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F. Dabbene, J. Brinster, D. Abdo, E. Porcheron, P. Lemaitre, G. Mignot, R. Kapulla, S. Paranjape, M. Kamnev, A. Khizbullin

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EXPERIMENTAL ACTIVITIES ON STRATIFICATION AND MIXING OF A GAS MIXTURE UNDER THE CONDITIONS OF A SEVERE ACCIDENT WITH INTERVENTION OF MITIGATING MEASURES PERFORMED IN THE ERCOSAM-SAMARA PROJECT

F. Dabbene[1*], J. Brinster[1], D. Abdo[1], E. Porcheron[2], P. Lemaitre[2],
G. Mignot[3], R. Kapulla[3], S. Paranjape[3], M. Kamnev[4], A. Khizbullin[4]
[1] *CEA, Saclay, DEN/DANS/DM2S/STMF - F-91191 Gif-sur-Yvette Cedex, France*
[2] *Institut de Radioprotection et de Sûreté Nucléaire, F-91192 Gif-sur-Yvette Cedex, France*
[3] *Paul Scherrer Institut, CH-5232 Villigen PSI Switzerland*
[4] *JSC Afrikantov OKB Mechanical Engineering, Nizhny Novgorod, 603074, Russian Federation*
[*] *Contact author: frederic.dabbene@cea.fr*

Abstract

The ERCOSAM-SAMARA project is based on severe accident scenarios involving large amounts of hydrogen leading to explosive atmospheres. A generic scenario was scaled down according to the facilities involved in the project: TOSQAN from IRSN, SPOT from JSC Afrikantov OKBM, MISTRA from CEA and PANDA from PSI. Each scenario is divided into two sequences. The first one is dedicated to the establishment of the hydrogen explosive atmosphere. The second one consists in the impacts of different mitigation means namely spray, cooler or thermal effects of passive auto-catalytic recombiner (Heater device). Tests dedicated to spray system were not performed in SPOT and to cooler not in TOSQAN. Heater mitigation means was investigated in MISTRA and PANDA. Thus, an amount of fourteen tests were performed in the project. In this paper we present the experimental work performed in each facility as well as an overview of the experimental results.

I. INTRODUCTION

The EURATOM co-financed ERCOSAM project and the ROSATOM co-financed SAMARA project have been conducted in parallel during the period 2010-2014 to investigate the containment thermal-hydraulics of current and future Light Water Reactors for severe accident management with two main objectives. The first was to determine the strength of representative hydrogen stratification that can be established from existing plant calculations of Loss Of Coolant Accident (LOCA). The second was to determine whether this stratification can be broken down by the operation of Severe Accident Management (SAM) devices.

According to project objectives, the possibility to obtain a rich hydrogen layer was analysed with a generic containment and a generic scenario was scaled down according to the facilities involved in the project [1]. Each scenario is divided into two sequences. The first one is dedicated to the establishment of the hydrogen explosive atmosphere. The second one consists in the impacts of different mitigation means namely spray, cooler or Passive Auto-catalytic Recombiner (PAR). This paper present the experimental part of the program. Companion papers are devoted to numerical simulations [2, 3] and physical analysis [4].

In the first section, test facilities involved in the project are presented. In the second section, test protocols are identified and experimental results are highlighted. To conclude, key points are summarised.

II. FACILITY DESCRIPTION

Tests with comparable initial and boundary conditions in facility with different geometrical scales and compartmentalisation allow for insights on the phenomenology to be associated with investigated accident scenarios. They also allow to identify the effects which could be facility dependent and therefore not to be expected in real plant containment. Thus, facilities involved in the ERCOSAM-SAMARA project, TOSQAN from IRSN [5], SPOT from JSC Afrikantov OKBM [6], MISTRA from CEA [7] and PANDA from PSI [8], operate at a different scale (from $7\,\mathrm{m}^3$ for TOSQAN to about $180\,\mathrm{m}^3$ for PANDA). Moreover, MISTRA is compartmented with internal structures while in PANDA two vessels are connected with a pipe. In all facilities, for safety purpose, H_2 is simulated by helium.

In this section, each facility is described with particular attention paid to equipments used in the project.

II.A TOSQAN

The TOSQAN facility was developed by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) from 1998 in order to perform thermal hydraulics containment studies in the field of severe accidents in Pressurised Water Reactor (PWR), especially linked with the hydrogen risk.

General principle. The TOSQAN enclosure is a cylindrical chamber of stainless steel (height of 3930 mm and diameter of 1500 mm) and a sump connected on the basement of the TOSQAN cylindrical chamber (height of 870 mm and diameter of 684 mm). A schematic view of TOSQAN facility can be seen in Figure 1. The total internal volume (including the sump) is $7\,\mathrm{m}^3$.

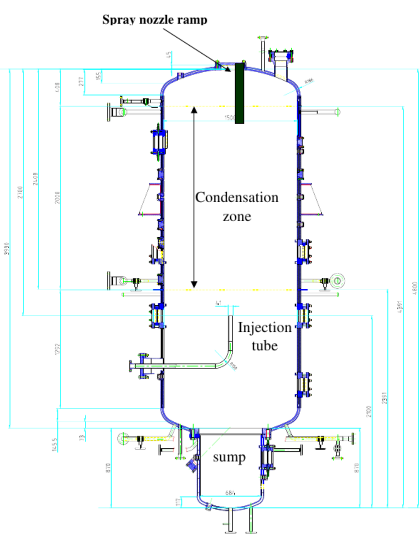

Figure 1: Schematic view of the TOSQAN facility.

Wall temperature. The whole wall is thermostatically controlled, being made of double shield of stainless steel, within which circulates the heat-transport fluid (mineral oil). The envelope is divided into two zones, in order to fix two different values of the wall temperature. The top and bottom parts of the vessel, including sump, have the same temperature, called the *hot temperature*. On the middle zone (Figure 1), which constitutes the so-called condensation zone, we impose a different temperature, called the *cold temperature* or the temperature of the *cold wall*.

The circumference of each part of the vessel is divided into 8 vertical identical and independent sectors, inside which the oil flows from bottom to top. In each sector the oil flows upwards in horizontal zigzags in elementary channels of rectangular section. This device insures the same temperature of the walls along the circumference at each height of the vessel. The *cold wall* temperature may vary with the vertical direction when the condensed mass flux is high but no more than 2^oC. During spray test, a small decrease of the temperature of the low part of the non condensing wall (including sump wall) is measured.

Inlets and outlets. At the bottom of the facility, the height of the main injection tube is 2100 mm, directed towards the top of the vessel in the centre of it. The steel thickness of the tube is 4.5 mm. Its internal diameter is 41 mm. The tube is totally empty, and contains no particular device for velocity profile or turbulence. At the top of the facility, the injector is a stainless steel cylindrical tube of 13 mm of internal diameter, bored with 6 holes of 0.9 mm of internal diameter. These holes are located in the horizontal plan, on each side of the tube at height of 4773 mm and a radius of 0.01, 0.03 and 0.04 mm. All gases, steam, air, and helium, can be heated before injection in the vessel. Only non condensable gases can be injected through the tube at the top of the facility.

The condensed water is collected at the bottom of the *cold wall* and flows in a small heated vessel connected to the TOSQAN vessel. The mass flow rate is then measured.

A special device is used to drain the water out of TOSQAN without accumulation in the sump. The temperature and the mass flow rate of the drained water are measured during the test.

Spray system. The inner spray system located in the dome of the enclosure on the vertical axis is composed of a single nozzle. For ERCOSAM tests a full cone nozzle is used with a nozzle elevation of 4150 mm and a spray angle of -57^o. During spraying, water injected by the nozzle is collected in the sump area. No impaction of water droplets occurs directly on the vertical walls of the main vessel. Water sprays can be injected up to 80^oC depending of the mass flow rate with the use of a heating device in order to simulate the indirect injection mode.

II.B SPOT

The SPOT facility was commissioned in December 2007. It is located at JSC Afrikantov OKBM (N. Novgorod, Russia) and designed to investigate processes in the containment and containment passive heat-removal systems.

General principle. SPOT includes several equipment and systems. Among them, the SPOT containment model is intended to obtain the steam-gas mixture parameters, which simulate operating conditions in the NPP containment during LOCA. The vessel is a vertical cylindrical container with the elliptical top and bottom made of low alloyed steel 13Mn6 (height of 7850 mm and diameter of 3200 mm). A schematic view of SPOT vessel can be seen in Figure 2. The total internal volume is 59 m^3.

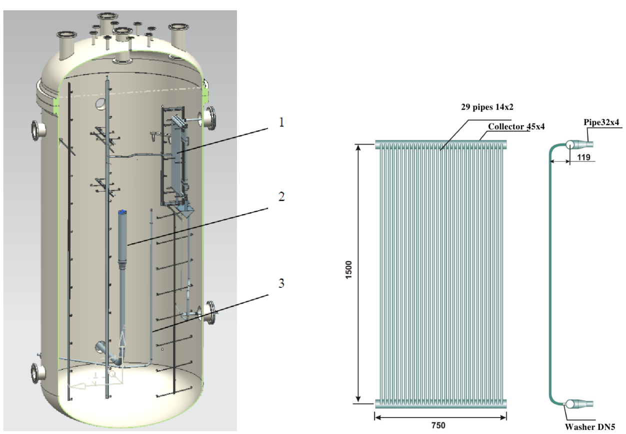

Figure 2: Schematic view of the SPOT facility (1-Cooler, 2-Steam injection pipe, 3- Helium injection pipe) and cooler device.

Wall temperature. The outer surface of the containment model is thermally insulated (insulation thickness of 150 mm with an heat conductivity of 0.05 W/m/K. Vessel heat loss .vs. steam gas mixture temperature is given in Figure 3. As example, it is about 2.2 kW when the mixture temperature is 120^{o}C.

Inlets and outlets. Steam is injected to the middle part of the containment model via the pipe vertically placed in the vessel centre (Figure 2, label 2). The inlet steam injection pipe has the inner diameter of 100 mm, which expands to 155 mm at the height of approximately 3240 mm from the containment model bottom using an adaptor installed. The material of the steam injection pipe is stainless steel 1.4541. The wall thickness is 6.5 mm. The nominal height of steam injection is 4850 mm from the bottom of the containment model and centred. In the lower point of the steam pipe, a line is installed to drain the condensate to the lower condensate tank.

Helium injection pipe is located inside the vessel at the distance of 600 mm from the vessel centre (Figure 2, label 3); it is placed axially between the steam injection

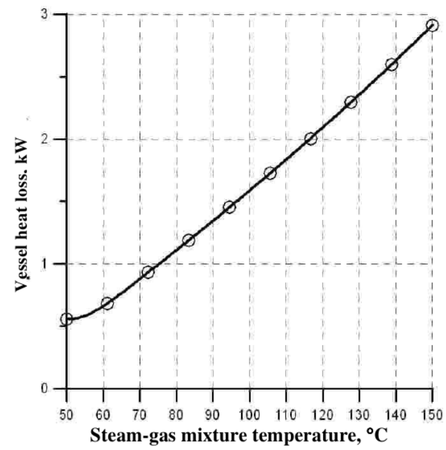

Figure 3: SPOT vessel heat losses .vs. steam gas temperature.

pipe and the cooler. At the vessel inlet, the strip heater is installed on the helium injection pipe to maintain the assigned temperature of the gas being injected. The nominal height of the injection point is 4850 mm from the vessel bottom. The helium injection pipe has the inner diameter of 32 mm. The material of the helium injection pipe is stainless steel 1.4541; the wall thickness is 4 mm.

Cooler. The cooler consists of one row of 29 straight pipes (Figure 2). The outer diameter of the pipes is 14 mm and the wall thickness is 2 mm. The height of the pipes is 1500 mm. From the top and bottom, heat-exchange pipes are connected to collectors. The outer diameter of the collectors is 45 mm and the wall thickness is 3 mm. The pitch of adjacent heat-exchange pipes is 11 mm. Collectors are connected to the detached connection using pipes with outer diameter 32 mm and the wall thickness 4 mm, which are connected to pipes of the cooling circuit. The collector length is 750 mm. The heat-exchange surface is 2.12 m^2. Stainless steel 1.4541 is used as the material for the cooler. The distance from the collector axis to the heat-exchange pipe axis is 119 mm. Cold feed water is supplied via the lower pipe, and heated water is removed via the upper pipe. To provide stable water circulation through the cooler, the inlet of each heat exchange pipe is fitted with the throttling orifice of 5 mm nominal diameter. The cooler is placed inside the vessel at the height of approximately 4630 mm from the vessel bottom to the cooler lower collector and at the distance of 500 mm from the vessel wall to the cooler central pipe axis (Figure 2, label 1). The height from the cooler upper-collector axis to the vessel-top inner surface is 1730 mm.

II.C MISTRA

The MISTRA (MItigation and STRAtification) experimental programme, started in 1998, is part of CEA's programme on severe accidents and is focused on the containment thermal hydraulics and hydrogen risk management. The MISTRA facility corresponds to a linear length scale ratio of 0.1 with a typical French PWR containment.

General principle. The MISTRA facility is a stainless steel (type 304L) containment thermally insulated with a free volume of 97.6 m^3 (Figure 4). The internal diameter is 4250 mm and the maximal internal height 7380 mm. MISTRA comprises two cells, a flat cap and a bottom that are fixed together with twin flanges. A steel cylinder is also inserted inside the MISTRA facility. It consists of two cylindrical shells with a diameter of 1906 mm and a height of 4219 mm. The bottom of the lower cylinder is located at 1245 mm and the top at 5464 mm. At connection between these two shells, a ring floor is added to provide a partitioning of the flow. The external board of this floor is located at an altitude of 3658 mm, and a radius of 1728 mm.

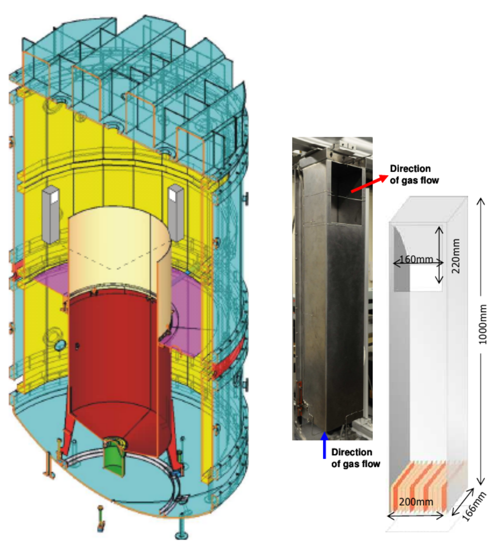

Figure 4: Schematic view of the MISTRA facility with Heaters in situation.

Wall temperature. The external part of the vessel is not temperature regulated but thermally insulated with 200 mm of rock wool. The total mass of stainless steel is about 40 tons. The stainless steel wall thicknesses are for the side walls 15 mm, for the bottom 25 mm, for the flanges 110 mm and for the ceiling, 119 mm. This last value is an equivalent thickness due to the presence of many stiffeners as the ceiling is flat.

On top of each other, three cylindrical thermally regulated walls, the so-called *condensers*, are inserted inside the containment along the stainless steel containment wall. They are specially designed to ensure well-controlled boundary conditions ($\pm 1^o$C). The internal diameter is 3794 mm and the total condensing height lies in the range 1285 mm to 7280 mm (with for the lower condenser height of 2187 mm and the middle and the upper condensers height of 1784 mm). The external part is insulated with 20 mm of synthetic foam.

In the so-called *dead volume* behind the condensers, spurious condensation may occur during experiments with steam injection due to heat losses at the not thermally regulated external wall of the containment.

Inlets and outlets. The steam is produced by a large boiler and injected by three different lines in the containment. The steam mass flow rate is up to 140 g/s, controlled and measured with sonic nozzles that ensure a constant flow rate independently of the downward operating conditions. The main injection line used in ERCOSAM tests is upward at the ring plate height of 3660 mm, with the radial position of 1346 mm and the angular position of 165^o. In that case, a removable chimney is added above the injector nozzle of 72 mm in diameter. A diffusion cone ensures a flat velocity at the nozzle exit but, due to the chimney, it is no more valid at the tube exit. All the steam lines are isolated with rock wool and equipped by drain valve to remove any water plug before test.

Helium is injected at the same location as steam.

Specific circuits are used to measure wall condensation mass flow rate at the containment, the inner compartment and each condenser locations.

Spray system. The spray circuit allows water droplet injection from the near centre of the ceiling (elevation of 6496 mm, radius of 50 mm and angular position of 97^o5), with different types of nozzle. The nozzle used in ERCOSAM is a Hollow cone (distributed by Lechler under the reference 373.084.17.BN) with an orifice diameter of 0.38 inch and a nominal spray angle at 40 Psi of 62^o.

Due to the angle of the spray and its elevation, the complete spray penetrates inside the inner compartment. In the present configuration water coming from the inner of the compartment is derived through a drain to the bottom part of MISTRA. Since the drain is designed for low water condensation flow rate, it is undersized to the much higher spray mass flow rate. Hence water accumulates in the bottom part of the compartment during the spray phase and is transferred through the drain to the bottom of MISTRA during and after the spray. It is about 0.315 kg/s for a spray mass flow rate of 1 kg/s. Moreover, from the beginning of the spray phase up to the end of the test, water is not removed from MISTRA, so that it accumulates in the bottom part of the facility.

Cooler. No specific system has been designed for cooler test in MISTRA. The cooler test consists in the cooling down of the middle condenser of the facility in order to promote the steam condensation at the middle condenser.

Heater. The heaters are electrically powered, and are used to simulate the thermal effect of a PAR (Figure 4). The heater design is based on the real PAR model Siemens FR90/1-150 (full scale, $1000 \times 200 \times 166\,\mathrm{mm}^3$). The flow inlet is located at the bottom face of the heater ($200 \times 166\,\mathrm{mm}^2$) while the flow outlet is located at the top, on the front side ($220 \times 160\,\mathrm{mm}^2$). Each heater is built in stainless-steel and is equipped with a heating module located in a rack at the bottom part of the housing. The heating module of each Heater is made of 14 parallel stainless steel plates, each equipped with a heating wire inserted inside the plate. The heating power is delivered by Joule heat and the maximum electrical power is limited to 6 kW.

The Heater inlet elevation is 5150 mm (Figure 4). Hence, the heater outlet is above the top of the inner cylinder. The outlet radial position is 1470 mm, in between the inner cylinder and the condenser radius. One heater is located at the angular position of 0^o and the second one at 270^o.

II.D PANDA

The PANDA facility is located at the Paul Scherrer Institut (PSI). It has a modular structure with interconnected structures and pools. It was used to investigate passive decay-heat removal systems, stratification breakup, gas mixing and related containment phenomena for a number of next-generation as well as current light water reactors.

General principle. In the ERCOSAM test series, only two vessels and some auxiliary components of the facility were used (Figure 5). Each cylindrical vessel has an inner height of 7984 mm and an inner volume of $89.9\,\mathrm{m}^3$. They are connected by a Interconnecting Pipe (IP) with a large diameter of 928 mm and 5175 mm in length. The total volume is $183.3\,\mathrm{m}^3$.

Each of the two vessels is fabricated of four sections of stainless steel (DIN 1.4571) with a constant outer diameter of 4000 mm but with an inner diameter varying with the different wall thickness of the sections (from 3957 mm to 3964 mm). Two cylindrical sections are in the centre part of each vessel and two curved closures are at the bottom and at the top.

Wall temperature. The PANDA vessels and the IP were carefully insulated using two layers of rockwool, each 100 mm thick. The heat losses of PANDA have been experimentally determined by heating up the facility with steam to a pressure of about 4.15 bar

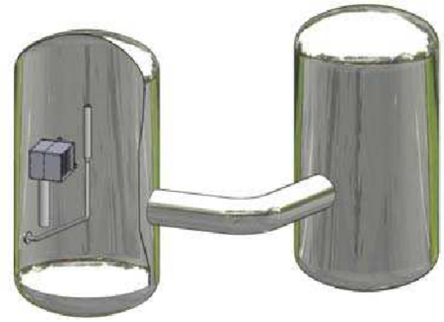

Figure 5: Schematic view of PANDA facility with cooler in situation.

and a corresponding saturated temperature of 418 K, and by measuring the cool-down of the system, which lasted about 27 hours. The results of the determination of the heat losses in the two vessels and the IP are summarised in Table 1. It includes the heat loss

Temperature [^{o}C]	Q_{loss} **[kW]**
105	12.44
110	13.67
115	14.66
120	16.13
125	17.39
130	19.00
135	21.68

Table 1: PANDA heat losses as a function of the fluid temperature

of about 3 kW in average associated with the leak estimated to 2×10^{-3} kg/s detected after PE4 test was performed. For the remaining tests the leak was fixed and the leak rate was decreased to 8×10^{-5} kg/s which is negligible compared to the ERCOSAM injection flow rate (74×10^{-3} kg/s steam). So, the associated heat losses.

Inlets and outlets. The outlet of the steam and helium injection pipe is located at 4000 mm from the bottom of Vessel 1. The 200 mm pipe is installed in the centre of Vessel 1.

Spray system. The outlet of the spray is located in the centre axis 6900 mm from the bottom of Vessel 1. A hollow cone and a full cone spray nozzle have been used during the spray test series. The former is the same as in MISTRA. The latter is provided by SSCO Spraying System AG under the reference HH-30 and has a spray opening angle of 30^o.

Cooler. The cooler is located 4000 mm above the bottom of Vessel 1 (Figure 5), at 500 mm from the wall on the 305^o azimuthal direction according to the reference frame (opposite side to the IP). The cooler consists of a casing with three open faces (at the top, facing the wall and facing the IP) which stands an array of 224 cooling tubes composing height vertical tube serpentines (Figure 6). The cooler casing is made of stainless

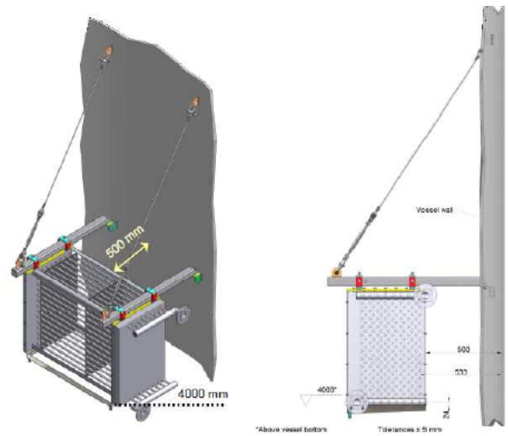

Figure 6: Sketch of the PANDA cooler device.

steel 1.4404 whereas the cooling tube are made of stainless steel 1.4571. The inlet flow enters the cooler line at the top and then is divided into the eight streams corresponding to the eight vertical serpentine tubes. Condensate water accumulating at the bottom of the cooler casing is drained by two temperature resistant polymer pipes to the bottom of the Vessel 1.

Heater. A one meter height electrical Heater is used to simulate an operating PAR (Figure 6). The Heater is located 4200 mm above the bottom of Vessel 1, at 500 mm from the wall on the 135^o azimuthal direction according to the reference frame (IP side). It has a maximum output power of 10 kW. The casing had two open faces. One is located at the top front face of the casing with the opening of $330 \times 200\,\mathrm{mm}^2$. The other is at the bottom face of the casing with the horizontal opening of $370 \times 170\,\mathrm{mm}^2$. The casing made of 2 mm thick stainless-steel 1.4404 covers the heating elements.

III. TEST DESCRIPTION

Each scenario is divided into two sequences (Figure 8). According to severe accident scenario the first sequence is divided in three Phases and is dedicated to the establishment of the hydrogen explosive atmosphere: Phases 1 and 2 are linked to the LOCA blowdown (steam injection) and to the core damage (hydrogen injection). The Phase 3 is a relaxation phase with no more injections (post core damage phase). The second sequence (Phase 4) is the mitigation phase and consists in the impacts of different mitigation means

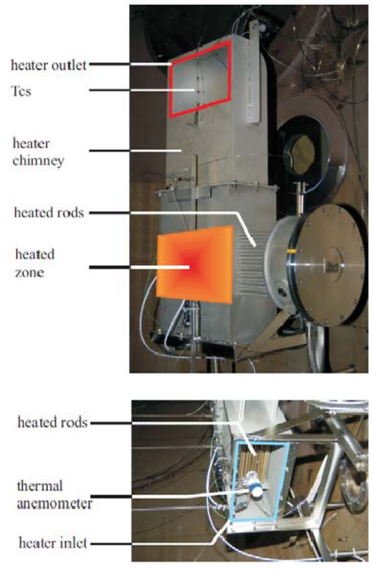

Figure 7: Sketch of the PANDA Heater device.

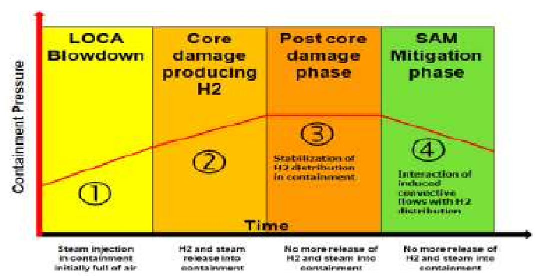

Figure 8: Test phases according to severe accident scenario.

namely spray, cooler or thermal effects of passive autocatalytic recombiner. For safety reasons, helium is used instead of hydrogen. Hence, hydrogen consumption and steam production with PAR cannot be recovered and only thermal effects are simulated with specific Heater devices.

Despite the fact that several aspects of the tests performed in each facility are different, an effort has been made to define the Phase 4 for selected tests with comparable initial and boundary conditions. Test protocols were scaled down from a generic containment and a generic scenario [1]. At the end of injection phases, the following target conditions have to be reached: a total pressure of about 2.5 bar, about 10%vol of helium in the helium layer, and about 60%vol of steam above the injection. The remaining tests have been defined to address parameters which provide a broader understanding on the basic phenomenology.

III.A Test Overview

Tests dedicated to spray system were not performed in SPOT. Heater mitigation means was investigated in MISTRA and PANDA, cooler process in MISTRA, TOSQAN and SPOT. An amount of fourteen tests were performed in the project (Table 2).

TOSQAN	**Test**	**SAM**
[9, 10]	T114	Spray (FC)
	T115	Spray (FC)
	T116	Spray (FC)
SPOT	**Test**	**SAM**
[11, 12]	S1	Cooler
	S2	Cooler
MISTRA	**Test**	**SAM**
[13, 14]	MERCO_0	No SAM
[15, 16]	MERCO_1	Spray (HC)
[17, 18]	MERCO_2	Cooler
[19, 20]	MERCO_3	Heater
[19, 20]	MERCO_4	Heater
PANDA	**Test**	**SAM**
[21, 22]	PE1	Spray (HC)
[23, 24]	PE2	Spray (FC)
[25, 26]	PE3	Cooler
[27, 28]	PE4	Heater
[29, 30]	PE5	Cooler

Table 2: ERCOSAM-SAMARA experiments (FC=Full cone, HC=Hollow cone)

In TOSQAN, three tests have been performed (T114, T115, T116) addressing the effect of spray activation, and a full cone spray nozzle has been used. In MISTRA tests address the effect of activation of a hollow cone spray nozzle (MERCO_1), a cooler (MERCO_2), one heat source (MERCO_3), two heat sources (MERCO_4). In addition a reference test (MERCO_0) has been performed without SAM activation and with an extended Phase 3, to observe the effect of diffusion and natural circulation on the gas mixture composition evolution. In PANDA, one test has been performed with activation of a hollow cone spray nozzle (PE1), one test with a full cone nozzle (PE2), two tests with a cooler (PE3 and PE5) and one test with one heat source (PE4). In SPOT two tests have been performed with activation of a cooler (S1 and S2).

To be representative of the conditions in the generic containment and to obtain target conditions, it is necessary to consider a preconditioning phase, Phase 0, to provide compatible initial conditions to the Phase 1. In MISTRA, condensers are set to 120^{o}C, containment wall is heated up to 110^{o}C and a nearly homogeneous air/steam mixture at 113^{o}C and 1.5 bar with 5%vol of steam is generated. In PANDA, the pressure is 2 bar, the steam concentration is 50% and the gas as well as the wall temperature is 105^{o}C (resp. 135^{o}C) for PE1, PE3 and PE4 tests (resp. PE2 and PE5). In SPOT, the pressure is 2 bar, the wall temperature about 105^{o}C, the gas temperature 103^{o}C and the steam concentration 53%. In TOSQAN, dry air at 1 bar and several temperatures (120^{o}C, 129^{o}C and 140^{o}C respectively in T114, T115 and T116 tests) are observed according to the prescribed hot and cold wall temperatures (Table 3).

Test	**Hot Wall**	**Cold Wall**
T114	120^{o}C	120^{o}C
T115	140^{o}C	110^{o}C
T116	140^{o}C	140^{o}C

Table 3: *Hot* and *cold wall* temperatures in TOSQAN.

III.B Stratification Build Up

The global phenomena taking place in Phases 1 (steam release, Table 4), 2 (helium release, Table 5) and 3 (stabilisation, Table 6) are: containment pressurisation (TOSQAN: 2.2 − 2.8 bar; MISTRA: 2.56 bar; SPOT: 2.5 bar; PANDA: 2.5 bar, and gas mixture stratification build-up (helium in the upper layer of the vessel, e.g. TOSQAN: up to 100%; MISTRA: 9.5% in average at the upper condenser elevation; SPOT: 12%; PANDA: 12-14%). In MISTRA, pressure slope in time is modified twice due to spurious condensation at the cap on one hand, and at the containment behind the condensers on the other hand.

Test	**Q (g/s)**	**Temp. (^{o}C)**	**Delay (s)**
SPOT	24	120/127	P=2.5 bar
MISTRA	39	116/178	1710
PANDA	73	137	P=2.5 bar
T114	—	—	—
T115	4/10/15	130/160	2400
T116	4	140/169	1000

Table 4: Steam injection, Phase 1.

Test	**Q (g/s)**	**Temp. (^{o}C)**	**Delay (s)**
SPOT	1	100	750
MISTRA	30	135/140	33
PANDA	4	125	350
T114	0.8	140	P=2.5 bar
T115	0.4	140	200
T116	0.4	140	200

Table 5: Helium injection, Phase 2.

Test	Between Steam & He injection	Phase 3 (s)
S1	250	600
S2	300	—
MISTRA	200	600
PANDA	480	500
T114	—	—
T115	—	—
T116	200	400

Table 6: Relaxation Phases.

Moreover, thermal stratification was observed in the vessel wall and gas space. The thermal stratification was related to the injection conditions, (such as injection exit elevation), to the facility characteristics (presence of concentrated heat sinks, inter-compartment flow transport) and to the condensation and re-evaporation phenomena, which were taking place in some of the tests due to the specified initial and boundary conditions.

III.C SAM activation

The global phenomena which took place in Phase 4 (activation of spray, cooler or Heater), were containment depressurisation (cooler and spray), as well as gas atmosphere mixing (cooler, spray, Heater).

Spray tests. The same HC spray nozzle and spray injection flow rate has been used in MERCO_1 and PE1 tests (see Table 7), so that it was possible to investigate the effect on the gas species evolution of spray activation for two types of multi-compartments facilities. The PE2 test was performed using a full cone nozzle, and spray water injection conditions as for the PE1 test. Comparing these two PANDA tests allowed for study of the effect of a spray induced flow pattern, which can be more uniformly distributed in the case of the hollow cone nozzle. The T114, T115, T116 tests have been performed with a full cone nozzle and for different initial and boundary conditions and allowed the observation of the phenomenology evolution in a smaller scale facility.

Test	Q(g/s)	T(^{o}C)	Delay (s)
MERCO_1	1000	30	1500
PE1	1000	30	2000
PE2	840	30	2000
T114	30	30	6000
T115	30	30	6000
T116	30	30	6000

Table 7: Spray conditions, Phase 4.

The PE1 (HC nozzle) and PE2 (FC nozzle) tests had similar depressurisation rates; the containment pressure decreased from 2.5 bar to 1.5 bar in about 2000 s. Nonetheless in the PE1 test, the phenomenology associated with gas species evolution was more complex, due to the initial higher gas/wall thermal stratification in the vessel. This further affected the condensation and re-evaporation phenomena as well as the inter-compartment flow transport. As result, in the PE1 test the helium-rich layer was broken more quickly than in PE2 (Figure 9).

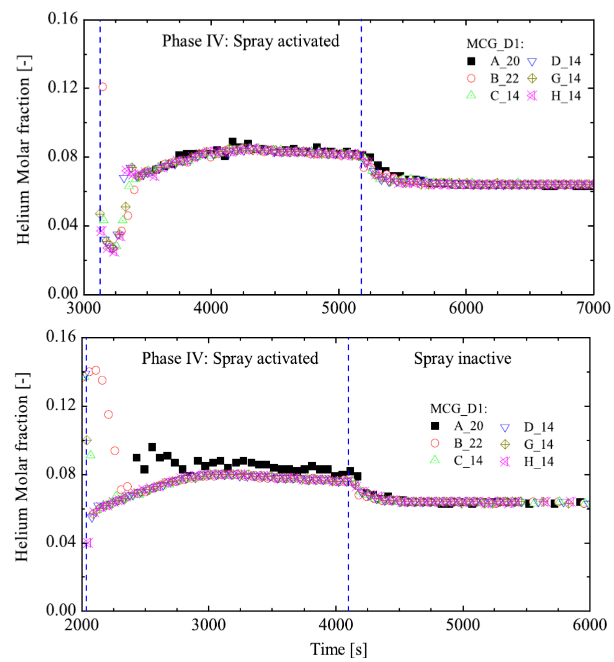

Figure 9: PANDA. Helium molar fraction evolution observed in Vessel 1 during spray Phase 4 in PE1 (top), PE2 (bottom).

In MERCO_1 test (HC nozzle), the pressure decreased from 2.56 bar to 1.5 bar in about 1500 s and in a shorter time the helium-rich layer was broken. In the T115 test the pressure decreases to 1.7 bar in about 5000 s. The injection of the spray droplets in the hot helium (T114), and in the air/steam mixture at low saturation ratio (T116) induces the vaporisation of a fraction of the injected droplets (Figure 10) which is coupled to the re-evaporation of the fallen droplets in the sump. Therefore vaporisation effects prevail on the condensation of steam on the injected spray droplets and as a consequence lead the facility pressure increase.

Cooler Tests. The PE3, PE5, MERCO_2, S1 and S2 tests have been performed by activating a heat sink in phase 4, for example cooler devices or, in the case of MERCO_2, a condenser (see Table 8). The initial vessel wall and fluid condition for PE5 and S2 tests

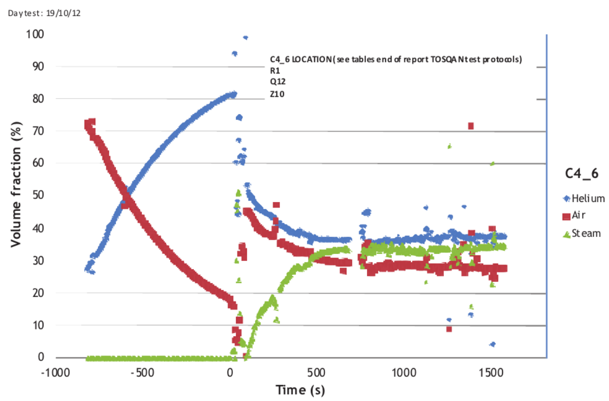

Figure 10: T114. Steam, air and Helium molar fraction evolution in time.

were defined in such a way as to avoid wall condensation and therefore to observe specifically the effect from the cooler operation. These two tests permitted observation of the effect of cooler design for two different facility scales. The combined cooler and wall condensation effects have been investigated in PE3 test. The controlled wall condensation has been investigated in MERCO_2 with the middle condenser acting as heat sink. The S1 and S2 tests have been defined with the cooler and the source release in the middle region of the containment as for PE3 and PE5 tests. The S1 test has been defined with the same scenarios as PE3. In the S2 test the cooler has been activated during the helium release phase to observe the cooler effect on the helium stratification build-up during the helium release and on the overall mixing (after the helium release phase has been completed).

Test	**Cooling process**
S1	Q=0.30 kg/s at 24^{o}C for 7500s
S2	Q=0.25 kg/s at 24^{o}C for 750+7500s
MERCO_2	Middle condenser at 80^{o}C
PE3 & PE5	Q=0.5 kg/s at 30^{o}C for 7200s

Table 8: Cooling process, Phase 4.

When cooler is activated, the containment pressure decreased more slowly than in the spray tests. In the PE3 test the pressure decreased from 2.5 bar to 1.47 bar in 7710 s and in PE5 from 2.5 bar to 1.35 bar in 7262 s; in the MERCO_2 test from 2.56 bar to 2.2 bar in 2500 s; in the S1 test from 2.5 bar to 1.2 bar in 9380 s and in the S2 test from 2.5 bar to 1.2 bar in 9304 s.

The evolution of gas species, in particular the cooler's capability to destabilise a stratified hydrogen atmosphere, is related to the release conditions (radial and vertical release locations) for the given scenarios, the cooler design (exposed cooler tubes, or tubes inside a case with closed faces), the cooler position within the containment and with respect to the release location.

The cooler used in PE3 and PE5 tests was installed in the middle region of the PANDA containment, and the cooler design included cooling pipes inside a frame with open sides (leaving a possibility for the helium/steam/air mixture to leave the cooler flowing through the cooler pipes). The convection induced by the cooler was confined within 1 m above the cooler and therefore the helium rich-layer was only partially eroded (Figure 11).

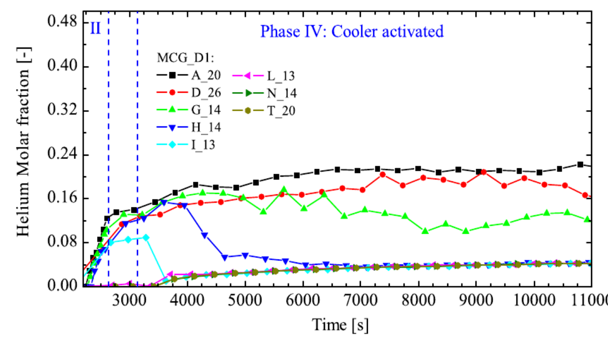

Figure 11: PE3. Helium molar fraction evolution in Vessel 1 for cooler Phase 4.

In the MERCO_2 test, with activation of the condenser installed in the medium elevation of the MISTRA containment, a stratified atmosphere consisting of two main zones persisted until the end of the test. A helium-rich layer remained in the free volume above the middle condenser. In the annular space between the middle condenser and the inner compartment and above the annular ring, remained a stable air-rich mixture.

In the S1 (Figure 12) and S2 tests, the convection induced by the cooler activation also lead to a partial erosion of the helium-rich layer located in the upper region of the facility. Moreover the activation of a cooler in the S2 test during the helium-release phase did not produce qualitative differences in the helium-rich layer break-up.

Heater Tests. The Phase 4 for the tests performed with a Heater, MERCO_3, MERCO_4 and PE4, have been defined considering Heater power curves resembling the energy which could be released by a PAR (see Table 9).

The metallic cases (box type geometry) for the Heater elements used in MISTRA and PANDA allowed similar flow paths, for example a horizontal opening at the inlet (vertical flow path into the Heater) and vertical opening at the exit (horizontal flow path at the exit of the Heater). In the PE4 test, the Heater ele-

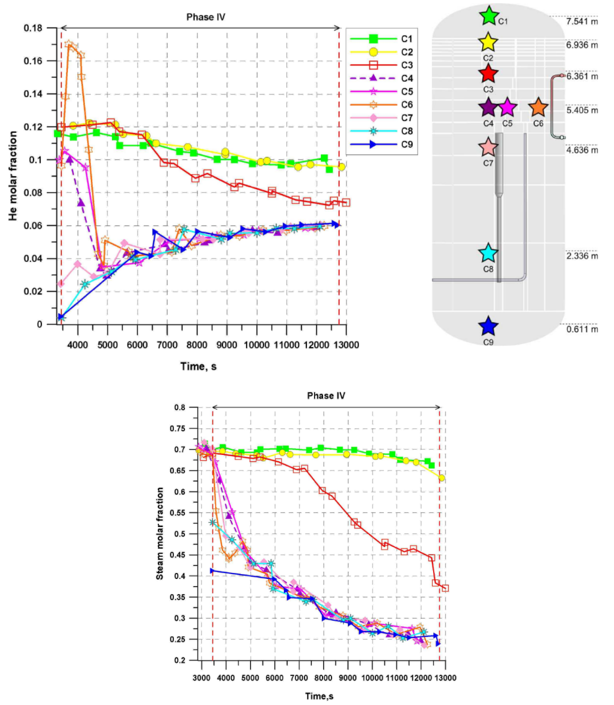

Figure 12: S1. Helium (top) and steam (bottom) molar fraction evolution for cooler Phase 4.

Test	Heat power (kW) @ time(s)
MERCO_3	1/6/6/1 @ t4/t4+4000/t4+6000/t4+10^4
MERCO_4	2 × (0.5/5.5/0.5) @ t4/t4+3500/t4+7000
PE4	1/10/1 @ t4/t4+3500/t4+7000

Table 9: Heater heat power, Phase 4.

ment was installed at an intermediate elevation near the interconnecting pipe elevation. The MERCO_3 test was performed with a single Heater installed in the periphery of the facility, in the region of the internal compartment exit elevation. The MERCO_4 test was performed with two Heater elements installed at the same elevation and radial location as in MERCO_3 but a different circumferential angle. By comparing the three tests, it was possible to observe the induced heat source convective flow for different facility geometries (PE4, MERCO_3) and moreover the flow pattern created by two heat sources (MERCO_4).

In all tests the heat loss from the facility walls prevailed over the heat source by the Heater/s and the pressure slightly decreased during the Heater activation. The convection induced by the Heater in PE4 lead to complete homogenisation of the gas mixture located above the heat source inlet elevation. A gas mixture with a lower helium content slightly diffused downward and flowed through the top of the IP towards Vessel 2. Nonetheless the Heater effect on gas mixing in the region below the Heater was rather limited (Figure 13).

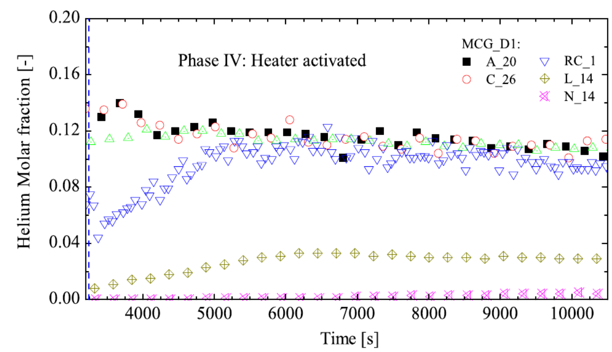

Figure 13: PE4. Helium molar fraction evolution in Vessel 1 for cooler Phase 4.

In MERCO_3 and MERCO_4, with the Heater located in the upper compartment region, the helium homogenisation extended to the elevation of the ring plate and, by comparison with MERCO_0, the facility compartments allowed the creation of flow patterns leading to the transport of helium below the Heater elevation faster than without SAM activation (Figure 14).

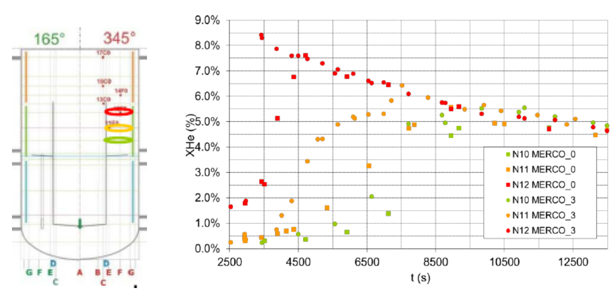

Figure 14: MERCO_0, 3 & 4 comparisons. He molar fraction evolution in time behind the middle condenser.

IV. CONCLUSION

The experimental and analytical investigations carried out within the EURATOM-ROSATOM ERCOSAM-SAMARA projects have contributed to the advancement of knowledge on issues that have relevance for reactor containment safety analysis. The phenomenology addressed in TOSQAN, MISTRA, SPOT and PANDA tests include pressurisation, gas stratification build-up, stratification break-up, gas mixing, condensation, re-evaporation, de-pressurisation under the effect of spray, cooler or Heater activation. These phenomena are expected to take place in the containment of LWR/HWR during a postulated severe accident with core degradation and release of hydrogen.

According to the scenario and facility specificities, the most efficient way to mixed the helium layer with the surrounding is spray activation: cooler only erodes the bottom of the helium layer while Heater homogenises the volume above its elevation. Nevertheless, latter results seem to indicate that the hydrogen cloud could be burned by PAR [31]. Moreover, it was demonstrated that downward transport of light gas by slow process (diffusion and thermal effects) is possible in complex geometries.

The experimental database obtained with the project has already been used by the project Organisations to assess various computational tools and to advance modelling capabilities and simulation approaches [2, 4]. A detailed description of the experiment phenomenology and of the test analysis is available in the various project reports. They have now to be published for dissemination purposes.

Acknowledgements

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References

[1] S. Benteboula, et al. EURATOM-ROSATOM-ERCOSAM-SAMARA projects scaling from nuclear power plant to experiments, These proceedings.

[2] M. Andreani, et al. Modelling of stratification and mixing of a gas mixture under the conditions of a severe accident with intervention of mitigation measures, These proceedings.

[3] T. Yudina, et al. HYMIX benchmarking tests: code to code comparison, These proceedings.

[4] J. Malet, et al. Analysis of stratification and mixing of a gas mixture under severe accident conditions with intervention of mitigation measures, These proceedings.

[5] E. Porcheron, et al. TOSQAN facility description, IRSN, ERCOSAM P3.2 (2011-04), 2011.

[6] M. Kamnev and A. Khizbullin. SPOT facility description, OKBM, ERCOSAM D5.11 (2012-09), 2012.

[7] J. Brinster, et al. MISTRA facility description, CEA, ERCOSAM P3.3 (2011-03), 2013.

[8] N Erkan, et al. PANDA facility description, PSI, ERCOSAM P3.1 (2011-02), 2011.

[9] C. Ledier, et al. TOSQAN test protocols for 114-115-116 test, IRSN, ERCOSAM P3.5 (2012-07), 2012.

[10] C. Ledier, et al. TOSQAN test report, ERCOSAM tests 114-115-116, 2013. IRSN internal report PSN-RES/SCA/LECEV/2013-32, ERCOSAM P3.8 (2013-09).

[11] M. Kamnev and A. Khizbullin. SPOT test protocols, JSC Afrikantov OKBM, ERCOSAM D5.12 (2013-15), 2013.

[12] M. Kamnev. SPOT data analysis report, JSC Afrikantov OKBM, ERCOSAM P3.14 (2014-01), 2014.

[13] D. Abdo, et al. Test protocol for MISTRA MERCO_0 test: Phases I to III without SAMs activation, CEA, ERCOSAM P3.4_MERCO_0 (2012-6a), 2012.

[14] D. Abdo, et al. Quick Look Report for MISTRA MERCO_0-Steam (01/12/2011) and MERCO_0 (07/02/2012 and 13/04/2012) tests, CEA, ERCOSAM P3.9A (2012-12), 2012.

[15] D. Abdo, et al. Test protocol for MISTRA MERCO_1 test: Hollow cone spray test, CEA, ERCOSAM P3.4_MERCO_1 (2012-6b), 2012.

[16] D. Abdo, et al. Quick Look Report for MISTRA MERCO_1 tests: Hollow cone spray test, CEA, ERCOSAM P3.9B (2012-12b), 2012.

[17] D. Abdo, et al. Test protocol for MISTRA MERCO_2 test: Middle condenser cooling test, CEA, ERCOSAM P3.4_MERCO_2 (2012-6c), 2012.

[18] D. Abdo, et al. Quick Look Report for MISTRA MERCO_2 tests: Middle condenser cooling test, CEA, ERCOSAM P3.9C (2012-12c), 2013.

[19] D. Abdo, et al. Test protocol for MISTRA MERCO_3 and MERCO_4 tests: Heater tests, CEA, ERCOSAM P3.4_MERCO_3&4 (2012-6d), 2012.

[20] D. Abdo, et al. Quick Look Report for MISTRA MERCO_3 and MERCO_4 tests: Heater tests, CEA, ERCOSAM P3.9D (2013-18), 2013.

[21] G. Mignot, et al. Test protocol for PANDA test PE1, hollow cone spray test, PSI, P3.6A (2012-02), 2012.

[22] G. Mignot, et al. Test report for PANDA test PE1, hollow cone spray test, PSI, ERCOSAM P3.7A (2012-17), 2012.

[23] G. Mignot, et al. Test protocol for PANDA test PE2, full cone spray test, PSI, P3.6B (2012-10), 2012.

[24] S. Paranjape, et al. Test report for PANDA test PE2, full cone spray test, PSI, ERCOSAM P3.7B (2013-03), 2013.

[25] G. Mignot, et al. Test protocol for PANDA test PE3, cooler test, PSI, P3.6C (2012-11), 2012.

[26] G. Mignot, et al. Test report for PANDA test PE3, cooler test with wall condensation, PSI, ERCOSAM P3.7C (2013-04), 2013.

[27] G. Mignot, et al. Test protocol for PANDA test PE4, heater test, PSI, P3.6D (2012-01), 2012.

[28] G. Mignot, et al. Test report for PANDA test PE4, heat source test, PSI, ERCOSAM P3.7D (2012-13), 2012.

[29] G. Mignot, et al. Test protocol for PANDA test PE5, cooler test, PSI, P3.6E (2012-16), 2012.

[30] R. Zboray, et al. Test report for PANDA test PE5, cooler test with wall condensation, PSI, ERCOSAM P3.7E (2013-05), 2013.

[31] F. Dabbene. PAR elevation influence on hydrogen floor layer depth. In *Proc. of NURETH-14*. Toronto, Canada, September 25-30, 2011.