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MODELLING OF STRATIFICATION AND MIXING OF A GAS MIXTURE UNDER THE CONDITIONS OF A SEVERE ACCIDENT WITH INTERVENTION OF MITIGATING MEASURES

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Abstract – *One of the objectives of the ERCOSAM-SAMARA projects was to assess capabilities of the current computational tools to predict the evolution of gas distribution in the containment under conditions relevant to a severe accident with hydrogen release. Various Lumped Parameter (LP) and CFD codes were used for the planning calculation, and pre- and post-test analyses. The planning calculations provided useful information for determining the most appropriate configurations, initial and boundary conditions used in the experiments. Pre–test calculations were performed for nearly all the tests, using nominal initial and boundary conditions provided in the test protocols, which resulted in discrepancies for the pressurisation rate, due to a large (and unexpected) sensitivity of the results to the initial conditions. In general, all the codes were able to capture the stratification build-up. Regarding the last phase of the tests, the pressure trends were properly reproduced and the effectiveness of various mitigation devices on gas mixing was properly represented although large discrepancies remain between calculations and measurements. Finally, post-test simulations were carried out using the actual initial and boundary conditions, and making use of the knowledge on various phenomena acquired in the pre-test analyses. Although in general pressure and gas distribution evolution could be properly represented, various discrepancies between simulations and data show that the representation of some phenomena would require additional analysis and refined modelling.*

I. INTRODUCTION

This paper provides an overview of the capability of state-of-the-art Lumped-Parameter (LP) and 3D/CFD computer codes to model the phenomena prevailing during a representative severe accident addressed in the ERCOSAM-SAMARA projects [1][2. The general objectives, methodology, and main outcome of the ERCOSAM-SAMARA projects have been illustrated in [1] and the companion papers [2][3], thus they will not be repeated here. Only the general aspects of the project that are necessary for a clear presentation of the analyses will be introduced in this section.

In relation to the specific objective to assess the computational methods, the objective of the project was twofold: 1) to establish whether for a test sequence representative of a severe accident in a LWR, chosen from existing plant calculations, stratification can be accurately simulated; 2) to investigate whether the codes can predict the evolution of the gas distribution produced by the operation of Severe Accident Management (SAMs) systems (spray, cooler and Passive Auto-catalytic Recombiners, PARs).

The code assessment was conducted against the experiments [4], which have been performed at “small scale” in TOSQAN (IRSN, Saclay), "medium scale" in the MISTRA (CEA, Saclay) and PANDA (PSI, Villigen) facilities in Europe, and in SPOT (JSC “Afrikantov OKBM”, Nizhny Novgorod) in the Russian Federation [5]. The analytical activity also included a code benchmarking [6] using the conceptual “nearly prototypical scale” facility HYMIX (IBRAE RAN, Moscow). The test scenario considered in the ERCOSAM-SAMARA projects represents a Small Break LOCA in a PWR with dry containment. The test condition of the different facilities was scaled down from the plant condition [3].

The approach followed in the ERCOSAM-SAMARA projects is to consider four distinct and consecutive phases [1]. Phase I addresses the blow-down, characterized by steam release during the postulated LOCA. Phase II simulates the phase of the accident leading to the release of hydrogen and steam into the containment. Phase III simulates the period of the accident when no more steam and hydrogen is released and Phase IV the phase where mitigation systems are activated. Two tests, one in TOSQAN and one is SPOT [4], featured a slightly different sequence, but the main results for these tests have no influence on the general conclusions based on the other tests.

To identify a representative sequence and develop the criteria to scale down the plant condition to the sizes of the experimental facilities, a methodology was defined and outlined in [3]. The planning calculations provided useful information for determining the most appropriate configurations, initial and boundary conditions to be used in the experiments. Additional sensitivity calculations were also performed to examine the effect of various parameters for the last phase of the experiments, where a spray, cooler or heater (simulating the thermal effect of an operating PAR) is activated. In this paper, some selected planning calculations will be presented.

Pre–test calculations were performed for nearly all the tests, using nominal initial and boundary conditions provided in the test protocols. In this paper, selected calculations will be discussed to illustrate the specific computational challenges posed by the phenomena prevailing in the tests.

Finally, post-test simulations were carried out using the actual initial and boundary conditions, and making use of the knowledge on various phenomena acquired in the pre-test analyses. Although in general all important aspects related to pressure and gas distribution evolution could be properly represented, it is still challenging to accurately simulate some details of the experiments. The paper will present some of the aspects that would require additional analysis.

This paper will also discuss some of the most interesting results observed in the analyses, and the remaining modelling issues. A synthesis of the work performed within the analytical activities is provided in the companion paper [7].

The codes used in the project include [7]: 1) LP codes (ASTEC, COCOSYS, KUPOL and TONUS LP); 2) 3D codes (GOTHIC, GASFLOW and TONUS); and 3) CFD codes (ANSYS-CFX , FLUENT and OpenFOAM).

II. PLANNING CALCULATIONS

Planning calculations were carried out for most tests, but their scope varied for the different facilities. They were especially comprehensive for PANDA, due to the need to define the most appropriate configurations and boundary conditions, and for SPOT, which was strongly modified to match the specific goals of the project.

The planning calculations addressed the choice of configurations and initial conditions, especially important for Phases I to III, and some design aspects and functional parameters of the components that affected the transient in Phase IV. It is important to notice that most of the main findings obtained by the planning calculations were later confirmed by the experimental results.

II.A. Configurations and initial conditions

The ranges of boundary conditions to be adopted for the tests in TOSQAN, MISTRA, PANDA, SPOT and HYMIX were based on the scaled down values of the ranges determined for the “generic containment” using certain scaling criteria and considering the specific geometry of each facility [3]. The main target values for the tests were defined:

―Pressure at the end of Phase I: 2.5 bar

―Helium concentration in the helium-rich layer of the vessel where the fluid is injected at the end of Phase III: 10%

In addition, the initial conditions were initially set to closely represent the accident scenario. In particular, the original scenario started from containment full of air at ambient conditions. However, this initial condition had to be modified in consideration of calculations for the generic containment. Indeed, both calculations with ASTEC [3] and more detailed calculations with GASFLOW (Fig. 1) showed that at the time before intervention of the SAMs (end of Phase III), steam would be uniformly distributed in the containment. This result indicated that, for designing tests representative of the actual scenario, position of the injection, initial and boundary conditions in the tests should be chosen to produce approximately this condition. A “modified scenario” was thus defined, with initial conditions different in the various facilities. For instance, for tests in SPOT, scoping calculations with KUPOL showed that due to the absence of a compartmentalization and mixing close to the injection (break room in Fig. 1), the use of prototypical initial conditions would lead to a strong steam stratification at the end of Phase III (Fig.2, left). To reduce the deviation of the expected transient in the facility from that calculated for the generic containment, the initial pressure was set at 2 bar in the "modified scenario", and the "mean" steam initial concentration at 50%. Fig.2 (right) shows the rather homogeneous steam distribution that can be obtained starting the transient with modified initial conditions. Similar results were obtained for PANDA using the GOTHIC code. In this case, additional simulations for Phase IV showed that the too strong steam stratification resulting from the use of the original initial conditions would alter the response of the system to the intervention of the SAMs, and therefore a "modified scenario" had to be adopted.

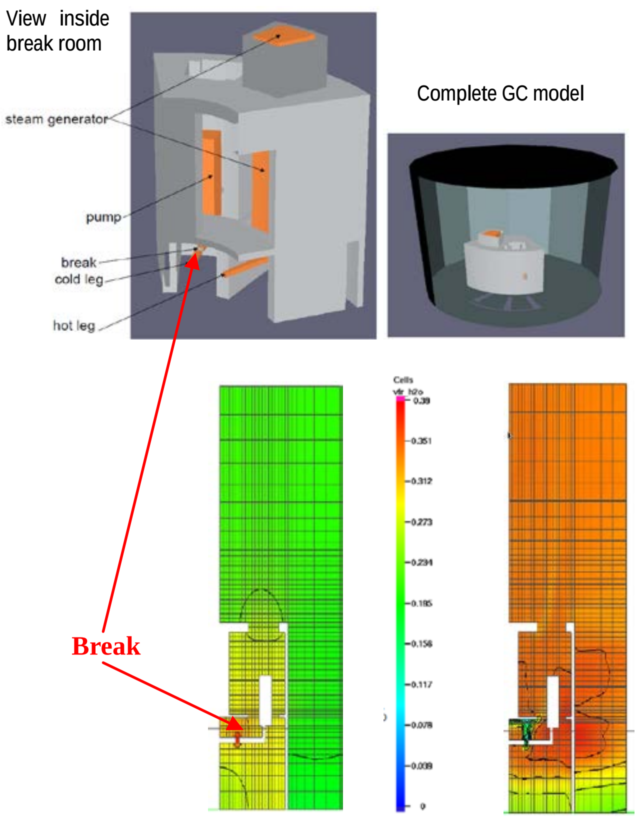

Fig.1. Calculations for the generic containment performed with the GASFLOW code. Top: GASFLOW model of break room placed in cylindrical containment; Bottom: steam distribution at the end of Phase I (left) and Phase III (right).

For MISTRA, the final choices for the modified initial conditions were made on the base of shake-down tests, which addressed configuration and conditions selected using the results of calculations with TONUS (using a 3-D model). Concerning the goal to achieve about 10% helium in the upper part of the vessel, planning calculations helped selecting flow rates and duration of injections that would lead to this condition.

Finally, in TOSQAN, the original scenario was chosen.

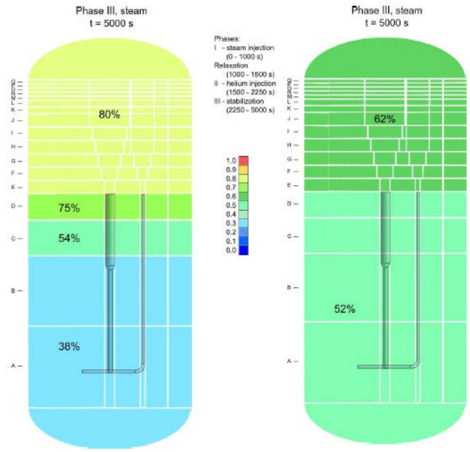

Fig.2. Planning calculations with KUPOL: steam distribution in the SPOT facility at the end of Phase III using the conditions of the original scenario (left) and the "modified scenario" (right).

II.B. Parameters for components (Phase IV)

Sensitivity calculations were performed to examine the effect of various parameters for the last phase of the experiments, where a spray, cooler or heater is activated.

For the spray tests, the parametric studies mainly addressed the effects of spray mass flow rate, water temperature, spray nozzle elevation, droplet diameter and wall temperature. For instance, for the tests in PANDA, calculations with the GOTHIC code [8] and GASFLOW showed how the depressurisation rate depends on spray mass flow rate and temperature.

For the heater tests in PANDA, the main parameters investigated were the effect of the elevation of the heater on the mixing, and the shape of the electrical power ramp to reproduce the linear increase of the power transferred to the fluid in the generic containment (Fig. 4). For tests in MISTRA, the planning calculations mostly addressed the characterisation of the heater model and the net effect on stratification of the heaters with respect to the transient (MERCO-0) without heater(s).

The planning calculations for the cooler concerned position of the component, its design, water flow rate and temperature. For the definition of tests in PANDA, the most important result was that the choice of a mid-height position would lead to the persistence of stratification [9] until the end of the cooler operation. This result (Fig. 3), indicates that the cooler would not break the stratification.

This interesting finding was considered to verify experimentally. Indeed, the two tests confirmed that the cooler could only affect the gas distribution below it and a short distance above, without inducing a global mixing [3]. A similar situation was also predicted for the tests in SPOT, where mixing did not extend to the upper part of the vessel during the cooler operation (Fig. 5).

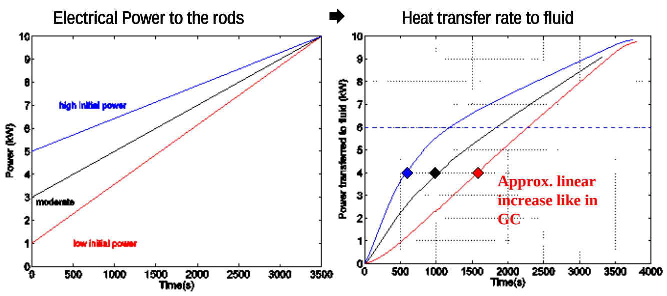

Fig.3. Planning calculations with GOTHIC: Power transferred to the fluid for various ramp shapes of electrical power supply for the test with heater in PANDA.

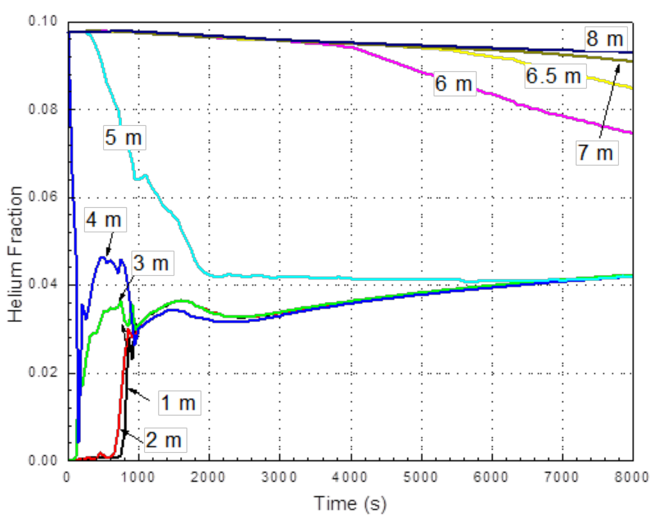

Fig.4. Planning calculations with GOTHIC for tests with a cooler in PANDA [9]: helium concentrations at various elevations for the case with cooler at 4 m.

III. PRE-TEST CALCULATIONS

Pre-test calculations were performed for most tests. In general, the phenomena could be reasonably well simulated. Each code has its adequate modeling capabilities, and the required user experience to properly select models and meshes applicable to a variety of conditions is available. On the other hand, significant discrepancies between calculations and measurements were observed.

In this section, selected calculations will be discussed to illustrate the performance of the codes, the lessons learned from the pre-test analyses and some computational challenges posed by the phenomena prevailing in the tests.

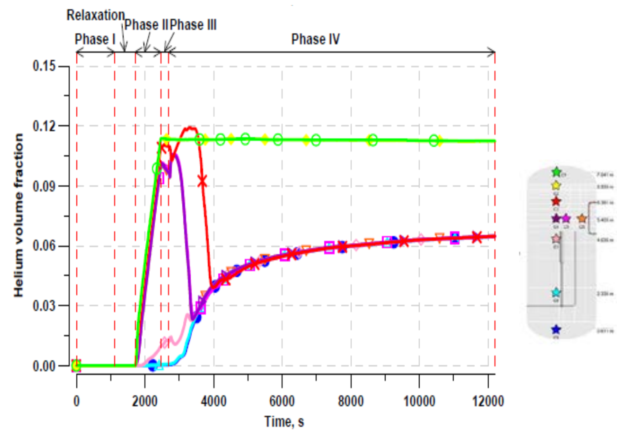

Fig.5. Planning calculations with KUPOL: helium concentrations at various elevations for test S1 in SPOT.

III.A. Phases I to III

For the first three phases of the tests, the main phenomena to predict are the pressurization and the steam and helium stratification. Figure 6 shows two examples of pressure time histories predicted for tests with condensation in PANDA and MISTRA. For both facilities the pressurization rate was overestimated.

However, the reasons are somewhat different. Indeed, in the case of PANDA, the reduced wall condensation was caused by the use of the nominal initial conditions provided in the test protocols. Parametric studies and finally the post-test analyses (Section IV) indicated that the discrepancies were mainly caused by inadequate representation of the initial distributions of gas composition (particularly the steam concentration), gas temperature and wall temperatures. The sensitivity of the results to the initial conditions was not obvious, and was an interesting result of the analyses. Note that the final value of the pressure in the end of Phase I was affected by the steam injection time.

In the case of MISTRA, the slower pressurisation in the last part of the steam injection phase is due to the inaccurate representation of initial conditions and heat losses at the cap and the spurious condensation behind the condensers.

In the case of the tests in SPOT, the codes also under-predicted the pressurization rate, where the initial conditions and thermal capacities of the structures were not properly taken into consideration.

For all these three facilities, pre-test calculations revealed the importance of a full characterization of the system for a successful prediction of the pressure evolution during a transient, which is usually considered easy to predict. On the other hand, for TOSQAN, where the wall temperature is controlled and the initial conditions (pure air and ambient temperature) were simpler to represent, the pressure could be predicted vey accurately, which confirms that the wall condensation models are adequate.

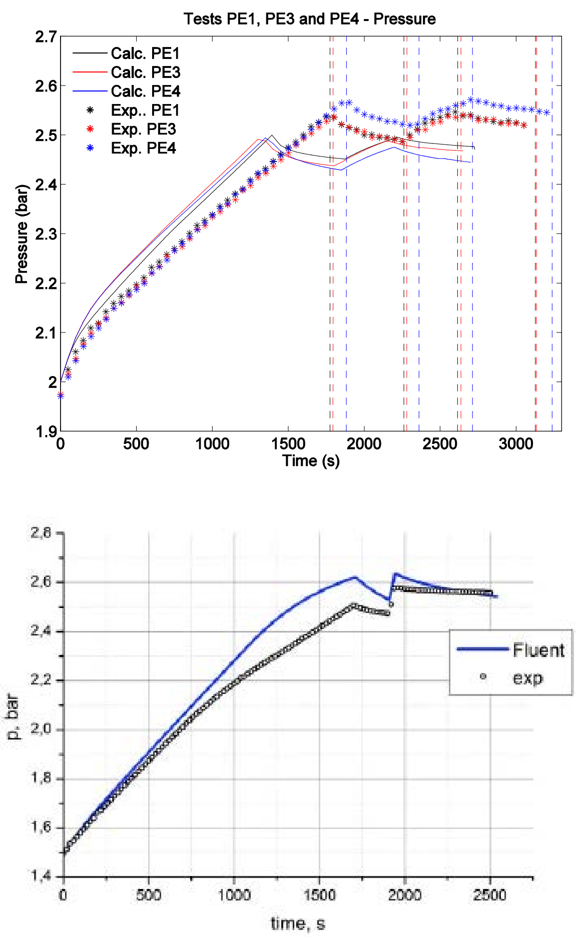

Fig.6. Pre-test calculations of pressurisation: (top) calculations with GOTHIC for tests in PANDA; (bottom) calculation with FLUENT for test MERCO-0 in MISTRA.

As regards steam and helium concentration distributions, all codes could predict the stratification, with discrepancies in the local steam and helium concentrations with the measured being generally small, varying from code to code and, for tests in PANDA, affected by the use of nominal boundary conditions. Figure 7 shows the comparison of the vertical distribution of steam at the end of Phase III calculated with a LP code and GOTHIC. The helium concentrations are not shown because the pre-test analyses were affected by a larger helium injection flow rate mistakenly used in the experiments.

For MISTRA, the analyses were more complicated, because of the convective motions promoted by the spurious heat losses behind the condensers [3]. Figure 8 shows the helium concentrations at various positions calculated with a LP code and a CFD code. Both codes overpredict the helium concentrations in the upper part of the vessel resulting from the helium injection, and tend to underpredict the mixing in the annular gap in the following relaxation phase.

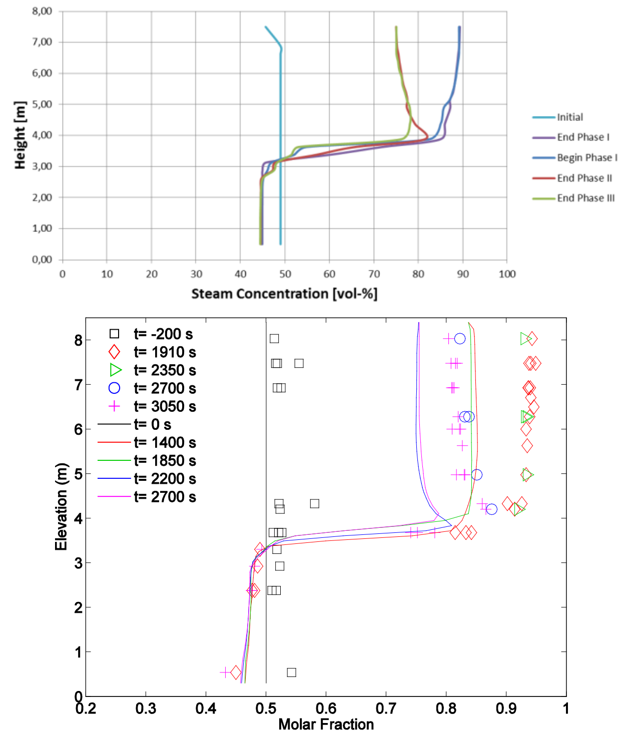

Fig.7. Pre-test calculations of steam vertical distribution in Vessel 1 for tests in PANDA with condensation: (top) calculations with the LP code COCOSYS; (bottom) calculations with GOTHIC (Symbols: data; Lines: simulation results)

It was shown by parametric studies and post-test analyses that the main reason for the discrepancies is the underprediction of the circulation behind the upper and (less) the middle condenser, caused by the inaccurate representation of heat losses and spurious condensation. It is interesting to note that the convective loops produced by the thermal field can affect the propagation of the light gas, which poses a major challenge to the codes. This issue is further discussed in Section IV.

Although the objective of the project was to address stratification (and the thermal effects directly affecting the processes influencing the gas distributions), an interesting issue arose in connection to overprediction of gas temperatures, especially in the tests without condensation. This general trend appeared at several locations, but especially large deviations were observed close to the steam injection elevation in the TOSQAN tests, where the thermal stratification was the steepest.

Figure 9 shows the gas temperatures in Vessel 1 of PANDA for test PE5 and TOSQAN for Test T116 calculated with the GOTHIC code. Large gas temperature overpredictions were also calculated by some LP codes, and also with some CFD codes (but not all) for tests with condensation, but for those tests the differences in the calculation of condensation rates (depending on the representation of initial and boundary conditions) and thus steam concentrations made the comparison more difficult. In general, the pre-test analyses revealed that the prediction of heat transfer rates between gas and structures, especially in regions nearly stagnant, could depend on the adequate representation of enhanced turbulent heat diffusivity and/or radiative heat transfer.

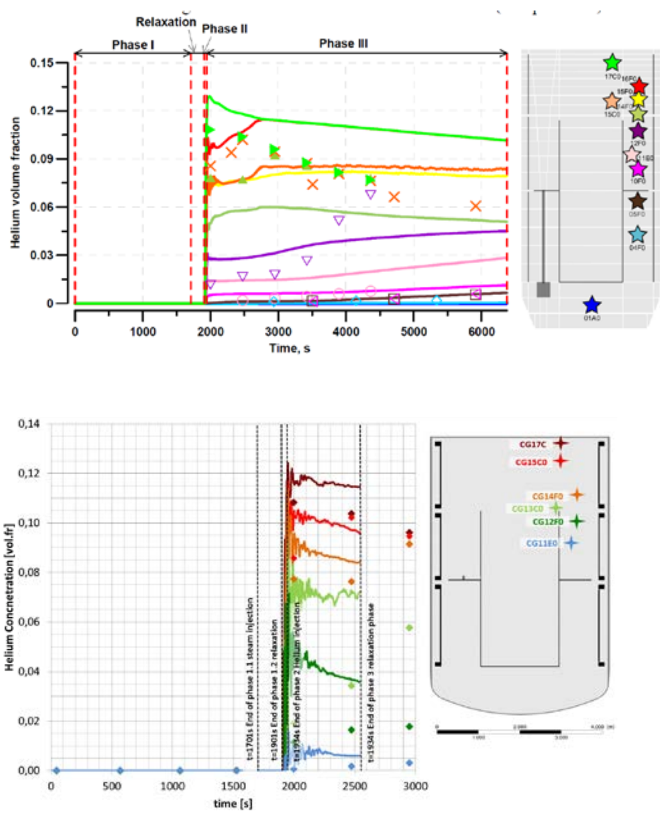

Fig.8. Pre-test calculations of helium concentrations at various locations in test MERCO-0: (top) calculations with LP code KUPOL; (bottom) calculations with the CFD code CFX. Symbols: data; Lines: simulation results.

III.B. Phase IV

For both the heater and cooler tests, no new specific issues could be identified for the PANDA tests, apart from those deriving from the reduced helium injected in the pre-test calculations (nominal boundary condition) and the neglect of the spurious condensation on the water lines in the cooler tests. For MISTRA, the main issue was the correct representation of the genuine effect of the activation of the components, with respect to the trend observed in test MERCO-0, and this issue was mainly addressed in the post-test analyses.

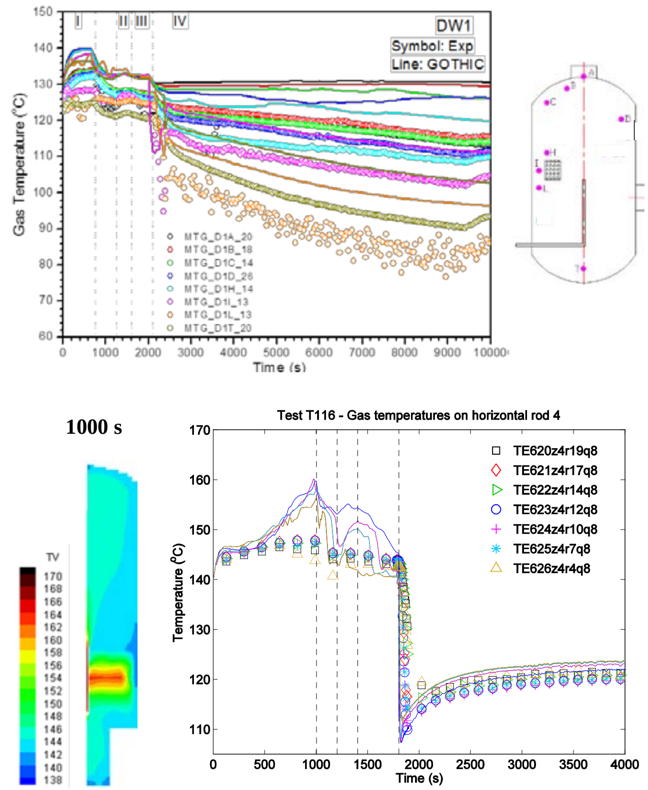

Fig.9. Pre-test calculations of gas temperatures with the GOTHIC code: (top) Vessel 1 of PANDA for test PE5; (bottom) Rod 4 (z=1.47 m) in TOSQAN for Test T116. Symbols: data; Lines: simulation results.

For the spray tests, the issue identified in the pre-test analysis was mainly the role played by re-evaporation at the walls for the depressurisation. Due to specific design of the TOSQAN facility and tests, re-evaporation in the sump was very large and not prototypical (for test T116 the spray caused pressure to increase instead of decrease), and therefore those tests will not be considered.

In PANDA and MISTRA, some common trends could be identified, which resulted in the understanding that post-test simulations required some modelling of the sump evaporation. Figure 10 shows the comparison between the calculations for test PE1 with FLUENT, which did not account for re-evaporation, and calculations with GOTHIC, where heat transfer between structures and liquid is modelled, which causes water to re-evaporate (the enhanced wall-to-gas heat transfer also contributes to the very good agreement). From the simulation with GOTHIC, it is possible also to get an idea of the magnitude of the re-evaporation rate, which was practically uninfluential in the first period of the spray operation, and became quite important towards the end of the depressurization transient.

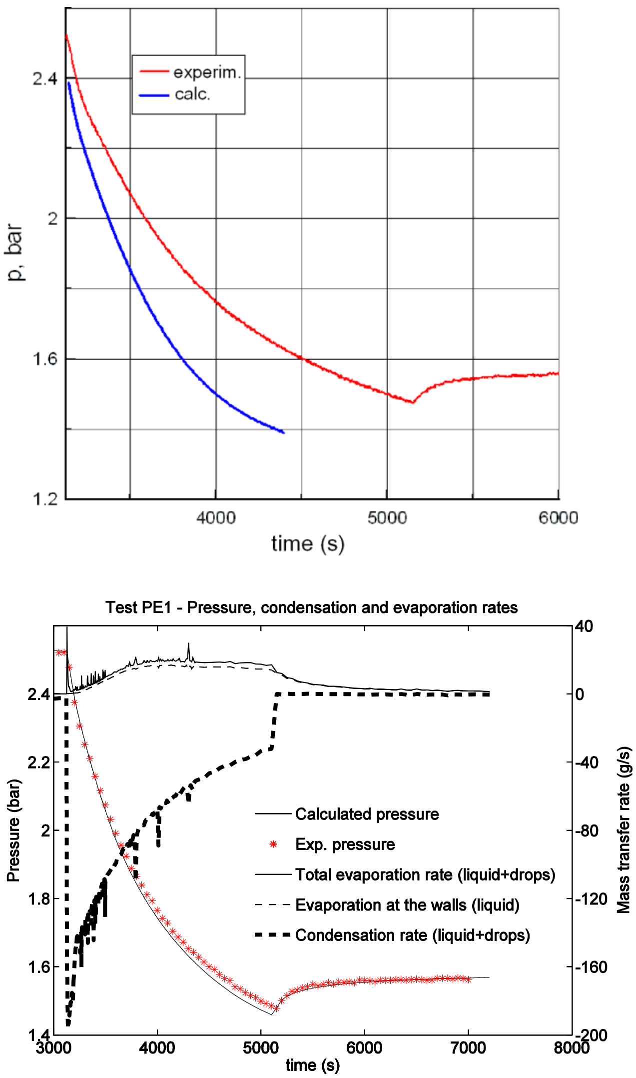

Fig.10. Pre-test calculations of pressure for test PE1 with: (top) FLUENT; (bottom) GOTHIC.

IV. POST-TEST CALCULATIONS

The post-test calculations mainly addressed the correct implementation of the actual initial and boundary conditions and the development (or use) of models for considering radiative heat transfer and water re-evaporation. Mesh and model parameters sensitivity studies were also performed, which also contributed to clarifying important issues.

IV.A. Phases I to III

Pressurisation was generally well predicted in all simulations when the initial conditions in PANDA, the heat losses in MISTRA and the actual initial conditions and thermal capacity of the structures in SPOT were used. Figure 11 shows sample results for PANDA and MISTRA.

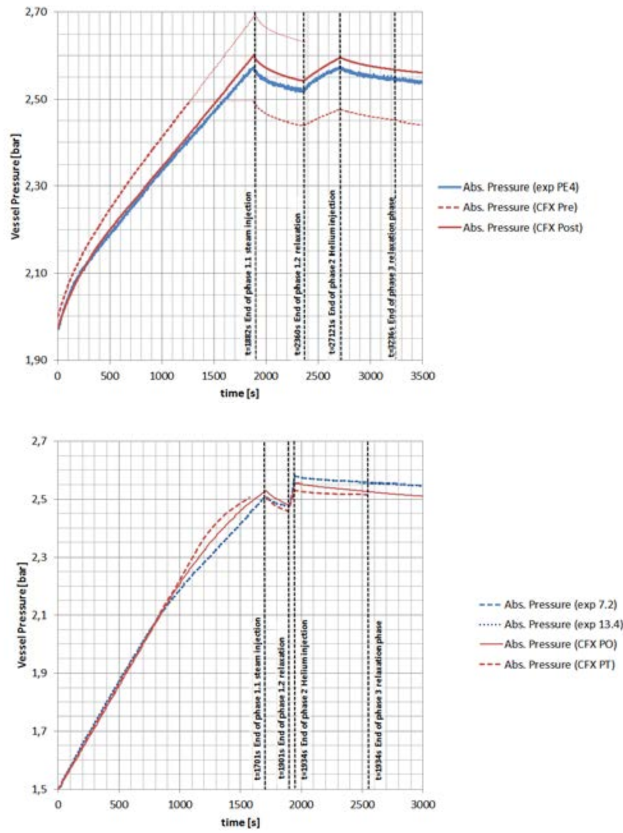

Fig.11. Pressure time-histories calculated in pre-test and post-test calculations by CFX for: (top) PANDA test PE4 and (bottom) MISTRA tests MERCO-0.

As regards stratification, the use of the actual boundary conditions resulted in a dramatic improvement of the helium concentration distribution for the PANDA tests. However, relatively large differences exist in the prediction of the peak concentrations and distribution in the region above the injection, with under- and over-predictions of ± 3%. The most accurate results were obtained with CFX, with the differences between CFX and FLUENT (>2%) being not well understood. Figure 12 shows the helium concentrations at various locations calculated with FLUENT for three tests in PANDA, MISTRA and SPOT. The code, using the standard k-ε turbulence model, consistently overpredicts the peak concentration in all tests (for PANDA, these results are similar to those obtained with FLUENT by other users). Further investigations are currently performed: preliminary results with a different turbulence model (top of Fig. 12) show the effect of an appropriate selection.

Figure 12 also shows that for the simple geometry of SPOT, the other codes (GOTHIC [10] and two LP codes) could calculate the helium distribution quite accurately.

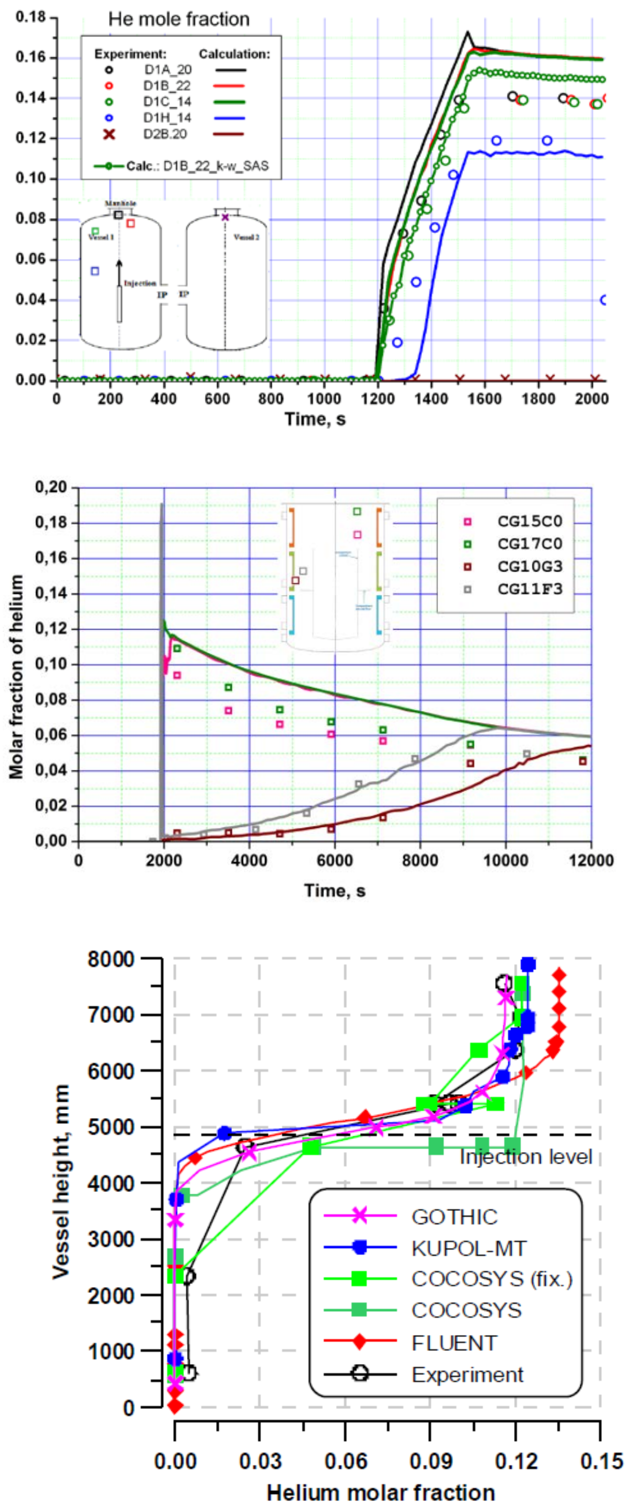

Fig.12. Post-test helium concentrations calculated with FLUENT for: (top) test PE1 in PANDA; (middle) test MERCO-0 in MISTRA; (bottom) test S1 in SPOT. Also in the middle figure, symbols represent data and lines simulation results.

Concerning the distribution in MISTRA, the simulations with CFX could provide evidence that improved prediction of the helium distribution is linked to the correct representation of the circulation behind the condensers.

Figure 13 shows that a substantial gas mass flow rate behind the upper condenser resulted in much better predictions of the helium concentrations than those obtained in the pre-test analysis. The main modifications in the model between the pre- and post-test simulations were the more accurate initial conditions, a refined mesh, and the use of radiative heat transfer model.

The mixing during the relaxation phase could not be predicted by the LP codes, which have difficulty to account for natural convection effects driven by spatially non-uniform heat transfer with the structures. Actually, the difficulty to reproduce these processes is the most important limitation of LP codes observed in the project.

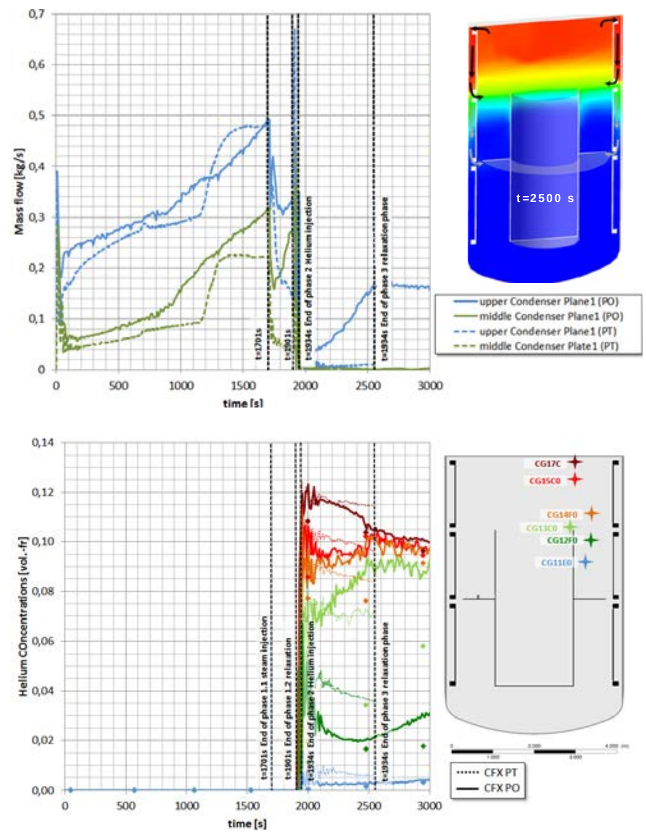

Fig.13. Post-test calculation of test MERCO-0 with CFX: (top) helium concentration distribution and circulation behind the condensers; (bottom) helium concentrations at various locations. Symbols: data; Lines: simulation results.

The gas temperatures were generally over-predicted for the tests without condensation, it can be observed that in calculations with GOTHIC (Fig. 14) for test PE2 the gas temperatures could be well predicted by using a higher convective heat transfer coefficient (multiplication factor of 5), which can be justified by the enhanced turbulence produced by the jet. It can therefore be debated whether radiative heat transfer should be really modelled to reduce the discrepancies observed in the calculations with the CFD codes. For the nearly stagnant region at the interface of the stratification front, the same correction for test T116 also produced much better results. In this case, however, the enhanced convective heat transfer is more difficult to justify. It is therefore open whether the high temperatures (up to 15 K overprediction) calculated with the CFD codes (Fig. 15) are due to the missing modeling of radiative heat transfer or to the inadequate modelling of turbulent diffusivity (and therefore convective heat transfer at the wall) in a nearly stagnant region.

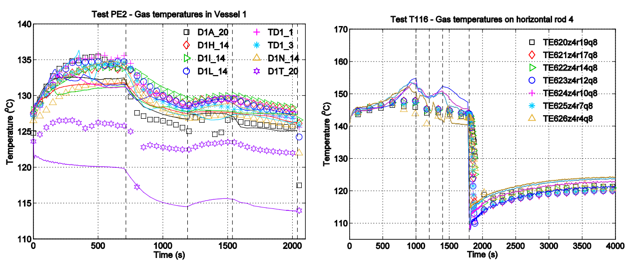

Fig.14. Post-test calculation of gas temperatures in test PE2 (left) and T116 (right) with GOTHIC (Symbols: data; Lines: simulation results).

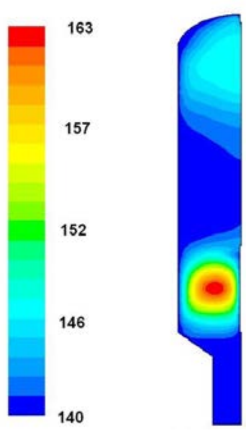

Fig.15. Post-test calculation of gas temperatures (^{o}C) in test T116 with FLUENT.

IV.B. Phase IV

The depressurization in the tests with spray in PANDA and MISTRA could be well predicted by the simulations with the re-evaporation modelled. Figure 16 shows the results obtained for test PE2 with the GOTHIC, FLUENT and the LP code ASTEC, and Fig. 17 the results for MERCO-2 with FLUENT. The parametric studies indicate that modelling the re-evaporation is essential for the calculation of the long-term depressurization, and this cannot be easily represented within a LP code.

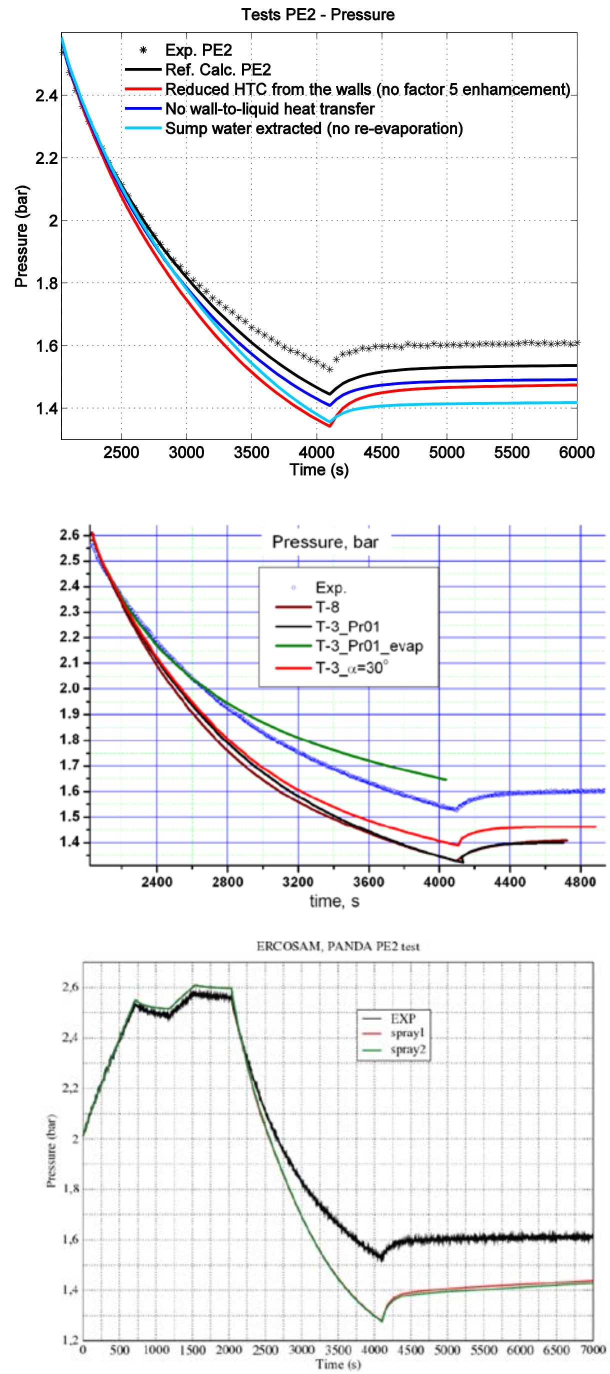

Fig.16. Post-test calculations of depressurization caused by spray in test PE2 with: (top) GOTHIC; (middle) FLUENT and various model choices; (bottom) with the LP code ASTEC (assuming two droplet trajectories).

Additionally, the parametric study with GOTHIC suggests that the effect of wall-to-gas heat transfer could be as important as water re-evaporation, and consideration of the enhanced heat transfer due to turbulence produced by the spray could be necessary for obtaining accurate predictions (the use of standard correlations without enhancement factor leads to substantial underprediction of the final pressure). This cannot be justified at this stage and remains an open issue, as well as the possible role of radiative heat transfer in enhancing wall-to-fluid heat transfer (to both steam and droplets).

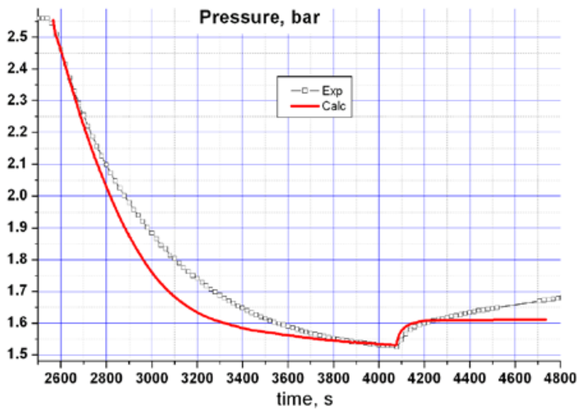

Fig.17. Post-test calculations of depressurization caused by spray: Test MERCO-1 simulated with FLUENT.

The stratification break-up caused by the spray is very fast, and all simulations captured this effect. The only difficulty seems to predict the mixing time above the spray nozzle, but this is unlikely to be an important issue. It is also worth to point out that parametric studies with FLUENT [11] showed that in addition to the average velocity, only the spray angle had a large effect on the global mixing, which explains why the codes without considering the details of the droplet injection also showed good results. The LP codes can predict stratification break-up, and the major discrepancies in local concentrations near the spray nozzle reported in the simulation with ASTEC (large transient increase during the initial few hundred seconds) are probably related to specific features of the code, which require further investigation.

As regards the test with heaters, the main variables are reasonably well predicted by all codes for the test in PANDA. Most simulations neglected radiative heat transfer, some accounting for this effect by reducing the convective heat transfer from the heater rods to the fluid. Figure 18 shows the good representation of the mixing in the simulation with FLUENT, where radiation was not represented. It is noted that the mixing, like in the experiment, is limited to the region above the heater inlet. In-depth analyses with CFX, however, showed the importance of radiative heat transfer, which affects various important aspects of the transient. Figure 19 shows that during the period of heater operation, the radiative heat transfer to the walls was twice larger as compared to the convective heat transfer.

The two tests in MISTRA were more challenging, because the simulations should represent the genuine effect of the heaters during a slow transient strongly affected by the natural evolution of the system under the effect of heat losses, diffusion effects and circulation loops behind the condensers (Fig. 13).

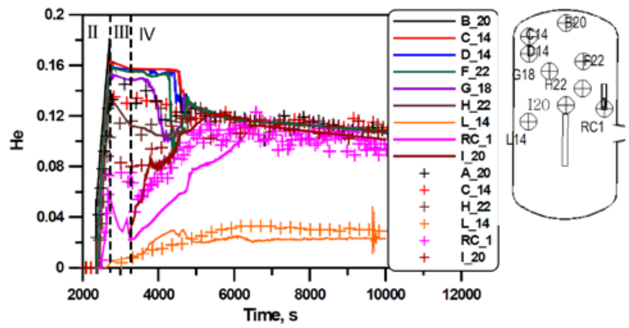

Fig.18. Post-test calculations of helium mixing caused by a heater: Test PE4 simulated with FLUENT (Symbols: data; Lines: simulation results).

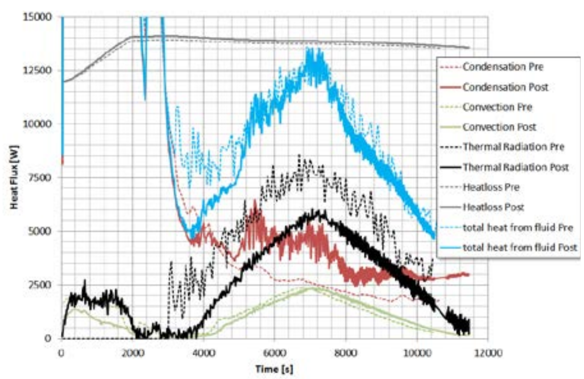

Fig.19. Post-test calculations of test PE4 with CFX: contributions to total heat transfer to the vessel walls by the various heat exchange modes.

For this test, the few CFD simulations addressing this issue were reasonably successful in predicting the genuine mixing effect of the heat source(s), which consists mainly in local differences but does affect little the global homogenization process (Fig. 20). On the other hand, LP codes were less accurate in predicting mixing at various locations, mainly due to the difficulty to represent diffusion and convective motions behind the condensers. Figure 21 shows the discrepancies in the calculation of helium concentrations observed in the simulations with the TONUS-LP.

The tests with a cooler in PANDA and SPOT were the most difficult tests to predict, owing to the complex geometry of the coolers and the time-history of the helium concentrations above the cooler critically dependent on the interaction of several processes. The test MERCO-2, on the other hand, due to the simpler geometry (cooling plate) and position at the top of the vessel, posed less problems [12].

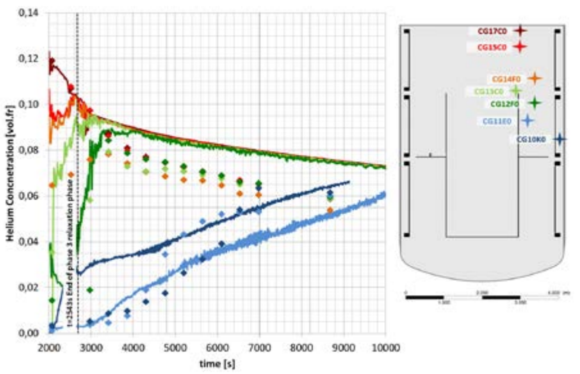

Fig.20. Post-test calculations of helium mixing caused by a heater: Test MERCO-3 simulated with CFX (Symbols: data; Lines: simulation results).

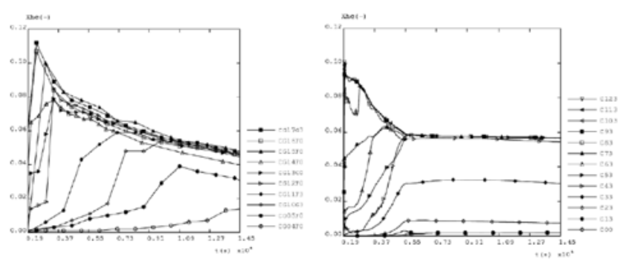

Fig.21. Post-test calculations of helium mixing caused by a heater: simulations with TONUS-LP (right), compared with measured data (left) for test MERCO-3.

The depressurization caused by the cooler could be well predicted with all codes. However, the evolution of the helium stratification could not be simulated with the same accuracy. Figure 21 shows the results obtained in the simulation for Test PE3 with the GOTHIC code, where the spurious effects of condensation on the water feed line was also considered. The most obvious discrepancies are that the increase in helium concentration in the upper part of the vessel and the faster stratification erosion process were not well captured.

Figure 23 shows the helium vertical profile at the end of Phase IV in the test S1 in SPOT. None of the codes could accurately predict the final distribution, with some codes predicting full mixing, and other codes overpredicting the helium concentrations in the upper part of the vessel.

V. CONCLUSIONS

Analyses of stratification and mixing investigated in the experiments performed within the ERCOSAM-SAMARA projects were carried-out by a variety of codes, ranging from LP codes to CFD codes. In general the performance of all codes can be rated as fairly successful, especially if one considers that the predictions of the planning and pre-tests calculations were confirmed by the experimental results. The results indicate that code and models are well developed, and sufficient know-how is available to use them with confidence for new conditions.

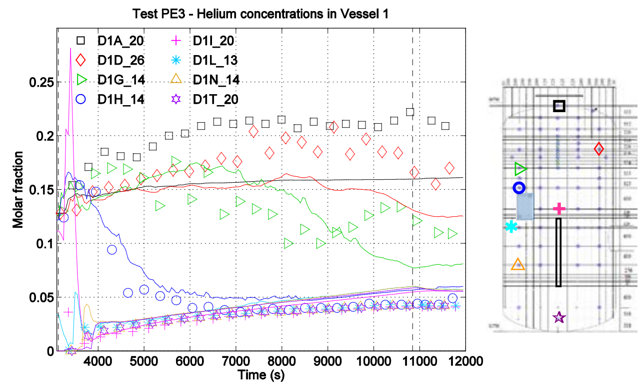

Fig.22. Post-test calculations of helium mixing caused by a cooler: simulations with GOTHIC for Test PE3 (Symbols: data; Lines: simulations results).

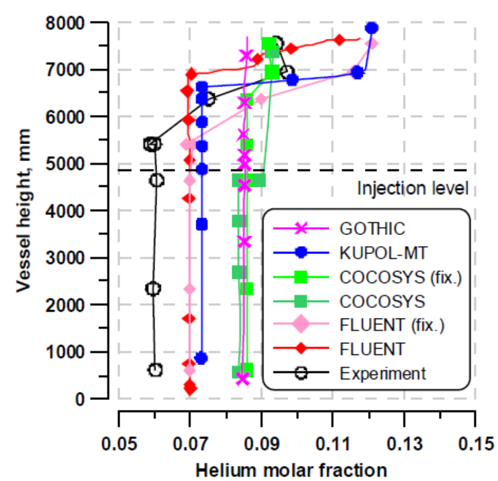

Fig.23. Post-test calculations of vertical helium distribution in test S1 in SPOT with various codes.

Stratification build-up could be predicted rather well by all codes. It should be emphasised that the post-test analyses showed that the codes could also take into account the sensitivity of the pressurization to the details of the initial distributions of gas concentrations, and gas and wall temperatures. However, important deviations from the experimental results were observed in the calculation of the peak helium concentration in both PANDA and MISTRA. Further investigations will be needed to clarify the causes of discrepancies up to 3%.

The transients produced by the intervention of the mitigating measures could also be predicted reasonably well by all codes, although some important issues could be identified, which require further studies, refined modelling and additional assessment.

The analyses of tests with a heater put in evidence the role played by radiative heat transfer. Although for the tests conducted in this project, where only the thermal effect of the PARs were addressed, the modelling of radiation was not crucial for the simulation of mixing, the prediction of other variables was clearly affected by the correct representation of all heat transfer modes. For the simulation of actual PARs, it is thus expected that radiative heat transfer should be taken into consideration. Another important result was that the LP codes cannot properly represent the effect of heat transfer between fluid and structures on convective loops and diffusion processes, which control the transport of light gas.

The mixing caused by the intervention of a spray could be well simulated, although the depressurization towards the end of the transient could not be predicted accurately by all codes. For the late period of the transient, water re-evaporation from the sump and heat transfer from the walls (either convective or by radiation) strongly affects the pressure decay. Some codes modelled these phenomena, and could predict pretty well the final pressure. However, tuning parameters were introduced or rather strong simplifications were adopted. For these phenomena, refined modelling is required.

The tests with a cooler of tube bundle design were the most difficult to predict. Indeed, no code could accurately simulate the evolution of the helium stratification resulting from the activation of the component. It could be thus concluded that transients associated with cooler operation require further investigations.

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