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 of the novel methodology under development is in fact to provide more accurate predictions of a nuclear power plant by coupling 1D simulations of the primary system components (handled by TRACE) with typical 3D phenomena occurring in containment compartments (better captured by the dedicated code GOTHIC).

During 2011, the recruitment of the scientific staff was successfully completed and the project activities could on that basis be launched. In that context, reviews of passive safety systems and code coupling techniques were carried out and models for TRACE and GOTHIC of various parts of the PANDA test facility were completed. This large-scale facility, built and operated at PSI, was selected for the analysis in view of the availability of integral test experiments challenging the interaction of containment phenomena with primary system behaviour. In this respect, the numerical coupling between the two mentioned thermal-hydraulic codes is foreseen and related verification and validation activities are being prepared. The coupled code will be validated with experimental data from relevant integral tests, e.g. the PANDA ISP-42 experiments.

Aimed also at training the scientific staff in the utilization of the two different thermal-hydraulic codes, a systematic study of a particularly critical component of the PANDA facility, i.e. the Passive Containment Condenser (PCC), was carried out with stand-alone calculational models. The PCC – consisting of a vertical tube heat exchanger submerged in a water pool located on top of the facility – plays a fundamental role in cooling the containment and mitigating its pressure increase in response to a generic incidental sequence leading to steam release into the containment. The main scientifically relevant results obtained by applying separately the TRACE and GOTHIC codes to predict the performance of the same safety system are presented in this report.

Project goals

The PASSPORT project was recently launched as a joint research activity between ENSI and the Paul Scherrer Institut (PSI) and involves a collaboration between the STARS project at the Laboratory for Reactor Physics and System Behaviour (LRS) and the Laboratory for Thermal-Hydraulics (LTH). The PASSPORT activities aim 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 and feedback effects between primary side and containment. As this might be relevant not only for safety analyses of current operating G-II reactor types but also in order to bring forward state-of-the-art in this area for the analysis of GIII/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, one first main 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 test-effects experiments with special emphasis on tests where interactions between primary side/containment systems are mainly driven by physical phenomena. These types of tests would indeed be the most challenging ones for the methodology and therefore, simulating these accurately would provide stronger confidence in the acquired capabilities and range of applicability.

For 2011, the specific objectives of the project were as follows:

- Review of safety systems in LWR reactors with identification of dominant phenomena between plant primary system and containment system;
- Literature survey on the development of strategies for coupling 1D/3D with special emphasis on coupling the reactor systems with the containment behaviour in NPP including those employing passive safety systems;
- Review and identification of available experimental database (e.g. PANDA) of relevance for the validation of the coupling methodology to be developed;
- Development of 1D system model (TRACE) as well as 3D containment model (GOTHIC) for selected experimental test(s).

This report presents the status and progress achieved during 2011 in relation to the above objectives and outlines the perspectives for 2012.

Survey of systems and designs with primary side/containment coupling

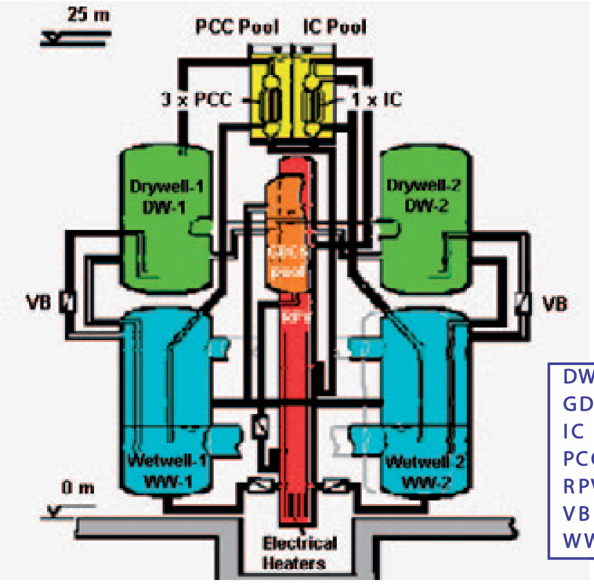
A literature review was carried out and published as technical report [1] in order to identify the systems and phenomena that must be addressed by the new methodology. Even though strong interaction between the primary system and the containment may occur whether or not passive safety systems are involved, the passive systems are, as a consequence of their design, more likely to be significantly affected by such phenomena. The literature study was hence focused on passive safety systems. Furthermore, the review was restricted to three specific GIII+ reactor concepts (the AP1000, ESBWR and KERENA) which rely completely or to a very large extent on passive safety systems. The study thus covers a wide range of passive systems. The conclusions should, in general, be applicable also to reactors of GIII or GII, which may only partially rely on passive systems.

Review of code coupling techniques

As a preparation for the planned coupling of the TRACE and GOTHIC codes the literature was reviewed in order to identify and evaluate various coupling techniques. The results of this study have been documented in a technical report [2]. It was concluded that the preferable method to couple these codes is to exchange information at the end of each timestep avoiding modification of the numerical solution algorithms of each code. Either explicit or implicit time-stepping may be considered, where the latter option would have to be based on fixed point iterations involving both codes at each timestep whereas the first option may require very small timesteps to maintain numerical stability.

PANDA ISP-42 experiment as first situation target

The International Standard Problem (ISP) 42 is a series of tests performed at the PSI PANDA facility shown in Figure 1 and that were originally de-



DW	DryWell
GDCS	Gravity Driven Cooling System
IC	Isolation Condenser
PCC	Passive Containment Condenser
RPV	Reactor Pressure Vessel
VB	Vacuum Breaker
WW	WetWell

Figure 1:
Schematic representation of the PANDA test facility as used in the ISP-42 experiment.

signed to simulate the passive safety systems and containment of General Electric's SBWR reactor concept.

A large number of lumped parameter codes have been benchmarked against these tests in an international effort including both a blind [3] and an open [4] benchmark. The TRACE code, however, did not take part in the original benchmark as the code was in a too early stage of development at the time. At least one limited study of the ISP-42 experiment with TRACE has been performed later [5] but it is apparent that these experiments have not been fully utilized as a validation case for the TRACE code.

Trace model for PANDA ISP-42 and scoping validation tests

As the PANDA ISP-42 program was identified as a suitable first situation target for benchmarking the TRACE and GOTHIC codes, first on a standalone basis and then in a couple mode and because of the reasons mentioned above, a TRACE model was during the year developed for the PANDA facility.

The developed TRACE model has so far been applied to Phases A (drywell pressurization) and B (core flooding) of the ISP-42 experiment but can relatively easily be extended to cover the remaining phases as well. The results have been found to be in reasonable agreement with experimental data and fully comparable with the performance of other system codes as well as the earlier independent TRACE simulation of the same experiment. As illustration, Figure 2 compares experimental and simulated pressure of steam and noncondensable gas in the drywell during Phase A of the ISP-42 experiment, showing hence an excellent agreement.

Trace and gothic modelling of PCC heat exchanger

A particularly complex component in the PANDA facility is the Passive Containment Cooling System

Figure 2:
Experimental and TRACE simulated pressure in PANDA drywell for ISP-42, Phase A.

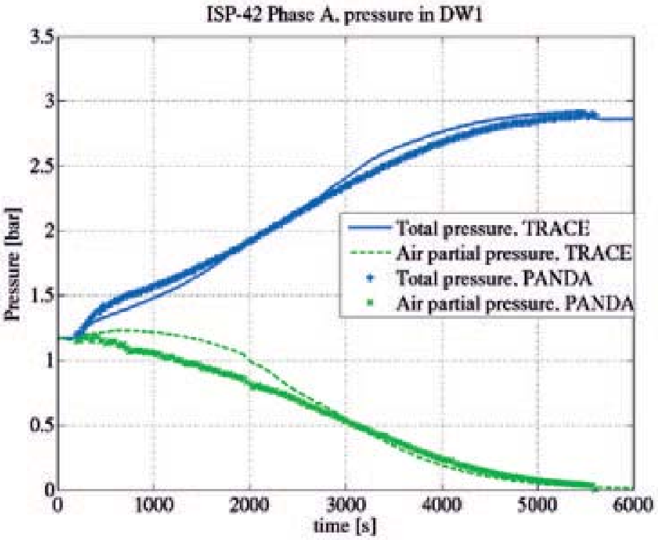
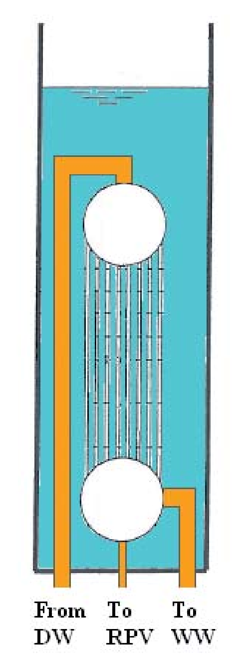


Figure 3:
Approximate design of PCC heat exchanger with feed, drain and vent pipes. Drawing is not to scale.

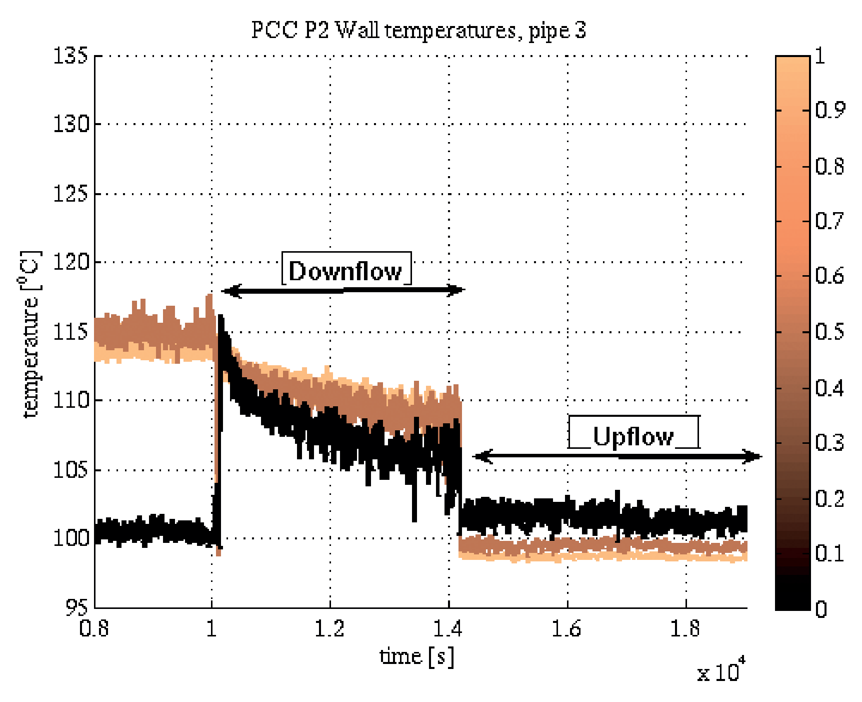


(PCCS). As shown in Figure 3, it consists of a heat exchanger with a large number of vertical pipes submerged in a pool of water located on the top of the mock-up.

Accurately simulating the PCC is necessary in order to correctly predict the pressure and temperature in the containment volume. Moreover, the PCC is designed to operate in a wide range of conditions including the presence of non-condensable gases of various concentrations. It has been observed experimentally in the PANDA facility that complex flow patterns seem to establish in the PCC heat exchanger when a light non-condensable gas (helium) is present on the primary side [6]. As these flow patterns had not been predicted by available models of the PCC, it was decided to investigate whether a more detailed model of the heat exchanger would be able to reproduce them. Therefore, a fine nodalization, taking into account the slight variation in length among heat exchanger pipes, was developed for the TRACE code. The model did, indeed, qualitatively reproduce the observed flow patterns but also suggested that unsteady flow patterns may develop when a heavy non-condensable gas (air) is trapped in the PCC. Thorough inspection of the experimental data shows indications of flow instabilities even though they do not correspond exactly to the simulated flow patterns, as exemplified in Figure 4 and Figure 5.

Concerning GOTHIC, based on the open literature [7] and up to the experience collected at PSI [8], the crudest approximation identified in relation to previous GOTHIC models of the PANDA large-scale facility is the representation of the condensation

Figure 4:
Experimental wall temperature at four axial locations in one PCC pipe from T1.2 experiment. Data show that temperature gradient spontaneously reverses, indicating that flow direction has reversed as well.



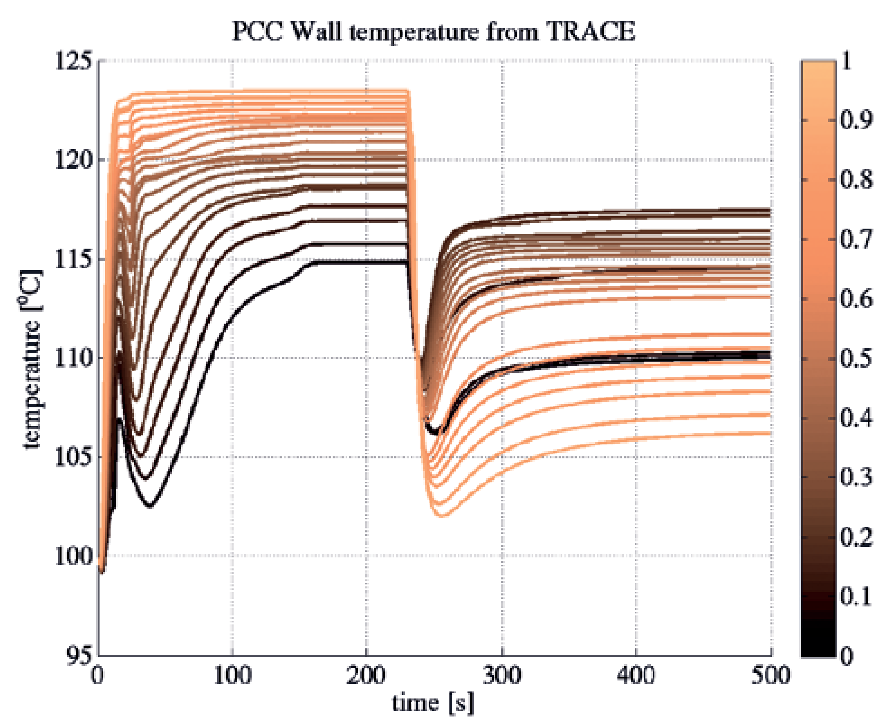


Figure 5: *TRACE simulated temperature gradient in one PCC pipe. The flow spontaneously reverses in a way that resembles the experimental observations.*

process in the PCC tubes and of its coupling with the pool serving as final heat sink.

Therefore, in order to challenge a stand-alone application of GOTHIC to this critical component of PANDA, and highlight related benefits as well as drawbacks, a detailed model of PCC HX (Heat eXchanger) and pool was set up. The developed nodalization shown in Figure 6 consists of volumes representing the horizontal upper drum, a generic vertical pipe and the horizontal lower drum, with reasonable axial discretization. Primary side volumes are thermally connected to the pool volumes, where a medium-fine level of details is applied.

As part of the review conducted so far with regards to available experimental data, it was found that a specific separate effect test in the PANDA facility (other than the integral large-scale ISP-42 experiment) was indeed conducted with the specific and dedicated objective to conceptually characterize the PCC HX component. This test, referred as IPSS (Innovative Passive Safety Systems) Test B-series, was therefore selected here to validate the above PCC HX model. As illustrated in Figure 7, GOTHIC capabilities permit to reproduce the natural circulation flow pattern promoting water evaporation at the surface, as well as the water temperature distribution in the pool. The pool heats up due to

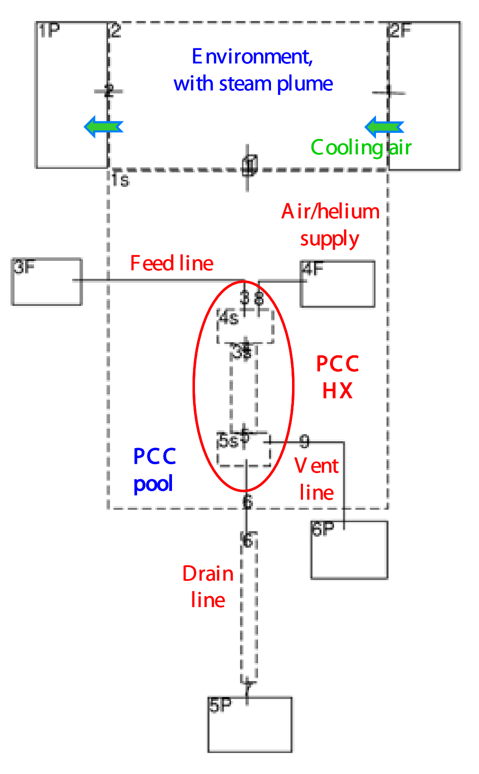
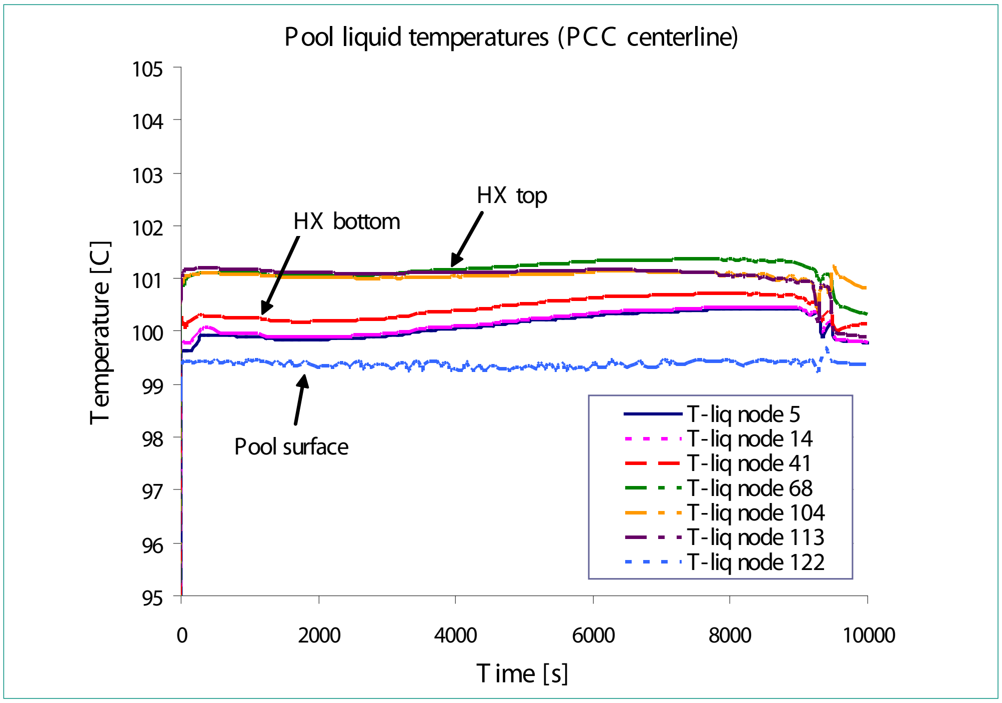


Figure 6: *PCCS nodalization developed with the GOTHIC code. PCC HX tubes are discretized axially in 8 nodes (1D model), whereas PCC pool comprises 126 nodes (3D model, 3 x 3 x 14). Connections with other PANDA components are simulated as well.*

Figure 7:

Pool liquid temperature behaviour at steady-state conditions. Simulation of IPSS project Test B1 (pure steam at 3 bar).

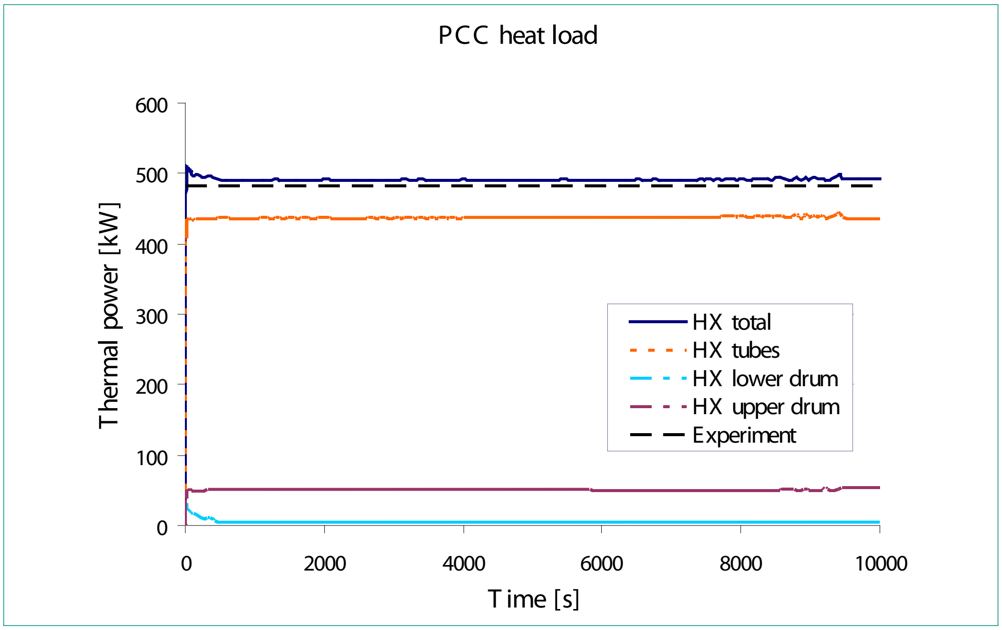


HX thermal power, with higher temperature close to top of HX and an equilibrium value fixed by the saturation temperature at the surface.

The simulation of also the primary side of PCC with GOTHIC code allows calculating in-pipe condensation phenomena typically grasped by 1D system codes (e.g., TRACE). Benchmarks between codes are possible, and are currently underway on the basis of single-component test experimental data available from PANDA [9]. Full spectrum of condensation phenomena involving pure steam (at several pressure levels: 3 bar, 6 bar and 9 bar) and steam/gas mixture (with non-condensable gases both heavier – air – and lighter – helium – than steam) have been analysed. According to the recommended built-in condensation model of GOTHIC, a good matching with experimental exchanged power has been obtained, as shown in Figure 8.

Figure 8:

PCC thermal power at steady-state conditions (IPSS Test B1, pure steam at 3 bar). Contribution of lower drum is negligible.



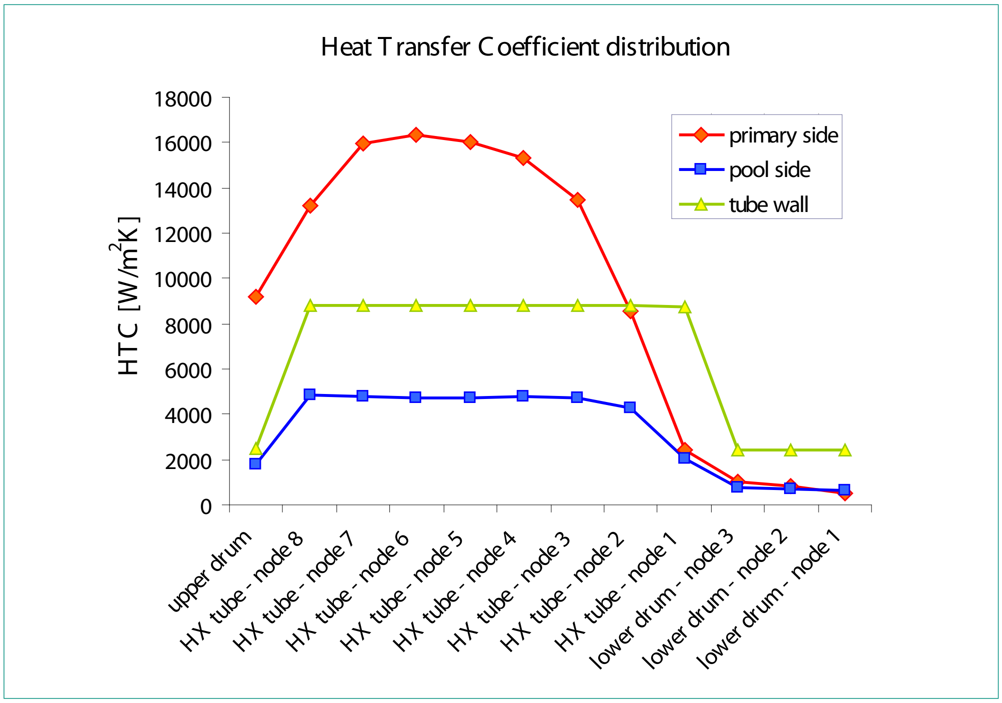


Figure 7:
PCC heat transfer coefficient distribution. The condensation process terminates before the end of the tubes.

A slight overprediction of the condensation heat transfer can be pointed out, as the heat transfer vanishes a bit before the bottom of the tubes once all the steam in-flow is condensed. This is illustrated in Figure 9 that shows the axial distribution of the condensation heat transfer coefficient, pool boiling heat transfer coefficient and the thermal conductance of HX walls.

National Cooperation

The project is carried out in a close collaboration between the Laboratory of Reactor Physics and Systems Behaviour (LRS), the Laboratory for Thermal-Hydraulics (LTH) and ENSI. Synergies with the Swiss federal polytechnic institutes ETHZ/EPFL are expected with the preparation and supervision of relevant MSc and PhD theses.

International Cooperation

At the international level, a strong collaboration on the topic of passive safety exists between PSI and AREVA. This vendor is currently carrying out an experimental program on a large-scale facility (INKA) representing primary and containment side of KERENA, a G-III+ reactor employing passive safety systems.

Assessment 2011 and Perspectives for 2012

The planned literature reviews of system interactions and code coupling strategies have been carried out and published during 2011. Also, a survey of available experimental database, both at PSI and externally, has been started and although this has not been completed yet, it has allowed to identify and select the PANDA ISP-42 experiment as first situation target. For this case, the development of models for the TRACE and GOTHIC codes was initiated and preliminary verification and validation cases were analysed with both codes on a stand-alone basis.

For 2012, the following work is planned:

- A comprehensive review of available experimental facilities and datasets that may be of interest for the project, including experiments carried out at PSI as well as externally, will be completed with as main objective to identify additional situation targets for validation of the coupled code system.
- Models for GOTHIC and TRACE of the PANDA facility will be finalized and validated with data from the ISP-42 experiments.
- The development of a coupling scheme between TRACE and GOTHIC will be started.
- A verification of the numerical coupling will be conducted for selected simplified test cases.

The events in Fukushima and the subsequent suspension of the new-builds in Switzerland have led, upon ENSI's request, to a change in the fields of application for the PASSPORT project such as to focus more on processes inside the containment of existing reactors instead of Gen III/III+ reactors as was previously planned. This decision has however no bearing on the development and validation of the methodology for the code coupling between TRACE and GOTHIC. Therefore, at the time of writing, detailed specifications for future fields of application remain under preparation.

Publications

[1] *C. Adamsson,* Project PASSPORT – A literature survey of passive safety systems, PSI report TM-41-11-20, 2011.

[2] *C. Adamsson,* Project PASSPORT – Coupling system codes and field codes, a literature study, PSI report TM-41-11-21, 2011.

References

[3] *D. Lübbesmeyer and S.N. Aksan,* ISP42 (PANDA Tests) Blind Phase Comparison Report, NEA/CSNI/R(2003)6, May 2003.

[4] *D. Lübbesmeyer and S.N. Aksan,* ISP42 (PANDA Tests) Open Phase Comparison Report, NEA/CSNI/R(2003)7, May 2003.

[5] *M. Zavisca and S. Bajorek,* Assessment of the TRACE Reactor Analysis Code against Selected Panda Transient Data, in Proceedings of the 14th International Conference on Nuclear Engineering (ICONE 14), Miami, FL, USA, July 17–20, 2006.

[6] *D. Paladino, O. Auban, M. Huggenberger, and J. Dreier,* A PANDA integral test on the effect of light gas on a Passive Containment Cooling System (PCCS), Nuclear Engineering and Design, vol. 241, no. 11, pp. 4551–4561, November 2011.

[7] *V. Benčik,* Analysis of OECD/CSNI ISP-42 Phase A PANDA Experiment using RE-LAP5/mod3.3 and GOTHIC 7.2a Code, in Proceedings of the International Conference Nuclear Energy for New Europe 2009, Bled, Slovenia, September 14-17, 2009.

[8] *M. Andreani,* Pretest calculations of Phase A of ISP-42 (PANDA) using the GOTHIC con-tainment code and comparison with the experimental results, Nuclear Technology, vol. 148, pp. 35–47, October 2004.

[9] *M. Huggenberger, C. Aubert, J. Dreier, O. Fischer, S. Lomperski, and H.J. Strassberger,* IPSS Project, PANDA Isolation Condenser Steady-State Tests, Test Report, PSI report TM-42-97-04, December 1999.