ASTEC applications to VVER reactors

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Abstract: The requirements of the IRSN-GRS integral code ASTEC for simulation of the whole sequences of severe accidents in LWR include its applicability to VVER severe accidents. Thus, a program of collaboration with Eastern European organizations was set up around VVER applications, first through bilateral actions and then via the EVITA 5th FWP project: validation on VVER-specific experiments and plant applications. The ASTEC V0 version has been applied to sequences in VVER–440 or –1000 (station blackout, large break and small break LOCAs). Most VVER features, including the safety systems, are correctly simulated by the code, for instance the VVER-440 bubble condenser towers, the primary circuit depressurisation, the water injection systems, etc… In parallel, preliminary applications of the new ASTEC V1 version, delivered mid-2002, show that this version should allow to improve the simulations, and also in the future to represent new VVER designs. For instance, the application to the real Loss of Feedwater transient on the Russian Kalinin VVER-1000 gave results close to the plant measurements. Validation results are correct on the EREC T5 experiment (VVER-440 containment thermalhydraulics), PACTEL ISP33 experiment (VVER-440 RCS thermalhydraulics) and on HD experiments (H_2 distribution in a VVER-1000 containment). This version now needs consolidation through extensive validation and benchmarks with codes such as MELCOR or ICARE/CATHARE.

1 INTRODUCTION

The integral code ASTEC (**A**ccident **S**ource **T**erm **E**valuation **C**ode) has been commonly developed by IRSN and GRS with the aim to get a fast running code for the simulation of the total severe accidents sequences in LWR from the initiating event up to the possible fission products release to the environment. The code shall cover all-important phenomena, which can occur in PWR, BWR and VVER and new reactor designs like EPR, etc. The code shall be applied to accident sequence studies, probabilistic safety assessments, investigations on accident management procedures and to the support to experiments. Since the code requirements include the code applicability to VVER severe accidents, a program of collaboration with Eastern European organizations was set up around VVER applications: validation on VVER-specific experiments and plant applications. This collaboration began first through bilateral actions and then continued in the international frame of the EVITA project ("European Validation of the InTegrated ASTEC code") in the E.C. 5th Framework Program.

In particular, the first version, ASTEC V0, has been applied in the last three years to sequences in VVER Nuclear Power Plants (NPP), either –440 type or –1000 type. Moreover, some preliminary VVER applications of the new version ASTEC V1, released mid-2002, have already been performed. This paper presents the status of these VVER applications with a detailed analysis of some of them.

2 STATUS OF THE ASTEC CODE

The current official version is ASTEC V0.3 that was delivered in late 2000 to 17 European partners (utilities, designers, safety authorities, R&D organizations), with its whole documentation including a synthesis of validation work (on 30 separate-effect or coupled-effect tests and on FPT1 Phébus-FP integral test). This delivery took place in the EVITA frame (02/2000 – 08/2003) coordinated by GRS with a strong IRSN implication. Its objective is to gather users' experience feedback on code use, capabilities to represent Severe Accident Management measures, and guidance for further validation. The partners include 5 east-European ones: UJD, VUJE and IVS (Slovakia), NRI (Czech Rep.) and VEIKI (Hungary).

This version has been applied to numerous scenarios for French and German PWR as well as for VVER-440 and -1000. Let us recall that the main limit of this version is the absence of the front-end phase calculation, and thus the need of an upstream calculation with a thermalhydraulics reference code (for instance CATHARE code).

A new version ASTEC V1 was delivered to the same European partners mid-2002, again in the EVITA frame. It allows calculation of the front-end phase and includes improvements of core degradation models. Its modules are:

- CESAR for RCS (Reactor Cooling System) 2-phase thermalhydraulics during the front-end phase and the degradation phase,
- DIVA for core degradation, including late phase phenomena (molten pool, corium slump to lower head, corium in lower head) and vessel failure. Both CESAR and DIVA modules replace in ASTEC V1 the VULCAIN module which was present in the ASTEC V0 version.
- ELSA: release of FP (fission products) from fuel rods and debris and of materials from control rods, using a semi-empirical approach.
- SOPHAEROS: FP vapor and aerosol transport in RCS.
- RUPUICUV: corium discharge from vessel to cavity with cavity pressurisation and potential DCH (Direct Containment Heating).
- WEX (which replaces in ASTEC V1 the WECHSL module present in the ASTEC V0 version): MCCI in the cavity.
- CPA: multi-compartment containment simulation, including thermal-hydraulics, hydrogen combustion, and aerosol and FP behaviour.
- IODE: iodine behaviour in the containment (sump and gas phase).
- ISODOP: decay heat and activity of FP and actinide isotopes in core, RCS, containment and environment.
- SYSINT: management of safety systems (spray, high and low pressure injection, accumulators…),
- MDB: Material Data Bank which gathers in only one location within the code all material properties used by the modules, including also isotopes and chemical reactions.

Main efforts will now tend first to consolidation of this new version, through benchmarks with other codes (ICARE/CATHARE for core degradation, MAAP4 and MELCOR for the complete scenarios) and through an extensive validation. In parallel, modelling improvements will mainly concern reflooding of a degraded core, MCCI (with a totally new module MEDICIS under development) and H_2 combustion in the containment.

3 ASTEC VALIDATION ON VVER EXPERIMENTS

The validation of the V0 version was performed on a large scope of separate-effect tests, thus covering the main phenomena involved in the course of severe accidents. Most of these phenomena, along with the range of physical parameters, are similar in PWR and in VVER. But, in order to address more precisely some VVER-specific phenomena or conditions, a matrix of VVER-specific experiments was built first in close collaboration with NSI/RRC-KI [1, 2] and then extended in the EVITA frame (Table 1). This matrix covers the following main aspects:

- core degradation, including VVER-440 specificities such as bundle shrouds and fuel followers (which implies the presence of fuel in the vessel lower head when the upper part of control rods is within the core),
- thermalhydraulics (and FP transport) in a RCS with horizontal SGs,
- thermalhydraulics in a containment, including VVER-440 specificities such as bubble condenser towers.

Three such code applications are presented below:

- CPA validation on the HD experiments (work by NSI/RRC-KI, Russia),
- CPA validation on the EREC T5 experiment (work by VEIKI, Hungary).
- CESAR validation on the PACTEL ISP-33 experiment (work by IVS, Slovakia).

Two other applications should be performed before mid-2003 in the EVITA frame: PSAERO-HORIZON and CORA-W2.

Validation of H_2 distribution modelling in the containment on HD experiments [1, 3]

H_2 distribution in a VVER-1000/V320 multi-compartment containment was studied in the HD Russian facility. The containment model of 20 m^3 volume was divided in 9 connected cells. The CPA module was applied to 4 experiments which differed by locations of H_2 feeding (steam generator or SG compartment, reactor cavity, pressuriser valve) and H_2 injection flow rate (low and uniform, or initially high and later on lower). A satisfactory agreement with measurements was obtained for the evolution of H_2 concentration in the containment compartments, within the range of experimental errors. The best agreement was obtained for H_2 feeding at the bottom location, which is the most common case in the VVER-1000 accidents (source in the RCS compartments or in SG compartments or in the reactor cavity).

Validation of containment thermalhydraulics modelling on EREC T5 experiment

The facility simulates the leaktight rooms of the Paks VVER-440 NPP with a scale of 1:100 and includes bubble condenser towers. The T5 experiment simulates a large break LOCA. The CPA results were compared with experimental ones and with CONTAIN results:

- good agreement for pressure peaks and time histories,
- good agreement for most temperatures, except in one SG box zone where the atmosphere in CPA later reaches saturated conditions. But both codes overestimate the temperatures in the gas room of the tray and in the air trap,
- higher calculated pressure difference on the tray, which is partly explained by the absence of account for tray walls deformation. The pressure oscillations are reproduced with CPA but with different amplitude and frequency than in the experiment (Fig. 1), whereas CONTAIN only shows the first peak. After first oscillations, the pressure difference corresponds to the measurement,
- the water heat up in the tray calculated by CPA is in the range of the measured values,
- the calculated flow rates between the SG box and the localisation tower are similar for both codes.

Validation of RCS thermalhydraulics modelling on PACTEL ISP 33 experiment

The ISP-33, organized in 1992-1993 in Finland on the scaled-down experimental facility PACTEL, was a unique experiment devoted to performances of VVER-440 reactors during SBLOCA conditions without water injection [4]. The volumetric scaling factor of the facility was 1:305. Elevations were preserved in full height to match the natural circulation gravitational heads.

The main goal of ISP-33 and the corresponding experiment was to study natural circulation in a VVER-440 primary system including several single- and two-phase natural circulation modes. For this purpose the primary coolant mass was reduced stepwise until the core heat-up started. The core power was kept constant corresponding to decay heat level and the secondary side heat sink was preserved during the experiment.

Up to the 2nd draining, the overall behaviour of the primary system was well predicted by CESAR calculation. After the second draining, the swell level in the upper plenum dropped below the hot leg nozzles level and the flow rate in loops became stagnant. The hot leg loop seals prevented the steam from upper plenum to reach the steam generators. Consequently, primary pressure rose sharply and opening set point for primary safety valve was reached. Some water escaped through the primary safety valve. After short flow stagnation, multiple loop seal clearings occurred. The effect of flow stagnation was well predicted by ASTEC code. After the 3rd draining, relatively stable two-phase flow was established in both experiment and calculation. However, the predicted mass-flow-rate through loops and pressure decrease after the draining were too low. Since the 4th draining the course of the primary pressure was correct and the overall behaviour of the primary system was well predicted. The start of core heat-up occurred in the experiment after 7th draining, when the primary inventory drops to 35% of its nominal value. CESAR predicted properly (although with a 500 s time delay) the start of core heat-up after 7th draining (Fig. 2). As soon as the maximum cladding temperature reached 350°C, the core heaters were switched off and depressurisation of the secondary side took place.

Based on the results obtained, it can be stated that the CESAR code is fully applicable to such kind of simulations as ISP-33. The overall behaviour of the system was well predicted. The crucial (from the safety point of view) phenomenon of the experiment – the start of core heat-up versus primary inventory – was well matched, too. Some limitations were found in the underestimation of the mass flow rate in primary system under degraded primary inventory.

Compared to the results of other codes used in ISP-33 post-test analysis, the CESAR accuracy seems to be on “good average” level. Nearly all of the submitted calculations (as well as a recent analysis with the code RELAP5-3D [5]) predicted the start of core heat-up one drainage later than in the experiment while it was not the case with CESAR.

4 ASTEC APPLICATIONS TO VVER SCENARIOS

4.1 ASTEC V0 applications

Several ASTEC V0 applications on VVER reactor scenarios were performed in 2000-02 either in the EVITA frame or in the frame of bilateral collaboration with VUJE (Slovakia) and NSI/RRC-KI (Russia):

- for VVER-1000: station blackout (by NRI), LBLOCA (by NSI/RRC-KI),
- for VVER-440 sequences : station blackout (440/213, by UJD, Slovakia), LBLOCA (440/230, by VUJE), MBLOCA (440/213, by VUJE).

In most of these studies, results were compared with those of integral codes such as MELCOR and MAAP4/VVER. The overall conclusion is satisfactory: the same general trends of reactor behaviour were obtained but discrepancies arose on some results such as in-vessel hydrogen production and MCCI. Another outcome was that the limits of the VULCAIN models are reached: lack of flexibility to simulate some VVER specificities (bundle shrouds, fuel followers) and no 2-phase thermalhydraulics in the loops.

Some examples of such applications are shown with more details below.

Application to LBLOCA on VVER 440/230:

The containment was nodalised in 10 zones, using the DRASYS specific model of the CPA module for simulating EWST (Emergency Water Storage Tanks) with circulation condensers. Within the vessel, Zry of the core shrouds and the fuel followers in the vessel lower plenum had to be neglected in VULCAIN.

The calculated H_2 production is shown in Fig. 3 and the main results are summarised in the Table 2:

- for in-vessel phenomena, discrepancies come mainly from model differences (Zry-oxidation correlations, corium behaviour in vessel lower plenum, etc.) and from some VULCAIN limitations,
- comparable cumulative release from fuel of FP and aerosols is obtained. The total FP retention factors in all RCS volumes are slightly higher in ASTEC (around 0.4) than in MAAP4/VVER (between 0.20 and 0.46). Note that only ASTEC models aerosol retention in Steam Generator horizontal tubes,

- MCCI is less intensive with ASTEC (5 times less gas H_2 and CO release) because of less non-oxidized metal in the corium ejected from the vessel lower plenum. Note that the MAAP4 calculation of core degradation continues after vessel rupture but the ASTEC one does not.

Application to TMLB on VVER 1000:

A comparison was performed with MELCOR 1.8.5 results on a TMLB (blackout) sequence for a VVER-1000/320/W unit, focusing on the in-vessel phase. The containment nodalisation was coarse with 5 control volumes.
Since VULCAIN starts after core uncovery, water mass balance between both codes had to be adjusted by fixing in VULCAIN the water level in the reactor vessel. Note that MELCOR predicted different levels in the core and the downcomer due to pressure head caused by remaining water in the intermediate loop. Besides, the steam source from the primary circuit to the containment before core uncovery and start of primary system calculation by ASTEC was taken from MELCOR calculations.
The agreement of the results for the primary system was satisfactory in the early period of core damage using the VULCAIN option of U-Zr-O liquefaction and relocation at eutectic temperatures lower than melting temperature of UO_2: start of cladding oxidation (8 871 s for ASTEC and 9865 s for MELCOR), fission product gap release (11 103 s in ASTEC and 9 958 s in MELCOR), complete core uncovery (11 357 s for ASTEC and 10 800 s for MELCOR). The total in-vessel H_2 production compared to MELCOR was about 30 % lower.
Discrepancies were observed in the late in-vessel phase due to model differences:

- in MELCOR, corium relocation to the lower plenum is gradual and produces more steam. After core plate failure, molten corium and debris relocate and form a debris bed, which leads to a fast boil-off of the remaining water and to vessel lower head heat-up. This causes significant steam production, oxidation, and steam source to the containment. The core plate failure occurred in MELCOR at 12 174 s and, after more than one-hour period of vessel bottom head dry out, the vessel failure at 16 900 s.
- in ASTEC V0, no contact of molten fuel with the water below the core plate occurs before core plate failure or before lateral slump through the baffles. Here in this calculation, corium relocation occurred at 16 323 s, but preceded immediately vessel failure. This very short delay between corium slump and lower head failure is due to imperfect models in this VULCAIN version (improvements are under way to correct these models). This prevented any significant boil-off of the remaining water and thus significant steam release.

These differences in the core models led to quite different steam sources to containment. For this reason, the containment results agree well before core uncovery and in the early in-vessel phase, but not well in the late in-vessel phase (Fig.4). In this latter phase, with ASTEC, the temperature is slightly rising, which corresponds to a very weak release of gases, especially steam, through the valve. And the pressure drops due to steam condensation on cold walls and the condensate is drained to the sump full of water, where it does not re-evaporate. Water storage for Emergency Cooling System in the recirculation sump during normal operation is a special feature of VVER-1000 containment. The MELCOR results show that containment pressure does not increase much too.

4.2 ASTEC V1 applications

The first ASTEC V1 VVER applications focused in priority on the RCS thermalhydraulic behaviour because of the importance of these phenomena on the sequence events. Another reason is the large experience already acquired on VVER applications of the IRSN ICARE2 mechanistic code for core degradation: the new module DIVA is derived form the ICARE2 code and will take high benefit from this experience.
Several CESAR-DIVA applications have been performed in 2001-02 in the frame of bilateral collaboration with VUJE (Slovakia) and NSI/RRC-KI (Russia), on the following scenarios:

- real transient of Loss of Feedwater on Russian Kalinin VVER-1000 with CESAR alone [1] (by NSI/RRC-KI).
- TMLB on VVER-440/V213 with CESAR alone (by VUJE), with comparison with RELAP5-3D and MAAP4 results. This application showed that the simplest nodalisation of SG tubes (3 volumes in

vertical direction and only 1 in horizontal direction) can be recommended for analysis of medium and large break LOCAs, where the secondary side response is not so important.
- SBLOCA and LBLOCA (under way by NSI/RRC-KI) on Balakovo Russian VVER-1000 with coupled calculations CESAR-DIVA.
- MBLOCA on VVER-440 (under way by VUJE), including simulation of bundle shrouds in the core and of fuel followers in the lower plenum.

Other ASTEC V1 sequence calculations will be performed on VVER in EVITA until mid-2003, including FP behaviour in core, RCS and containment.

Three examples of such applications are shown with more details below.

CESAR application to LFW transient in the Russian Kalinin NPP [1]:

This real transient is a Loss of Feedwater to one SG in the Unit 1 of Kalinin NPP in July 96.
After obtaining a good agreement of the steady state with respect to the plant data, the transient was calculated using as boundary conditions the reactor power and the feedwater flowrate to the SGs. Good agreement was obtained on event chronology and on the most important thermalhydraulic parameters: time of pump trip, time of scram, SG collapsed water levels, PRZ water level, primary pressure drops in SG (Fig.5) (less good for non-damaged SGs) and in reactor vessel. But discrepancies on SG pressure as a function of time were observed: all SGs do not behave similarly in the reality while CESAR results show a temporary pressure decrease in all SGs.
The computing time on a DEC computer was half the real time of transient.
This application has shown that CESAR is well applicable for description of water level evolution in horizontal SG as well as for thermalhydraulic behaviour of a VVER-1000 NPP during a LFW transient.

CESAR application to SBLOCA in a VVER-1000/V320 NPP:

The scenario is a SBLOCA (70 mm diameter break in cold leg of loop with pressuriser) with station black-out.
The same input data than for the ICARE-CATHARE calculations were used, except a rougher nodalisation and a simplified modelling of a relief device steam-atmosphere (BRU-A). Transient results (until time 2800 s of core uncovery) showed similar results than ICARE-CATHARE ones (Fig.6), except with CESAR a slower accident progression and a lower coolant flow rate through the break.
Sensitivity calculations were performed on:
- BRU-A valve characteristics. Changing these characteristics mainly influenced the number of valve openings and closures, and thus cycling of primary and secondary pressures, but it did not practically influence the time when the primary pressure reaches the value of 5.89 MPa – pressure for beginning of the water injection from hydro-accumulators into the reactor.
- coolant flow rate through the break. Increasing the break equivalent diameter from 70 to 80 mm resulted in the respective increase of the flow rate through the break and in a better agreement of calculated primary pressure changes with the ICARE/CATHARE results, and finally also of time for beginning of the water injection from hydro-accumulators.

This application showed that the discrepancies with respect to ICARE-CATHARE are mainly due to a simplified modelling of valves and to the absence of a phase separation model at the break.

ASTEC V1 application to a MBLOCA in VVER-440/V213:

The scenario is a medium break LOCA (100 mm diameter break in cold leg of loop with pressuriser) with a station blackout and availability of 2 hydro-accumulators out of 4. ASTEC V1 results are compared with results from MAAP4-VVER, RELAP5 and SCDAP/RELAP5.
The 6 loops of the RCS are modelled. The DIVA vessel nodalisation up to core top (Fig. 7) includes the fuel followers (which include ≈10% of decay heat). The calculation includes firstly RCS depressurisation and gradual depletion of hydro-accumulators, and then core uncovery and subsequent start of fuel temperature increase.
DIVA results of core heat up evolution, followed by Zirconium oxidation of claddings and fuel and control assemblies shrouds, are in good agreement, especially with MAAP4 prediction (see table 3 for the calculated chronology). For illustration, the time history of fuel maximum temperature in central ring is

illustrated on Fig. 8. The main reason of slower fuel heat up in SCDAP calculation is the underestimation of Zirconium oxidation and consequently of the thermal power which is added to the decay heat.

This DIVA calculation is still under way: the time 4065 s corresponds to the start of magma creation in the core central ring just below the core support plate. This event leads to a strong interaction between magma and water and to water evaporation. The calculation will be carried on in the next months until vessel lower head rupture.

5 CONCLUSIONS

ASTEC V0 applications showed that most VVER features can be simulated correctly with the code, including for instance the VVER-440 bubble condenser towers. Some VULCAIN model limitations, such as a lack of flexibility in the geometry simulation, hindered to improve the results. As for simulation of accident management measures, the code allows to correctly represent most existing safety systems: primary circuit depressurisation, water injection systems, containment spray, and passive heat removal systems. Developments are still necessary for new generation VVER reactors, for instance for simulation of passive hydrogen removal system or core catchers.

Preliminary applications of the new ASTEC V1 version, delivered mid-2002, showed that this version should allow to improve the simulations. But it still needs further consolidation through extensive validation and through benchmarks with codes (ICARE/CATHARE, MELCOR, MAAP4…). Besides, a detailed analysis of needed model adaptations to VVER specificities will have to be done, for instance on the following phenomena:

- DCH: the differences of cavity geometry with respect to Western PWR could need an adaptation of corium entrainment models,
- iodine behaviour in containment : the presence of different paintings on walls than in Western PWR could modify the iodine-paintings interactions which have a strong influence on iodine long-term concentration in containment atmosphere,
- MCCI: specific materials of substrates could need some adaptations of the new MEDICIS models or of the MDB package.

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Table 1: Matrix of VVER-specific experiments for ASTEC validation

Experiment	ASTEC module	Main features of the experiment
CORA-W1	DIVA	VVER bundle degradation
CORA-W2	DIVA	VVER bundle degradation with B_4C control rod
RASPLAV AW-200-4	DIVA	Molten corium interaction with vessel lower head
PACTEL ISP33	CESAR	VVER-440 RCS thermalhydraulics
BETA V7.1	WEX/MEDICIS	MCCI with serpentine concrete (VVER-1000 substrate upper layer)
PSAERO, HORIZON	SOPHAEROS	FP/aerosol transport in RCS with horizontal SG
HD	CPA	H_2 distribution in a VVER-1000 multi-compartment containment mock-up
RUT	CPA	Combustion of mixtures air-steam-H_2 in containment
EREC	CPA	Thermalhydraulics in a VVER-440 containment with bubble condenser towers

Table 2: Comparison ASTEC-V0/MAAP4/VVER of main events in RCS for a LBLOCA on VVER 440/230

Event	MAAP4/VVER [s]	ASTEC [s]
Start of FP release from fuel	561	468
Total core dewatering	≈ 400	443
Start of U-O-Zr melting	1274	1410
Melting pool formation	≈ 2000	3021
First lateral corium slump in reactor vessel lower head	3054	4815
(Corium mass in lower head)	(≈ 2.0 t)	(2.4 t)
Reactor Vessel lower head dry-out	3894	-
Lower head vessel failure	8286	6963
(H_2 mass produced during the in-vessel phase)	(219 kg)	(187 kg)

Table 3: ASTEC-V1 results of chronology of main RCS events in RCS for a MBLOCA on VVER 440/213

	RELAP5/Mod3.2 (6 loops)	SCDAP/RELAP5 (2 loops)	MAAP4/VVER (2 loops)	ASTEC-V1 (6 loops)
Start of HA injection	55.0 s	65.0 s	210.0 s	65.0 s
HA empty	730.0 s	900.0 s	370.0 s	1040.0 s
Start of fuel temperature increase	1740.0 s	1850.0 s	1980. 0 s	1950.0 s
First cladding rupture	2400.0 s	2900.0 s	2630.0 s	2435.0 s
Start of U-O-Zr melting (temperature ≥ 2226 °C)	Not modelled	≈4500.0 s	3050.0 s	2950.0 s
(H_2 production at t=4065s) (mass of magma in core)	- -	(≈80.0 kg) -	(255.0 kg) (≈14.2 t)	(242.3 kg) (≈10.0 t)

Fig.1: CPA validation on EREC T5 experiment: pressure evolution along time (with comparison to CONTAIN results)

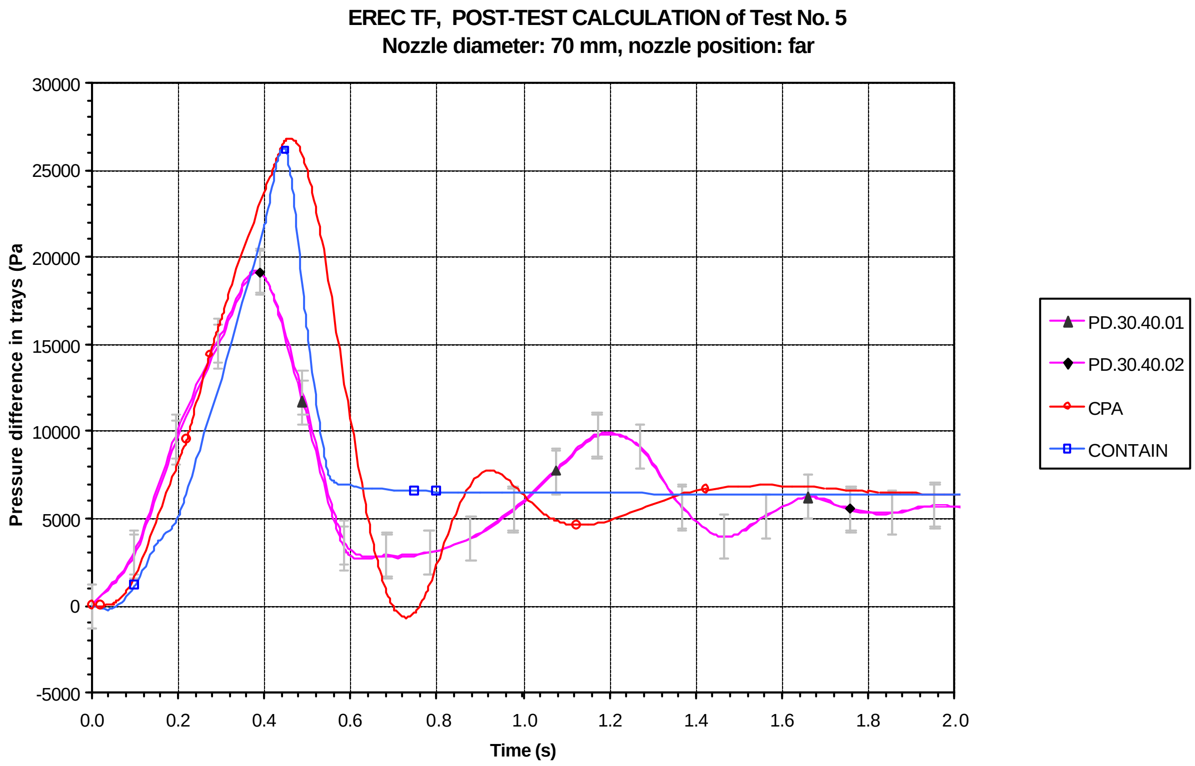

Fig.2: CESAR validation on PACTEL experiment (ISP33): pressure evolution in the pressuriser along time.

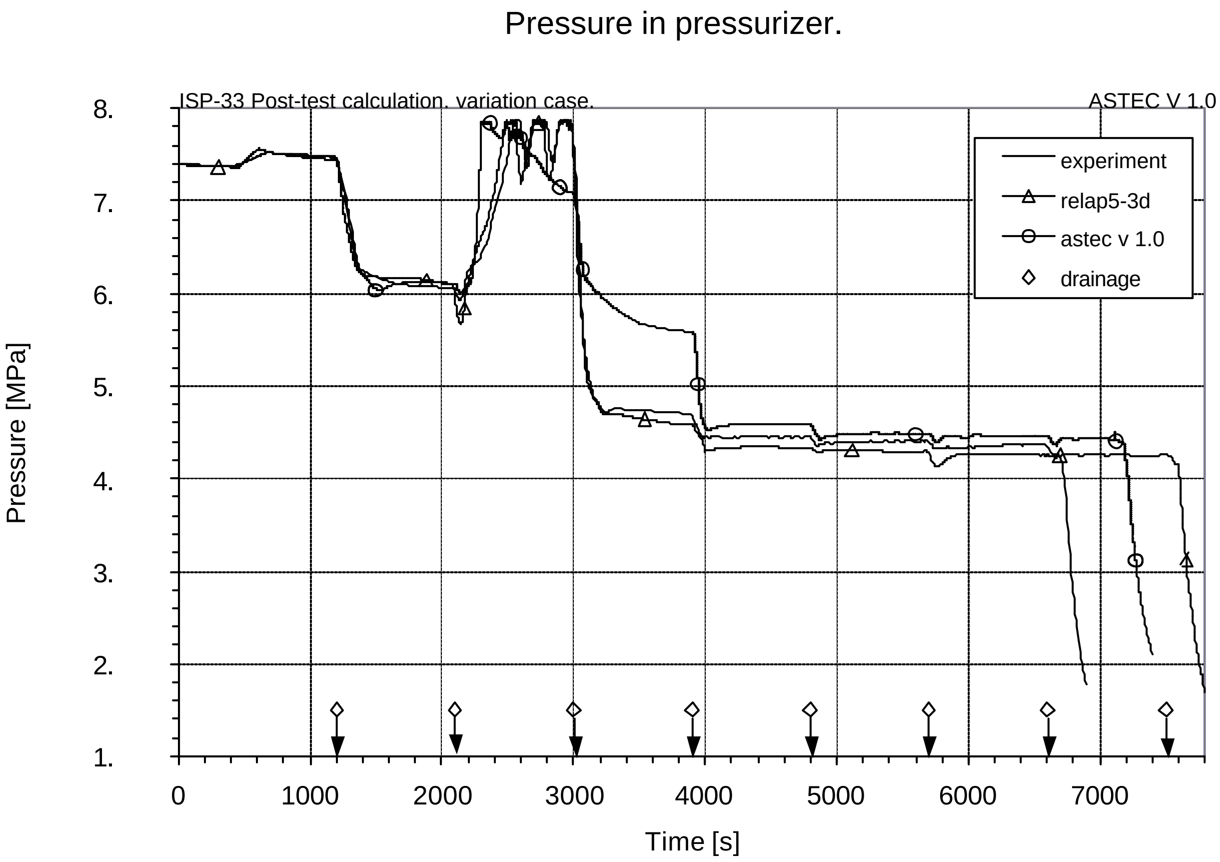

Fig. 3: ASTEC V0 application to LBLOCA in VVER-440: comparison with MAAP4 of hydrogen production

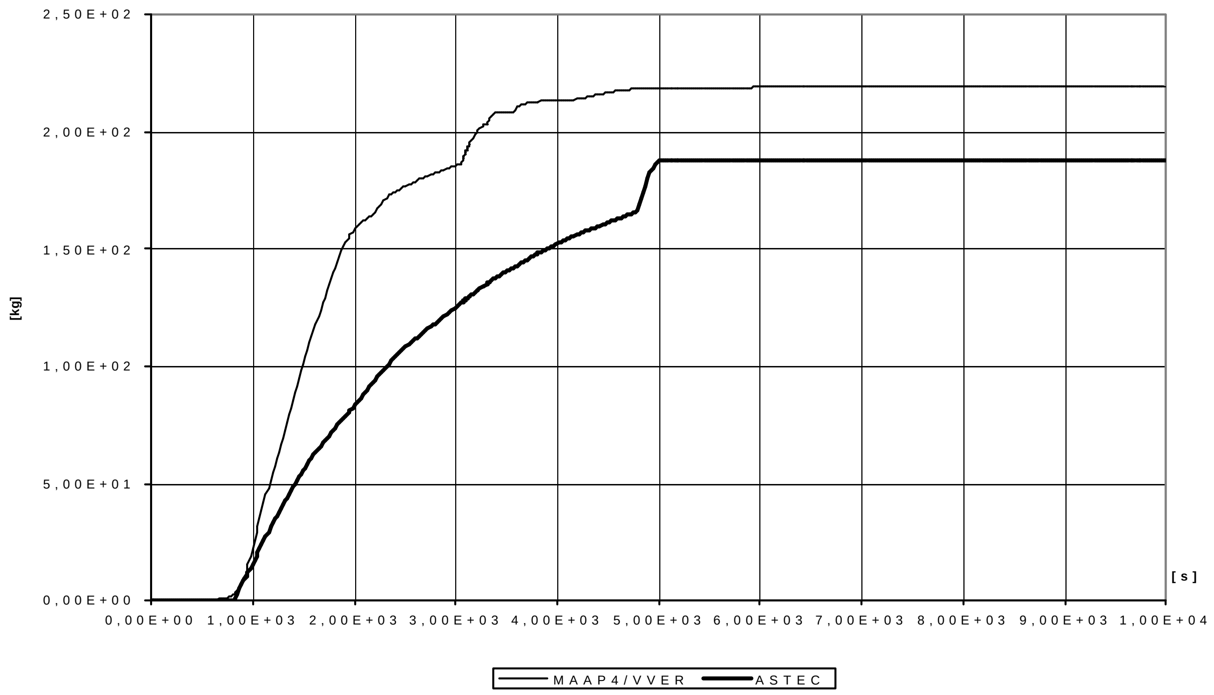

Fig. 4: ASTEC V0 application to TMLB in VVER-1000: comparison with MELCOR 1.8.5 of containment pressure evolution along time

Název:

Vytvoøil:

Náhled:
Tento obrázek EPS byl uložen
bez náhledu.
Poznámka:
Tento EPS obrázek je možné
vytisknout pouze na
postscriptové tiskárnì.

Fig. 5: CESAR application to Kalinin LFW transient: steam pressure in the damaged steam generator (SG-4)

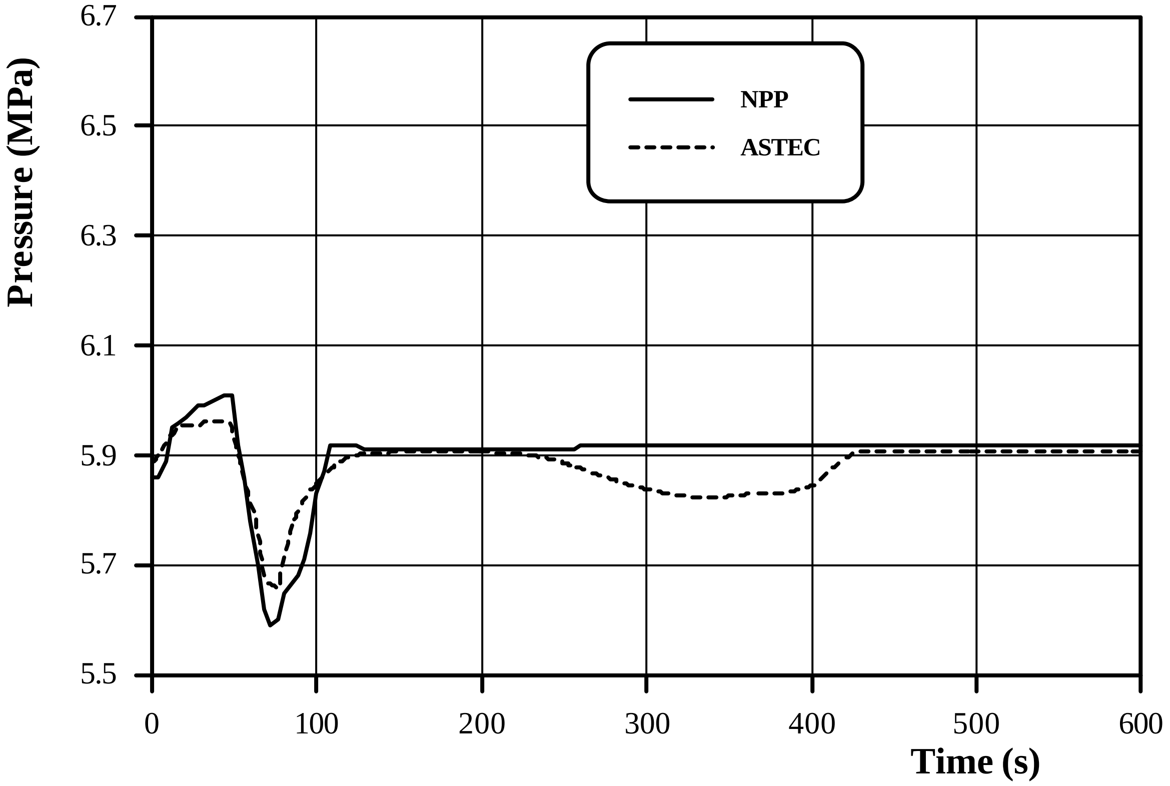

Fig.6: CESAR application to SBLOCA in VVER-1000: primary pressure in solid line and secondary pressure in dotted lines (left = CESAR, right = ICARE/CATHARE)

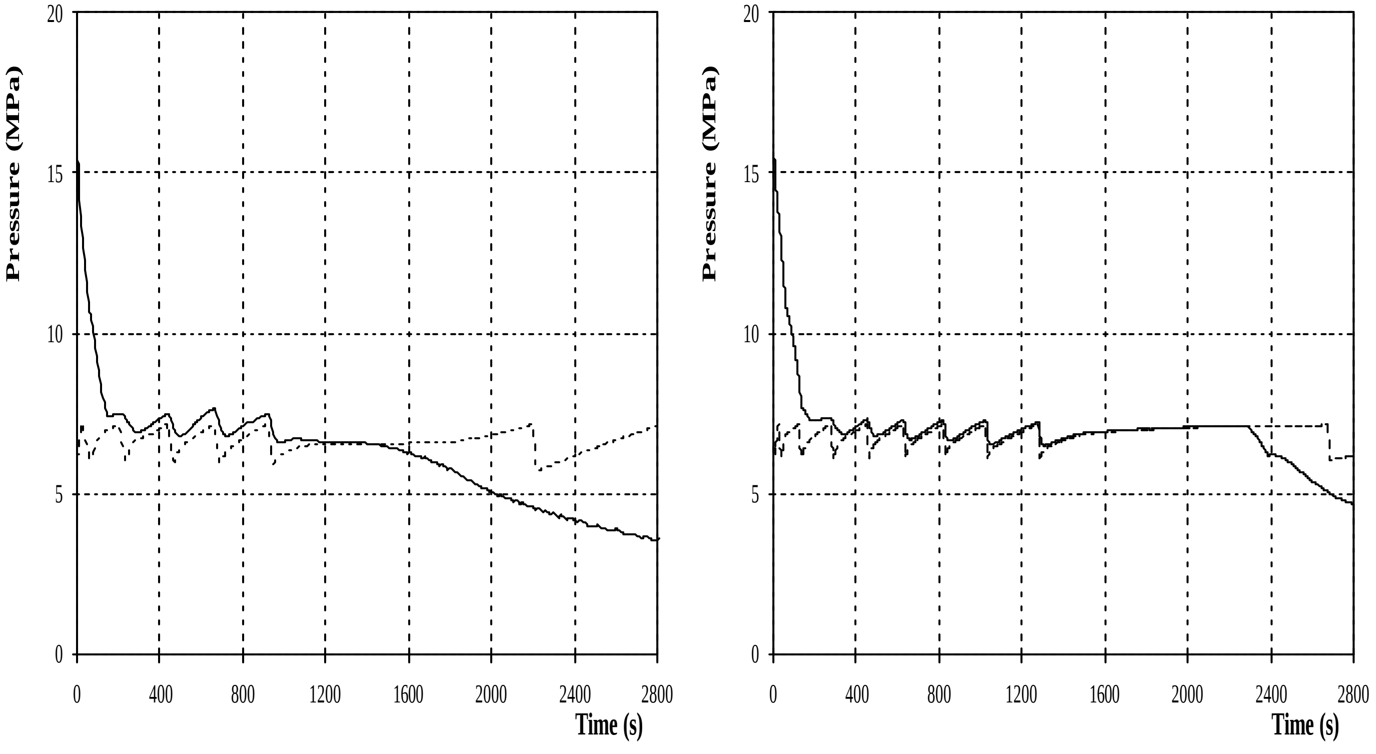

Fig. 7: DIVA nodalisation of a VVER-440/213 vessel.

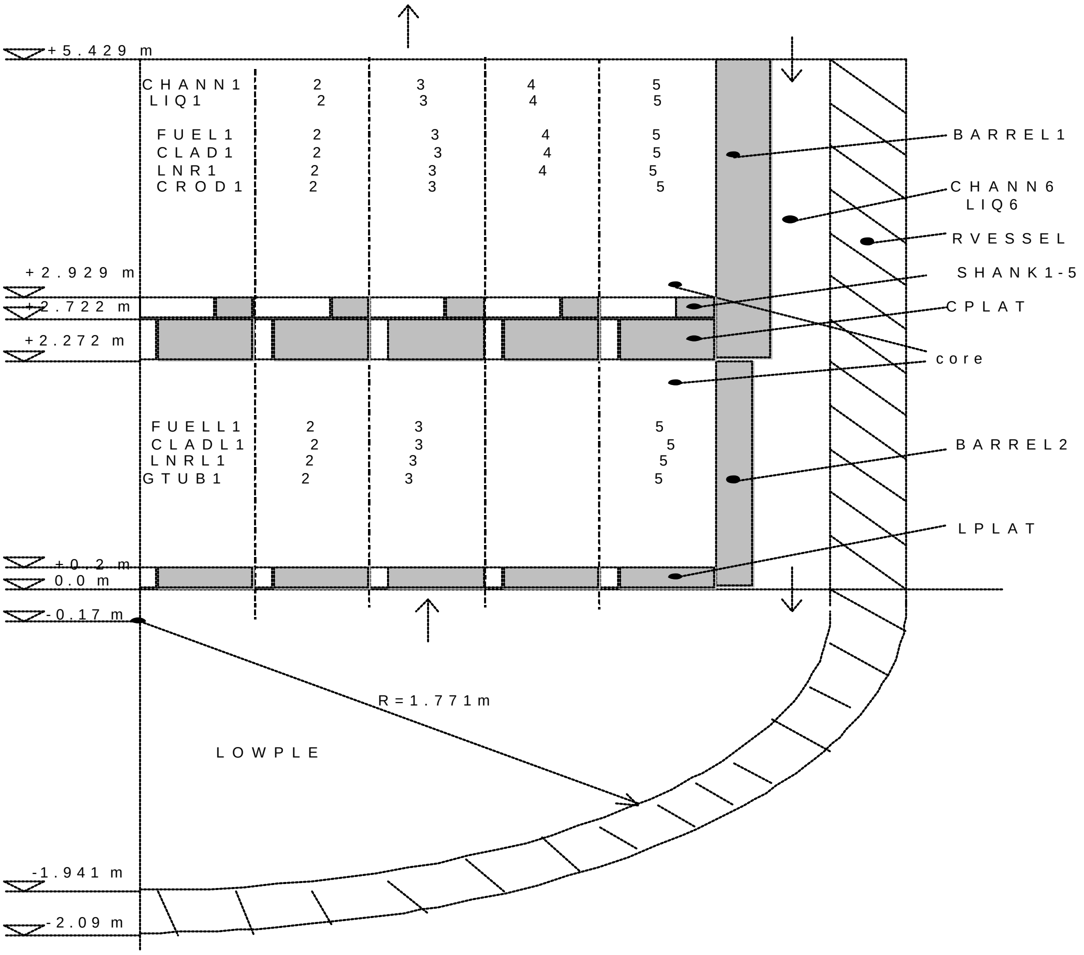

Fig. 8: ASTEC V1 MBLOCA calculation in a VVER-440/213 vessel: maximum fuel temperature (central ring, axial level = +4.8 m)