PERFORMANCE OF HYDROGEN MITIGATION SYSTEMS FOR A SCALED ACCIDENT SCENARIO: OVERVIEW OF ERCOSAM PROJECT EXPERIMENTAL RESULTS FOR THE PANDA FACILITY

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ABSTRACT

ERCOSAM and SAMARA are the acronyms for two parallel projects co-financed respectively by EURATOM and ROSATOM during the period 2010-2014 with the general aim to advance the knowledge on the phenomenology associated with the hydrogen and steam spreading and stratification in the LWR containment during a postulated severe accident. An overview of the results obtained during the experimental test campaign carried out in the PANDA facility at PSI during this project is presented. Five tests were conducted, which follow a predefined test sequence based on a postulated severe accident scenario, scaled from existing nuclear power plant design and leading to the formation of potentially explosive atmosphere. The test scenarios were divided into two parts, first the formation of a stratified helium atmosphere (substituting hydrogen) and then the activation of mitigation systems such as spray, cooler or recombiner (simulated by heater device). The activation of these systems leads to different responses in terms of depressurization rate, helium mixing with air and helium relocation within the facility. The activation of spray showed a fast depressurization of the facility - 100 *kPa* in 2000 *s* - as well as a complete and rapid homogenization of the gas concentrations in the vessels where the spray is injected. Cooler device resulted in a slower depressurization rate down to about 70 *kPa* in the first 2000 s. The mitigation of the helium stratification, however, is limited by the cooler capacity to mobilize gas located just above it. The heater device which simulates the thermal activity of a recombiner is enable to mobilize gas located just below its inlet.

KEYWORDS
ERCOSAM, Severe accident, hydrogen mitigation, cooler, spray, PAR, stratification erosion.

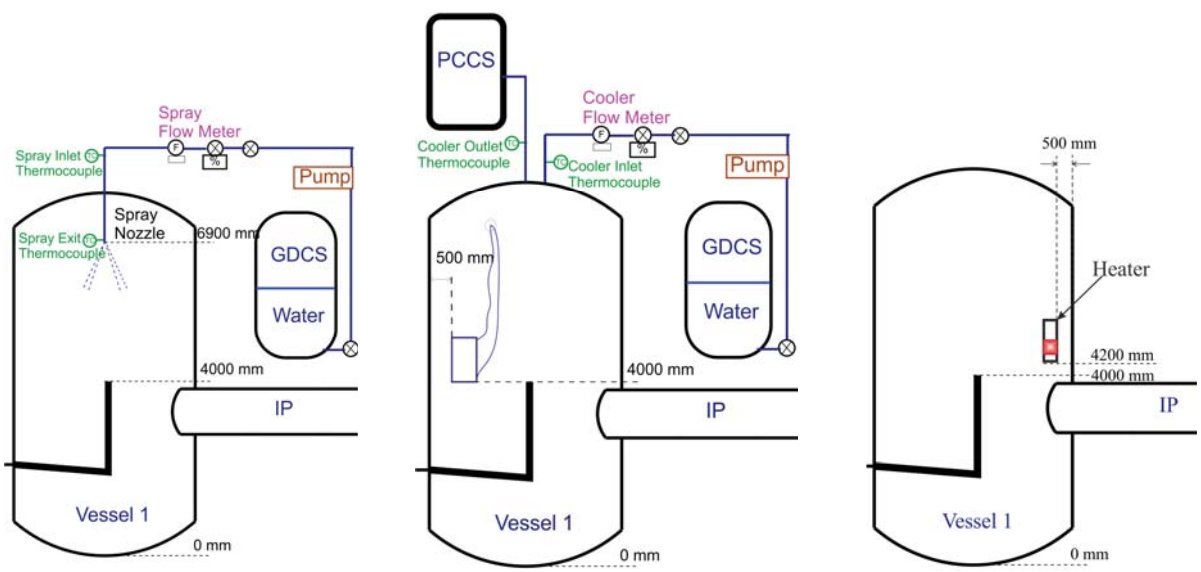
1. INTRODUCTION

Following a postulated severe accident, hydrogen will be released in the containment of nuclear power plants due to the oxidation of zirconium in fuel cladding with steam at high temperatures. The formation of pockets of hydrogen with high concentration may lead to deflagration or detonation, damaging safety equipments and challenging the containment integrity [1]. The containment atmosphere mixing and stratification phenomena have been identified as high ranking issues for LWR safety [2].The various thermal-hydraulic processes leading to the stratification of hydrogen and the potential destabilization or break-up of the hydrogen layer by the operation of engineered safety systems (e.g. coolers, sprays, and catalytic re-combiners) are complex due to a large number of inter-related or coupled processes, such as, buoyant jets and plumes, diffusive flow, mixing and stratification condensation and re-evaporation etc. Owing to this complexity of the phenomena involved, advanced Lumped Parameter (LP) and Computational Fluid Dynamics (CFD) codes, which are used for analyzing these accident scenarios, require extensive validation against experimental data with sufficient temporal and spatial resolution. In order to address these needs, EURATOM and ROSATOM have supported and co-financed two projects, ERCOSAM and SAMARA, respectively [1]. The two-fold goal of the project included establishing the likelihood of hydrogen stratification and determining whether this stratification, once established, can be removed by the operation of Severe Accident Management systems (SAMs); sprays, coolers and Passive Auto-catalytic Recombiners (PARs). To investigate these phenomena and identified eventual scaling effect on the phenomenology, an experimental study on containment hydrodynamics in the presence of activated safety systems was carried out in four facilities of different scale TOSQAN (IRSN, 7 m^3), MISTRA (CEA, 98 m^3) and PANDA (PSI, 184 m^3), **[**3**]**, for the ERCOSAM project and SPOT (JSC Afrikantov OKBM, 59 m^3) for the SAMARA project. The paper presents the results of the experiments that have been carried out in the PANDA facility and identified as PE1 to PE5.The objective is to verify experimentally for the selected scenario, the possibility to create a helium stratification atmosphere and the effect of the operation of different safety devices on the distribution and evolution of the gas temperature, pressure, and concentration in a simulated containment.

2. PANDA EXPERIMENTAL FACILITY AND TEST CONFIGURATION AND TEST PROCEDURE

2.1. Panda experimental facility and test configuration

The PANDA facility is a large scale, multi-compartmental thermal hydraulic facility suited for investigations related to the safety of current and advanced LWRs [3]. The containment compartments the reactor pressure vessel (RPV) and the gravity driven cooling system (GDCS) are simulated in the PANDA facility by six cylindrical pressure vessels. Various auxiliary systems are also available to maintain and control the necessary initial and boundary conditions during a test. The maximum operating conditions of the facility are 10 bar at 200 °C



(a) - PE1 and PE2 (b) – PE3 and PE5 (c) – PE4

Figure 1. Experimental set-ups for (a)-spray (b)-cooler and (c)-heater device tests.

In the ERCOSAM project, the experiments were carried out in a large double compartment with 183.3 m^3 total volume consisting of the two identical vessels (Vessel 1 and Vessel 2) having a height of 8 *m* and a diameter of 4 *m* each. Vessel 1 and 2 are connected by a large interconnecting pipe (IP) with a diameter of 1 *m*. The RPV was used as a steam source to inject superheated steam into Vessel 1, through a 200 *mm* diameter bent pipe with upward facing exit located at 4000 *m* from the bottom of Vessel 1, Figure1. The same pipe was used for the injection of helium. Four different safety systems were successively used during the experimental test campaign, namely, two spray nozzles, a cooler and a heater device.

Spray test

Each spray nozzle installed in the center of Vessel 1 was oriented downward, with its exit at 6900 *mm* from the bottom of the vessel, Figure 1-(a). A hollow cone spray nozzle designed to generate a swirling spray in the shape of a hollow cone with a cone angle of 60° was used first. Then a full cone spray nozzle designed to generate a full cone spray with a cone angle of 30° was used. For both configurations, the spray water flow rate was measured by a vortex flow meter, while the inlet and exit temperature of the spray flow was measured by two separate thermocouples as shown in Figure 1-(a).

Cooler test

The cooler was located 4000 *mm* from the bottom of the vessel and 500 *mm* distant from the wall opposite to the IP. It consists of 8 pipes located in a frame with only the bottom plate being installed which collects the water and the side plates which maintain the pipes. The external diameter of the pipes is 16 *mm* and the pipe wall thickness is 2 *mm*. The cooling water in- and out-flow is performed through flexible hoses. The inlet flow enters the cooler line at the top and is divided into the eight streams corresponding to the eight vertical serpentine tubes. The cooler water flow rate was measured by mean of a vortex flow meter, while the inlet and outlet temperatures of the cooler flow were measured by two separate thermocouples outside of Vessel 1 as shown in Figure 1-(b). The cooling water was collected into the PCC pool located in the upper part of the facility for the cooler tests, Figure 1-(b). For all spray and cooler test the GDCS vessel was used as water reservoir with a predefined water temperature (30 *°C*).

Heater test

A 10 *kW* electric heater device was used to simulate the heating effect of a working PAR on the containment atmosphere. It was located 4200 *mm* from the bottom of the Vessel and 500 *mm* distant from the wall on the same side of the IP, Figure 1-(c). The heater consisted of a staggered serpentine of heating rods located inside a 1 *m* high stainless steel chimney. A vertical inlet was located at the bottom of the chimney whereas a horizontal outlet prolonging a 90° deflection was located at the upper part of the chimney. In the test configuration, the heater outlet was directed towards the center of Vessel 1.

2.2. Instrumentation

The two main quantities measured in the PANDA vessels 1 and 2 during the tests are 1) temperature and 2) gas mixture composition. Besides these main quantities, the data acquisition allows for the measurement of absolute and differential pressures, injection flow rates and heating power. The measurement sensors are implemented in all the facility compartments, in the system lines and in the auxiliary systems.

For the temperature measurements around 380 K-type thermocouples (TCs) were used for measuring fluid, along with inside and outside wall temperatures of Vessel 1, Vessel 2 and the IP (Table 1).The high spatial resolution of the thermocouples is well suited for the envisaged code validation purposes.

The gas concentration could be measured in the PANDA facility by mean of two Mass Spectrometers (MS). Up to 118 sampling lines can be connected to the two MS. The system could measure any gas concentration and composition. The number of sampling lines used for measurements varied in each test and during the test evolution. Different scanning sequences were programmed to monitor facility preconditioning, initial test conditions and test evolution. A thermocouple was placed a few millimeters apart from each sampling line tip so that gas concentration and temperature measurements were available at almost the same spatial location. For steam/air/helium mixtures, an absolute error on the measured molar fraction of ±1.5 % was assessed.

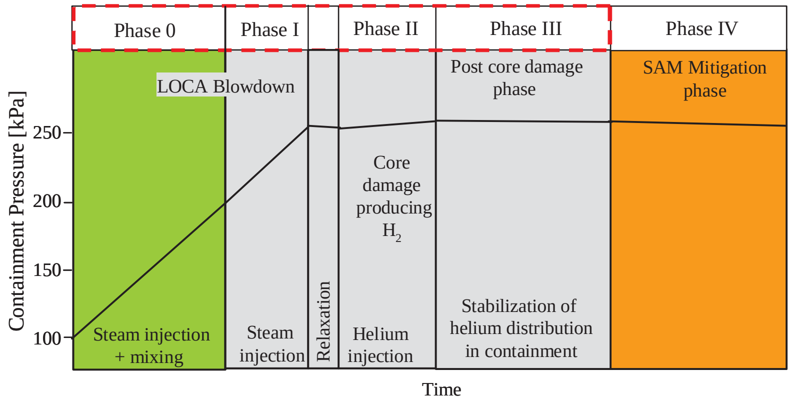


Figure 2. Schema of representing the test scenario followed during the PANDA experiments

The steam and water injections were measured with vortex flow meters with an accuracy of 1.1 % with respect to the measured value whereas the helium injection was measured by mean of thermal flowmeter with an accuracy of 5% with respect to the measured value.
Finally, for some specific test Particle Image Velocimetry was used to measured instant velocity field in the vessel itself, but the velocity fields are not subject of this article.

2.3. Test scenario

During preconditioning, the two vessels were heated up with steam to reach the desired wall temperature, 105 °*C* for the test with condensation and 135 °*C* for the test without wall condensation. After venting the steam out and injecting air, the facility was ready, with 100% air content and 100 *kPa* pressure, to initiate Phase 0 of the selected test scenario [4], Figure 2. The vessels were isolated from the environment by closing all venting lines and steam was injected in both vessels.

Table I. Initial and boundary conditions

Test	**PE1**	**PE2**	**PE3**	**PE4**	**PE5**
Safety device	Full cone spray	Hollow cone spray	Cooler	Heater	Cooler
Wall condensation	Yes	No	Yes	Yes	No
Initial pressure [*kPa*]	198	201	198	194	201
Initial wall temperature[°*C*]	~103	~128	~103	~103	~128
Phase I					
Steam mass flow rate[*g/s*]	73.4 ±*1.5*	72.6 ±*1.3*	73.4 ±*1.2*	73.4 ±*1.4*	72.7 ±*1.2*
Steam injection time [*s*]	1774	714	1794	1882	751
Relaxation time [*s*]	486	476	486	478	503
Phase II					
Helium mass flow rate [*g/s*]	5.33 ±*0.01*	5.33 ±*0.03*	5.32 ±*0.04*	5.33 ±*0.05*	5.33 ±*0.01*
Helium injection time [*s*]	352	344	350	350	344
Phase III					
Relaxation time [*s*]	512	502	498	524	500
Phase IV					
Activation time [*s*]	2030	2062	7710	7200	7262
Water Flow rate [*kg/s*]	1.03 ±*0.01*	0.876 ±*0.01*	0.504 ±*0.002*	-	0.500 ±*0.007*
Water temperature [°*C*]	30.5 ±*0.04*	30.7 ±*0.04*	31.18 ±*0.18*	-	30.9 ±*0.1*
Power [*kW*]	-	-	-	1 to 10	-

To ensure a homogeneous mixture in the facility, gas was additionally sucked from the top of both vessels and reinjected at the bottom of the vessels and the IP. The end of Phase 0 was defined with the pressure reaching 200 *kPa* and the gas mixture being composed of ~50% air and ~50% steam, by volume. The test procedure itself consisted of four phases, each corresponding to a phase of the postulated accident scenario discussed previously, and one additional relaxation phase with the following characteristics:

- Phase I: Superheated Steam at 140 *°C* was injected through the injection pipe at 74 *g/s*, until a pressure of 250 *kPa* was obtained in the vessels. The starting time, of this phase is considered as the starting time of the test.
- Relaxation Time: Phase during which the gas mixture composition in both vessels was extensively measured. Additionally the helium injection was prepared. This phase lasted for ~480 *s*.
- Phase II: Helium heated to about 125 *°C* was injected through the injection pipe with 5.33 *g/s*. This phase lasted for ~350 *s*. This injection time was chosen such that an average of 12% molar fraction was obtained in Vessel 1 in the volume above 4000 *mm*.
- Phase III: The facility was set to rest for ~500 *s* for the stabilization of the helium distribution in the vessels.
- Phase IV: The safety system was activated and the evolution of pressure, temperature and gas concentrations was measured extensively. The different parameters associated with the activation of the safety system are presented in Table I along with the initial and boundary conditions of each phase. Note that for test PE4, the activation of the heater device was defined as such: a power ramp from 1 to 10 *kW* for 3600 s and then from 10 to 1 *kW* in the next 3600 s.

The venting remained closed for the duration of the test such that the pressure evolution in the facility is a function of the facility heat losses, the mass source (injection) and phase change (condensation) occurring during the test. A particular emphasis was put on the wall condensation for the definition of the test. The two spray tests, despite different types of nozzles and water flow rates, present important cases in that the injected steam condensed on the wall in test PE1 while wall condensation is avoided in test PE2. In the same manner, the two cooler tests PE3 and PE5 differ only in the possibility for the steam to condense on the vessel wall during the test. This was done to follow a step by step approach to increase the complexity of the numerical simulation. In addition to the spray test PE1 and PE2, two tests were conducted outside of the project to complement the findings. The results of these tests have been reported by Sidharth et al. [5, 6].

3. RESULTS AND DISCUSSION

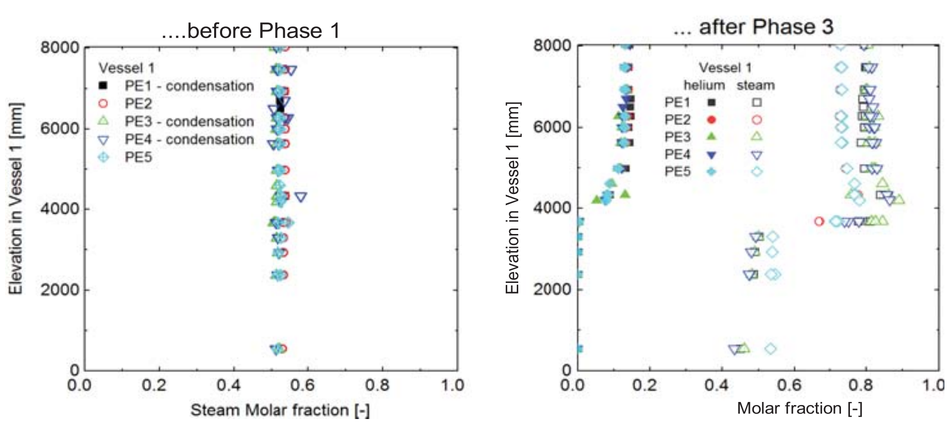
The content of this section represent a selection of the results obtained during the ERCOSAM experimental campaign in PANDA. At first, the steam/helium stratification build up is presented with a special emphasis on experimental procedure repeatability. Then a comparison of the effect of the activation of the different safety system on the stratification break up / erosion is presented in the second part. Finally a discussion related to the different observed flow patterns and to the efficiency of the devices forms the third part. More detailed discussions can be found in the project technical reports, which can be obtained through the participating agencies of the ERCOSAM project.

3.1. Formation of steam/helium stratification atmosphere– Phase I to III - Repeatability

The first three phases of the test scenarios aim to reproduce the formation of a stratified helium layer in a steam environment representative of the hydrogen build up expected in the postulated accident scenario.

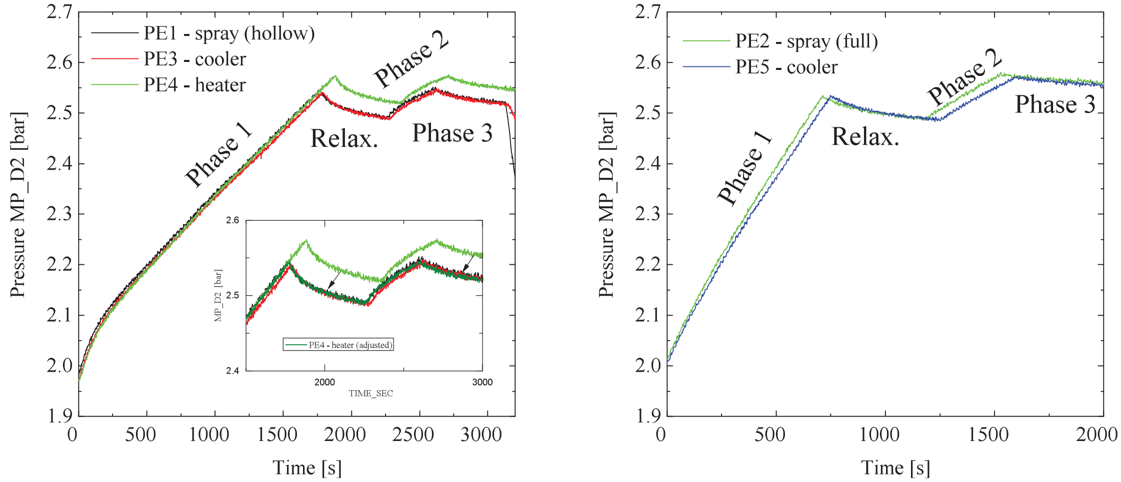
The results are grouped in tests allowing for wall condensation (PE1, PE3 and PE4) and the ones without wall condensation (PE2 and PE5).
<u>*Initial conditions:*</u> The initial concentration profiles measured in Vessel 1 before the beginning of Phase I and at the end of phase III are presented in Figure 3. A homogeneous mixture of 50% air and 50% steam in volume is present initially. The *condensing* tests have an initial wall temperature of 103 *°C* whereas the *non-condensing* tests have an initial wall temperature of 128 *°C*, Table I. The pressure measured at the beginning of Phase I was about 200 *kPa*, Table I.

<u>*Phase I*</u>: Steam is injected in Vessel 1 leading to an increase of the pressure and of the steam content in the facility. The evolution of the pressure during phase I to III is presented in Figure 4 and the evolution of the steam content in Phase I is presented in Figure 5.
Pressure evolution shows remarkable repeatability from test to test and although the steam injection lasted slightly longer for test PE4, the comparison remains valid if we adjust the maximum pressure at the end of Phase I to compare the pressure evolution in the following Phase II and III, Figure 5-(a) insert. The slight difference in the pressure evolution of PE2 and PE5, Figure -(b) originates from the presence of the cooler that leads to some spurious condensation and slows down the pressurization process. For example, after 250 *s* the pressure increases steadily at a rate of about 28 *Pa/s* for PE1 compared to 69 *Pa/s* for PE2. The difference accounts for the loss due to condensation to the wall. At the end of Phase I the pressure reaches about 255 *kPa* in the facility.
For PE1, representative of the tests with wall condensation, the steam content increases up to 0.95 in the upper part of Vessel 1, A_20 and H_14, while it decreases slightly in the lower part of the vessel, N_14 and T_20, Figure 5-(a). The injected superheated steam enters in a heavier gas environment such that, subject to positively buoyant force it flows to the upper part of the vessel. The steam accumulates and condenses on the wall, a process which is associated with an increase of the wall temperature. As the temperature rises, the allowed steam content rises as well (dictated by the corresponding saturation pressure). A strong steam concentration gradient is formed between the top of the facility and the injection level (y=4000 *mm*). Increased steam content at L level and on top of the IP, TD2_1, at t=500 *suggests* a transport of steam from Vessel 1 to Vessel 2 during Phase I, Figure 5-(a) and (b). For PE2, the steam content increases to 0.85 only, at the top of Vessel 1, A_20 and H_14 on Figure 5 -(b) and no decrease of the steam content is observed in the lower part of the vessel, T level. Inter-compartment flow is similar to the one observed for PE1, as depicted by L_14 and TD2_1 of Figure 5-(b).



(a) (b)

Figure 3. (a)Initial steam concentration and (b) intermediate steam/helium concentration vertical profile before activation of safety system for all five tests.

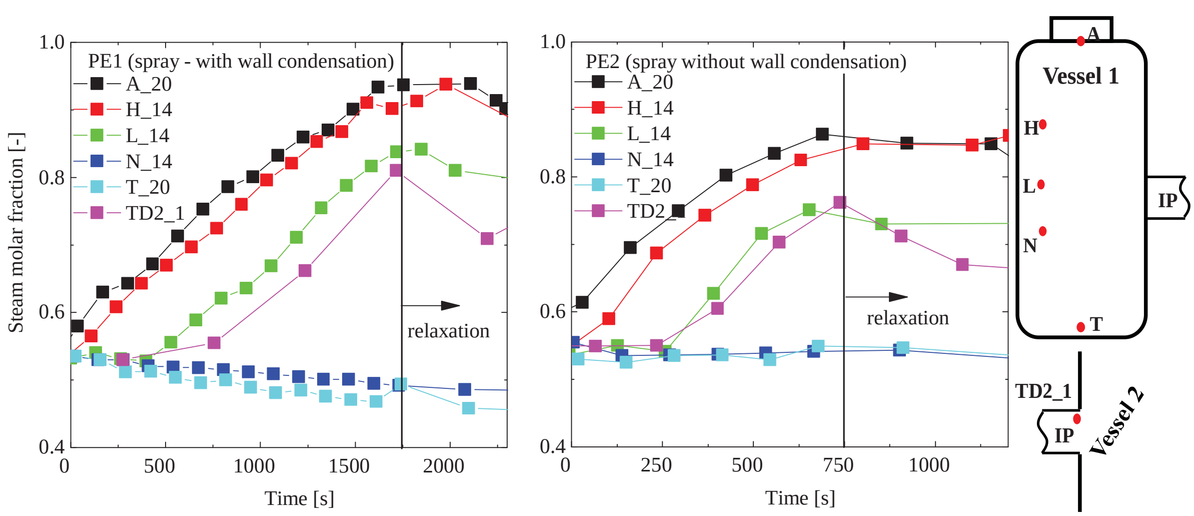


(a) (b)

Figure 4. Pressure evolution in Phases I to III for (a) PE1, PE3 and PE4 and (b) PE2 and PE5 tests

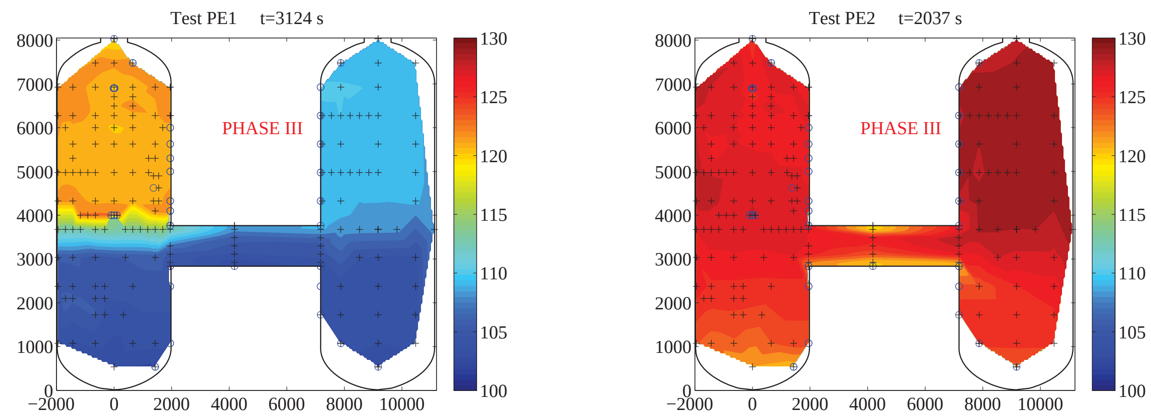
The steam stratification is also associated with a thermal stratification for the tests with wall condensations, PE1, PE3 and PE4, Figure 6-(a). The increase of the wall and gas temperature is observed mainly where the wall condensation occurs, in the upper part of Vessel 1 and to a lower extent the upper part of Vessel 2. The resulting thermal stratification remains all the way through Phase III as presented in Figure 6-(a). Two temperature contour maps depicted at the end of Phase III for PE1 and PE2 are presented in Figure 6-(a) and (b) respectively. A temperature difference of about 20°C between the bottom and the top of Vessel 1 is observed for PE1(a) while the temperature distribution remains homogenous in test PE2 (b). Overall, for PE2 the steam stratification build-up is not associated with an increase of the wall temperature as no condensation occurs. It also explains the fastest pressurization rate observed for the tests without wall condensation.

During the following relaxation phase the temperature and steam stratification remains confined above the IP and the pressure decreases slightly, Figure 4 and 5.



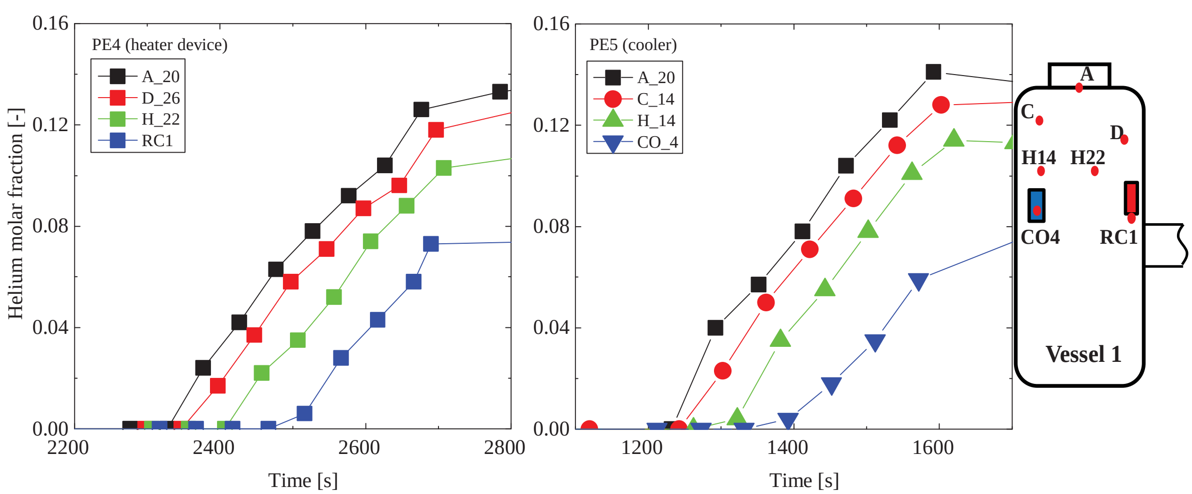
(a) (b)

Figure 5. Steam concentration evolution in Phase 1 for test PE1 (left) and PE2 (right).



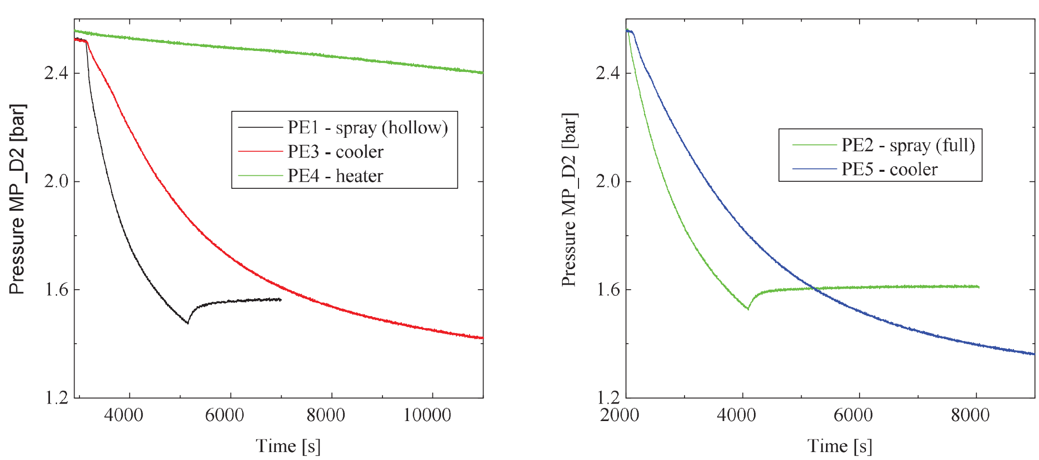
(a) (b)

Figure 6. Temperature contour map representing temperature distribution at the end of Phase III for (a) condensing environment PE1 test and (b) non-condensing environment PE2 test.



(a) (b)

Figure 7. Helium concentration evolution in Phase II for test (a) PE4 and (b) PE5 .



(a) (b)

Figure 8. Pressure evolution in Phase IV for (a) test PE1, PE3 and PE4 and (b) test PE2 and PE5.

Phase II and III: The evolution of helium molar fraction for PE4 and PE5 are presented in Figure 7-(a) and (b). During the helium injection, helium content increases in the upper part of Vessel 1 to reach about 0.14 at A_20 at the end of Phase II in both tests. It reaches the inlet of the heater for test PE4, RC1 in (a) , and immersed completely the cooler for test PE5, CO4 in (b). After the helium stratification buildup, the helium layer is stable throughout the relaxation phase III. Similar to the previous relaxation phase the pressure decreases slightly, Figure 4.

The concentration profiles obtained at the end of Phase III are presented in Figure 3-(b). Good repeatability of the final distribution of the helium and steam in Vessel 1 is observed for PE1, PE3 and PE4 on one hand and for PE2 and PE5 on the other hand. Strong helium/steam stratification was created above 4000 *mm* height with slightly lower steam content for the test with no wall condensation.

In addition, strong temperature stratification remains at the end of Phase III for the test with wall condensation as shown in Figure 6–(a)

3.2. Activation of safety system – Phase IV

The effect of the safety system on the gas and temperature distribution as well as on the pressure evolution is discussed in this section. During the activation of the safety systems the pressure decreases for all tests due to diverse reasons, Figure 8 (a) and (b). While the condensation process caused by the activation of the spray and the cooler governs mainly the pressure evolution in the facility, one cannot argue similarly for the heater test PE4. The depressurization observed during the heater test is mainly due to the heat loss of the facility estimated to range from 12.5 *kW* at 105 *°C* and 19 *kW* at 130 *°C,* which over compensates the electrical power of the heater (less than 10 *kW*). Overall the pressure decreases to 240 *kPa* within 7200 *s*. For test PE1 and PE2, the pressure decreases to 148 *kPa* and 152 *kPa*, respectively, within about 2000 *s* whereas it takes about 7200 *s* to reach 135 *kPa* and 142 *kPa* for the cooler tests PE3 and PE5, respectively. In terms of depressurization rate the spray appears more efficient regardless of the spray nozzle design. Note that after the sprays were stopped, an increase of about 20 *kPa* of the pressure was observed in the facility due to re-evaporation of the sump and reheating of the gas through heat transfer with the hot wall.

Two temperature contour maps were selected, at the beginning and at the end of Phase IV for PE1 (spray), PE3 (cooler) and PE4 (heater) tests to observe the evolution of the temperature distribution evolution due to the operation of the safety system, Figure 9. Note that the scales are not identical from map to map. Tests PE1 and PE3 can be considered as representative of their counterpart test PE2 and PE5, respectively.

For the spray test PE1, presented in Figures 10-(a) and -(b), the temperature contour maps show first a displacement of the hot gas mixture from the top of Vessel 1 to the bottom of Vessel 1 with some deflection toward the IP. Additionally, part of the hot gas mixture is transported initially (t=3146 *s*) through the upper part of the IP into Vessel 2 as depicted by the warmer temperature measured at the outlet of the IP Vessel 2. A rising plume from the IP to the top of Vessel 2 can be clearly identified as well. By the end of Phase IV of PE1, at t =4146 *s* the gas mixture has been homogeneously cooled down to 80 *°C* in Vessel 1 below the level of the spray injection. Above the spray level and on the side of the spray the gas temperature is higher (~90 *°C*). Finally, a reversal of the inter-compartment flow through the IP was observed, Figure 10-(b). The resulting cold gas mixture of Vessel 1 flows through the lower part of the IP to the bottom of Vessel 2.

For the cooler test PE3 presented in Figure 10-(c) and -(d), the contour map shows initially a strong cooling of the gas mixture in the direct surrounding of the cooler y=4000 *mm* up to y=6000 *mm* to a lower extend. By the end of the cooler operation, at t=10840 *s*, cold gas mixture (about 70 *°C*) appears to fall down on both sides of the cooler. In addition, the lower part of the original steam/helium rich layer presents a decrease in temperature with the formation of low temperature gradient from 90 *°C* to 105 *°C* between y=4000 *mm* and y=6500 *mm*, respectively. Finally, similar to the spray test, the cold steam depleted gas mixture flows toward the bottom of Vessel 2 through the lower part of the IP. A counter flow from Vessel 2 to Vessel 1 through the upper part of the IP is also observed. For the heater test PE4 presented in Figure 10-(e) and-(f), the contour maps show very little difference in the temperature distribution. Only a temperature increase from 120 °*C* at t=3520 *s* to 130 °*C* at t=10482 *s* in the upper part of Vessel 1 was observed. The stratification limit appears quite stable around the elevation of the heater inlet at y=4200 *mm*. In fact during the heater operation, the temperature increase leads to a swelling of the stratified layer that overflow through the IP towards the upper part of Vessel 2 but to a much lower extent than the inter-compartment flow observed in all other tests of the project.

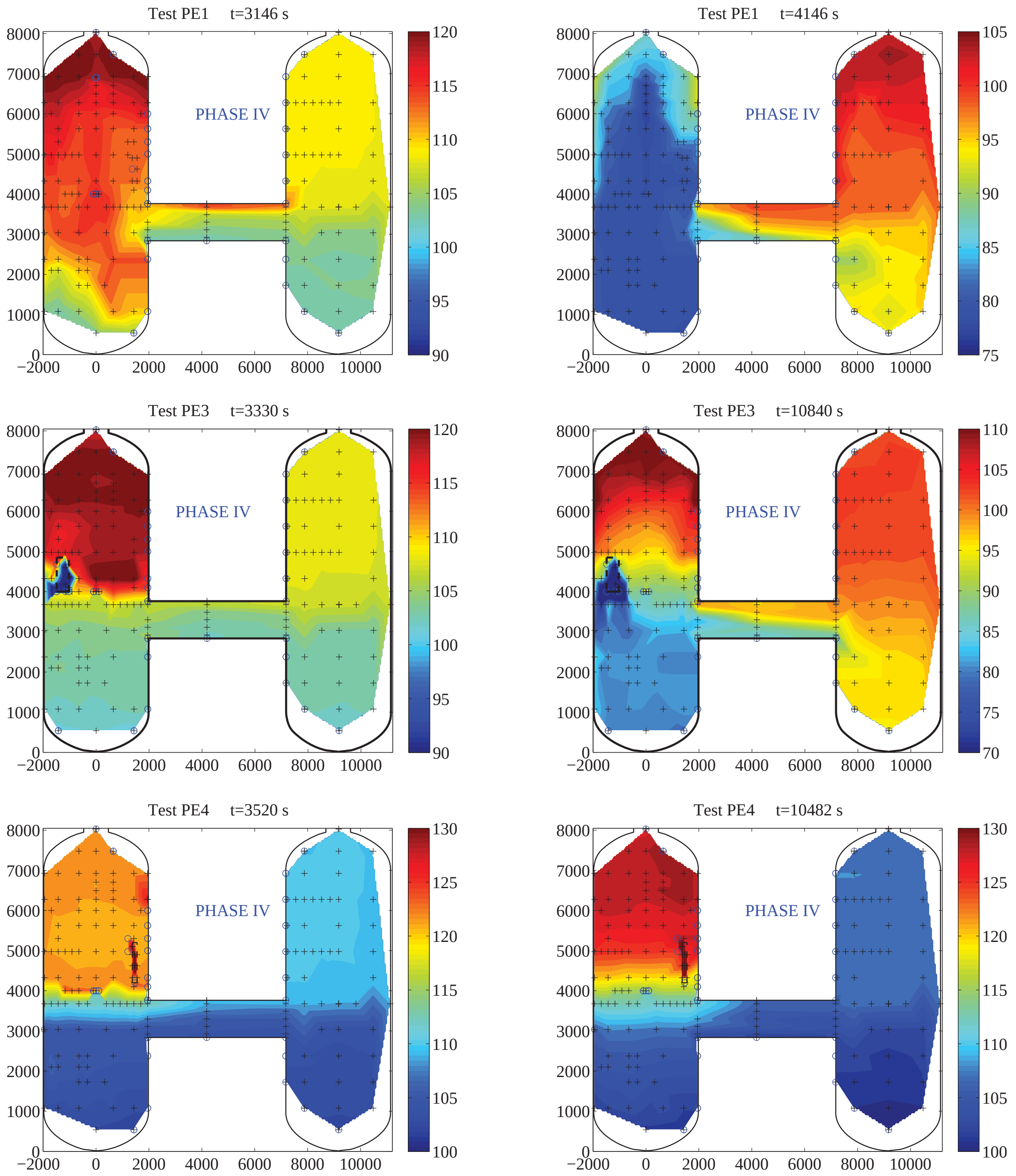
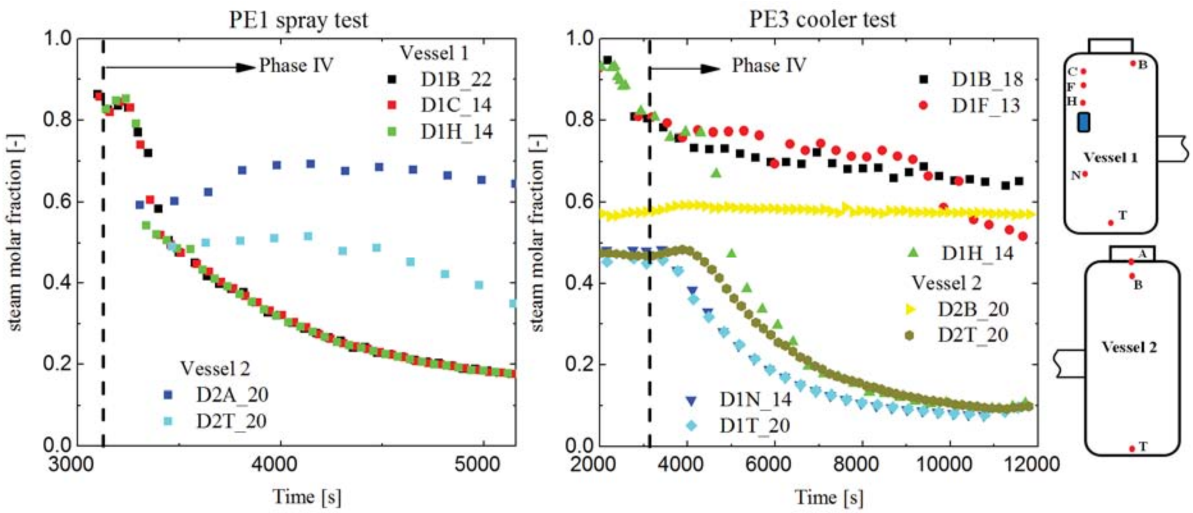


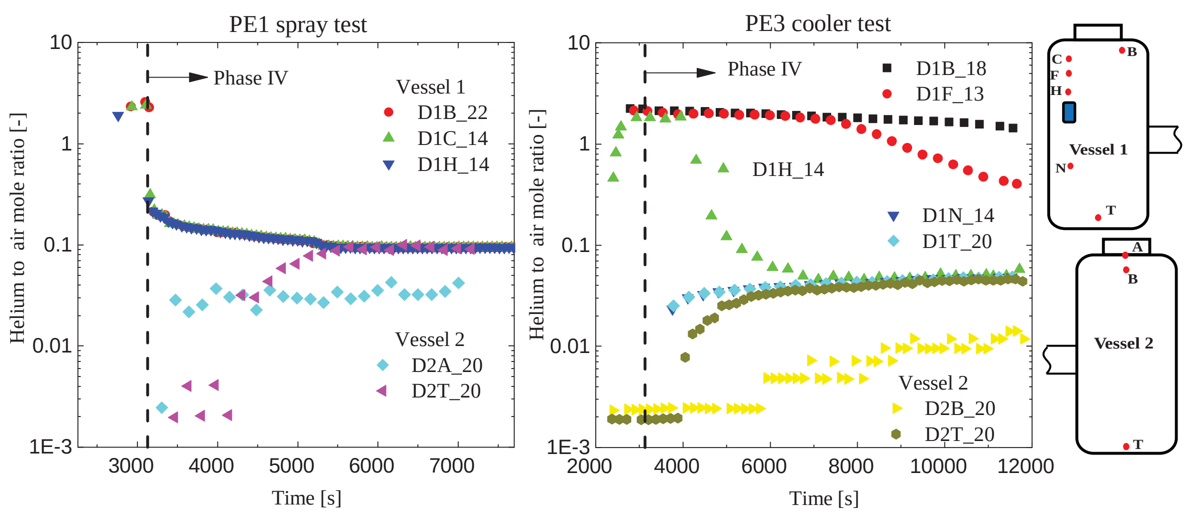
Figure 9. Selected temperature contour maps representing temperature distribution in vertical plane at the beginning (left side) and at the end (right side) of Phase IV for test PE1, PE3 and PE4.



(a) (b)

Figure 10. Steam content at selected position for test -(a) PE1 and -(b) PE3.

The gas concentration evolution for both tests PE1 and PE3 are presented in Figure 10 and 11. Steam content is represented in Figure 10 while the helium to air mole ratio was used in Figure 11. This last definition allow for the observation of the helium dilution within the non-condensable gas component.



(a) (b)

Figure 11. Helium to air mole ratio content at selected position for test –(a) PE1 and –(b) PE3.

For the spray test PE1, the steam content initially remains to a high level at 0.85 for the first 200 s before decreasing rapidly to ~0.5 at t= 3350 *s*, Figure 01-(a). An increase of steam content is observed in Vessel 2 at A level whereas a decrease down to 0.2 is observed in Vessel 1. This confirms the initial outflow toward the top of Vessel 2 (D2A_20 rises) through the IP followed by a flow toward the bottom of Vessel 2 (D2T_20 decreases). The helium to air mole ratio presented in Figure 11-(a) shows an almost instantaneous mixing of the two non-condensable phase within the entire Vessel 1 with a ratio falling

down from ~2.5 to 0.3. Once again the presence of helium is noticed in Vessel 2 first at D2A_20 after t=3400 *s* and then at D2T_20 level after t=4500 *s*.
For the cooler test PE3, Figure 10-(b), the decrease in steam content is observed in the lower part of Vessel 1 (D1N_14 and D1T_20). At t=4300 *s* the steam starts decreasing in the above vicinity of the cooler, D1H_14. The steam depletion is limited to the upper part of Vessel 1. D2B_18 sensor reads a steam molar fraction of 0.65 at the end of phase IV. The steam content remains also unchanged in the upper part of Vessel 2 whereas a the steam concentration in the lower part of Vessel 2 follows similar trends to the steam concentration measured in the bottom of Vessel 1, which confirms the flow from Vessel 1 to Vessel 2 suggested in the context of the discussion of the temperature contour maps. The helium concentration, Figure 11-(b), remains high in the upper part of Vessel 1 down to the vicinity of the cooler (D1H_14). The outflow of the cooler relocated the helium in the lower part of Vessels 1 and 2 as shown by the evolution of helium molar fraction at D1T_20 and D2T_20 locations. As a remark, similar trends were observed for the *non –condensing* test PE2 and PE5 with, for major difference, the initial helium to air mole ratio of the order of 1 instead of 2.5.

3.3. Overall flow patterns observed during safety device activation

The overall flow patterns observed in the facility during the activation of the spray, cooler and heater device are summarized in Figure 12.
For the tests PE1 (Figure 12 (a) to (c)) and PE2, a complete breakup of the stratification occur rapidly when the sprays are activated, leading to a homogenous gas mixture with lower helium content (a). A surge of gas mixture flows initially through the IP toward the upper part of Vessel 2 (b). Later in time the steam depletion of the gas mixture of Vessel 1 associated with lower temperature leads to the formation of a flow toward the bottom of Vessel 2. This flow remains until the end of phase IV (c).
For the tests PE3 (Figure 12 (d) to (f)) and PE5, the activation of the cooler immersed in the helium layer (d) leads to a rapid condensation of the steam located in the vicinity of the cooler associated with an initial release of helium rich gas (e). Downward outflow from the cooler are rapidly established due to the increase of air content as well as lower temperature. The helium layer is partially eroded by a convective loop between the two vessels. Warmer mixture flows from Vessel 2 to Vessel 1 where it rises due to buoyancy until the helium rich layer is reached. The gas mixture flows along the layer before falling down towards to the cooler. The mixing process is quite slow and inefficient (f). The cooler fails to mobilize helium located far away.
For test PE4, (Figure 12 (g) to (i)) the activation of the heater device initial immersed in the layer (g) leads to a convection loop that tends to homogenize the gas mixture up to the level of the heater inlet (h). Since helium was used to substitute hydrogen, the recombination that would lead to hydrogen depletion in the layer is missing. The flow pattern obtained with the heater device, however, shows the inability of the heater to mobilize gas mixture located far away below its inlet. At the end of Phase IV the stratification is still well established in the upper part of Vessel 1 (i).

4. CONCLUSIONS

Within the frame of the ERCOSAM project, five experiments were conducted successfully in the PANDA facility, Switzerland. An accident scenario was identified, that would lead to the formation of hydrogen stratification within the containment. The experimental conditions were defined as a scale down of the generic containment and adapted to the experimental facility by pre-test calculations and shake-down tests. The selected scenario consists of a steam injection phase, Phase I, a helium injection phase, Phase II, a relaxation period in Phase III and a safety device activation phase, Phase IV. Four different devices were tested, namely a full cone spray nozzle, a hollow cone spray nozzle, a cooler and a heater device representing the thermal activity of an autocatalytic recombiner. Finally, two different initial wall temperatures were used to control the condensation of steam to the wall. The first three phases, identical for test PE1, PE3 and PE4 with low initial wall temperature and for test PE2 and PE5 for higher wall temperature show very good repeatability in terms of pressure, temperature and gas distribution evolution. By the end of Phase III, stable helium stratification was created in the upper part of Vessel 1 before the activation of the safety device. When wall condensation occurs, the steam content reaches higher values in the upper part of Vessel 1 and a strong thermal stratification associated with the helium layer is observed.

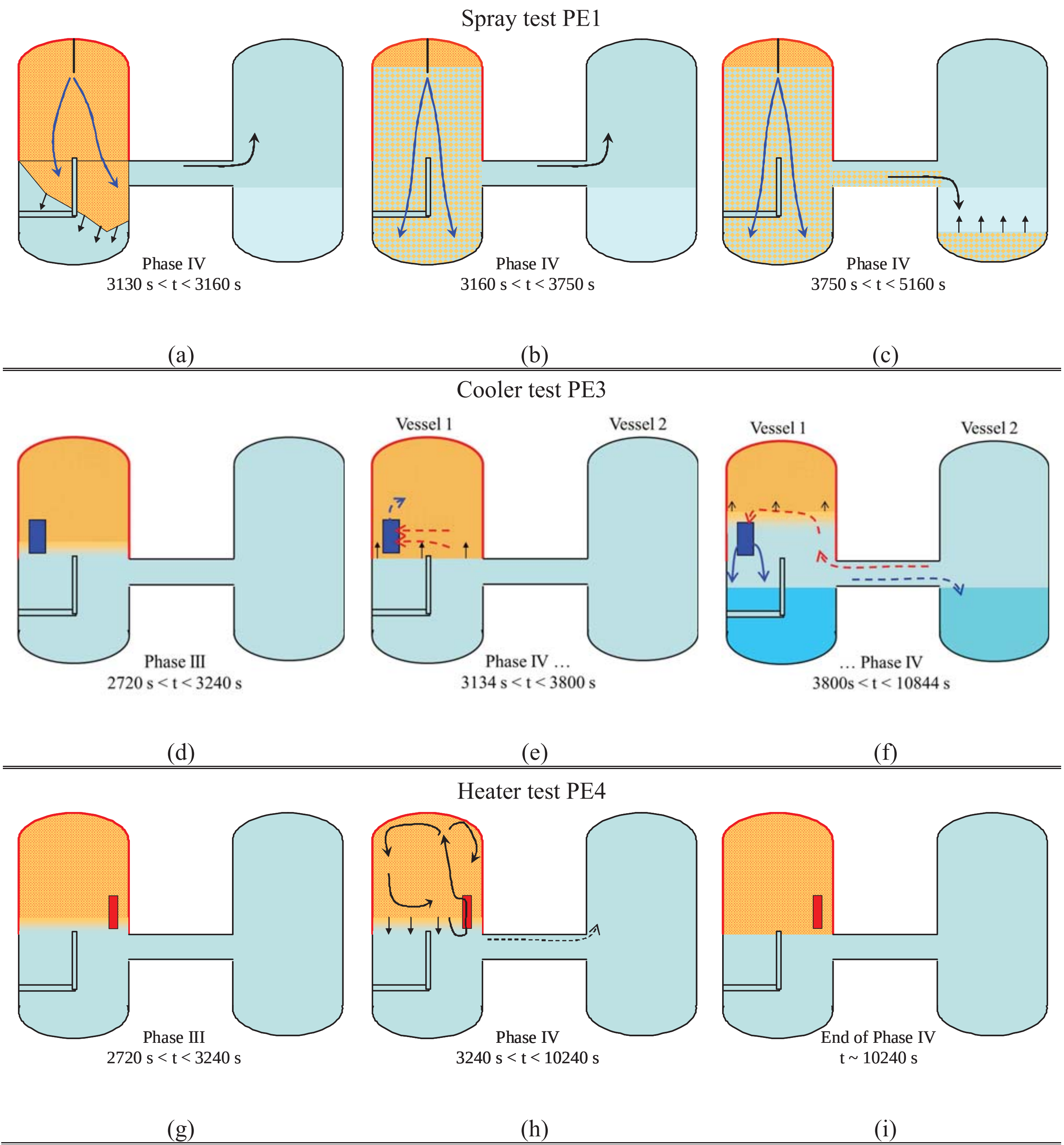


Figure 12. Flow patterns observed during the activation of the safety system in phase IV for test PE1, PE3 and PE4.

The spray nozzles, used in tests PE1 and PE2, are the most efficient in term of depressurization rate but also in terms of mixing process. During the spray activation, the entire gas space of Vessel 1 is affected and a rapid (few hundreds seconds) and homogenous mixing of the helium layer is observed.
The cooler used in test PE3 and PE5 is quite efficient in terms of depressurization rate due to the condensation and cooling of the gas that is induced, but still slower than the spray. In terms of mixing process, however, its efficiency is limited. The influence radius of the cooler is limited and confined to the gas space located from about 1 m just above it to the bottom of the vessel. Also the mixing process is much slower than for the spray.
For PE4, the heater efficiency can only be assessed in term of gas mixing. It appears that the influence radius of the heater is confined to the upper part of the Vessel 1 down to the level of the heater inlet. Very little mixing of the helium layer with the adjacent gas environment was observed. The mixing below the heater inlet is controlled by slow processes (diffusion and thermal effects), and affected by the specific geometry of the containment.
The experimental database obtained with the projects has already been used by the project Organizations to assess various computational tools and to advance modeling capabilities and simulation approaches. The two step approach (pre- and post-test analysis) resulted in a substantial and generally valuable progress in the modelling of phenomena associated with spray, cooler and heater operation, and therefore in the confidence to apply several codes to containment safety analysis.

ACKNOWLEDGMENTS

The ERCOSAM project (contract n° 249691) is co-financed by the European Commission within the 7th EURATOM Framework Programme on Nuclear Fission and Radiation Protection. The SAMARA project is co-financed by ROSATOM. This support is greatly acknowledged.

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