
European Validation of ASTEC-V1 through the EVITA project

H.-J. Allelein *

K. Neu *

J.P. Van Dorsselaere **

N. Trégourès **

M.K. Koch ***

M. Bendiab ***

L. Kubisova ****

* *GRS, Köln (Germany)*

** *IRSN, Cadarache (France)*

*** *Ruhr-Uni-Bochum/LEE (Germany)*

**** *UJD SR, Bratislava (Slovak Rep.)*

1 OBJECTIVES

The European Validation of the Integral Code ASTEC (EVITA) involves 19 partners from eight European countries plus JRC. It started in February 2000 and ended in July 2003. The main objective is to distribute the severe accident integral code Accident Source Term Evaluation Code (ASTEC), jointly developed by “Institut de radioprotection et de sûreté nucléaire” (IRSN, France) and “Gesellschaft für Anlagen- und Reaktorsicherheit” (GRS, Germany), to European partners in order to apply the validation strategy issued from the VASA project (4th European Community Framework Programme).

Severe accident management (SAM) measures are currently being developed and implemented at Nuclear Power Plants (NPP) worldwide in order to prevent or to mitigate severe accidents. This needs a deep understanding of processes leading to severe accidents and of phenomena related to them. As greater account of severe accident measures is taken in the regulation of plants, there will be the need to show a greater degree of validation of codes and a better understanding of uncertainties and their impact on plant evaluations.

The EVITA evaluation of ASTEC code capabilities and the corresponding feedback towards the code development is an important step towards the intention to provide end-users (like utilities, vendors and licensing authorities) with a well validated European integral code for the simulation of severe accidents in NPPs.

2 CHALLENGES TO BE MET

To fulfil the objectives nearby described, systems of computer codes, so-called “integral” codes, are being developed to simulate the scenario of a hypothetical severe accident in a light water reactor, from the initial event until the possible radiological release of fission products out of the containment. They couple the predominant physical phenomena that occur in the different parts of the reactor and

simulate the actuation of safety systems by procedures and by operators. In order to study a great number of scenarios, a compromise must be found between precision of models and calculation time. This search of compromise is a real challenge for such integral codes. Such codes have been developed in the United States (MAAP4, MELCOR) and are used worldwide.

In France and in Germany, experimental and analytical work in the field of severe accidents were successfully performed in a distinct manner. It is evident that French and German organisations did not want to use severe accident codes as 'black boxes' without detailed knowledge of what is going on inside the code. Consequently, the French IRSN and the German GRS decided to co-operate in development and validation of a new integral code ASTEC that would contain the best available modelling.

The needs for such a code are: source term determination studies, PSA level 2 (PSA-2) studies, accident management studies, as well as detailed analyses of particular phenomena to improve the understanding of the phenomenology.

As the great number of users has significantly increased especially the level of MELCOR, IRSN and GRS - learning from this - opened the ASTEC use for extended validation and generic application to a wide spectrum of European organisations, first realised in EVITA. The objective was also to get an evaluation of the code capabilities, especially its user-friendliness.

Following the complementary dualism of risk- and phenomenon-oriented validation strategies, experiments and severe accident plant sequences have been selected for the ASTEC validation and application process:

- Validation on high-quality experiments such as International Standard Problems (ISP) of OECD,
- Plant applications on different types of NPP (PWR, VVER) with activation of safety systems (spray, venting, etc..).

Each case included a comparison with internationally used codes which should represent the State of the Art in modelling: detailed codes for validation, integral codes for plant applications. Some examples of results are given below.

3 EXAMPLES FOR ASTEC-V1 RESULTS

3.1 ASTEC-V1 validation against experiments

Out of the large validation matrix for the modules of ASTEC-V1 on numerous experiments the validation of the recently introduced module DIVA (for core degradation) is shown in a stand alone version on the **QUENCH-05** experiment and in a coupled version with CESAR (for circuit thermalhydraulics) and ELSA (for fission product release) on the experiment **Loft-FP-2** .

3.1.1 ASTEC-V1 validation on the QUENCH-05 experiment

The QUENCH-05 experiment was designed to study the cool-down behavior of pre-oxidized cladding at high temperature (2000 K) by injecting cold steam from the bottom at 50 g/s. The test assembly consists of a central unheated rod and twenty fuel rod simulators, electrically heated over a length of 1024 mm, disposed in a square array of 14.3 mm pitch. The cladding of the fuel rod simulators is identical in material and dimension to PWRs. The test bundle is surrounded by a Zircaloy shroud.

A calculation of the QUENCH-05 experiment with DIVA from the heat-up phase to the quenching phase has been performed, with a particular interest on the hydrogen production.

The test can be divided into 4 phases. The warm-up phase (heating the bundle to a steady state of 900 K), the heat-up phase (raising the temperature up to 1500 K) the pre-oxidation phase (stabilizing the temperature at 1500 K for 3500 s) and the transient phase. An oxidation excursion starts in the rod bundle at 5985 s at 850mm when the temperature reached 1870 K. At $t = 6003$ s significant hydrogen production is measured, the maximum cladding temperature is around 1900 K. At $t = 6010$ s the quenching of the bundle by steam starts. The steam injection leads to a rapid cooling of the rods: within 1 second all rod cladding temperatures start to drop. Around 200 s after the beginning of the quenching, the test bundle temperature is below 700 K.

The DIVA model consists of the test section from -250 mm up to +1350 mm, which includes the heated part of the rods from 0mm to +1024 mm. The total axial length is divided into either 10, 20 or 45 meshes of equal height to allow an investigation of the influence of the discretisation. In radial direction, the bundle is represented by four rods: the central unheated rod, one equivalent rod for the eight mid-radius heated rods, one for the twelve outermost heated rods and one for the four corners Zircaloy rods. The influence of the oxidation model on the temperature evolution was studied using the URBANIC, CATHCART and PRATER correlations.

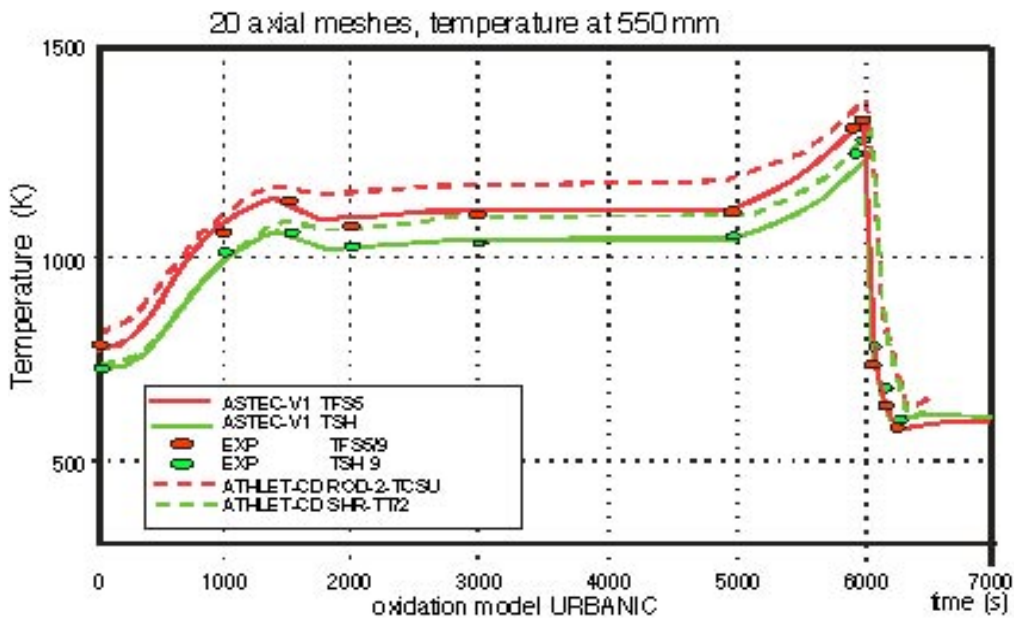


Figure 1: QUENCH-05, ASTEC-V1 results for shroud and cladding temperatures at 550 mm (solid lines) compared to ATHLET CD results (dashed) and experiments (dots)

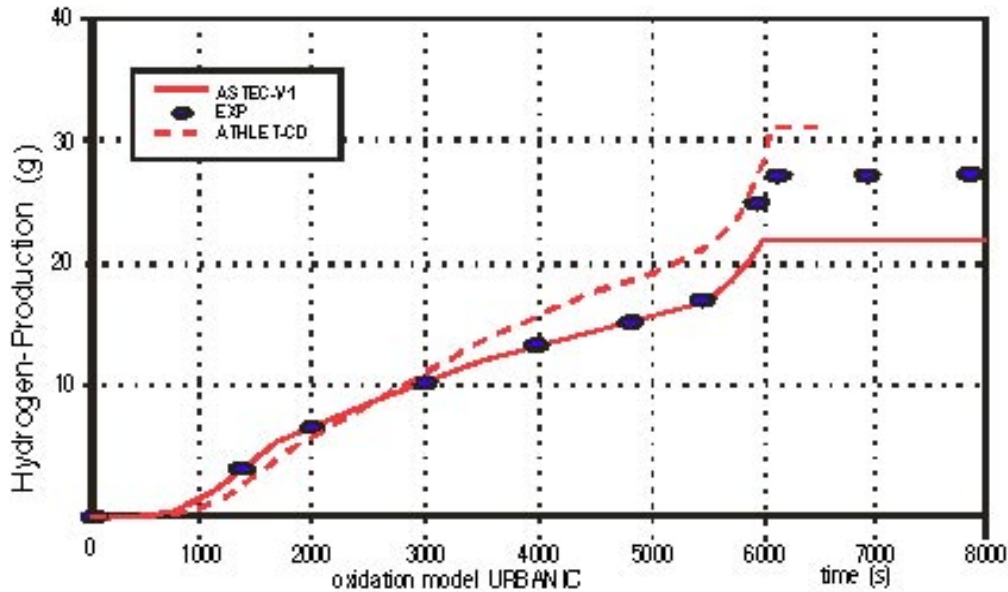


Figure 2: QUENCH-05, ASTEC-V1 result for the H₂-production (solid line) compared to ATHLET CD result (dashed) and experiment (dots)

The overall agreement between the experimental data and the DIVA calculation is very good. The results presented in Figure 1 give an example for a nodalisation with 20 axial meshes using the URBANIC correlation for a height of 550 mm of rod nr. 5 and the shroud. The solid lines are the DIVA predictions and the dots represent the experimental results. The hydrogen production predicted by the URBANIC model (Figure 2) is in a very good agreement with the experimental data up to $t = 5500$ s. From $t = 5500$ s to $t = 6000$ s, the experimental results show a sharp increase in the hydrogen production (almost 10 g). This is not well captured by the URBANIC model which tends to under-predict the rod temperature at higher rod level and, as a consequence, the rise in the hydrogen production. It appears that the temperature at which the kinetics of the chemical reaction changes ($T = 1853$ K) is too high. The URBANIC model predicts a total hydrogen production of 22 g in the case of the 20 axial meshes while the experimental value is 27 g. The agreement between the experimental data and the CATHCART and PRATER models is not as good with 19 g. These models tend to underestimate the hydrogen production at low temperatures. The dashed lines in Figure 1 and 2 show the ATHLET-CD results. ATHLET-CD trends to overestimate the temperatures in the fuel rods and the shroud. The integral hydrogen production is slightly overestimated as a consequence of the higher rod temperatures. The tendency of ATHLET CD to overestimate the rod temperatures correspond also with the results of the ISP45. However a part of these deviations could be caused by the different adjustment modes of the inlet temperatures in DIVA and ATHLET.

3.1.2 ASTEC-V1 validation on the Loft-FP-2 experiment

The modules CESAR (for circuit thermalhydraulics), DIVA (for core degradation) and ELSA (for fission product release) of ASTEC-V1 were used. The results of the calculation are compared with measured values of the experiment and with calculations performed with the code ATHLET-CD. The calculated circuit pressure in Figure 3 agrees qualitatively very well with the experimental pressure progression during the simulated test phase of 1800 s. Only the period between 200 s and

400 s, when the pressure gradient is greater in ASTEC than in the experiment, is responsible for an underestimation of the primary pressure until the end of the Transient Phase.

Hydrogen was produced by the oxidation of the rod claddings, the guide tubes and the shroud inner and outer surface. Although no detailed measurements exist, it is supposed that 205 ± 11 g were generated during the Transient Phase. But this does not include the mass stored in the circuit before the reflooding of the system.

Figure 4 presents the accumulated hydrogen production for ASTEC and ATHLET-CD. Both codes over predict the assumed 205 g. An older version of ATHLET-CD calculated more than 500 g before reflooding whereas ASTEC calculates 272 g. The simulation with an improved ATHLET-CD Version amounts to 266 g.

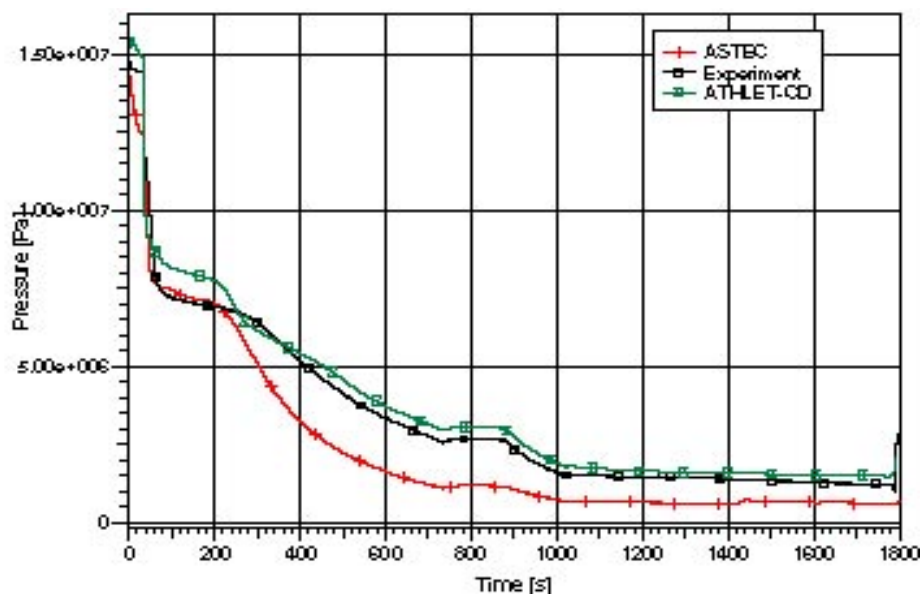


Figure 3: Loft-FP-2, Primary Pressure

A comparison of the released elements masses is only possible at the end of the Transient Phase since only the experimental values for the final state are available. Figure 5 depicts the accumulated values for Kr, Xe, Cs, I and Te for the ASTEC calculation compared to the experiment. The released mass of Kr was 0.0174 g in the experiment compared to 0.026 g in ASTEC. Regarding the noble gas Xe, 0.26 g were calculated and 0.19 g measured. For Cs 0.218 g was the simulated release mass and 0.108 g the experimental one. Hence, regarding absolute values the calculated values reach the range of the experimental ones. But if the calculation results are related to the measured ones the deviations are notable. Common to all elements is the start of release at about 1050 s. For other elements like Ba, Sr or La, for example, the released masses are in the range of 10^{-6} g and therefore not observable in the diagram. The greatest amount of it is released immediately after 1050 s. A small amount comes from the escalation after 1600 s.

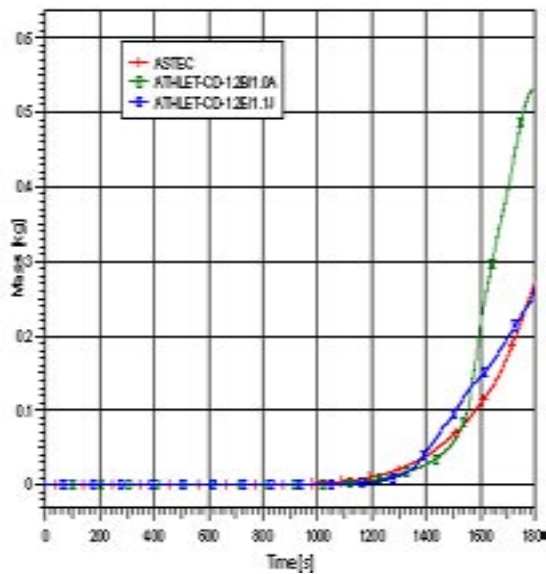


Figure 4: Loft-FP-2, Total hydrogen from the core

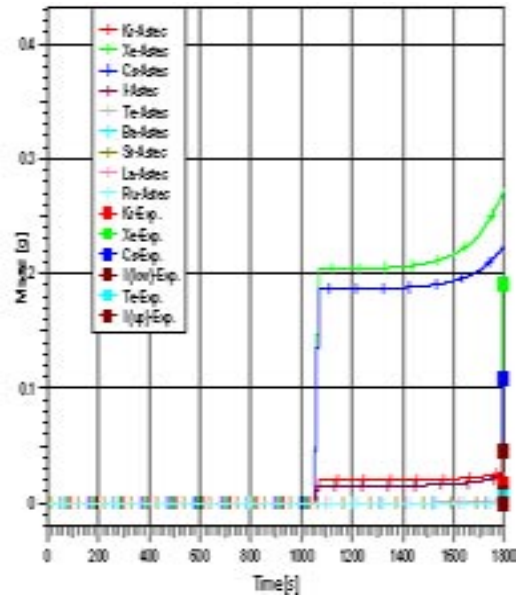


Figure 5: Loft-FP-2, Fission product release

The results of the Loft-FP-2 post-test calculations are very encouraging for ASTEC-V1, even if a considerable effort was necessary to meet this high quality of calculation.

3.2 ASTEC plant applications

At the end of the project more than 10 plant calculations on different types of NPP (PWR, VVER) with comparisons to other codes have been presented. The quality of these application calculations showed a large variety. One calculation of each reactor type has been selected for presentation, a PWR calculation on a KONVOI plant of GRS and a VVER-440/V-213 application of UJD.

3.2.1 PWR 1300 Mwe

The ASTEC code has been applied to a German PWR 1300 MWe for a SBLOCA (200 cm² leak in the hot leg of the pressurizer loop). The ASTEC-V1 modules CESAR, DIVA and CPA (for containment behaviour) are activated. The containment is modelled with 25 nodes corresponding to the MELCOR nodalization. The event is a 200 cm² leak in the pressurizer hot leg. The results are compared to MELCOR 1.8.4 and to a former calculation with the previous code version ASTEC-V0. After a steady state calculation of 300 s the event starts at 0.0 s with the opening of the break. Scram occurs at a pressure drop of 132 bar and feeding starts at 110 bar with the HPSI followed by the accumulator injection at 26 bar and the LPSI at 10 bar. When the water supply is finished the heat up of the core starts. DIVA is started at 4450 s shortly before the beginning of cladding oxidation. During core degradation hydrogen is released to the containment and slump of part of corium into the vessel lower head takes place. The calculation stops at 7240 s with an error in the energy balance in the corium. The agreement between ASTEC-V1 and MELCOR in the investigated time span is good. The pressure agreement in the primary system is good until the oxidation phase starts (Figure 6).

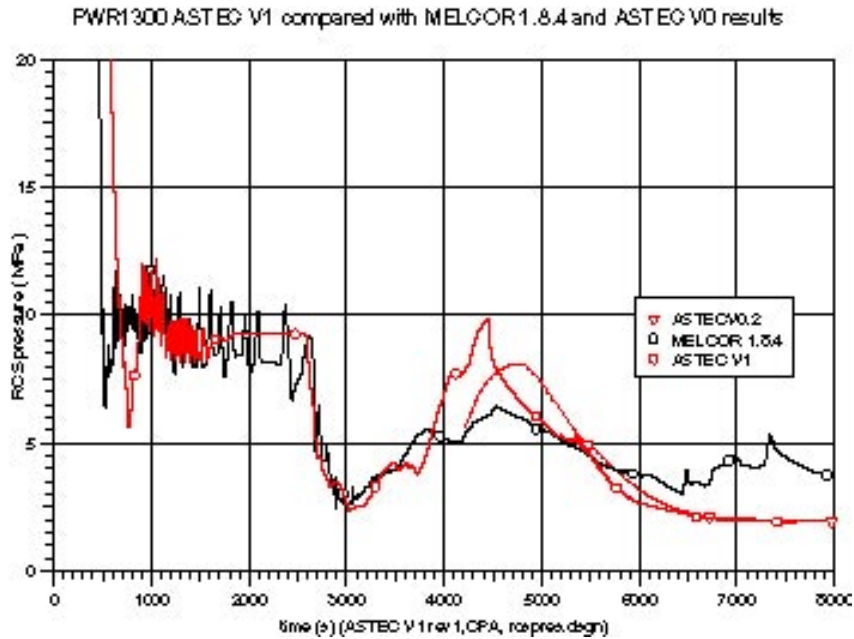


Figure 6: PWR 1300, Primary pressure compared to MELCOR and ASTEC V0

Then a faster heat up of the core and an earlier H_2 -production is observed with ASTEC (Figure 8). The coincidence of the containment pressure is good until the release of the fission products at about 6000 s (Figure 7). In the further course of the event the pressure is underestimated in ASTEC because the MELCOR pressure increases due to decay heat of the fission products, which is not considered in this ASTEC-V1 calculation. The integral H_2 -release to the containment (Figure 8) is in a better agreement with MELCOR than for ASTEC-V0 (let us remember that the front end of ASTEC-V0 was taken from tables of MELCOR results). The temperature in the core is higher in ASTEC and cladding oxidation occurs earlier. Discrepancies in the results between the two codes are mainly caused by a lower pressure decrease of ASTEC-V1. The start of the cold sided accumulator within 500 s is disabled. The release of water and steam through the break is significantly lower in ASTEC-V1. The continuation of the calculation until complete melt down of the core and the failure of the reactor vessel could not be achieved because of convergence problems in the CESAR/DIVA coupled calculation.

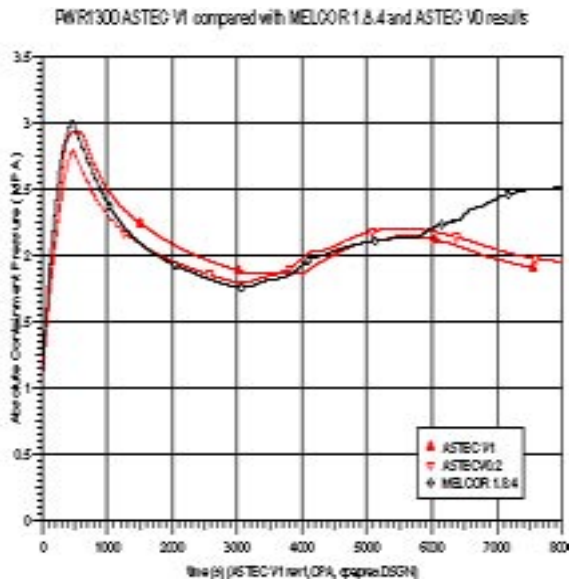


Figure 7: PWR 1300, Containment pressure compared to MELCOR and ASTEC V0

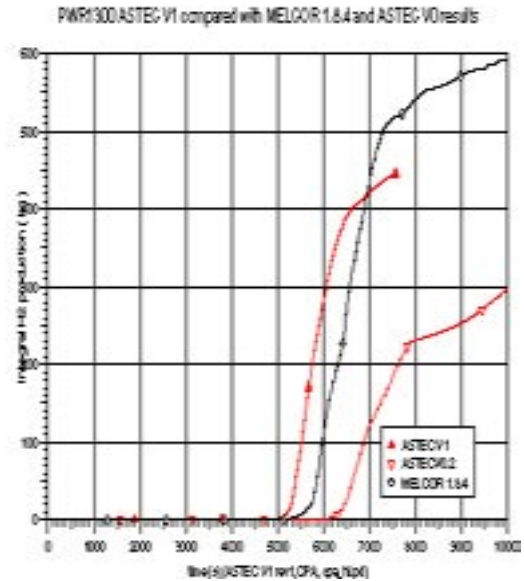


Figure 8: PWR 1300, Hydrogen production compared to MELCOR and ASTEC V0

3.2.2 VVER-440/V-213

The analyses are performed with the ASTEC-V1 modules CESAR and DIVA. The accident sequence analysed was a Station Blackout (SBO) with manually opening of the pressurizer valves. Only passive systems, i.e. accumulators, are available.

When the core exit temperature exceeds 550 °C, the operator opens the pressurizer safety valve to depressurise the primary system, allowing the accumulators to inject. A parametric study with four ASTEC-V1 calculations differing in the number of hydro-accumulators (2, 4), the model of SG steam dump stations to atmosphere and the starting time point of DIVA (which can be selected by the user) were performed in order to compare the influence of the changes with the MELCOR results.

After the PRZ-valve is opened, the pressure in the primary decreases rapidly. When the primary pressure is below 6 MPa, the accumulator injection begins (at 21400 s in MELCOR, and at 22110 s or 22121 s in ASTEC-analysis), leading to a rapid core recovery. The agreement between ASTEC-V1 and MELCOR in the primary pressure evolution is good (Figure 9). There is a difference in the initial water inventories of the circuits in the ASTEC input deck, comparing to the MELCOR data: not very high for the primary circuit (about + 2.3 % in ASTEC with respect to MELCOR) but substantial for the secondary circuit (about + 21.4 % with respect to MELCOR). The ASTEC data correspond to the real situation in the plant. Whereas the model of the SGs is not very well prepared in the MELCOR input deck, it was necessary to decrease the initial water mass on the secondary side artificially. Due to lower water inventory, the SGs in the MELCOR analyses are depleted earlier by about 5000s. This earlier loss of the secondary heat sink in MELCOR leads to the earlier heat up and pressurization of the primary circuit followed by the earlier cycling of the PORV and loss of primary system inventory. In the ASTEC analyses, sufficient heat removal through the secondary side and unchanged primary inventory are maintained, practically until the manual opening of the PORV. After the operator action, the primary inventory is lost through the opened PORV. The trend of water mass decreasing is very similar in the both codes. The general behaviour of the systems and the trends of the calculated parameters are in a good agreement.

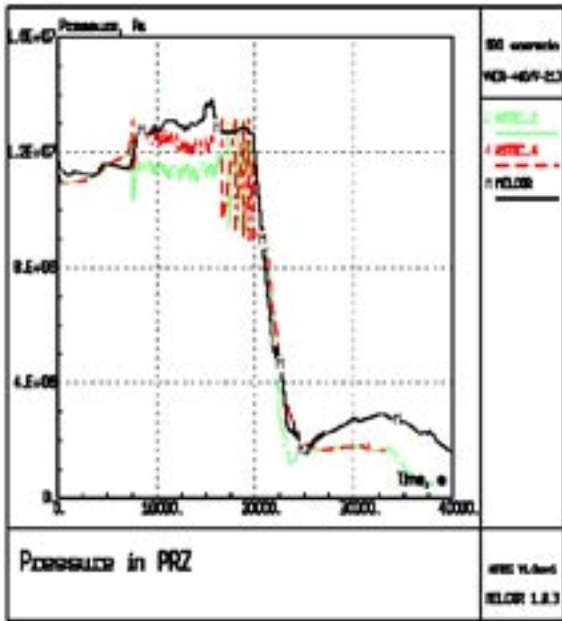


Figure 9: VVER 440/V213, Primary pressure comparison with MELCOR

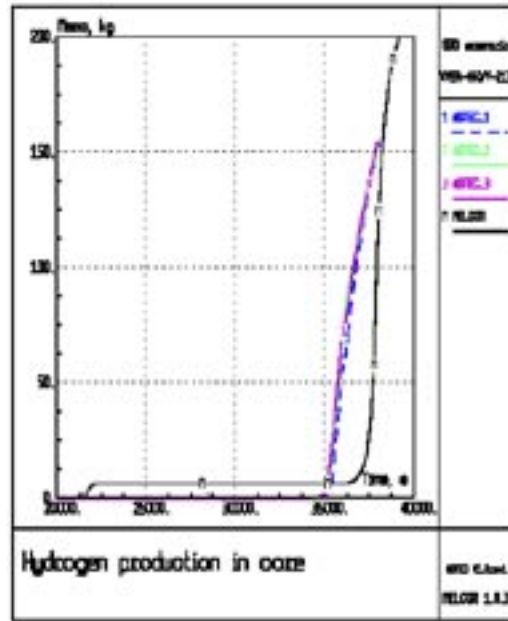


Figure 10: VVER 440/V213, Hydrogen production comparison with MELCOR

Differences are mainly caused by differences in the input decks of ASTEC and MELCOR models (e.g. initial water inventories, identical power profiles, etc.).

After permanent core uncovering, the fuel rods in the upper regions of the core are heated up and the oxidation of cladding starts, around 34110 s in ASTEC and 36200 s in MELCOR. The primary inventory is continuously decreasing and the core is very soon completely uncovered (34510 s to 35580 s in ASTEC and 36915 s in MELCOR). By the end of the ASTEC calculation, about 153 kg of hydrogen were produced. As seen in Figure 10, the hydrogen production in MELCOR at this time point is almost the same.

Difficulties with the ASTEC-V1 code were observed in the operation of the PRZ-valve. The triggering of the set point with the core exit temperature is not possible, because before switching to DIVA this value is not available. Furthermore the operation of the valve that is defined by a hysteresis function seems to be not correct, because the maximum and minimum zone pressures regulated seem to be oscillating within a range higher (see Figure 9) than defined by the hysteresis function.

It was impossible to calculate the accident sequence with ASTEC-V1 up to any deeper core degradation and failure of the vessel. Further improvements of the code robustness are seen to be necessary.

4 ACHIEVEMENTS

ASTEC versions V0 and V1 were installed successfully on the partners' platforms. The extensive portability check concluded that the ASTEC user should not fear portability effects. One of the partners' conclusions was that the level of ASTEC models was near the state of the art in most domains. Of course understanding and thus adequate modelling is still missing, like in all other codes, in some domains: reflooding of a degraded core, MCCI, iodine behaviour in RCS, etc... Obviously recommendations were made to continue efforts of validation and plant application. The new version V1 allows simulating complete scenarios including the front-end phase. Both developing organisations, GRS and IRSN, which will continue to assure the code maintenance beyond EVITA, ensure that the EVITA outcomes will be respected for the future ASTEC development. Some of the above needed improvements are already foreseen, as well as the extension to Boiling Water Reactors.

Further recommendations are given to improve:

- Management of input decks: tools for automatic check, standard inputs for generic plant applications;
- Visualisation / post-processing (remark: actually the GRS visualisation tool ATLAS will be coupled to the next code version);
- Users' support, including: continuous training courses (not only for beginners, but for experienced users too), wish for faster response of the ASTEC Maintenance team, more complete and detailed code documentation.

The plant applications with the first version of ASTEC V1 showed that the code is still not so robust that a sequence is calculated up to a foreseen end. Suggestions are made especially for increasing the robustness of the coupling of the two new modules CESAR-DIVA that calculate the circuit thermal hydraulics and the core degradation.

With respect to computing time, the EVITA users - researchers, licensing authorities and industry - accepted the definition elaborated in the VASA project as target, that a full sequence calculation (incl. post-processing) should not need more than 12 hours.

The progress since the beginning of the project where only a preliminary code version was available is important. The actual version allows to simulate the entire sequence of events during a severe accident. Besides, a first level of validation was attained successfully within the project. As EVITA has very successfully made the first step into the intention to provide end-users (like utilities, vendors and licensing authorities) with a well validated European integral code for the simulation of severe accidents in NPPs, the EVITA partners strongly recommend to continue validation, benchmarking and application of ASTEC. This work is foreseen in SARNET (Severe Accident Research Network) in the 6th Framework Programme where ASTEC will play a key role as the reference European integral code.

The backbone of SARNET will be provided by the integral computer code ASTEC. IRSN and GRS commit, within their capabilities and financial availabilities, to make their best efforts to provide the necessary maintenance and developments for satisfying the Network users. In particular, actions will be taken to integrate in ASTEC the current knowledge and all the future knowledge generated by research activities performed within SARNET. Most of the ongoing research activities will have the ultimate objective to provide ASTEC with appropriate physical modelling. In addition, the tool will be adapted, through mostly co-operative actions, so as to be used for any reactor application in Europe.

5 PARTNERSHIP

19 partners from eight European countries plus JRC, all having an excellent expertise on severe accidents and code use, were involved in the project, including researchers, licensing authorities and industry. Significant progress on evaluation of ASTEC code capabilities by partners was made possible thanks to a close cooperation inside the project between code users and the IRSN-GRS code development team.

6 SELECTED REFERENCES

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