nks
Nordisk kernesikkerhedsforskning
Norrænar kjarnöryggisrannsóknir
Pohjoismainen ydinturvallisuustutkimus
Nordisk kjernesikkerhetsforskning
Nordisk kärnsäkerhetsforskning
Nordic nuclear safety research

NKS-111
ISBN 87-7893-171-1

Condensation Pool Experiments with Steam Using DN200 Blowdown Pipe

J. Laine & M. Puustinen
Lappeenranta University of Technology, Finland

August 2005

Abstract

This report summarizes the results of the condensation pool experiments with steam using a DN200 blowdown pipe. Altogether five experiment series, each consisting of several steam blows, were carried out in December 2004 with a scaled-down test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the experiments was to increase the understanding of different phenomena in the condensation pool during steam discharge.

Key words

Experiments, condensation, blowdown, steam, chugging

NKS-111
ISBN 87-7893-171-1

Electronic report, August 2005

The report can be obtained from
NKS Secretariat
NKS-775
P.O. Box 49
DK - 4000 Roskilde, Denmark

Phone +45 4677 4045
Fax +45 4677 4046
www.nks.org
e-mail nks@nks.org

Research Report
Lappeenranta University of Technology
Nuclear Safety Research Unit

POOLEX 4/2004

CONDENSATION POOL EXPERIMENTS WITH STEAM USING DN200 BLOWDOWN PIPE

Jani Laine, Markku Puustinen

Lappeenranta University of Technology
Department of Energy and Environmental Technology
Nuclear Safety Research Unit
P.O. Box 20, FIN-53851 LAPPEENRANTA, FINLAND
Phone +358 5 621 11, Telefax +358 5 621 2379

Lappeenranta, 18.3.2005

LAPPEENRANTA
UNIVERSITY OF TECHNOLOGY

Research organization and address	**Customer**	
Lappeenranta University of Technology Nuclear Safety Research Unit P.O. Box 20 FIN-53851 LAPPEENRANTA, FINLAND	VYR / SAFIR NKS	
Project manager	**Contact person**	
Markku Puustinen	Eija-Karita Puska (SAFIR) Petra Lundström (NKS)	
Diary code	**Order reference**	
Project title and reference code	**Report identification & Pages**	**Date**
SAFIR / POOLEX NKS / Delipool	POOLEX 4/2004 41 p. + app. 4 p.	18.3.2005

Report title and author(s)

CONDENSATION POOL EXPERIMENTS WITH STEAM USING DN200 BLOWDOWN PIPE

Jani Laine, Markku Puustinen

Summary

This Report summarizes the results of the condensation pool experiments with steam using a DN200 blowdown pipe. Altogether five experiment series, each consisting of several steam blows, were carried out in December 2004 with a scaled down test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the experiments was to increase the understanding of different phenomena in the condensation pool during steam discharge.

The test pool was a stainless steel tank with a wall thickness of 4 mm and a bottom thickness of 5 mm at atmospheric pressure containing 15 m^3 of water. The PACTEL test facility was used as a steam source. During the experiments the initial pressure of the steam source ranged from 0.3 MPa to 3.0 MPa and pool water bulk temperature from 11°C to 76°C. The test rig was equipped with high-speed measurement instrumentation for capturing investigated phenomena (due to rapid condensation of steam). The data acquisition program recorded data with the frequency of 10 kHz. A digital high-speed video camera was used for visual observation of the pool interior.

During the experiments three different condensation modes were observed; condensation inside the blowdown pipe, chugging and condensation oscillations. Which one of these condensation modes was dominating, was determined by the pool water temperature and steam flow.

With cold pool water and low steam flow, condensation took place inside the blowdown pipe. As the pool water temperature and/or steam flow got higher, transition to chugging mode took place. In this mode, steam bubbles formed at the pipe outlet. After rapid condensation, underpressure sucked water back into the pipe. Further increase of steam flow caused a transition to the condensation oscillations mode, during which the steam-water interface oscillated at the pipe outlet like a flickering candle flame. The condensation oscillations mode and particularly the chugging mode caused notable loads to the pool structures.

Distribution

O. Nevander (TVO), H. Sjövall (TVO), J. Hyvärinen (STUK), N. Lahtinen (STUK), H. Ollikkala (STUK), L. Pöllänen (STUK), P. Lundström (Fortum), O. Kymäläinen (Fortum), A. Daavittila (VTT PRO), H. Räty (VTT PRO), O. Keski-Rahkonen (VTT RTE), J. Vihavainen (LTY), P. Pankakoski (VTT TUO), J. Aurela (KTM), H. Heimburger (STUK), E. Virtanen (STUK), M. Tuomainen (STUK), P. Smeekes (TVO), J. Tuunanen (TVO), M. Harti (Fortum), R. Munther (Tekes), A. Saarenheimo (VTT TUO), P. Kauppinen (VTT TUO), K. Calonius (VTT TUO), A. Timperi (VTT TUO), E. K. Puska (VTT PRO), T. Pättikangas (VTT PRO), H. Pokela (VTT PRO), J. Poikolainen (VTT PRO), I. Lindholm (VTT PRO), R. Kyrki-Rajamäki (LTY)

Principal author or Project manager	**Reviewed by**
Markku Puustinen, Senior Research Scientist	Vesa Riikonen, Senior Research Scientist
Approved by	**Availability statement**
Heikki Purhonen, Senior Research Scientist	Public

PREFACE

The condensation pool studies started in Nuclear Safety Research Unit at Lappeenranta University of Technology (LUT) in 2001 within the FINnish research programme on NUclear power plant Safety (FINNUS). The tests were designed to correspond to the conditions in the Finnish BWRs and the test programme was partially funded by Teollisuuden Voima Oy (TVO).

In these tests, the formation, size and distribution of non-condensable gas bubbles in the condensation pool was studied experimentally with a scaled down pool test facility. Also the effect of non-condensable gas on the performance of an ECCS pump was examined. The test conditions were modeled with Fluent CFD-code at VTT. The Fluent simulations were utilized in the planning phase of the tests to select the position, size and number of blowdown pipes. The post-test calculations were carried out for code validation purposes.

A new research project called Condensation POOL EXperiments (POOLEX) started in 2003 within the SAfety of Nuclear Power Plants - FInnish National Research Programme (SAFIR). The POOLEX project continues the work done within the FINNUS programme [1]. In the new tests, steam instead of non-condensable gas is injected into the condensation pool test rig. The study is funded by the State Nuclear Waste Management Fund (VYR) and by the Nordic nuclear safety research (NKS).

CONTENTS

LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

NOMENCLATURE

A	area
c	thermal capacity
d	diameter
E	Young's modulus
g	acceleration of gravity
G	mass flux
k	thermal conductivity
p	pressure
Q	volumetric flow rate
R_m	tensile strength
$R_{p0.2}$	proof strength (causes irreversible 0.2%-strain)
$R_{p1.0}$	proof strength (causes irreversible 1.0%-strain)
T	temperature

Greek symbols

α	thermal expansion coefficient
Δ	change
ε	strain
ν	Poisson's coefficient
ρ	density
σ	stress

Abbreviations

AVI	Audio Video Interleave
BWR	boiling water reactor
ECCS	emergency core cooling system
fps	frames per second
LOCA	loss-of-coolant accident
LUT	Lappeenranta University of Technology
NKS	Nordic nuclear safety research
PACTEL	parallel channel test loop
POOLEX	condensation pool experiments project
RAM	random access memory
SAFIR	Safety of Nuclear Power Plants – Finnish National Research Programme
SG	steam generator
SRV	safety/relief valve
TVO	Teollisuuden Voima Oy
VTT	Technical Research Centre of Finland
VYR	State Nuclear Waste Management Fund

1 INTRODUCTION

During a possible loss-of-coolant accident (LOCA) a large amount of non-condensable (nitrogen) and condensable (steam) gas will be blown from the upper drywell of the containment to the condensation pool through the blowdown pipes at the Olkiluoto type boiling water reactors (BWRs). The wetwell pool serves as the major heat sink for condensation of steam. The blowdown causes both dynamic and structural loads to the condensation pool. There might also be a risk that the gas discharging to the pool could push its way to the emergency core cooling systems (ECCS) and undermine their performance. Figure 1 shows the schematic of the Olkiluoto type BWR containment.

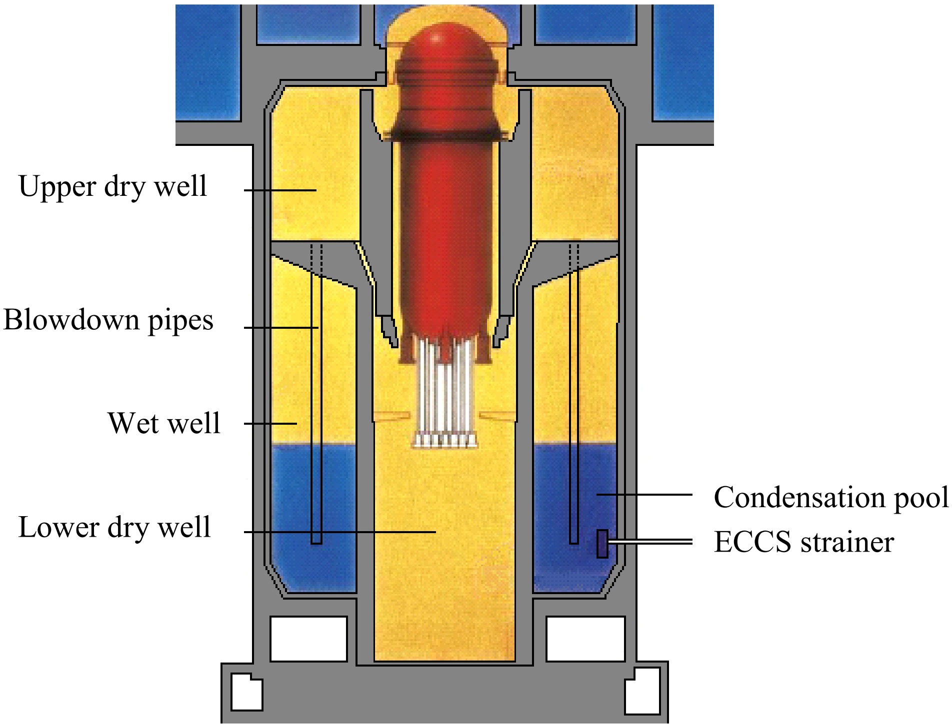


Figure 1. Schematic of the Olkiluoto type BWR containment.

The main objective of the POOLEX project is to increase the understanding of different phenomena in the condensation pool during steam injection. These phenomena could be connected to bubble dynamics issues such as bubble growth, upward acceleration, detachment and break-up. The bubbles interact with pool water by heat transfer, steam condensation and possibly evaporation, and momentum exchange via buoyancy and drag forces. Pressure oscillations due to rapid condensation are also among the issues of interest. The investigation of the steam injection phenomenon requires high-grade measuring techniques. For example, to estimate the loads on the pool structures by condensation pressure oscillations the frequency and the amplitude of the oscillations have to be measured. The needs and resources for instrumentation, data acquisition and visualization were reviewed before proceeding to detailed steam blowdown tests. Also, the operational limits of the existing pool test facility were verified before that.

Experiment results of the POOLEX project, supposing that they are exact and of high-quality, can be used for the validation of different numerical methods for simulating steam injection through a blowdown pipe into liquid. Experimental studies on the process of formation, detachment and break-up and the simultaneous condensation of large steam bubbles are still sparse and thus the improvement of models for bubble dynamics is necessary for the reduction of uncertainties in predicting condensation pool behaviour during steam injection. Some of the models are applicable also outside the BWR scenarios, e.g. for the quench tank operation in the pressurizer vent line of a Pressurized Water Reactor (PWR), for the bubble condenser in a VVER-440/213 reactor system, or in case of a submerged steam generator pipe break.

With the aid of high-speed video observations, to be used in the POOLEX experiments, the validity of correlations for steam bubble size and break-up heights as a function of total volumetric flow-rate and of pool sub-cooling could be investigated. In determining condensation rates during bubble formation direct measurement of heat and mass transfer is desirable, but virtually impossible. However, the process of direct-contact condensation of large steam bubbles in water is well suited for visual observation. Interfaces are macroscopic and well visible. To some extent, condensation rates can be determined indirectly from volume rates-of-change estimated from video images.

The development work of 3D two-phase flow models for computational fluid dynamics (CFD) codes can be assisted by the POOLEX experiments. Furthermore, the (one-directional or bi-directional) coupling of CFD and structural analysis codes in solving fluid-structure interactions could be facilitated with the aid of load measurements of the steam blowdown experiments.

In 2003, Lappeenranta University of Technology (LUT) performed eight series of preliminary condensation pool experiments with steam using DN80 and DN100 blowdown pipes [2]. After that some improvements were made to the measurement instrumentation and also to the data acquisition system. In March 2004, three more preliminary experiments series were carried out using a DN200 blowdown pipe [3].

After the pre-tests, more high speed instrumentation (particularly pressure transducers) was added to the test rig. A new faster data acquisition system was bought in order to be able to measure and record adequate number of measurement channels with high sampling rate (10 kHz). For more accurate observation of steam bubbles, the test rig was furnished with a digital high-speed video camera.

In this report, the results of the first detailed steam test series are presented. First, chapter two presents the different condensation modes during LOCA steam discharge. Chapter three gives a short description of the test facility and its measurements as well as of the new data acquisition system used. The test programme is introduced in chapter four. The test results are presented and shortly discussed in chapter five. A brief stress analysis is made in chapter six. Chapter seven summarizes the findings of the test series.

2 CONDENSATION MODES DURING LOCA OR SAFETY/RELIEF VALVE BLOWDOWN

In the handbook of thermal hydraulics of BWRs, Lahey and Moody present a map of condensation modes that have been observed during either LOCA or safety/relief valve (SRV) steam discharge, see Figure 2.

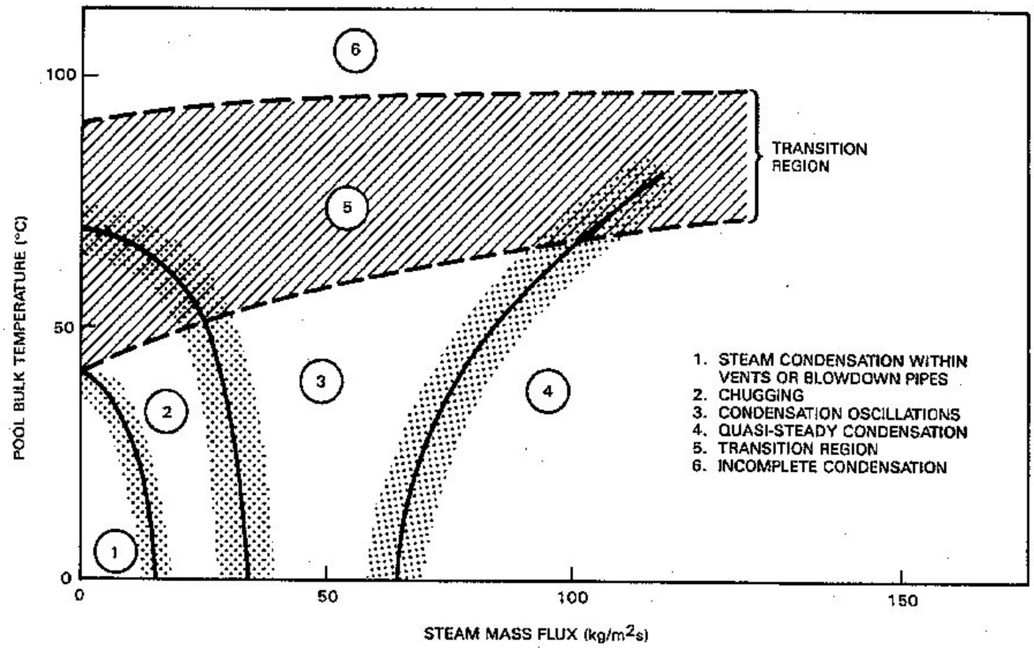


Figure 2. Condensation mode map for pure steam discharge [4].

With low steam mass flux and cold pool water temperature, condensation takes place within vents or blowdown pipes. A sharp drop in local steam pressure occurs as steam condenses rapidly when interacting with cold pool water. Because the condensation process is very rapid, an underpressure develops inside the blowdown pipe. Immediately after that, a condensation-induced water hammer is initiated as the pipe begins to fill with water. At the end of the collapse, a high pressure pulse occurs when the pipe is filled with water. In this condensation mode, steam-water interface moves strongly up and down inside the blowdown pipe.

As the steam mass flux increases, chugging or random condensation phenomena will commence. In chugging, the steam-water interface moves downwards inside the blowdown pipe and a steam bubble is formed at the pipe outlet. The bubble condenses rapidly and negative pressure is generated. The steam-water interface begins to move upwards inside the pipe until the steam pressure is high enough to stop the interface and start to push it downwards again. Chugging imposes dynamic loads on submerged pool structures [4].

Increasing the steam mass flux further leads to condensation oscillations. In this case, steam-water interface undergoes a condensation event totally in the pool. Steam bubble forms at the pipe outlet and begins to collapse. However, the high steam flow rate prevents water re-entry into the blowdown pipe. The next bubble is formed resulting to a condensation event and the cycle is repeated. The steam-water interface seems to oscillate at the pipe outlet somewhat like a flickering candle flame [4]. Condensation oscillations cause unsteady loads on submerged pool structures [4].

With very high steam flows quasi-steady condensation is a dominating condensation mode. In this mode, high steam mass flux keeps steam-water interface on the pipe outlet. Because the steam condenses steadily, no large loads occur on submerged pool structures.

3 TEST FACILITY

The pool test facility was originally scaled and constructed for the experiments with a non-condensable gas [1]. After some modifications, the preliminary experiments with steam were executed by using the same pool test facility and DN80, DN100 and DN200 blowdown pipes [2, 3]. More high-frequency instrumentation, particularly pressure transducers, was added to the test rig before the first detailed test series. A new data acquisition system capable of measuring and recording a larger number of channels with adequate sampling rates than the system used in the pre-tests was bought and installed. For more accurate observation of steam bubbles, the test rig was furnished with a digital high-speed video camera. A sketch of the test rig is presented in Figure 3. Table 1 shows the main dimensions of the test rig compared to Olkiluoto plant conditions.

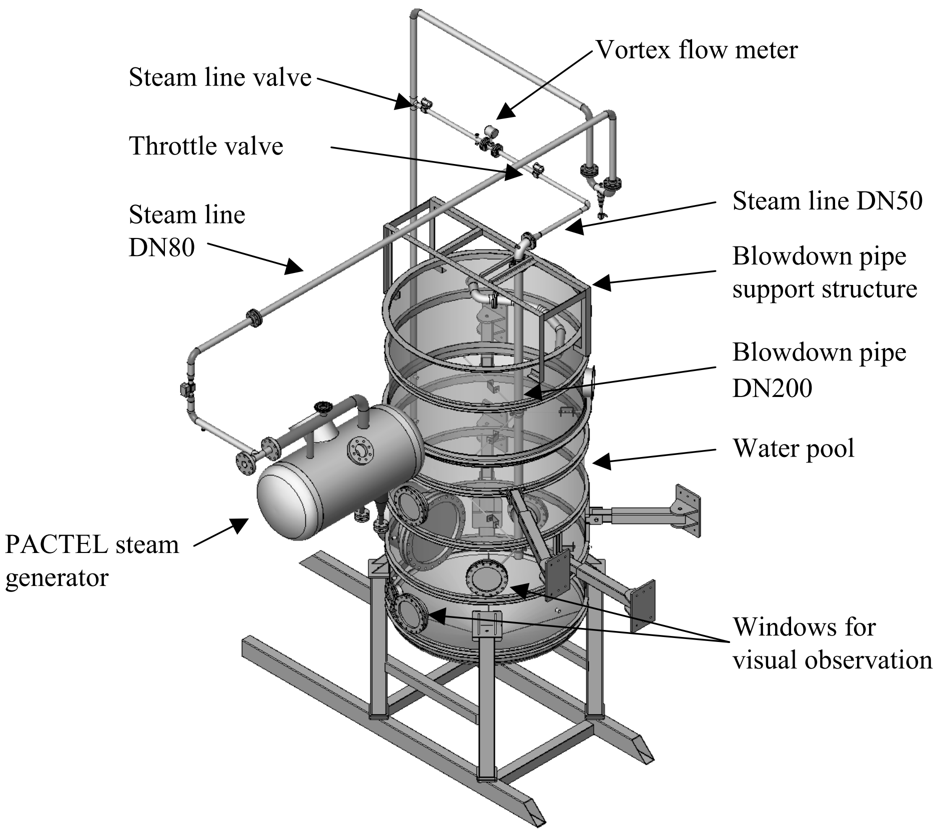


Figure 3. POOLEX test rig.

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

	Test rig	Olkiluoto 1 and 2
Number of the blowdown pipes	1	16
Inner diameter of the blowdown pipe [mm]	214.1	600
Pool cross-sectional area [m^2]	4.5	287.5
Water level in the pool [m]	3.5	9.5
Pipes submerged [m]	2.0	6.5
A_{pipes}/A_{pool}x100%	0.8	1.6

3.1 MEASUREMENT INSRUMENTATION

The test facility is equipped with thermocouples for measuring steam and pool water temperatures (T), with pressure transducers (P) for observing pressure behavior in the blowdown pipe, in the steam line and at the pool bottom and with one pressure transducer (DP) for detecting the pool water level. Steam flow is measured with a vortex flow meter in the DN50 steam line. Additional instrumentation includes four strain gauges (ST) on the pool outer wall, valve position sensors and a high-speed video camera trigger. Appendix 1 shows the exact measurement locations. Table 2 lists the identification codes and error estimations of the measurements. The error estimations are calculated on the basis of variance analysis. The results agree with normal distributed data with 95% confidence interval.

Temperatures are measured by K-type thermocouples. In the pre-tests, ∅ 0.5 mm thermocouples proved to be fast enough for capturing the investigated phenomena with sufficient accuracy.

Pressure oscillations in the blowdown pipe are measured by high-frequency pressure transducers (model: Kyowa PVL-100K). Also the pressure transducer on the pool bottom is a high-frequency transducer (model: Kyowa PVL-5K). Frequency response of the amplifier is 1 kHz.

Uniaxial foil strain gauges are attached with glue onto the pool outside wall, both above and below the rounding between the pool wall and bottom. The gauge length and width are 5.0 mm and 1.4 mm, respectively. Two of the gauges measure strains in circumferential direction and two in axial direction. Frequency response of the amplifier is 5 kHz.

Table 2. Measurement instrumentation

Code	Measurement	Error estimation
T1	Temperature in the blowdown pipe	±3.8°C
T2	Temperature in the blowdown pipe	±3.8°C
T3	Temperature in the blowdown pipe	±3.8°C
T13	Temperature in the steam line	±3.5°C
T14	Temperature in the pool	±2.7°C
T15	Temperature at the pool bottom	±3.8°C
T16	Temperature on the pool outer wall	±2.6°C
P1	Pressure in the blowdown pipe	±93 kPa
P2	Pressure in the blowdown pipe	±93 kPa
P3	Pressure in the blowdown pipe	±93 kPa
DP6	Water level in the pool	±0.06 m
P7	Pressure in the steam line	±93 kPa
P8	Pressure in the steam generator	±60 kPa
P9	Pressure at the pool bottom	±5 kPa
F1	Volumetric flow rate in the steam line	±4.9 l/s
ST1	Strain on the pool outer wall	±21 µS[1]
ST2	Strain on the pool outer wall	±21 µS[1]
ST3	Strain on the pool outer wall	±21 µS[1]
ST4	Strain on the pool outer wall	±21 µS[1]
Trig	High speed camera trigger	Not defined
Valve	Valve position	Not defined

3.2 DIGITAL HIGH-SPEED VIDEO CAMERA

A Citius Imaging digital high-speed video camera (model C10) is used for visual observation of the pool interior. The camera works in close co-operation with a PC, which is used for controlling, display and storage. The camera is a single unit and it is connected to the PC through the USB bus. Several cameras can be networked e.g. for recording the same event from different angles simultaneously. [5]

The video is at first stored to the RAM-memory in the camera (in AVI-format). From there it is transferred onto the PC hard disk. The camera is furnished with the maximum available amount of memory; 2 GB. The camera can achieve over 10000 frames/second (fps) recording speed and up to 652x496 pixels resolution with 256 shades of gray. [5]

However, speed and maximum recording time depend on the resolution used. During the experiments a recording speed of approximately 220 fps with maximum available resolution (400x338) was used mostly. With these set-ups the maximum recording time is 73 seconds (29 MB/s). Table 3 shows more examples of resolution/speed/recording time combinations that can be attained with the camera.

[1] The error estimates do not contain the effect of the strain gauge and the amplifier.

Table 3. Examples of resolution, speed and maximum recording time combinations of Citius Imaging high-speed digital video camera C10. [5]

Resolution [pixels]	Speed [fps]	Max. recording time [s]
640x480	99	70.9
340x256	330	74.7
172x128	1154	84.5
84x64	3551	112.5
40x20	10652	252

3.3 DATA ACQUISITION

A new National Instruments data acquisition system was acquired to enable high-speed multi-channel measurements. Measurement software is LabView 7.1.

National Instruments PCI-PXI-SCXI measurement system is a PC-driven measurement system with a LabView user interface. The maximum number of measurement channels is 96 with additional eight channels for strain measurements. The maximum recording frequency depends on the number of measurements and is in the region of 300 kHz for all measured channels combined.

Separate HPVee based software is used for monitoring and recording the essential measurements of the PACTEL facility producing the steam. Both data acquisition systems measure signals as volts. After the experiments, the voltage readings are converted to engineering units by using special conversion software.

The used data recording frequency of LabView was 10 kHz (in test STB-16-9 1000 Hz and in STB-17 2000 Hz) for measurements P1-P3, P9 and ST1-ST4. For temperature measurements T1-T3 and T16 the data recording frequency was 200 Hz (in the pre-tests the 122 Hz data recording frequency was found to be fast enough for capturing the investigated phenomena). The temperature measurements are therefore averages of 50 measured points (in STB-16-9 of 5 points and in STB-17 of 10 points). Residual measurements are recorded by HPVee software with the frequency of 1 Hz.

A separate measurement channel is used for steam line valve position information. Approximately 3.6 V means that the valve is fully open, and approximately 1.1 V that it is fully closed. Voltage under 1.1 V means the valve is opening. Both HPVee and LabView record the channel.

A separate measurement channel is also used for a digital high-speed video camera triggering. When the camera gets a signal from the trigger it starts to record. Depending on the adjustment, the camera either records the events from the triggering moment towards the future or from the past until the triggering moment. Boundary signal for the camera is approximately 3.5 V. One additional channel records the exposure of the camera. Table 4 shows the structure of the engineering unit measurement database.

A high data recording frequency produces a large amount of measurement data. With the used data recording frequency and the number of measurement channels (10 kHz / 12 channels and 200 Hz / 5 channels for temperature readings), LabView produces approximately 17 MB of data per a 10 second time interval. As a comparison, HPVee produces no more than approximately 1 kB of data / 10 seconds. The large amount of measurement data causes problems when processing and archiving data.

Table 4. Structure of the measurement database

<experiment>_LabView_1.dat				
Data recording frequency: 200 Hz				
1	**2**	**3**	**4**	**5**
Time	T1	T2	T3	T15
[s]	[°C]	[°C]	[°C]	[°C]

<experiment>_LabView_2.dat											
Data recording frequency: 10 kHz											
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Time	P1	P2	P3	P9	ST1	ST2	ST3	ST4	Trig	Pulse	Valve
[s]	[bar]	[bar]	[bar]	[bar]	[μS]	[μS]	[μS]	[μS]	[V]	[V]	[V]

<experiment>_HPVee.dat								
Data recording frequency: 1 Hz								
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Time	P8	P7	T14	T13	T16	DP6	F1	Valve
[s]	[bar]	[bar]	[°C]	[°C]	[°C]	[m]	[l/s]	[V]

4 TEST PROGRAMME

The test plan and objectives for the detailed condensation pool experiments of 2004 are reported in reference [6]. The test programme in December 2004 consisted of five test series. Each test series included four to ten separate blowdown tests. The total number of the tests was 37. All tests were performed by using the DN200 blowdown pipe. Steam generators of the PACTEL test facility were used as a steam source during the experiments [7]. Before each experiment series the pool was filled with water to the level of approximately 3.5 m i.e. the blowdown pipe outlet was submerged by 2 m. The position of the throttle valve (located just after the flow meter in the steam line) was adjusted before the blows so that the steam flow rate would be inside the measurement range (0…285 l/s). During the pressure build-up phase and between the individual tests the steam line was heated with a small bypass flow. After the desired pressure in the steam generators had been achieved the remote-controlled shut-off valve in the steam line was opened. As a result, the blowdown pipe was filled with steam that immediately pushed its way to the pool. The steam flow may have contained a small amount of air. During the experiments all three PACTEL steam generators were used to produce steam.

During STB-13 some problems were met. Thermocouple T14 was broken and the strain gauges were connected to the amplifier backwards. As a result of this, the strain gauge readings were backwards also. During the first and second steam blowdown of STB-13 (labeled as STB-13-1 and STB-13-2) data recording of the LabView system did not work. During the other test series problems did not occur. To reduce the size of the measurement data files, the recording frequency of the LabView system was set to the values of 1000 Hz and 2000 Hz in STB-16-9 and STB-17, respectively. Table 5 shows the initial test parameters.

Table 5. Initial parameters for POOLEX tests.

Test series	Steam generator initial pressure [MPa]	Comments/problems
STB-13	0.5 - 0.6	T14 broke, strain gauges connected backwards, LabView did not work during STB-13-1 and STB-13-2
STB-14	0.5	-
STB-15	0.4 - 0.5	-
STB-16	0.3 – 0.5	LabView data recording frequency 1000 Hz in STB-16-9
STB-17	1.0 – 3.0	LabView data recording frequency 2000 Hz

5 ANALYSIS OF THE EXPERIMENTS

The following chapters give a more detailed description of the test program and also try to analyse the observed phenomena of the experiments.

5.1 STB-13

In the first test series, four separate blowdowns (labeled from STB-13-1 to STB-13-4) were executed. The main purpose of the test series was to test the functioning of the digital high-speed video camera, of the measurement instrumentation and of the data acquisition program. During the test series the steam generator initial pressure varied from 0.5 MPa to 0.6 MPa (all three SGs in use). Before the first blowdown was initiated the pool water temperature was 15°C. After the last blowdown the pool water temperature had increased to 27°C. During the blowdowns the steam mass flux ranged from 4 kg/m^2 to12 kg/m^{2}s. Figure 4 shows the steam volumetric flow rate, temperature and pressure during STB-13.

As mentioned in the previous chapter, data recording using the LabView system did not work during STB-13-1 and STB-13-2. During STB-13-3 LabView recorded data for 73 s (period 2710…2783 s in Figure 4) and during STB-13-4 for 168 s (period 3840…4008 s in Figure 4). The total amount of measurement data was approx. 410 MB (241 s · 1.7 MB/s).

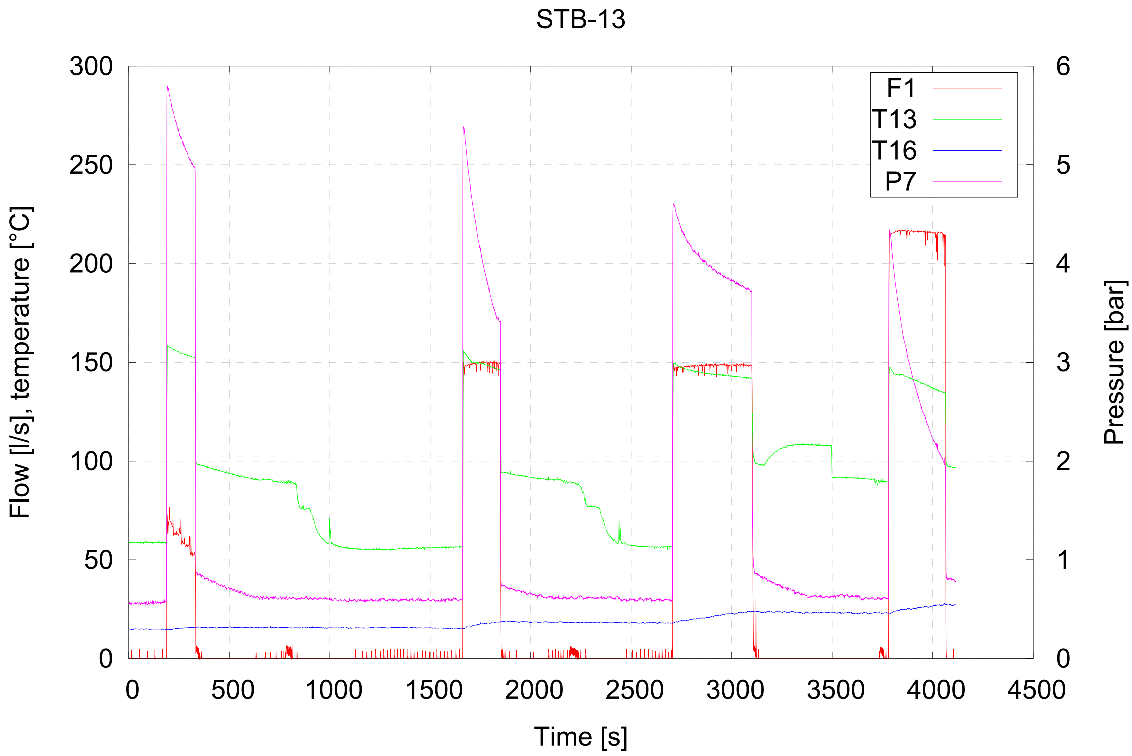


Figure 4. Steam volumetric flow (F1), temperature (T13) and pressure (P7) in STB-13. T16 is temperature on the pool outer wall in the vicinity of the strain gauges.

Because both the pool water temperature (15°C…27°C) and steam mass flux (4 kg/m^{2}s…12 kg/m^{2}s) were quite low, steam condensed within the blowdown pipe. A sharp drop in steam pressure occurred when steam interacted with the cold water and condensed rapidly. The rapid condensation process generated an underpressure inside the blowdown pipe. The longest underpressure phase lasted approximately for 0.5 seconds. Due to the collapse of the steam volume, a water hammer developed and propagated inside the blowdown pipe. As a result, a high pressure pulse occurred when the pipe was filled with water. The maximum registered pressure pulse inside the blowdown pipe was 1.6 MPa, see Figure 5. During the test steam-water interface moved strongly up and down inside the blowdown pipe, see Figure 6. This is characteristic of the condensation mode in question.

During the blows both the pressure transducer on the pool bottom (P9) and strain gauges on the pool outer wall (ST1…ST4) registered oscillations with a frequency of 10 Hz. Because steam condensed within the blowdown pipe, neither the pressure transducer on the pool bottom nor the strain gauges on the pool outer wall measured high loads. The maximum amplitude of pressure pulses was 30 kPa and the maximum amplitude of strains 100 µS (registered by ST3).

Appendix 2 shows a condensation mode map. All STB-13 blows (marked as four purple crosses) are located in the region 1; condensation within vents or blowdown pipes.

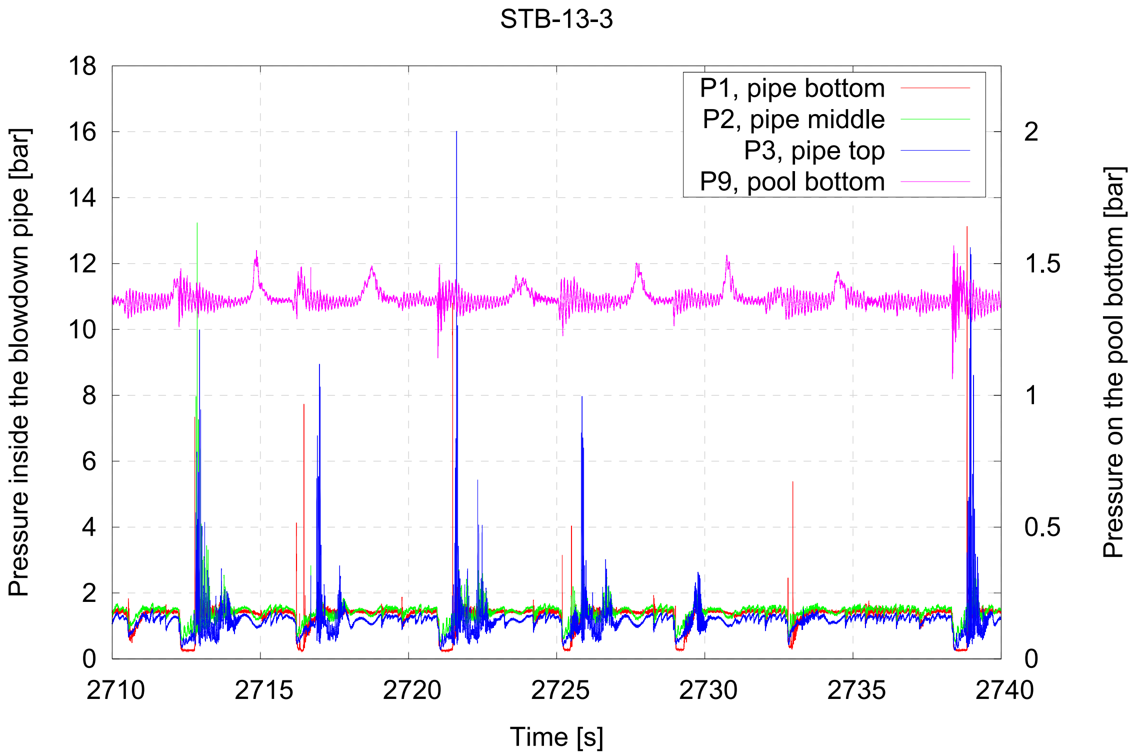


Figure 5. Pressures during STB-13-3 between 2710…2740 seconds.

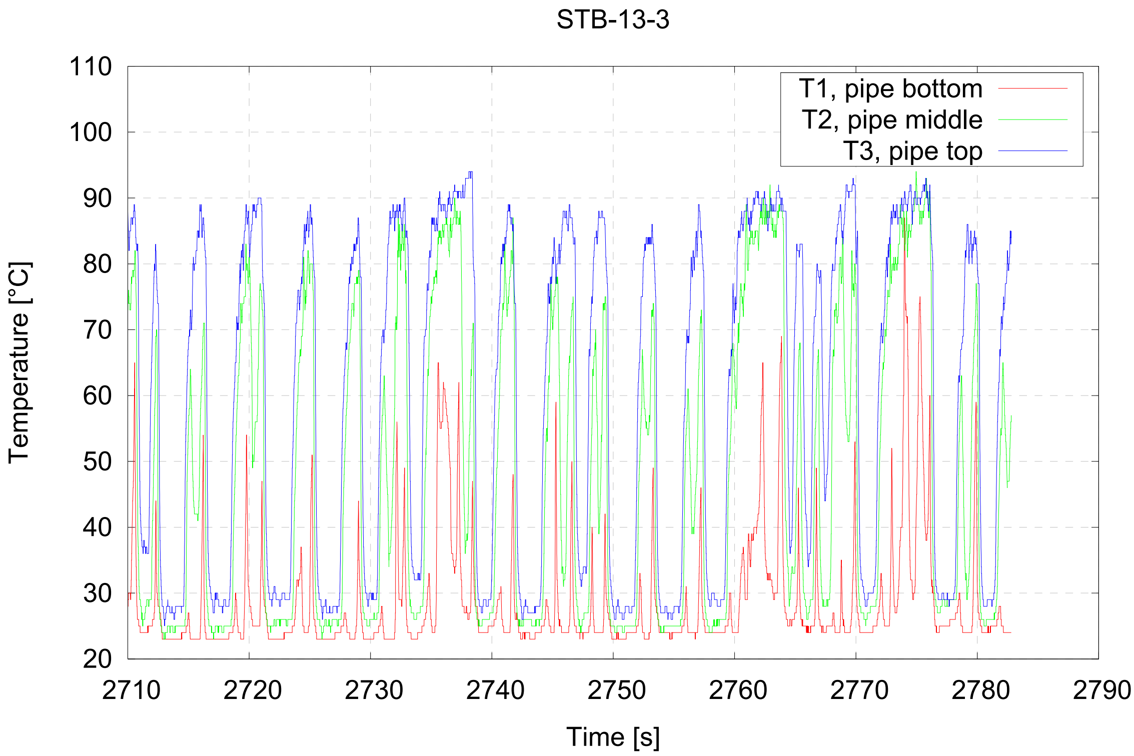


Figure 6. Temperatures inside the blowdown pipe during STB-13-3.

Table 6 summarizes the values of main parameters during experiment STB-13. In the table, the steam blowdown column lists the time periods when steam was blown into the pool. The LabView data recording column lists the time periods when data was recorded using LabView software. T_{pool} shows pool water temperature during LabView data recording (for STB-13-1 and STB-13-2 before and after the blowdown). Steam mass flux (G_{steam}) is calculated on the basis of the volumetric flow rate measurement F1 (Q), steam density (ρ) and cross-sectional area of the blowdown pipe (A), see Equation 1. Steam density is determined on the basis of the temperature measurement T13 and pressure measurement P7.

$$G_{steam} = \frac{Q\rho}{A} \tag{1}$$

Table 6. Main parameters during STB-13

Test	Steam generator initial pressure [MPa]	Steam blowdown [s]	LabView data recording [s]
STB-13-1	0.6	189…332	-
STB-13-2	0.6	1662…1850	-
STB-13-3	0.5	2706…3112	2710…2783
STB-13-4	0.5	3781…4064	3840…4008

Test	Values during LabView data recording				
	T_{pool} [°C]	G_{steam} [kg/m^{2}s]	p_{max} in the DN200 pipe [MPa]	Δp_{max} on the pool bottom [kPa]	$\Delta\varepsilon_{max}$ [µS]
STB-13-1	15…16	6…4	Not known	Not known	Not known
STB-13-2	16…19	12…8	Not known	Not known	Not known
STB-13-3	19…20	10…9	1.6	30	100
STB-13-4	25…27	11..7	1.6	30	100

5.2 STB-14

STB-14 consisted of eight separate blowdowns (labeled from STB-14-1 to STB-14-8). The purpose of this test series was to study the formation and condensation of steam bubbles as a function of pool water temperature. The initial steam generator pressure was 0.5 MPa (all three SGs in use) in every single blowdown. The pool water temperature rose from 37°C to 68°C during the series. The steam mass flux varied from 8 kg/m^{2}s to 12 kg/m^{2}s. Figure 7 shows the steam volumetric flow rate, temperature and pressure during STB-14.

LabView recorded data during every single blowdown. To measure loads caused by a water plug hit to the pool bottom in the beginning of the blowdowns, data recording was started few seconds before initiating steam blowdowns in STB-14-6 and STB-14-8.

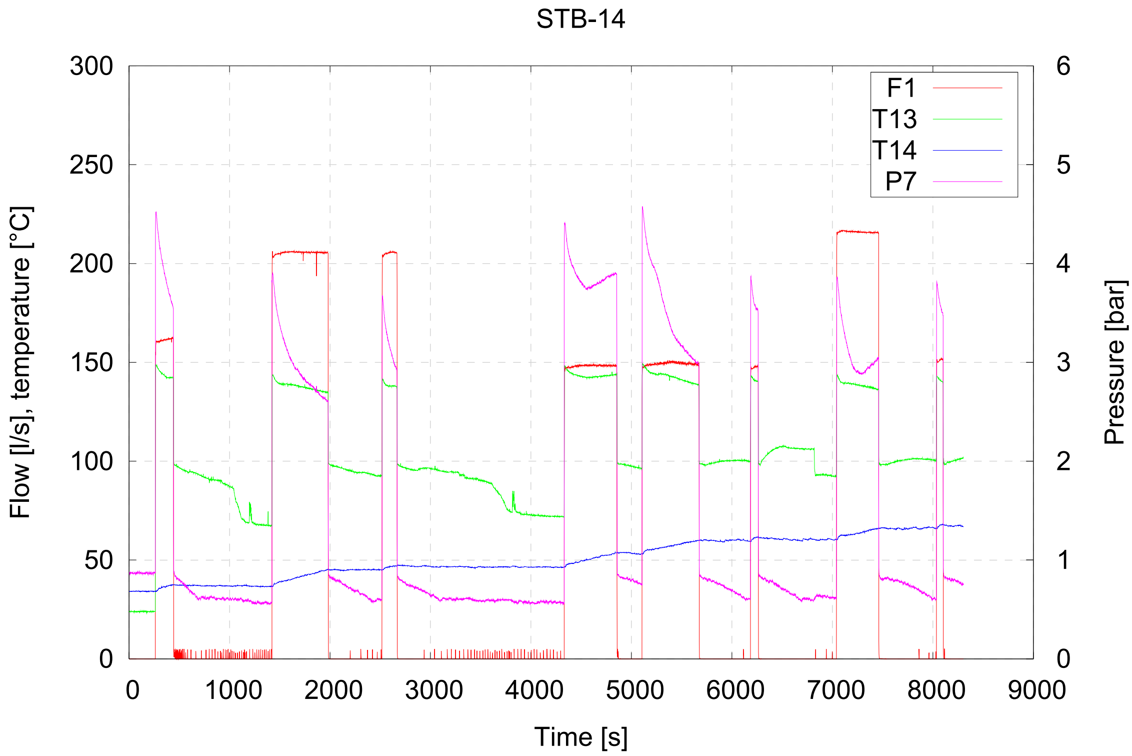


Figure 7. Steam volumetric flow (F1), temperature (T13) and pressure (P7) in STB-14. T14 is water temperature on the pool bottom.

During the blowdowns chugging phenomena was the dominating condensation mode. For this reason steam bubbles formed at the pipe outlet. In the early phase of the test series the bubbles were small. As the pool water temperature rose, still larger and larger bubbles formed at the pipe outlet. The maximum diameter of the bubbles was approximately two times the DN200 blowdown pipe diameter. Figure 8 shows some typical steam bubbles that formed during STB-14. The collapse times of the steam bubbles (see Table 7) were estimated by observing high-speed videos.

Figure 9 shows frame captures from the formation and collapse of one steam bubble (the steam bubble in question is the one on the top left frame in Figure 8). At 45.80 s, the donut-shaped bubble reached its maximum size (diameter approximately 300 mm). The collapse time of the steam bubble was about 20 ms. After the rapid collapse had occurred an underpressure developed inside the blowdown pipe and water was sucked in (see the white circle on the pipe outlet in the last five frames of Figure 9).

Figure 10 shows temperatures in the blowdown pipe during the formation and collapse of the steam bubble. Temperature readings dropped rapidly after the steam bubble collapsed and water was sucked into the blowdown pipe.

Figure 11 show pressures in the blowdown pipe and on the pool bottom. It can be seen that the underpressure phase lasted for 0.4 seconds. After that, a condensation-induced water hammer propagated inside the blowdown pipe. The maximum pressure pulse (more than

1.2 MPa) was registered by the pressure transducer P1. The collapse caused a 20 kPa pressure load on the pool bottom.

Figure 12 shows strain gauge readings. The strain gauges on the pool outer wall registered oscillations with a frequency of around 10 Hz during the blow. Rapid condensation of the steam bubble at the pipe outlet after 45.80 s caused a maximum strain amplitude of 180 µS (measured by the strain gauge ST3).

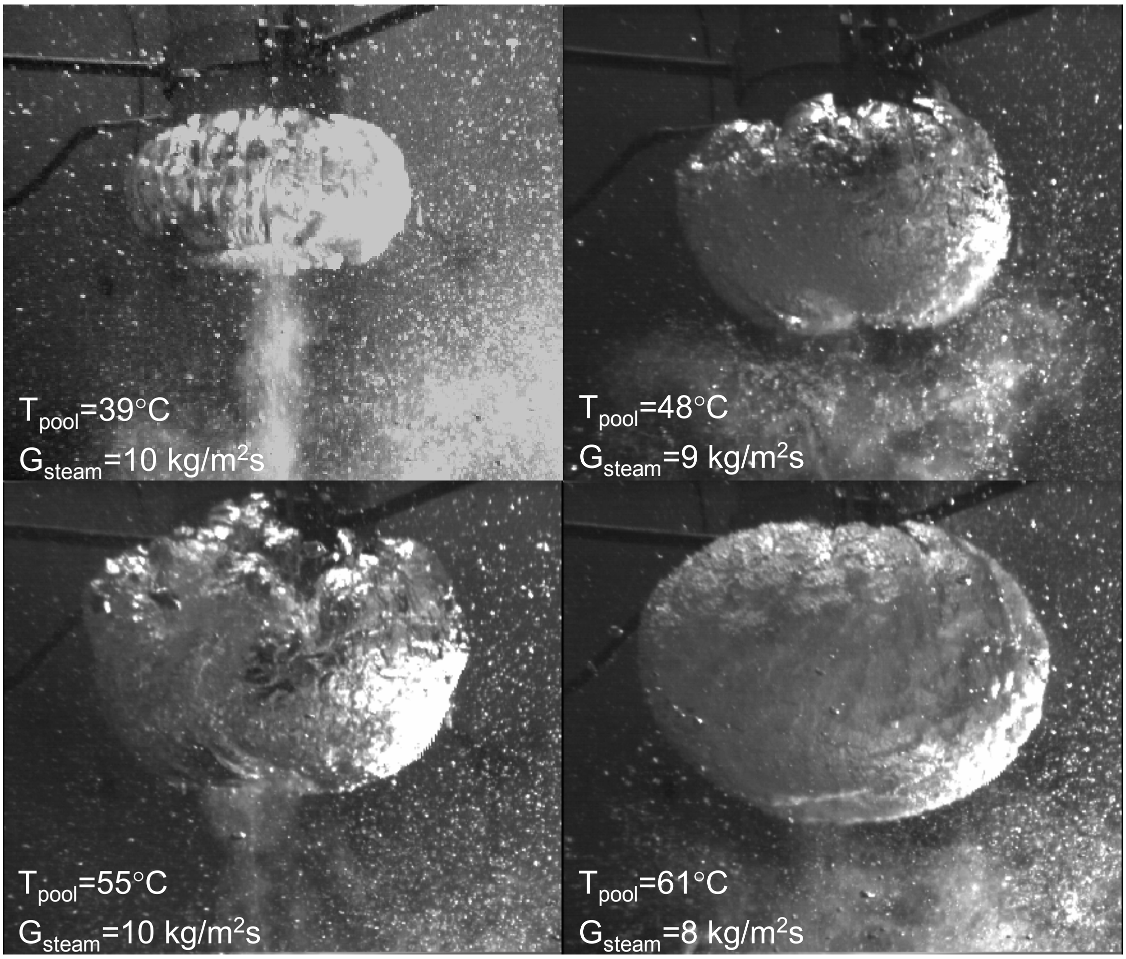
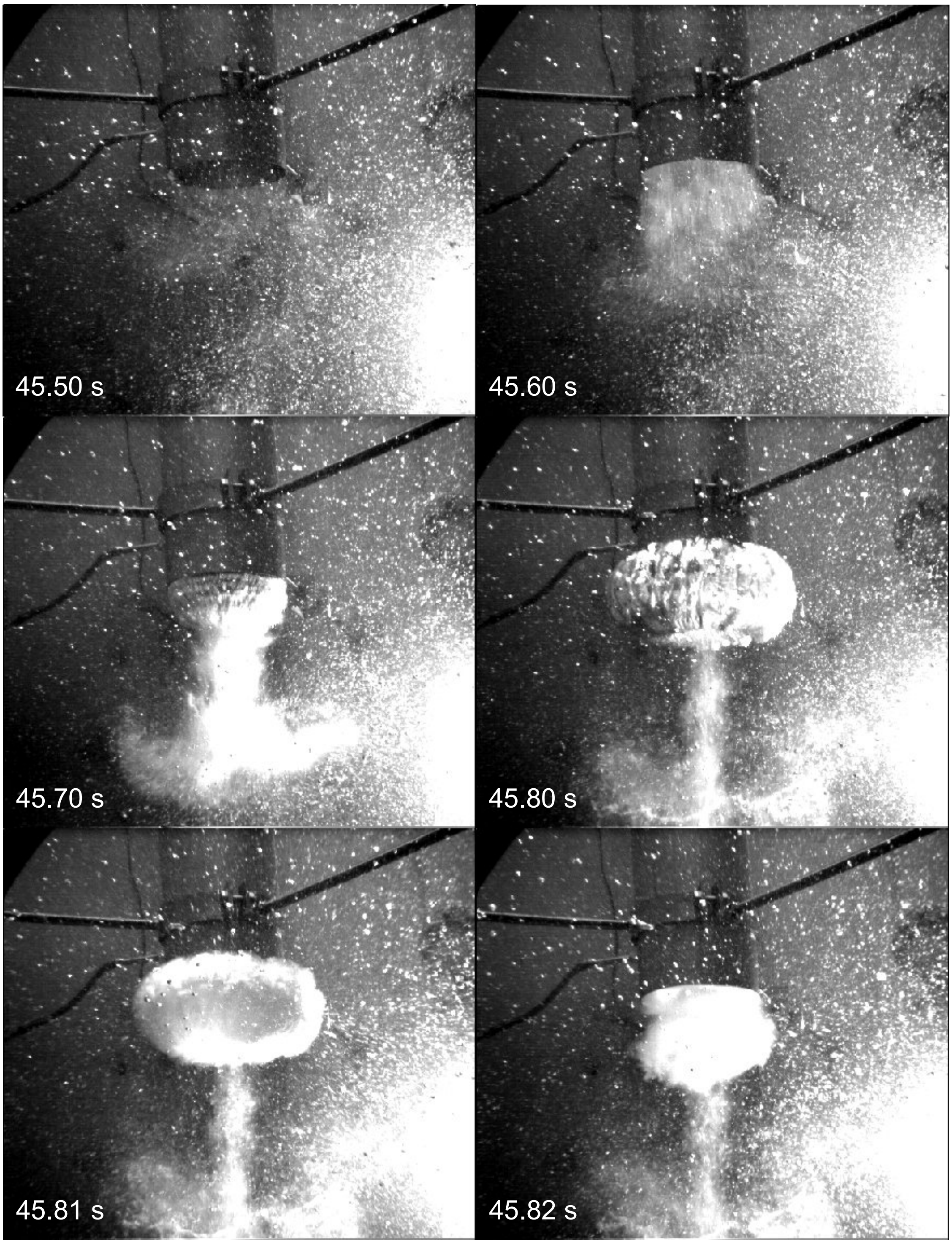


Figure 8. Frame captures from STB-14.

Table 7. Collapse times of the steam bubbles presented in Figure 8

Bubble	Collapse time [ms]	Bubble diameter [mm]
Top left	20	300
Top right	50	350
Bottom left	50	400
Bottom right	60	450


45.50 s
45.60 s
45.70 s
45.80 s
45.81 s
45.82 s

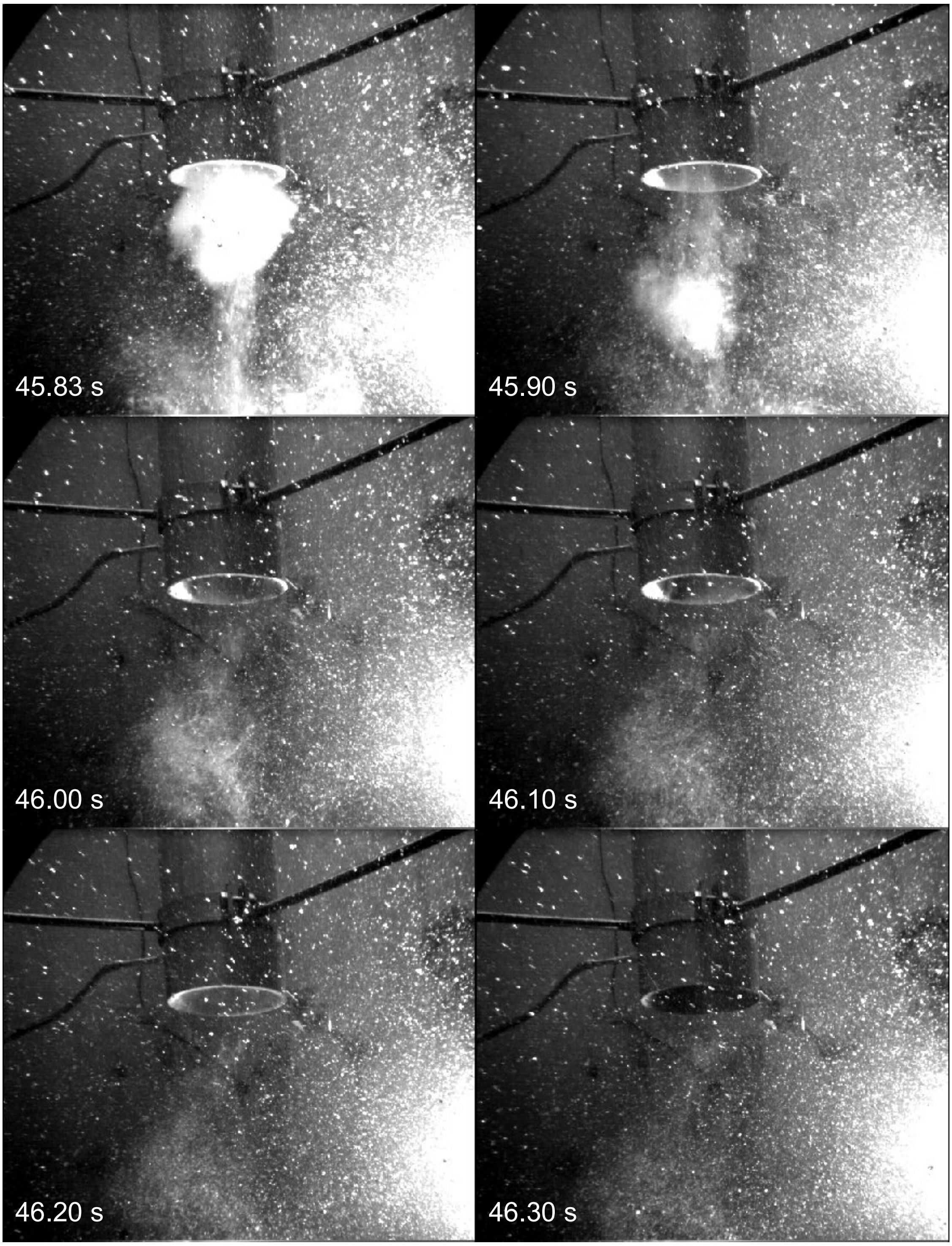


Figure 9. Frame captures from STB-14-2. T_{pool} is 39°C and G_{steam} 10 kg/m^{2}s.

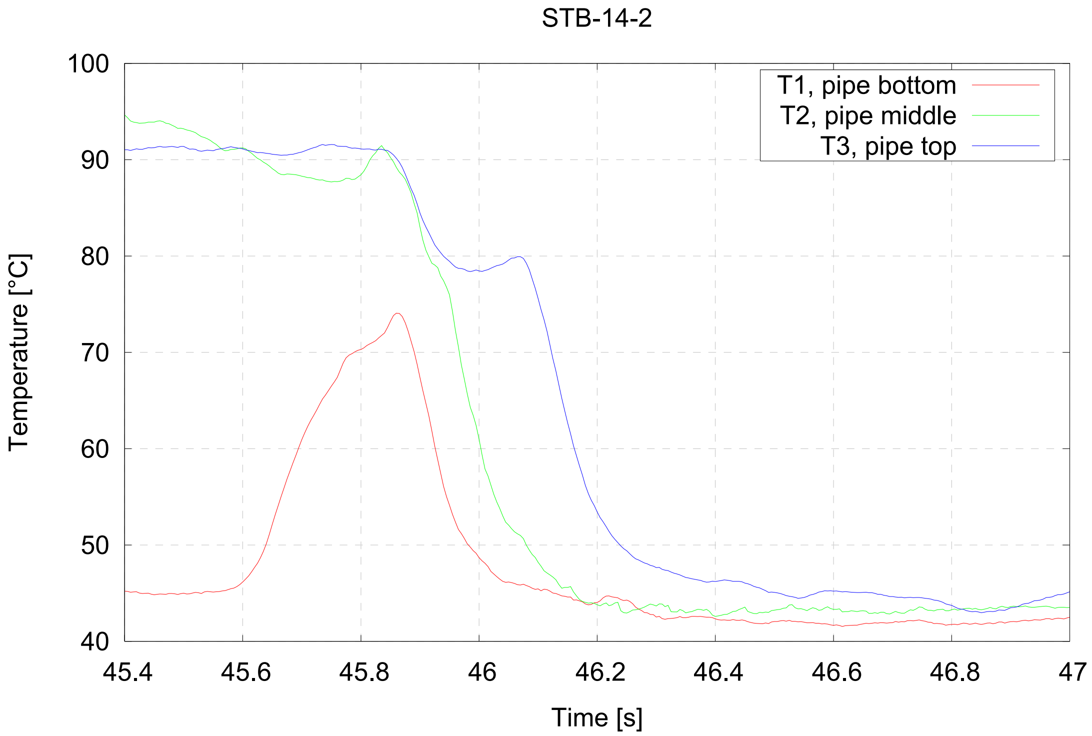


Figure 10. Temperatures in the blowdown pipe during STB-14-2 between 45.4 s…47.0 s. Note that the timescale is not exactly the same as in Figure 9.

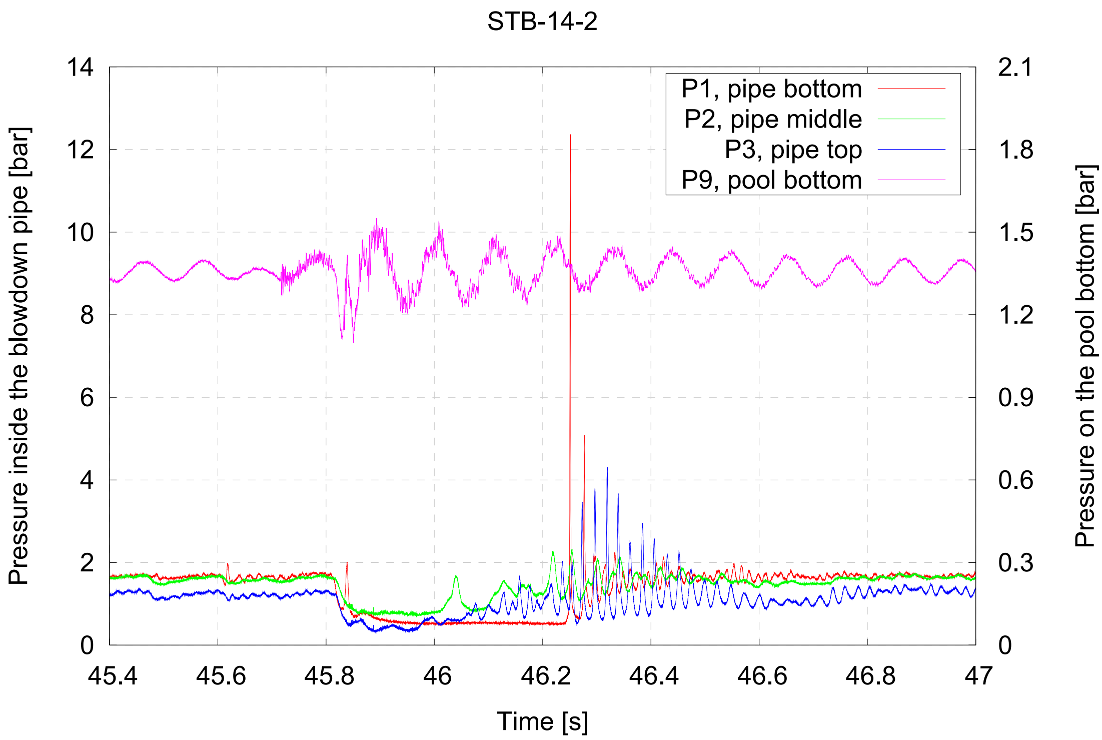


Figure 11. Pressures during STB-14-2 between 45.4 s…47.0 s. Note that the timescale is not exactly the same as in Figure 9.

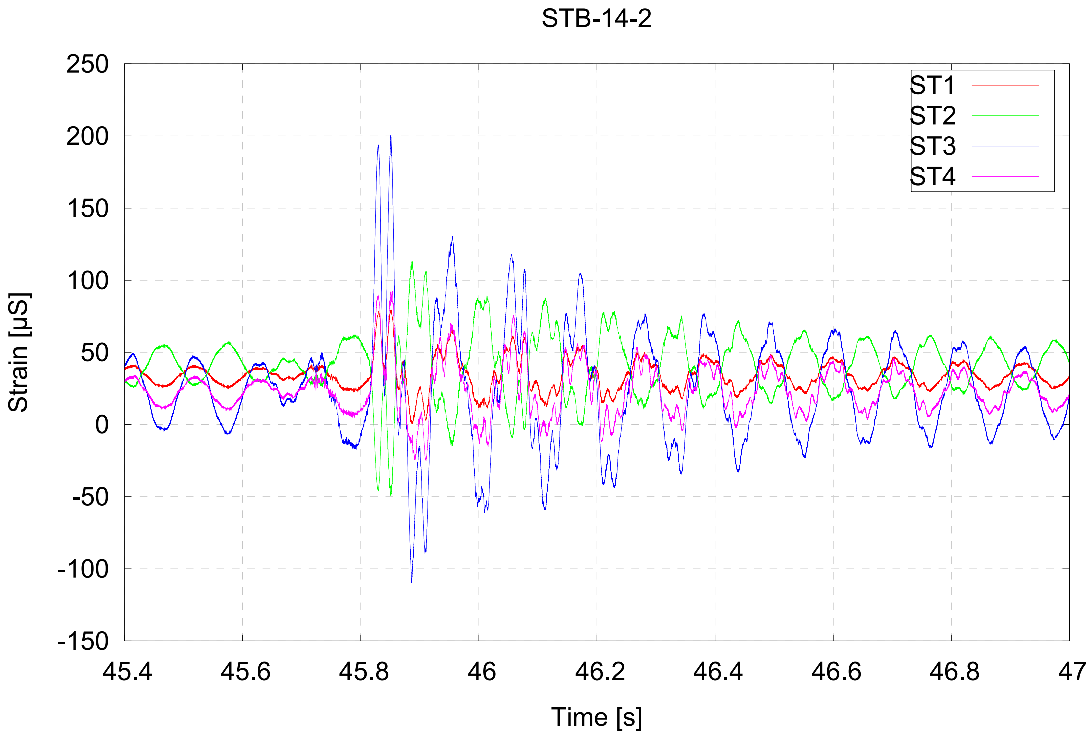


Figure 12. Strains during STB-14-2 between 45.4 s…47.0 s. Note that the timescale is not exactly the same as in Figure 9.

Table 8 summarizes the values of main parameters during experiment STB-14. Chugging phenomenon caused loads to the submerged pool structures. Pressure loads were registered inside the blowdown pipe after a low-pressure void was filled with water. The maximum measured pressure pulse inside the blowdown pipe was 1.3 MPa.

The strain gauges on the pool outer wall registered oscillations with the maximum amplitude of 220 µS (measured by ST3 during STB-14-8). The strains registered by the strain gauges are discussed in more detail in chapter 6.2.

The highest measured pressure load on the pool bottom was 40 kPa. This load was also caused by condensation-induced water hammer and not by a water plug hit to the pool bottom in the beginning of the blowdown. The load caused by the water plug hit after initiating the blowdown was measured during STB-14-6 and STB-14-8. Because of rather low steam generator initial pressure (0.5 MPa) the loads caused by the water plug hits were not higher than 15 kPa (in STB-14-6) and 25 kPa (in STB-14-8).

Appendix 2 shows a condensation mode map. All STB-14 blows (marked as eight blue crosses) are located in the chugging region.

Table 8. Main parameters during STB-14

Test	Steam generator initial pressure [MPa]	Steam blowdown [s]	LabView data recording [s]
STB-14-1	0.5	262…442	380…430
STB-14-2	0.5	1423…1980	1485…1575
STB-14-3	0.5	2518…2667	2580…2660
STB-14-4	0.5	4331…4855	4380…4437
STB-14-5	0.5	5105…5673	5115…5190
STB-14-6	0.5	6185…6261	6181…6256
STB-14-7	0.5	7041…7460	7080…7133
STB-14-8	0.5	8035…8102	8032…8107

Test	Values during LabView data recording				
	T_{pool} [°C]	G_{steam} [kg/m^{2}s]	p_{max} in the DN200 pipe [MPa]	Δp_{max} on the pool bottom [kPa]	$\Delta\varepsilon_{max}$ [µS]
STB-14-1	37	9	1.3	20	150
STB-14-2	39…40	11…10	1.2	25	180
STB-14-3	46…47	10…9	1.3	25	120
STB-14-4	48…49	9	1.1	20	100
STB-14-5	53…55	10…9	1.0	30	200
STB-14-6	59…62	9…8	0.9	25	180
STB-14-7	62	12…11	0.9	35	210
STB-14-8	66…68	9…8	0.9	40	220

5.3 STB-15

STB-15 consisted of six separate steam blowdowns. The first blowdown lasted approximately for 3000 s. During this long blowdown measurement data was not recorded for the whole duration of the blow. Instead, five short time intervals were recorded by using LabView software. So, the total number of LabView data recording periods was ten (labeled from STB-15-1 to STB-15-10). The purpose of the test was to study steam bubble formation frequency as a function of pool water temperature and steam mass flux. The initial pressure of the steam generator was 0.4-0.5 MPa (all three SGs in use). The pool water temperature rose from 49°C to 76°C during the series. Steam mass flux varied from 5 kg/m^{2}s to 12 kg/m^{2}s. Figure 13 shows the steam volumetric flow rate, temperature and pressure during STB-15.

To measure loads caused by a water plug hit to the pool bottom in the beginning of the blowdowns, LabView data recording was started few seconds before initiating steam blowdowns in STB-15-6 and STB-15-7.

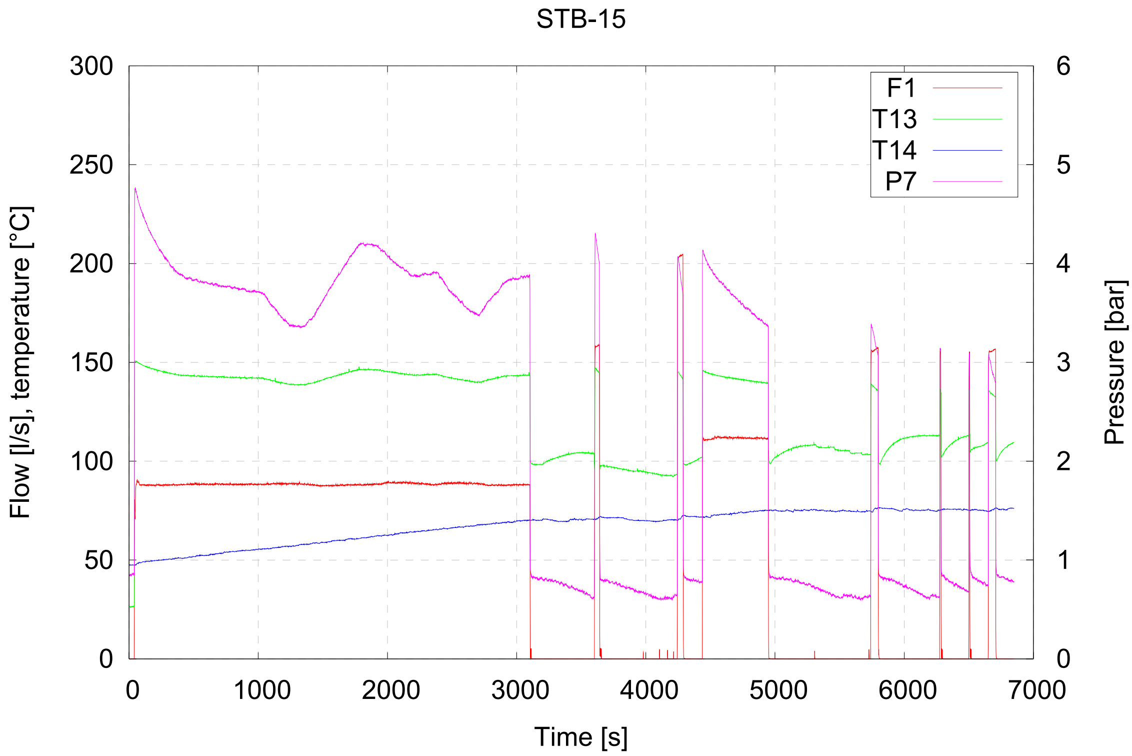


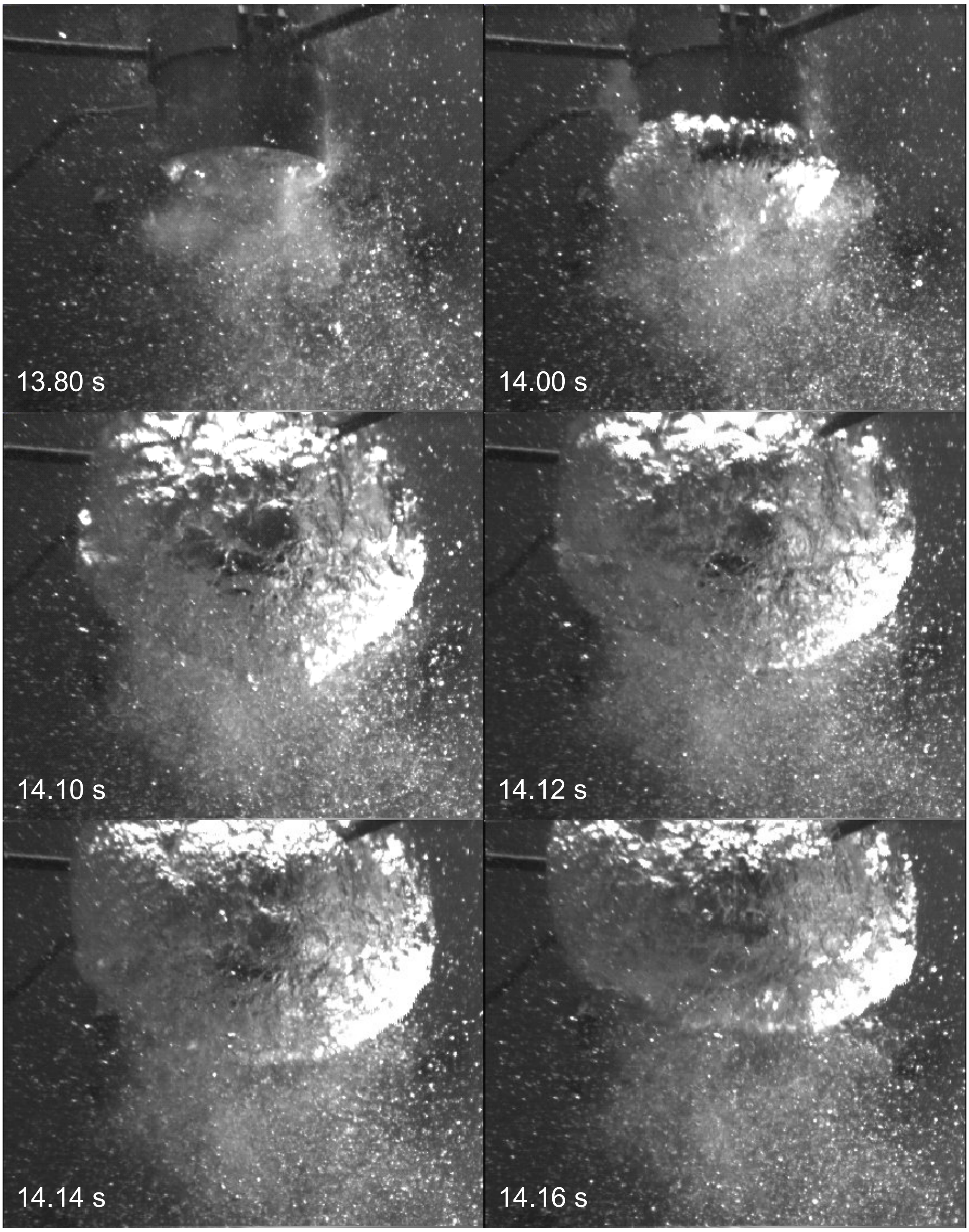
Figure 13. Steam volumetric flow (F1), temperature (T13) and pressure (P7) in STB-15. T14 is water temperature on the pool bottom. Note that data files STB-15-1…STB-15-5 were all recorded during the first long blowdown.

Figure 14 shows the formation and collapse of one steam bubble. This large bubble formed during STB-15-9 when the pool water temperature was 76°C and the steam mass flux 8 kg/m^{2}s. The maximum diameter of the bubble was approximately 500 mm and the collapse time 70…80 ms.

Figure 15 shows temperatures in the blowdown pipe during the formation and collapse of the steam bubble in Figure 14. Only the temperature reading of T1, which is closest to pipe outlet, dropped slightly after the collapse of the steam bubble.

Figure 16 shows pressures in the blowdown pipe and on the pool bottom during the formation and collapse of the same bubble. Due to warm pool water, condensation inside the blowdown pipe was not so rapid and a sudden collapse of the steam volume was missing. As a result, no significant underpressure and water hammer phenomenon developed inside the pipe. The maximum pressure pulse (registered by P1) was not greater than 0.4 MPa. The pressure transducer on the pool bottom registered a pressure load of 25 kPa at the same time.

Figure 17 shows strain gauge readings from the same time interval. Condensation of the steam bubble at the pipe outlet caused maximum strain amplitude of 180 µS (measured by the strain gauge ST3).


13.80 s
14.00 s
14.10 s
14.12 s
14.14 s
14.16 s

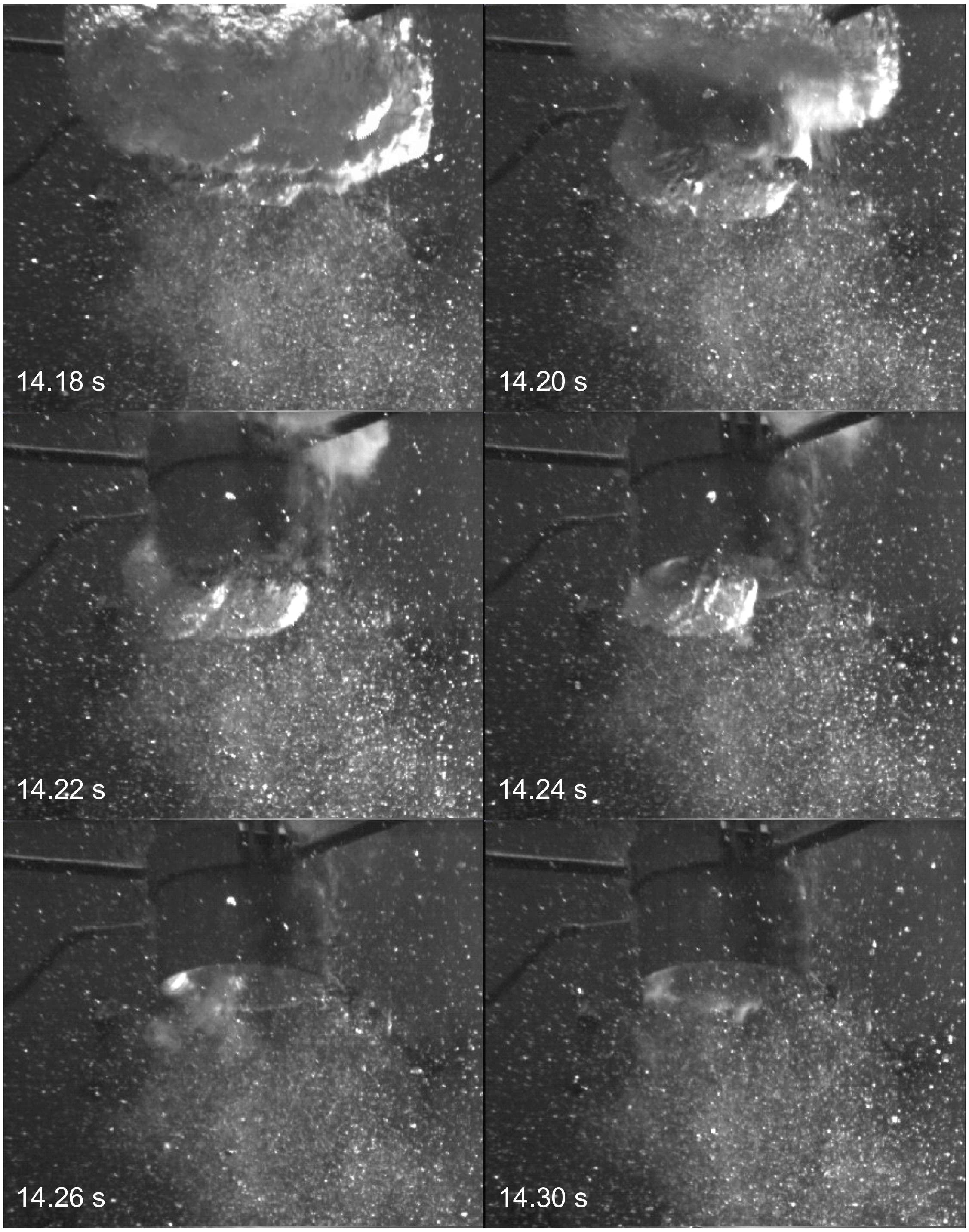


Figure 14. Frame captures from STB-15-9. T_{pool} *is 76°C and* G_{steam} *8 kg/m²s.*

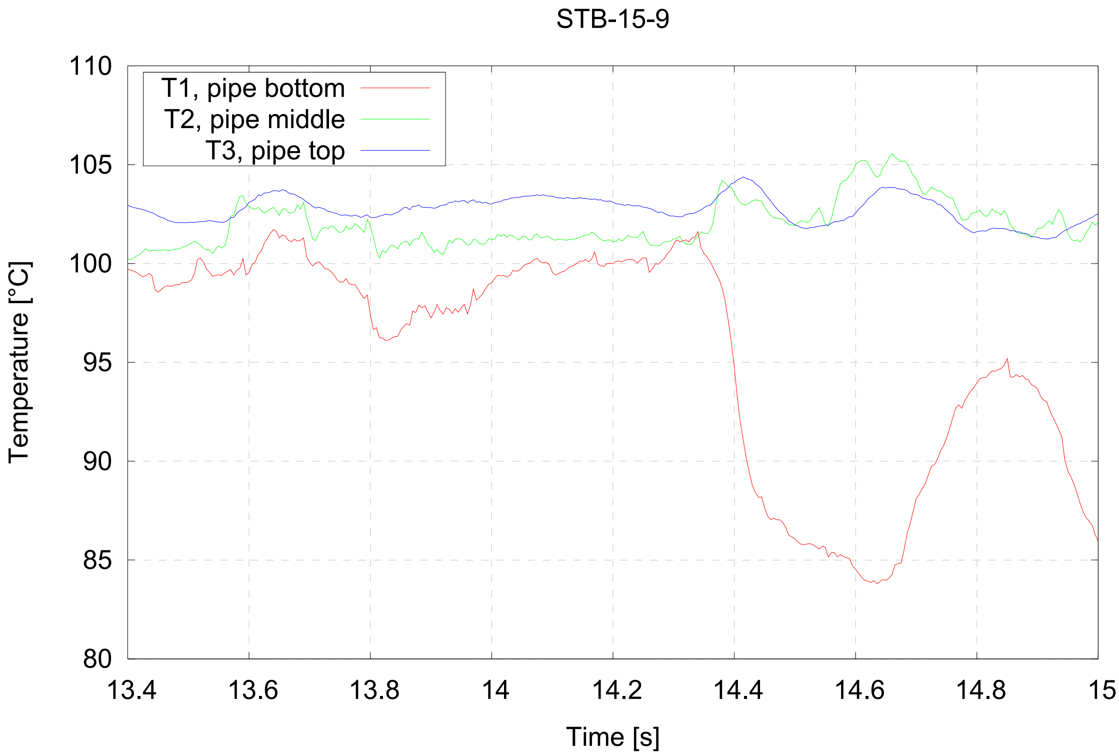


Figure 15. Temperatures in the blowdown pipe during STB-15-9 between 13.4 s…15.0 s. Note that the timescale is not exactly the same as in Figure 14.

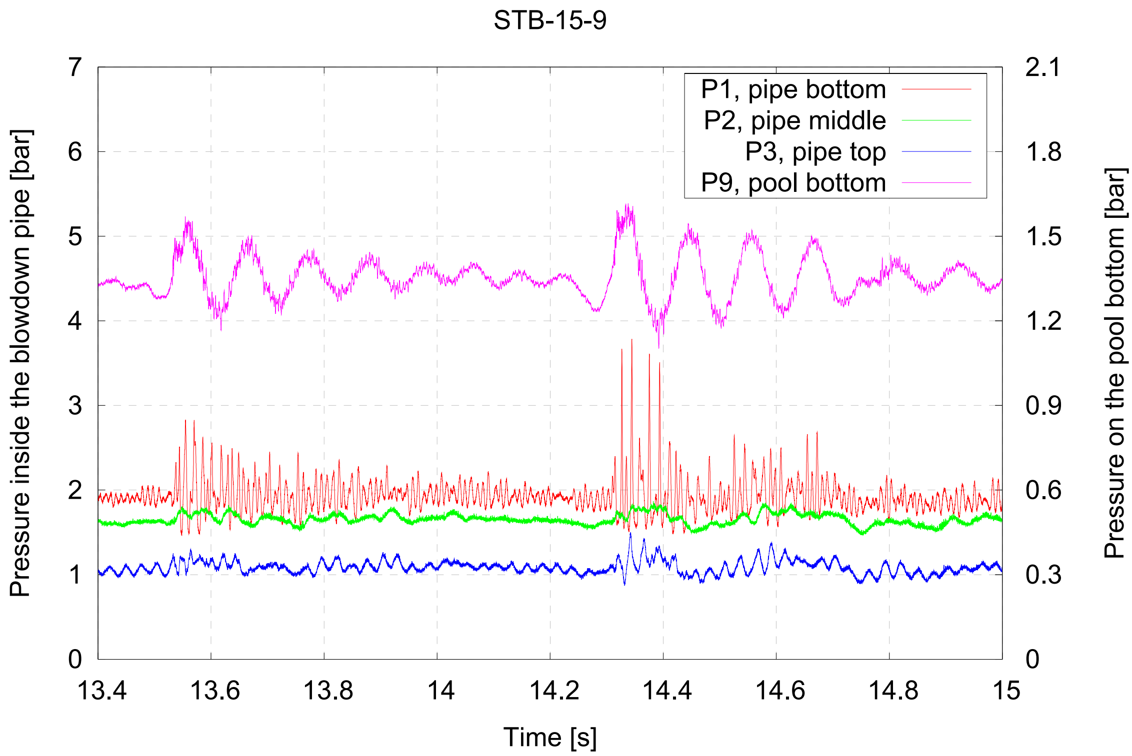


Figure 16. Pressures during STB-15-9 between 13.4 s…15.0 s. Note that the timescale is not exactly the same as in Figure 14.

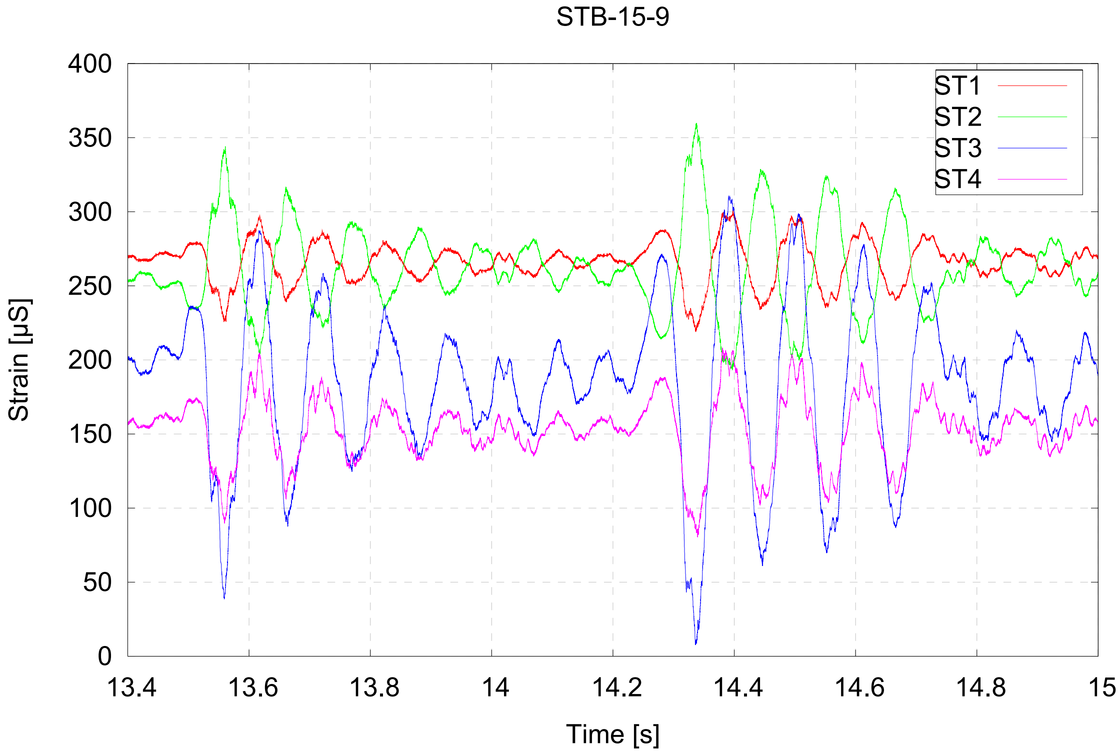


Figure 17. Strains during STB-15-9 between 13.4 s…15.0 s. Note that the timescale is not exactly the same as in Figure 14.

Table 9 summarizes the values of main parameters during experiment STB-15. Collapse of steam bubbles caused loads to the submerged pool structures. The maximum measured pressure pulse inside the blowdown pipe (1.3 MPa in STB-15-1) was of the same magnitude as during the previous test series During STB-15-1, the pool water temperature was still under 50 °C and considerable amount of condensation took place inside the blowdown pipe. As the pool water temperature rose, less and less water was sucked into the blowdown pipe after the collapse of steam bubbles and pressure loads registered by the transducers inside the pipe got smaller and smaller.

The highest measured pressure load on the pool bottom was 60 kPa. The load was caused by a water plug hit to the pool bottom after the blowdown was initiated in STB-15-6. The maximum load on the pool bottom caused by a condensation-induced water hammer was 40 kPa (STB-15-7). It was measured with a steam mass flux of 11…12 kg/m^2s and with a pool water temperature of over 70 °C. The maximum load value is exactly the same as during the previous STB-14 series.

The strain gauges on the pool outer wall registered oscillations with the maximum amplitude of 240 µS (measured by ST3 during STB-15-7). The strains caused by collapsing steam bubbles are discussed in more detail in chapter 6.2.

Table 10 shows the steam bubble formation frequency during STB-15 estimated on the basis of video captures and pressure measurement data. Due to low steam mass flux, frequencies are quite low. From these results, it can be concluded that the steam bubble formation frequency increases with increasing steam mass flux, but is also affected by the pool water temperature. Appendix 2 shows a condensation mode map. STB-15 blowdowns are marked as green crosses and are located mainly on the overlapping area of the chugging and transition regions. The last blows of the series into quite warm pool water belong clearly to the transition region.

Table 9. Main parameters during STB-15

Test	Steam generator initial pressure [MPa]	Steam blowdown [s]	LabView data recording [s]
STB-15-1	0.5	41…3103	100…146
STB-15-2	0.5	41…3103	930…984
STB-15-3	0.5	41…3103	1620…1670
STB-15-4	0.5	41…3103	2300…2356
STB-15-5	0.5	41…3103	3040…3089
STB-15-6	0.5	3604…3642	3601…3644
STB-15-7	0.5	4244…4289	4241…4290
STB-15-8	0.5	4438…4949	4900…4944
STB-15-9	0.4	5741…5799	5760…5795
STB-15-10	0.4	6650…6707	6670…6700

Test	Values during LabView data recording				
	T_{pool} [°C]	G_{steam} [kg/m^{2}s]	p_{max} in the DN200 pipe [MPa]	Δp_{max} on the pool bottom [kPa]	$\Delta\varepsilon_{max}$ [µS]
STB-15-1	49	6	1.3	15	60
STB-15-2	55	5	0.8	15	70
STB-15-3	60	5	1.2	20	120
STB-15-4	65	5	0.7	30	120
STB-15-5	70	5	0.6	25	140
STB-15-6	70…71	10	0.6	60	220
STB-15-7	71…72	12…11	0.8	40	240
STB-15-8	75	6	0.6	30	180
STB-15-9	75…76	8…7	0.4	30	180
STB-15-10	76	7	0.4	30	180

Table 10. Steam bubble formation frequency during STB-15

Test	Steam bubble formation frequency [Hz]
STB-15-1	0.5
STB-15-2	0.5
STB-15-3	0.5
STB-15-4	0.5
STB-15-5	0.5
STB-15-6	0.9…1.0
STB-15-7	1.2…1.4
STB-15-8	1.0…1.2
STB-15-9	1.4…1.6
STB-15-10	1.2…1.4

5.4 STB-16

STB-16 consisted of nine separate steam blowdowns (labeled from STB-16-1 to STB-16-9). The purpose of this test series was to measure high pressure loads inside the blowdown pipe caused by condensation-induced water hammer. To get conditions where high pressure pulses would be present, the pool was initially filled with cold water (11°C). After the last blowdown the pool water temperature had increased to 17°C. The initial steam generator pressure in the beginning of individual blows was either 0.3 MPa or 0.5 MPa (all three SGs in use). The control valve in the steam line was fully open during STB-16-4 and STB-16-5. For this reason the flow meter measurement range (285 l/s) was exceeded during these two blows. Figure 18 shows the flow rate, temperature and pressure of steam during STB-16.

LabView recorded data during every single blowdown. Data recording was started few seconds before initiating the steam blowdowns. In addition, data recording was not stopped until after terminating the steam blowdowns. Data recording frequency was 10 kHz except during the last blowdown. The duration of the last blowdown (STB-16-9) was approximately 300 s. To reduce the amount of measurement data, the LabView data recording frequency was reduced to the value of 1000 Hz in STB-16-9. For temperature readings the data recording frequency was 200 Hz.

During the blows steam condensed within the blowdown pipe and steam-water interface moved strongly up and down inside the pipe just like in test STB-13. Due to colder pool water temperature (15°C…27°C in STB-13 vs. 11°C…17°C in STB-16) much higher pressure pulses were measured inside the blowdown pipe. The highest pulse was 3.9 MPa and it was registered during STB-16-4, see Figure 19. Contrary to the earlier series with the DN200 pipe in spring 2004, the highest pressure pulses were now measured by the uppermost transducer (P3) in the blowdown pipe and not by P1 close to the pipe bottom.

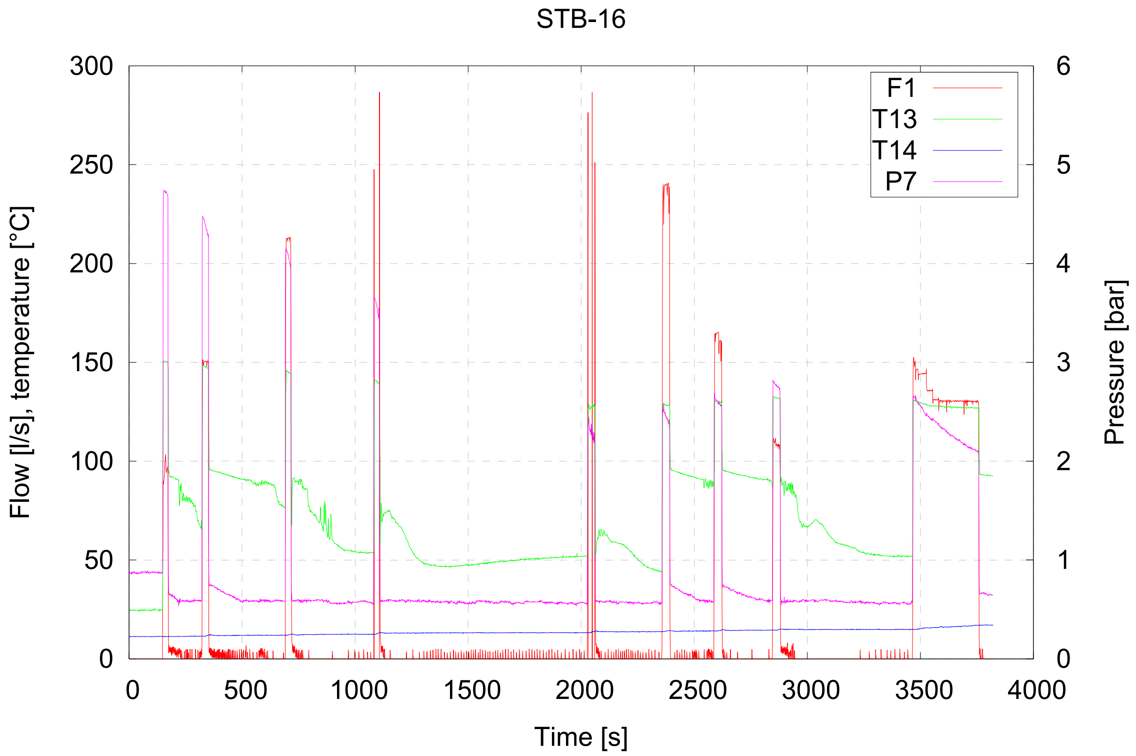


Figure 18. Steam volumetric flow (F1), temperature (T13) and pressure (P7) in STB-16. T14 is water temperature on the pool bottom. Note that the flow meter measurement range (285 l/s) was exceeded during STB-16-4 and STB-16-5.

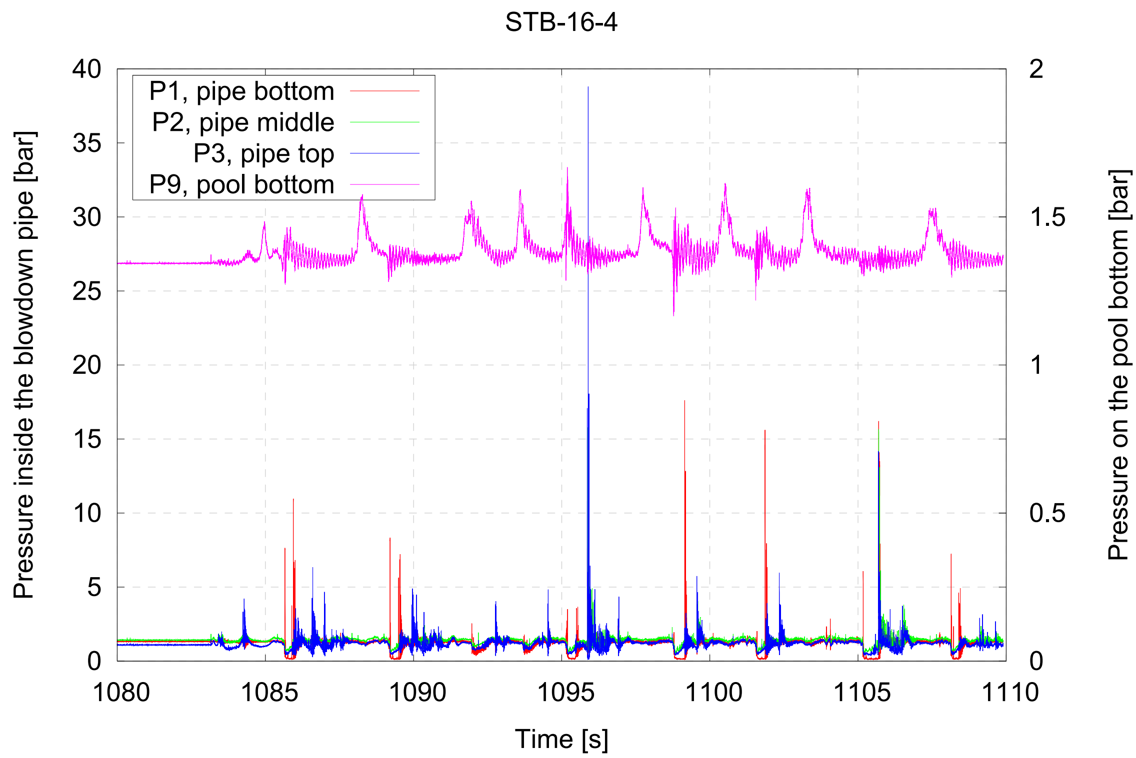


Figure 19. Pressures in STB-16-4.

Because steam condensed within the blowdown pipe, neither the pressure transducer on the pool bottom nor the strain gauges on the pool outer wall measured high loads. The maximum pressure pulse amplitude was 40 kPa and the maximum strain amplitude 90 µS (registered by ST3), see Table 11. These maximum values are approximately the same as during STB-13 (30 kPa and 100 µS, see Table 6).

Appendix 2 shows a condensation mode map. All STB-16 blowdowns (marked as six red crosses) are located close to the bottom left hand corner in region 1 i.e. condensation within vents or blowdown pipes.

Table 11. Main parameters during STB-16

Test	Steam generator initial pressure [MPa]	Steam blowdown [s]	LabView data recording [s]
STB-16-1	0.5	149…172	141…176
STB-16-2	0.5	323…351	316…353
STB-16-3	0.5	692…716	680…719
STB-16-4	0.5	1083…1108	1071…1110
STB-16-5	0.3	2028…2061	2020…2062
STB-16-6	0.3	2358…2391	2350…2392
STB-16-7	0.3	2588…2622	2580…2622
STB-16-8	0.3	2847…2880	2840…2882
STB-16-9	0.3	3466…3758	3460…3760

Test	Values during LabView data recording				
	T_{pool} [°C]	G_{steam} [kg/m^{2}s]	p_{max} in the DN200 pipe [MPa]	Δp_{max} on the pool bottom [kPa]	$\Delta\varepsilon_{max}$ [µS]
STB-16-1	11	7	1.0	15	40
STB-16-2	11…12	10	1.4	15	70
STB-16-3	12	13	2.0	40	90
STB-16-4	12…13	Not known	3.9	30	80
STB-16-5	13…14	Not known	2.0	15	60
STB-16-6	14	9	1.6	20	50
STB-16-7	14	7…6	1.4	10	30
STB-16-8	14…15	5	1.3	10	70
STB-16-9	15…17	6…4	1.7	20	60

5.5 STB-17

The purpose of STB-17 was to produce an undisturbed steam flow through the blowdown pipe into the pool (quasi-steady condensation mode) i.e. steam flow rate would be high enough to prevent water ingress into the blowdown pipe. To achieve these conditions the steam generator initial pressure was raised higher than before (1.0 MPa…3.0 MPa) and the control valve in the steam line was kept fully open during the blows. As expected, the flow meter measurement range (285 l/s) was exceeded during every single blowdown. To reduce the size of measurement files, the recording frequency of pressure and strain gauge data was set to the value of 2000 Hz. For the temperature readings the data recording frequency was the same as during the previous tests i.e. 200 Hz. Six separate blowdowns with different initial pressure levels were performed. Figure 20 shows the flow rate, temperature and pressure of steam during STB-17. Figure 21 shows the temperatures in the blowdown pipe from different blows plotted in the same graph.

From Figure 21 it can be seen how steam-water interface moved strongly up and down inside the blowdown pipe during STB-17-1…STB-17-4 indicating chugging phenomena. In STB-17-5 and STB-17-6, steam flow rate was high enough to prevent water ingress into the blowdown pipe. However, steam-water interface oscillated at the pipe outlet like a flickering candle flame. The condensation mode observed during the last two blows belongs to the region 3 i.e. condensation oscillations. The desired quasi-steady condensation mode (region 4) was not fully achieved during STB-17. The available steam mass flow from the PACTEL steam generators was not high enough for the condensation mode to cover region 4 with the used DN200 blowdown pipe. During the condensation oscillations mode the maximum pressure pulse amplitude on the pool bottom was 30 kPa and the maximum strain amplitude 130 µS (registered by ST3).

In the beginning of the blowdowns, water plugs were pushed strongly from the blowdown pipe to the pool bottom. This caused loads to the pool walls. The loads were registered both by the strain gauges on the pool outer wall and by the pressure transducer on the pool bottom. The strains registered by the strain gauges are discussed in more detail in chapter 6.4. The maximum pressure pulse on the pool bottom (390 kPa) was registered in STB-17-4 (Figure 22). Table 12 shows the values of main parameters during STB-17.

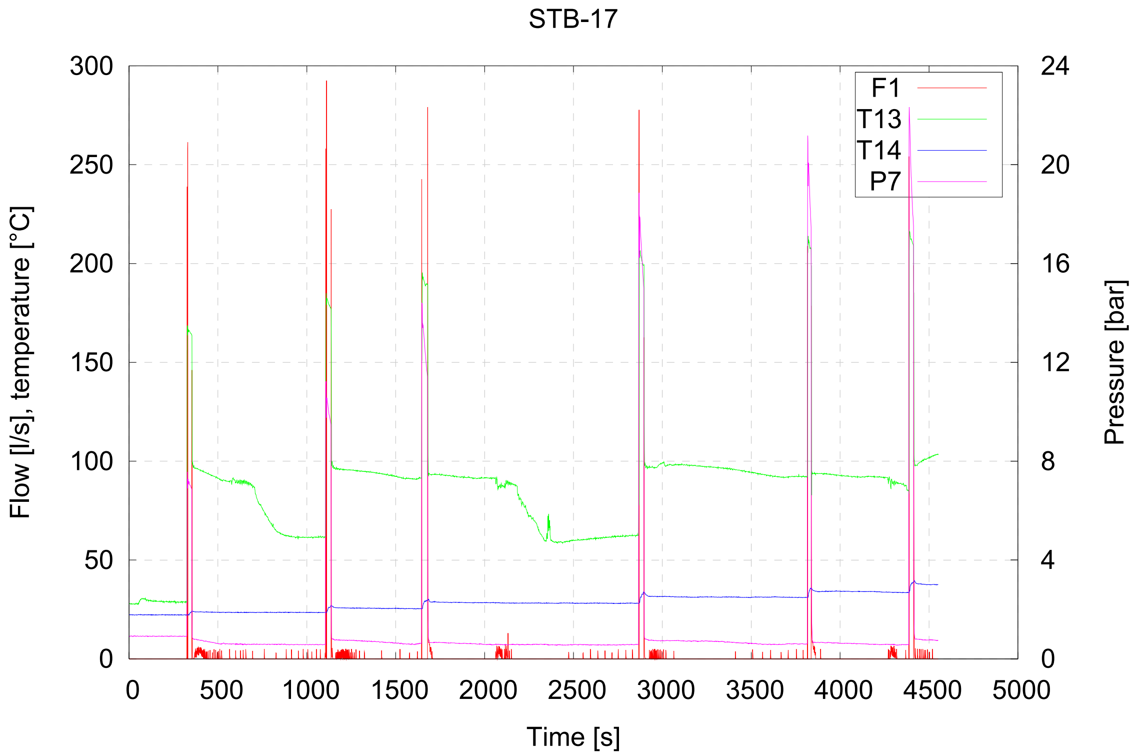


Figure 20. Steam volumetric flow (F1), temperature (T13) and pressure (P7) in STB-17. T14 is water temperature on the pool bottom. Note that the flow meter measurement range (285 l/s) was exceeded during the blows.

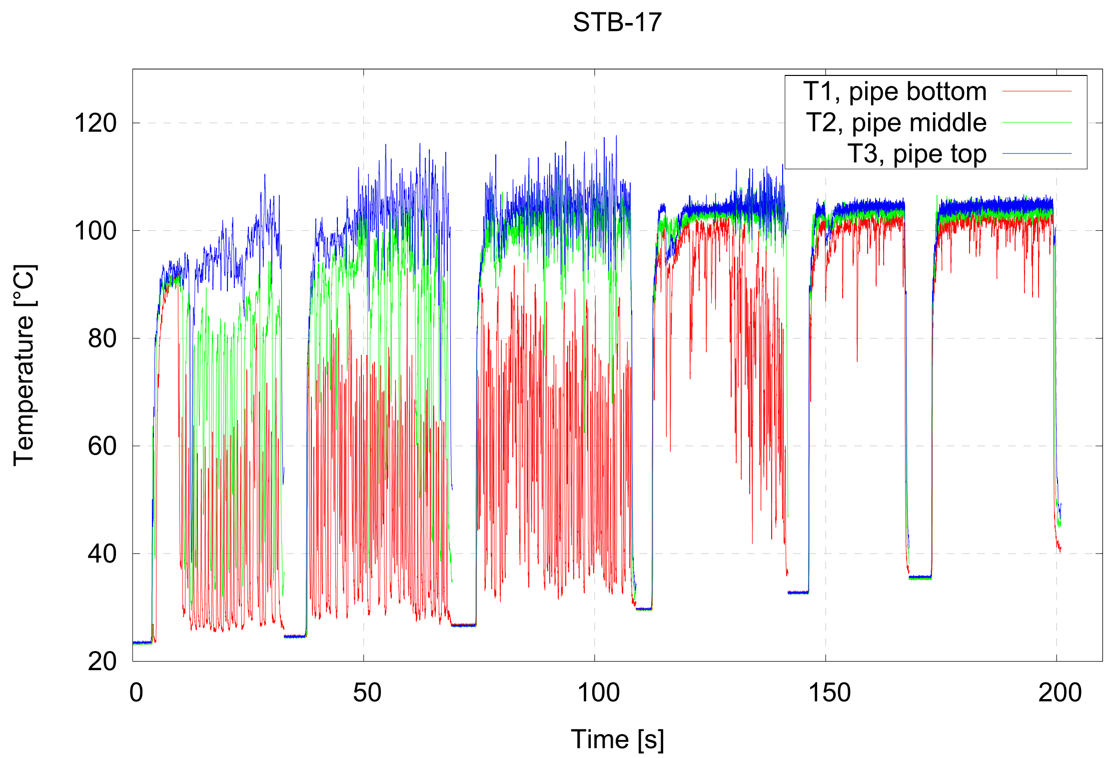


Figure 21. Temperatures in the blowdown pipe during the six separate blows in STB-17 plotted in the same graph. Note that the timescale is not the same as in Figure 20.

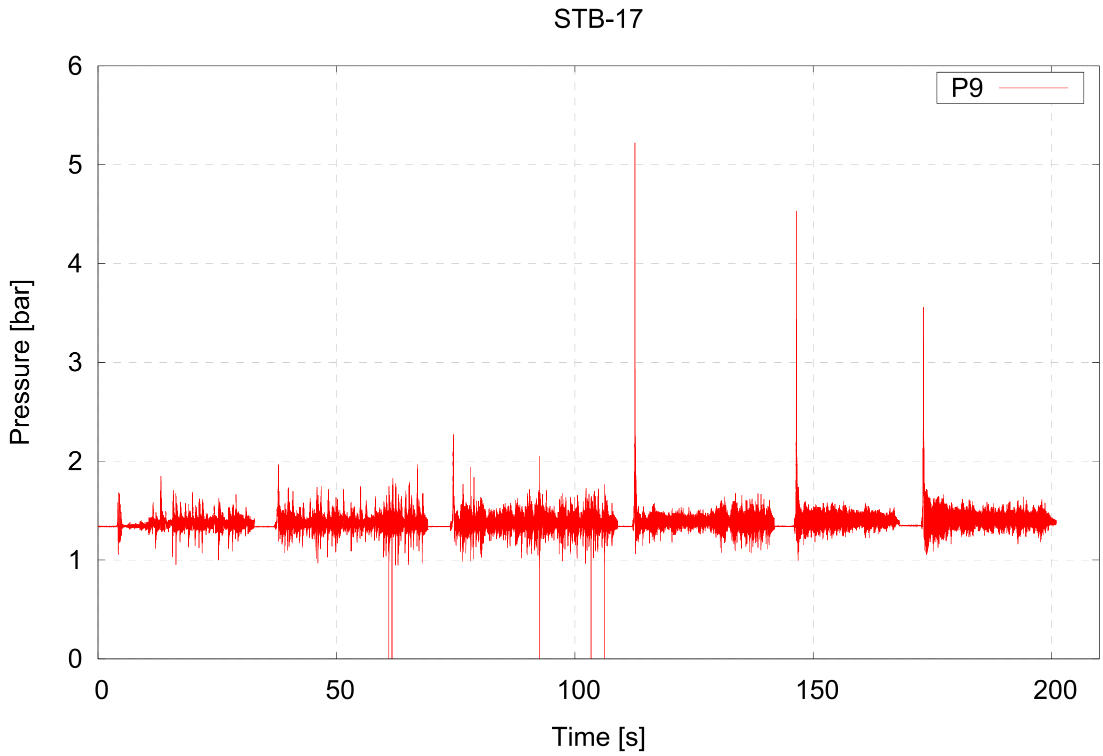


Figure 22. Pressures on the pool bottom in STB-17 plotted in the same graph. Note that the timescale is not the same as in Figure 20.

Table 12. Main parameters during STB-17

Test	Steam generator initial pressure [MPa]	Steam blowdown [s]	LabView data recording [s]
STB-17-1	1.0	325…353	321…354
STB-17-2	1.5	1106…1137	1102…1138
STB-17-3	2.0	1646…1680	1641…1681
STB-17-4	2.5	2867…2896	2864…2897
STB-17-5	2.7	3816…3837	3812…3838
STB-17-6	3.0	4387…4413	4382…4415

Test	Values during LabView data recording				
	T_{pool} [°C]	G_{steam} [kg/m^{2}s]	p_{max} in the DN200 pipe [MPa]	Δp_{max} on the pool bottom [kPa]	$\Delta\varepsilon_{max}$ [µS]
STB-17-1	22…23	Not known	0.8	50	220
STB-17-2	23…25	Not known	0.9	60	270
STB-17-3	25…28	Not known	1.4	90	270
STB-17-4	28…31	Not known	1.2	390	330
STB-17-5	31…34	Not known	1.8	320	320
STB-17-6	34…37	Not known	1.8	220	280

6 STRESS ANALYSIS

During the experiments loads were caused to the pool structures at least due to four different reasons: hydrostatic pressure of water, rapid collapse of steam bubbles (chugging phenomena), condensation oscillations and water plug hit to the pool bottom.

Stress values can be calculated with the help of measured strains (ε) by using Hooke's law:

$$\sigma = E\varepsilon , \qquad (2)$$

where E is Young's modulus. The physical and mechanical properties of the pool production material AISI 304 are shown in Table 13 and Table 14, respectively.

Table 13. Physical properties of AISI 304 as a function of temperature [8]

T [°C]	ρ [kg/m³]	E [GPa]	ν	α [1/K]	c [J/kgK]	k [W/mK]
20	7900	200	0.3	16.0E-06	500	15
100		194		16.0E-06		
200		186		16.5E-06		

Table 14. Mechanical properties of AISI 304 as a function of temperature [8]

T [°C]	$R_{p0.2}$ [MPa]	$R_{p1.0}$ [MPa]	R_m [MPa]
20	210	250	520...720
100	157	191	
200	127	157	

6.1 STRESSES DUE TO HYDROSTATIC PRESSURE OF WATER

To take into account the stresses due to hydrostatic pressure of water, the pool was drained totally after STB-15 and STB-16. Figures 23 and 24 show the measured strains (ST1…ST4) and the pool outer wall temperature near the strain gauges (T16).

Before the first draining was initiated water level in the pool was 3.36 m and pool outer wall temperature 31°C. The maximum strain value of 228 µS (235 µS - 7 µS) was measured by the strain gauge ST3 (below the rounding, hoop direction). During the draining the pool outer wall temperature near the strain gauges stayed virtually constant. According to Equation 2, the strain value of 228 µS corresponds to 46 MPa of stress.

Before the second draining was initiated water level in the pool was 3.22 m and pool outer wall temperature less than 18°C. The maximum strain value of 236 µS (186 µS – (-50 µS)) was measured again by the strain gauge ST3. During the draining the pool wall temperature increased about 1.5 °C because of thermal stratification of water. This caused a 24 µS increase to the strain values ($1.5\,°C \cdot 16 \cdot 10^{-6}\,\frac{1}{°C}$). The strain caused by the mere static mass of water was therefore 212 µS. This value corresponds to 42 MPa of stress.

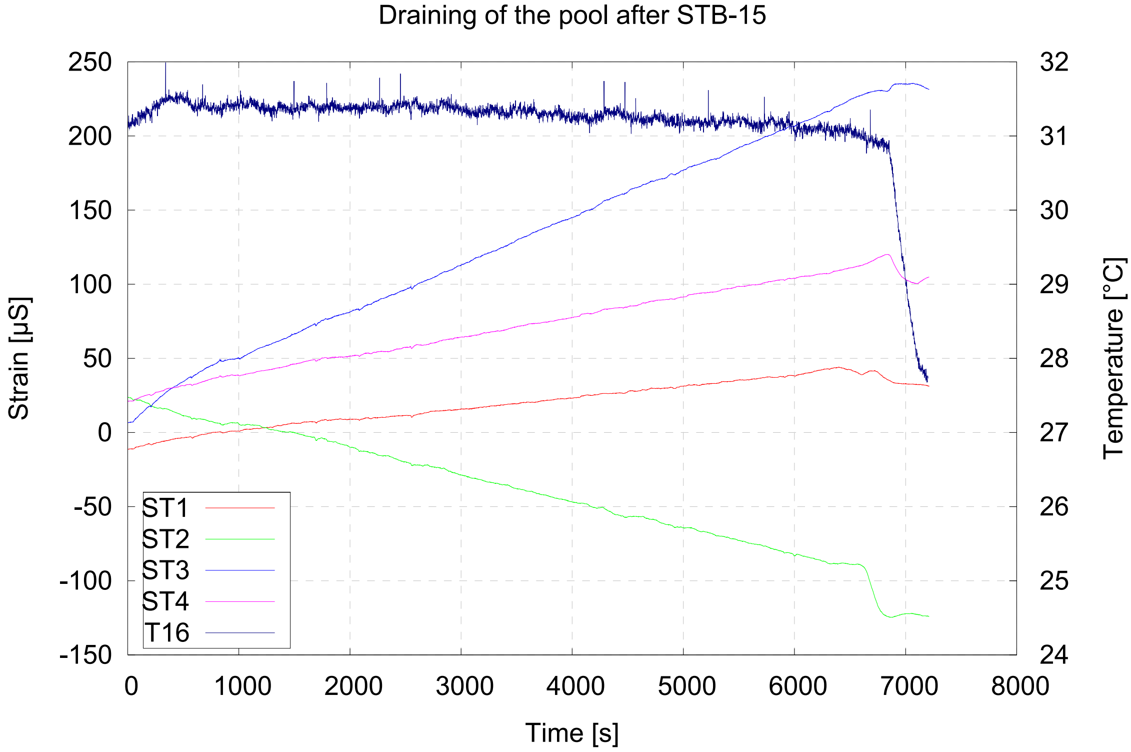


Figure 23. Strains and pool outer wall temperature near the strain gauges when the pool was drained totally after STB-15.

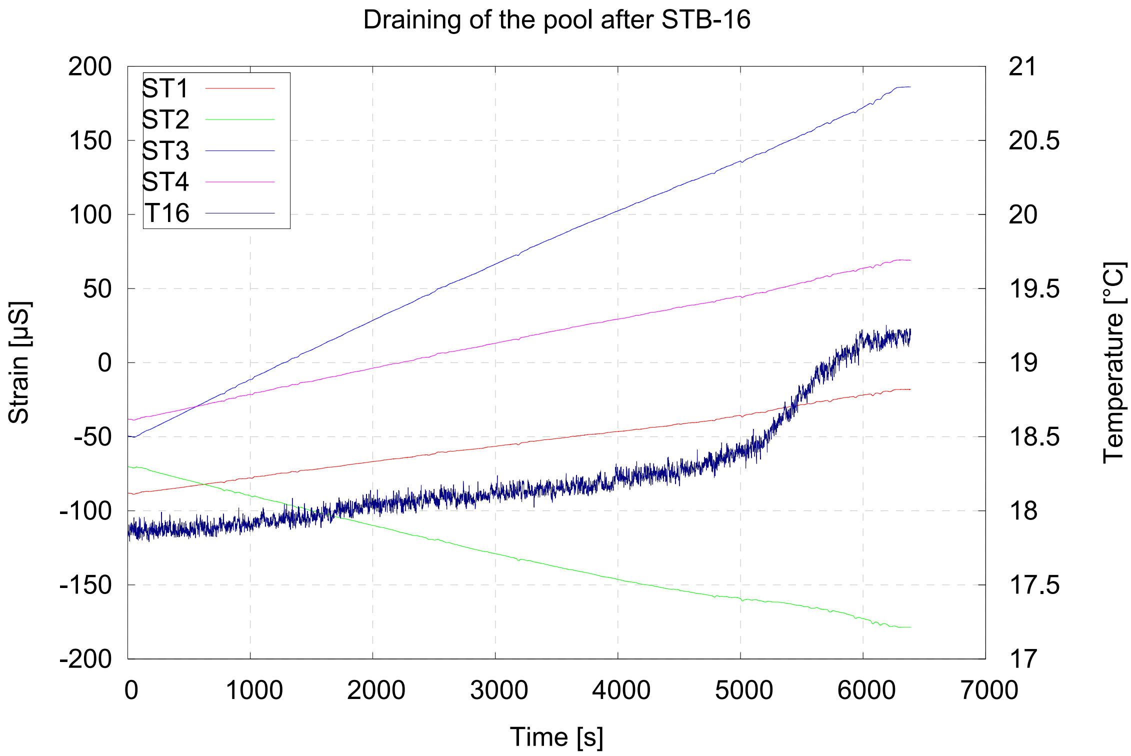


Figure 24. Strains and pool outer wall temperature near the strain gauges when the pool was drained totally after STB-16.

According to the CFD simulations and structural analysis (performed by VTT Processes and VTT Industrial Systems) the maximum hoop stress at the centre of the pool bottom rounding in the pool outer wall is approximately twice the hoop stress at the location of the strain gauge ST3. Also, the maximum von Mises stress at the bottom rounding is approximately three times the hoop stress at the location of the strain gauge ST3. [9]

According to the strain gauge measurements and computer simulations, the maximum von Mises stresses at the pool bottom rounding due to the hydrostatic pressure of water were about 137 MPa (water level 3.36 m) and 127 MPa (water level 3.22 m).

6.2 STRESSES DUE TO CHUGGING PHENOMENON

The largest observed steam bubbles formed at the pipe outlet during STB-15 because the pool water temperature was in that test even more than 70°C. Rapid condensation of bubbles initiated condensation-induced water hammers. This caused dynamic loadings to the submerged pool structures. The maximum strain amplitude of 240 µS was measured by the strain gauge ST3 in STB-15-7 with steam mass flux of 12 kg/m^{2}s and pool water temperature of 71°C, see Figure 25. The strain amplitude of 240 µS corresponds to 48 MPa of stress. The frequency of the strain gauge signal oscillations was approximately 10 Hz.

According to the strain gauge measurements and computer simulations, the maximum von Mises stress amplitude at the pool bottom rounding due to chugging was approximately 140 MPa and the mean value caused by the static mass of water (approximately 13000 kg) was 130 MPa. Thus the maximum von Mises stress could have been 270 MPa. This kind of load is so notable that it causes plastic deformation, see Table 14.

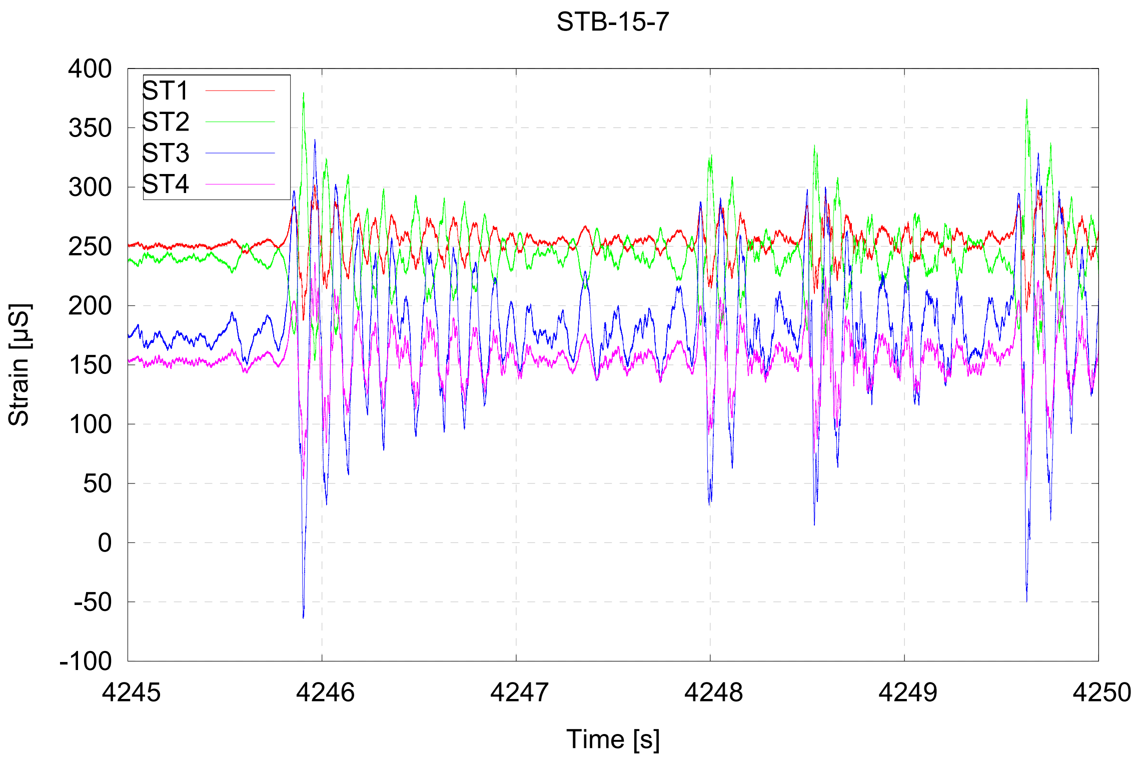


Figure 25. Strains in STB-15-7 between 4245…4250 s.

6.3 STRESSES DUE TO CONDENSATION OSCILLATIONS

In STB-17-5 and STB-17-6 the dominating condensation mode was condensation oscillations. In this mode, steam flow rate is high enough to prevent water ingress into the blowdown pipe. Steam-water interface seems to oscillate at the pipe outlet like a flickering candle flame. Condensation oscillations cause unsteady loads on submerged pool structures.

The maximum strain amplitude of 130 µS was measured by the strain gauge ST3 in STB-17-6, see Figure 26. This strain amplitude corresponds to 26 MPa of stress and approximately to 80 MPa of von Mises stress at the pool bottom rounding. When taking into account the stress caused by the static mass of water (130 MPa) the maximum von Mises stress could have been 210 MPa.

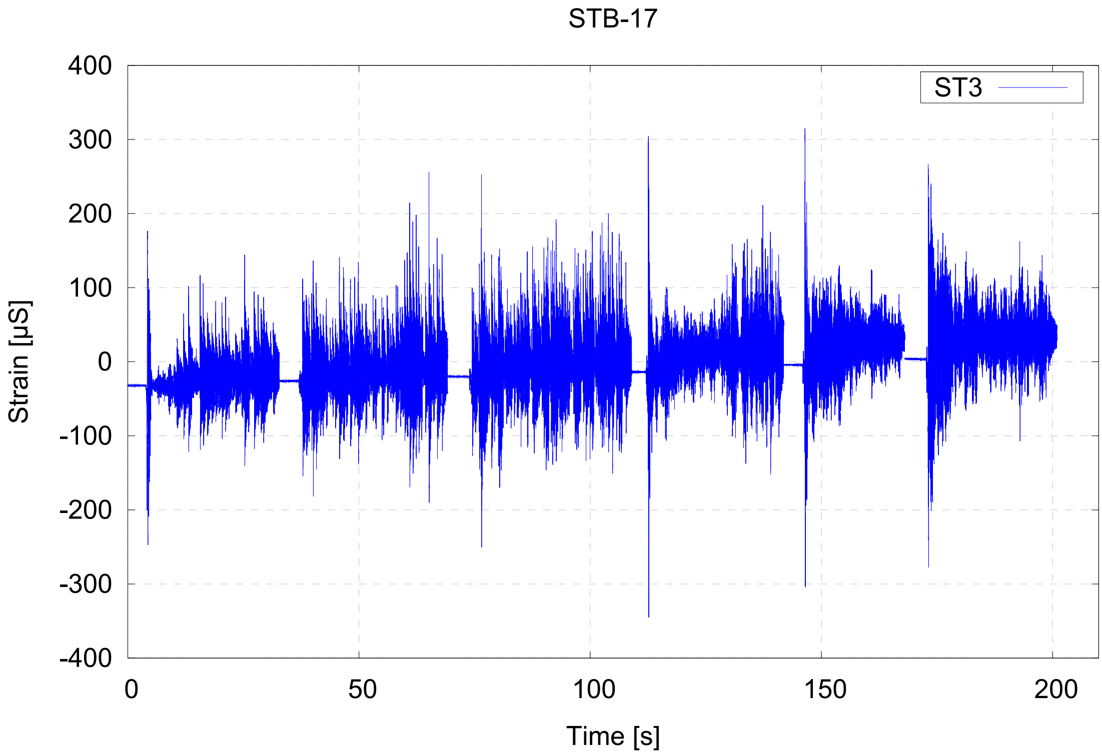


Figure 26. Strains measured by ST3 in STB-17 plotted in the same graph. Note that the timescale is not the same as in Figure 20.

6.4 STRESSES DUE TO WATER PLUG HIT TO THE POOL BOTTOM

The highest strain values were observed in test series STB-17, when the steam generator initial pressure was raised even to 3.0 MPa. Due to high steam pressure water plugs hit strongly to the pool bottom after initiating the steam blowdowns.

The maximum strain amplitude of 330 µS was measured by the strain gauge ST3 in STB-17-4, see Figure 26 and Figure 27. This strain amplitude corresponds to 66 MPa of stress and approximately to 200 MPa of von Mises stress at the pool bottom rounding. When taking into account the stress caused by the static mass of water (130 MPa) the maximum von Mises stress could have been 330 MPa. This kind of load causes plastic deformation, see Table 14.

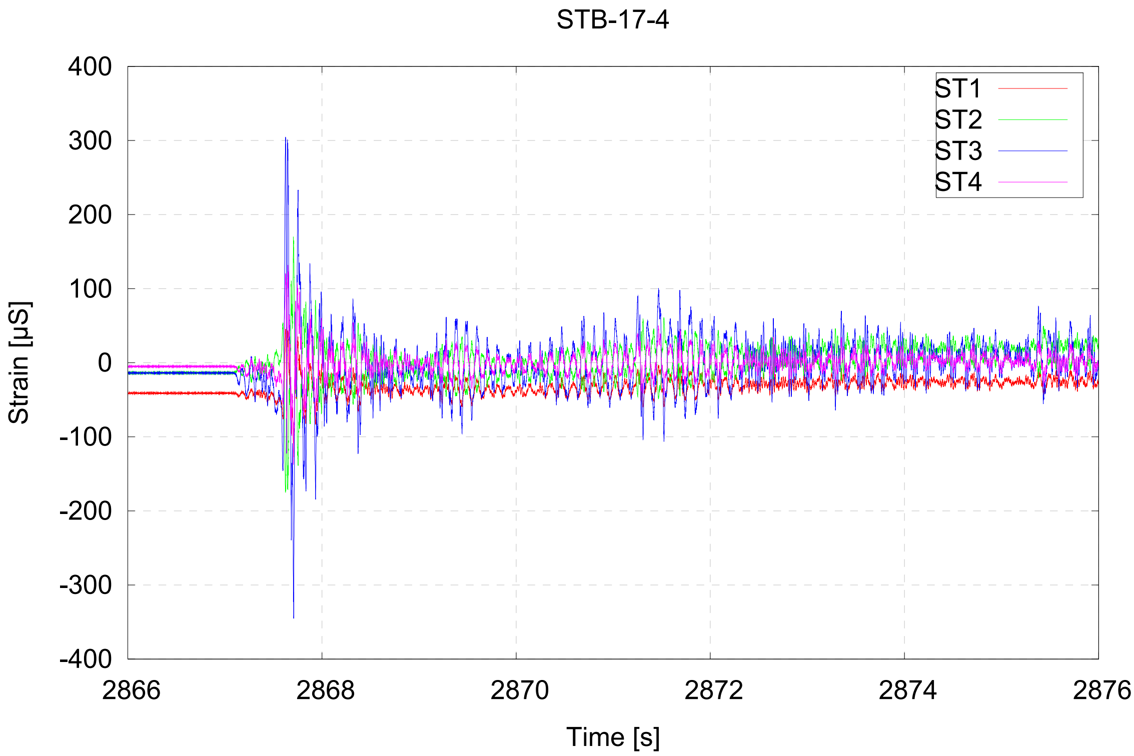


Figure 27. Strains in STB-17-4 between 2866...2876 s. The steam blowdown was initiated at 2867 s.

7 SUMMARY AND CONCLUSIONS

Total of five experiment series were carried out to test steam injection into a large water pool with a scaled down test facility designed and constructed at Lappeenranta University of Technology. The initial system pressure of the steam source (the nearby PACTEL facility) before the blowdown ranged from 0.3 MPa to 3.0 MPa. Pool water bulk temperature varied from 11°C to 76°C. The experiments were performed using a DN200 (∅219.1x2.5) blowdown pipe. During the experiments the data acquisition system recorded data with a frequency of 10 kHz. A digital high-speed video camera was used for accurate observation of steam bubbles during the tests.

During the experiments three different condensation modes were observed; condensation inside the blowdown pipe, chugging and condensation oscillations. Which one of these condensation modes was dominating, was determined by the pool water temperature and steam mass flow.

With cold water and low steam mass flow, the steam condensated already inside the blowdown pipe. As the steam condensed rapidly, an underpressure developed inside the blowdown pipe. Sometimes the underpressure phase lasted even for 0.5 seconds. After that, a condensation-induced water hammer developed inside the blowdown pipe. As a result, the pressure transducers registered high pressure pulses inside the blowdown pipe. The highest registered pulse was 3.9 MPa. Because steam condensed mainly within the blowdown pipe, neither the pressure transducer on the pool bottom nor the strain gauges on the pool outer wall measured high loads.

As the pool water temperature and/or steam flow got higher, transition to chugging mode took place. In this mode, steam flow pushed steam-water interface downwards inside the blowdown pipe and a steam bubble formed at the pipe outlet. The bubble condensed rapidly and the pressure value dropped below atmospheric pressure. Steam-water interface moved upwards inside the blowdown pipe until steam pressure was high enough to stop the interface and push it downwards again. Chugging phenomenon caused dynamic loads to the pool structures. Both the strain gauges on the pool outer wall and the pressure transducer on the pool bottom registered oscillations with a frequency of 10 Hz. According to strain gauge measurements and computer analysis (performed by VTT Processes and VTT Industrial Systems), the maximum von Mises stress amplitude at the pool bottom rounding was approximately 140 MPa. The mean stress value due to hydrostatic load of water in the tests was approximately 130 MPa. Thus, the maximum von Mises stress could have been even 270 MPa. This kind of stress causes plastic deformation. The maximum pressure pulses on the pool bottom and inside the blowdown pipe were 40 kPa and 1.3 MPa, respectively.

Further increase of steam flow caused a transition to condensation oscillations mode. In this mode, steam-water interface underwent a condensation event totally in the pool. A steam bubble formed at the pipe outlet and began to collapse. The high steam flow rate prevented water re-entry into the blowdown pipe. The next bubble was formed after the condensation event and the cycle was repeated. Also condensation oscillations mode caused dynamic loads to the pool structures. The maximum von Mises stress amplitude at the pool bottom rounding was approximately 80 MPa. The maximum pressure pulses on the pool bottom and inside the blowdown pipe were 30 kPa and 0.6 MPa, respectively.

When the steam generator initial pressure was raised up to 1.0 MPa…3.0 MPa water plugs hit strongly to the pool bottom after initiating the blowdowns. This caused notable loads to the pool structures. The maximum von Mises stress amplitude at the pool bottom rounding was even 200 MPa and the maximum pressure pulse on the pool bottom 390 kPa.

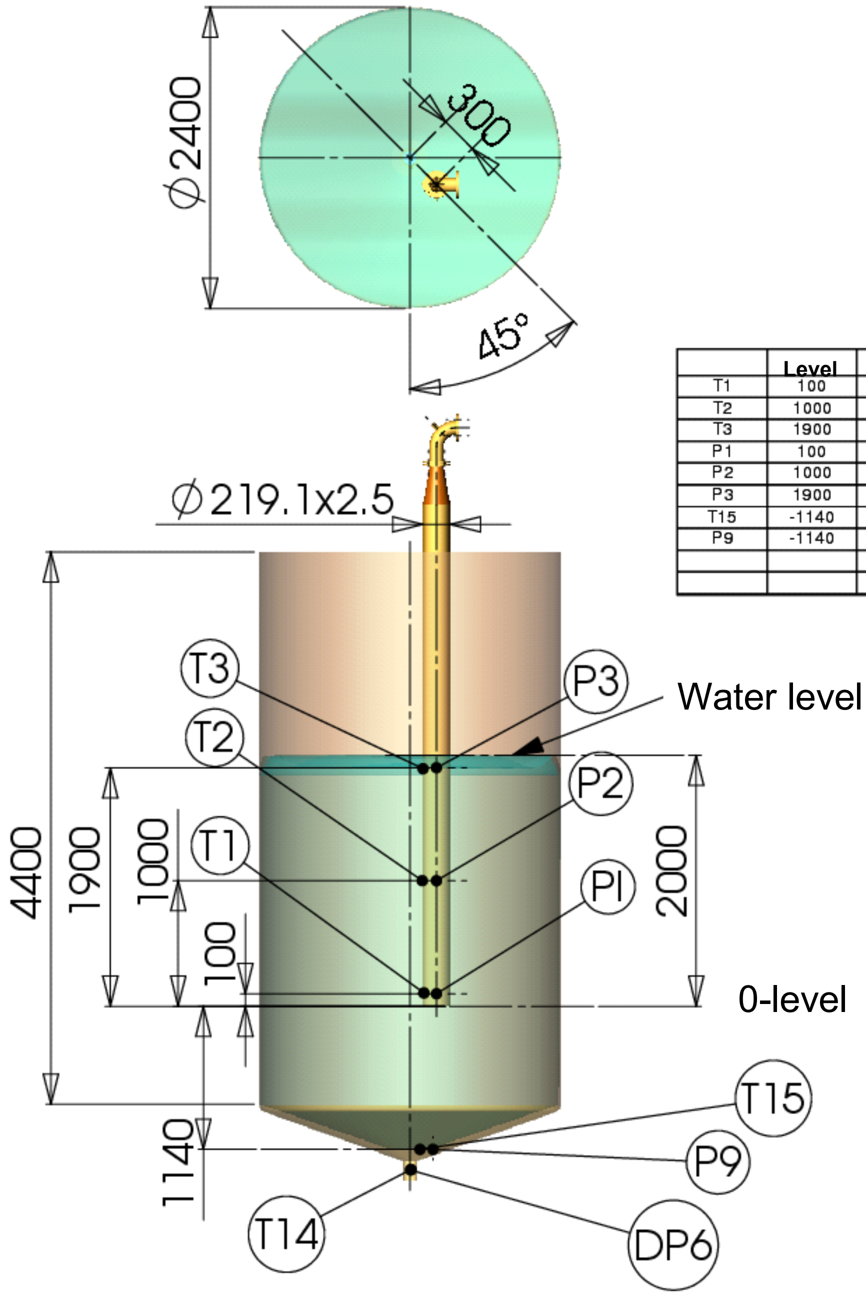
The next step in the POOLEX project is to execute thermal stratification tests in the spring of 2005. In these tests, temperature stratification of the pool water during steam discharge will be studied. The test situation corresponds for example to the later phase of a LBLOCA in a BWR condensation pool. Before the tests can be performed, more instrumentation (thermocouples) will be added to the test rig. Later in 2005, more detailed experiments on chugging and experiments with two blowdown pipes are planned.

8 REFERENCES

1. Laine, J., Condensation Pool Experiments with Non-condensable Gas. Lappeenranta University of Technology. 2002. Research Report TOKE-2/2002.

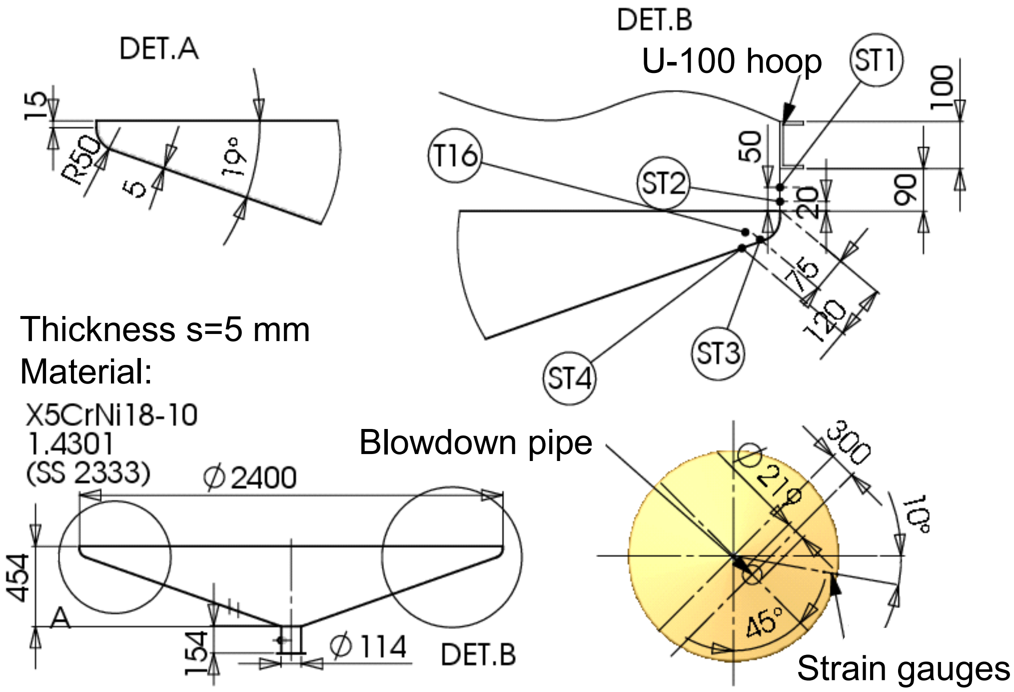
2. Laine, J., Puustinen, M., Preliminary Condensation Pool Experiments with Steam Using DN80 and DN100 Blowdown Pipes. Lappeenranta University of Technology. 2003. Research Report POOLEX 4/2003.
3. Laine, J., Puustinen M., Preliminary Condensation Pool Experiments with Steam Using DN200 Blowdown Pipes. Lappeenranta University of Technology. 2004. Research Report POOLEX 1/2004.
4. Lahey, R. T., Moody, F. J., The Thermal-Hydraulics of a Boiling Water Reactor. American Nuclear Society, Illinois. 2nd edition. 1993.
5. http://www.citiusimaging.com
6. Puustinen, M., Test plan for detailed condensation pool experiments with DN200 blowdown pipe in 2004. Lappeenranta University of Technology. 2004. Technical Report POOLEX 3/2004.
7. Tuunanen, J., Kouhia, J., Purhonen, H., Riikonen, V., Puustinen, M., Semken, R. S., Partanen, H., Saure, I., Pylkkö, H., General description of the PACTEL test facility. Espoo: VTT. 1998. VTT Research Notes 1929. ISBN 951-38-5338-1.
8. Standards: SFS-EN 10088-1 and SFS-EN 10088-2, 1995.
9. Timperi, A., Pättikangas, T., Calonius, K., Tuunanen, J. Poikolainen, J., Saarenheimo, A., Numerical Analyses of a Water Pool under Loadings Caused by a Condensation Induced Water Hammer. Espoo: VTT. 2004. Research Report BTUO72-031198.

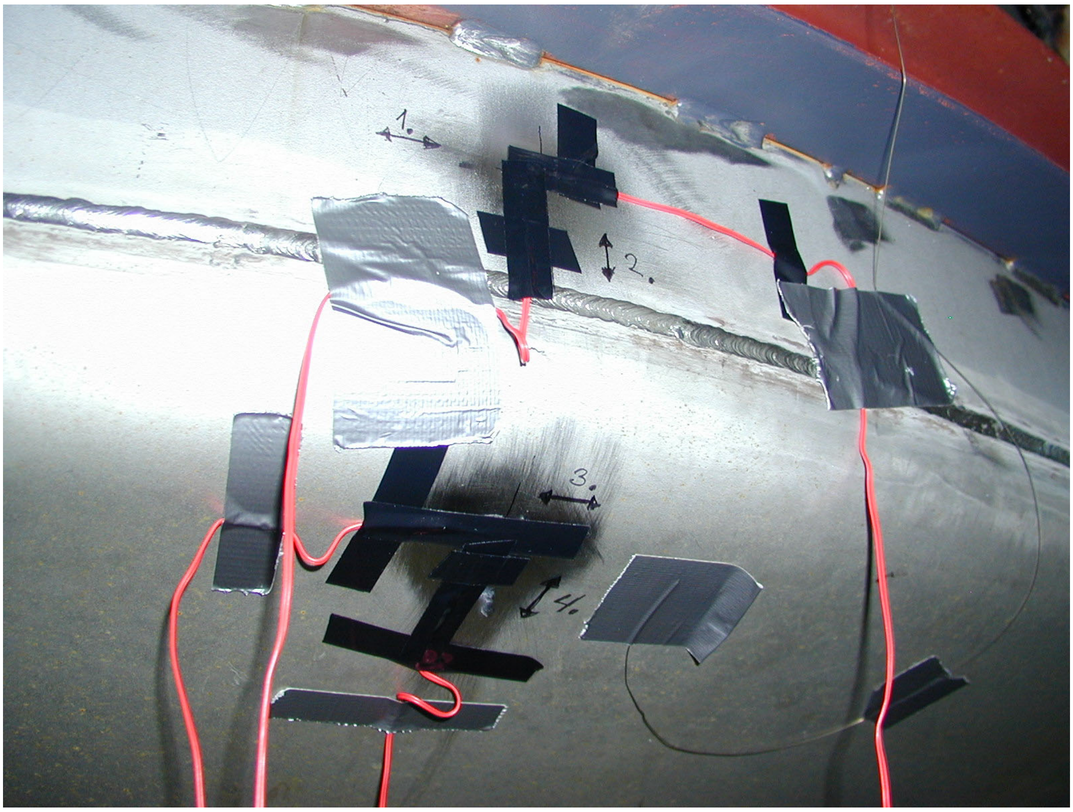
APPENDIX 1. INSRUMENTATION OF THE POOLEX TEST RIG



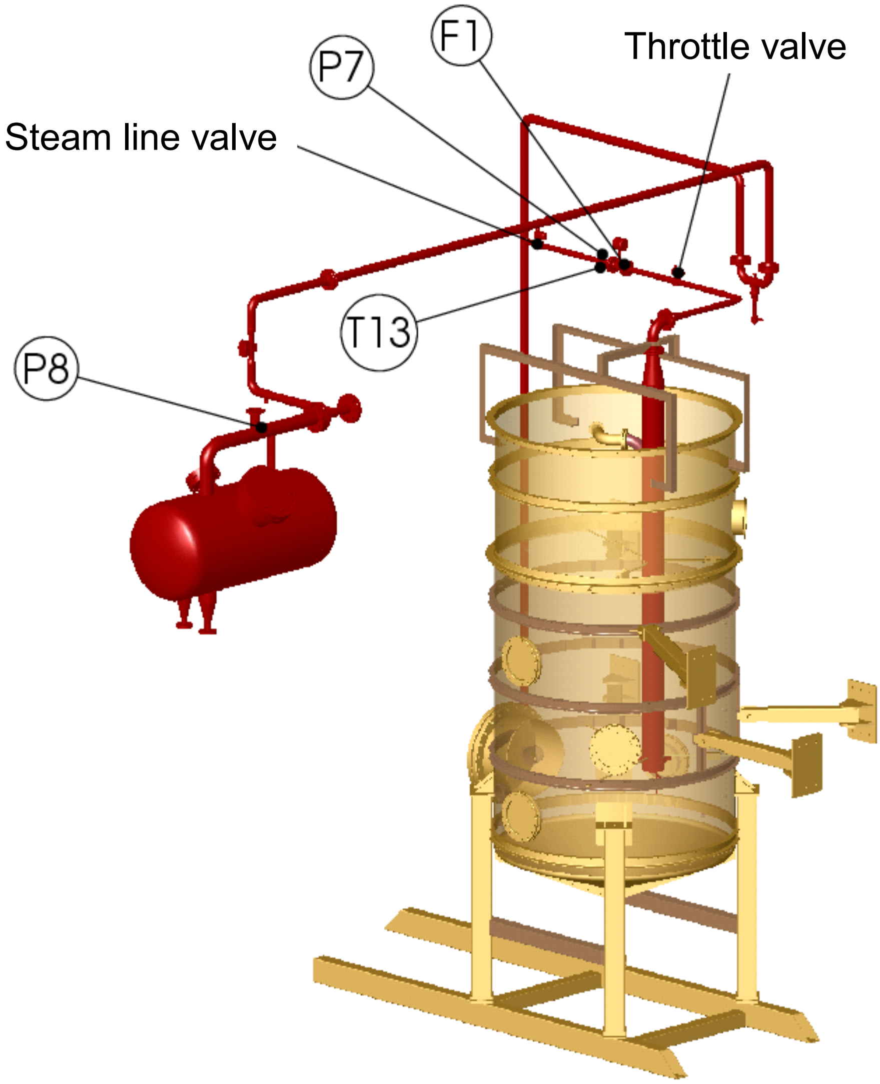
	Level	
T1	100	
T2	1000	
T3	1900	
P1	100	
P2	1000	
P3	1900	
T15	-1140	
P9	-1140	

Instrumentation inside the blowdown pipe and on the pool bottom



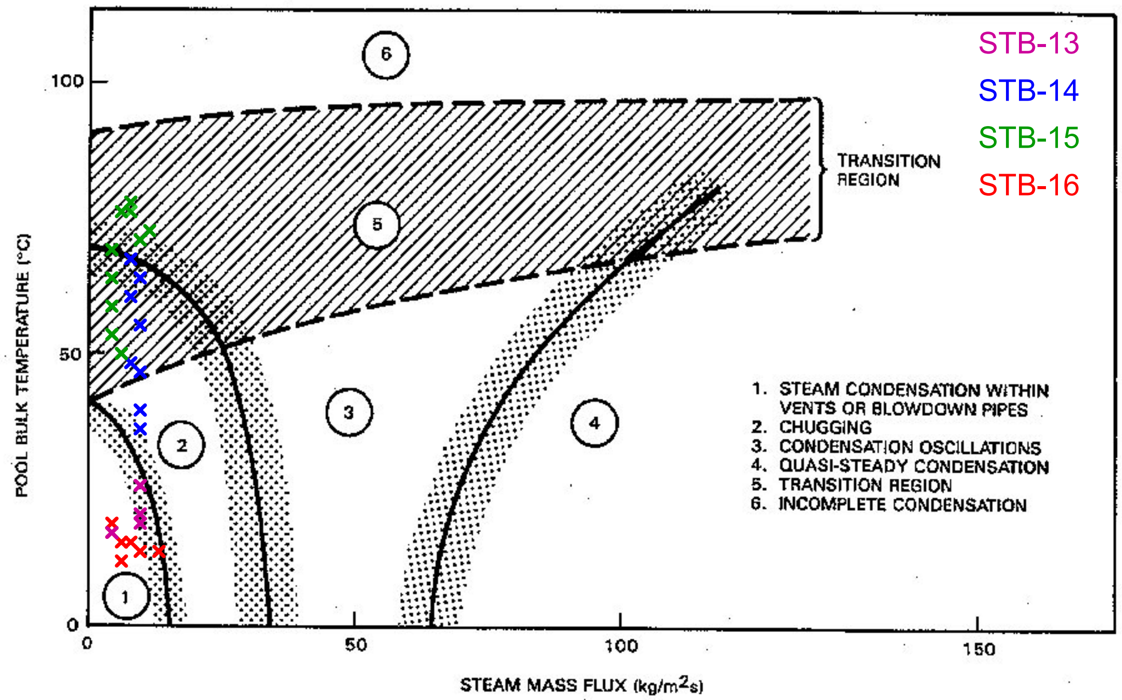


Strain gauges on the outer wall of the pool



Flow rate, temperature and pressure of steam

APPENDIX 2. CONDENSATION MODE MAP



Condensation mode map for pure steam discharge [4]. Crosses of different colors illustrate separate blowdowns during STB-13, STB-14, STB-15 and STB-16.

Bibliographic Data Sheet **NKS-111**

Title	Condensation Pool Experiments with Steam Using DN200 Blowdown Pipe
Author(s)	J. Laine & M. Puustinen
Affiliation(s)	Lappeenranta University of Technology, Finland
ISBN	87-7893-171-1 *Electronic report*
Date	August 2005
Project	NKS_R_2002_01
No. of pages	41 p. + app. 4 p.
No. of tables	14
No. of illustrations	27
No. of references	9
Abstract	This report summarizes the results of the condensation pool experiments with steam using a DN200 blowdown pipe. Altogether five experiment series, each consisting of several steam blows, were carried out in December 2004 with a scaled-down test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the experiments was to increase the understanding of different phenomena in the condensation pool during steam discharge.
Key words	Experiments, condensation, blowdown, steam, chugging

Available on request from the NKS Secretariat, P.O.Box 49, DK-4000 Roskilde, Denmark.
Phone (+45) 4677 4045, fax (+45) 4677 4046, e-mail nks@nks.org, www.nks.org