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ASTEC code validation versus ICE P1-P8 experiments: comparison of two different experiences

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ASTEC is a system code developed by IRSN for the analysis of Severe Accidents in fission nuclear reactors. In recent years, the code has been extended to cope also with incidental transients in fusion installations. The scope of the present work is to provide an additional validation of the ASTEC code against the 8 tests performed in the upgraded Ingress of Coolant Event (ICE) facility. This facility is a scaled reproduction of the Pressure Suppression System (PSS) of the ITER machine. The simulations of the different tests have been performed by two different teams, one formed by C.r.e.a.t.e and ENEA researchers and the second one by University of Pisa and IRSN researchers. The first objective of these validation activities conducted by both teams is to confirm that ASTEC is indeed able to globally model the progression and consequence of an in-vessel LOCA in the ITER facility. Second goal is to identify, through sensitivity analyses, the phenomena for which additional R&D efforts are needed. In both cases the initial ICE experimental data have been treated as boundary conditions. Interesting outcomes have been obtained because ASTEC demonstrated to fit the most part of the phenomena involved in the accidental transients, but for some of them, i.e. the jet impingement effect, gives controversial results. The two groups highlighted independently these issues.

Key words: ASTEC, LOCA, ICE, validation, PSS, ITER

1. Introduction

ASTEC (Accident Source Term Evaluation Code) is a system code developed by the French "*Institut de Radioprotection et de Sûreté Nucléaire*" (IRSN), to compute severe accident scenarios in nuclear fission reactors. It was also intensively developed and validated in the framework of the SARNET Network, co-funded by the European Commission from 2004 to 2013, to capitalize the knowledges acquired in the last fifteen years in the severe accident field [1]. Its capabilities have been in parallel extended by IRSN to address the main accident sequences that may occur in the fusion installations, in particular in ITER [2].

The scope of the work is to provide an independent ASTEC validation for fusion applications against the eight tests performed in the upgraded ICE facility, built in JAERI laboratories (Naka, J), a 1/1600-scale model of the ITER machine PSS. These experimental tests (P1 - P8) were carried-out to assess the influence of the suppression tank connection and the presence of a drain tank on the reached maximum pressure inside the Vacuum Vessel (VV) during an in-vessel LOCA. The goal is to demonstrate that ASTEC is able to simulate the main phenomena characterizing the accidental thermal-hydraulic transient in a fusion plant and its weaknesses, requiring a further code development.

2. ASTEC code

The current ASTEC V2.1 version consists in different modules each devoted to the analysis of a specific domain of a nuclear power plant [3]. The code combines a lumped-parameter approach for large size volumes and a 5-equations thermal-hydraulics approach for coolant circuits. For the evaluation of PSS two models are available: DRASYS and INSERTION [4]. DRASYS allows the simulation of short-term (vent clearing, and pool swelling) and long-term phenomena (quasi-steady temperature and pressure increases, and vapour condensation in the pool and in the relief pipes), while INSERTION only the simulation of the long-term ones.

Preliminary analysis of the physical and chemical phenomena involved in the ITER accidents showed [2] that most of the ASTEC models, developed for fission reactors, were already applicable in the fusion plant context. This is true in particular for the thermal-hydraulics in the ITER large-size volumes, after water or air ingress into the VV, and for two-phase thermal-hydraulics in the cooling circuits.

3. ICE facility

The ICE (Inlet of Coolant Event) experimental facility was built by JAERI (former JAEA) in Naka (Japan) with the following main objectives: the demonstration of the efficiency of the PSS design to mitigate in-vessel LOCAs and to provide experimental data to improve the safety simulation codes. The main components (figure 1) are a boiler, a Plasma Chamber (PC), a simulated DiVertor (DV), a simplified VV, a Suppression Tank (ST) and a Drain Tank (DT). The boiler volume is 0.631 m^3 (diameter 700 mm). The maximum amount of water

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stored in the boiler is about 0.2 m^3, pressurized by nitrogen gas up to 4.2 MPa.

The PC volume is about 0.59 m^3 (diameter of 600 mm). The VV is connected to the bottom of the PC through the DV orifice plate, bearing 4 holes to allow the water flow from PC to VV, 4.0 cm^2 each. The volume of the simplified VV is 0.34 m^3 (diameter 500 mm). Electric heaters maintain the desired temperatures on the PC, DV, and VV walls.

The DT is of about 0.4 m^3, connected to the bottom of the VV through a drain line (16.1 mm in diameter and about 2 m in length). This drain line is initially closed by a magnetic valve, opening when the VV pressure exceeds 110 kPa.

The ST volume is 0.93 m^3 (inner diameter 800 mm), connected with the PC upper part through different relief pipes (inner diameter of 35.5 mm each). These relief pipes are initially closed by magnetic valves, opening when the PC pressure exceeds 150 kPa. No electrical heaters nor insulation layers are installed on the outer DT and ST walls.

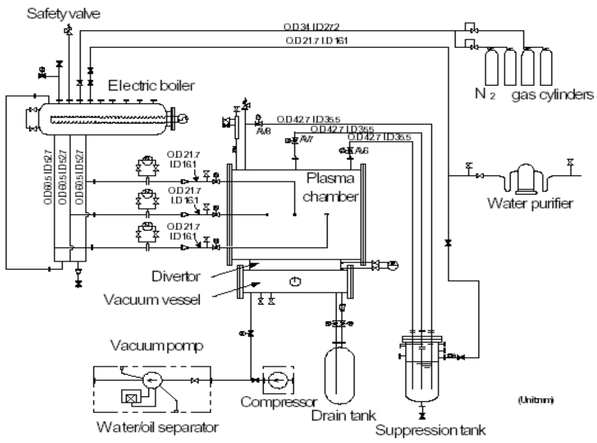

Figure 1. ICE facility layout.

4. Experimental campaign

The ICE upgraded experimental campaign consists in eight tests.

Table 1: ICE-Upgraded facility: P1-P8 tests.

	P1	P2	P3	P4	P5	P6	P7	P8
No Relief pipes	3	1	3	3	3	1	1	1
No nozzles	3	3	3	3	3	1	1	3
Nozzle Φ (mm)	7.3	7.3	7.3	7.3	2	2	2	2
PC Temp. (°C)	230	230	230	230	230	230	230	230
VV Temp. (°C)	230	100	100	100	100	210	100	100
DV Temp (°C)	230	150	150	150	140	210	150	150
Injection (s)	45	45	45	45	45	600	600	200
Water Temp. (°C)	150	125	150	125	125	230	125	125
Water Pres. (MPa)	2	2	2	3	2	4	2	2

The 8 tests differ for the number and the size of the nozzles connecting the boiler to the PC, the duration of the water injection, the initial VV atmospheric/wall temperatures, the injected water pressure and temperature, and the number of relief pipes connecting the PC to the ST.

Table 1 summarizes the conditions of these eight ICE tests. Note that, an initial PC temperature of 230 °C was imposed in all these tests. In the present paper, the P1 and P7 tests only are discussed, being the most representative ones of the whole experimental campaign.

5. ENEA model and UNIPI model

In the following "ENEA model" and "UNIPI (UNIversity of Pisa) model" identify the different approaches to the ICE nodalization. ENEA model consists of 4 volumes (PC, VV, DT, ST), 11 junctions connecting the different volumes and 16 heat structures, all around the volumes, and another one between PC and VV to simulate the DV. The PC and the VV are connected by means of four atmospheric plus four drain junctions, while the VV and the DT are connected by one atmospheric junction plus one drain junction. One atmospheric junction connects the PC with the ST. Atmospheric junctions allow the transport of gas/steam only, while the drain ones of water only.

The UNIPI model consists of 5 zones, 7 junctions, and 13 walls. The five zones represent the PC, the VV, the DT, the ST, and the Drain Line (DL). An atmospheric plus a drain junction connect the PC to the VV. In a similar way, an atmospheric plus a drain junction connect the VV to the DL, and the DL to the DT. Finally, the last atmospheric junction connects the PC to the ST. Twelve out of thirteen walls represent the outer tank's walls. Seven walls are connected to DT, five to ST, one to DL. As in the ENEA model, the last wall represents the DV plate.

The differences between the two models are:

- In the ENEA model the DL is not represented as an independent zone, but with an atmospheric junction plus a water junction, without thermal inertia.
- The ST is simulated with ASTEC-DRASYS in the ENEA model, and with the ASTEC-INSERTION in the UNIPI model.
- In the experiments, a delay in the opening of the magnetic valves, placed in the relief pipes and in the drain line, was highlighted. This delay ranges between 1.0 and 1.5 s. UNIPI model considers this delay, while ENEA model actuates the valve opening at the experimental pressure at which the valves opening occur that, due to this delay, is much higher than the theoretical one.
- Because of the small PC and VV dimensions (less than 1 m^3), ENEA model deems the outer walls of utmost importance for the correct evaluation of the heat transfer phenomena. In turn, UNIPI model considers another nodalization, neglecting these walls, due to the fact that temperatures were controlled (in the experiments) to keep the volumes in "adiabatic" conditions.
- The water jet impingement on the PC inner surfaces is considered in the ENEA model, while UNIPI model the jet impingement is not considered.

- The water and steam flows between PC and VV through the divertor slits and, in a second phase, between VV and DT through the DL change dynamically. In the ENEA model, constant flow areas are employed for the water and steam junctions connecting the PC to the VV, and the VV to the DT. In turn, UNIPI model adopts a control logic modifying the flow areas of the atmospheric and drain junctions, connecting the different zones, according to the water amount contained in the PC and the VV.
- Both models assume the boundary conditions according to [5], but the temperature of the injected water in the UNIPI model is slightly increased during the first 7 s of each test, to improve the code's predictions.
- UNIPI model also employs a control logic to shift heat exchanges of the DT, DL and ST walls toward the gaseous or the liquid parts according to the water amount present in these tanks at any given time. ENEA model assumes the heat transfer coefficients calculated by ASTEC as reliable for the two phases.

6. P1 test results

The total pressure in PC (figure 2) is generally well reproduced by both models, but UNIPI model underestimated the initial pressure peak of about 40 kPa, and ENEA shifts it of about 2.5 s. At the end of the injection phase, both models start to provide almost identical results. In the ENEA model, the total pressure predictions during the first 45 s are strongly influenced by the jet impingement against the PC walls. An impact area of 1.27 m^3 (1/3 of the total lateral area of the PC) was assumed and 70% of the water flow rate was the jet impingement fraction that provided the best results. A sensitivity study on the jet impingement model was also performed by UNIPI, assuming different water impact fractions and impacted wall areas (a specific wall was added in the nodalization to active the jet impingement model). In any case, poor predictions were obtained, leading to the complete deactivation of jet impingement in the UNIPI model.

In turn, for the two models great differences exist, in particular for the PC atmospheric temperatures, instead the PC liquid temperatures are in line each other (Figure 3). Only the experimental data coming from the thermocouple (T10) are shown [5] in the graph. T10 is representative of the other thermocouples placed in the PC volume. In fact, the differences among the temperatures measured are in a little range. The UNIPI PC temperatures (atmospheric and liquid) are in agreement with the experimental one, except during the first 6 s. In turn, the ENEA model always presents a higher atmospheric temperature if compared with UNIPI model. Highlighting the agreement among the T10 temperature with the water temperatures predicted by the two models, it is plausible to infer that the T10 thermocouple was placed in a wet zone inside the PC or water droplets deposition occurred on this probe.

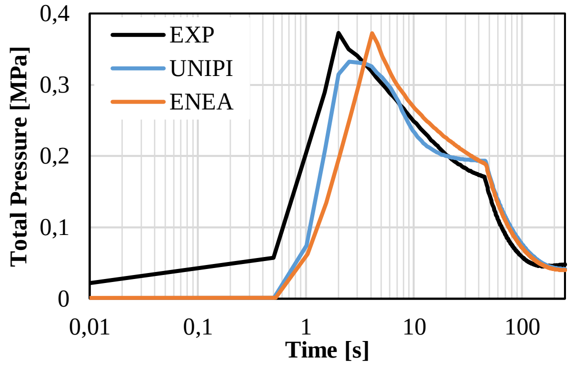

Figure 2. Total pressure in the PC (P1 test).

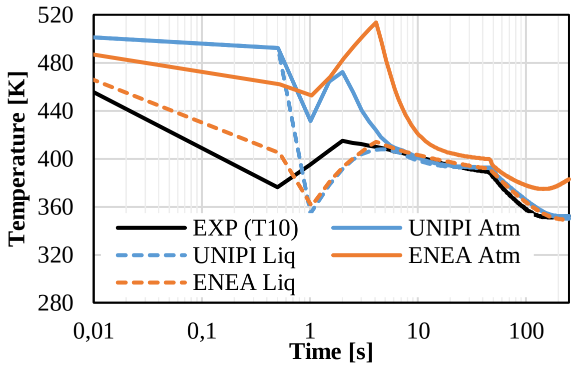

Figure 3. Atmospheric and liquid temperatures in the PC (P1 test).

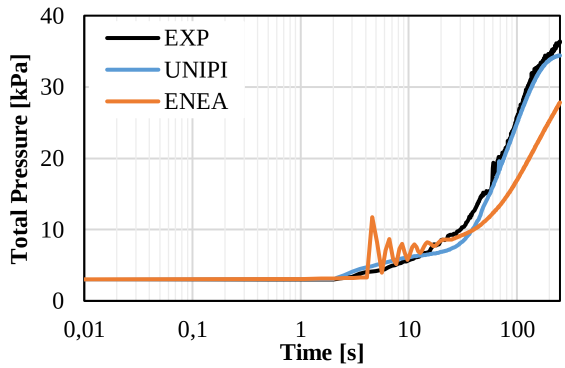

Figure 4. Total pressure in the ST (P1 test).

In Figure 4 the total pressure evolution in the ST is shown. ST is the most important volume of the system, since it drives the overall facility behavior. The results shown by the two models well underline the differences between the two PSS models implemented in ASTEC. Employing the DRASYS model (by ENEA) total pressure spikes are shown for the initial 25 s, while a quite smoother behavior is shown with the INSERTION model (used by UNIPI). During this first phase, the experimental data show a slow pressure increase, but also a very strong pool swelling. After 25 s, both models start to predict smoother results, but the ENEA model presents a worse performance and the difference with the experimental results becomes significant. As a preliminary conclusion, the DRASYS model seems not adequate for sub-atmospheric transients. In turn, the UNIPI predictions well agree with the experimental ST data for the first 250 s of the P1 test.

7. P7 test results

Compared to the P1 test, the ASTEC predictions for the P7 test confirm the previously obtained results but also highlight some peculiarities. The magnitude of the total pressure peak in the PC (Figure 5) is well reproduced by both the models but, employing the UNIPI model, this peak is shifted in time of about 30 s. The absence of the jet impingement could be the cause of this pressurization delay. For the ENEA model, the PC pressure in the long term is higher than the experimental as well as the ST one (Figure 6). As for the P1 test, the agreement of the PC water temperature by the two models (figure 7) with the T10 experimental temperature is satisfactory, unless in the very first phase for the UNIPI model. These results further strengthening the interpretation of the possible position of the T10 thermocouple in a PC wet zone or of the water droplets presence on the probe surface.

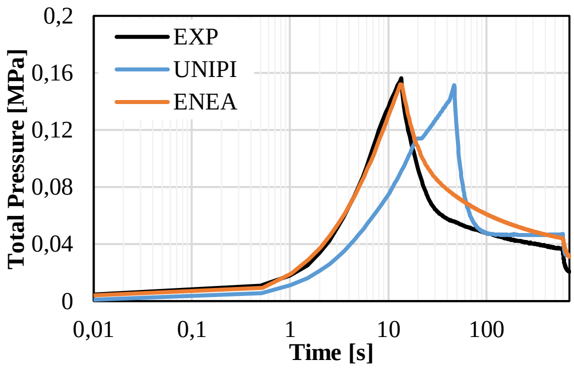

Figure 5. Total pressure in the PC (P7 test).

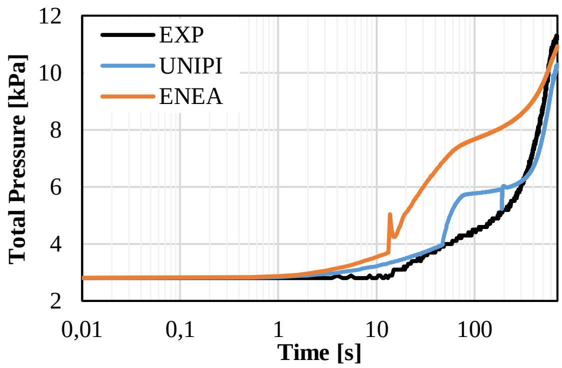

Figure 6. Total pressure in the ST (P7 test).

Finally, a good evaluation of the ST total pressure is obtained by UNIPI model (Figure 6) meaning that the INSERTION model is probably more suitable for the simulation of sub-atmospheric pressure conditions than the DRASYS one (employed by ENEA). Although, definitive conclusions cannot be drawn because also the other differences, characterizing the models created by ENEA and UNIPI, may influence the obtained ST results.

8. Conclusions

ASTEC simulations have been carried out versus ICE upgraded experiments about a water leak in volumes at sub-atmospheric pressure conditions. The performances of the code, verified by means of two independently developed models (ENEA model and UNIPI model), are quite in agreement with the experimental pressures and temperatures trends in the discharge volume (PC).

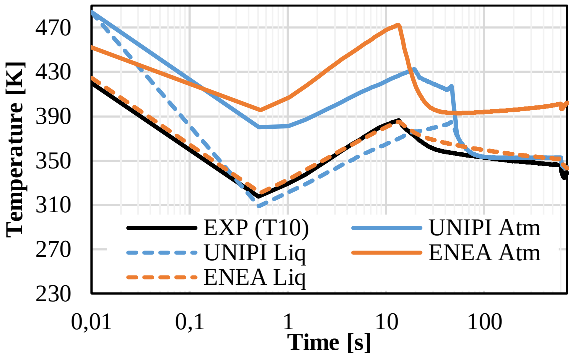

Figure 7. Atmospheric and liquid temperatures in the PC (P7 test).

On the contrary, ASTEC-DRASYS model presents some problems in the simulation of a sub-atmospheric PSS while the ASTEC-INSERTION model seems more suitable for such conditions. Furthermore, also the jet impingement in ASTEC has to be assessed more widely. In ENEA model it works correctly when activated in the PC volume for both the tests (P1 and P7), but the steam production, to be discharged into the ST, appears under-evaluated for the P1 test and over-estimated for the P7 test. Similar outcomes have been also obtained for the remaining ICE tests (P2, P3, P4, P5, P6, P8). The whole documentations about the ASTEC validation versus P1-P8 ICE experiments are available in ENEA and UNIPI technical reports.

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