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OVERVIEW ON THE PANDA TEST FACILITY AND ISP-42 PANDA TESTS
DATA BASE

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KEY WORDS

Thermal-hydraulics, passive decay heat systems, passive containment cooling, containment
testing for advanced reactor designs.

LECTURE OBJECTIVES

As an example of test facilities in which passive decay heat removal systems are tested, PANDA
test facility and ISP-42- PANDA tests will provide an overview on experimental validation and data
base. A short overview on the test programs performed in this facility is also given.

1. INTRODUCTION

PANDA is a large-scale facility, which has been constructed at the Paul Scherrer Institute (PSI)
for the investigation of both overall dynamic response and the key phenomena of passive containment
systems during the long-term heat removal phase for Advanced Light Water Reactors (ALWRs).
Using a modular concept with a basic set of cylindrical vessels (typical diameter 4m), which are
interconnected by piping, the facility can be adapted to simulate different passive containment designs
(Fig.1).

Since early 1990’s, there has been number of projects related to the use of PANDA test facility for
various evolutionary reactor designs, e.g., SBWR, ESBWR, SWR-1000, etc. Different PCCS concepts
were experimentally investigated in the PANDA test facility with some minor modifications in the
facility for each program. This is being a confirmation of its flexibility, due to the modular
construction, in use of various applications. The earlier investigations in the PANDA test facility, in
addition to the current and future investigations, will be briefly provided in coming sections.

In PANDA test facility some tests were also performed for use as the basis of International
Standard Problem number 42 (ISP-42). The OECD/NEA Committee on the Safety of Nuclear
Installations (CSNI) approved, at its meeting on December 3-5, 1997, an International Standard
Problem (ISP) involving a test in the PANDA facility, based on a recommendation from the Principal
Working Group 2 (PWG2) on System Behaviour. The main interest for this ISP is code validation in relation to a range of LWR and advanced LWR (ALWR) (mainly) containment issues that have been designated as important and involving thermalhydraulic phenomena. The ISP-42 test was subdivided in six well-defined sequential phases, restricting the phenomena, which are taking place in each test phase, to a reasonable number and separating them as much as possible. This gives the ISP-42 participants the choice to calculate one, several, or all of the six test phases, depending on the type of transient and the phenomena that they are interested in. For each test phase, the initial and boundary conditions are defined separately so that if there are code model deficiencies in the preceding test phase the calculations for the next phase can be started and performed independently. Overview on the ISP-42 PANDA test with a sample result obtained from Phase-A and summary of the major conclusions from the ISP-42 exercise are also presented in this paper.

2. SUMMARY OF PANDA FACILITY DESCRIPTION

PANDA is a large-scale facility, which has been constructed at the Paul Scherrer Institute (PSI) for the investigation of both overall dynamic response and the key phenomena of passive containment systems during the long term heat removal phase for Advanced Light Water Reactors (ALWRs). The facility has been configured to simulate the containment of a passive BWR, but the phenomena, which are taking place, are of a more generic character and of interest to LWR containment’s in general. Using a modular concept with a basic set of cylindrical vessels (typical diameter 4m) which are interconnected by piping, the facility can be adapted to simulate different passive containment designs. The facility configuration used for ISP-42 tests is a scaled down model of European Simplified BWR containment and safety systems. After a detailed scaling analysis, power and volumes are scaled 1:40, and pressure, relevant heights and pressure drops are 1:1.

As can be seen from the 3-dimensional drawing of figure 1 and it is illustrated in the schematic sketch of figure 2, the PANDA facility mainly consists of six large pressure vessels, simulating the various containment volumes. One of these vessels represents the Reactor Pressure Vessel (RPV), which acts as the steam source during a transient. RPV contains at its bottom a core simulator consisting of 115 electrically heated heater elements, which are located in a shroud acting as a riser/down-comer configuration and thus enabling natural circulation in the lower two thirds of the RPV. Electrical heater rods simulate the history of core decay heat generation with programmable power generation, maximum being 1.5 MW. The RPV is connected to the PANDA facility via the two Main Steam Lines (steam supply to the system), the PCC drain line (liquid return of the condensed steam in the PCCs) and the GDCS drain line. At the top of the RPV, an additional flange may be used for helium injection.

Two other large cylindrical vessels of an inner height 8.0 m and an inner volume of 89.9 m$^3$ each, represent the Drywell (DW), connected each other with a large diameter dry-well connection pipe (outer diameter of 1.0 m). The dry-well as a whole is connected to the rest of the system via the two Main Steam Lines (steam supply to the system and input from RPV), the PCC feed lines (output of dry-well), the Main Vent Lines (output of dry-well) and the Vacuum Breaker Lines (input to dry-well, in case the wet-well pressure exceeds the dry-well pressure). At the top of the dry-well-1, air may be injected to simulate a sudden release of trapped air into the system. The two DW vessels are filled with gas. Except under start-up conditions, this is more or less pure steam (air fraction is quite small).

The other two large cylindrical vessels, of inner volume of 115.9 m$^3$ each and an inner height of 10.11 m, filled with water at a level of approximately 4m, represent the Wetwell (WW, also called suppression chamber). The two WW vessels are connected each other by two large diameter pipes of 4m length each, one in the liquid section of the wetwell (1.5 m diameter), and the other one in the gas space of the wetwell (1.0 m diameter). The wetwell as a whole is connected to the PANDA facility via the two Main Vent Lines (input), the three PCC vent lines (input), the two pressure equalization
lines and the Vacuum Breaker Lines (output, in case the wetwell pressure exceeds the dry-well pressure significantly).

The last vessel primarily represents a Gravity Driven Cooling System (GDCS) pool with a volume of $17.6 \, \text{m}^3$ and inner height of $6.06 \, \text{m}$, and it can function as additional containment volume for wetwell gas space. The GDCS tank is connected to the rest of the facility via the GDCS drain line to RPV (output) and the pressure equalization line to the wetwell vessels. GDCS drain line connects the inside bottom of the GDCS tank with the lower part of the downcomer of the RPV. A check valve allows only one directional flow from the tank to the RPV. To establish similar pressure in the gas spaces of GDCS tank and wetwell, the pressure equalization line connects GDCS tank with the gas space of the two wetwells.

In addition, four rectangular pools open to the atmosphere are located on top of the facility. These pools may be equipped with immersed heat exchangers and used as heat sinks outside the containment, or as cooling storage pools in other configuration. As mentioned earlier, the modular facility arrangement provides the flexibility needed to investigate a variety of containment design. For the ISP-42 tests, these pools contain three Passive Containment Coolers (PCCs) connected to dry-well. Each of the three PCCs consists of a PCC unit, which is submerged in a separate water pool, where the bottom of the pool is located $19.8 \, \text{m}$ above the ground floor. The PCC unit is a heat exchanger and is made of an upper drum, a tube bundle (20 tubes, diameter of $0.0508 \, \text{m}$ and length of between $1.778 \, \text{m}$ and $2.066 \, \text{m}$), and a lower collector drum. Each PCC unit is submerged into the secondary side water inside the PCC pool tank and is connected to the drywell and the rest of the system via the PCC feed line (input) at the top of the upper drum, whereas the PCC lower drum has two connections, one of them is the PCC vent line (non-condensable output) on the right side of the lower drum and the other one is the PCC drain line (output) at the bottom of the lower drum. Steam/air mixture enters from the top of the PCC unit, and then the steam part is condensed in the tube bundle and drained out of the PCCs via the drain line to the RPV, whereas non-condensable may be vented via the vent line to the wetwell. The two PCC units are connected to one of the drywell, the third unit is connected to the other drywell. The fact that the three PCC units are connected to two drywell vessels allows asymmetric behaviour and creates flows between these vessels. Such an asymmetric flow also occurs with equal flow resistance from the RPV to two of the drywell vessels when all three PCCs are in operation.

The different vessels and the primary side of the PCCs are connected to each other by means of different pipes. The major system lines are: Main Steam Lines (MSLs), which connect the upper part of the RPV with dry-well-1 and dry-well-2, respectively; Main Vent Lines (MVLs) connect the lower part of the dry-well with the wetwell pool, approximately $1.8 \, \text{m}$ below the surface of the pool. Each MVL enters its respective wetwell vessel nearly at the top and is then led inside the vessel to the pool. The exit of the MVL pipe is submerged in the pool water.

In general, BWR containment concepts rely on Vacuum Breaker (VB) installed between the drywell and wetwell. Their function is not to allow the wetwell pressure to exceed drywell pressure by a certain margin. There are two vacuum breakers connecting the upper part of the two wetwells to the lower part of the two dry-wells by VB lines (VBLs) in the PANDA facility. The operation of the actual vacuum breaker is simulated in PANDA by control valves. These are opened and closed by the facility control system when the measured differential pressure between the wetwell and the dry-well exceeds an upper and a lower limit, respectively. Therefore, under normal conditions, the lines are closed by the VB valves. Additional auxiliary lines are available to establish the desired stationary conditions at the beginning of each of the sequences of the experiment. These lines are not shown in figures 1 and 2.

The system line pressure losses were carefully scaled using orifices and the theoretical line resistances were measured and verified by system characterization tests. In addition all vessels and system lines were carefully insulated using rock-wool and the heat losses were determined and
provided, separately. The facility is instrumented with over 500 sensors and axial distributions of temperatures and non-condensable concentrations in the vessels can be obtained from thermocouple, pressure and (a limited number) of oxygen (air) probe measurements. Further detailed description of the PANDA test facility for ISP-42 test series can be found in reference [1], and the boundary and initial conditions with the list of measurement locations for each phases of the ISP-42 are provided in reference [2].

3. EARLIER INVESTIGATIONS IN PANDA TEST FACILITY

In early 1990’s, the Simplified Boiling Water Reactor (SBWR) design was used as reference design for the PANDA test facility (Figure 3), and the main goal of the project were the experimental and analytical investigation of the start-up and long-term operation of the passive containment cooling system of the SBWR and related aspects [3] and [4]. In a first test series, the steady-state characteristics of the PCCS condenser units were investigated. In addition, ten integral system tests were performed addressing specific topics of concept demonstration, asymmetric steam injection, reduced condenser capacity, isolation condenser and PCC system interaction, and vacuum breaker leakage.

European SBWR (ESBWR) was also simulated in PANDA test facility using different scaling as in SBWR simulation and some component modifications were done (Figure 2). Series of transient system tests were carried out in the PANDA facility to investigate the performance of the passive containment cooling system of the ESBWR [5]. Eight system tests in PANDA with challenging conditions were performed to explore the real PCCS limitations, e.g., low water level in PCC pool, deferred release of “trapped air” in drywell. During one of the tests, helium was injected (as simulation of hydrogen) to simulate beyond design basis accident conditions.

Further, different PCCS concepts were experimentally investigated in the existing PANDA test facility (Figure 4). In this specific case SWR-1000 Building condenser was simulated and tested by using different scaling and also some specific limited modifications in the facility (confirming the flexibility of the modular construction of the PANDA test facility) [6].

On the basis of the ESBWR configuration for the PANDA test facility, ISP-42 tests were performed. Further details on ISP-42 exercise are provided in the next sections.

4. ISP-42 PANDA TEST OUTLINE AND OVERVIEW

Following a proposal, the OECD/NEA Committee on the Safety of Nuclear Installations approved, at its meeting on December 3-5, 1997, a new International Standard Problem (ISP) involving a test in the PANDA facility, based on a recommendation from the Principal Working Group 2 (PWG2) on System Behaviour. The main interest for this ISP is code validation in relation to a range of LWR and advanced LWR (ALWR) (mainly) containment issues that have been designated as important and involving thermohydraulic phenomena. This ISP on PANDA test is also financially supported by the research foundation of the Swiss Utilities (Project- und Studienfonds der Elektrizitätswirtschaft, PSEL).

A preparatory meeting in March 1998 was called to discuss the scenario of the proposed ISP with some representatives from the OECD member countries. The ISP-test scenario has been defined taking into account the recommendations received from the representatives who attended this meeting and also comments received from other organizations. The ISP-PANDA test was performed on 21/22 April 1998, taking about 14 hours. Since the first phase of ISP-42 was going to be conducted as a “double-blind” or “blind” exercise, the experimental data was locked. In the second phase, the “open”
exercise has been conducted by providing the ISP-42 PANDA test data to the participants and by performing post-test analysis.

ISP-42 PANDA test scenario was established to cover many typical LWR and ALWR containment and primary system phenomena. The test was subdivided in six well-defined sequential phases, restricting the phenomena, which are taking place in each test phase, to a reasonable number and separating them as much as possible. This gives the ISP-42 participants the choice to calculate one, several, or all of the six test phases, depending on the type of transient and the phenomena that they are interested in. For each test phase, the initial and boundary conditions are defined separately so that if there are code model deficiencies in the preceding test phase the calculations for the next phase can be started and performed independently.

The main issues and phenomena covered in the ISP-42 PANDA test are the following:

- Transient and quasi steady-state operation of a passive containment cooling system (condenser immersed in pool)
- Coupled primary system and containment behavior and phenomena
- Reactor Pressure Vessel (RPV) operation at low power and low pressure under natural circulation conditions
- Gravity driven ECCS injection in an initially saturated RPV
- Venting of a steam/non-condensable gas mixture (through an immersed vent pipe into a wetwell compartment)
- Steam condensation in the presence of non-condensable gases in tubes
- Mixing and stratification of light (helium) and/or heavy (air) gases with steam in large volumes (3D effects, steam jets, air or helium release)
- Mixing and stratification in large water pools.

The ISP-42 PANDA departs to some degree from the traditional procedures in that it has to some extent an exploratory character: it is partly designed to answer certain interesting questions with respect to how far can system or containment codes go in addressing the classes of phenomena investigated and what could be expected either from available "commercial" CFD codes or "large mesh" codes suitable for containment analysis. Thus one of the outcomes of the ISP could be the clarification of certain development needs in relation to the calculational precision needed and the safety relevance of considering in detail certain particular phenomena.

The first part of the ISP-42 was "blind" or "double blind" for the organizations that have no previous familiarity with the facility, as noted above. Only the system description and the phase initial and boundary conditions were given to the participants for the blind part of the ISP. After completing the "blind" part, an open part was initiated by providing all the ISP-PANDA test data to the interested organizations. It should be emphasized again that the various phases of the test are clearly defined by providing simple initial and boundary conditions; thus participants were not forced to do the entire ISP but were able to choose the phases of interest to their organizations. Different sets of codes were also used for the various phases, as appropriate.

The configuration used for ISP-42 was corresponding to the European Simplified Boiling Water Reactor (ESBWR) containment and passive decay heat removal system at about 1:40 volumetric and power scale, and full scale for time and thermodynamic state (Figure 2). The actual test took over ten hours, including all conditioning and test phases. The ISP-42 PANDA test consists of six phases, A through F. These phases represent a sequence of concatenated operating modes or processes as used for the simulation and study of the behaviour of ALWR containment's with passive safety systems. Each of these phases in fact a separate experiment, with its own initial and boundary conditions The six different test phases are listed as below:

Phase A: Passive Containment Cooling System Start-up
Phase B: Gravity-Driven Cooling System Discharge  
Phase C: Long-Term Passive Decay Heat Removal  
Phase D: Overload at Pure-Steam Conditions  
Phase E: Release of Hidden Air  
Phase F: Release of Light Gas in Reactor Pressure Vessel

The ISP-42 participants in the exercise chose the number of test phases they wished to calculate. Ten organisations from nine countries did participate in the "blind" phase pre-test calculations. 49 submitted calculational results are included in the "blind" phase comparisons report [7]. A large number of physical parameters were selected for comparison. In general, most of the predicted results were in quite good agreement with the test results; however, some prediction cases differed significantly and the reasons for these differences were in detail discussed.

The experimental data was distributed to all ISP-42 participants for their post-test calculations by June 2000. There were 27 new submissions for different phases of "open" phase analyses of ISP-42 by some of the participants, 8 organizations from 8 countries. “Open” phase submissions, comparisons, and analyses for ISP-42 are based on the outcome of the results presented in the “blind” phase report of ISP-42 [7]. It is to be noted that as outcome of the good results obtained in the “blind” phase comparisons, some ISP-42 participants decided not to submit “open” phase calculations. Consequently, the number of submissions for “open” phase was less than “blind” phase and they were mostly dealing with improvements of system modelling (re-nodalization) or the modifications of the code physical models. One of the submissions using GOTHIC code, in relation to test phase E, was a new submission. The detailed comparisons and analyses of the “open” phase of the ISP-42 were issued as a separate report [8]. Improvements on the cases submitted were observed with the recent versions of the codes, use of some other physical models and re-nodalization of the system depending on the specific phenomenon observed in the six phases of the ISP-42. In addition to the good results obtained in the “blind” phase, these improvements also provided additional good agreements with the test results. Some of the prediction cases still differed significantly, for these cases the reasons of differences were identified to some limited degree.

5. SHORT DESCRIPTION OF ISP-42 PHASE-A TEST AND SOME RESULTS AS EXAMPLE CASE

The objective of the first test phase (Phase A) of ISP-42 was to investigate the startup of a passive cooling system when steam is injected into a cold vessel filled with air and to observe the resulting gas mixing and system behaviour.

A sketch of the setup used for this phase is shown in Figure 5. Here, the parts of the system filled with water are slightly darker than those filled with steam, air, or a steam/air mixture. As it can be seen from Figure 5, all three PCCs are operational, and there is no interconnection between the different PCC pools. The GDCS is filled with water whereas the water level in the RPV is much below the downcomer entrance/ riser exit. The main vent lines and the vacuum breaker lines are not operational for this test and therefore are not depicted in this scheme.

At zero seconds, RPV power has been switched on thus allowing steam to flow into the two drywell vessels. There, the steam slowly diluted the gas content of the drywell, which initially consisted of pure cold air and was also partially condensed at the cold vessel walls. Due to the inflow of additional gas (steam) into the drywell, pressure in the drywell as well as in the PCCs increased until it exceeded wetwell pressure approximately 10 kPa, the hydrostatic head at the outlet of the PCC vent lines. Then, drywell content partially was pushed through the PCC primary sides into the two
wetwell pools via the PCC vent lines; the rest of the steam was stored in the drywells or has been condensed on the drywell walls. As long as the feed flow is small (due to a high condensation rate at the drywell walls) or and the steam content of the flow mixture is low, no condensation has taken place in the PCCs. Instead, the mixture has been vented into the wetwells where the steam content has been condensed and the air content was separated into the gas space. Here, the separated air increased the amount of gas in the gas space thus increasing the system pressure. After some time into the transient, the dilution of the initial air content by the steam has been progressed and steam condensation started in the PCC tubes removing significant amounts of steam out of the vent flow, thus decreasing the inflow of air into the wetwell gas space, which resulted in a decrease of the pressure increase. The condensed steam has flown through the drain lines back into the RPV whereas a reduced gas flow is vented into the wetwells. During the final almost stationary part of the experiment, nearly the whole gas flow consisted of steam, which was condensed in the PCC tubes removing steam in the same order of magnitude than produced in the RPV, which resulted in ceasing the inflow of air into the wetwell gas space and consequently the pressure increase in the primary system. Further details on the description of phase -A- can be obtained from refs. .

The phenomena, which may be expected during this test, are:

- System pressurization due to a delayed startup of the passive containment coolers (PCCs)
- Injection of a hot steam jet into the cold air atmosphere of both drywell vessels. This includes:
  - Gas mixing and/or stratification in the drywell vessels and in the gas spaces of the two wetwell vessels
  - Steam condensation on walls for a wide range of gas flow rates and non-condensable gas (air) fractions
- PCC performance. This includes:
  - Steam condensation in tubes for a wide range of gas flow rates and non-condensable gas (air) fractions
  - Air/steam venting from drywell to wetwell pools, gas plumes in the wetwell pools

The time behaviour of the pressures defines the response of the whole system to the specific transient and it is the first item of the phenomena to be investigated as well as the main parameter with respect to safety issues. As may be seen in figure 6, all ISP-42 phase-A test participants except one predicted the right time behaviour for the system pressure (i.e. a steady increase followed by a turn into a approximately stationary phase when the energy balance has become close to zero). The decrease of the liquid mass inventory in the RPV determines the production of steam, which is injected into the two drywells. The injected steam partly condenses in the drywells (at least at the beginning of the transient) and afterwards mostly condenses on the primary sides of the PCCs. Figure 7 shows the comparison of the liquid mass inventory predictions in the RPV to the experimental data.

The three Passive Containment Coolers (PCCs) on top of the PANDA building remove the heat out of the primary system by condensing the steam on the primary side and evaporating the water on the secondary side water pools. The amount of steam removed out of the gas space of the primary system (which includes wetwell, drywell and GDCS gas spaces) either by condensing in the PCCs or in the wetwell pools, which controls the final system pressure. Therefore, correctly predicting the performance of the three PCCs was one of the key issues for the correct simulation of the whole system, assuming that the influence of air transport to the wetwell gas space was correctly modelled and the effect of stratification/mixing in the wetwell pool was negligible which is shown as comparison of calculated to experimental data in figures 9 and 10 as axial temperature distribution at 500 s and 4000s of the transient. In addition, figure 8 for the drywell pressure provides some indication of the “User Effect”. The same code used by different organizations, in this case RELAP5 and CATHARE codes, produced quite different results as seen in this figure. For further detailed analysis of the comparisons of the calculated and experimental data for ISP-42 Phase-A, interested reader can refer to the references [7] and [8].
6. SUMMARY OF THE MAJOR CONCLUSIONS FROM ISP-42 PANDA TEST

Some of the major conclusions drawn on the basis of the six phases of the ISP-42 post test cases and also covering the “blind” phase results can be summarized as follows (Interested readers should refer to references [7] and [8] for more detailed information):

- Objectives set at the beginning of this ISP-42 activity have been achieved, even though very demanding efforts needed for such multiple exercises with six different phases.
- Most important parameter in relation to reactor safety, the containment pressure history has been calculated sufficiently correct for most of the ISP-42 participants for all six phases of ISP-42.
- The overall best results were obtained by the lumped parameter code SPECTRA
- Although system codes like CATHARE or RELAP5 were not designed to calculate typical containment problems in low pressure environments in the presence of large amounts of noncondensibles, they produced acceptable results. Containment code COCOSYS also produced globally acceptable results.
- Some codes (like GOTHIC) had problems to model specific equipment (e.g. PCCs) properly, some tuning of physical models, which needed some knowledge of the facility behaviour, were introduced. The RELAP5 or CATHARE codes were superior with respect to the higher flexibility to simulate special components and, in this case, specifically the modelling of the PCCs.
- Most of the major deviations could be attributed to problems with the nodalization or simply input errors rather than deficiencies of the specific codes. For example, in the case of RELAP5 and CATHARE, the same code used by different organizations produced quite different results (“user effect” and also different level of experience of the code users).
- It was observed that major attention should be given to provide the appropriate input parameters, which are used in the analysis. As an example, use of loss coefficients and their distribution, especially for low power, low pressure transients as in ISP-42, is a very important factor. Even though experimentally measured data are provided to the code users, due to modelling necessities specific to the computer code used, there could be substantial deviations in the input data. In order to ensure the appropriateness of these types of parameters, every input model could be reviewed as carefully as possible. An important factor is the computer code user’s discipline. This discipline cannot be forced, or substituted by Quality Assurance (QA) procedures. But it may help to reduce inappropriate use of some input parameters.
- For simple physical situations (e.g., well-mixed conditions in phase A), choice of a lumped parameter approach is permitted. In such cases, little gain in predictive capability is achieved at the cost of very large computation time for 3-D simulation and detailed nodalizations. Sensitivity studies can help to select the appropriate detailed nodalization and needed sophistication of physical models, and determine criteria for reasonable compromises between accuracy and computing time or costs.
- 3-D models such as in GOTHIC code include right physical representation of phenomena but number of difficulties currently prevents to take full advantage of these capabilities, e.g., accurate calculation of stratified conditions and its effect on system pressure (global parameter). Consequently, further assessment of 3-D models and advanced modelling features (e.g., turbulence) are necessary using well defined separate effects experiments for specific phenomena related to containment multi-compartment geometries.
- The use of CFD codes still exploratory, as they usually lack built-in physical models, interfaces (boundary conditions) with other components are difficult to set, and they occasionally show problems with respect to convergence. Consequently, there was no submission with CFD codes.
- The knowledge gained in ISP-42 and other PANDA tests indicated the need to improve and upgrade some of the instrumentation, e.g., improved measurement of injected medium,
improved measurement of local concentration of air, helium and steam in the gas spaces of the different PANDA compartments.

- The data set produced for the six phases of the ISP-42 PANDA tests will be used as the basis of assessment of computer codes in relation to the passive containment cooling systems in the next future, at least next ten years. These data will be available to the requesting organizations through NEA-Data Bank and European Community Project CERTA.

7. RECENT AND FUTURE INVESTIGATIONS IN PANDA TEST FACILITY

In this section, the test programs, which are performed in the recent years together with the investigations planned for the future, are provided in brief form. These programs are being TEMPEST, NACUSP, and SETH/PANDA. TEMPEST and NACUSP are performed within the 5th Frame Work Program of EU and SETH/PANDA was performed within a cooperative program of OECD/NEA. Presently a new project called SETH-2 is in progress in cooperation with OECD/NEA.

The primary objective of TEMPEST (Testing and Enhanced Modelling of Passive Evolutionary Systems Technology for Containment Cooling) was to validate and improve advanced modelling methods, with emphasis on CFD and other tools with 3-D capabilities [9]. It included experimental investigations of the effect of light gases on containment behaviour and of new design features for accident mitigation, as well as evaluation of the performance of CFD codes and containment codes. The objectives of the PANDA tests in the TEMPEST project were:

- To assess effects of light gases on PCCs and containment performance
- To investigate new accident mitigating design feature (Drywell Gas Recirculation System, DGRS)
- To provide a database for assessing the capabilities of CFD and other 3-D codes. For this purpose, improved instrumentation (including concentration measurements by means of a mass spectrometer) was installed in the PANDA test facility.

The configuration of the system was similar to that used for the ESBWR tests (Figure 2). The DGRS consisted of a fan blower, sucking gas from the vent lines of the PCCs and re-injecting the gas into the Drywell. Total of five tests were performed (including symmetric and asymmetric injection conditions).

The NACUSP project offers the opportunity to validate the codes in relation to the capability to simulate natural circulation behaviour at low pressure [10]. In the PANDA test facility, 25 tests have been carried out in order to investigate natural circulation and stability, at low pressure and low power conditions. The test configuration (Figure 11) includes the Reactor Pressure Vessel (RPV) with core simulator, riser and down-comer (DC) and a condenser submerged in a pool, which is used as a heat sink. The configuration used for the NACUSP tests (not using any of the large vessels used for containment tests) demonstrates again the flexibility of the facility, and its multi-purpose feature. The tests were performed at a constant power, balanced by a specific condenser heat removal capacity (which was kept constant all over the test period). The test matrix allowed for varying the RPV power and pressure, and also other parameters influencing the natural circulation such as water level in the RPV and the core inlet hydraulic resistance.

OECD/NEA SETH project was an international cooperation project. It had also a component SETH/PANDA and it utilized the PANDA test facility. The program addressed relevant safety issues in both PWR and BWR containment gas spaces with steam and air (or helium to simulate hydrogen) as working fluids. The PANDA facility was used for this purpose with relatively minor hardware changes and several instrumentation improvements. The objective of SETH/PANDA was to provide a
better understanding of 3D phenomena and the database needed for the validation of advanced codes through a set of experiments. The experiments aimed to study the mixing and distribution of steam and non-condensable gas (air or helium) in multidimensional, well-defined geometry configurations, at scales approaching those of actual containment buildings or compartments, under a variety of well-established initial and boundary conditions. The tests revealed the nature of mixing and stratification phenomena under accident conditions of interest to current and advanced power reactors and produced data for field code development and validation. The investigations included three series of tests characterized by wall plumes (Figure 12), free plumes and horizontal high-momentum jet [11]. In addition to these series of tests, one specific three-gas test, which is identified in the SETH project as Test 25, with air, steam and helium has been carried out. Analytical activities performed by the project participants aimed at the assessment of strengths and drawbacks of different codes in analyzing the phenomena occurring in these PANDA tests. The analytical activities revealed a number of simulation challenges in relation to: gas transport and stratification for the case of high flow exit elevations, prediction of peak gas temperature (mainly in the near-wall plume test series), stratification disruption and erosion for the case of the three gas test, condensation and condensate transport and re-evaporation phenomena. While the SETH/PANDA tests were designed to produce the conditions for stratification build-up, the test program related to the second phase of the project (i.e. SETH-2) the PANDA investigations will deal with stratification break-up. In the SETH-2 project, tests will be made also in the MISTRA Facility (France). The main phenomena studied in the PANDA SETH-2 tests are gas mixing stratification (Figure 13), natural/forced convection, direct-contact/wall condensation, occurring inside LWR containment compartments. Thus, these test series complement the data produced in PANDA SETH, where conditions leading to build-up of stratification were studied. The total number of tests to be performed in the PANDA facility in the frame of the SETH-2 project is 24.

8. CONCLUDING REMARKS

The extensive database established using the PANDA test facility contributes, for the years to come, to further improve containment cooling systems and containment design of passive plants; and allow for system code, containment code and CFD code assessment in a wide parameter range and also for different phenomena.

NOMENCLATURE

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<th>Description</th>
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<tbody>
<tr>
<td>ABWR</td>
<td>Advanced Boiling Water Reactor</td>
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<tr>
<td>ALWR</td>
<td>Advanced Light Water Reactor</td>
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<tr>
<td>CSNI</td>
<td>Committee on the Safety of Nuclear Installations</td>
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<td>AP600</td>
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<tr>
<td>BWR</td>
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<td>CFD</td>
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<td>Down-comer</td>
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</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>GDCS</td>
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</tr>
<tr>
<td>IC</td>
<td>Isolation Condenser</td>
</tr>
<tr>
<td>ISP</td>
<td>International Standard Problem</td>
</tr>
<tr>
<td>LOCA</td>
<td>Loss Of Coolant Accident</td>
</tr>
<tr>
<td>LWR</td>
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<tr>
<td>MVL</td>
<td>Main vent line</td>
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<tr>
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<td>Nuclear Energy Agency</td>
</tr>
<tr>
<td>OECD</td>
<td>Organization for Economic Cooperation and Development</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>PANDA</td>
<td>Passive Nachwärmeabfuhr- und Druckabbau- Testanlage (Passive Decay Heat Removal and Depressurization Test Facility)</td>
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<td>PCC</td>
<td>Passive Containment Cooling</td>
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<tr>
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<tr>
<td>RPV</td>
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<td>SESAR (Senior Group of experts of CSNI) Thermal Hydraulics</td>
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<td>Siede Wasser Reaktor, 1000Mwe</td>
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<td>VB</td>
<td>Vacuum Breaker</td>
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<td>WW</td>
<td>Wetwell</td>
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REFERENCES


Figure 1: 3-D View of the PANDA test facility
Figure 2: Schematic of the PANDA test facility for the ESBWR configuration
Figure 3: SBWR versus PANDA test facility

Figure 4: SWR 1000 versus PANDA test facility
Figure 5: ISP-42 Phase A: Passive Containment Cooling System Start-up

Figure 6: Comparison of drywell pressure calculations (blind and open phases) with experimental data for Phase A of ISP-42
Figure 7: Comparison of liquid mass inventory predictions (blind and open phases) with experimental data (Reactor Pressure Vessel) for Phase A of ISP-42

Figure 8: Drywell pressure RELAP5/Mod3 and CATHARE code calculations compared to experimental data for Phase A of ISP-42
Figure 9: Measured and Predicted axial temperature distribution in wetwell-1 at 500s for Phase A of ISP-42

Figure 10: Measured and Predicted axial temperature distribution in wetwell-1 at 4000s for Phase A of ISP-42
RPV dimensions:
- Height: 19.2 m
- Diameter ID: 1.23 m
- Volume: 22.9 m³
- Riser height: 9.5 m
- Riser ID: 1.05 m

Maximum operating conditions:
- Power: 1500 kW
- Pressure: 10 bar
- Temperature: 180 °C

Figure 11: PANDA Experimental Facility, Natural-circulation loop and condensation/cooling loop (NACUSP) Configuration

PANDA near wall plume test configuration

Measurement locations:
- Temperatures/Concentrations
- PIV measurement area

Velocity Map Measured in DW1 with PIV

Figure 12: OECD/NEA, SETH/PANDA Schematic for Wall Plume Test Configuration and Sample Test Data