



International Agreement Report

Post-Test Analysis of P5 Experiment in PANDA Facility With TRAC-BF1 Code

Prepared by
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ACRONYMS

ALWR:	Advanced Boiling Water Reactor
BWR:	Boiling Water Reactor
CIEMAT:	Centro de Investigaciones Energeticas Medioambientales Tecnológicas
DW:	Drywell
ESBWR:	European Simplified Boiling Water Reactor
GDCS:	Gravity Driven Cooling System
IC:	Isolation Condenser
KEMA:	Keuringsdienst Elektrotechnische Materialen
LOCA:	Loss-Of-Fluid Accident
MSL:	Main Steam Line
MSLB:	Main Steam Line Break
PANDA:	Passive Nachwarmeabfuhr und Druckabbau
PCCS:	Passive Containment Cooling System
RELAP:	Reactor Excursion Leak Analysis Program
RPV:	Reactor Pressure Vessel
SBWR:	Simplified Boiling Water Reactor
TEPSS:	Technology Enhancement for Passive Safety Systems
WW:	Wetwell

POST-TEST ANALYSIS OF P5 EXPERIMENT IN PANDA FACILITY WITH TRAC-BF1 CODE

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ABSTRACT

As a part of the TEPSS project, within the last fourth Framework Programme of the European Union R&D activities, an investigation focused on the residual heat removal passive safety systems in the future boiling water reactors was performed using PANDA facility and the codes RELAP5, MELCOR and TRAC-BF1. The main purpose was to ensure the capacity of these passive safety systems under a wide range of different conditions and hypothesis on the availability of them as well as to assess the quality of some of the most commonly used codes to predict the containment response within a LOCA. The plant design chosen as reference was the ESBWR, which is a special version of the SBWR adapted to reach licensing conditions in European countries.

The PANDA facility, located in the Paul Scherrer Institute (Switzerland), has been extensively used in the past for testing the passive condenser performance for the SBWR. According to the reference plant, PANDA facility was appropriately modified. A set of eight tests was executed covering different conditions in the containment for the LOCA scenario, such as asymmetric conditions for the gas distribution in the drywell as well as for the passive condensers availability and the effect of trapped air in the drywell among others.

The assessment of codes was rather challenging, since RELAP5 and TRAC-BF1 are thermal-hydraulic codes usually employed in transients within the primary circuit in a current plant. Thus, they have a well proved response in the conditions where strong changes of the momentum are expected, like normally occur in forced convection situations associated with valves and pumps. However, in containment buildings equipped with passive safety systems, the expected phenomena are related with changes in the density, that is natural convection. In addition, some other phenomena like condensation in the presence of non-condensable gases are also characteristic in the scenario. For that reason, there were also MELCOR predictions, since this code incorporate containment modelling, although it has no special models for the passive condensers in the containment.

The general response of all the codes was rather acceptable, being all of them able to predict well the overall behaviour of PANDA concerning pressure, mass flow rates and pool boil-off. Nevertheless, some limitations were showed regarding 3D-effects such as in-vessel mixing and recirculation.

This report describes the calculations performed with TRAC-BF1 code for P5 test.

1. INTRODUCTION

Within TEPSS project (Technology Enhancement for Passive Safety Systems), belonging to the fourth Framework Programme of the European Union, the UPV and CIEMAT have performed the post-test analysis of PANDA experiments P with TRAC-BF1 code. The main objective in the TEPSS project was to make significant additions to the technology base of advanced passive-type Boiling Water Reactors (BWR) designs which offer enhanced safety and improved public acceptance through product design simplicity and increased safety margins [1].

The TEPSS project has undertaken research needed to support advances in the following areas:

- Improved countermeasures against pool stratification, including studies of deep pool thermal plumes and testing of concepts for avoiding or minimising hot, stratified pool regions.
- Improved designs of containments, including tests on the passive decay heat removal in an advanced concept Boiling Water Reactors.
- Enhanced aerosol removal features, including tests demonstrating that passive heat removal systems can act as an effective aerosol filter and that the containment decay heat removal is not endangered by aerosol deposition in the containment cooling condenser tubes.

In all cases, experimental work has been supported by balanced analytical efforts to identify and understand governing phenomena, and to produce usable correlations and reliable analytical models.

Within the area concerning the passive removal of residual heat, the main purpose was the understanding and prediction of relevant phenomena through the most commonly used codes. The codes used (MELCOR, RELAP5 and TRAC-BF1) performed calculations against a set of eight tests conducted in PANDA facility. PANDA facility has been widely used for testing passive systems of the SBWR (Simplified Boiling Water Reactor) [2]. In TEPSS project, the reference design was the European Simplified Boiling Water Reactor (ESBWR) [3], which is an adapted version of the SBWR to reach the licensing requirements in Europe. This reference design lead to the introduction of some modifications in PANDA facility.

PANDA experimental facility, located in the Paul Scherrer Institute (Switzerland), is designed to offer, among others, data on the cooling conditions in containment with the so-called containment passive condenser system (PCCS). The relevant phenomena include the mixing of steam and non-condensable gases, the condensation of steam in the presence of non-condensable gases and the mixing processes and thermal stratification in pools.

This work presents the main results of the simulation performed with TRAC-BF1 code for the P5 test. The calculation of PANDA response with TRAC-BF1 code is a challenging exercise. The thermal-hydraulic codes are normally used in the simulation

of transients where strong changes of momentum are expected, associated to the operation of pumps and valves. However, in the passive designs the dominant drag forces are due to density changes (natural convection). Thus, since the conservation equations are not optimised for such regimes, this kind of calculations consumes a huge time machine. In addition, involving phenomena as condensation in the presence of non-condensable gases and natural circulation makes more challenging this simulation.

2. THE PANDA FACILITY AND TESTS

The large-scale PANDA facility (see Figure 1) is intended to make progress in the investigation of passive ALWR containment phenomena and the simulation of the system response [4]. The PANDA facility, that is scaled 1:1 in height and 1:40 in volume and power compared to the ESBWR reference design, has a modular structure with separate vessels that represent the RPV, DW, WW including the SP, and the GDCS. The DW and WW are represented by pairs of interconnected vessels (DW1, DW2, and WW1, WW2) to better model mixing and the effects of non-uniform distribution of steam and non-condensable gases on the operation of the PCCS. Piping between the vessels represents important flow paths between the RPV, DW and WW, including the broken steam line from RPV in the DW, the main vents from DW-to-WW, the GDCS drain to the RPV, the vacuum breakers (VB) connecting the DW and WW and lines to and from the PCCS. The gas space above the GDCS pool is connected to the WW gas space rather than the DW as in the SBWR design. Electric heaters in the RPV are used to simulate post-LOCA decay heat.

The PCCS heat exchangers and their pools are represented in PANDA at full height, with the number of heat exchanger tubes reduced in accordance with the 1/40 volume scaling. As can be seen in Figure 1, the PCC2 and PCC3 exchangers are connected to DW2 and the PCC1 heat exchanger to DW1. This arrangement provided asymmetry in the heat removal capacity from the DW vessels. PANDA also includes an isolation condenser (IC) heat exchanger with its pool, again scaled at full height with a reduced number of tubes.

PANDA is designed to simulate the long-term phase of the ESBWR LOCA transient, beginning approximately one hour after initiation of the accident. It simulates the accident sequence following the rupture of a main steam line (MSL), the design basis accident for the ESBWR containment. Water that has condensed at the primary side of the IC/PCC units flows from the IC/PCC lower headers back to the RPV. The non-condensable gases and/or excess steam are purged from the condenser lower headers to the suppression chamber of the WWs.

In the PANDA P-series, performed for the TEPSS project, a total number of eight test runs have been executed. A schematic of the PANDA P-test series is depicted in Figure 2. The general objectives of the P-series were to:

- investigate the effect of the new design on the long-term containment response after a LOCA;
- demonstrate that the decay heat removal systems operate as intended under different accident scenarios;

- provide a data base for computer code assessment and analysis of particular phenomena.

For each test except P8, the initial conditions have been established on the predicted state of the RPV and the containment vessels of the ESBWR reference design about 1 hr after reactor scram. This means that the DWs were mostly filled with steam and the WW contained non-condensable air, whereas the system pressure was approximately 2-4 bars.

P1/8: The P1/8 test was actually a combination of two separate tests, the P1 "Base Case" test, and the P8 "PCC Pool Boil Down" test. Test P1 represented a simulation of the long-term PCC cooling phase starting 1 hr after a Main Steam Line Break (MSLB) LOCA. At that time, the GDSCS injection phase has ended and steam production caused by decay heat in the RPV has recovered. The break flow from the RPV was directed equally to both DW vessels. All three PCC units were connected to the DWs with drain and vent lines open. The IC was not available. The PCC pools were isolated from each other and initially filled with water at saturation temperature. No refilling of the PCC pools was done during the 20 hour test.

The P8 test ("PCC Pool Boil Down") studied the effect of low PCC pool level on the long-term PCC system performance. The test was executed as an extension of P1 and it provided information about the containment behaviour after the 72 hour period (no operator action).

P2: The "Early Start" test objective was to provide data for the transition period from the GDSCS injection phase to the long-term PCC cooling phase of the post-LOCA transient. The test was initiated at 20 mins into the LOCA, when the water level in the RPV is low and subcooled water from the GDSCS pool is draining to the RPV, thereby suppressing temporarily the steam production in the RPV. The test duration was 6 hours.

P3: The "PCCS Start-Up" test demonstrated the PCC system start-up with the condensers and DW initially filled with non-condensable gas, which represented the most challenging condition for PCC start-up. Only the two PCCs connected to DW2 were operable and the break flow was directed to DW2. Consequently, DW1 represented a "dead-end" volume. The test duration was 8 hrs.

P4: The P4 test investigated how trapped air a DW, released later in the transient, would affect the PCCS performance. The air release has been simulated by injecting air into DW1, 4 hours after test initiation for a period of 30 minutes. The initial conditions and the facility configuration were nearly identical to the "Base Case" test, P1. The test duration of the P4 test was 8 hours.

P5: In the "Symmetric Case, Two PCCs Only" test, each DW had one PCC connected and the break flow was directed equally to both DWs. It was anticipated that in the early phase of the test two PCCs would not be able to remove all the decay heat from the DW. Starting at 4 hours into the transient, air was injected into DW1 for a period of 30 minutes. The test duration was 8 hours [5].

P6: The objective of the "Systems Interaction Test" was to examine the system interaction between the IC operating in parallel with the PCC units. In addition, the effect of DW to

WW bypass leakage on the containment performance was investigated. The steam produced was directed to the IC and via the DWs to the three PCC units. After 4 hrs, the (vacuum breaker) leakage path was opened. The IC operated for the first 7 hrs only. The test duration was 12 hrs.

P7: The objective of the "Severe Accident" test was to investigate the PCC performance under the conditions of a severe accident, where hydrogen may be released to the containment due to the steam oxidation of Zircaloy cladding. Only the two PCC units connected to DW2 were operable and all steam flow was directed to DW2, thereby leaving DW1 as a dead volume. To simulate the hydrogen release into the containment, helium as a substitute was injected between 4 and 6 hrs into the top of DW1. The test duration was 8 hrs.

3. TRAC-BF1 MODEL FOR PANDA

The TRAC-BF1 input deck, depicted in Figure 3, is based on a former input developed by KEMA Nederland B.V [6]. This model has been derived from geometrical data concerning the PANDA facility, as used for the SBWR.

In the original input deck, the WW and the DW were modelled with a TRAC-BF1 3D component VESSEL, but the liquid-gas interface level-tracking model has important problems working with 3D components. Therefore, it was impossible to run a test with a liquid-gas interface present in the WW. Using a suitable combination of 1D components lead to very unstable results in the level movement. Moreover, the code crashed so frequently during several test runs that it was decided to use a pressure boundary condition for simulating the WW. Therefore, a BREAK component is connected at the end of the discharge line. This BREAK component follows, at any moment, a pressure curve composed by the experimental pressure measured in the WW gas region including the hydrostatic head from the surface of the WW pool in order to simulate the WW pool behaviour.

The BREAK component is thus a practical solution in order to run the PANDA test using the current TRAC-BF1 code. Therefore, it was not possible to give predictions about the WW behaviour, but the remainder of the PANDA values were well calculated.

The main vents and the vacuum breaker valves were both connected to the BREAK component that simulates the WW. However, it was possible to model the two PANDA drywells by means of the 3D VESSEL component that was split into two regions connected by a PIPE component. In addition, a special condensation model in the presence of non-condensable gases was implemented in the code [7].

The RPV was modelled with a 1D component combination. A CHAN component models the electric heater. The heaters were placed at the first five cells of this CHAN component. The chimney was modelled by a TEE and the raiser by a CHAN and a TEE combination.

Regarding the passive condensers PCC and IC, PIPE components were used to simulate the heat exchanger tubes and the upper plenum. The lower plenum was modelled by a TEE component, for simulating the separation between the steam and the condensate.

Finally, the GDSCS was modelled by a PIPE, and a VALVE represented its connection to the RPV. The equalisation line was replaced by a pressure condition with the same pressure as the WW.

4. MAIN RESULTS

During the first phase of the experiment, the PCC condensers were not able to take the whole load and, as a result, the pressure differences between drywell and wetwell began to rise. This fact led to the discharge to the suppression pool through the main vent lines. After four hours in the transient, cold air was injected in the drywell number one (DW1), increasing the drywell pressure and producing additional discharges through the main vent lines to the suppression pool. One and a half-hour after, the process turned back to normality.

Despite the limitations imposed by the TRAC-BF1 model of PANDA, the post-test results are acceptable [8]. In the Figure 4 the evolution of the drywell pressure is presented, which shows a rather agreement with the experimental measures. The steam produced in the RPV was equally discharged to the two vessels representing the drywell (DW1 and DW2). The TRAC-BF1 predictions of the main steam line mass flow represent very accurately the experimental data (see Figure 5).

Figures 6 and 7 show the feed flow to the two available PCC units, respectively. Both condensers began to work immediately after the beginning of the transient. The TRAC-BF1 predictions show an overestimation of the feed flow from the drywell to the PCC units during the first half of the transient. This discrepancy is directly attributed to how is modelled the WW in the TRAC-BF1 model of PANDA. As it was mentioned before, it was not possible to simulate the suppression pool due to the shortcomings of the level-tracking model of the code. Thus, since during the first period of the test the gas present in the drywell was vented to both the condenser units and the suppression pool by the main vents, TRAC-BF1 is unable to reproduce the experimental values, because in the TRAC-BF1 model there is no main vent lines and the whole discharge is produced to the condenser units. After the injection of air in the drywell the predictions of TRAC-BF1 show a rather good agreement with the experimental values.

Figure 8 shows the evolution of the drywell temperature. The experimental curve behaves practically constant and shows a slightly increase in the air injection period, as a consequence of the reduced capacity of the PCC to remove the heat. The TRAC-BF1 predictions are in an acceptable agreement excepting for the first hour, where the code predicts a temperature peak. This is due to the limitations of the TRAC-BF1 models when dealing with great amount of air in near saturation conditions inside the 3D components. The three-dimensional modelling of such scenario makes the code to be very unstable and an important quantity of extra air appears virtually. This virtual creation of air does not affect the drywell pressure, since it appears at expenses of the steam, affecting thus to the heat transfer determination.

Figures 9 and 10 present the tube temperature evolution in the condenser units PCC1 and PCC3, respectively. After the injection of air at four hours in the transient, the PCC capacity is slightly reduced, as reflects the small increase of the tube temperature. The trend of the PCC tubes temperature is well predicted by TRAC-BF1. However, there is

a temperature peak during the first hour, as a consequence of the strong increase of the temperature predicted for the drywell.

Finally, Figures 11 and 12 show the evolution of the air partial pressure in each drywell, DW1 and DW2 respectively. The curves make again noticeable one of the TRAC-BF1 problems when dealing with air in 3D components. In the predictions of TRAC-BF1 the air behaves in an oscillatory way and at the beginning of the transient the code produces an artificial mass of air, which will affect to the heat transfer processes. The TRAC-BF1 predictions of the air partial pressure show a strong increase at the beginning of the test. After this spurious of initial air mass, the code estimates acceptably the air partial pressure. Moreover, it is worth to note that TRAC-BF1 is able to predict the asymmetrical behaviour of the drywell due to the cold air injection, as seen in the figures, where the air partial pressure increase at four hours is more sharp in the drywell number 1.

5. CONCLUSIONS

The test P5 demonstrated that trapped air, released from the DW later in the transient, only affects temporarily the performance of the passive containment cooling system. Only two PCC units operable caused an extended main vent-clearing phase with energy transfer to the WW, ending up with a correspondingly higher system pressure.

TRAC-BF1 has many problems in dealing with 3D scenarios with the presence of a great amount of air. This fact causes most of the discrepancies encountered in the predictions. However, once the phenomena associated with air disappear the predictions are in good agreement with the experimental results and have physical meaning during the whole transient. The shortcomings of the level-tracking model affect somewhat the results, since they affect the total water inventory of the system. A mention should be made of the excessive computing time, which limits somewhat the applicability of TRAC-BF1 to partial studies instead of integral ones.

Therefore, the TRAC-BF1 code has passed the challenging calculation of a containment scenario with passive-cooling safety systems. Worth to note the good response of the code for determining the condensation phenomena in the presence of non-condensable gas, because of the new condensation model, developed by UPV and CIEMAT, and implemented by UPV into the code, which enhances the code capacity for such processes. Finally, it seems necessary the revision and improvement of some models in TRAC-BF1, especially the level-tracking one, in order to make the code so reliable for passive plants as is for the current reactors.

The calculations have been performed in a convex machine, and the computing time was around a week.

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- [8] J. Polo, "Post-test Analysis of PANDA test P5. TEPSS Project (WP2)", DFN/SN-18/IF-98, INNO-TEPSS(98)-D15, 1999.

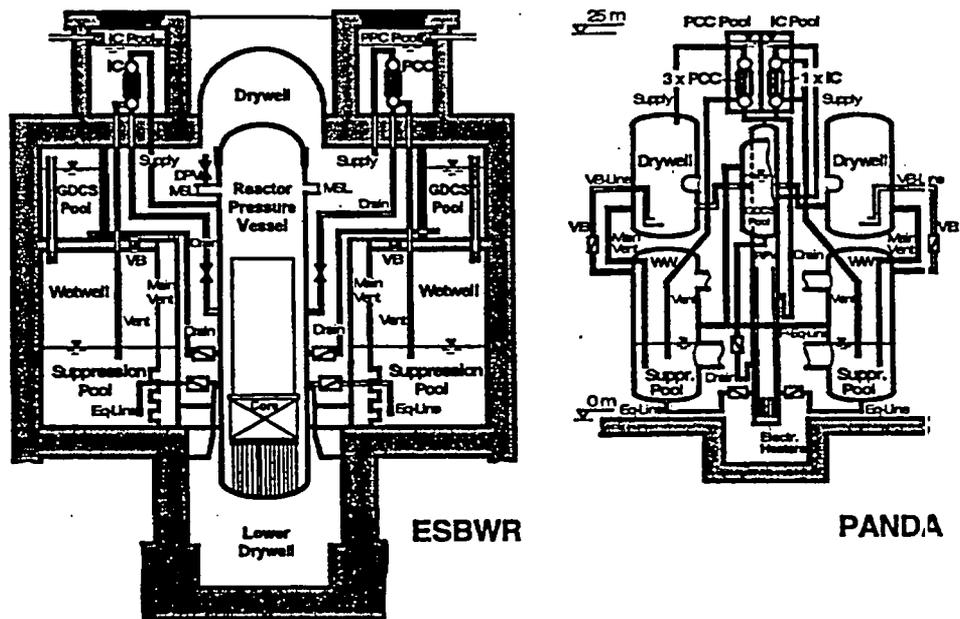
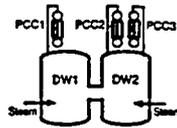


Figure 1. Comparative scheme of ESBWR and PANDA

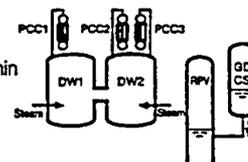
P1 Base Case

MSL break LOCA + 1 hr
(long-term PCCS cooling phase)



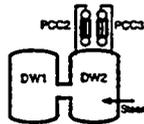
P2 Early Start

MSL break LOCA + 20 min
(transition from GD/CS injection to long-term PCCS cooling phase)



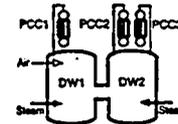
P3 PCCS Start-up

DW initially filled with air
(demonstrate PCCS start-up under challenging conditions)



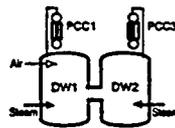
P4 Trapped Air in DW:

Air released during transient
(investigation of how n/c gas affects PCCS performance)



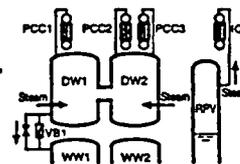
P5 Symmetric Case, Two PCCs Only

PCC2 isolated,
air supply to DW later in transient
(MV clearing phase, caused by reduced PCC capacity)



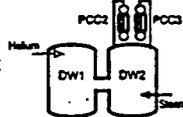
P6 Systems Interaction

ICS and PCCS in parallel,
DW1 to WW1 leakage
(is PCCS performance adversely affected?)



P7 Severe Accident

All break flow to DW2,
PCC1 isolated,
He supply to DW later in transient
(simulation of hydrogen release and reduced PCC capacity)



P8 PCC Pool Boil Down

Extension of Base Case P1,
(how do low PCC pool levels affect containment performance?)

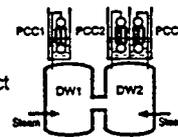
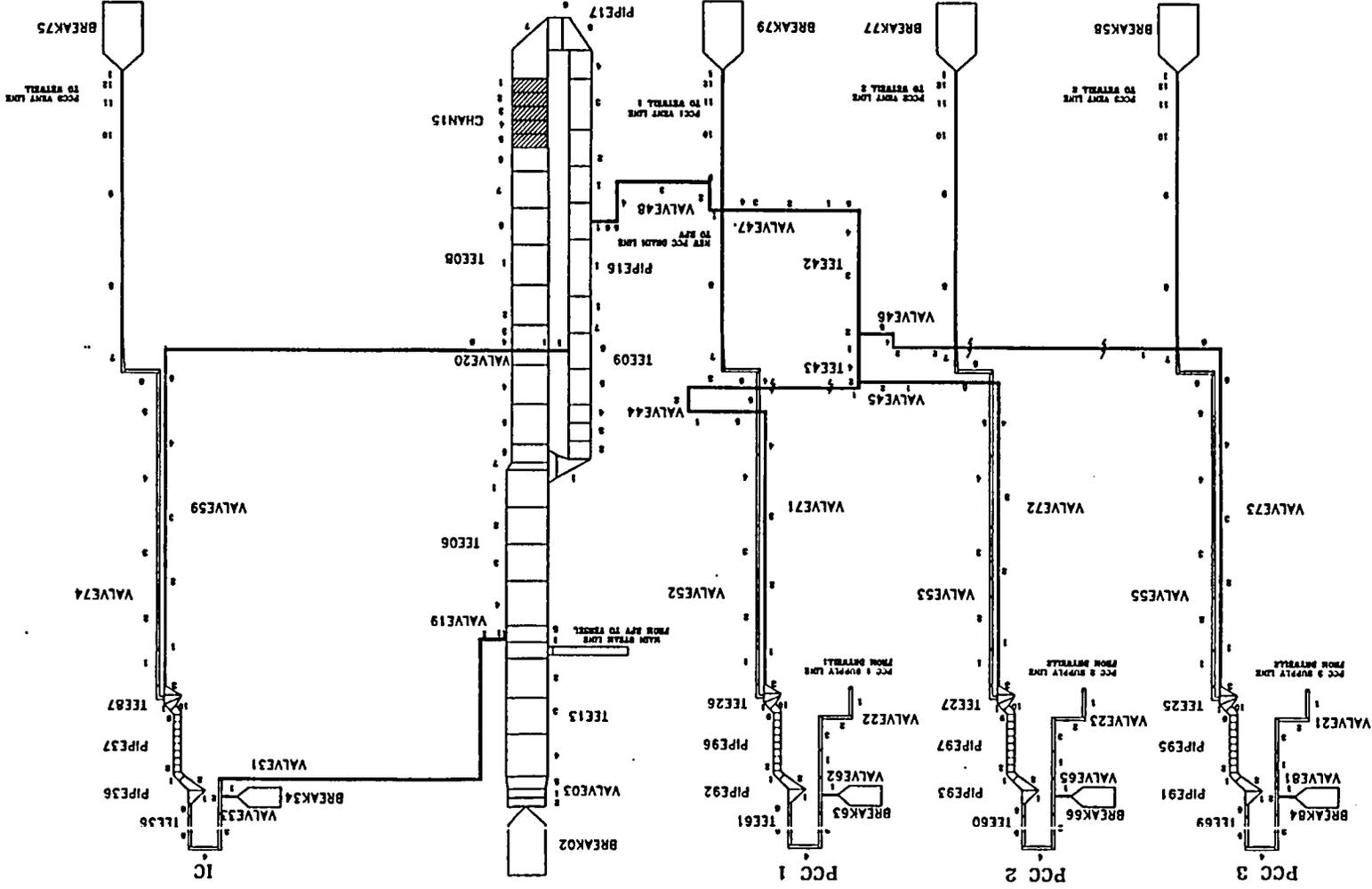


Figure 2. Boundary conditions of P-tests in PANDA

Figure 3. Nodalisation of PANDA with TRAC/BF1 code



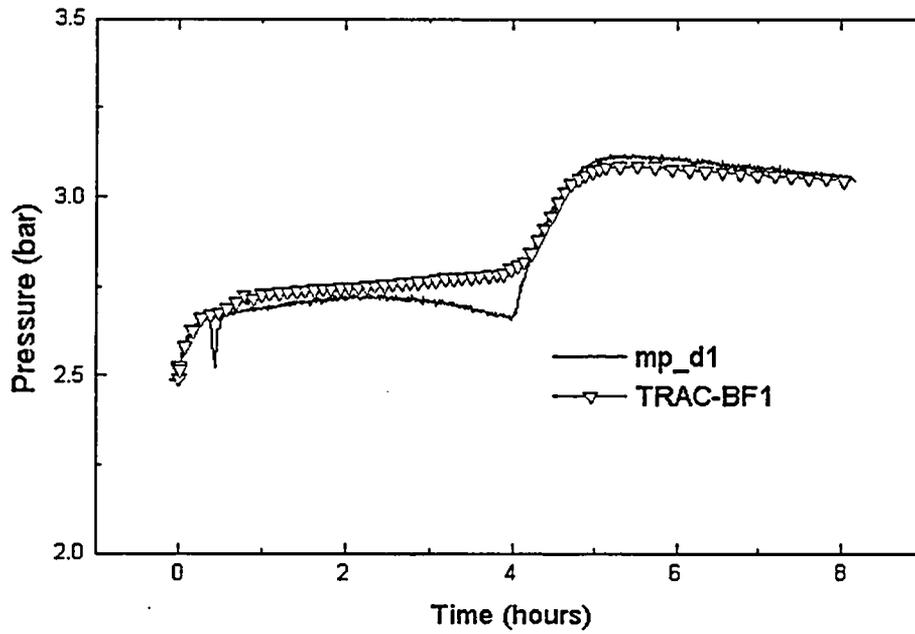


Figure 4. Pressure in the drywell

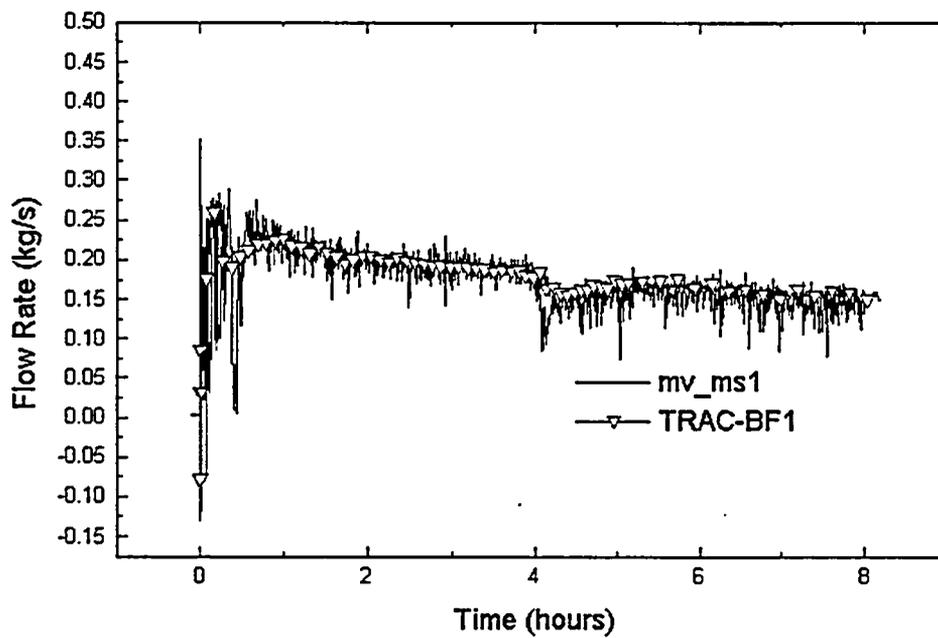


Figure 5. Main steam line mass flow rate

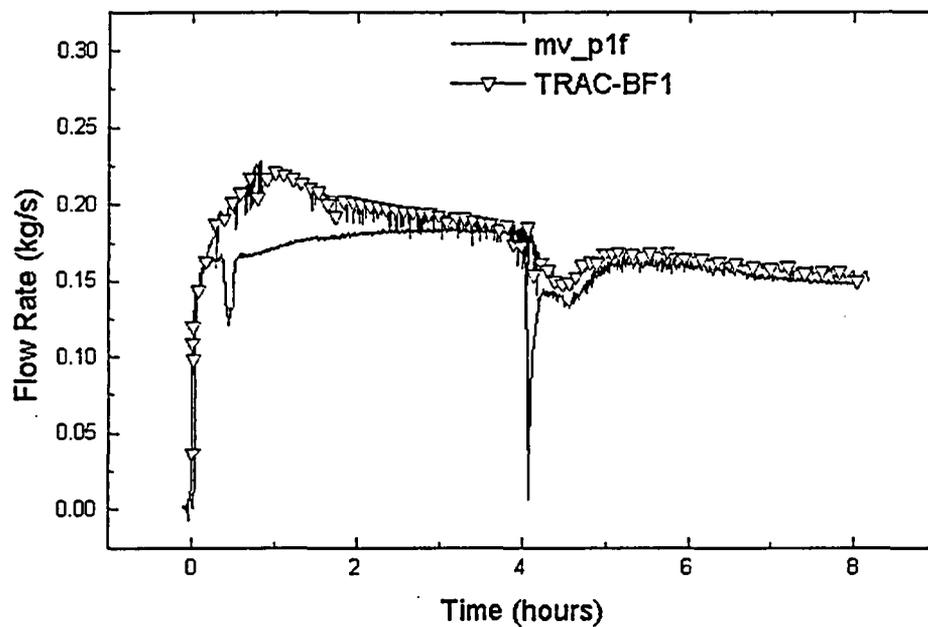


Figure 6. PCC1 feed flow rate

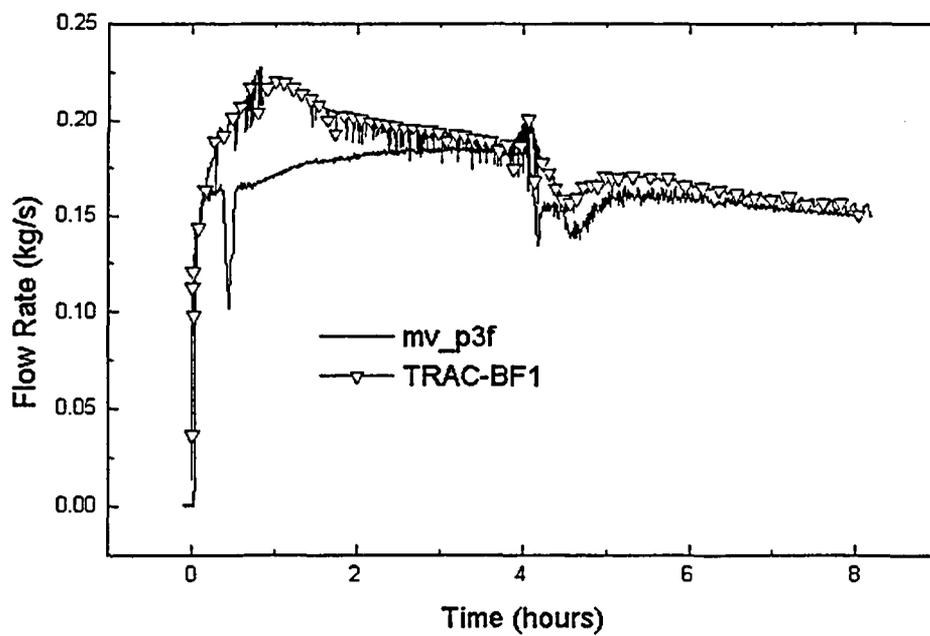


Figure 7. PCC3 feed flow rate

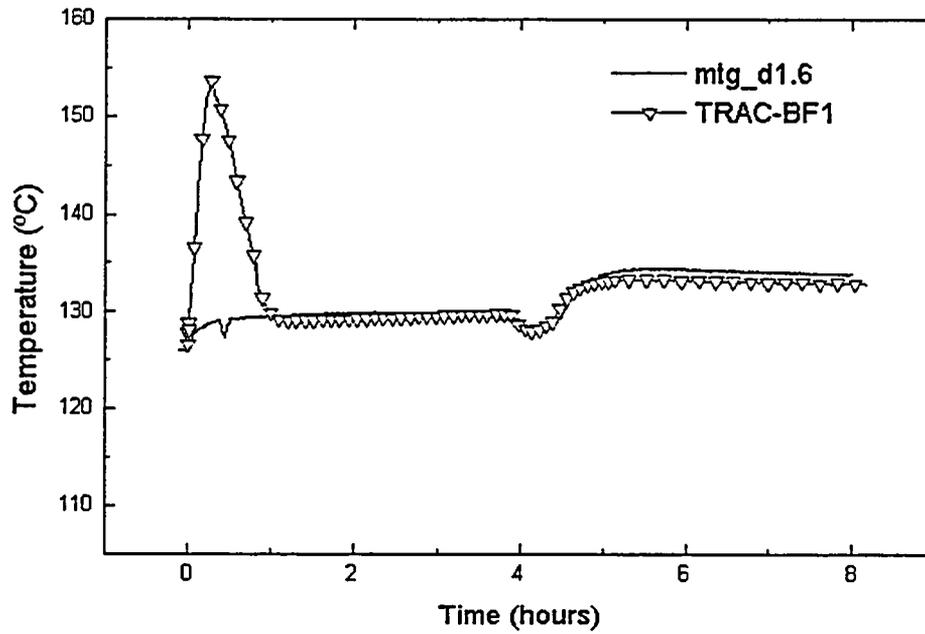


Figure 8. Drywell temperature evolution

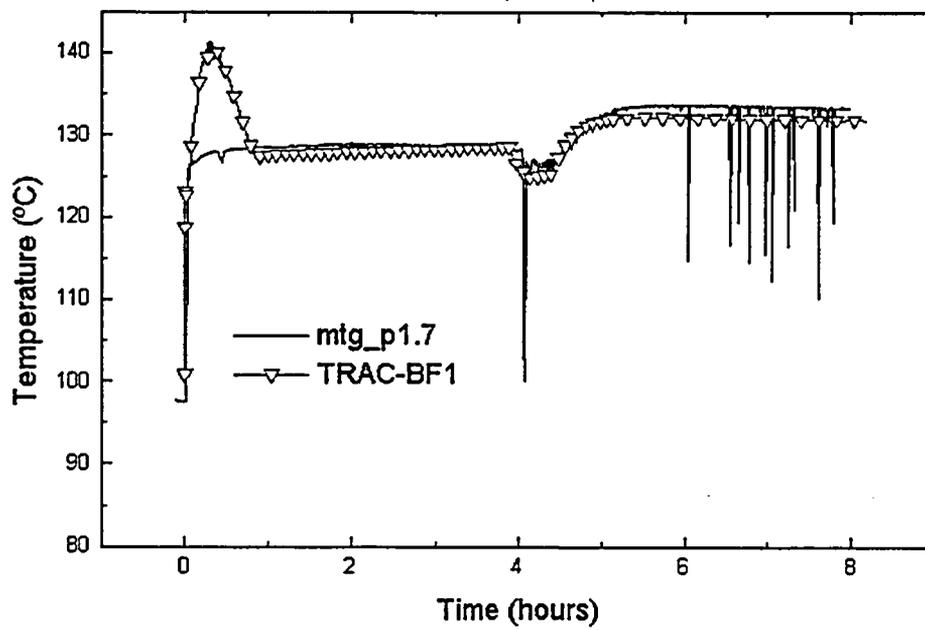


Figure 9. PCC1 tube temperature

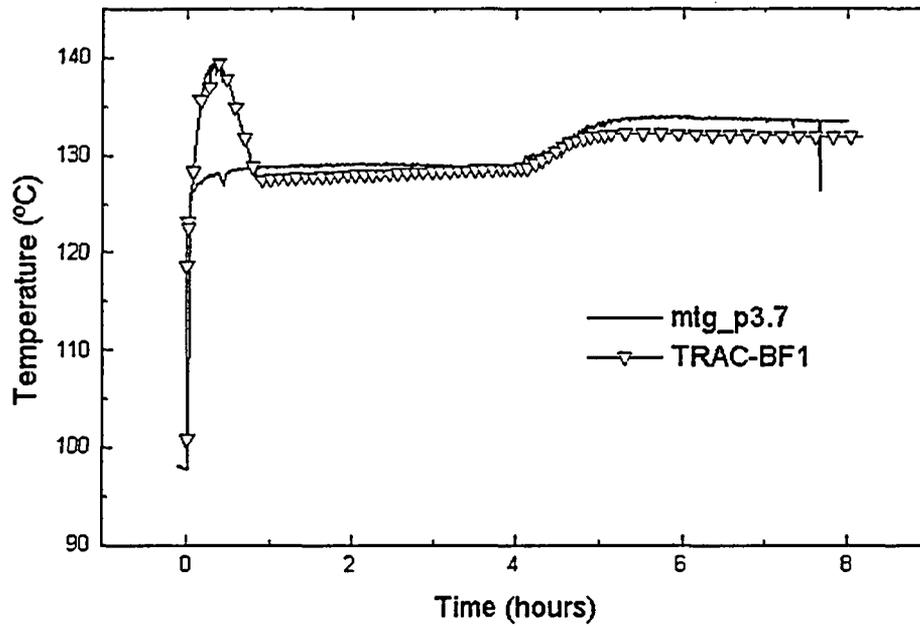


Figure 10. PCC3 tube temperature

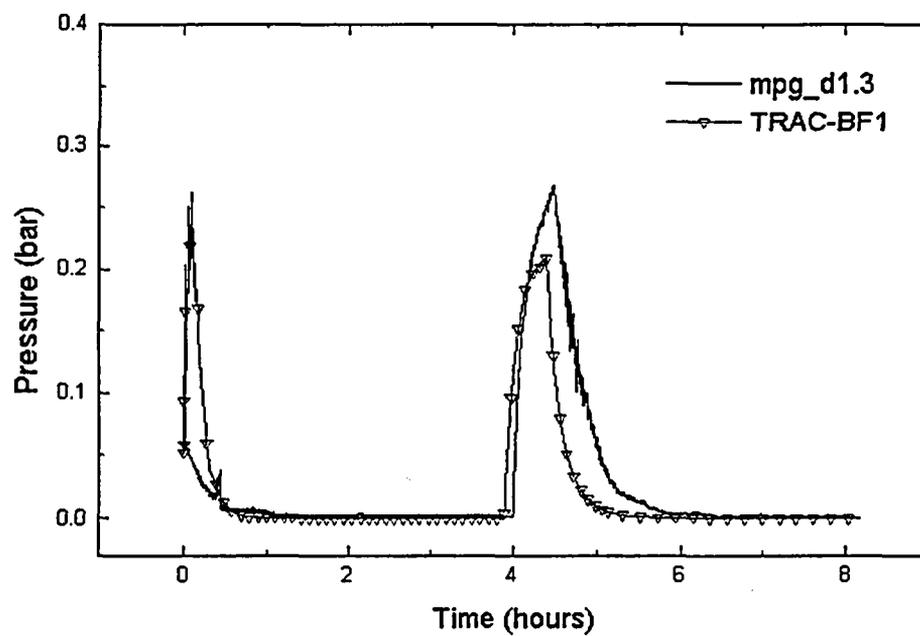


Figure 11. DW1 air partial pressure

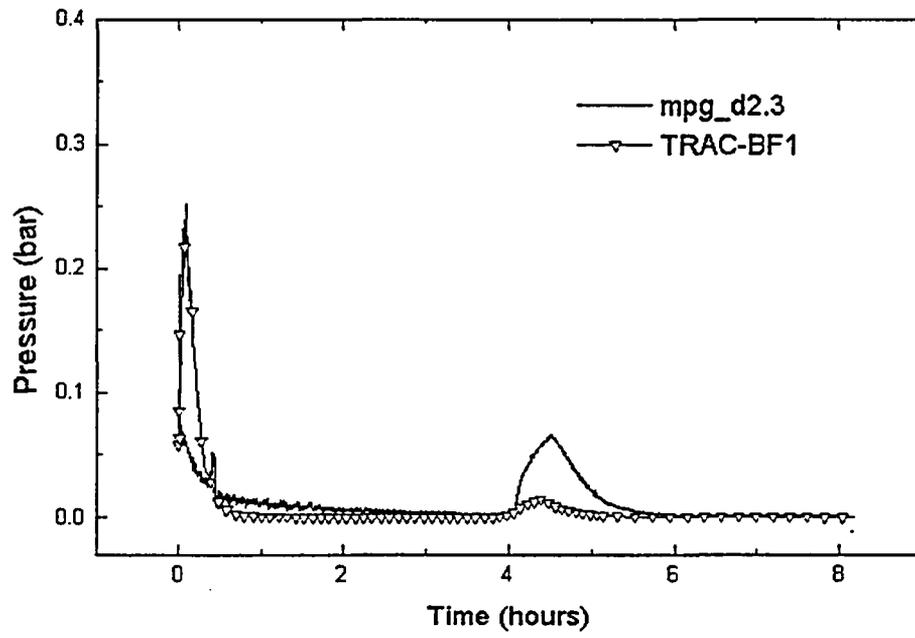
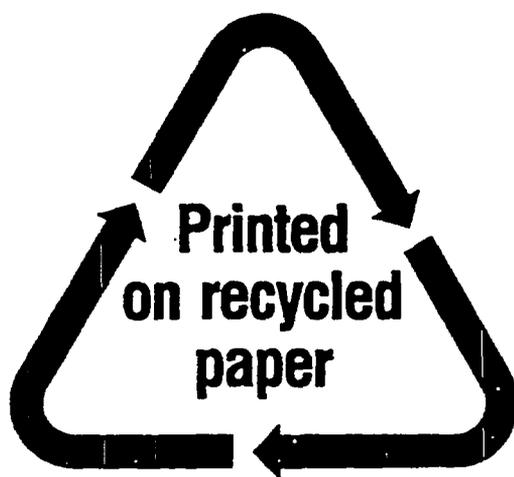
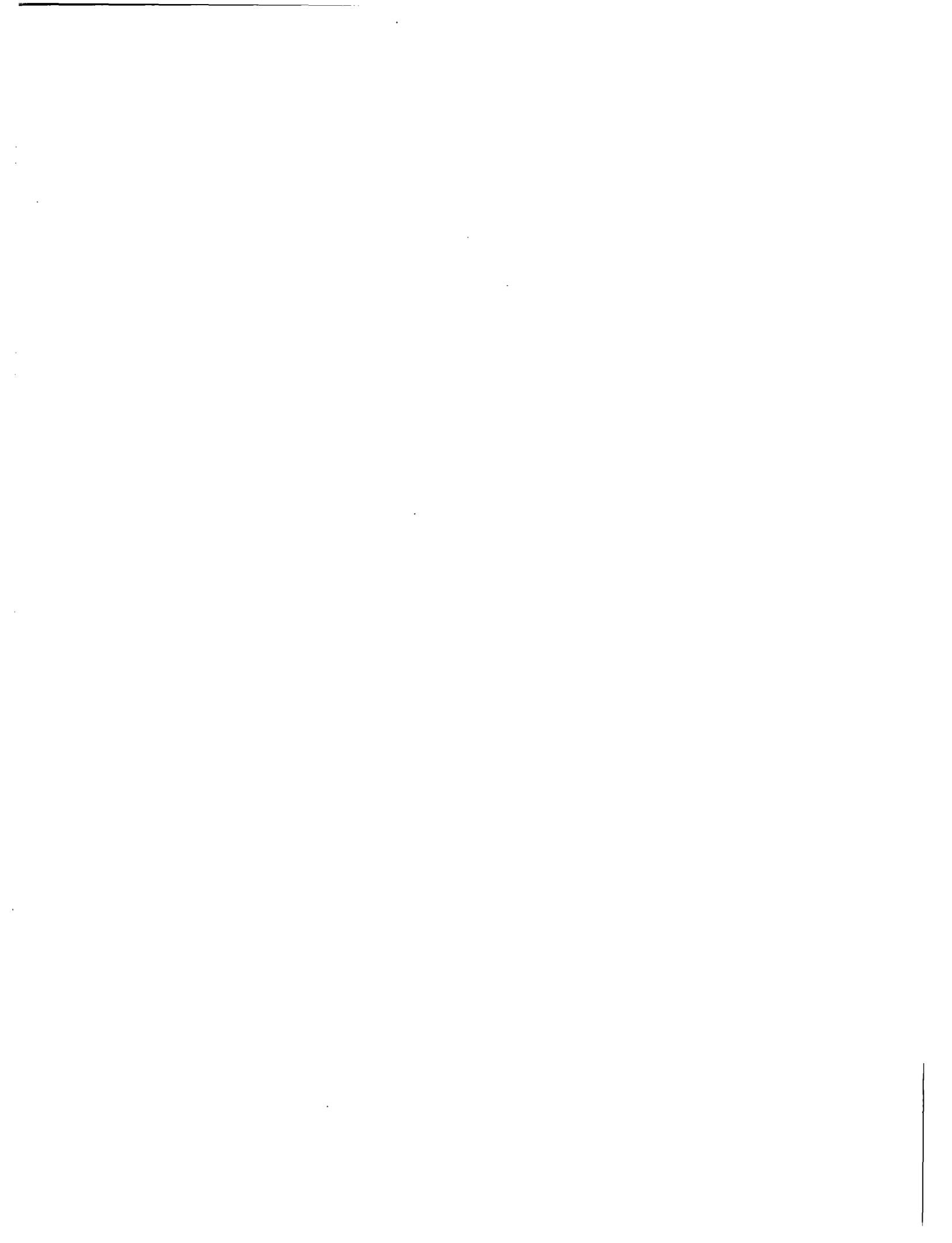


Figure 12. DW2 air partial pressure

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<p>As a part of the TEPSS project, within the last fourth Framework Programme of the European Union R&D activities, an investigation focused on the residual heat removal passive safety systems in the future boiling water reactors was performed using PANDA facility and the codes RELAP5, MELCOR and TRAC-BF1. The main purpose was to ensure the capacity of these passive safety systems under a wide range of different conditions and hypothesis on the availability of them as well as to assess the quality of some of the most commonly used codes to predict the containment response within a LOCA. The plant design chosen as reference was the ESBWR, which is a special version of the SBWR adapted to reach licensing conditions in European countries. The PANDA facility, located in the Paul Scherrer Institute (Switzerland), has been extensively used in the past for testing the passive condenser performance for the SBWR. According to the reference plant, PANDA facility was appropriately modified. A set of eight tests was executed covering different conditions in the containment for the LOCA scenario, such as asymmetric conditions for the gas distribution in the drywell as well as for the passive condensers availability and the effect of trapped air in the drywell among others.</p>						
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