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Mixing Tests with an RHR Nozzle in PPOOLEX

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Abstract

This report summarizes the results of the RHR nozzle tests carried out in the PPOOLEX facility at LUT in 2016. The test facility is a closed stainless steel vessel divided into two compartments, drywell and wetwell. For the RHR nozzle tests the PPOOLEX facility was equipped with a model of an RHR nozzle and an associated water injection line.

The main objective of the tests was to obtain additional data for the development of the EMS and EHS models to be implemented in GOTHIC code by KTH. Mixing of a thermally stratified pool with the help of water injection through an RHR nozzle was of special interest. Particularly the effects of nozzle orientation, ΔT in the pool, injection water temperature and injection water mass flow rate were studied.

In the tests there were two stratification phases and two mixing phases. During the stratification phases two regions with clearly different water temperatures and a narrow thermocline region between them developed in the pool. When the target temperature difference between the bottom and the top layer of the pool had been reached the mixing process was initiated by starting water injection into the pool through the RHR nozzle.

With the vertical orientation of the RHR nozzle mixing was otherwise successful but incomplete above the nozzle elevation. This was the case with both of the used water injection flow rates, 0.5 kg/s and 0.3 kg/s.

Compete mixing was achieved with the horizontal orientation of the RHR nozzle by using a large injection flow rate (1.0-1.05 kg/s). The pool mixed in about 4000 seconds. With a 0.3 kg/s injection flow rate the water volume above the thermocline started to cool down as soon as the mixing phase started whereas below the thermocline the mixing process proceeded very slowly and only a small fraction of the bottom volume mixed completely before the test was terminated because the wetwell became full of water.

These tests in PPOOLEX verified that orientation of an RHR nozzle plays an important role in the success of the mixing process of a thermally stratified pool. The nozzle injection flow rate, injection water temperature and ΔT in the pool have an effect on the mixing process but it is not as dominant as the nozzle orientation.

Key words

condensation pool, RHR nozzle, mixing

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CONTENTS

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
SPA	SPArger experiment series
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.

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.

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 the 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.

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 in the test series carried out in 2014, 2015 and 2016 [13, 14, and 15]. In this report the RHR nozzle tests on mixing efficiency 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 at the end of 2006. PPOOLEX models the containment of a BWR type nuclear power plant. During the years the facility has gone through several modifications and enhancements as well as improvements of instrumentation. For the RHR nozzle tests described in this report the facility was equipped with a model of an RHR system nozzle. The PPOOLEX facility is described in more detail in reference [16]. 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 inner 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 containments of the Olkiluoto BWR units (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.

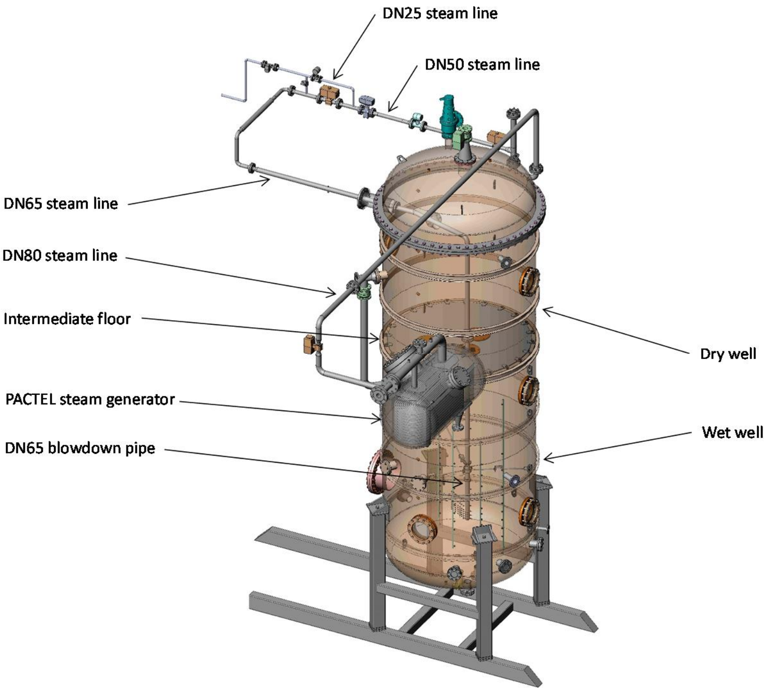

Figure 1. PPOOLEX test vessel.

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 [17] 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 RHR SYSTEM NOZZLE

For the RHR nozzle tests the PPOOLEX facility was equipped with a model of an RHR nozzle on the basis of suggestions from KTH presented in Figure 2. Both vertical and horizontal position of the nozzle were used in the tests. Mixing nozzles in BWR pools are oriented horizontally.

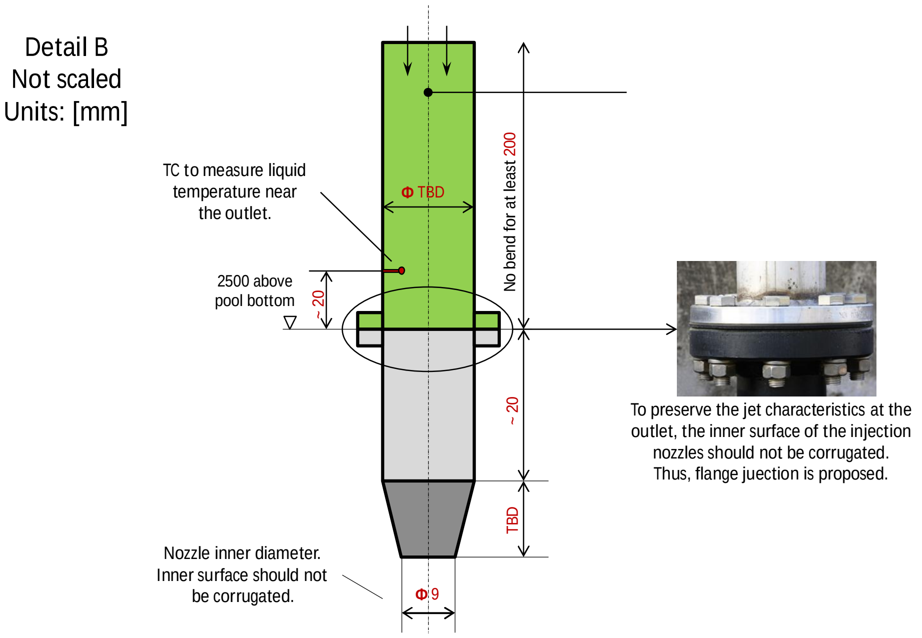

Figure 2. Proposal from KTH for an RHR nozzle to be installed to PPOOLEX.

To keep the manufacturing process as simple as possible it was decided that standard pipe parts will be used. As a result the RHR nozzle differs somewhat from the original proposal. Figure 3 shows the final construction of the nozzle installed to the PPOOLEX facility in its vertical position.

Due to different kind of internal structures in the pool it was impossible to install the nozzle exactly at the centre of the pool when in vertical position as proposed. The water jet from the nozzle would have hit some of the structures instantly thus destroying the purpose of the tests. Therefore the nozzle was about 100 mm off the pool centre. For the horizontal position the construction was tilted 90 degrees and the nozzle tip was about 350 mm off the pool centre.

Figure 3. RHR nozzle in PPOOLEX.

The support rods for the nozzle base pipe were attached to the DN65 sparger pipe. The distance of the nozzle base pipe from the sparger pipe was 370 mm.

Injection water to the nozzle was delivered via a hose connected to a lead-in close to the pool bottom. Water was taken from the water-supply system of the laboratory. The junction for the temperature measurement of the injection water can be seen in Figure 3 as well. Flow meter was in the injection line outside the pool.

The tip of the nozzle was not cone-shaped as suggested in the proposal by KTH. Instead a regular pipe connector was used. The tip of the nozzle was about 500 mm below the pool water surface at the beginning of the tests both in the vertical and horizontal cases. During the tests the pool water level rose and the nozzle became more and more submerged.

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. 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…4056) 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 RHR nozzle, no extra temperature measurements were added to PPOOLEX at this time except the one used for measuring the injection water temperature.

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

2.6 CCTV SYSTEM

A closed circuit television (CCTV) system with standard video cameras having a frame rate of 25 fps and 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 [18].

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 RHR nozzle tests labelled as NZL-T0V, NZL-T1V and NZL-T1H were carried out in the PPOOLEX facility. V in the test label indicates that the nozzle was in vertical position and H that it was in horizontal position. The NZL-T0V test was a shakedown test for verifying the correct functioning of all the systems and for getting initial data from the RHR nozzle operation in order to tune the test parameters of the follow-up tests. The main purpose of the tests was to obtain additional data for the development of the EMS and EHS models to be implemented in the GOTHIC code by KTH. Mixing of a thermally stratified pool with the help of water injection through an RHR nozzle was of special interest. Particularly the effects of nozzle orientation, ΔT in the pool, injection water temperature and injection water mass flow rate were studied.

Detailed test specifications were put together on the basis of pre-test simulations with the GOTHIC code by KTH before the tests and by taking into account the initial results from the shakedown test [19, 20 and 21]. In all the tests the stratified condition was created by injecting steam into the pool water via the sparger pipe. 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. Before the mixing phase, done with the RHR nozzle, the steam injection was stopped.

In NZL-T0V and NZL-T1H there were two stratification phases. In both, the target temperature difference between the bottom and the top layer of the pool was 25 °C. In NZL-T1V the first stratification phase ended when the temperature difference was 25 °C and the second phase when it was 45 °C.

In NZL-T0V the first and second mixing phases were both started with a 0.3 kg/s water injection flow rate but the flow rate was increased to 0.5 kg/s after about 4200 s during the first phase and after about 2500 s during the second phase. At the end of the first mixing phase the flow rate was still increased to 0.56 kg/s for about 225 seconds. In NZL-T1V there were two mixing phases, the first one with 0.5 kg/s and the second one with 0.3 kg/s. In NZL-T1H the first mixing was done with 1 kg/s for about 2300 seconds and then with maximum available 1.05 kg/s for about 2200 seconds. The second mixing was done with 0.3 kg/s. During the first mixing phase in NZL-T0V and NZL-T1V the temperature of injected water was about 45 °C and during all other mixing periods it was about 20 °C. Due to the large RHR nozzle injection rate in NZL-T1H the wetwell pool was almost full of water after the first mixing phase and therefore some water was drained from the pool in order to enable the second stratification and mixing phase. Since the pool was mixed and at a uniform temperature at the time of the drainage, the procedure could be done without ruining the results of the second phases.

Before the tests, the wetwell pool was filled with isothermal water (~18 °C in NZL-T0V and NZL-T1V and ~17 °C in NZL-T1H) to the level of 3.0 m, i.e. the sparger pipe outlet was submerged by 1.8 m. The target temperature in the beginning of the stratification phase was 20 °C. During the clearing phase before the stratification period a higher steam flow rate (slightly above 200 g/s for about 200-250 seconds) was used to warm up the pipes and as a result the pool water temperature rose to about 20 °C in NZL-T1V and NZL-T1H and to about 22 °C in NZL-T0V. The steam discharge rate into the PPOOLEX vessel was controlled with the help of the pressure level of the steam source (PACTEL steam generator) and a remote-operated control valve (S2002) in the DN50 steam line.

The tests were started from atmospheric conditions in PPOOLEX. After the correct initial steam generator pressure (0.6 MPa) had been reached, the remote-controlled cut-off valve (X2100) in the DN50 steam line was opened and the clearing phase started. The stratification process was initiated by reducing the steam flow rate to the desired level (about 110-120 g/s). When the desired temperature difference between the bottom and surface layers of the pool had been reached, steam injection was stopped and water injection via the RHR nozzle line started.

The main parameters of the NZL-T0V, NZL-T1V and NZL-T1H tests are listed in Table 2, correspondingly.

Table 2. Parameter values of the RHR nozzle tests NZL-T0V, NZL-T1V and NZL-T1H.

Test	Initial water level [m]	Initial water temperature [°C]	Steam/water flow rate [g/s]			
			Stratification I	Mixing I	Stratification II	Mixing II
NZL-T0V	3.0	~18	~116 (ΔT~25°C)	~300/500/560	~112 (ΔT~25°C)	~300
NZL T1V	3.0	~18	~121 (ΔT~25°C)	~500	~109 (ΔT~45°C)	~300
NZL-T1H	3.0	~17	~120 (ΔT~25°C)	~1000/1050	~121 (ΔT~25°C)	~300

4 TEST RESULTS

The following chapters give a more detailed description of the NZL-T1V and NZL-T1H tests and present the observed phenomena. The key results of the shakedown test NZL-T0V are identical with those of the NZL-T1V test and therefore they are not presented here.

4.1 NZL-T1V

Water was expelled out of the sparger pipe as soon as steam injection was initiated at the start of the clearing phase. For the first stratification phase the steam mass flow rate was decreased to 116 g/s. With this kind of flow rate steam flows through the injection holes of the sparger as small horizontal jets and condenses mainly outside the sparger pipe. Because no chugging kind of phenomenon existed and the steam jets were too weak to create much turbulence in the pool, suitable conditions for thermal stratification to occur prevailed.

During the mixing phases the sparger pipe was filled with water, because steam injection was stopped. As soon as the second stratification phase was started the pipe emptied of water again. Figure 4 shows the steam mass and volumetric flow rate curves in the NZL-T1V test during both stratification periods.

As the target temperature difference between the bottom and the top layer of the pool was reached steam injection was stopped and the mixing phase began. The water injection flow rate through the vertical RHR nozzle and the injection water temperature for both of the mixing phases in the NZL-T1V test are shown in Figure 5. Note that outside the mixing phases, when water is not flowing through the nozzle, the water temperature measurement tends show values close to the prevailing temperature in the wetwell gas space because the thermocouple is attached just above the nozzle and is thus located in the wetwell.

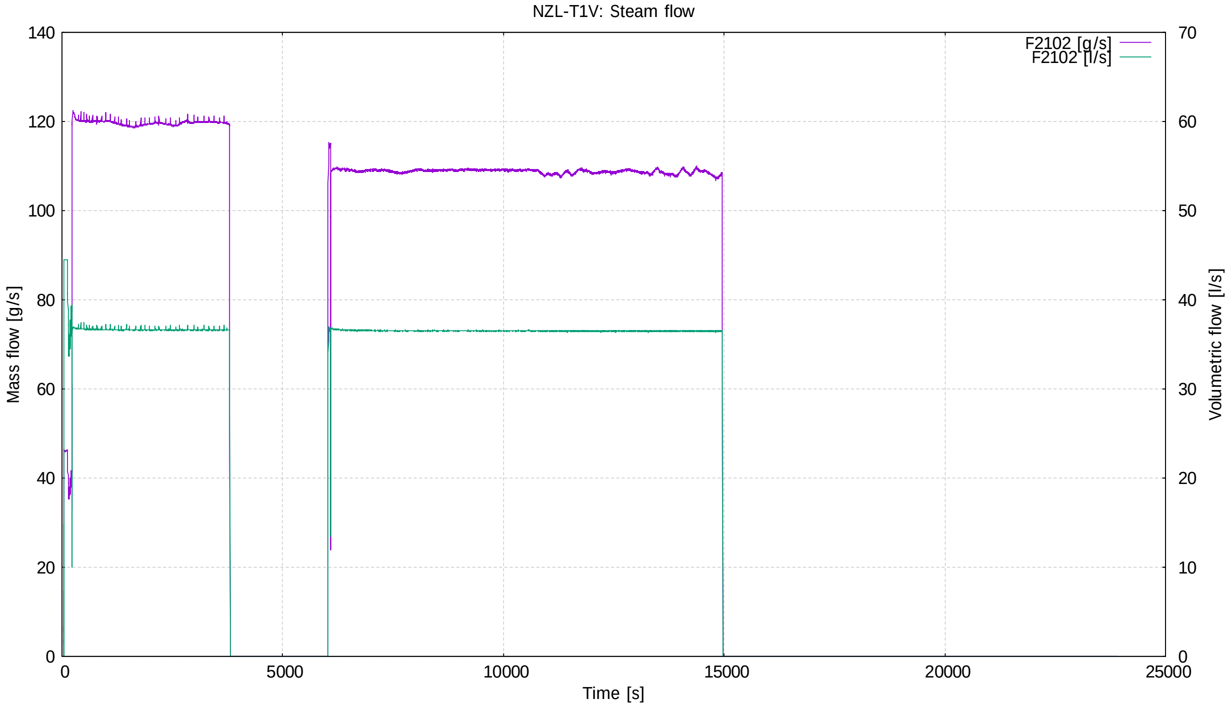

Figure 4. Mass and volumetric steam flow rates during both stratification periods in the NZL-T1V test.

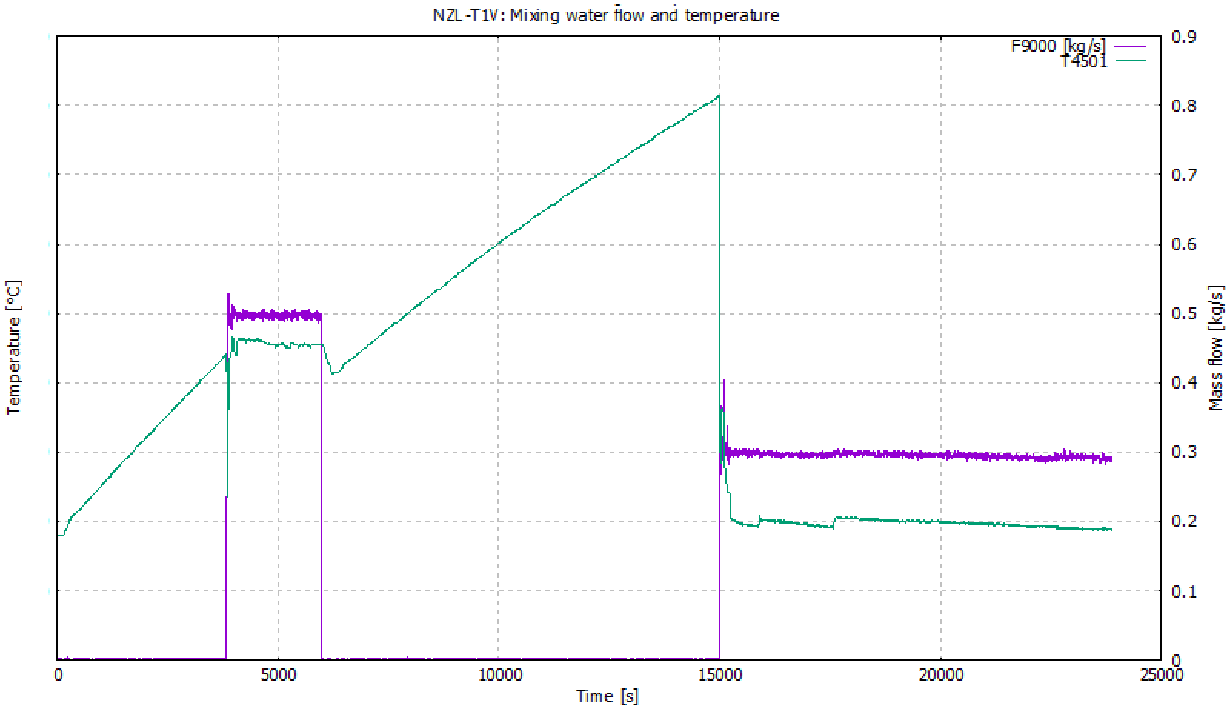

Figure 5. Water injection flow rate through the RHR nozzle and injection water temperature during both mixing phases in the NZL-T1V test.

During the stratification phases two regions with clearly different water temperatures developed in the pool. In the first stratification phase 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. In the second stratification phase this region first remained at the temperature established during the first mixing phase but then slowly started to cool down due to heat losses through the wet well wall. The upper part of the pool volume instead heated up almost uniformly in both stratification phases. The heat-up process was driven by the flow of warm condensed water upwards from the sparger outlet as well as by conduction through the pipe wall. Between these two regions there was a narrow thermocline region.

Figure 6 presents the vertical temperature distribution in the wetwell pool during both stratification and mixing phases in the NZL-T1V test. The temperature measurements attached to the vertical rods in the pool indicate that the thermocline between the cold and warm water was around the TC measurements at the elevation of 772 mm in the end of the first stratification phase and around the TC measurements at the elevation of 672 mm in the end of the second stratification phase. The exact elevation of the thermocline and its thickness is impossible to determine because the minimum distance between the TCs is 100 mm at the region in question. The oscillating behaviour of the temperature curves measured by the TC at the 672 mm and 772 elevations further confirms that the thermocline was around those elevations in the end of the stratification phases. The curves also reveal that the elevation of the thermocline moved slowly downwards during both stratification phases.

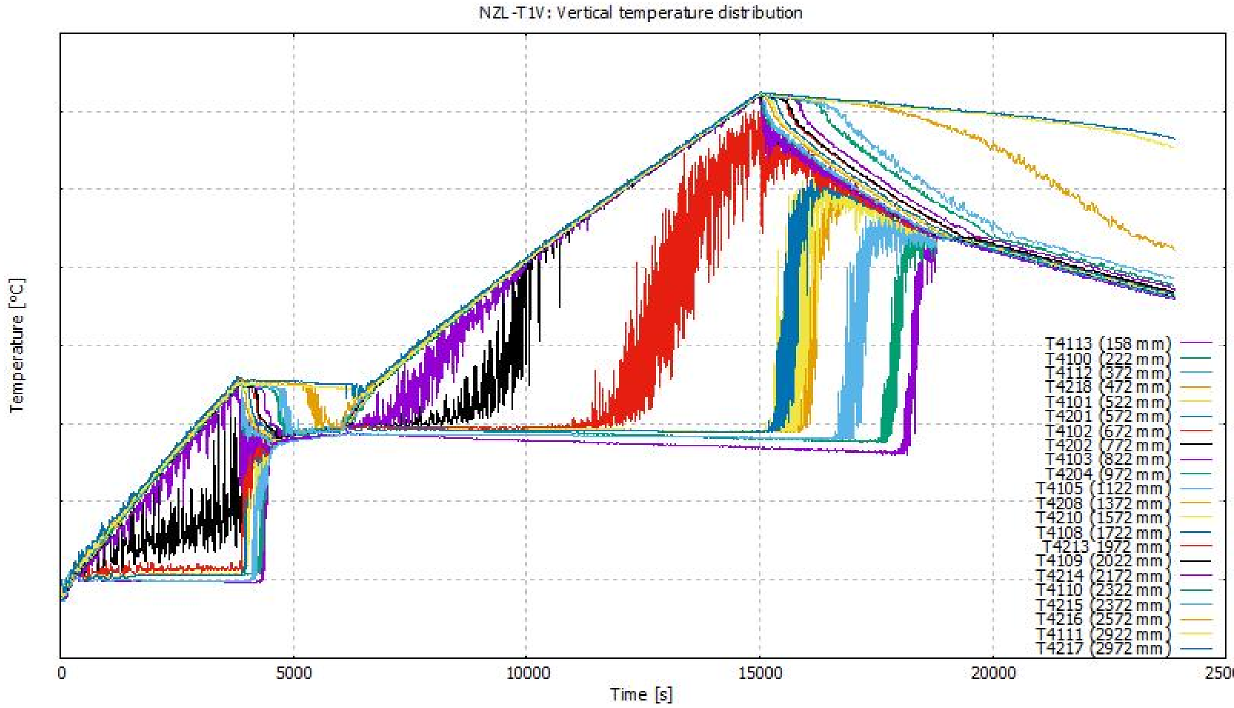

Figure 6. Vertical temperature distribution in wetwell pool during both stratification and mixing phases in the NZL-T1V test.

Figure 6 reveals that with the vertical orientation of the RHR nozzle mixing was otherwise successful but incomplete above the nozzle elevation (about 2.5 m). This is the case with both of the used water injection flow rates, 0.5 kg/s and 0.3 kg/s. In the first mixing phase with the 25 °C temperature difference and 0.5 kg/s injection rate even the lowest level of the pool becomes completely mixed surprisingly fast, in about 700 seconds. The bulk temperature of the mixed volume sets at about 40 °C. In the second mixing phase with the 45 °C temperature difference and

0.3 kg/s injection rate mixing of the bottom volume takes about 3800 seconds and the bulk temperature of the mixed volume has a decreasing trend. This decreasing trend is visible also in the temperature curves above the nozzle elevation thus indicating that the nozzle injection has a slight cooling effect there.

The development of the vertical temperature profile of the pool water over the whole NZL-T1V test can be seen from Figure 7. The initial uniform temperature profile first changes to a stratified situation (the 3800 s curve) and then back to an almost uniform and mixed situation, apart from the elevations above the nozzle, at the end of the first mixing phase (the 6000 s curve). The same process is repeated during the second stratification and mixing periods. The profile at the end of the second stratification phase is shown by the 14950 s curve and the final profile at the end of the test by the 23900 s curve. The test was terminated when the wet well compartment was full of water.

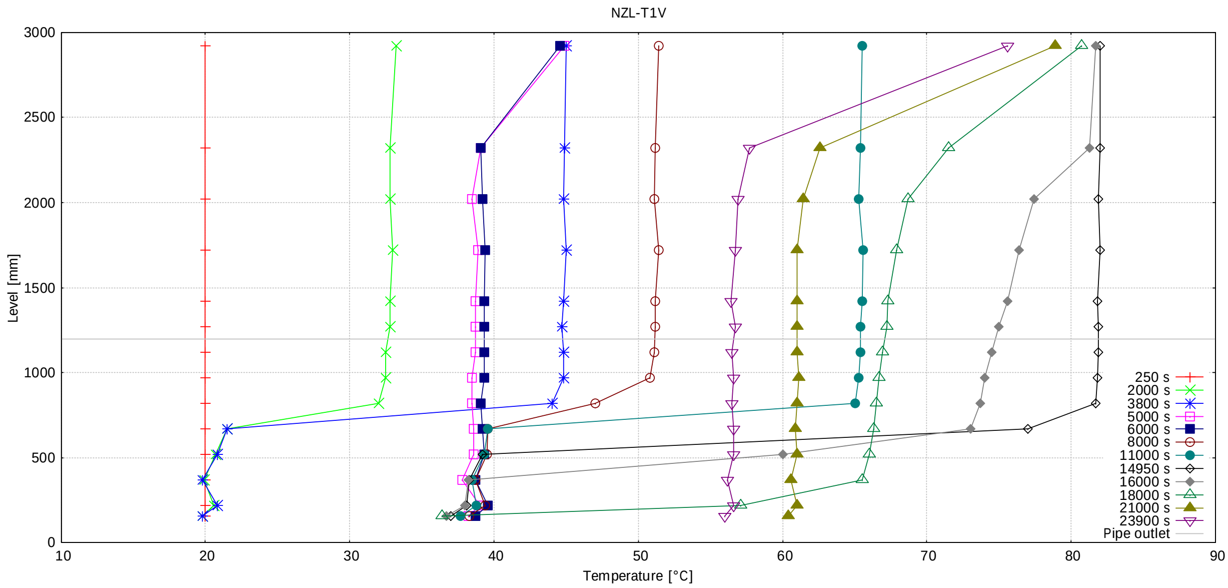

Figure 7. Development of vertical temperature profile of pool water in the NZL-T1V test.

Even during the stratified phases the temperature curves are almost straight vertical lines outside the thermocline region indicating rather constant water temperature distribution elsewhere in the pool. The slow movement of the thermocline downwards as the test proceeded can also be seen from Figure 7.

4.2 NZL-T1H

During the first stratification phase the steam mass flow rate was about 120 g/s and during the second phase about 121 g/s. A thermally stratified situation (ΔT~25°C) developed nicely in both stratification phases as expected, since no mixing effects were present due to the lack of chugging at the exit holes of the sparger pipe and internal circulation below the sparger head elevation.

Again, steam injection was stopped and the mixing phase was started when the target temperature difference between the bottom and the top layer of the pool had been reached. The water injection flow rate through the RHR nozzle, now in a horizontal position, and the injection water temperature for both of the mixing phases in the NZL-T1H test are shown in Figure 8.

Figure 9 presents the vertical temperature distribution in the wetwell pool during both stratification and mixing phases in the NZL-T1H test. Just as in the NZL-T1V test, two regions with clearly different water temperatures developed in the pool during the stratification phases. Water at the bottom volume remained either at the value prevailing in the beginning of the phase (stratification I) or slowly started to cool down due to heat losses (stratification II), while the upper part of the pool volume heated up almost uniformly. Again, a narrow slowly downwards moving thermocline developed between these two regions.

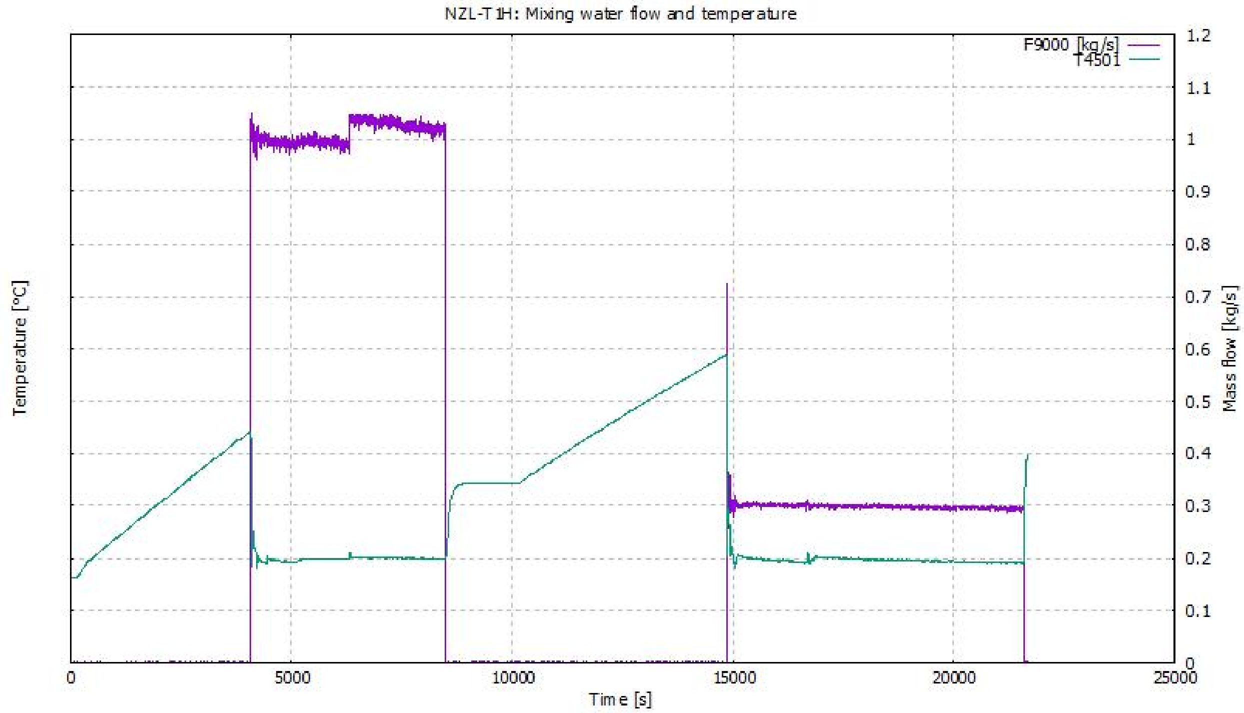

Figure 8. Water injection flow rate through the RHR nozzle and injection water temperature during both mixing phases in the NZL-T1H test.

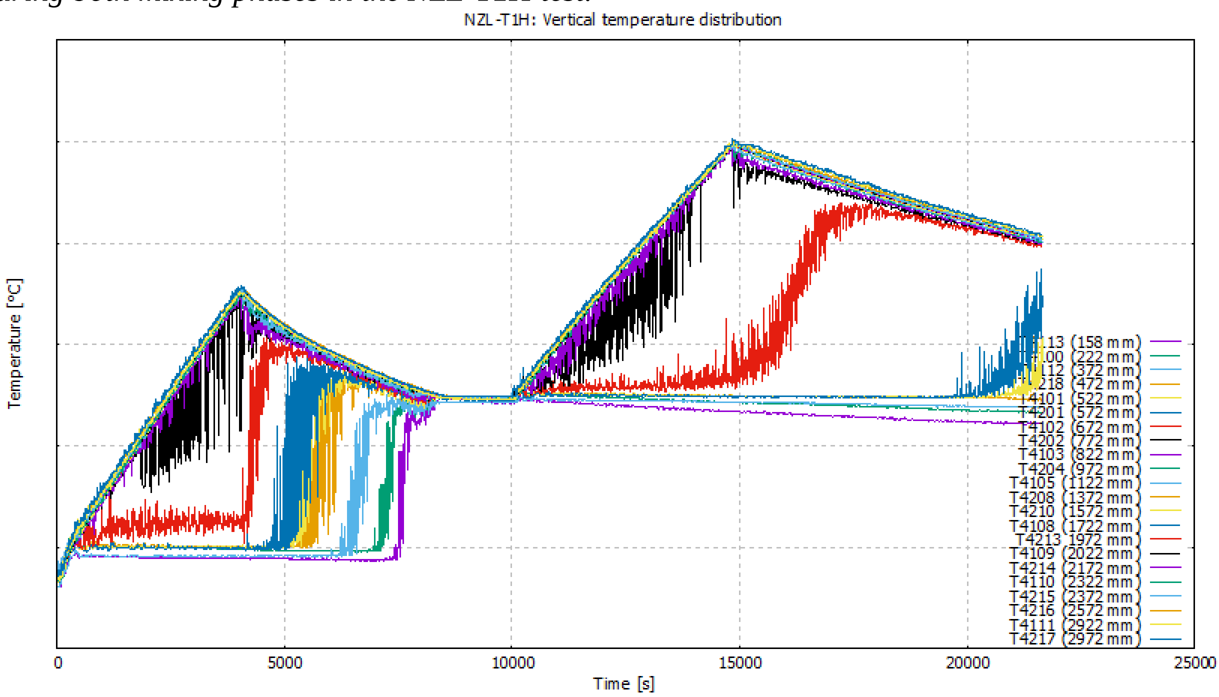

Figure 9. Vertical temperature distribution in wetwell pool during both stratification and mixing phases in the NZL-T1H test.

It seems that during the first stratification phase the thermocline settles on a just slightly lower elevation than in the NZL-T1V test. The curve of the TC on the elevation of 672 mm reveals this. At the end of the second stratification phase the thermocline is surprisingly close to the same elevation as in NZL-T1V if it is taken into account that the tests had a different target ΔT for the second stratification phase as well as different initial pool bulk temperature in the beginning of the phase.

From Figure 9 one can see that compete mixing was achieved during the first mixing phase. The horizontal orientation of the RHR nozzle as well as the large injection flow rate (1.0-1.05 kg/s) contributed to this. The pool mixed in about 4000 seconds. The wetwell pool was almost full of water at the end of the first mixing phase. Water level was dropped to the elevation of 3.5 m by draining water through the bottom valve before the second stratification phase was started.

In the second mixing phase the water injection rate through the RHR nozzle was again only 0.3 kg/s as in NZL-T1V. The water volume above the thermocline starts to cool down as soon as the mixing phase is started. Below the thermocline the mixing process instead proceeds now very slowly and only the TC on the elevation of 672 mm indicates complete mixing and the TCs on the elevations of 572 mm and 522 mm indicate partial mixing before the test needs to be terminated due to wetwell becoming full of water.

Figure 10 shows the development of the vertical temperature profile of the pool water over the whole NZL-T1H test. The change from the initial uniform temperature profile to a stratified situation is presented by the 250 s, 2000 s and 4000 s curves. The complete mixing after the first mixing phase is visible from the 8500 s curve. The profile at the end of the second stratification phase can be seen from the 14800 s curve and the situation when the test was terminated from the 21580 s curve.

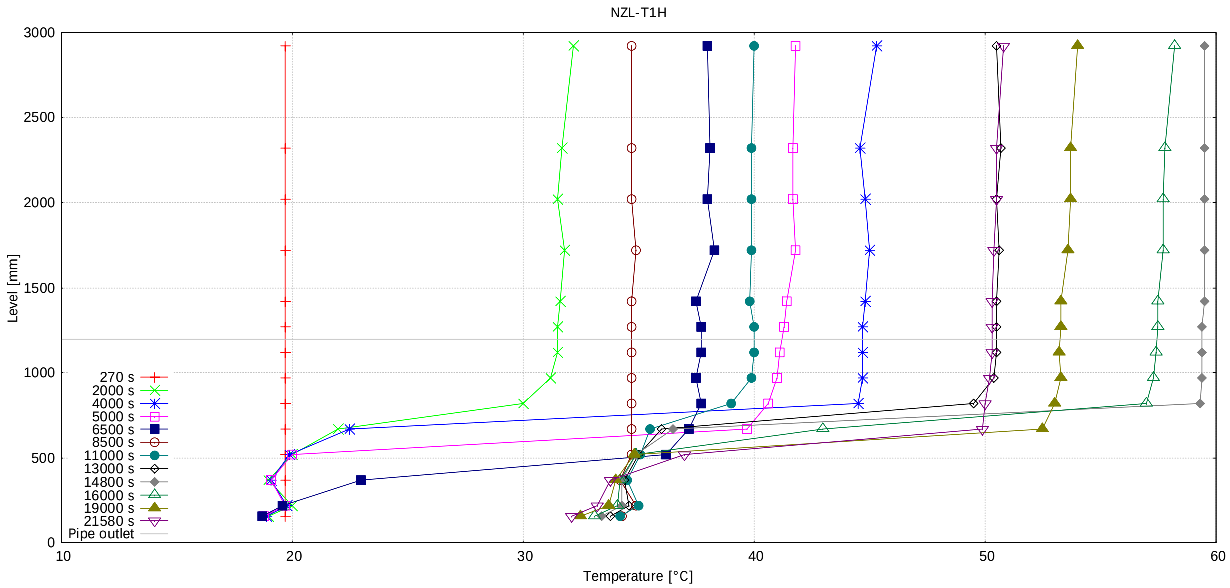

Figure 10. Development of vertical temperature profile of pool water in the NZL-T1H test.

As in NZL-T1V the temperature curves are almost straight vertical lines outside the thermocline region during the stratified phases indicating rather constant water temperature distribution there.

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the RHR nozzle tests (NZL-T0V, NZL-T1V and NZL-T1H) carried out in the PPOOLEX facility at LUT in 2016. The test facility is a closed stainless steel vessel divided into two compartments, drywell and wetwell. In the NZL tests the drywell compartment was bypassed, i.e. the sparger pipe in the wetwell was connected directly to the steam line coming from the PACTEL facility which acted as a steam source. For the RHR nozzle tests the PPOOLEX facility was equipped with a model of an RHR nozzle and an associated water injection line.

The main objective of the tests was to obtain additional data for the development of the EMS and EHS models to be implemented in the GOTHIC code by KTH. The test parameters were selected by KTH on the basis of pre-test simulations. Mixing of a thermally stratified pool with the help of water injection through an RHR nozzle was of special interest. Particularly the effects of nozzle orientation, ΔT in the pool, injection water temperature and injection water mass flow rate were studied.

In the tests there were two stratification phases and two mixing phases. The stratified condition was created by injecting steam into the pool water via a sparger pipe. During the stratification phases two regions with clearly different water temperatures and a narrow thermocline region between them developed in the pool. When the target temperature difference between the bottom and the top layer of the pool had been reached, the mixing process was initiated by starting water injection into the pool through the RHR nozzle.

With the vertical orientation of the RHR nozzle mixing was otherwise successful but incomplete above the nozzle elevation. This was the case with both of the used water injection flow rates, 0.5 kg/s and 0.3 kg/s. Not even the larger ΔT in the pool in the 0.3 kg/s case prevented mixing of the volume below the nozzle elevation.

Complete mixing was achieved with the horizontal orientation of the RHR nozzle by using a large injection flow rate (1.0-1.05 kg/s). The pool mixed in about 4000 seconds. With a 0.3 kg/s injection flow rate the water volume above the thermocline started to cool down as soon as the mixing phase started, whereas below the thermocline the mixing process proceeded very slowly and only a small fraction of the bottom volume mixed completely before the test was terminated because the wetwell became full of water.

By comparing to the shakedown test (NZL-T0V), not presented in this report in more detail, it can be concluded that the effect of injection water temperature on the duration of the mixing process is evident. With the injection water of 45 °C in NZL-T0V the mixing process is about twice as long as with the injection water of 20 °C in NZL-T1V, when the other test parameters are about the same.

These tests in PPOOLEX verified that orientation of an RHR nozzle plays an important role in the success of the mixing process of a thermally stratified pool. The nozzle injection flow rate, injection water temperature and ΔT in the pool have an effect on the mixing process but it is not as dominant as the effect of the nozzle orientation.

6 REFERENCES

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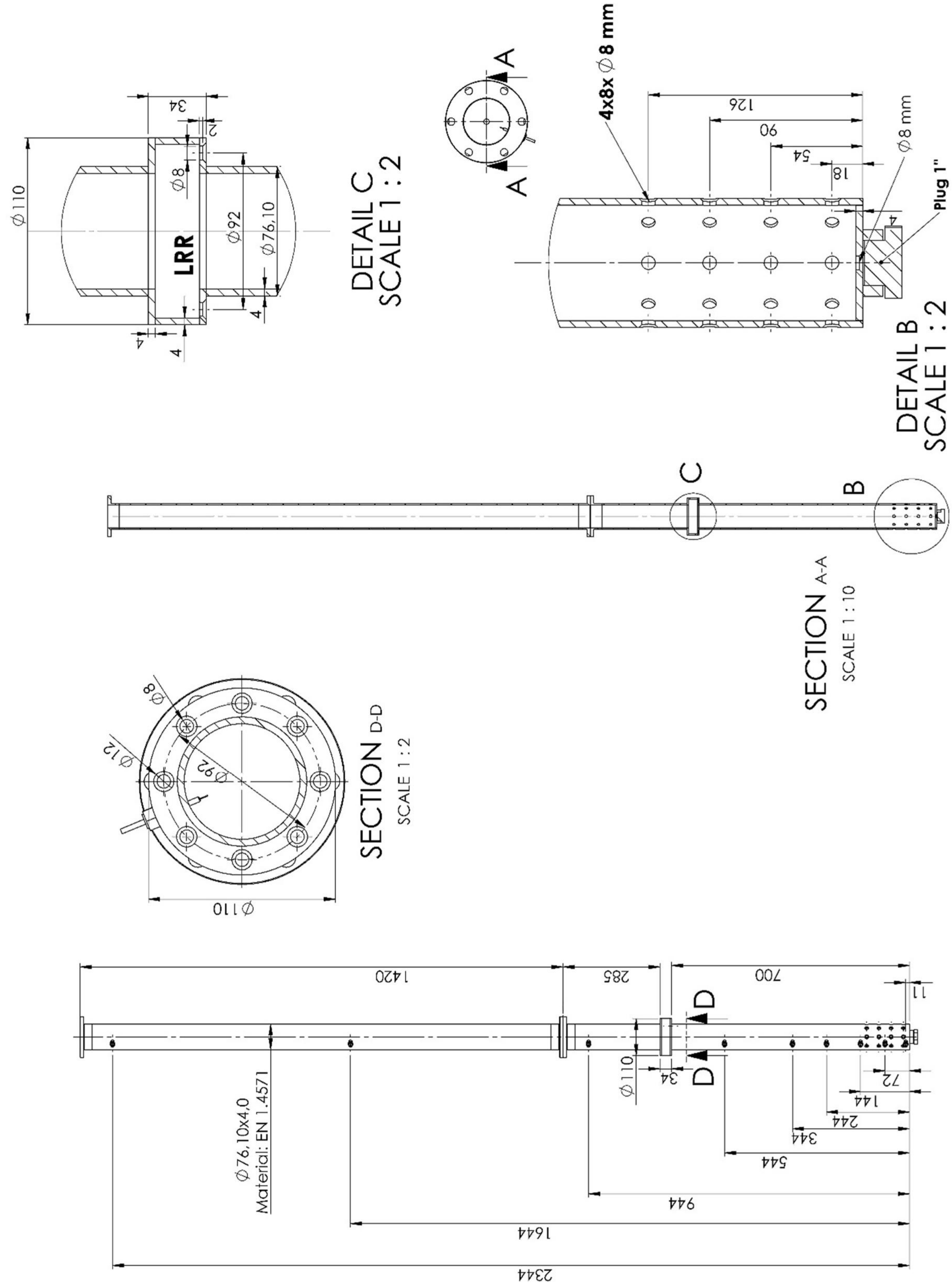
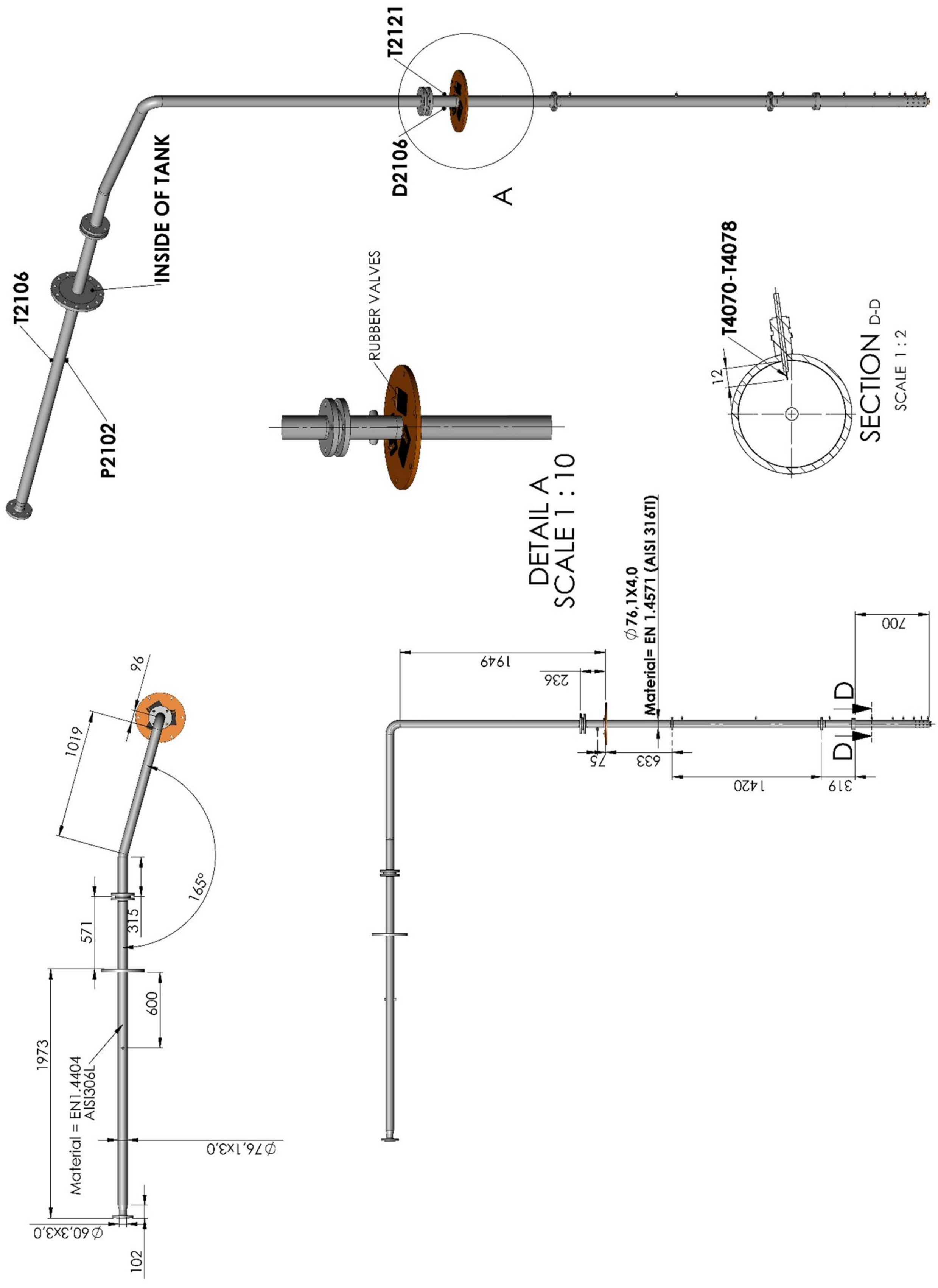
APPENDIX 1: PPOOLEX drawings

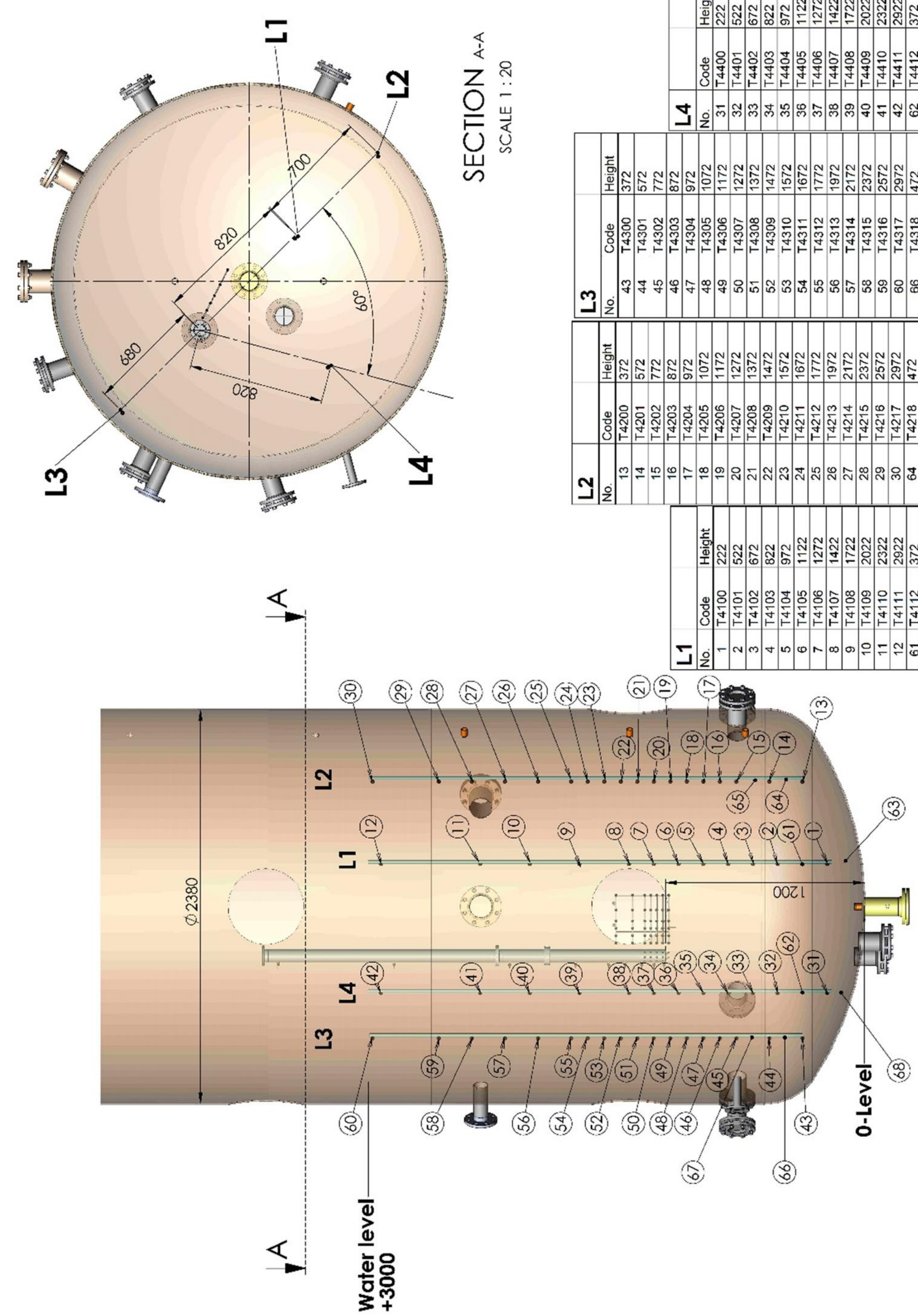


DN65 sparger pipe.



DN65 steam line.

APPENDIX 2: PPOOLEX instrumentation



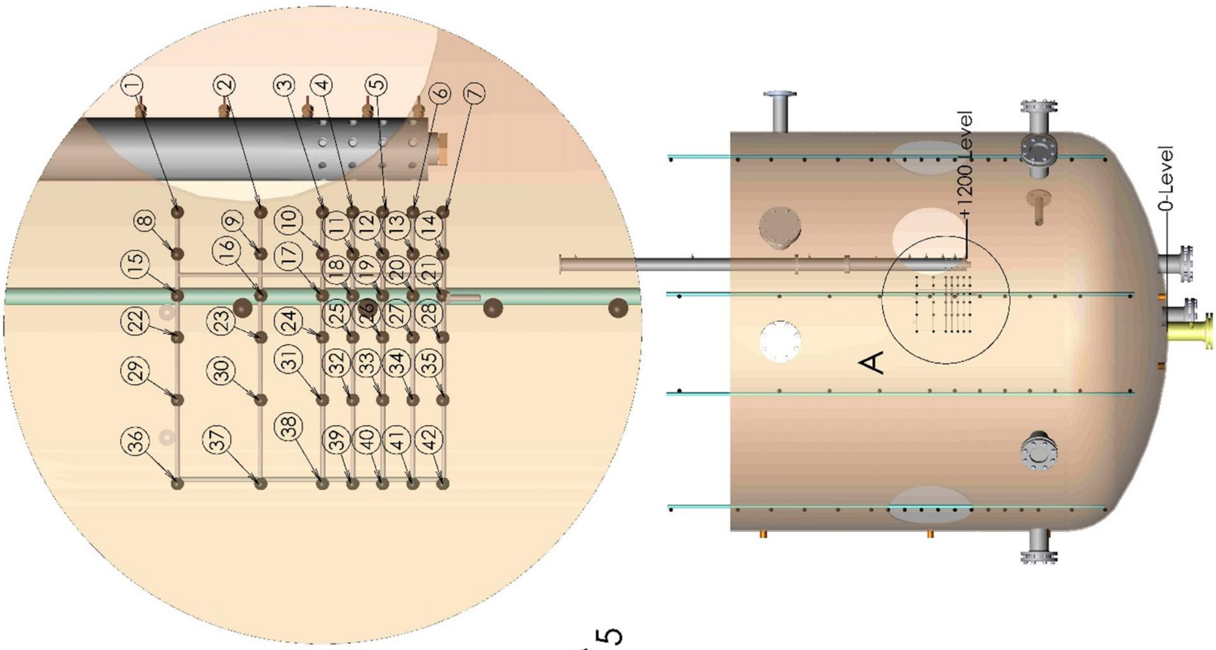
L1		
No.	Code	Height
1	T4100	222
2	T4101	522
3	T4102	672
4	T4103	822
5	T4104	972
6	T4105	1122
7	T4106	1272
8	T4107	1422
9	T4108	1722
10	T4109	2022
11	T4110	2322
12	T4111	2922
61	T4112	372
63	T4113	158

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

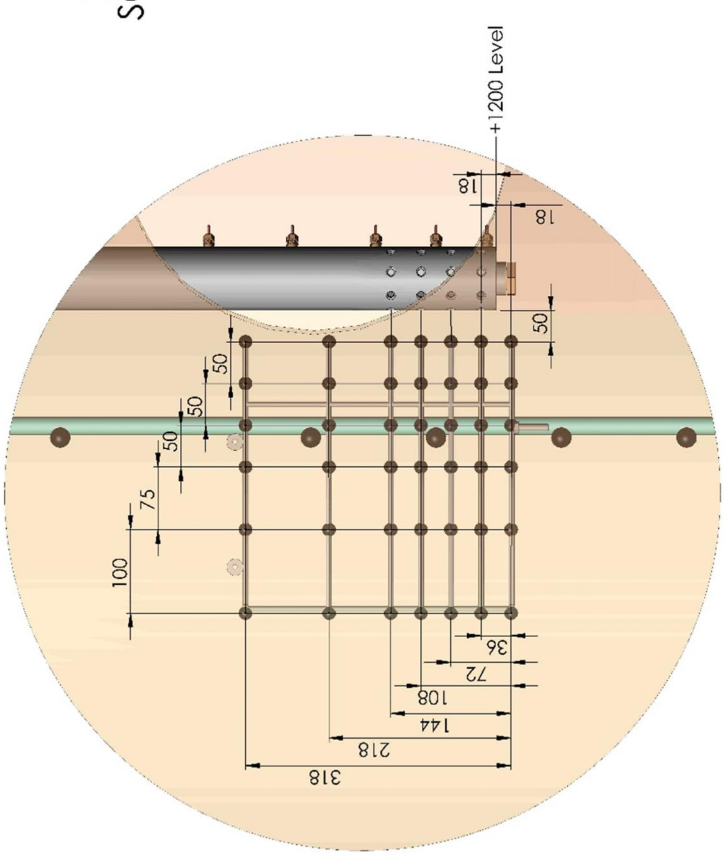
L4		
No.	Code	Height
31	T4400	222
32	T4401	522
33	T4402	672
34	T4403	822
35	T4404	972
36	T4405	1122
37	T4406	1272
38	T4407	1422
39	T4408	1722
40	T4409	2022
41	T4410	2322
42	T4411	2922
62	T4412	372
68	T4413	158

Four trains of temperature measurements in the wetwell.

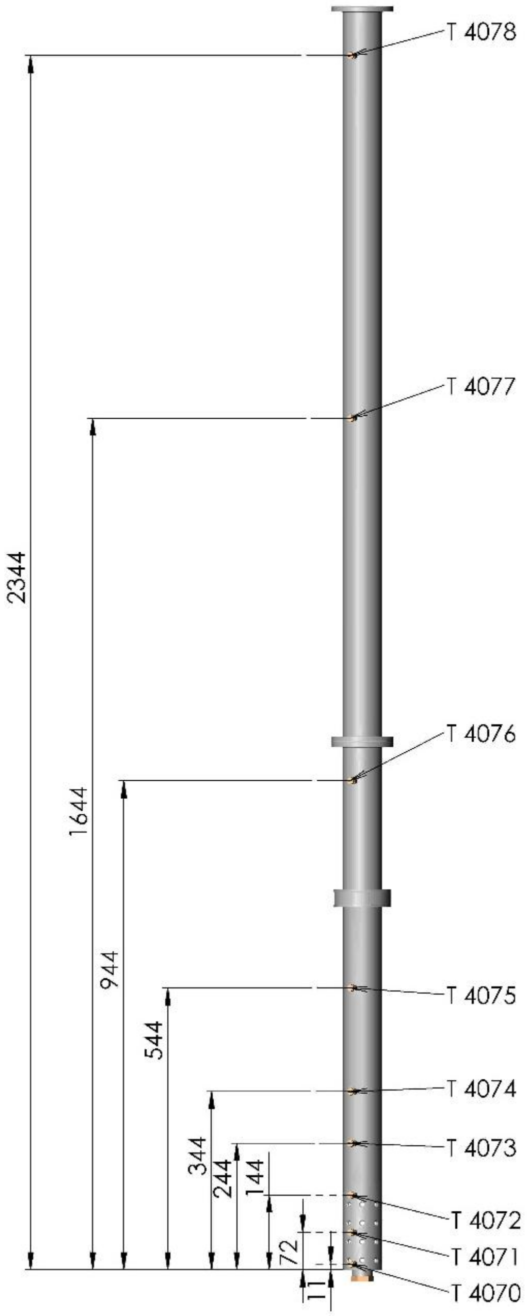


DETAIL A
SCALE 1 : 5

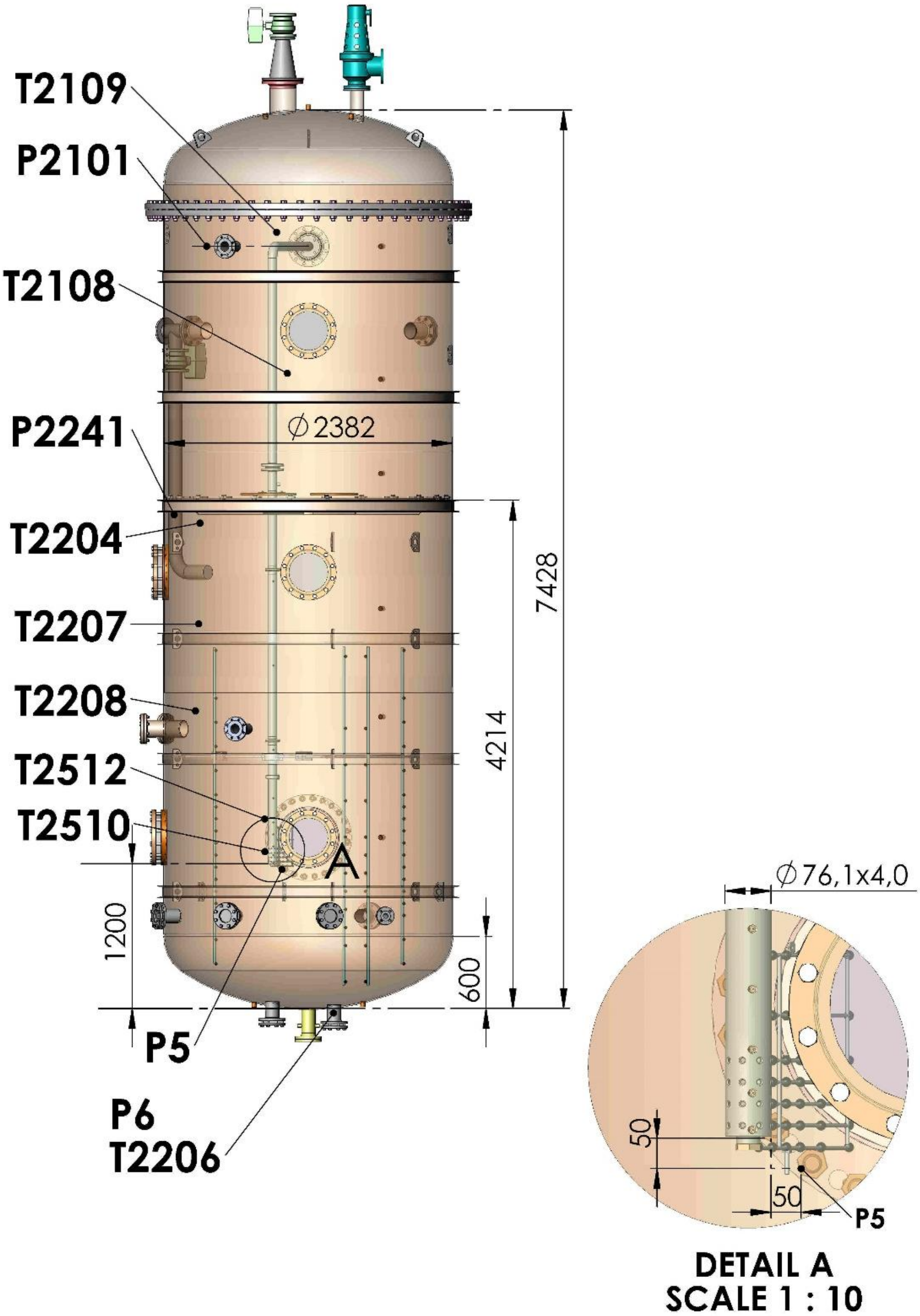
No.	Code	No.	Code	No.	Code
1	T4000	16	T4021	31	T4042
2	T4001	17	T4022	32	T4043
3	T4002	18	T4023	33	T4044
4	T4003	19	T4024	34	T4045
5	T4004	20	T4025	35	T4046
6	T4005	21	T4026	36	T4050
7	T4006	22	T4030	37	T4051
8	T4010	23	T4031	38	T4052
9	T4011	24	T4032	39	T4053
10	T4012	25	T4033	40	T4054
11	T4013	26	T4034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



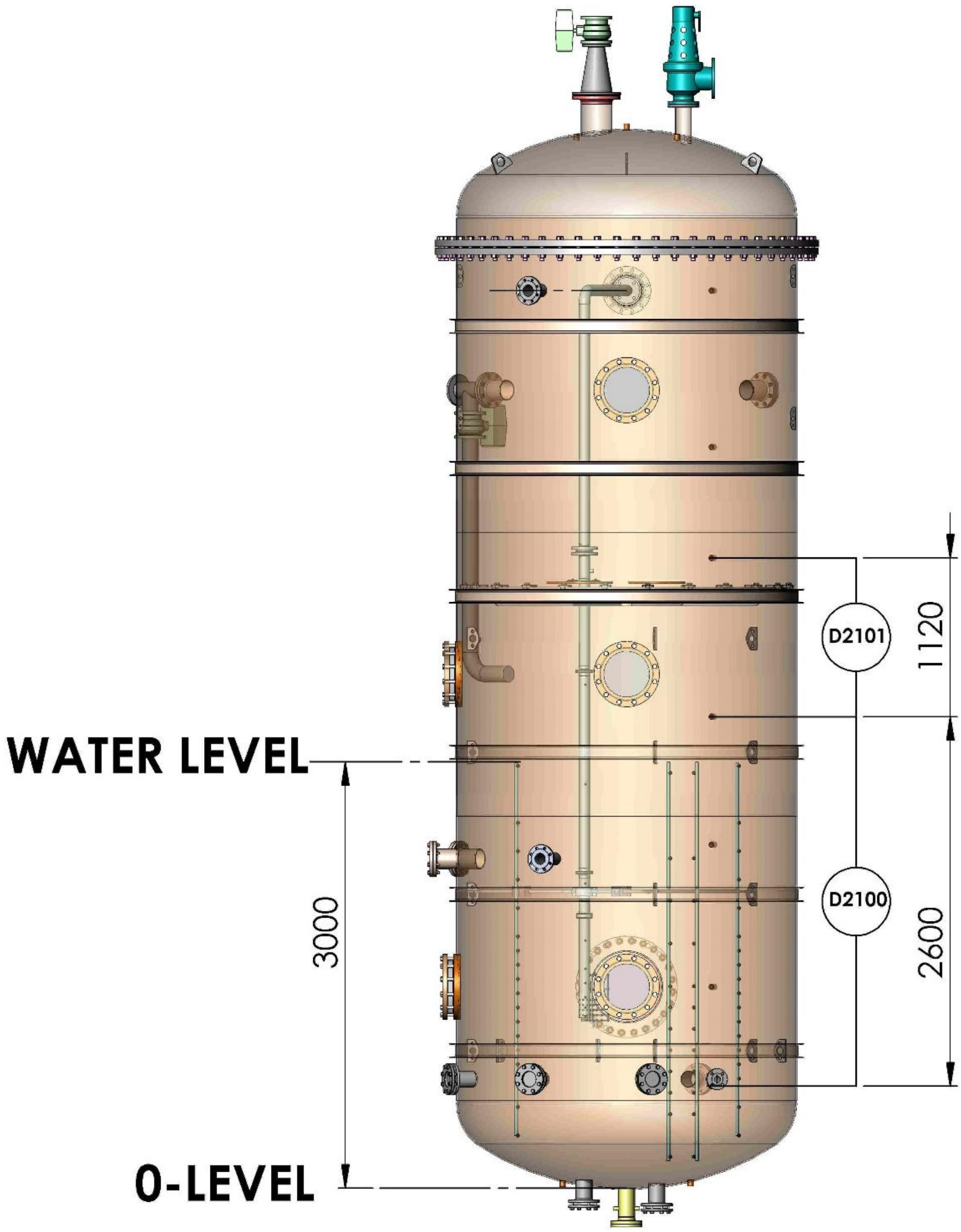
6x7 grid of temperature measurements in the wetwell.



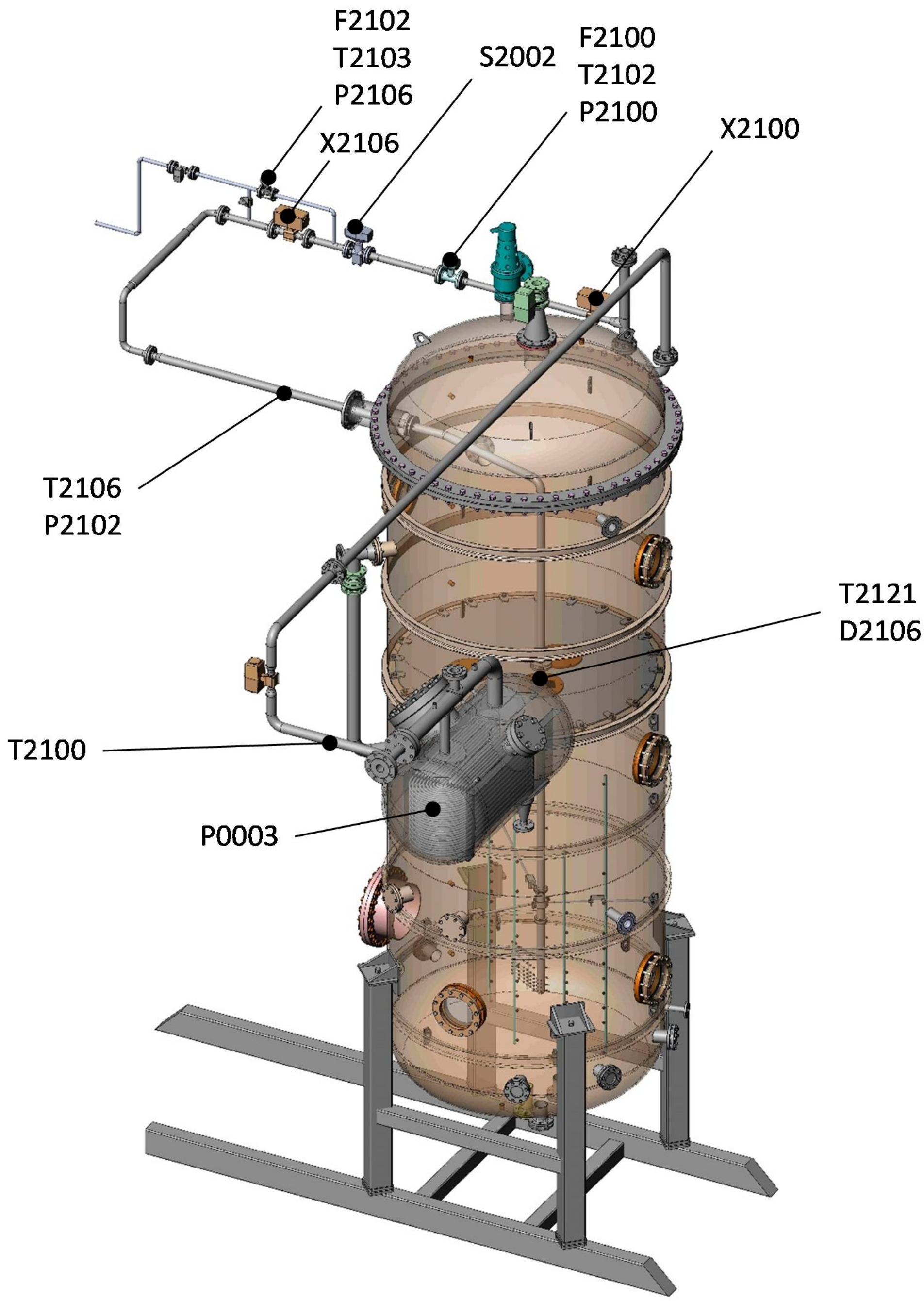
Temperature measurements inside the sparger pipe.



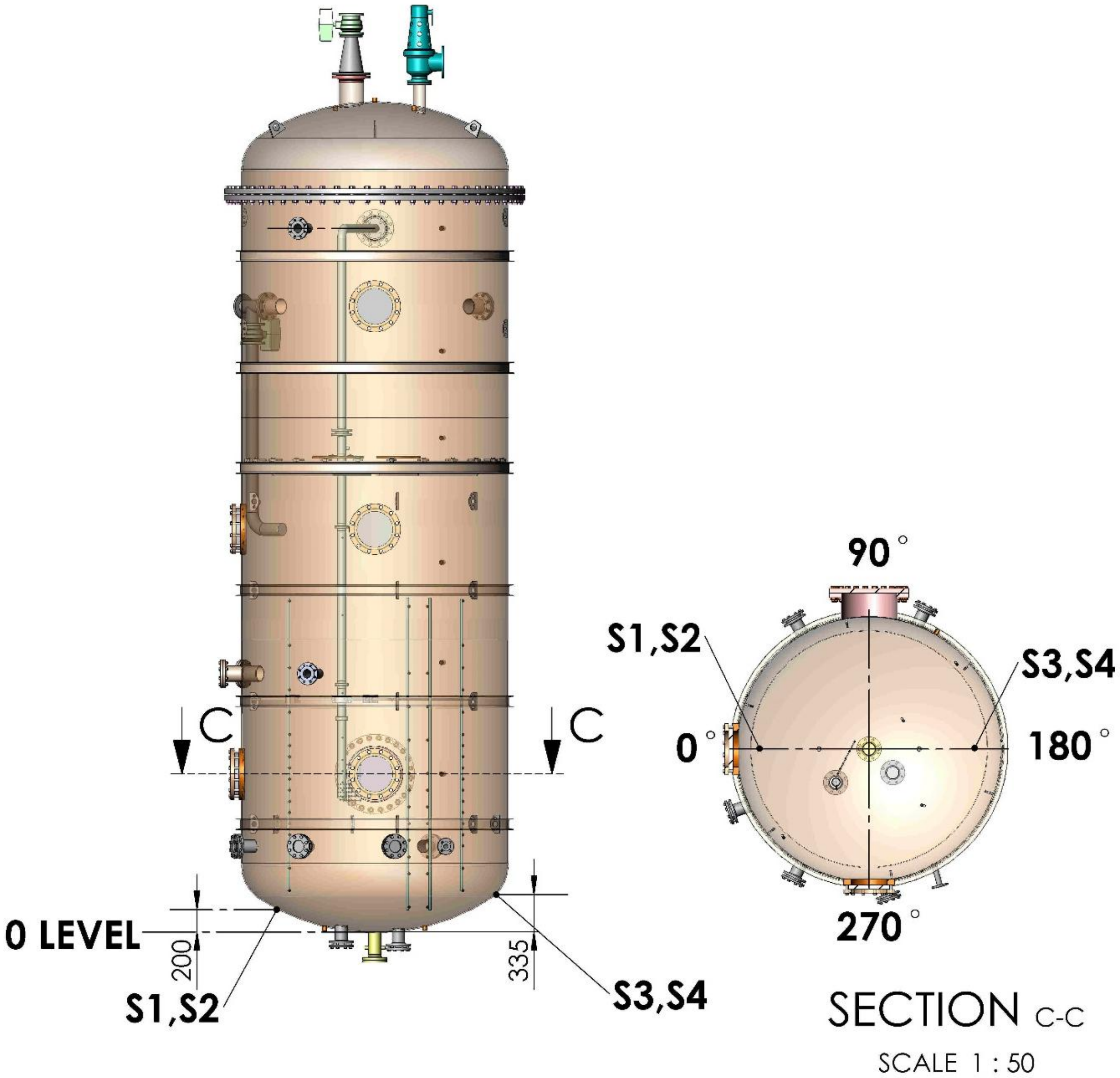
Test vessel measurements.



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	-	RHR nozzle injection 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	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
Temperature	T4045	1218	Wetwell	±2 °C	LabView
Temperature	T4046	1182	Wetwell	±2 °C	LabView
Temperature	T4050	1500	Wetwell	±2 °C	FieldPoint
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 NZL experiment series.

APPENDIX 3: PPOOLEX test facility photographs

Lower part of the sparger pipe.

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Abstract
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This report summarizes the results of the RHR nozzle tests carried out in the PPOOLEX facility at LUT in 2016. The test facility is a closed stainless steel vessel divided into two compartments, drywell and wetwell. For the RHR nozzle tests the PPOOLEX facility was equipped with a model of an RHR nozzle and an associated water injection line.

The main objective of the tests was to obtain additional data for the development of the EMS and EHS models to be implemented in GOTHIC code by KTH. Mixing of a thermally stratified pool with the help of water injection through an RHR nozzle was of special interest. Particularly the effects of nozzle orientation, ΔT in the pool, injection water temperature and injection water mass flow rate were studied.

In the tests there were two stratification phases and two mixing phases. During the stratification phases two regions with clearly different water temperatures and a narrow thermocline region between them developed in the pool. When the target temperature difference between the bottom and the top layer of the pool had been reached the mixing process was initiated by starting water injection into the pool through the RHR nozzle.

With the vertical orientation of the RHR nozzle mixing was otherwise successful but incomplete above the nozzle elevation. This was the case with both of the used water injection flow rates, 0.5 kg/s and 0.3 kg/s.

Compete mixing was achieved with the horizontal orientation of the RHR nozzle by using a large injection flow rate (1.0-1.05 kg/s). The pool mixed in about 4000 seconds. With a 0.3 kg/s injection flow rate the water volume above the thermocline started to cool down as soon as the mixing phase started whereas below the thermocline the mixing process proceeded very slowly and only a small fraction of the bottom volume mixed completely before the test was terminated because the wetwell became full of water.

These tests in PPOOLEX verified that orientation of an RHR nozzle plays an important role in the success of the mixing process of a thermally stratified pool. The nozzle injection flow rate, injection water temperature and ΔT in the pool have an effect on the mixing process but it is not as dominant as the nozzle orientation.

Key words: condensation pool, RHR nozzle, mixing

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