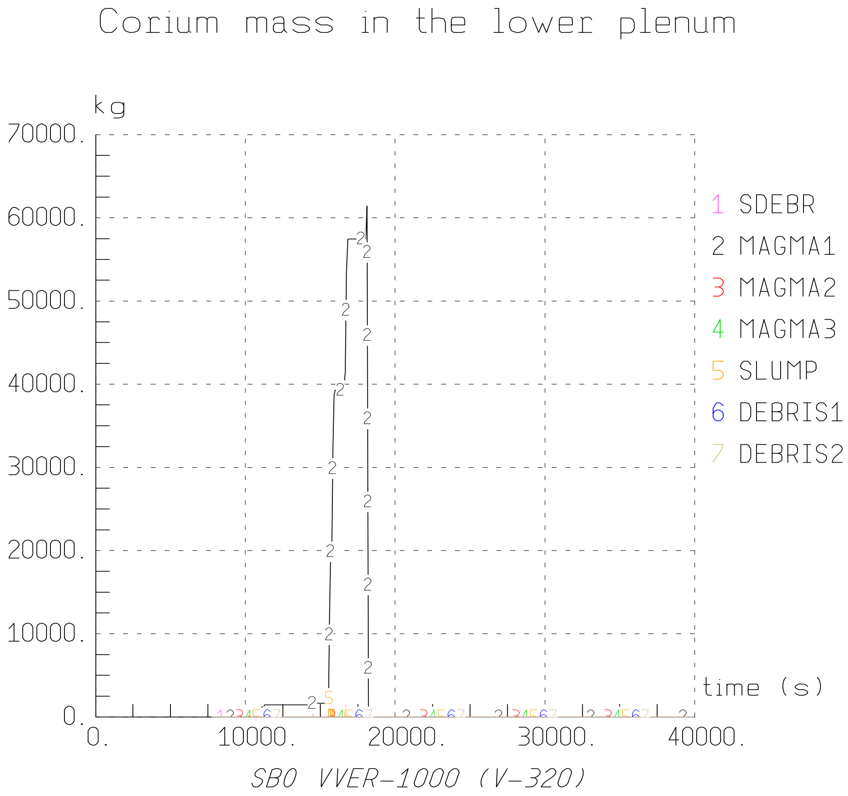

Fig. 30 ASTECv2 SBO without HPIS actuation; Corium Mass in the Lower Plenum

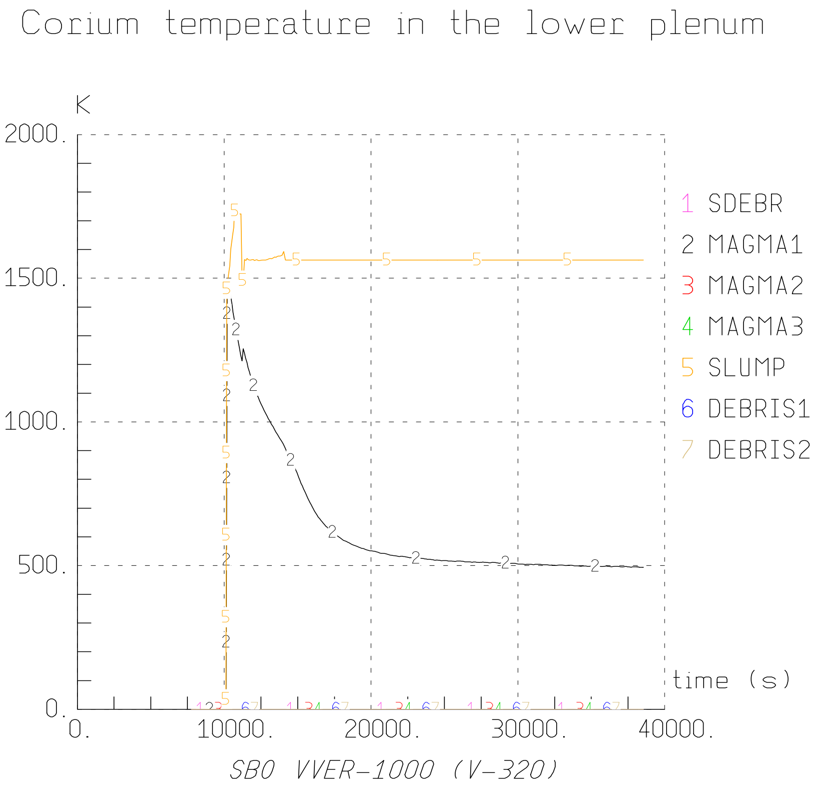

Fig. 31 ASTECv2 SBO with actuation one HPP at 14000s; Corium Temperature in the Lower Plenum

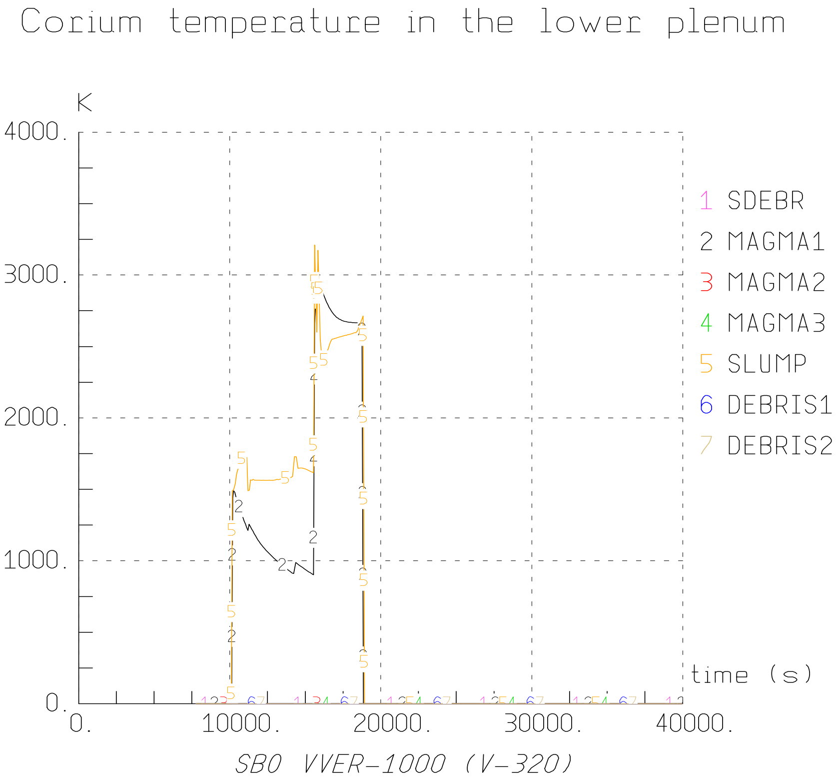

Fig. 32 ASTECv2 SBO with actuation one HPP at 16000s; Corium Temperature in the Lower Plenum

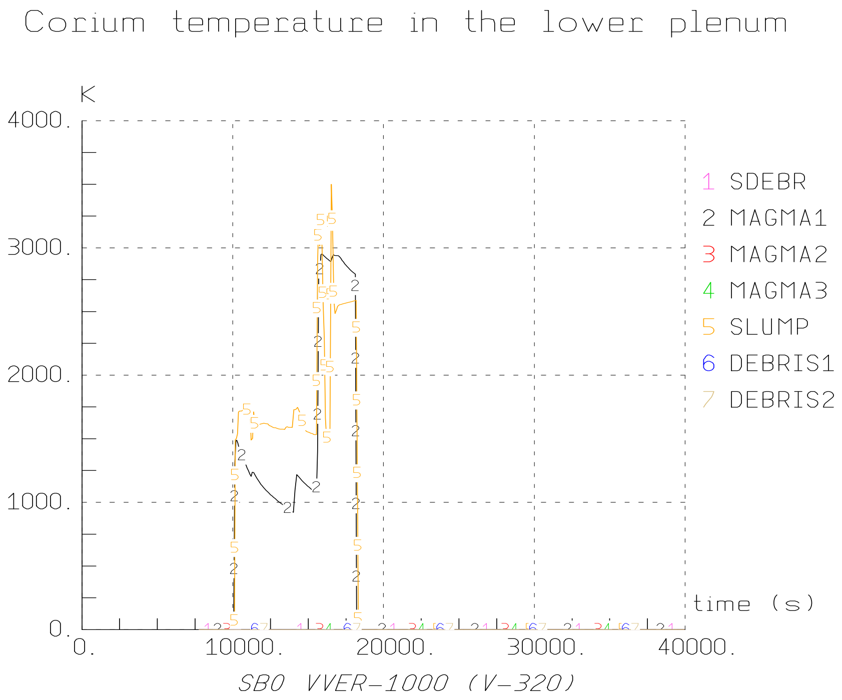

Fig. 33 ASTECv2 SBO with actuation one HPP at 17000s: Corium Temperature in the Lower Plenum

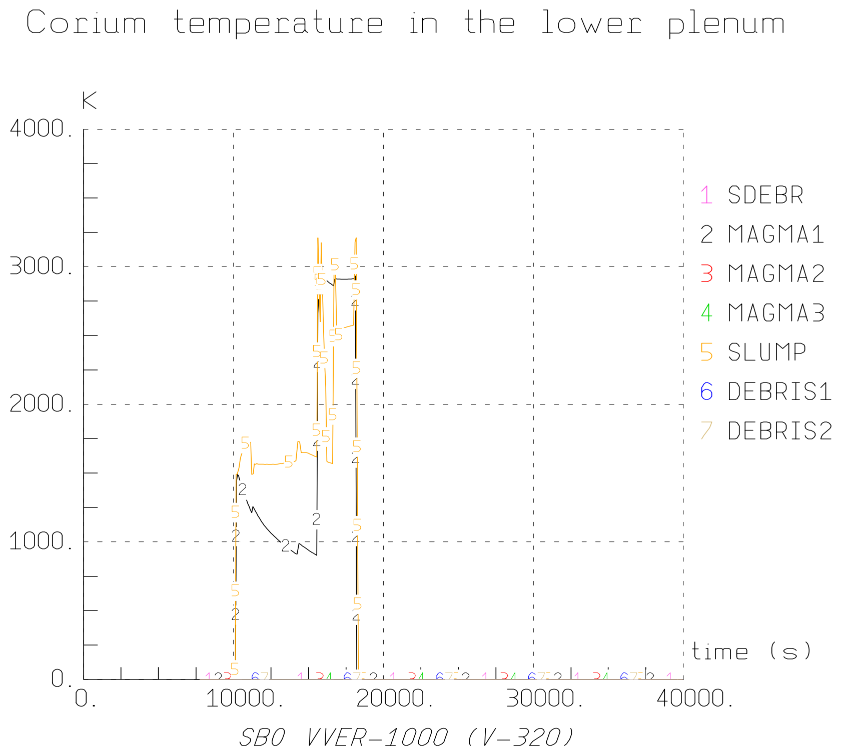

Fig. 34 ASTECv2 SBO without HPIS actuation; Corium Temperature in the Lower Plenum

V. CONCLUSIONS

The main conclusion of this investigation is that primary side HPIS reflooding at overheated reactor core is successful if it starts before slump of corium with FPs in lower plenum.

HPIS actuation after significant corium slump leads to reactor vessel failure, which occurs with some delay of 10 min in comparison with the case without reflooding. So the main conclusion is that reactor vessel failure will happen, even if water injection is started 2000 sec before vessel failure.

In case of significant corium slump it is recommended to perform in-vessel melt retention by external cooling of the

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reactor vessel or to take further measures in order to prevent basement melt through after relocation of corium to the cavity.

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