PASSPORT

Methodology for the analysis of safety system performance in relation to coupled plant system and containment processes

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ABSTRACT

The PASSPORT project aims at the development and validation of a novel computational methodology for the performance assessment of LWR safety systems during design-basis accidents and beyond-design-basis accidents. The primary objective is to provide an integrated analysis tool for the treatment of interactions between the primary circuit and the containment, by developing a numerical coupling scheme between the TRACE (primary system) and GOTHIC (containment) codes.

During 2013, the validation activities for the in-house coupled TRACE-GOTHIC code were completed. The ISP-42 integral test experiment, Phase B, in the large-scale PANDA facility was selected as validation case. Interactions between the primary reactor system and containment were identified in the activation of the passive emergency cooling system and relative feedbacks on the gas distribution in the drywell compartment. For an objective evaluation of the added-value of the coupling, the same experiment was simulated using stand-alone versions of the two codes and models, and compared with the coupled code solution. Despite the large uncertainty associated with the initial conditions of this particular experiment, the TRACE-GOTHIC coupled code was proven to reproduce the pressure transient with an accuracy that matches the results obtained with the TRACE and GOTHIC codes used separately. As a matter of fact, the coupled code was found to be able to simulate the experimental data better than either of the two individual codes in the early stage of the transient. And an additional advantage is that the coupled code system makes available in a single evaluation model the three-dimensional capabilities of GOTHIC for prediction of gas distribution in a multi-compartment geometry. As a last step, the coupled code was applied to simulate a postulated Loss-Of-Coolant-Accident (LOCA) using a simplified plant/containment model representative of Swiss operating nuclear power plants. This case study involved comparing TRACE stand-alone, TRACE with one iteration prescribing the back-pressure transient from GOTHIC stand-alone, and TRACE-GOTHIC coupled instance. With reference to the selected accident, the differences were deemed between minimal and negligible. However, these results were obtained based on simplified representations of the various components and systems. Therefore, a confirmation of these findings would truly require proceeding with a more detailed coupled model. Furthermore, it is considered likely that further improvements of the coupled simulation could be achieved after implementation, with the coupled model now available, of the recirculation cooling mode between containment sump and the safety injection system of the primary circuit. As the project is now being completed, these studies are not planned to be conducted but could be part of further research related to advanced coupled plant/containment methodologies and analyses.

Project goals

The PASSPORT project was launched as a joint research activity between ENSI and the Paul Scherrer Institut (PSI) and involves a technical collaboration between the STARS project at the Laboratory for Reactor Physics and Systems Behaviour (LRS) and the Laboratory for Thermal-Hydraulics (LTH). The PASSPORT activities aimed at the development and validation of a novel computational methodology for the performance assessment of LWR safety systems during design-basis-accidents and beyond-design-basis accidents. One foreseen advantage of this methodology is to allow for a more advanced modelling and thereby more accurate simulations of accidents involving weak to strong interactions between the primary coolant circuit and the containment. As this might be relevant not only for safety analyses of current operating Gen-II reactor types but also in order to bring forward the state-of-the-art in this area for the analysis of Gen-III/III+ concepts, especially those relying on passive systems, the underlying principle is to achieve a comprehensive and generic methodology for a wide range of applications. Thus, the primary objective is to develop a numerical coupling scheme between the best-estimate state-of-the-art codes TRACE for 1-D system analysis and GOTHIC for 3-D containment behaviour. The second and complementary objective is to validate this methodology on the basis of available integral and/or separate effect test experiments, with special emphasis on tests where interactions between primary coolant/containment systems are mainly driven by physical phenomena. As a last step, the applicability of the coupled methodology for safety analyses of the nuclear power plants operating in Switzerland (Gen-II) was investigated.

For 2013, the specific objectives of the project were as follows.

- Conclusion and scientific publication of the validation activities for the coupled system/containment code by using data from the PANDA ISP-42 integral test experiment.
- Exploration of additional experimental tests and analyses to enlarge the validation basis as well as of supplementary capabilities for the coupling.
- Simulation of a postulated accident in a Swiss-like nuclear power plant using the coupled code and an ad-hoc demonstrative GOTHIC model of the containment.

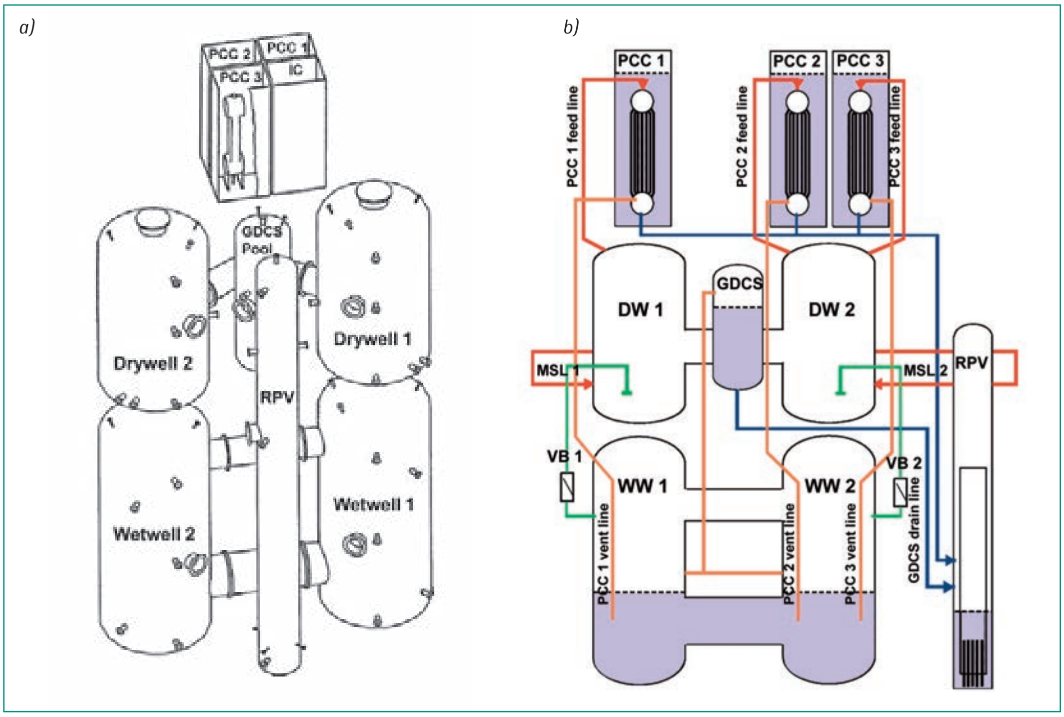
This report presents the status and progress achieved during 2013 in relation to the above objectives and depicts the outcome and achievements of the whole project.

Work carried out and results obtained

Definition of the target scenario

Advanced Light Water Reactors (ALWRs) with passive safety systems, which rely on relatively weak gravity and buoyancy forces, exhibit a higher

Figure 1: *PANDA facility: vessel layout (a) and configuration for Phase B of ISP-42 (b).*



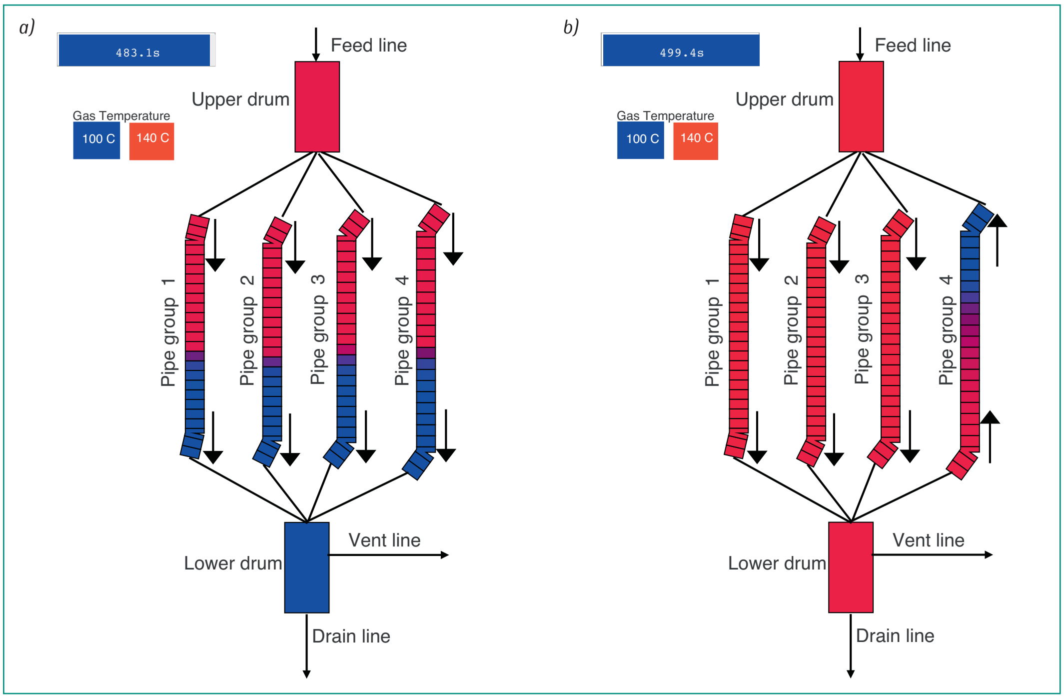


Figure 2:
Example from the TRACE model of the simulated flow and temperature distribution pattern in the PCC for normal operating mode (a) and for recirculatory flow (b).

degree of interaction between the primary system and the containment compared to reactors with traditional active safety systems. In order to accurately simulate the effects of the containment pressure on the primary system behaviour it becomes necessary to couple the system and containment codes and execute them as a single model. Then, the availability of an appropriate integral test is a necessary step to perform the code assessment.

The PANDA facility at PSI [1] has been identified as the premiere source of assessment. In particular, the ISP-42 integral test series – investigating the overall performance of the ESBWR passive concept – was considered as a suitable validation option. Interactions between primary reactor system and containment have been identified in the ISP-42 Phase B, including the activation of the passive emergency core cooling system GDCS (Gravity Driven Cooling System) and the effects of the discharge of subcooled water into the RPV (Reactor Pressure Vessel). The GDCS injection, passively triggered when the hydrostatic head wins the pressure difference between RPV and containment, is the most typical example of such coupled phenomenology. Figure 1 shows a 3-D sketch of the PANDA facility and the configuration used for Phase B of ISP-42.

Pre-studies on the PANDA facility

As previously reported, pre-studies on the PANDA facility were carried out with stand-alone calculational models developed with TRACE and GOTHIC with the objective of comparing the capabilities of the two codes in simulating one typical cooling system. The Passive Containment Cooling System (PCCS), which in the ESBWR design consists of passive condensers submerged in a boiling pool on top of the containment, was studied. TRACE and GOTHIC have been independently assessed on a variety of phenomena characterizing the primary side of the condenser (condensation of steam in vertical tubes, with and without non-condensable gas) and the secondary side (subcooled pool boiling). The code assessment made use of separate effect test data, available from the series of the B-tests [2].

The PCC systems are designed to remove the decay heat from the containment, following an accident where the RPV is depressurized. They rely on the condensation of steam in the steam-air (or steam-

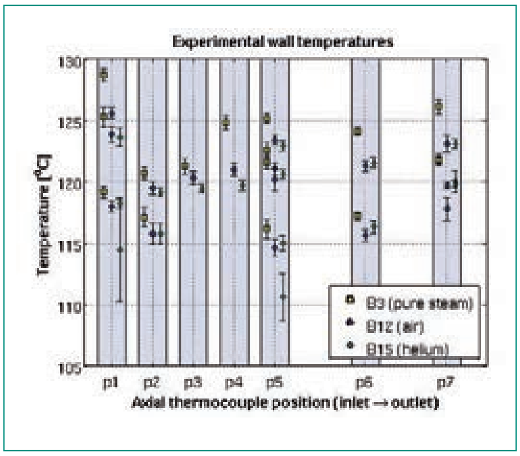


Figure 3:
Comparison of the experimental wall temperatures in case of pure steam and heavy (air) and light (helium) non-condensable gas.

nitrogen) mixture, which transfers the residual heat to the water of the external pool and, from there, to the environment. Performance of the PCCS in presence of light gas (hydrogen, simulated by helium) must be considered to account for postulated accidents with core heat-up.

The studies showed that both codes were able to achieve fair agreement with experiments. The GOTHIC containment code could be applied to simulate passive safety systems with pipe geometry and related phenomena, such as natural circulation in a two-phase loop. As concerns the performance of the PCC (namely, heat transfer degradation due to non-condensable gas), the GOTHIC model generally predicted the overall performance better than the TRACE model even though the general trends were well predicted by both codes. The pool boiling model of TRACE (Gorenflo correlation [3]) was proven to perform better than the model of GOTHIC (Chen correlation [4]).

More insight – considered for publication – has uncovered another issue that helps to explain some discrepancies between models and experiments. Whereas the experiments showed that the «light» gas helium has a larger impact on the PCC performance, both GOTHIC and TRACE models have predicted an opposite behaviour (i.e., less degradation of the heat transfer with same molar fraction of helium compared to «heavy» gas air). These results have been interpreted in view of the pre-study indicating that the light gas (helium), due to buoyancy force, may accumulate in the upper part of the PCC pipes and induce a circulatory flow pattern (Figure 2). This different mode of operation of the PCC is likely to be less efficient than the normal operation mode. The degradation of the heat transfer due to accumulation of non-condensable gas is made evident by the outer wall temperatures (Figure 3). It is shown that in case of helium the degradation is more localized and occurring in the centre and at the top (heat transfer deterioration from simulations occurs instead primarily in the lower part of the tubes). This can be seen as an indication that the flow pattern might have reversed in the experiments in a way that was not captured by the models.

Development of a numerical coupling between TRACE and GOTHIC

The coupled code has been based on TRACE version 5.0, patch 2 [5] and GOTHIC version 7.2b [6]. The coupling allows the two-phase mixture as well as non-condensable gases to flow from the domain of one code into the domain of the other at an arbitrary number of coupling points. Each code treats the coupling points essentially as boundary conditions that are continuously updated based on data provided by the other code. This principle minimizes the ingress that has to be made into the codes as the implementation is restricted to the boundary conditions without modifying the actual equation solvers of the codes.

During 2013, the coupling scheme and its implementation were verified in several steps, starting

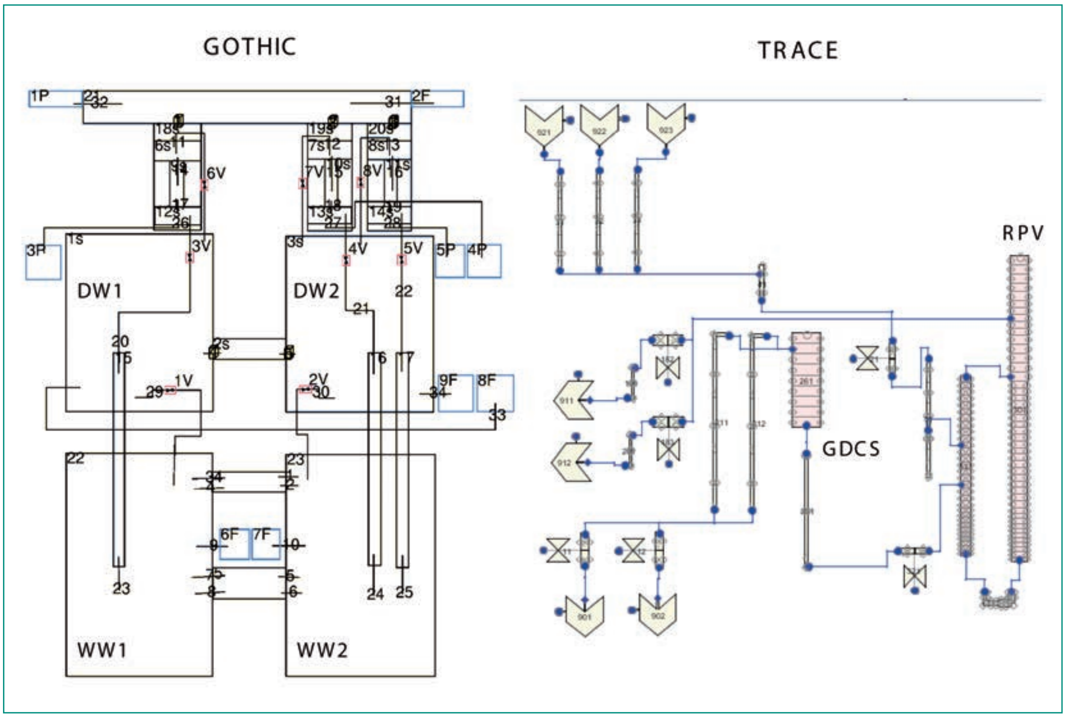


Figure 4: *TRACE-GOTHIC model of the PANDA facility and coupling points.*

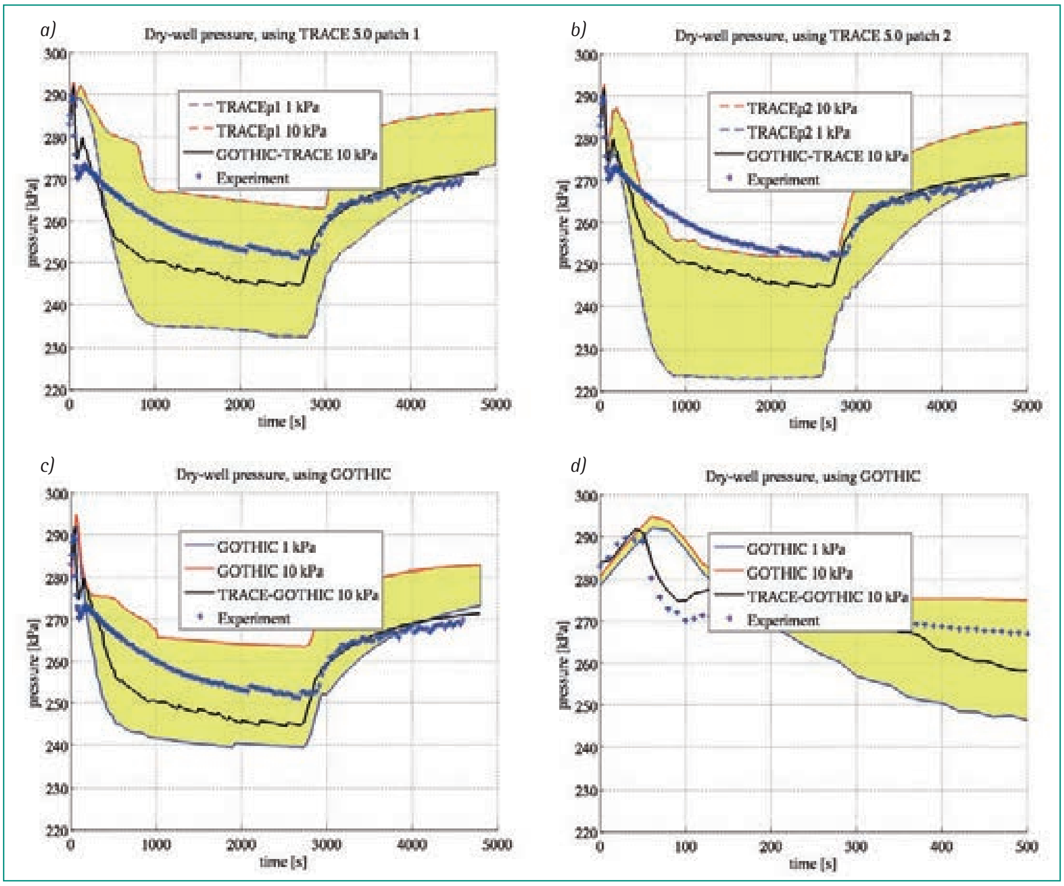


Figure 5:
ISP-42 Phase B DW pressure transient simulated with TRACE-GOTHIC code compared with TRACE 5.0 patch 1 (a), TRACE 5.0 patch 2 (b) and GOTHIC ver.7.2b (c). Plot (d) shows the early phase, just after GDCS injection.

from small GOTHIC models involving various lumped and subdivided volumes and connected by one or more junctions. Liquid, vapour and non-condensable gases were made to pass through these junctions by means of gravity, initial pressure differences or forced by connecting a flow boundary condition to one or more of the volumes. The results were satisfactory, as also by partially repeating the study published previously. The validation results were finally based on the simulation of the ISP-42, Phase B, integral test as described next.

Validation results for the TRACE-GOTHIC coupled code

The validation case has been simulated first with TRACE and GOTHIC used separately and then in a coupled mode. When using the coupled TRACE-GOTHIC code, the model of PANDA was partitioned so that each code was used where its models were deemed most appropriate, as depicted in Figure 4. The PCCS was modelled in GOTHIC according to the outcome of the aforementioned studies. In total seven coupling points between the TRACE and GOTHIC models were introduced, namely in the three PCCS drain lines, the two main steam lines and the GDCS pressure equalization lines.

The stand-alone analyses on the Phase B of the ISP-42 have shown that this particular experiment is highly sensitive to the initial concentration of air in the DW (DryWell), which was, unfortunately, not measured with sufficient accuracy in the experiment. The validation was hence conducted by varying this parameter within a reasonable range (from 1 kPa to 10 kPa air partial pressure), in order to assess the sensitivity.

The time evolution of the DW and wetwell pressure is the most significant parameter for safety considerations. The simulated and experimental DW pressures are shown in Figure 5. As a reference, the results of simulations using stand-alone versions of TRACE and GOTHIC are shown with 1 kPa and 10 kPa of initial air pressure. The band formed by the two simulations with different air pressure may be regarded as an uncertainty related to the incomplete knowledge of the initial air pressure. The stand-alone analyses, as well as the coupled calculation, have been used to corroborate a physical interpretation of the highlighted sensitivity. The amount of the pressure reduction in the DW is related to the time the PCCS stays active after the steam source has vanished and this time is determined by the rate of accumulation of air in the PCCS. With a small concentration of air in the

DW the PCCS takes longer time to shut down and hence the pressure reduction is larger. The pressure transient in the system is also influenced by the initial fast loss of pressure induced by the prompt condensation when the cold water from the GDCS enters the RPV and quenches the boiling. This effect was, specifically, better predicted using TRACE 5.0 patch 2 compared to earlier version patch 1 (compare Figure 5-(b) with Figure 5-(a)), thanks probably to some change in the heat transfer models. Therefore, the coupled code (using TRACE 5.0 patch 2 for the RPV) predicts the early phase of the transient better than the stand-alone GOTHIC code (Figure 5-(d)). The pressure behaviour affects also the predicted time of resumption of boiling (via the saturation temperature). All in all, the pressure is thus a fundamental parameter of this system as it is coupled to many different aspects of the transient but can, unfortunately, not be predicted with any great accuracy.

The main motivation to simulate the containment with GOTHIC rather than a simpler lumped parameter model is to better capture the distribution of various gases in the containment vessel. The present experiment is known to be very sensitive to the presence of air in the DW and, during this transient, air is released back in the DW following any VB (Vacuum Breaker) opening (when DW pressure decreases below wetwell pressure). An example of the 3D distribution of air as calculated by GOTHIC

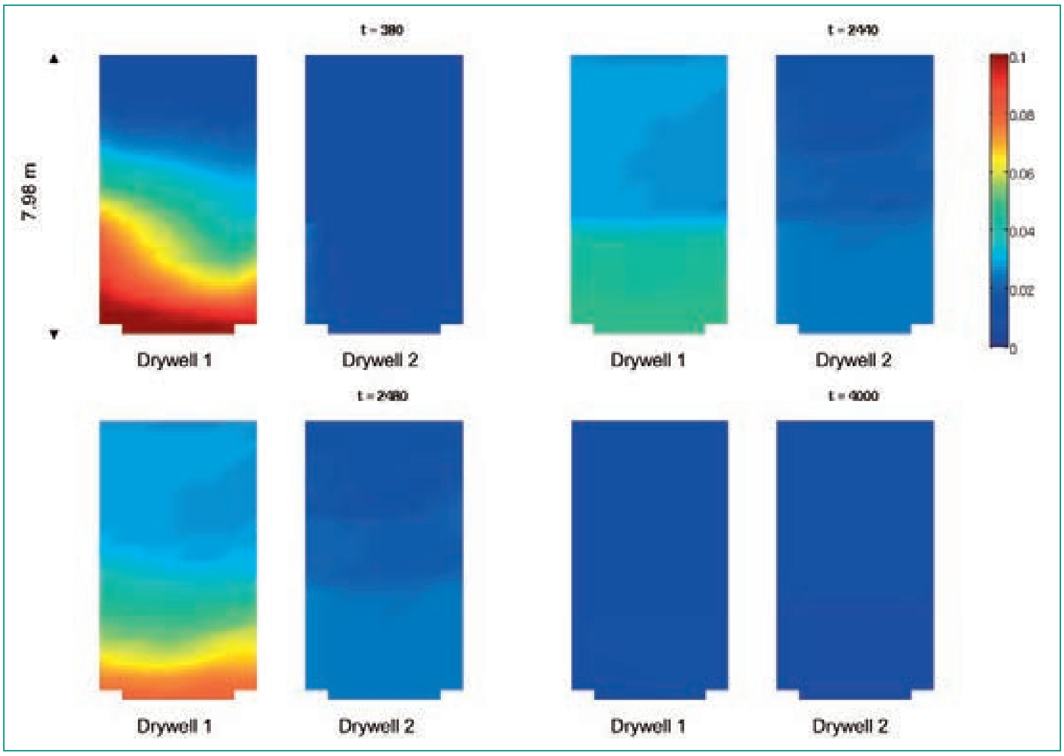


Figure 6: *Distribution of air (molar fraction) in the two drywells resulting from the opening of VB, as predicted by GOTHIC 3D model.*

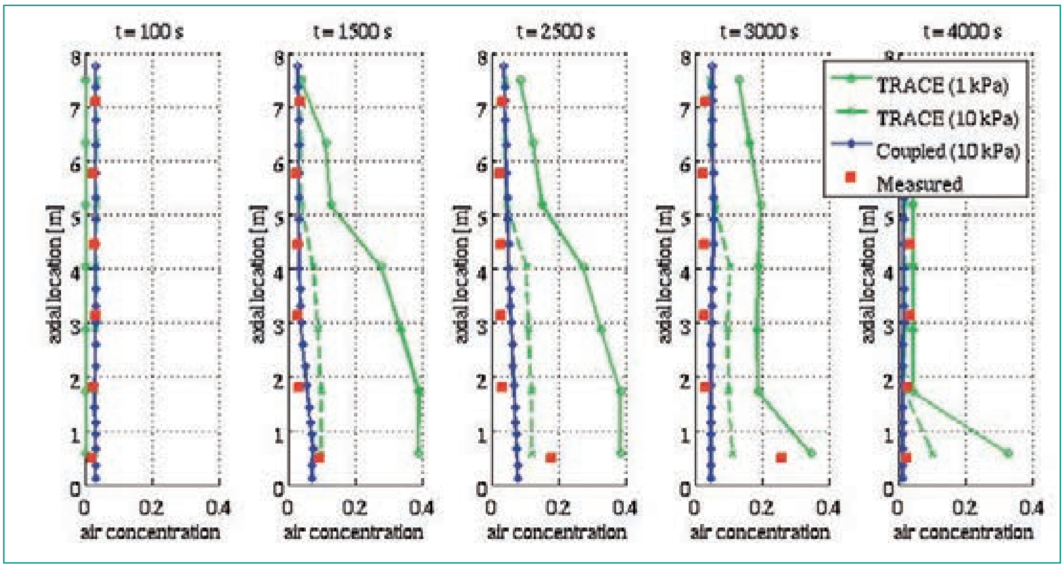


Figure 7: *Axial air profile in DW1 from TRACE and coupled code calculations compared with measurements.*

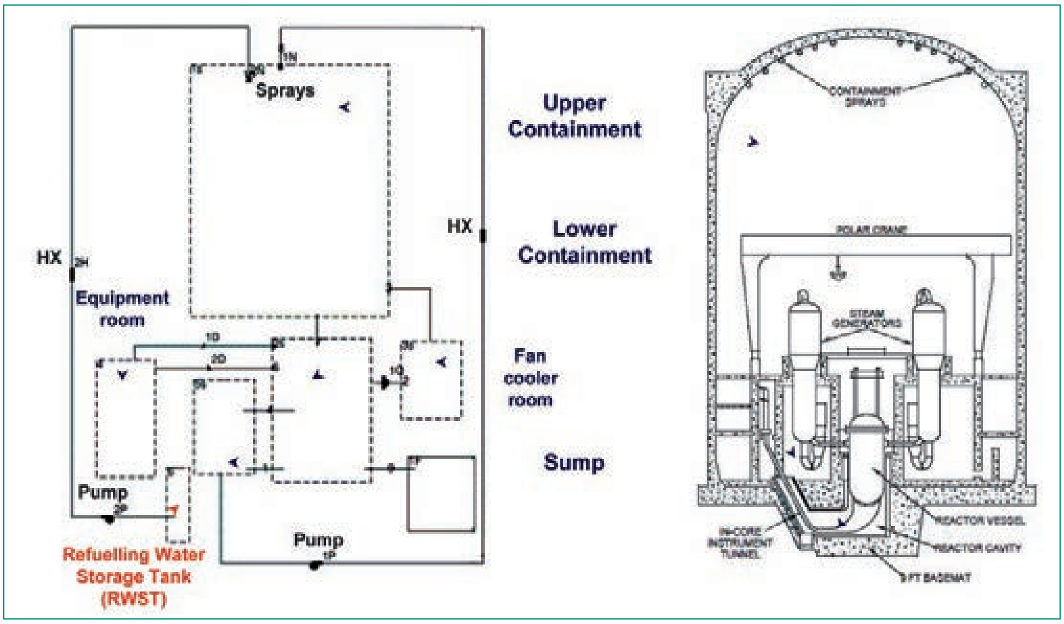


Figure 8:
GOTHIC demonstrative model for a large dry PWR containment.

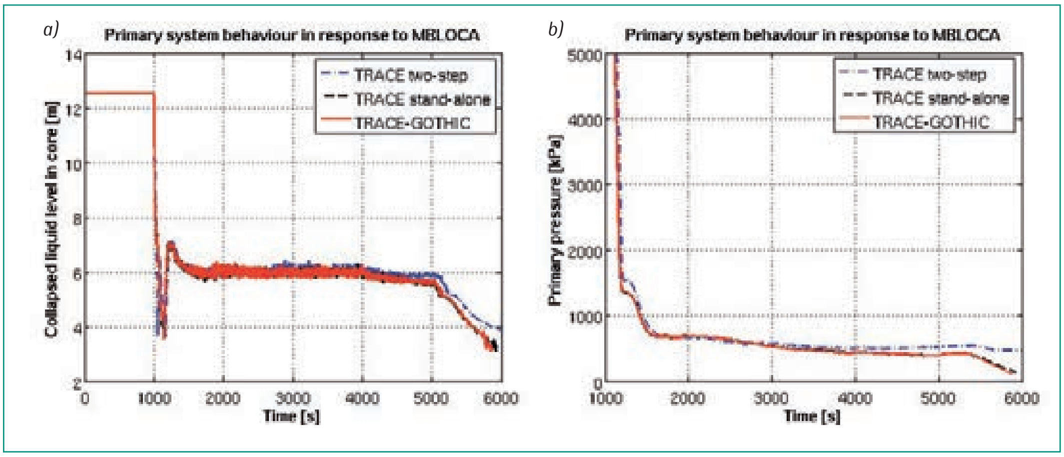


Figure 9:
Primary system response from TRACE stand-alone, two-step and coupled code calculations: level in RPV (a) and primary pressure (b).

is shown in Figure 6. The axial air concentration profiles in DW1, as calculated with TRACE and the coupled code, are compared with the experimental profile in Figure 7. It must be noted, however, that the predicted amount of air in the DW depends on the time the vacuum breaker stays open (strongly dependent on initial air concentration); hence, just qualitative observations could be made. After the VB opening the experiments indicate that most of the air entering from the wetwell (WW) stays close to the bottom of the DW. The coupled code (using GOTHIC for the DW), on the other hand, predicts a more uniform distribution, whereas the profile predicted by TRACE (1 kPa initial air pressure) shows some stratification. In the late stage, however, all air is expelled from the DW when the boiling in the RPV resumes. This is well predicted by GOTHIC while TRACE predicts that some air remains at the bottom in contradiction with experimental data.
The whole validation results are planned for journal publication in 2014.

Application of the coupled code to LOCA simulation in a nuclear power plant

The TRACE-GOTHIC coupled code was finally used to simulate a Loss Of Coolant Accident (LOCA) for an operating Gen-II reactor [7]. A PWR system was selected and to that aim, a demonstrative containment model was developed to represent the essentials of a large dry PWR containment (Figure 8). The containment model was adapted to match with the TRACE model of a reference PWR plant [8] (it turned out to be crucial to add a Refueling Water Storage Tank (RWST) as water source for the spray injection during the early blowdown phase).
The investigated sequence is a Medium Break LOCA (MBLOCA) with failure of the recirculation cooling. It is assumed that the operator fails to align the Safety Injection System (SIS) from the RWST to the containment sump (the same should apply for the spray system). Therefore, when the RWST is empty, the SIS stops, cooling of the core is not possible anymore and core damage takes place

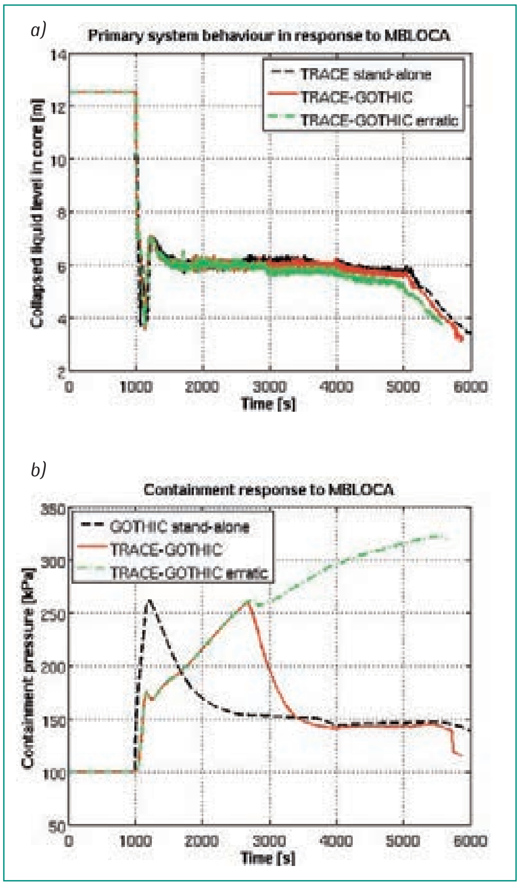


Figure 10: *Final assessment of coupled code calculations for a G-II system: primary system (a) and containment (b) response.*

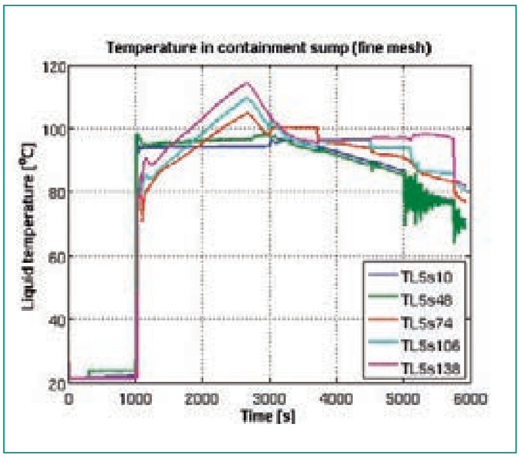


Figure 11: *Illustrative behaviour of temperature in containment sump.*

(the accident turns into a severe accident with fuel cladding temperature rising) [8].

The same case was repeated with TRACE stand-alone (constant atmospheric pressure as boundary condition), TRACE two-step analysis (containment pressure transient calculated with the GOTHIC model as boundary condition) and a TRACE-GOTHIC coupled instance. Coupled phenomena were investigated on the response of the primary system by comparing the coolant level in the core and the primary pressure transient (Figure 9). The difference between the several approaches was minimal and deemed negligible. The two-step case predicts a slightly higher level in RPV at the end of the transient as a result of a conservatively high back-pressure calculated with GOTHIC by disabling the active safety in the containment (sprayers and fan cooler).

On the whole, the coupled code proved to be sufficiently robust to simulate an entire LOCA in a Gen-II system (most challenging phase is the blowdown, due to high pressure difference among the two sides of the break). Nonetheless, some problems related to the coupled code were identified. The choked flow model in TRACE was often a disturbing issue in the simulations (independently of the coupling) – by unrealistically enlarging the loss of coolant (Figure 10-(a)) – as well as numerical disturbances were affecting the prediction of the blowdown peak occurrence (Figure 10-(b)).

The effectiveness of the coupled code should be tested on a longer-term scale, where the situation here depicted might change (it is needed a lower pressure on the primary side to make effective the influence of the containment pressure). One foreseen continuation of the work could be the implementation of the sump recirculation mode with the coupled code, to assess the influence of thermal stratification in the sump on the ECCS performance (Figure 11).

National Cooperation

The project has been carried out in a close collaboration between the Laboratory of Reactor Physics and Systems Behaviour (LRS), the Laboratory for Thermal-Hydraulics (LTH) and ENSI. The lessons learned from the project are expected to promote synergies with the Swiss federal polytechnic institutes ETHZ/EPFL, through the preparation and super-vision of MSc and PhD theses.

International Cooperation

The application of TRACE-GOTHIC to a Gen-II system has been performed by organizing the MSc thesis work (4 month internship) for a student coming from École Centrale Paris and enrolled in the European Master in Innovation in Nuclear Energy (EMINE) program.

Assessment 2013 and Perspectives for 2014

The main goals for 2013 and for the whole project were achieved as follows. First, the benchmark of GOTHIC and TRACE on the simulation of different PANDA experiments has led to a good understanding of the capabilities and limitations of the two codes and thus hinted at the potential complementarities in a coupled configuration. Then, TRACE and GOTHIC have been successfully coupled (fully explicit coupling scheme with synchronized adaptive time steps) and the coupled code has been validated against the ISP-42, Phase B experiment. The simulation with coupled TRACE-GOTHIC permitted to corroborate a physical interpretation drawn on the high sensitivity of the selected transient to initial conditions, as well as it was useful to better simulate the early stage. The 3-D capabilities of GOTHIC can be exploited to better capture the distribution of various gases in the containment. The coupled code facilitates an integrated analysis of the primary reactor system and the containment and, finally, was exploited to build a single evaluation model for LOCA simulation in a Gen-II nuclear power plant. With reference to the selected accident, the coupled code has performed as the system and containment codes applied separately and sequentially (one iteration). Recommendations for future work are as follows.

- Extension of the capabilities of the coupling, by implementing a thermal coupling (via heat structures) and a better treatment of the droplet field in the GOTHIC coupled instance.
- Extension of the LOCA simulation to a longer term, by implementing a recirculation line between containment sump and the ECCS and simulation of respective coupled phenomena.

As the project is now being completed, the above studies are not planned to be conducted but could be part of further research related to advanced coupled plant/containment methodologies and analyses. Therefore, the main objectives for 2014 are to complete the remaining scientific publications and the project report.

Publications

D. Papini, C. Adamsson, M. Andreani, and H.-M. Prasser. Assessment of GOTHIC and TRACE codes against selected PANDA experiments on a passive containment condenser, Submitted to Nuclear Engineering and Design.

C. Adamsson, D. Papini, O. Zerkak, and H-M. Prasser. Simulation of International Standard Problem ISP-42 Phase B using In-House Coupled Code GOTHIC-TRACE, in Proceedings of the 15th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-15), Pisa, Italy, May 12–17, 2013.

D. Papini, C. Adamsson, M. Andreani, and H-M. Prasser. Simulation of International Standard Problem ISP-42 Phase B using the Containment Code GOTHIC, in: Proceedings of the 15th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-15), Pisa, Italy, May 12–17, 2013.

C. Adamsson, D. Papini, O. Zerkak, and H.-M. Prasser. Simulation of ISP-42 experiment with TRACE-GOTHIC coupled code, To be submitted to Nuclear Engineering and Design.

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