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Preliminary Spray Tests in PPOOLEX

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Abstract

This report summarizes the results of the preliminary spray tests carried out in the PPOOLEX facility at LUT. The test facility is a closed stainless steel vessel divided into two compartments, drywell and wetwell. For the spray tests the facility was equipped with a model of a spray injection system with four nozzles.
The main objective of the tests was to study interplay between suppression pool behaviour and the spray system operation. Particularly we were interested to find out if mixing of a thermally stratified pool with the help of spray injection from above is possible. An additional goal was to obtain data for improving simulation models related to spray operation in CFD and system codes as well as contribute to the development of the EMS and EHS models for sprays to be implemented in the GOTHIC code by KTH.
In the first two tests the initial stratified situation was created by injecting first warm and then cold water from the tap into the wetwell. In the third test the stratified situation was created with the help of small steam injection through the model of the sparger pipe in PPOOLEX by starting from a cold state. In all three tests, the spray injection flow rate was the maximum available from the water supply system of the laboratory i.e. about 128 l/min. When divided to the four spray nozzles it gives 32 l/min per nozzle.
In the first two tests, mixing of the topmost layers of the pool was achieved easily. The initial temperature difference between the bottom and surface was 28 °C and 33 °, respectively. It can be speculated that the whole water volume could have been mixed if the tests had been continued for a longer period of time.
In the third test, complete mixing of the initial 60 °C temperature difference between the pool bottom and the surface layer was achieved in about 4200 seconds as a result of internal circulation in the pool induced by the density difference between the cold spray water and warm pool water. The pool water level rose by 2 meters during the spray operation.
These preliminary spray tests in PPOOLEX indicate that it might be possible to mix a stratified pool with the help of spray injection from above. If spray injection was continued long enough internal circulation developed and finally mixed the pool.

Key words

condensation pool, spray, mixing

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PRELIMINARY SPRAY TESTS IN PPOOLEX

Markku Puustinen, Antti Räsänen, Eetu Kotro

Summary

This report summarizes the results of the preliminary spray tests carried out in the PPOOLEX facility at LUT. The test facility is a closed stainless steel vessel divided into two compartments, drywell and wetwell. For the spray tests the facility was equipped with a model of a spray injection system with four nozzles.

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In the first two tests the initial stratified situation was created by injecting first warm and then cold water from the tap into the wetwell. In the third test the stratified situation was created with the help of small steam injection through the model of the sparger pipe in PPOOLEX by starting from a cold state. In all three tests, the spray injection flow rate was the maximum available from the water supply system of the laboratory i.e. about 128 l/min. When divided to the four spray nozzles it gives 32 l/min per nozzle.

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These preliminary spray tests in PPOOLEX indicate that it might be possible to mix a stratified pool with the help of spray injection from above. If spray injection was continued long enough internal circulation developed and finally mixed the pool. The effect of different parameters, not varied in these preliminary tests, is the subject of the forthcoming spray tests in PPOOLEX in 2017.

Distribution

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CONTENTS

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NOMENCLATURE

Symbols

A	Area
D	Pressure difference measurement
F	Flow rate measurement
P	Pressure measurement
S	Strain measurement
T	Temperature measurement

Abbreviations

BWR	Boiling Water Reactor
CCTV	Closed Circuit TeleVision
CFD	Computational Fluid Dynamics
CONDEX	CONdensation EXperiments project
DCC	Direct Contact Condensation
ECCS	Emergency Core Cooling System
EHS	Effective Heat Source
EMS	Effective Momentum Source
EXCOP	EXperimental studies on COntainment Phenomena project
INSTAB	couplings and INSTABilities in reactor systems project
KTH	Kungliga Tekniska Högskolan
LOCA	Loss-Of-Coolant Accident
LUT	Lappeenranta University of Technology
MSLB	Main Steam Line Break
NKS	Nordic nuclear safety research
NORTHNET	NORdic nuclear reactor Thermal-Hydraulics NETwork
PACTEL	PArallel Channel TEst Loop
POOLEX	condensation POOL EXperiments project
PPOOLEX	Pressurized condensation POOL EXperiments test facility
PSP	Pressure Suppression Pool
RHR	Residual Heat Removal
SAFIR	SAfety of nuclear power plants - FInnish national Research programme
SRV	Safety/Relief Valve
SSM	Strålsäkerhetsmyndigheten
TC	ThermoCouple
VTT	Technical Research Centre of Finland
VYR	State nuclear waste management fund

1 INTRODUCTION

A pressure suppression pool (PSP) of a BWR reactor containment serves as a heat sink and steam condenser during a postulated main steam line break (MSLB) or loss of coolant accident (LOCA) inside the containment or during safety relief valve (SRV) opening in normal operations. It thus prevents containment pressure build-up when steam released from the reactor vessel is vented through the blowdown pipes (in case of MSLB and LOCA) or through the spargers (in case of SRV operation) to the pool. Furthermore, spray systems in the containment are designed to reduce pressure build-up in such accident scenarios, where steam is present in the gas space of the wetwell and/or in the drywell.

Different phenomena inside the drywell and wetwell compartments of BWR containment during steam discharge has been extensively studied in the PPOOLEX test facility at LUT and simulated with computer codes during recent years in the framework of the national research programmes on nuclear power plant safety (SAFIR, SAFIR2014) as well as via participation to NORTHNET RM3 and NKS research projects in co-operation with VTT and Kungliga Tekniska Högskolan (KTH). Research topics have included, for example, dynamic loads caused to PSP structures by direct contact condensation (DCC), behaviour of parallel blowdown pipes during the chugging flow mode, effect of blowdown pipe outlet design on structural loads, wall condensation in the drywell and development/break-up of thermal stratification in the PSP [1…10].

The current SAFIR2018/INSTAB project as well as the related NKS and SSM funded research efforts aim to broaden the database to cover experiments with SRV spargers, residual heat removal (RHR) system nozzles, strainers and containment spray systems. Calculation models and numerical methods including CFD and system codes are developed and validated on the basis of the PPOOLEX experiment results at VTT and KTH within the SAFIR2018, NKS, and SSM funded projects. Also analytical support is provided for the experimental part by pre- and post-calculations of the experiments.

As a result of steam venting into the suppression pool the coolant temperature in the pool gradually increases. With certain flow modes a thermally stratified condition could develop where the pool's surface temperature is higher than the pool bulk temperature. This leads to a reduction of the pool's pressure suppression capacity because the pool surface temperature determines the steam partial pressure in the wetwell gas space. An increase of the pool's surface temperature due to stratification can therefore lead to a significant increase in containment pressure if mixing of the pool coolant inventory fails [11]. Pool mixing can occur due to steam injection itself if the injection flow mode changes as a result of increasing or decreasing steam flow rate. Mixing can be achieved also with the help of plant systems designed for that purpose or as a result of water suction from the pool by the Emergency Core Cooling System (ECCS) pumps or water injection into the pool via the RHR system nozzles. Operation of spray system in the wetwell could also have an effect on the behaviour of a thermally stratified suppression pool. It has been suggested that mixing induced by spray had a role in the pressure drop in Fukushima Unit 3 where pressure build-up in the containment during the first 20 hours after station blackout was attributed to stratification in the pool.

A spray injection system was constructed and installed to the wetwell compartment of the PPOOLEX facility at the end of 2016 and preliminary wetwell spray tests were carried out in January 2017. Mixing of a thermally stratified pool with the help of spray injection from above was of interest. In addition, verification data for improving simulation models in CFD and system codes at VTT and KTH was provided.

KTH has developed the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models for steam injection through a vertical pipe submerged in a pool and proposed them to be used for simulation of thermal stratification and mixing during a steam injection into a large pool of water [12]. These models have been implemented in GOTHIC® software and validated against POOLEX and PPOOLEX tests carried out at LUT. Excellent agreement in averaged pool temperature and water level in the pool between the experiment and simulation has been achieved. The development of thermal stratification and mixing of the pool are also well captured in the simulations. The EMS and EHS models will be available to be implemented also in the APROS containment code for the calculation of phenomena related to pool stratification and mixing. At the moment KTH is improving the EHS and EMS models for blowdown pipes in order to reduce uncertainties and enhance accuracy in predictions as well as extending the models to SRV spargers and RHR system nozzles in order to be able to carry out comprehensive safety analysis of realistic transients in a BWR containment. In future the EMS/EHS models will be developed and validated also for a spray system operation in the wetwell.

Suitable experimental data is limited for validation of the EHS and EMS models. So far, the only available and sufficiently detailed experimental vent pipe data are the POOLEX/PPOOLEX steam discharge experiments with blowdown pipes. The PPOOLEX database was broadened to cover SRV spargers and RHR system nozzles in the test series carried out in 2014, 2015 and 2016 [13, 14, 15 and 16]. In this report the preliminary spray tests in PPOOLEX are described. Chapter two gives a short description of the test facility and its measurements. The test parameters, initial conditions and test procedure are introduced in chapter three. The test results are presented and discussed in chapter four. Chapter five summarizes the findings of the test series.

2 PPOOLEX TEST FACILITY

The PPOOLEX test facility was taken into use at LUT in the end of 2006. PPOOLEX models the containment of a BWR plant. During the years the facility has gone through several modifications and enhancements as well as improvements of instrumentation. For the preliminary spray tests described in this report the facility was equipped with a model of a wetwell spray system with four nozzles. The PPOOLEX facility is described in more detail in reference [17]. However, the main features of the facility and its instrumentation are introduced below.

2.1 TEST VESSEL

The PPOOLEX facility consists of a wetwell compartment (condensation pool), drywell compartment, inlet plenum and air/steam-line piping. An intermediate floor separates the compartments from each other. Usually a route for gas/steam flow from the drywell to the wetwell is created by a vertical blowdown pipe attached underneath the floor. During the sparger tests the drywell compartment was, however, bypassed i.e. steam was blown directly into the wetwell via the sparger pipe.

The main component of the facility is the ~31 m^3 cylindrical test vessel, 7.45 m in height and 2.4 m in diameter. It is constructed from three plate cylinder segments and two dome segments. The test facility is able to withstand considerable structural loads caused by rapid condensation of steam.

The dry and wetwell sections are volumetrically scaled according to the compartment volumes of the Olkiluoto containment (ratio approximately1:320). There are several windows for visual observation in both compartments. A DN100 (∅ 114.3 x 2.5 mm) drain pipe with a manual valve is connected to the vessel bottom. A relief valve connection is mounted on the vessel head. The removable vessel head and a man hole (DN500) in the wetwell compartment wall provide access to the interior of the vessel for maintenance and modifications of internals and instrumentation. The drywell is thermally insulated.

A sketch of the test vessel is shown in Figure 1. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

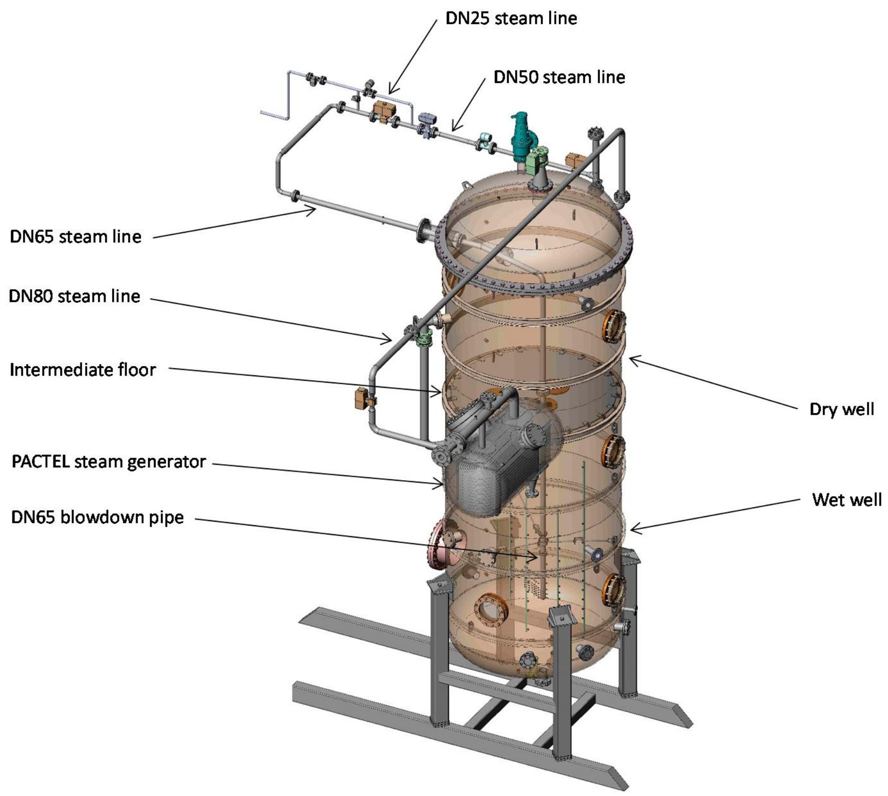

Figure 1. PPOOLEX test vessel.

Table 1. Test facility vs. Olkiluoto 1 and 2 BWRs

	PPOOLEX test facility	Olkiluoto 1 and 2
Number of blowdown pipes	1-2	16
Inner diameter of the blowdown pipe [mm]	214.1	600
Suppression pool cross-sectional area [m^2]	4.45	287.5
Drywell volume [m^3]	13.3	4350
Wetwell volume [m^3]	17.8	5725
Nominal water volume in the suppression pool [m^3]	8.38*	2700
Nominal water level in the suppression pool [m]	2.14*	9.5
Pipes submerged [m]	1.05	6.5
A_{pipes}/A_{pool}x100%	0.8 / 1.6**	1.6

* Water volume and level can be chosen according to the experiment type in question. The values listed in the table are based on the ratio of nominal water and gas volumes in the plant.
** With one / two blowdown pipes.

2.2 PIPING

Steam needed in the tests is generated with the nearby PACTEL [18] test facility, which has a core section of 1 MW heating power and three horizontal steam generators. Steam is led through a thermally insulated steam line, made of sections of standard DN80 (Ø88.9x3.2), DN50 (Ø60.3x3.0) and DN65 (Ø76.1x3.0) pipes, from the PACTEL steam generators towards the PPOOLEX test vessel. The section of the steam piping inside the drywell (bypass) is made of uninsulated DN65 (Ø76.1x3.0) pipe.

2.3 SPARGER PIPE

The DN65 (Ø76.1x4.0) sparger type blowdown pipe is positioned vertically inside the pool in a non-axisymmetric location, i.e. the pipe is 420 mm away from the centre of the condensation pool. The total length of the sparger pipe is approx. 5.0 m. The pipe is made from austenitic stainless steel EN 1.4571.

There are 32 Ø8 mm holes drilled radially in the lower part of the pipe (sparger head). These holes are in four rows, eight holes in each row. There is a load reduction ring 700 mm above the pipe outlet with 8 axially drilled Ø8 mm holes.

2.4 WETWELL SPRAY SYSTEM

For the preliminary spray tests the PPOOLEX facility was equipped with a model of a wetwell spray system. (Figure 2). It consists of four spray nozzles, an injection pipeline and supporting structures. Each spray nozzle is at a 0.6 m distance from the vessel wall. The nozzles are in a square lattice and about 0.85 m from each other.

Figure 2. Spray system with four nozzles in PPOOLEX wetwell.

In 2015, single spray nozzle tests with different capacity full cone nozzles were carried out in an open test environment in order to develop a measurement procedure for determining droplet size and velocity distributions of the spray jets [19]. The shadowgraphy application of the PIV measurement system was used. The model of the spray nozzles installed to PPOOLEX in 2016 is B1/2HH-40 FULLJET. A similar nozzle was tested also in the single spray nozzle tests in 2015.

The orifice diameter of the nozzle is 6.2 mm. The nozzle properties provided by the manufacturer are presented in Table 2 and Table 3 [20].

Table 2. Capacity of the spray nozzle used in the tests with different pressure values

Pressure over nozzle [bar]	0.4	0.5	0.7	1.5	3.0	6.0	7.0	10.0
Capacity [l/min]	11.9	13.1	15.2	21.0	29.0	39.0	44.0	52.0

Table 3. Spray angle of the nozzle used in the tests with different pressure values

Pressure over nozzle [bar]	0.5	1.5	6.0
Spray angle [deg]	88	91	83

Water for the PPOOLEX spray system is taken from the water-supply pipe of the laboratory and led via a pipeline and flexible hose, connected to a lead-in close to the pool bottom, to the spray header. In the header water is divided to the four nozzles. Each nozzle has its own manual shut-off valve. Injection flow through the nozzles was balanced with those valves before the system was lifted up and attached with supporting rods to the wall of the wetwell compartment. Spray water flow and temperature are measured in the injection pipeline outside the pool.

2.5 MEASUREMENT INSTRUMENTATION

The applied instrumentation depends on the experiments in question. Normally, the test facility is equipped with several thermocouples (T) for measuring steam, pool water and structure temperatures and with pressure transducers (P) for observing pressures in the drywell, inside the blowdown pipes, at the condensation pool bottom and in the gas space of the wetwell. Steam flow rate is measured with a vortex flow meter (F) in the steam line. Flow rate of the spray water is measured with magnetic flow meter installed to the injection pipeline. Additional instrumentation includes, for example, strain gauges (S) on the pool outer wall and valve position sensors.

For the sparger tests a 6x7 grid of temperature measurements (thermocouples T4000–T4056) was installed in the pool in front of the injection holes of the sparger head. For measuring vertical temperature distribution inside the sparger pipe nine temperature measurements (thermocouples T4070…T4078) were installed with a varying interval. Four trains of temperature measurements (thermocouples T4100…T4113, T4200…T4219, T4300…T4319 and T4400…T4413) were installed in the pool below the water level for detecting vertical temperature distribution. Since these vertical trains with TCs suit well for detecting the behaviour of the pool also in the tests with the spray system no extra temperature measurements were added to PPOOLEX at this time except the one used for measuring spray injection water temperature.

Figures in Appendix 2 show the locations of the PPOOLEX measurements during the spray test series and the table in Appendix 2 lists their identification codes and other details.

2.6 CCTV SYSTEM

Standard video cameras with 25 fps connected to a laptop computer were used for visual observation of the test vessel interior during the test series.

2.7 DATA ACQUISITION

National Instruments PXIe PC-driven measurement system was used for data acquisition. The system enables high-speed multi-channel measurements. The maximum number of measurement channels is 64 with additional eight channels for strain gauge measurements. The maximum recording capacity depends on the number of measurements and is in the region of three hundred thousand samples per second. Measurement software was LabView 2015. The data acquisition system is discussed in more detail in reference [21].

Self-made software using the National Instruments FieldPoint measurement system was used for monitoring and recording the essential measurements of the PACTEL facility generating the steam. Both data acquisition systems measure signals as volts. After the tests, the voltage readings are converted to engineering units with conversion software.

The used measurement frequency of LabView was 20 Hz. The rest of the measurements (for example temperature, pressure and flow rate in the steam line) were recorded by the self-made software with the frequency of 0.67 Hz.

3 TEST PROGRAM

Three preliminary spray tests labelled as SPR-T1, SPR-T2 and SPR-T3 were carried out in the PPOOLEX facility in January 2017. Interplay between suppression pool behaviour and the spray system was of interest. The main purpose of the tests was to find out if mixing of a thermally stratified pool with the help of spray injection from above is possible. An additional goal was to obtain data for improving simulation models related to spray operation in CFD and system codes as well as contribute to the development of the EMS and EHS models for sprays to be implemented in the GOTHIC code by KTH.

In these preliminary spray tests in PPOOLEX there was not much variation in the test parameters since only the spray injection flow rate was varied in the first test. The spray water temperature and the initial level of pool water were practically the same in all the tests. The same spray nozzles were used throughout the series. The effect of these parameters is the subject of the forthcoming spray tests in PPOOLEX in 2017.

In first two spray tests the initial stratified situation was created by injecting first warm and then cold water from the tap into the wetwell. The injection of cold water was done cautiously to prevent the warm and cold water from mixing. In the third test the stratified situation was created with the help of steam injection through the model of the sparger pipe in PPOOLEX by starting from a cold state. Minimum steam flow rate, which prevents water from entering to the sparger head, was used in order to get a clear stratified region in the pool. Just before the spray injection was started the steam injection through the sparger was stopped.

In SPR-T1, the water level was at the elevation of 1.31 m after the filling with cold water stopped. The temperature difference between the bottom and the top layer of the pool before the initiation of spray injection was about 28 °C and the thickness of the warm water layer about 120-140 mm. In SPR-T2 the temperature difference was about 33 °C and the thickness of the layer about 200-220 mm. The water level was 1.42 m. In SPR-T3, almost a 60 °C temperature difference between the bottom and the top layer of the pool was created with the help of the steam injection. The thermocline between the hot and cold water was somewhere around the 800 mm elevation. Since the water level was at about 1.5 m the thickness of the warm water layer was thus about 700 mm. In these preliminary spray tests a considerably lower initial pool water level than normally in PPOOLEX tests was used. The reason for this was the grid of temperature measurements in front of the sparger head (Figure 3). It was thought that with the help of the dense TC grid it would be possible to evaluate how deep the mixing effect of spray injection penetrates and therefore the water level was initialized close to the top of the grid. The exact locations of the TCs in the grid can be found from the drawings presenting PPOOLEX instrumentation in Appendix 2.

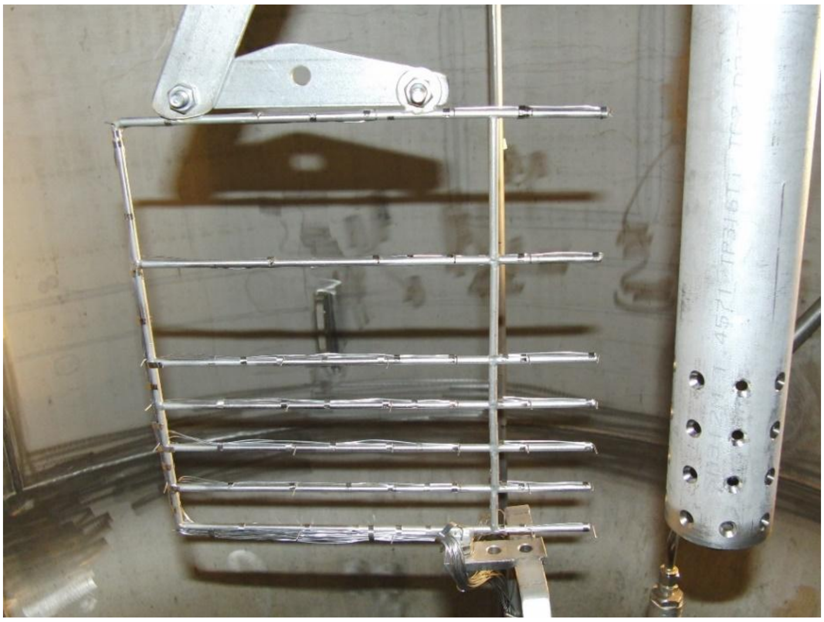

Figure 3. Grid of thermocouples close to the head of the sparger pipe.

In all three tests, the spray injection flow rate was the maximum available from the water supply system of the laboratory i.e. about 128 l/min. When divided to the four spray nozzles it gives 32 l/min per nozzle. That is 7 l/min under the 39 l/min capacity of the nozzle with the 6 bar pressure difference between the water supply system and PPOOLEX.

In SPR-T1 and SPR-T2, the spray injection continued for about 460 s and 1370 s, respectively. During the spray operation the pool water level increased about 200 mm in SPR-T1 and about 600 mm in SPR-T2. In SPR-T3, the spray injection was stopped after about 4260 s. At this time the pool water level had increased by over 2 meters. As cold water as possible was taken from the tap for the spray in all the tests. At the initialization of the spray the water temperature was about 20 °C but dropped very soon below 12 °C and then few degrees below that during the injection.

The tests were started from atmospheric conditions in PPOOLEX. In SPR-T1 and SPR-T2, there was no pressure increase during the tests because the valve in the pressure balancing line between the drywell and wetwell as well as the valve to atmosphere on top of the drywell were open. In SPR-T3, the top valve was closed. The vessel pressure increased to 1.2 bar during the stratification phase and almost to 1.7 bar during the spray operation due to compression of the gas space by increasing water level. This pressure increase had a slight decreasing effect on the spray injection flow rate. The main parameters of the SPR-T1, SPR-T2 and SPR-T3 tests are listed in Table 4.

Table 4. Parameter values of the spray tests SPR-T1, SPR-T2 and SPR-T3 in PPOOLEX

Test	Initial water level [m]	Vessel pressure after stratification/spray [bar]	Water temperature after stratification bottom/surface [°C]	Spray injection flow rate [l/min]	Spray water temperature [°C]
SPR-T1	1.31	1.0/1.0	~11/39	~128	~12…10
SPR-T2	1.42	1.0/1.0	~11/44	~128	~12…9
SPR-T3	1.50	1.2/1.68	~10/70	~128…124	~12…8

4 TEST RESULTS

The following chapters give a more detailed description of the SPR-T1, SPR-T2 and SPR-T3 tests and present the observations. The SPR-T1 and SPR-T2 tests are much alike and they are therefore presented in the same chapter. The SPR-T3 test had a different method for creating the thermally stratified condition as well as a longer duration and it is therefore discussed in its own chapter.

4.1 SPR-T1 AND SPR-T2

Both in the SPR-T1 and SPR-T2 test the initial stratified condition was artificially created by injecting first warm and then cold water from the tap into the wetwell of the PPOOLEX facility. As a result there was a layer of warm water with the thickness of about 130 mm in SPR-T1 and 200 mm in SPR-T2 on top of the cold water volume before the spray injection was started. Figure 4 shows the spray injection volumetric flow rate and spray water temperature in the SPR-T2 test.

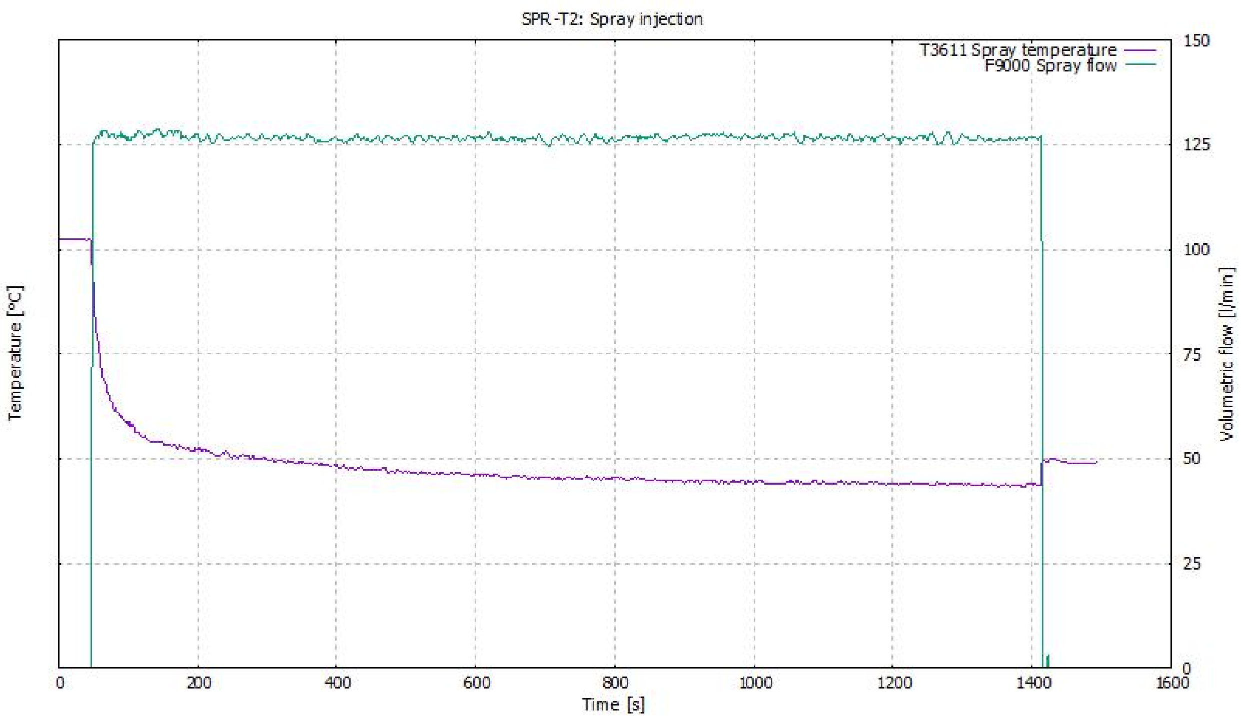

Figure 4. Spray water volumetric flow rate and temperature in SPR-T2.

Figure 5 presents the development of temperature distribution in the surface layer of pool water in SPR-T2 as measured by the TCs in the grid in front of the sparger head. The measurements are from the vertical line farthest away of the sparger head. The elevation of each measurement is expressed as a distance from the bottom horizontal rod of the grid, see Appendix 2 for more details.

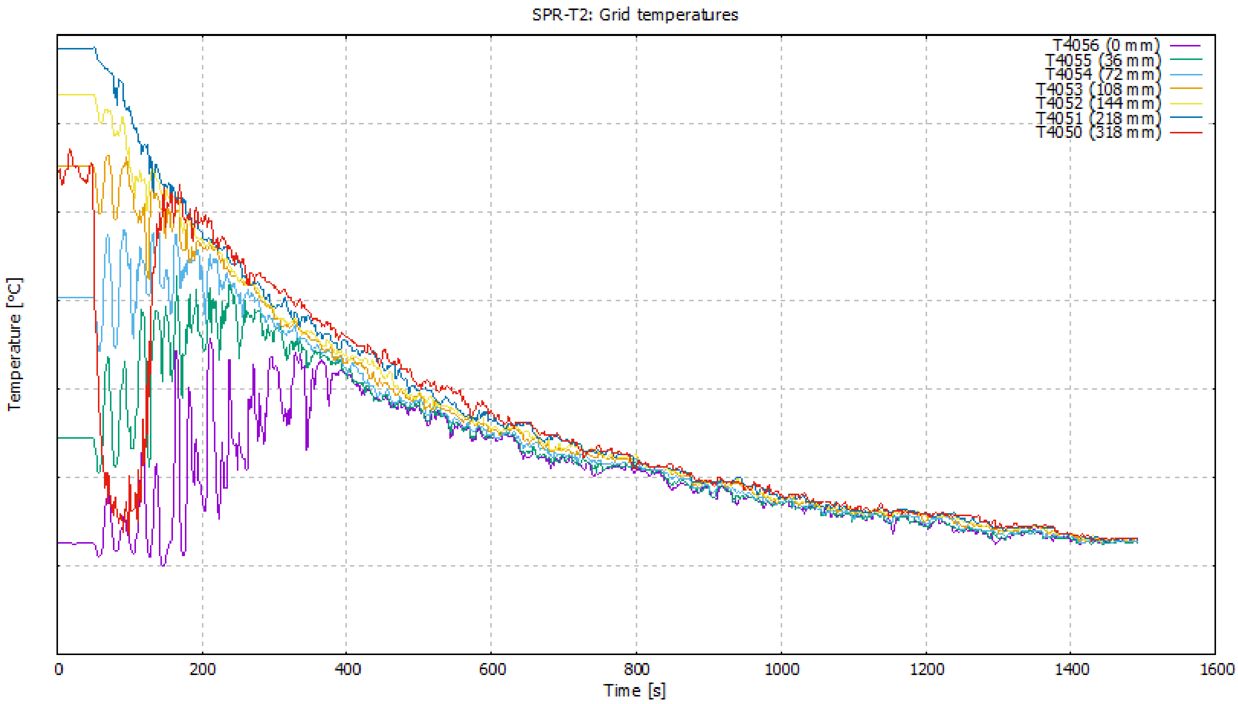

Figure 5. Temperature distribution in the surface layer of pool water in the SPR-T2 test.

Before the spray injection was started (at 45 s) all the other TCs were submerged except the topmost T4050 at the elevation of 318 mm. It measured the temperature of the gas space. There was not a sharp thermocline, where the water temperature would have changed from cold to warm, but instead the shift was continuous in nature.

As the spray injection started the two top measurements below the water surface (T4051 and T4052) started to indicate decreasing temperatures. The other submerged measurements indicated oscillations with an amplitude of few degrees. The T4050 measurement above the water surface showed a sharp drop in temperature due to the strong cooling effect of the spray in the gas space. At about 150 seconds also that topmost TC became submerged as the water level increased due to sprayed water.

The TCs at the 0 mm and 36 mm elevations soon started to indicate increasing temperatures accompanied with oscillations. The decreasing trend of T4051 and T4052 continued and one by one the other TCs in the middle elevations also started to show decreasing temperatures. Before 400 seconds the curves of all the TCs had practically united indicating a mixed condition at the elevations covered by the TC grid. For the rest of the test the decreasing trend of these temperature curves continued. The behaviour of the measurements of the TC grid was similar in the SPR-T1 test with the exception that at the start of the spray injection the two topmost TCs were above the water surface. The test was also shorter than SPR-T2 but anyway long enough to verify complete mixing at the elevations covered by the TC grid.

The SPR-T1 and SPR-T2 tests were continued still for some time after the grid temperature measurements indicated a mixed situation. However, the whole pool was not mixed at the end of the tests. This can be seen from the temperature curves of a vertical TC measurement train presented in Figure 6. The elevation of each TC is from the pool bottom.

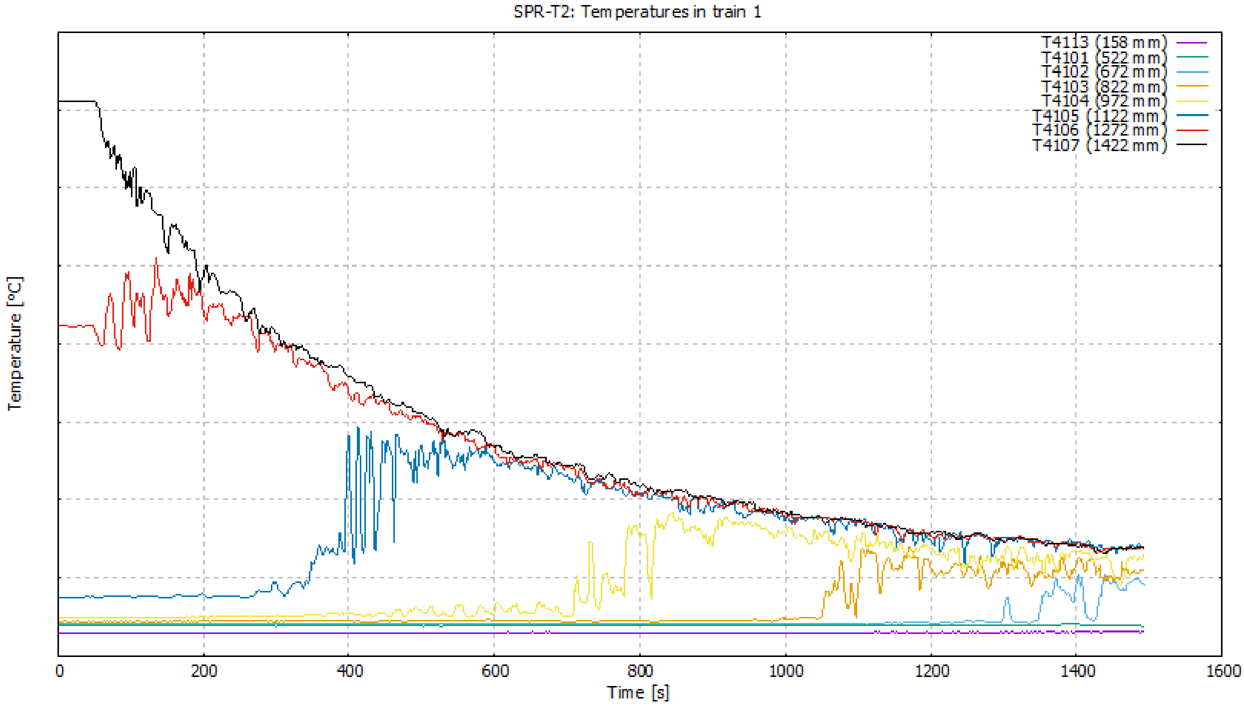

Figure 6. Temperature distribution over the pool water volume in the SPR-T2 test.

Again the measurement close to the surface layer (T4107) indicated cool down as soon as the spray injection was started. The next TC downwards (T4106) showed some oscillations before joining the decreasing trend of the topmost TC. These two TCs are at the elevations covered also by the grid measurements discussed in the preceding paragraphs. The first TC below the elevation of the grid and the sparger head (T4105) started to indicate an increasing trend with oscillations before the 400 second point and then joined the curves of the two top measurements at about 600 s. The same kind of behaviour was later visible in the curves of the next three TCs downwards (T4104, T4103 and T4102). The two TCs at the lowest elevations (T4101 and T4113) remained at their original temperature thus not taking any part to the mixing process. The behaviour over the whole pool water volume in the SPR-T1 test matches that of the SPR-T2 test presented above i.e. complete mixing was not achieved. It can be speculated that the whole water volume could have been mixed if the SPR-T1 and SPR-T2 tests had been continued for a longer period of time. In these first tests the aim was, however, to study the behaviour of the surface layers and therefore the tests were terminated after some time when complete mixing was observed at the elevations covered by the TC grid.

4.2 SPR-T3

In the SPR-T3 test, the initial stratified condition was created by blowing steam with a small flow rate into the PPOOLEX pool through the model of the SRV sparger pipe. The steam flow into the pool was divided to eight horizontally oriented jets in the holes at the sparger head. The heat-up process was driven by flow of warm condensed water upwards from the sparger outlet as well as by conduction through the pipe wall. As a result two regions with clearly different water temperatures developed in the pool. The pool bulk temperature established after the clearing phase in the beginning of the test prevailed in the region close to the pool bottom where the steam jets had no effect. The upper part of the pool volume instead heated up almost uniformly. Between these two regions there was a narrow thermocline region at about the 800 mm elevation. Since the water level was at about 1.5 m in the end of the stratification phase the thickness of the warm water layer on top of the cold bottom was thus about 700 mm. The TC grid in front of the sparger head was now totally in the warm water volume and therefore it couldn't be used for detecting the progression of the mixing process in detail during the initial period of spray injection as was the case in the SPR-T1 and SPR-T2 tests.

The heat-up process with the help of steam injection produced a somewhat sharper boundary between the cold and warm water volumes than the filling method with cold and warm water used in the SPR-T1 and SPR-T2 tests. However, the exact thickness of the thermocline can't be determined because the minimum distance between the TC measurements is 100 mm at the region in question. The elevation of the thermocline moved slowly downwards during the stratification phase.

Steam injection through the sparger pipe was stopped at 13400 s before spray operation was started. With this heat-up method the stratification process takes a considerable amount of time and therefore also the total duration of the test is much longer than in the two preceding tests. Figure 7 shows the spray injection volumetric flow rate and spray water temperature in the SPR-T3 test.

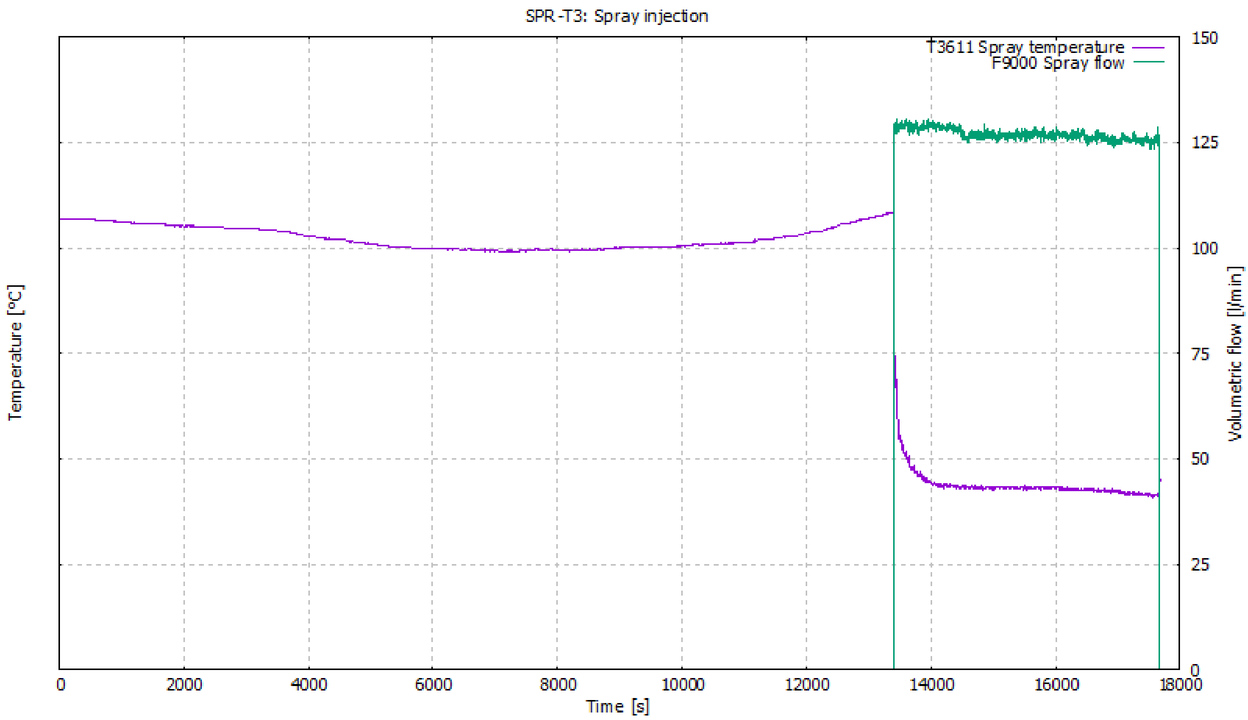

Figure 7. Spray water volumetric flow rate and temperature in SPR-T3.

The development of stratification until 13400 s into the experiment can be clearly seen in Figure 8, where the vertical temperature distribution over the pool volume is presented with selected TC measurements from trains of 1 and 2. Temperatures close to the pool bottom remain at their initial value throughout the stratification phase while the water surface temperatures heat-up almost linearly. The T4103 measurement is at the elevation of the thermocline and shows thus temperatures between the bottom and surface values. The topmost TCs in the measurement trains are above the water level during the stratification phase. They measure initially higher temperatures in the gas space but soon after 2000 s they fall behind the temperature of the heated-up water volume.

As the spray injection started the measurements close to the surface layer indicated immediate cool down, for example T4106 in Figure 8. This decreasing trend continued until the end of the test. The measurement at the elevation of the thermocline (T4103) experienced the same kind of behaviour. The measurements in the cold water region (T4113…T4102 in Figure 8) united with the measurements above them one by one as the mixing process proceeded deeper and deeper.

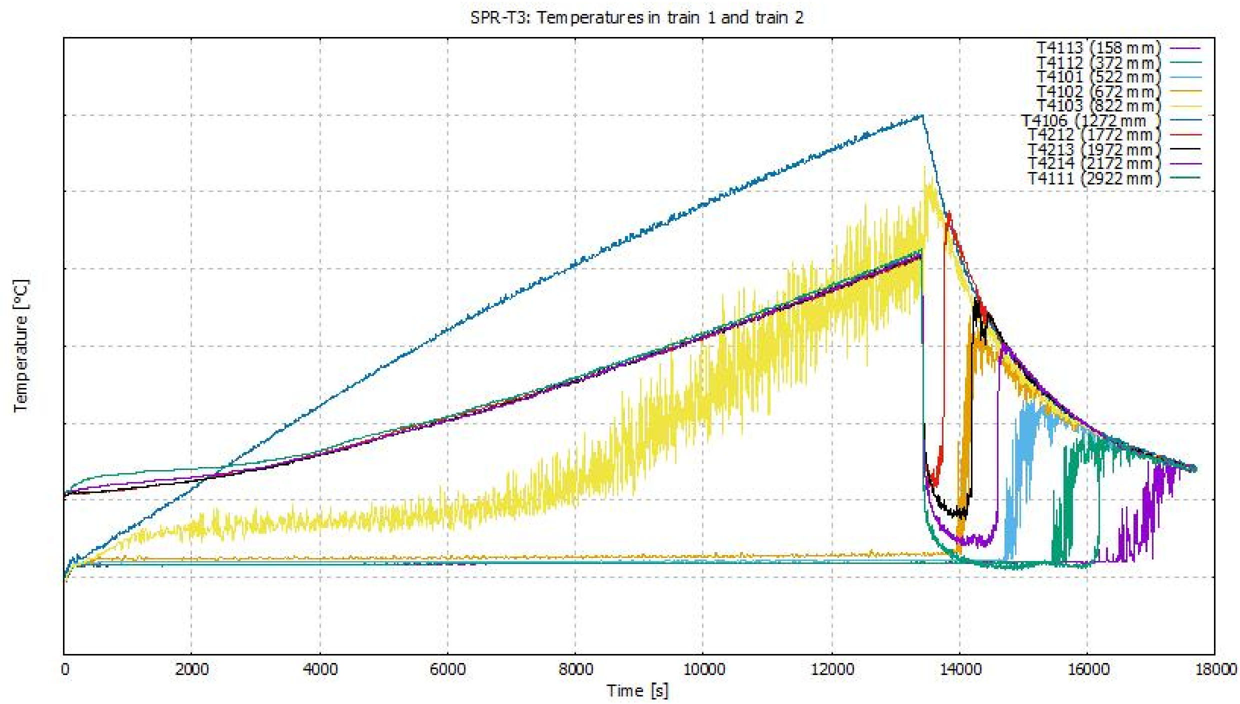

Figure 8. Vertical temperature distribution over the pool volume in the SPR-T3 test.

The topmost TCs, which were above the water level in the beginning of the spray injection, showed a sharp drop in temperature due to the strong cooling effect of the spray in the gas space. As these TCs became submerged during the spray operation they first showed temperatures of cold sprayed water at the top layer of the pool but then started to indicate the progression of the mixing process downwards by showing uniform temperatures with the other measurements.

Figure 8 reveals that compete mixing of the wetwell pool was achieved with the help of the spray injection from above. Internal circulation developed in the pool as the cold and therefore more dense sprayed water pushed its way downwards. The pool mixed in about 4200 seconds. However, the pool water level rose during the spray operation by 2 meters (Figure 9).

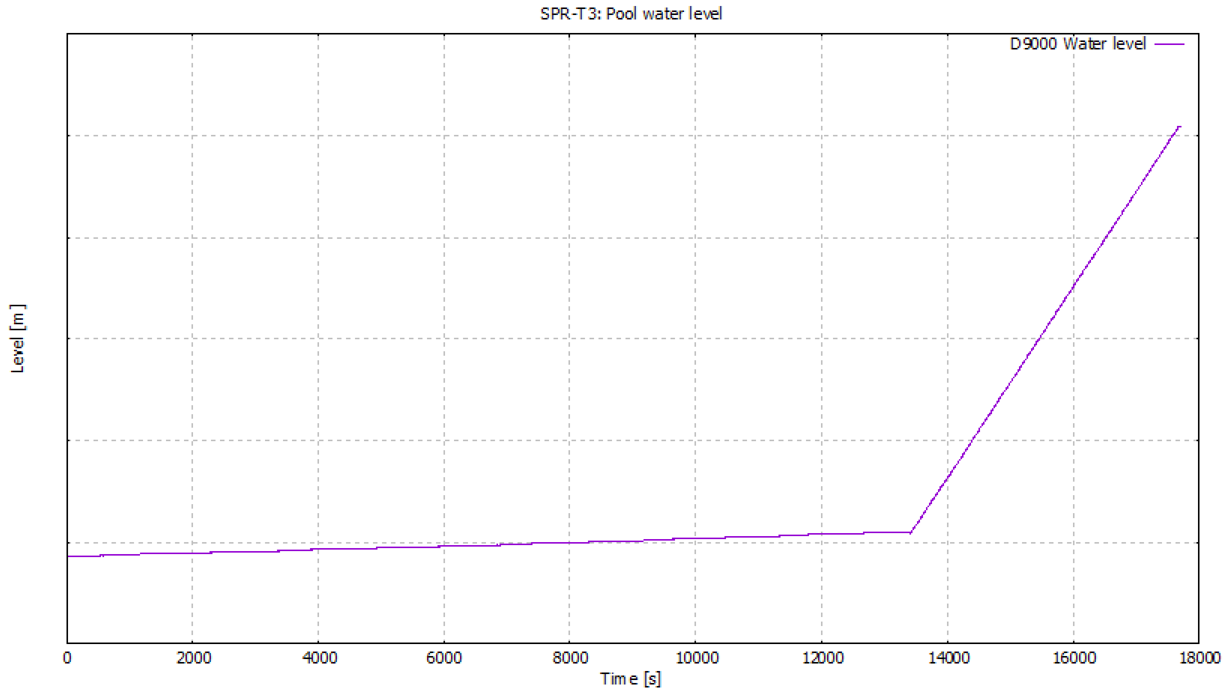

Figure 9. Wetwell water level during the stratification and spray injection phases in SPR-T3.

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the preliminary spray tests (SPR-T1, SPR-T2 and SPR-T3) carried out in the PPOOLEX facility at LUT. The test facility is a closed stainless steel vessel divided into two compartments, drywell and wetwell. For the spray tests the PPOOLEX facility was equipped with a model of a spray injection system with four nozzles and an associated water injection line.

The main objective of the tests was to study interplay between suppression pool behaviour and the spray system operation. Particularly we were interested to find out if mixing of a thermally stratified pool with the help of spray injection from above is possible. An additional goal was to obtain data for improving simulation models related to spray operation in CFD and system codes as well as contribute to the development of the EMS and EHS models for sprays to be implemented in the GOTHIC code by KTH.

In the first two tests the initial stratified situation was created by injecting first warm and then cold water from the tap into the wetwell. The injection of cold water was done cautiously to prevent the warm and cold water from mixing. In the third test the stratified situation was created with the help of small steam injection through the model of the sparger pipe in PPOOLEX by starting from a cold state. In all three tests, the spray injection flow rate was the maximum available from the water supply system of the laboratory i.e. about 128 l/min. When divided to the four spray nozzles it gives 32 l/min per nozzle. As cold water as possible was taken from the tap for the spray. At the initialization of the spray the water temperature was about 20 °C but dropped very soon below 12 °C and then few degrees below that during the injection.

In the SPR-T1 and SPR-T2 tests, mixing of the topmost layers of the pool was achieved easily. The initial temperature difference between the bottom and surface was 28 °C and 33 °, respectively.

It can be speculated that the whole water volume could have been mixed if the tests had been continued for a longer period of time.

In the SPR-T3 test, complete mixing of the initial 60 °C temperature difference between the pool bottom and the surface layer was achieved in about 4200 seconds as a result of internal circulation in the pool induced by the density difference between the cold spray water and warm pool water. The pool water level rose by 2 meters during the mixing process.

These preliminary spray tests in PPOOLEX indicate that it might be possible to mix a stratified pool with the help of spray injection from above. If spray injection was continued long enough internal circulation developed and finally mixed the pool. However, there was not much variation in the test parameters since only the spray injection flow rate was varied in the first test. The spray water temperature and the initial level of pool water were practically the same in all the tests. The same spray nozzles were used throughout the series. The effect of these parameters is the subject of the forthcoming spray tests in PPOOLEX in 2017.

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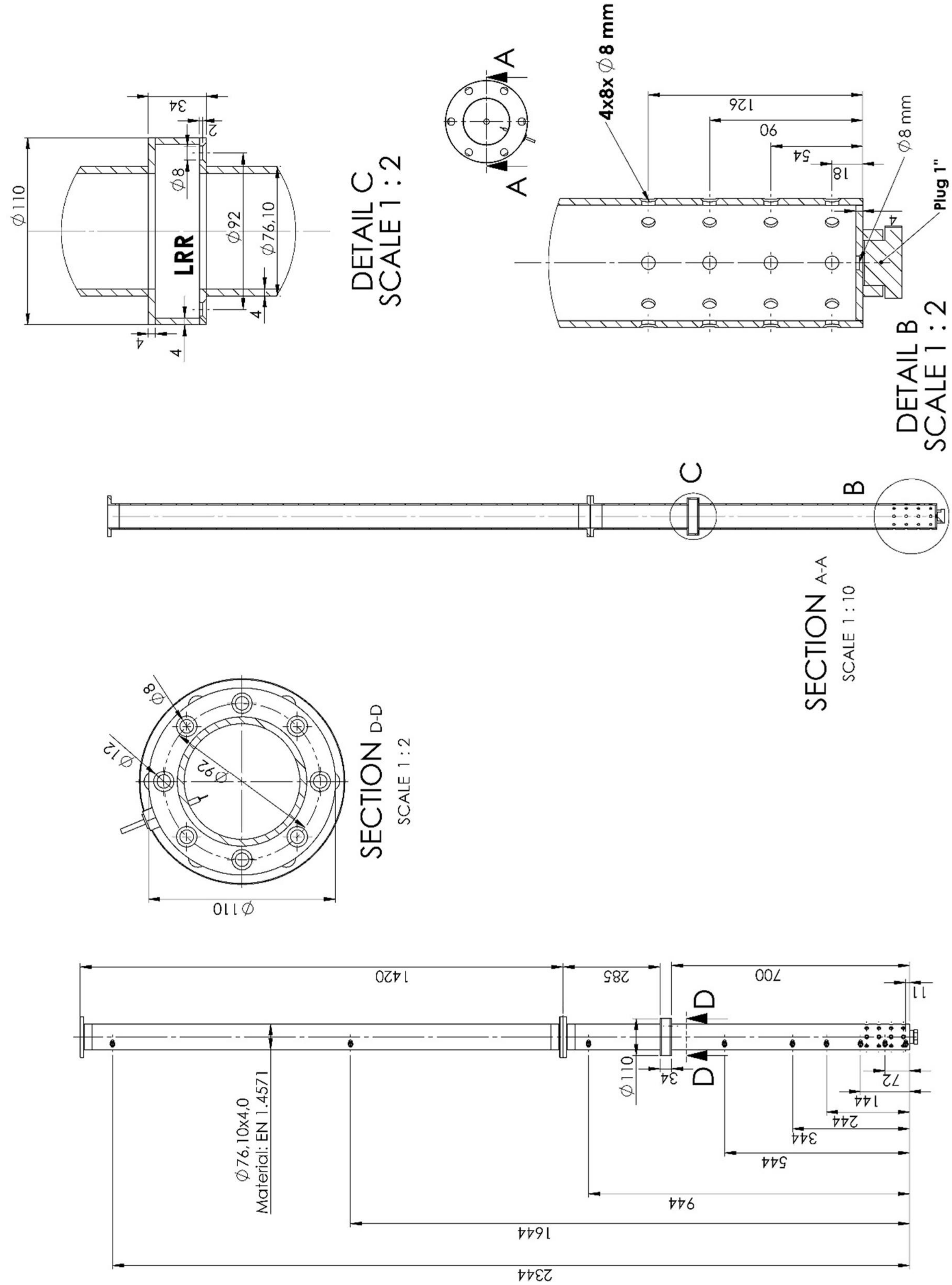
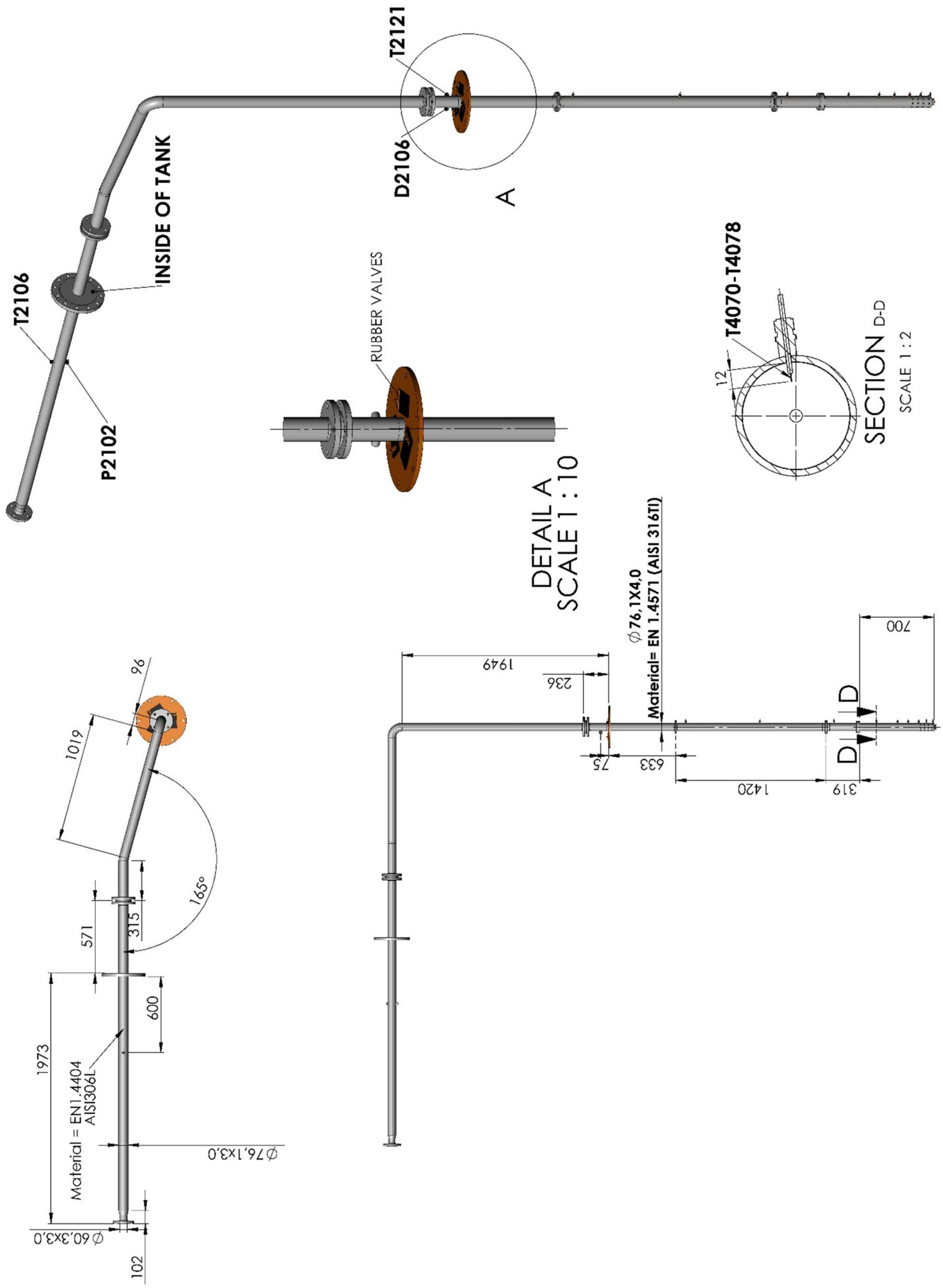
APPENDIX 1: PPOOLEX drawings

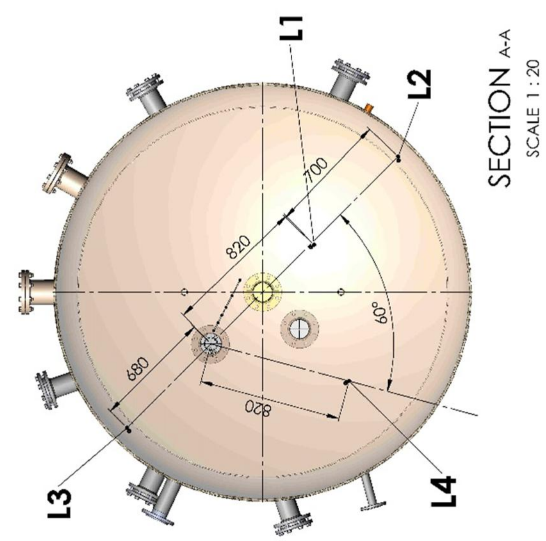


DN65 sparger pipe.



DN65 steam line.

APPENDIX 2: PPOOLEX instrumentation



L1

No.	Code	Height
1	T4100	222
2	T4101	522
3	T4102	672
4	T4103	822
5	T4104	972
6	T4105	1122
7	T4106	1272
8	T4107	1422
9	T4108	1722
10	T4109	2022
11	T4110	2322
12	T4111	2922
61	T4112	372
63	T4113	158

L2

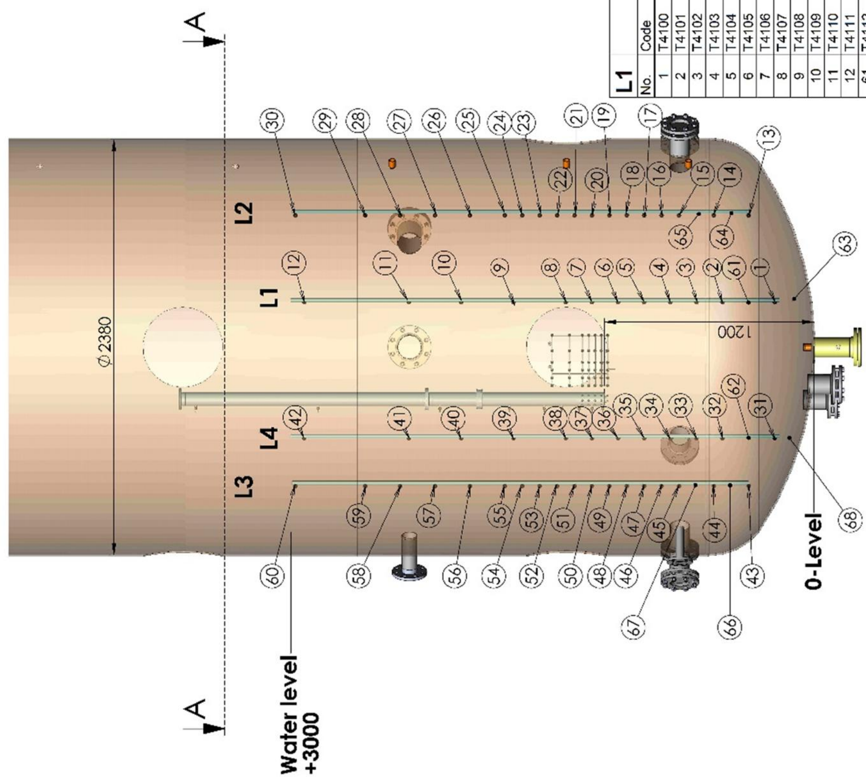
No.	Code	Height
13	T4200	372
14	T4201	572
15	T4202	772
16	T4203	872
17	T4204	972
18	T4205	1072
19	T4206	1172
20	T4207	1272
21	T4208	1372
22	T4209	1472
23	T4210	1572
24	T4211	1672
25	T4212	1772
26	T4213	1972
27	T4214	2172
28	T4215	2372
29	T4216	2572
30	T4217	2972
64	T4218	472
65	T4219	672

L3

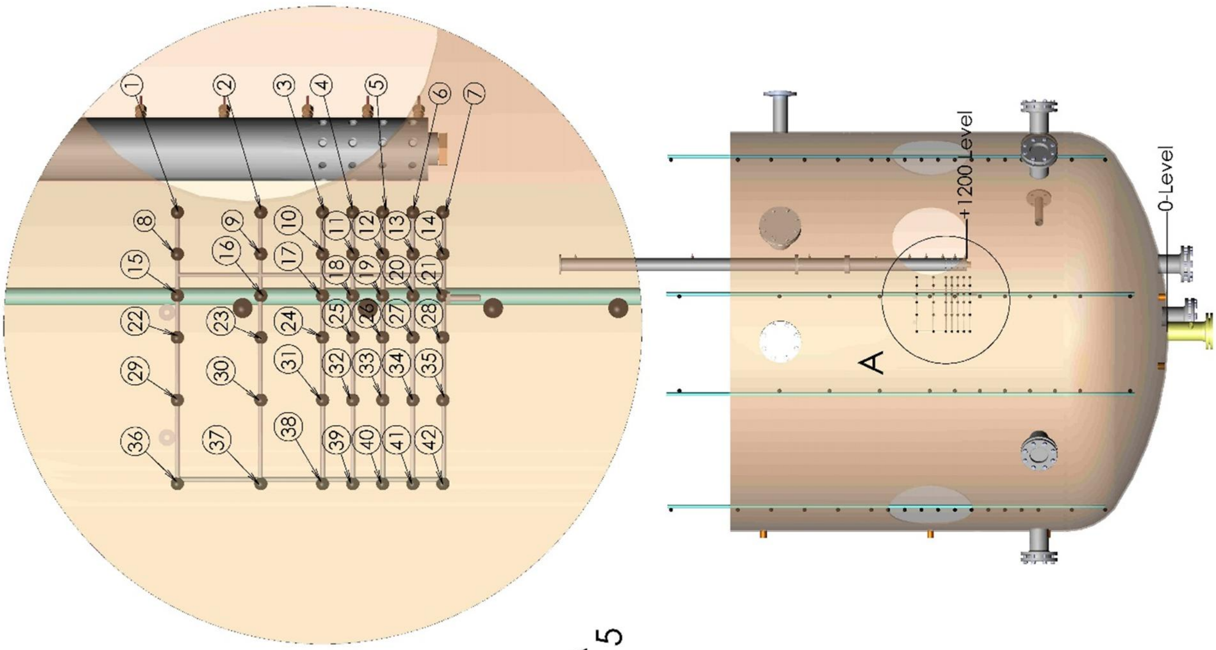
No.	Code	Height
43	T4300	372
44	T4301	572
45	T4302	772
46	T4303	872
47	T4304	972
48	T4305	1072
49	T4306	1172
50	T4307	1272
51	T4308	1372
52	T4309	1472
53	T4310	1572
54	T4311	1672
55	T4312	1772
56	T4313	1972
57	T4314	2172
58	T4315	2372
59	T4316	2572
60	T4317	2972
66	T4318	472
67	T4319	672

L4

No.	Code	Height
31	T4400	222
32	T4401	522
33	T4402	672
34	T4403	822
35	T4404	972
36	T4405	1122
37	T4406	1272
38	T4407	1422
39	T4408	1722
40	T4409	2022
41	T4410	2322
42	T4411	2922
62	T4412	372
68	T4413	158

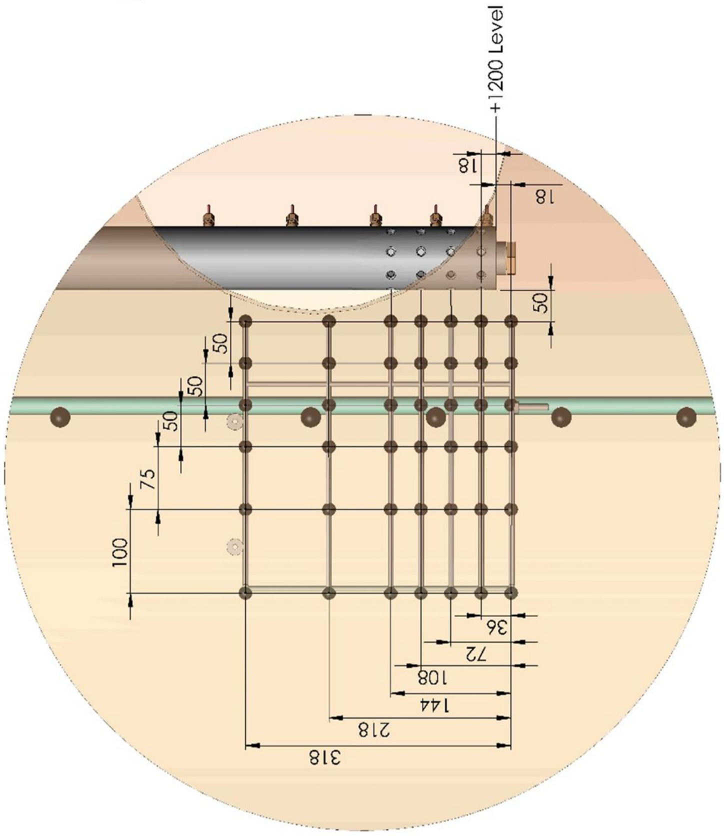


Four trains of temperature measurements in the wetwell.



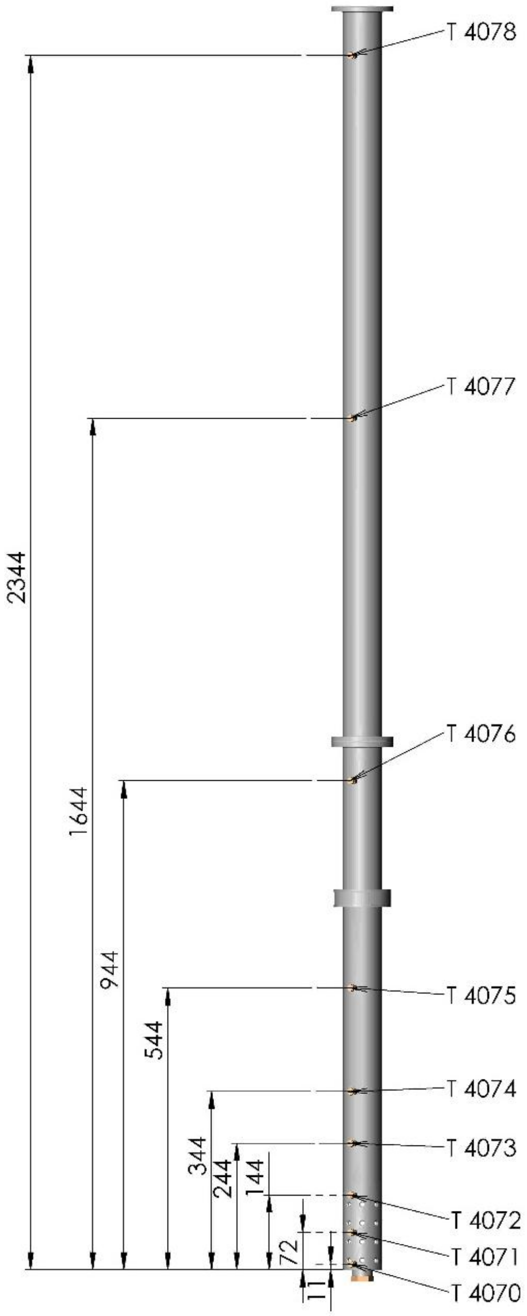
No.	Code	No.	Code	No.	Code
1	T4000	16	T4021	31	T4042
2	T4001	17	T4022	32	T4043
3	T4002	18	T4023	33	T4044
4	T4003	19	T4024	34	T4045
5	T4004	20	T4025	35	T4046
6	T4005	21	T4026	36	T4050
7	T4006	22	T4030	37	T4051
8	T4010	23	T4031	38	T4052
9	T4011	24	T4032	39	T4053
10	T4012	25	T4033	40	T4054
11	T4013	26	T4034	41	T4055
12	T4014	27	T4035	42	T4056
13	T4015	28	T4036		
14	T4016	29	T4040		
15	T4020	30	T4041		

DETAIL A
SCALE 1 : 5

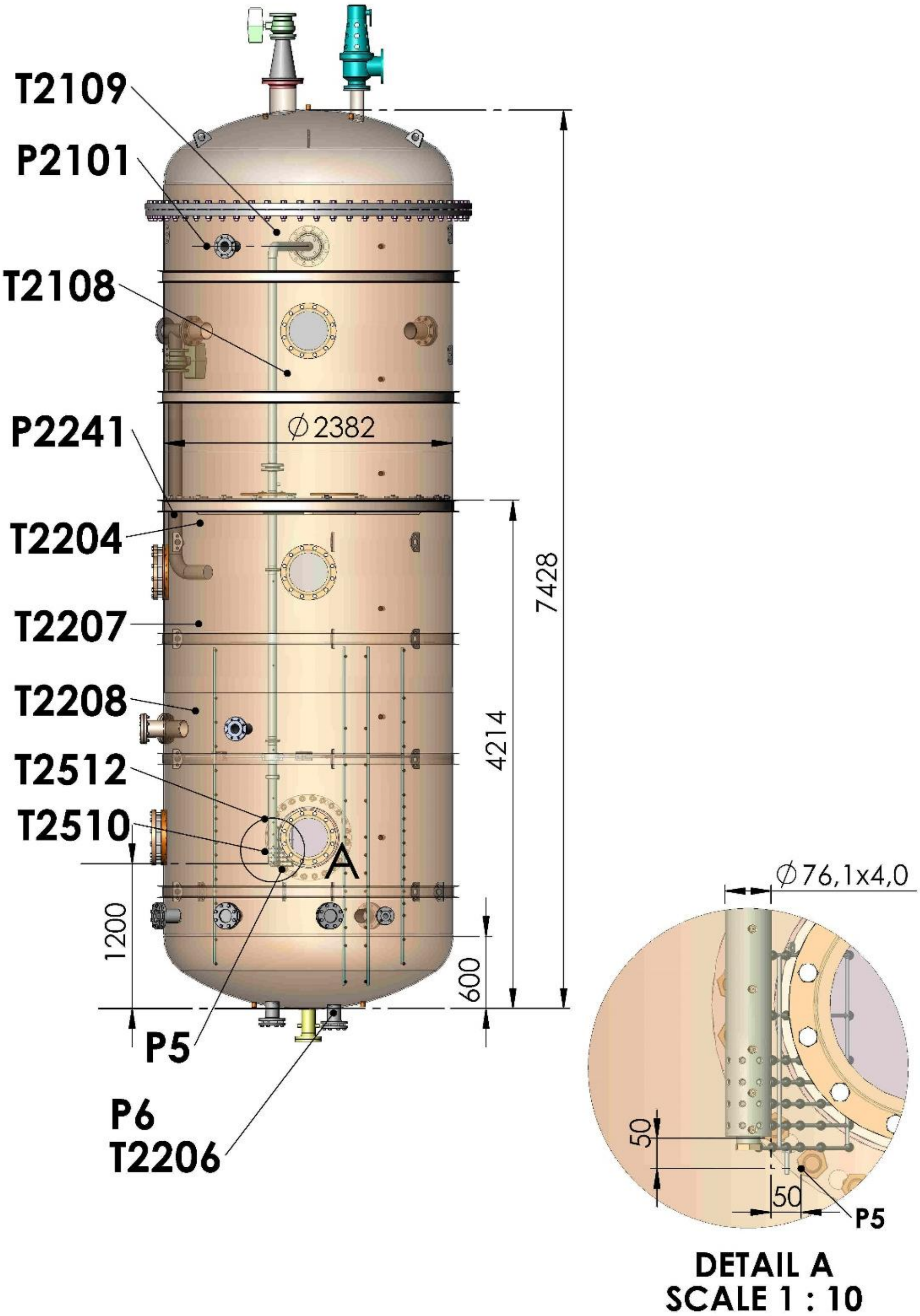


6x7 grid of temperature measurements in the wetwell.

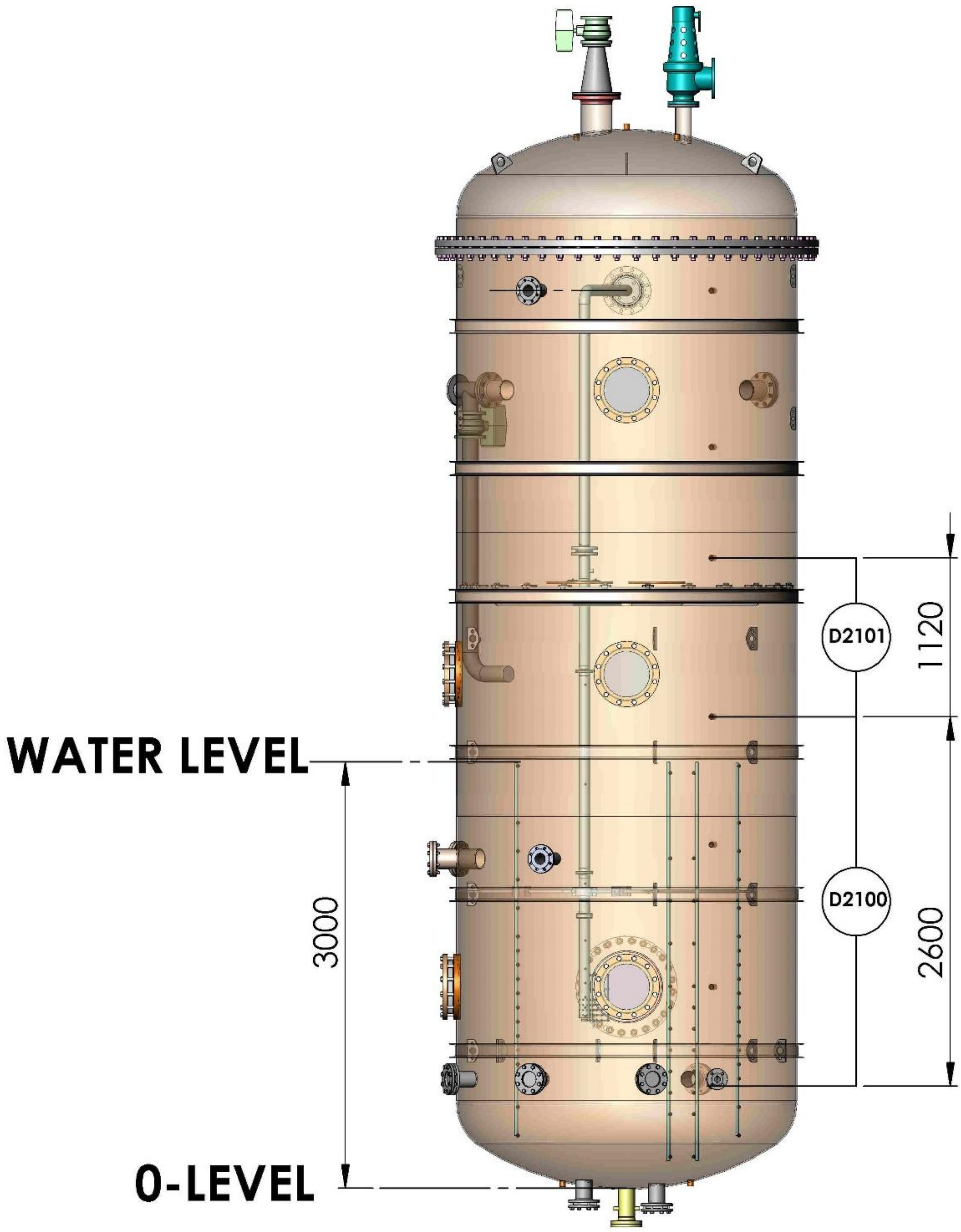
Open your mind. LUT.
Lappeenranta University of Technology



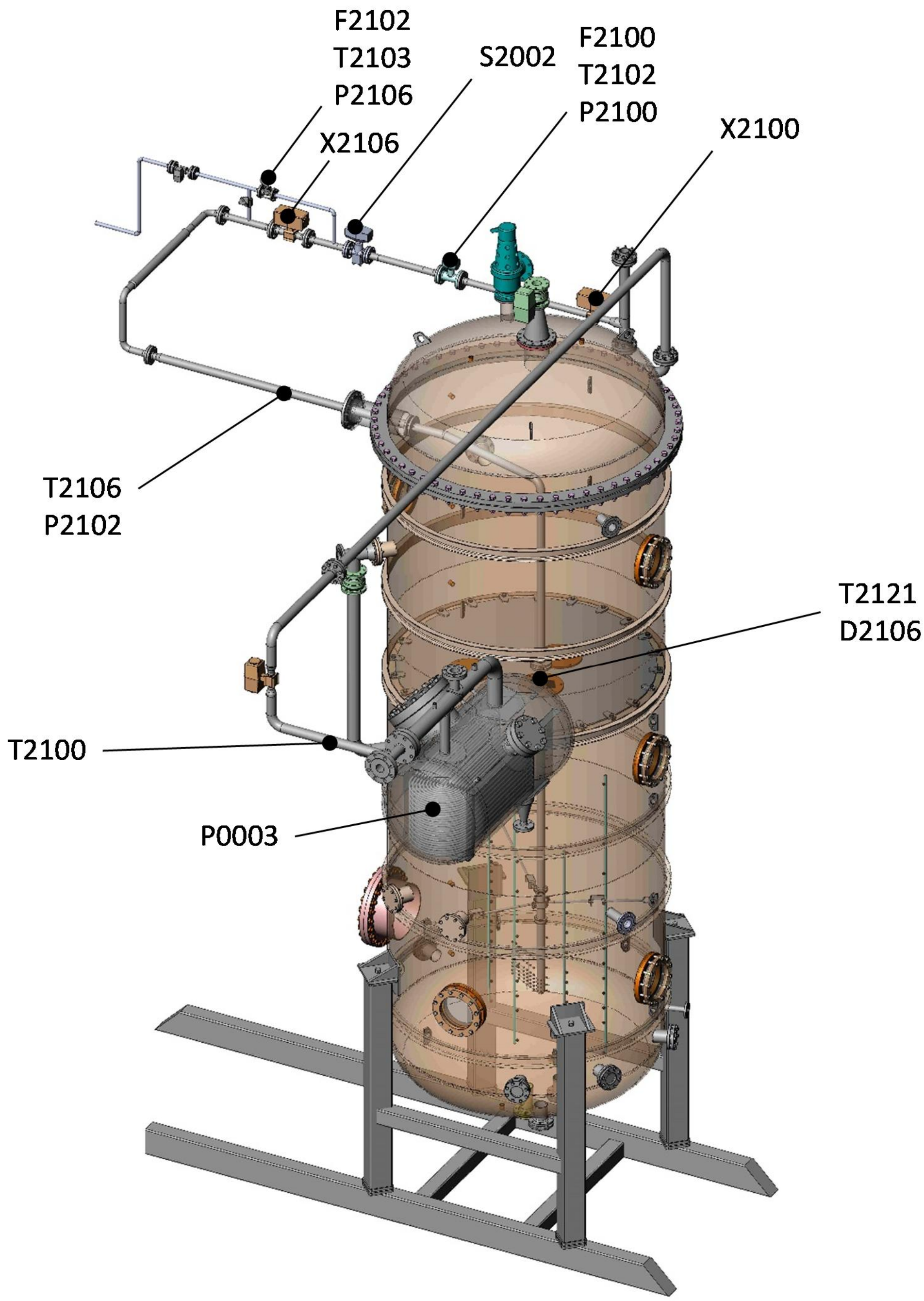
Temperature measurements inside the sparger pipe.



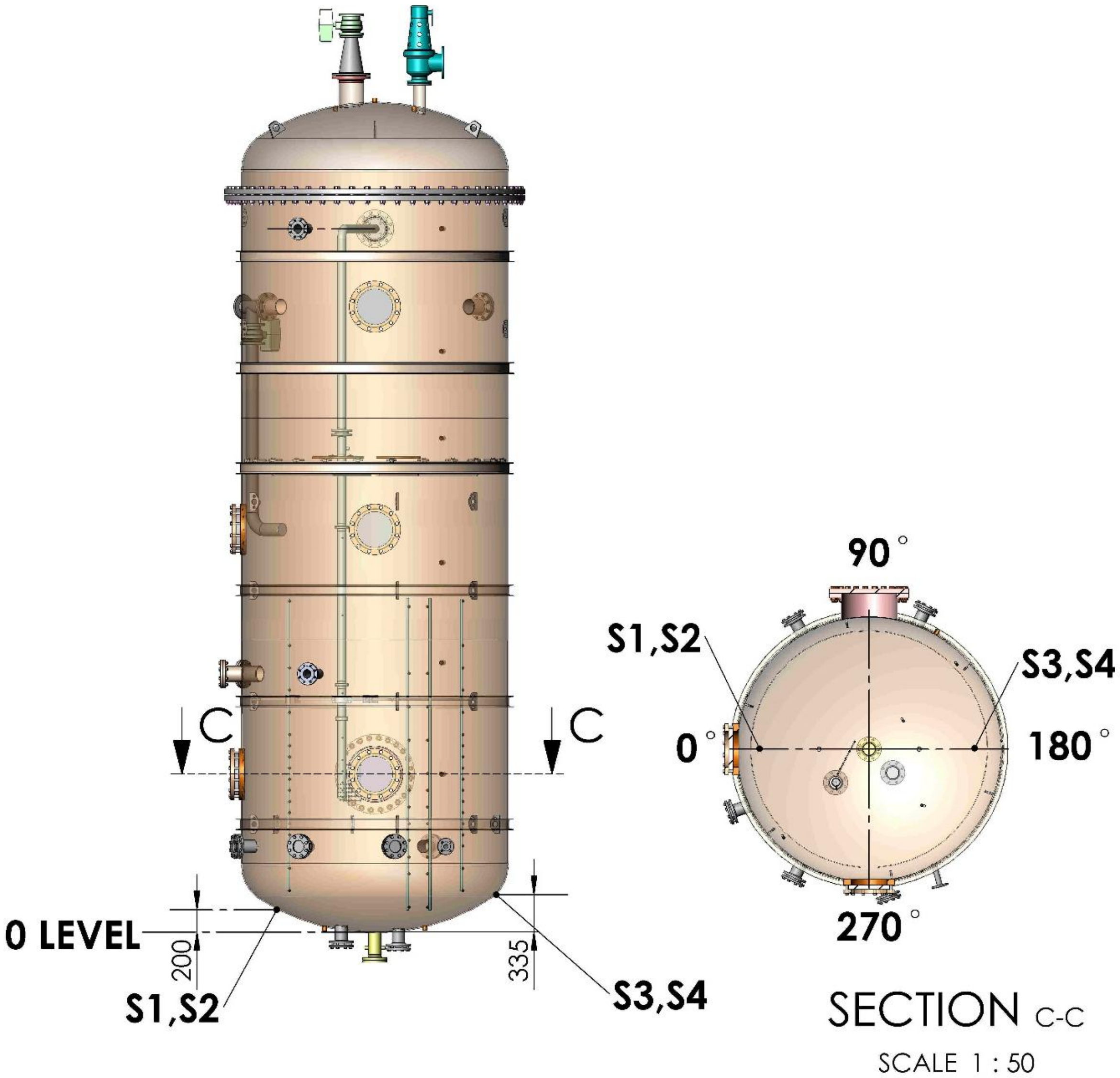
Test vessel measurements.



Pressure difference measurements. Nominal water level is 3.0 m.



Measurements in the steam line.



Strain gauges on the outer wall of the pool bottom.

Measurement	Code	Elevation	Location	Error estimation	Measurement software
Camera trigger	C1	-	Wetwell	Not defined	LabView
Pressure difference	D2100	700–3300	Wetwell	±0.05 m	FieldPoint
Pressure difference	D2101	3300–4420	Wetwell–drywell	±4 000 Pa	FieldPoint
Pressure difference	D2106	4347	Blowdown pipe–drywell	±3 000 Pa	FieldPoint
Pressure difference	D9000	-130-5800	Wetwell	±0.1 m	FieldPoint
Flow rate	F2100	-	DN50 steam line	±5 l/s	FieldPoint
Flow rate	F2102	-	DN25 steam line	±0.7 l/s	FieldPoint
Flow rate	F9000	-	Spray line	±0.007 kg/s	FieldPoint
Pressure	P0003	-	Steam generator 1	±0.3 bar	FieldPoint
Pressure	P0004	-	Steam generator 2	±0.3 bar	FieldPoint
Pressure	P0005	-	Steam generator 3	±0.3 bar	FieldPoint
Pressure	P5	1150	Blowdown pipe outlet	±0.7 bar	LabView
Pressure	P6	-15	Wetwell bottom	±0.5 bar	LabView
Pressure	P2100	-	DN50 steam line	±0.2 bar	FieldPoint
Pressure	P2101	6300	Drywell	±0.03 bar	FieldPoint
Pressure	P2102	-	Inlet plenum	±0.03 bar	FieldPoint
Pressure	P2106	-	DN25 steam line	±0.06 bar	FieldPoint
Pressure	P2241	4200	Wetwell gas space	±0.05 bar	FieldPoint
Control valve position	S2002	-	DN50 Steam line	Not defined	FieldPoint
Strain	S1	200	Bottom segment	Not defined	LabView
Strain	S2	200	Bottom segment	Not defined	LabView
Strain	S3	335	Bottom segment	Not defined	LabView
Strain	S4	335	Bottom segment	Not defined	LabView
Temperature	T1279	-3260	Laboratory	±0.1 °C	FieldPoint
Temperature	T1280	-1260	Laboratory	±0.1 °C	FieldPoint
Temperature	T1281	740	Laboratory	±1.8 °C	FieldPoint
Temperature	T1282	2740	Laboratory	±0.1 °C	FieldPoint
Temperature	T1283	4740	Laboratory	±0.1 °C	FieldPoint
Temperature	T1284	6740	Laboratory	±0.1 °C	FieldPoint
Temperature	T1285	8740	Laboratory	±0.1 °C	FieldPoint
Temperature	T2100	-	DN80 steam line	±3 °C	FieldPoint
Temperature	T2102	-	DN50 steam line	±2 °C	FieldPoint
Temperature	T2103	-	DN25 steam line	±2 °C	FieldPoint
Temperature	T2106	-	Inlet plenum	±2 °C	FieldPoint
Temperature	T2108	5200	Drywell	±2 °C	FieldPoint
Temperature	T2109	6390	Drywell	±2 °C	FieldPoint
Temperature	T2121	4347	Blowdown pipe	±2 °C	FieldPoint
Temperature	T2204	4010	Wetwell gas space	±2 °C	FieldPoint
Temperature	T2206	-15	Wetwell bottom	±2 °C	FieldPoint
Temperature	T2207	3185	Wetwell gas space	±2 °C	FieldPoint
Temperature	T2208	2360	Wetwell gas space	±2 °C	FieldPoint
Temperature	T2510	1295	Wetwell	±2 °C	FieldPoint
Temperature	T2512	1565	Wetwell	±2 °C	FieldPoint
Temperature	T3611	1565	Spray line	±2 °C	FieldPoint
Temperature	T4000	1500	Wetwell	±2 °C	FieldPoint
Temperature	T4001	1400	Wetwell	±2 °C	LabView

Temperature	T4002	1326	Wetwell	±2 °C	LabView
Temperature	T4003	1290	Wetwell	±2 °C	LabView
Temperature	T4004	1254	Wetwell	±2 °C	LabView
Temperature	T4005	1218	Wetwell	±2 °C	LabView
Temperature	T4006	1182	Wetwell	±2 °C	LabView
Temperature	T4010	1500	Wetwell	±2 °C	FieldPoint
Temperature	T4011	1400	Wetwell	±2 °C	LabView
Temperature	T4012	1326	Wetwell	±2 °C	LabView
Temperature	T4013	1290	Wetwell	±2 °C	LabView
Temperature	T4014	1254	Wetwell	±2 °C	LabView
Temperature	T4015	1218	Wetwell	±2 °C	LabView
Temperature	T4016	1182	Wetwell	±2 °C	LabView
Temperature	T4020	1500	Wetwell	±2 °C	LabView
Temperature	T4021	1400	Wetwell	±2 °C	LabView
Temperature	T4022	1326	Wetwell	±2 °C	LabView
Temperature	T4023	1290	Wetwell	±2 °C	LabView
Temperature	T4024	1254	Wetwell	±2 °C	LabView
Temperature	T4025	1218	Wetwell	±2 °C	LabView
Temperature	T4026	1182	Wetwell	±2 °C	LabView
Temperature	T4030	1500	Wetwell	±2 °C	LabView
Temperature	T4031	1400	Wetwell	±2 °C	LabView
Temperature	T4032	1326	Wetwell	±2 °C	LabView
Temperature	T4033	1290	Wetwell	±2 °C	LabView
Temperature	T4034	1254	Wetwell	±2 °C	LabView
Temperature	T4035	1218	Wetwell	±2 °C	LabView
Temperature	T4036	1182	Wetwell	±2 °C	LabView
Temperature	T4040	1500	Wetwell	±2 °C	FieldPoint
Temperature	T4041	1400	Wetwell	±2 °C	LabView
Temperature	T4042	1326	Wetwell	±2 °C	LabView
Temperature	T4043	1290	Wetwell	±2 °C	LabView
Temperature	T4044	1254	Wetwell	±2 °C	LabView
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Temperature	T4051	1400	Wetwell	±2 °C	FieldPoint
Temperature	T4052	1326	Wetwell	±2 °C	FieldPoint
Temperature	T4053	1290	Wetwell	±2 °C	FieldPoint
Temperature	T4054	1254	Wetwell	±2 °C	FieldPoint
Temperature	T4055	1218	Wetwell	±2 °C	FieldPoint
Temperature	T4056	1182	Wetwell	±2 °C	FieldPoint
Temperature	T4070	1211	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4071	1272	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4072	1344	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4073	1444	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4074	1544	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4075	1744	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4076	2144	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4077	2844	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4078	3544	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4100	222	Wetwell	±2 °C	FieldPoint
Temperature	T4101	522	Wetwell	±2 °C	FieldPoint
Temperature	T4102	672	Wetwell	±2 °C	FieldPoint

Temperature	T4103	822	Wetwell	±2 °C	FieldPoint
Temperature	T4104	972	Wetwell	±2 °C	FieldPoint
Temperature	T4105	1122	Wetwell	±2 °C	FieldPoint
Temperature	T4106	1272	Wetwell	±2 °C	FieldPoint
Temperature	T4107	1422	Wetwell	±2 °C	FieldPoint
Temperature	T4108	1722	Wetwell	±2 °C	FieldPoint
Temperature	T4109	2022	Wetwell	±2 °C	FieldPoint
Temperature	T4110	2322	Wetwell	±2 °C	FieldPoint
Temperature	T4111	2922	Wetwell	±2 °C	FieldPoint
Temperature	T4112	372	Wetwell	±2 °C	FieldPoint
Temperature	T4113	158	Wetwell	±2 °C	FieldPoint
Temperature	T4200	372	Wetwell	±2 °C	FieldPoint
Temperature	T4201	572	Wetwell	±2 °C	FieldPoint
Temperature	T4202	772	Wetwell	±2 °C	FieldPoint
Temperature	T4203	872	Wetwell	±2 °C	FieldPoint
Temperature	T4204	972	Wetwell	±2 °C	FieldPoint
Temperature	T4205	1072	Wetwell	±2 °C	FieldPoint
Temperature	T4206	1172	Wetwell	±2 °C	FieldPoint
Temperature	T4207	1272	Wetwell	±2 °C	FieldPoint
Temperature	T4208	1372	Wetwell	±2 °C	FieldPoint
Temperature	T4210	1572	Wetwell	±2 °C	FieldPoint
Temperature	T4212	1772	Wetwell	±2 °C	FieldPoint
Temperature	T4213	1972	Wetwell	±2 °C	FieldPoint
Temperature	T4214	2172	Wetwell	±2 °C	FieldPoint
Temperature	T4215	2372	Wetwell	±2 °C	FieldPoint
Temperature	T4216	2572	Wetwell	±2 °C	FieldPoint
Temperature	T4217	2972	Wetwell	±2 °C	FieldPoint
Temperature	T4218	472	Wetwell	±2 °C	FieldPoint
Temperature	T4219	672	Wetwell	±2 °C	FieldPoint
Temperature	T4300	372	Wetwell	±2 °C	FieldPoint
Temperature	T4301	572	Wetwell	±2 °C	FieldPoint
Temperature	T4302	772	Wetwell	±2 °C	FieldPoint
Temperature	T4303	872	Wetwell	±2 °C	FieldPoint
Temperature	T4304	972	Wetwell	±2 °C	FieldPoint
Temperature	T4305	1072	Wetwell	±2 °C	FieldPoint
Temperature	T4306	1172	Wetwell	±2 °C	FieldPoint
Temperature	T4307	1272	Wetwell	±2 °C	FieldPoint
Temperature	T4308	1372	Wetwell	±2 °C	FieldPoint
Temperature	T4310	1572	Wetwell	±2 °C	FieldPoint
Temperature	T4312	1772	Wetwell	±2 °C	FieldPoint
Temperature	T4313	1972	Wetwell	±2 °C	FieldPoint
Temperature	T4314	2172	Wetwell	±2 °C	FieldPoint
Temperature	T4315	2372	Wetwell	±2 °C	FieldPoint
Temperature	T4316	2572	Wetwell	±2 °C	FieldPoint
Temperature	T4317	2972	Wetwell	±2 °C	FieldPoint
Temperature	T4318	472	Wetwell	±2 °C	FieldPoint
Temperature	T4319	672	Wetwell	±2 °C	FieldPoint
Temperature	T4400	222	Wetwell	±2 °C	FieldPoint
Temperature	T4401	522	Wetwell	±2 °C	FieldPoint
Temperature	T4402	672	Wetwell	±2 °C	FieldPoint
Temperature	T4403	822	Wetwell	±2 °C	FieldPoint
Temperature	T4404	972	Wetwell	±2 °C	FieldPoint

Temperature	T4405	1122	Wetwell	±2 °C	FieldPoint
Temperature	T4406	1272	Wetwell	±2 °C	FieldPoint
Temperature	T4407	1422	Wetwell	±2 °C	FieldPoint
Temperature	T4408	1722	Wetwell	±2 °C	FieldPoint
Temperature	T4409	2022	Wetwell	±2 °C	FieldPoint
Temperature	T4410	2322	Wetwell	±2 °C	FieldPoint
Temperature	T4411	2922	Wetwell	±2 °C	FieldPoint
Temperature	T4412	372	Wetwell	±2 °C	FieldPoint
Temperature	T4413	158	Wetwell	±2 °C	FieldPoint
Temperature	T4501	-	RHR nozzle injection line	±2 °C	FieldPoint
Cut-off valve position	V1	-	DN50 Steam line	Not defined	LabView
Cut-off valve position	X2100	-	DN50 Steam line	Not defined	FieldPoint
Steam partial pressure	X2102	5200	Drywell	Not defined	FieldPoint
Cut-off valve position	X2106	-	DN50 Steam line	Not defined	FieldPoint

Measurements of the PPOOLEX facility in the preliminary spray test.

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Abstract
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This report summarizes the results of the preliminary spray tests carried out in the PPOOLEX facility at LUT. The test facility is a closed stainless steel vessel divided into two compartments, drywell and wetwell. For the spray tests the facility was equipped with a model of a spray injection system with four nozzles.

The main objective of the tests was to study interplay between suppression pool behaviour and the spray system operation. Particularly we were interested to find out if mixing of a thermally stratified pool with the help of spray injection from above is possible. An additional goal was to obtain data for improving simulation models related to spray operation in CFD and system codes as well as contribute to the development of the EMS and EHS models for sprays to be implemented in the GOTHIC code by KTH.

In the first two tests the initial stratified situation was created by injecting first warm and then cold water from the tap into the wetwell. In the third test the stratified situation was created with the help of small steam injection through the model of the sparger pipe in PPOOLEX by starting from a cold state. In all three tests, the spray injection flow rate was the maximum available from the water supply system of the laboratory i.e. about 128 l/min. When divided to the four spray nozzles it gives 32 l/min per nozzle.

In the first two tests, mixing of the topmost layers of the pool was achieved easily. The initial temperature difference between the bottom and surface was 28 °C and 33 °, respectively. It can be speculated that the whole water volume could have been mixed if the tests had been continued for a longer period of time.

In the third test, complete mixing of the initial 60 °C temperature difference between the pool bottom and the surface layer was achieved in about 4200 seconds as a result of internal circulation in the pool induced by the density difference between the cold spray water and warm pool water. The pool water level rose by 2 meters during the spray operation.

These preliminary spray tests in PPOOLEX indicate that it might be possible to mix a stratified pool with the help of spray injection from above. If spray injection was continued long enough internal circulation developed and finally mixed the pool.

Key words: condensation pool, spray, mixing

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