



WGAMA PERSEO

Benchmark Results Report

**NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS**

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Foreword and acknowledgements

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All figures that do not include obvious source information were created for the activity of the benchmark. The source in these cases is “NEA data, 2021”.

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List of abbreviations

AA	Averaged amplitude
Apros	Advanced process simulation environment
ATHLET	Analysis of thermal hydraulics of leaks and transients
BWR	Boiling water reactor
CAMP	Code applications and maintenance programme
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (Alternative Energies and Atomic Energy Commission, France)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
CV	Control volume
CVH	Control volume hydrodynamics
DHR	Decay Heat Removal
DP	Differential pressure
ENEA	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy)
FDI	Fuel dispersal interactions
FFTBM	Fast Fourier transform based method
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (German nuclear safety organisation)
HS	Heat structure
HTC	Heat transfer coefficient
HX	Heat exchanger
HXP	Heat exchanger pool
IBRAE	Nuclear Safety Institute of the Russian Academy of Sciences
IC	Isolation condenser
ICAP	International code assessment and applications programme
INEL	Idaho National Engineering Laboratory
INL	Idaho National Laboratory
ISP	International standard problem
ITF	Integral test facilities
ITF CCVM	ITF computer code validation matrix
GEST	Generator separator test
KAERI	Korea Atomic Energy Research Institute
LOCA	Loss-of-coolant accidents
LWR	Light water reactors
MARS	Multidimensional analysis of reactor safety
NEA	Nuclear Energy Agency
NRG	Nuclear research and consultancy group
OP	Overall pool
PANTHERS	Performance analysis and testing of heat removal systems
PERSEO	In-pool energy removal system for emergency operation
PhW	Phenomenological window
POLITO	Politecnico di Torino
PRHR	Passive residual heat removal system
PV	Pressure vessel
PWR	Pressurised water reactor
RELAP	Reactor excursion and leak analysis programme
RPV	Reactor pressure vessel

SBWR	Simplified boiling water reactor
SETF	Separate effect test facility
SG	Steam generator
SIET	Società Informazioni Esperienze Termoidrauliche
SNAP	Symbolic nuclear analysis package
SOCRAT	System of codes for realistic assessment of severe accidents
SPACE	Safety and performance analysis code for nuclear power plants
SPECTRA	Sophisticated plant evaluation code for thermal-hydraulic response assessment
SPES	Simulatore pressurizzato per esperienze di sicurezza (Pressurised simulator for safety experiments)
SPV	Steam pressure vessel
TDV	Time-dependent volume
TF	Thermo-fluid
TFD	Thermo-fluid dynamics
TRACE	TRAC/RELAP advanced computational engine
UJV	ÚJV Řež, a. s.
UNIPi	Università di Pisa
UNIROMA1	Università di Roma “Sapienza”
UofU	University of Utah
US NRC	US Nuclear Regulatory Commission
VTT	Technical Research Centre of Finland
VVER	Water-cooled water moderator energy reactor (Russian design)
WF	Weighted frequency
WGAMA	Working Group on Analysis and Management of Accidents (NEA)

Executive summary

In the framework of the Nuclear Energy Agency (NEA) Working Group on Analysis and Management of Accidents (WGAMA), an activity on the design and safety assessment of thermal-hydraulic passive systems was conducted and a status report was drafted. Within this activity, an open benchmark exercise was carried out, hosted by ENEA and based on the experimental data developed in PERSEO, a full-scale component separate effect test facility for in-pool energy removal systems for emergency operations.

PERSEO was built at SIET laboratory (Piacenza, Italy) to study a new passive decay heat removal system operating in natural circulation. The main innovation in PERSEO is the presence of two pools connected by a line with a triggering valve. In this way it is possible to fill the pool where the emergency heat exchanger is located only when it is needed for safety reasons by using the water stored in a second separate pool. The operating parameters of PERSEO are characteristic of a generic boiling water reactor (BWR) type reactor or the secondary side of a generic pressurised water reactor (PWR) type reactor. Among the four actual tests performed in PERSEO, Test 7 was chosen for the benchmark activity for its completeness. The test is at full pressure (70 bar) and aims to verify the system stability with different water pool levels and the long-term cooling capability of the system.

Taking into account previous code applications on PERSEO tests, the main benchmark objective is to evaluate the capability of the adopted codes in the prediction of the heat transfer in a full-scale heat exchanger submerged in a liquid pool (both tube side and pool side). Moreover, it analysed the capability of the codes to evaluate the coupling processes between the two pools in the PERSEO system, connected in a two-phase natural circulation circuit, and the phenomena occurring in the pools themselves (e.g. thermal stratification, natural convection). The goal of the benchmark is also to characterise the user effect to predict the heat exchanger heat transfer (e.g. tuning of the heat transfer hydraulic diameter, tuning of fouling factors multiplier) and to test the code-user nodalisation strategies to model the phenomena taking place in large pools (e.g. 1D nodalisation, 2D fictitious nodalisation, 3D nodalisation if available in the adopted code).

The evaluation of the capability of the adopted codes was performed considering both a qualitative and a quantitative accuracy analysis. For both parts of Test 7, there are three phenomenological windows and for each window the relevant thermal-hydraulic aspects were identified in the transient. The fast Fourier transform based method (FFTBM) was used to evaluate quantitatively the accuracy of the simulations performed with the codes.

In general, it was found that almost all the adopted codes are qualitatively able to predict the phenomena that occurred in PERSEO Test 7. However, some qualitative and quantitative discrepancies with respect to the experimental data were found. The main limitation, observed in almost all the adopted codes, is the significant underestimation of the heat transfer between the heat exchanger and the pool. This was attributed by most of the participants to the underestimation of the tube side condensation heat transfer coefficient, and in some cases, also to the underestimation of the nucleate boiling heat transfer coefficient on the pool side. With the exception of the Nuclear Safety Institute of the Russian Academy of Sciences IBRAE, which adopted the SOCRAT code, the United States Nuclear Regulatory Commission (US NRC), which adopted the TRACE code, and Finland's Technical Research Centre VTT, which adopted the Apros code, all the other participants decided to modify the code or the nodalisation to correctly predict the heat transfer:

- GRS (ATHLET) used a developer version of ATHLET introducing Nusselt correlation (for laminar condensation), Kutateladze correlation (for laminar wavy condensation) and Chen correlation (for turbulent condensation);
- KAERI_a (MARS), KAERI_b (SPACE), POLITO (RELAP5-3D), UJV (RELAP5), UNIPI (RELAP5) and UNIROMA1 (RELAP5-3D) multiplied the heat transfer coefficient by a factor ranging from 2.2 to 3.0;
- NRG (SPECTRA) set the characteristic length for the film condensation to 5 cm, corresponding to a multiplier of 2.44 for the heat transfer coefficient;
- UofU (MELCOR) modified several sensitivity coefficients in the heat structure package and set a multiplier of 180 instead of 120 for the number of tubes.

This was possible thanks to the “open” nature of the benchmark, with the experimental data distributed to the participants before the beginning of the calculation phase. Therefore, an accurate evaluation of the validation domain and of the related scaling issues is fundamental for the application of the codes in the simulation of full-scale passive systems and a precondition for any reliability assessment of passive systems on the basis of these codes.

The other phenomenon which presented a significant difficulty is the prediction of the thermal stratification in the pools. However, it should be mentioned that in PERSEO Test 7 the thermal stratification is present mainly at the beginning and at the end of the transient when the passive system is not in operation; therefore, the missing prediction of the thermal stratification did not prevent a correct prediction of the behaviour of the passive system during the operation phase.

Considering the nodalisation strategy for the pools, the majority of the participants adopted a fictitious 2D nodalisation for the pools: two vertical hydraulic regions laterally connected through cross-flow junctions. This approach resulted in a more accurate prediction of the main phenomena occurring in the pools in PERSEO Test 7.

Considering previous related activities, and in particular the *State-of-The-Art Report on Scaling in System Thermal-Hydraulics Applications to Nuclear Reactor Safety and Design*, developed in the framework of the WGAMA (NEA, 2017^[8]), the PERSEO benchmark activity supports and highlights some of the recommendations consolidated in that report. In particular:

- The database of the existing SETF and ITF computer code validation matrix (CCVM) should be extended to include advanced reactors using passive safety systems.
- There is the need for well-instrumented tests for validating CFD for water-cooled reactors in relation to mixing problems, such as mixing with buoyancy effects in some passive systems (e.g. large pools of liquid as in the case of PERSEO).
- Full-height scaling and suitable flow areas (and volume size) are recommended for experimental simulation of passive systems where the important phenomena are the boiling and condensation processes and the buoyancy effect due to density change. Full height will provide an accurate characterisation of phenomena such as natural circulation and related stability.
- Systematically revisiting the scalability of system codes at the basic level of each closure law may be a good practice to improve the understanding of code scaling uncertainty and to improve the code’s documentation.

Considering the analysis of the results, the main lessons learnt in the present benchmark and the discussion in the third meeting of the WGAMA task group on thermal-hydraulic passive systems' design and safety assessment in water-cooled reactors (in Tirrenia, Italy, on 11-13 December 2019), the authors suggest as possible future research activities:

- Proposal 1: To analyse in detail the condensation heat transfer coefficient and direct contact condensation (namely downstream of the injector/sparger location with or without specific correlation) used by the various participants.
- Proposal 2: To make uncertainty and sensitivity analyses of Test 7 Part 2.
- Proposal 3: To evaluate whether 3D modelling leads to tangible improvements in comparison with experimental data.
- Proposal 4: To check the qualification of any procedure used to analyse the current tests at different pressures, or even using any other test conditions (using experimental data already available by ENEA).

1. Introduction and benchmark objectives

1.1. Benchmark history

In the framework of the Working Group on Analysis and Management of Accidents (WGAMA) of the Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI), an activity on the design and safety assessment of thermal-hydraulic passive systems was conducted and a status report was drafted. This activity included a benchmark exercise based on the experimental data developed in PERSEO, a full-scale, in-pool separate effect test facility for energy removal systems for emergency operation. The PERSEO benchmark was proposed by the Italian National Agency for New Technologies, Energy and Sustainable Development (ENEA) at the kick-off meeting of the group of experts for passive systems (Pisa, Italy, on 13-14 February 2018)¹. After approval by the working group, ENEA distributed the facility description report on 28 March 2018. ENEA, as approved by the working group at the kick-off meeting, also started an official benchmark call to other potentially interested benchmark participants at the end of March 2018. New participants who were not originally involved in the working group joined the benchmark. ENEA distributed the test data and description report on 4 June 2018. At the first passive systems group meeting (Karlstein, Germany, on 26-27 June 2018), ENEA presented the facility and Test 7 description, the preliminary results report outline, and the accuracy evaluation method for discussion. ENEA also proposed the time schedule (delivery of the results by 31 October 2018, with a possible discussion for an extension) and the parameters for the comparative analysis of the benchmark. On 2 July 2018, ENEA distributed the revised Test 7 report, the template for the participant description of the calculated results and the spreadsheet for the collection of the results. During the calculation phase some questions and answers were exchanged between ENEA and the participants and they are collected in Annex 2. At the second passive system group meeting (Tirrenia, Italy, on 27 February-1 March 2019), ENEA presented the current results and a first collective discussion of the comparative analysis took place. The participants showed their results and ENEA presented a preliminary fast Fourier transform based method (FFTBM) analysis and discussed with the participants the parameters and the related weighting factors to be selected for the final quantitative accuracy evaluation. The original deadline for submitting the final results was fixed for 31 March 2019 and the draft report was distributed to the participants on 13 July 2019. After the presentation of the activity at the 22nd WGAMA plenary meeting (16-19 September 2019), the Technical Research Centre of Finland (VTT) requested to join the benchmark. Considering some late submissions and the participants' interest in the activity, ENEA gave the possibility to update the report. The VTT participation and the late submissions were presented and approved at the last working group meeting (Tirrenia, Italy, on 11-13 December 2019). A new deadline (10 January 2020) was proposed and accepted at the same meeting. Nineteen organisations worldwide expressed interest in participating in the benchmark. Twelve

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1. Before the kick-off meeting a short questionnaire was distributed to the participants by UNIPI. Two of the questions were:

“Can your institution make available experimental data about passive systems? If yes, provide details about data and related qualification”.

“Is your institution interested in performing new analyses by numerical codes (e.g. system thermal hydraulic or CFD), eventually making use of experimental data made available by other institutions? If yes, a) inform whether your institution can write a “comparison report” including data of all participants in the activity; b) provide details about code of interest, etc.”

results from eleven organisations were submitted and eight organisations withdrew from the benchmark. POLITO supported ENEA during the benchmark activity.

1.2. Introduction to the PERSEO facility and selected test

PERSEO is a full-scale facility aimed at studying a new passive decay heat removal system operating in natural circulation. It was built at SIET laboratories in Piacenza (Italy) modifying the existing PANTHERS IC-PCC facility (Ferri, Achilli and Gandolfi, 2002^[1]). The operating parameters are characteristic of a generic BWR-type reactor or the secondary side of a generic PWR-type reactor. Such design does not include the presence of valves on the primary circuit.

PERSEO equipment was not designed to simulate a specific passive system of a particular reactor design (as it happened in the SPES and PANTHERS facilities, for example). Its main purpose is the assessment of the performance and the efficiency of a new in-pool heat exchanger configuration for decay heat removal, implementing natural circulation. In fact, the facility was conceived as an evolution of a previous CEA-ENEA proposal (thermal valve device (Ferri, Achilli and Gandolfi, 2002^[1]) (Bandini et al., 2011^[2]) (Ferri et al., 2005^[3])) which moved the SBWR-IC primary side drain line valve to the low pressure pool side. In this system proposal, the modality to start the operation of the system has been changed (now the HX pool starts empty) and therefore the dimensions of the pool have also been changed. For this, it represents well the physical phenomena in a real time scale.

There is no direct scaling relation between PERSEO and the PRHR of the AP-600, the IC of the SBWR or other designs. However, while the two pools' configuration is specific of the PERSEO design, the heat transfer data developed in PERSEO facility could be useful for the generic assessment of system codes for the full-scale heat transfer phenomena in HX in pool (tube side and pool side) of passive systems.

The main innovation in the PERSEO facility is the presence of two pools connected by a line with a triggering valve. In this way it is possible to fill the pool where the heat exchanger is located only when it is needed for safety reasons by using the water stored in a second separate pool that could be placed also outside the containment (in this case it should also be verified that the pressure drop in the steam line connecting the HXP and the OP does not excessively limit the natural circulation between the two pools).

The PERSEO experimental campaign was carried out at SIET in October and November 2002. Five shake-down tests were performed to characterise the main parameters of the facility and to verify the correct functioning of all the equipment (e.g. water pour-off from the OP and the HXP, structural integrity, pressurisation and heat-up of the pressure vessel). After that, four full tests were done to characterise the thermal-hydraulic behaviour and the operation/performance of the proposed design at different conditions, during a generic transient progression, and the related stability.

Among the four actual tests performed, Test 7 was selected and proposed by ENEA to the participants for the benchmark activity for its completeness. The test is at full pressure (70 bar) and it is aimed at verifying both the system stability with different water pool levels and the long-term cooling capability of the system. The test is divided into two parts, both described in this report addressing the stability and the long-term test.

The evaluation of the benchmark results was performed considering both a qualitative and a quantitative accuracy analysis. For both parts of Test 7, three phenomenological windows, and for each window the relevant thermal-hydraulic aspects, were identified in the transient. The fast Fourier transform-based method was used to evaluate quantitatively the accuracy of the simulations performed with system codes. In this report the basics of

FFTBM are also illustrated. For the PERSEO benchmark, the tool that was used was the JSI FFTBM Add-In 2007 developed at the Jožef Stefan Institute in Slovenia (Prošek, 2007^[4]) (Prošek and Leskovar, 2015^[5]) (Prošek, D’Auria and Mavko, 2002^[6]) (Prošek, Leskovar and Mavko, 2008^[7]). The data series provided by the participants had to be no longer than 10 000 points.

1.3. Advanced reactors and the role of the PERSEO experimental campaign

Advanced reactor designs, including those using passive systems, are in general characterised by some features in common with the current generation of reactors (e.g. large scale PWRs and BWRs) and by other features typical of their design (NEA, 2017^[8]) (NEA, 1996^[9]). In relation to the features in common with current reactors, advanced designs may be characterised by a different ranking of some phenomena. In relation to the features typical of advanced designs, this determines the occurrence of new kinds of phenomena and accident scenarios that can be grouped in: a) the containment process and interactions with the RCS, b) low pressure phenomena, and c) phenomena related specifically to new system components or reactor configurations.

Considering this, further experimental investigations are necessary to characterise the thermal-hydraulic behaviours specific of advanced reactors. In general, integral test facilities (ITF) (NEA, 2017^[8]) are used to investigate a) the overall system behaviours and the related phenomena and processes; b) the interaction of two or more components; and c) the local phenomena that are typical of the overall system design target function. Separate effect test facilities (SETF) (NEA, 2017^[8]) are designed to observe phenomena in selected zones in a nuclear power plant’s system or in specific plant components and some specific process in a particular period of a given transient; the major role of SET is to provide experimental data to develop and validate the physical models and/or empirical correlations under prototypical or simulated-conditions. Considering this, the PERSEO full-scale SETF, aimed at studying a new passive decay heat removal system operating in natural circulation, produced new full-scale experimental knowledge that can be used not only to characterise the PERSEO system but also to characterise some aspects of similar systems using a heat exchanger immersed in a pool. As underlined in the recommendations of (NEA, 2017^[8]), full-height scaling and suitable flow areas (and volume size) are recommended for experimental simulation of passive systems wherein the important phenomena are the boiling and condensation processes, and buoyancy effect due to density change. Full height will provide an accurate characterisation of phenomena such as natural circulation and related stability.

Taking into account the previous considerations, though PERSEO benchmark was not proposed and approved as an independent international standard problem (ISP) (NEA, 2017^[8]) (NEA, 2000^[10]) (NEA, 2012^[11]) activity but as embedded on the design and safety assessment of thermal-hydraulic passive systems was conducted and a status report was drafted, this activity can integrate the long-term ISP international co-operation activity (wherein scaling is one of the key topics of study), giving some insights on the code modelling capability in the prediction of full-scale heat transfer and other phenomena as thermal stratification within a pool, etc. Considering the interest of the international community in advanced reactors using passive systems (e.g. small modular reactors) this has been recognised by the benchmark participants as a great opportunity to test their code capability. This fact is also strengthened by the lesson learnt from the Fukushima Daiichi Nuclear Power Plant accident and the operation of the isolation condenser (IC). The PERSEO experimental campaign gives data that can be used, in first instance, to contribute to the full-scale understanding of the heat removal capability in heat exchangers as a function of the pool water level, integrating current knowledge.

1.4. Benchmark objectives

Previous code application analyses (Ferri et al., 2005^[3]) (Ferri et al., 2012^[12]) (Bandini, Meloni and Polidori, 2009^[13]) against experimental data have shown:

- The difficulty to have an accurate quantitative estimation of the experimental exchanged power. This is mostly related to an underestimation of the in-tube condensation. This determines the difficulty of matching the experimental power removed at different HXP levels.
- Discrepancies in the prediction of system instability with a steam/cold water interface in the injector; such instability takes place when the level in the HXP is so low as to not generate enough steam to start a circulation between the two pools.
- Discrepancies in the prediction of the steam condensation in the HXP due to the income of cold water after the opening of the triggering valve.
- That by using a 1D code with 2D fictitious nodalisation (parallel channels connected by lateral junctions) a general good agreement with the experimental data can be obtained, though a calibration of the nodalisation with the experimental data is needed.

Taking into account the previous considerations, the main benchmark purpose is to evaluate the capability of various codes in the prediction of heat transfer in a full-scale emergency heat exchanger submerged in a liquid pool (both tube side² and pool side) as a function of the pool liquid level. Other parameters are available to characterise the heat exchanger behaviour as steam and condensate flow rate, HX differential pressure, HX inlet and outlet temperatures and OP and HXP bottom/middle/upper temperatures. Moreover, it can be used to analyse the capability of the codes to evaluate the coupling processes between two pools, creating a natural circulation circuit that can be characterised in the facility by the power exchanged, the pools levels and temperatures, and the differential pressure across the injector. The phenomena occurring in the pools themselves, as thermal stratification and natural convection, can be also investigated.

In relation to the user effect, the target of the benchmark is also to characterise, as much as possible considering the measurements available, the user effect to predict the overall HX heat transfer (e.g. tuning of the heat transfer hydraulic diameter, tuning of fouling factors multiplier) and to test the code-user nodalisation strategy to model the phenomena taking place in large pools (e.g. 1D nodalisation, 2D fictitious nodalisation, 3D nodalisation if available in the adopted code). As limitations, in the facility it is not possible to have local values of the condensation heat transfer coefficient and to determine the location where the transition from the laminar to the turbulent condensation regime occurs. The instrumentation for temperature measurement in the pools is not CFD-grade; however, it gives some insights on the thermal stratification.

The absolute pressure of 70 bar of the Test 7, can be considered as a prototypical generic pressure for the RPV of the BWR and the secondary side of a PWR. The geometrical dimensions of the pools and the heat exchanger and the consequent power removed (about 20 MW) could be considered also representative of a generic full-scale plant situation during a transient progression. The axial thermal stratification in large pools, though the instrumentation of the facility cannot be considered with a CFD grade, and the transversal

2. In the present document “tube-side” is equivalent to “in-tube” and it is referred to the inner side of the tube.

temperature distribution (though there are really few transversal thermocouples) could give some insight for the validation of the 3D components in system thermal-hydraulic code.

Therefore, the main phenomena target of this benchmark could be:

- System instability with a steam/cold water interface in the injector (Test 7 Part 1/PhW1, Test 7 Part 2/PhW 1). This can give insight into the steam-liquid interaction: direct contact condensation of steam in pool water phenomenon.
- Investigation of the exchanged power trend versus the HXP level in two different conditions:
 - only for boiling-off in the HXP (Test 7 Part 1 PhW2) after the closure of the triggering valve;
 - boiling-off in the HXP with the triggering valve open (coupled natural circulation between the pools) and accelerated level decrease in both pools by opening of the OP discharge valve (Test 7 Part 2 PhW2).
- Within this regard, in agreement with the SETF nature of the facility, the data can be used to assess the code correlations for direct contact condensation and pool boiling heat transfer. This could give some insight in relation to the behaviour of emergency heat exchangers and isolation condensers: tube side and pool side convection heat transfer (IAEA-TECDOC-1677, 2012^[14]).
- Another important process to be simulated is the mass transfer between the two pools when the triggering valve opens and steam flow accelerated into the OP through the injector³. This configuration is specific to the PERSEO facility but the experimental data can be used to integrate the current knowledge in relation to the steam/water interaction and two-phase flow natural circulation in a loop (in this case composed by two connected pools).
- Testing the 1D nodalisation, fictitious 2D nodalisation (require an OPEN calculation tuning), a 3D component, available in some code, against natural circulation and thermal mixing in large pool (only one hydraulic region divided in different cells, two vertical hydraulic regions laterally connected by cross-flow junctions tuned on experimental data, 3D model application). Figure of merit for these analyses could be the axial temperature profile and different (few) temperature measurements at a fixed axial elevation.
- Characterisation of the “user effect” for the simulation of heat transfers in HX submerged in a large pool and the thermal-hydraulic behaviour of large pool.

Test 7 chosen for the benchmark covers both the start-up phase and the long-term operation of the system at full pressure, so it is relevant to characterise the system’s global behaviour (Mascari et al., 2019^[15]).

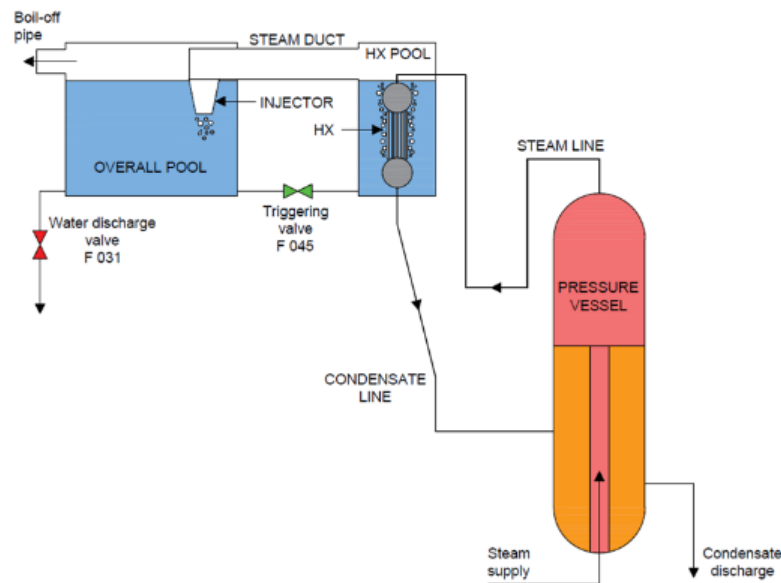
The phenomena identified for the benchmark and the related experimental measurements, necessary to characterise each of them, are reported in Section 4 (Table 4.1).

3. For the analysis of the code capability to simulate the occurring phenomenon, it would be helpful to have a measurement of the velocity downstream the injector. However, in the performed test this parameter was not measured.

2. PERSEO facility description

The PERSEO test facility was built at SIET laboratories in Piacenza (Italy) by modifying the existing PANTHERS IC-PCC facility considering the new passive system proposal and its requirements. The scheme of the PERSEO facility is depicted in Figure 2.1.

Figure 2.1. PERSEO facility scheme



Source: Mascari et al., 2019[15].

The main components of the PERSEO facility are [1]:

- The pressure vessel (43 m³ volume and 13 m height).
- The steam line from the pressure vessel to the HX upper header.
- The condensate line from the HX lower header to the pressure vessel.
- The HX (composed of two cylindrical headers and 120 vertical straight pipes). Some relevant HX geometrical data are reported in Table 2.1.
- The new heat exchanger pool (HXP) (29 m³ volume and 5.7 m height). The area of the HXP is the most important dimension for reproducing the expected prototypical physical behaviour of the proposed system. A 5.04 m² area was used, permitting prototype time-behaviour and sufficient steam/water separation at the top of pool (Ferri et al., 2005^[3]) (NEA, 2017^[8]).
- The overall pool (OP) (173 m³ volume and 5.8 m height). In this pool the old PANTHERS PCC heat exchanger is still present but not used in these tests⁴.
- The line connecting the OP and the HXP with the triggering valve.
- The steam duct connecting the two pools.

4. No information has been distributed to evaluate the influence of the remaining old PANTHERS PCC heat exchanger. This could be a source of uncertainty for the nodalisation development.

The pressure vessel is the multipurpose generator separator test (GEST) facility, available at SIET (SIET S.p.A., n.d._[16]); it is used to maintain the saturation condition typical of a generic BWR or of the secondary side of a generic PWR in the in-tube side of PERSEO facility. The GEST configuration can be changed according to the required test conditions target of the experimental campaign to be performed. The GEST facility configuration (e.g. steam separators and dryers) during the PERSEO experimental campaign is different from the previous experimental campaigns developed by SIET. It has to be underlined that the objective of the PERSEO facility is focused on the characterisation of the in-pool and in-tube heat transfer and the thermal-hydraulic coupling of the two pools during the operation of the proposed new passive system. In this way it is possible to thermal-hydraulically characterise its operating principles, behaviour and performance. Therefore, the in-tube circuit is used only to create a natural circulation loop to permit the heat transport and the consequent condensation of the steam, provided from the vessel, in the tube of the HX. Then the main target of the GEST facility for PERSEO testing is to provide the saturated steam (at the desired conditions) to be condensed during the test in the HX. Considering the general application of the system, the in-vessel circuit of PERSEO does not have any direct scaling relation with any BWR and PWR prototypical pressure drop circuit.

The pressure is kept constant by controlling the steam supply received from a nearby power plant. At the beginning of the test the HX, the feed line and the drain line are full of saturated steam; the HXP is full of air or steam depending on the test; the OP is full of cold water at the nominal level and the triggering valve is closed. To start the desired test, the triggering valve is opened and the heat exchanger pool is flooded by cold water and the heat transfer takes place from the heat exchanger to the pool. As soon as pool water boiling starts, the steam produced in the HXP is driven to the OP through the steam duct. The injector contributes to mix the water in the OP, thus limiting temperature stratification within the pool. When steam starts to be produced in the OP it is vented to the atmosphere through the boil-off pipe. When the injector is uncovered, no condensation is present anymore in the OP and the steam flows outside directly through the boil-off pipe. In some tests, water is drained from the OP to accelerate the transient phase with water level decreasing (Ferri, Achilli and Gandolfi, 2002_[1]) (Bandini et al., 2011_[2]).

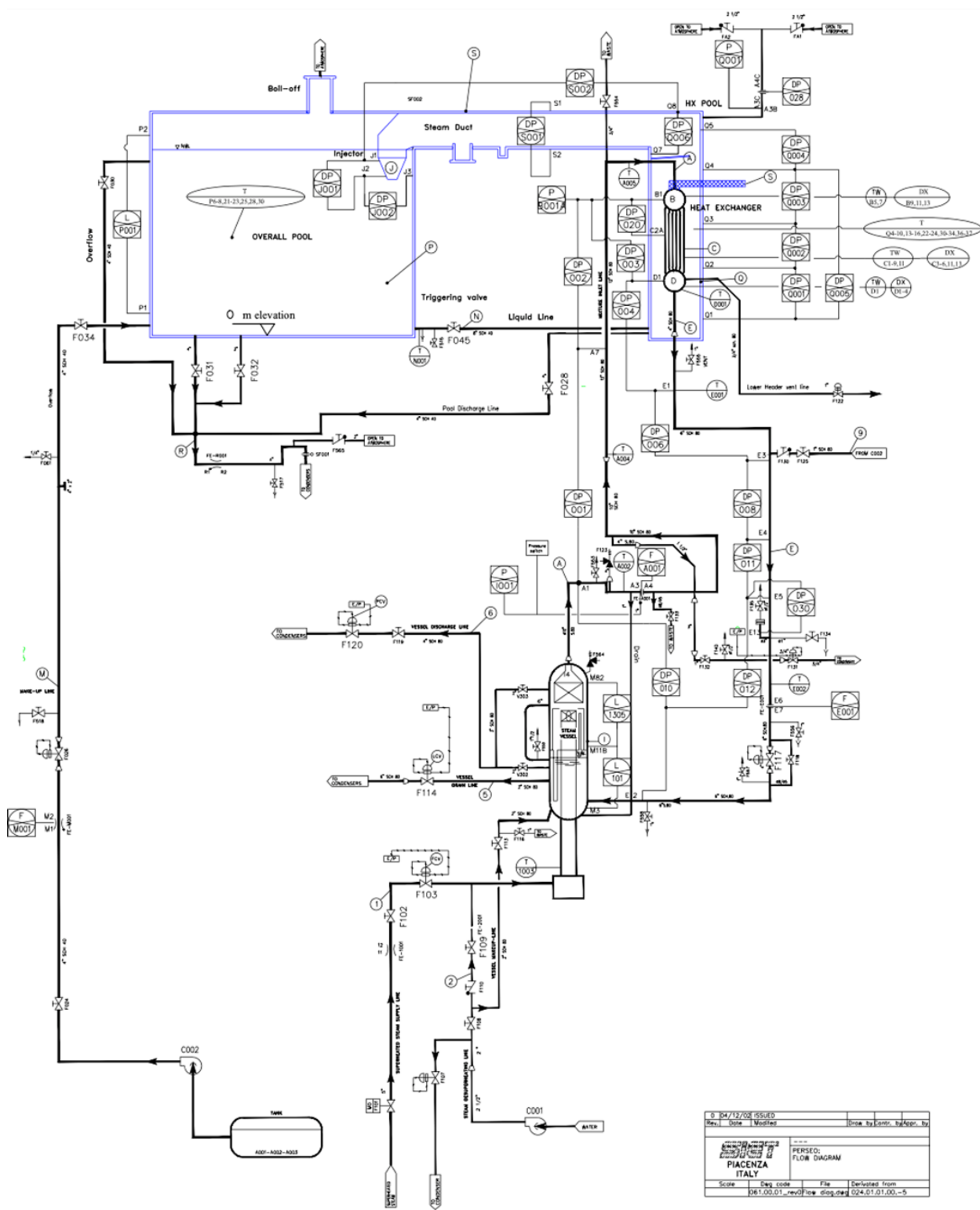
A complete description of PERSEO facility is available in reference (Ferri, Achilli and Gandolfi, 2002_[1]). Figure 2.2 shows the flow diagram of PERSEO facility. Figure 2.3 and Figure 2.4 show the dimensions and the location of the measurement instrumentation in the HXP and OP respectively. Figure 2.5 shows the geometrical details of the steam injector placed at the end of the steam duct. A list of all the measured variables (both directly measured and derived) is reported in reference (Ferri, Achilli and Gandolfi, 2002_[1]). Table 2.2 and Table 2.3 shows the list of the directly measured and derived quantities in the facility. Table 2.4 contains the materials of the main components based on the nodalisation available in ENEA (CATHARE code) and SIET (RELAP5 code).

Table 2.1. HX relevant geometrical data

HX tube outer diameter [mm]	50.8
HX tube thickness [mm]	2.3
HX tube average length [m]	1.8

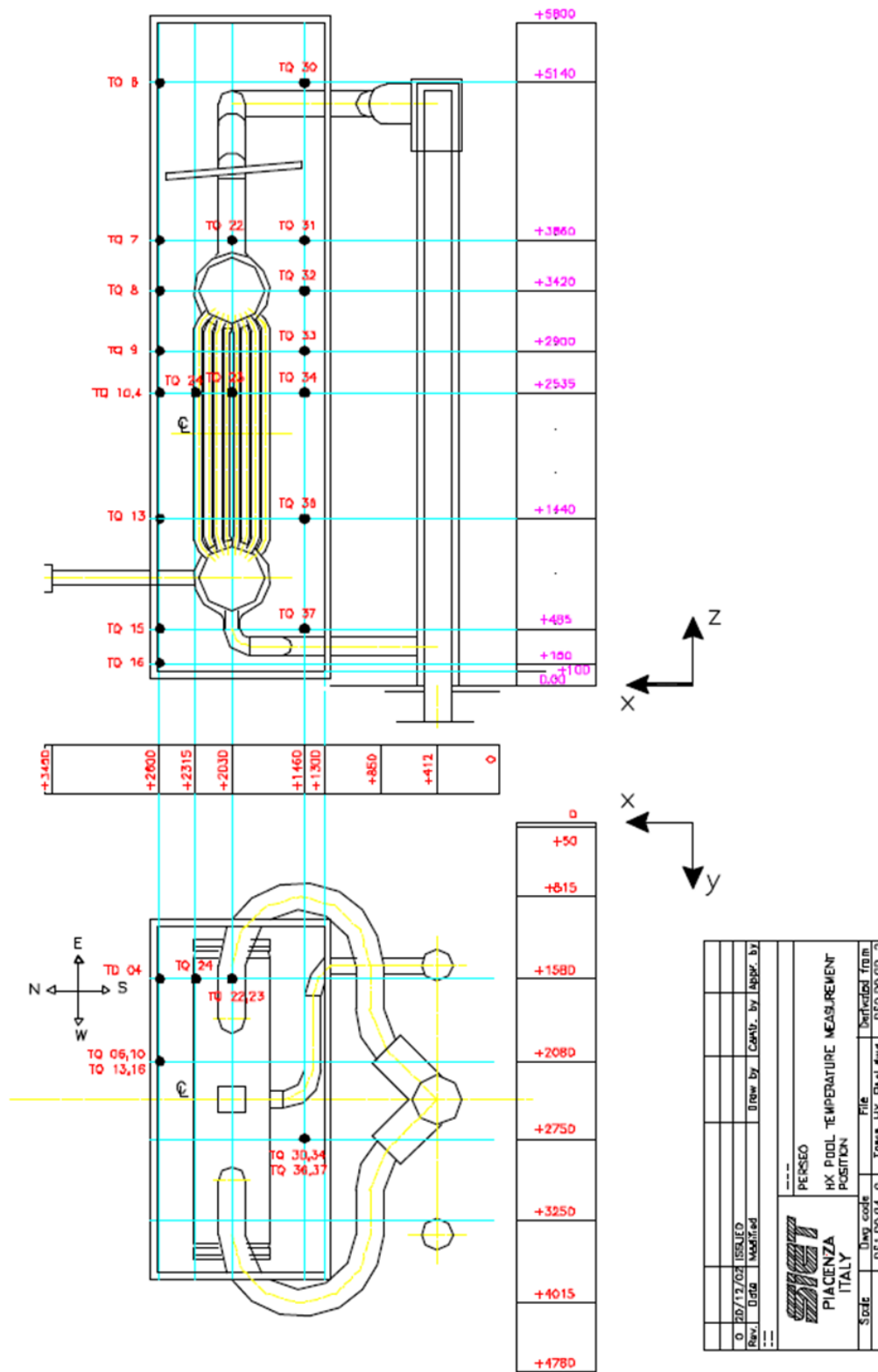
Source: Ferri, Achilli and Gandolfi, 2002_[1].

Figure 2.2. Flow diagram of PERSEO facility



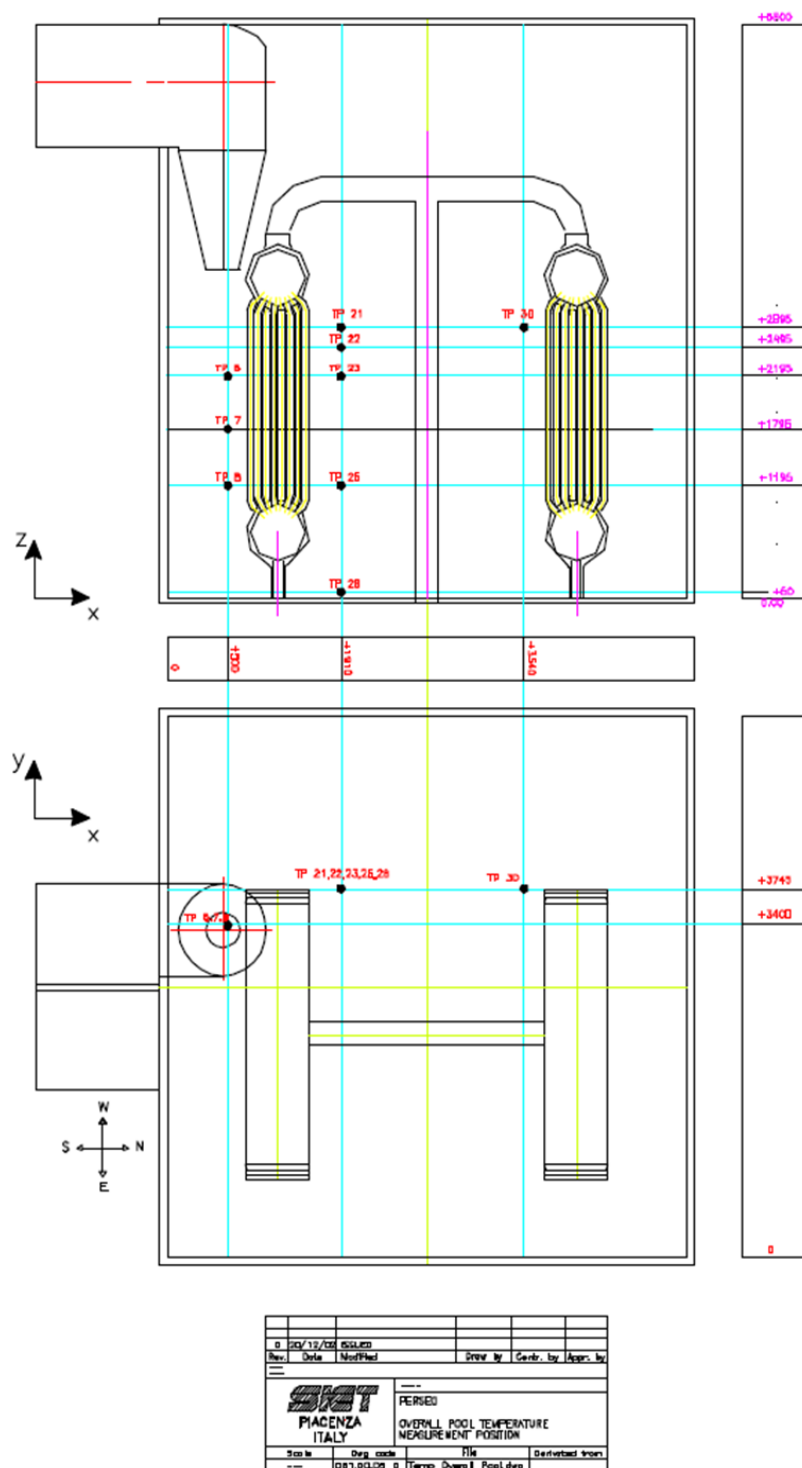
Source: Ferri, Achilli and Gandolfi, 2002[1].

Figure 2.3. Location of the temperature measurements in the HXP



Source: Ferri, Achilli and Gandolfi, 2002[1].

Figure 2.4. Location of the temperature measurements in the OP



Source: Ferri, Achilli and Gandolfi, 2002[1].

Figure 2.5. Geometrical detail of the steam injector

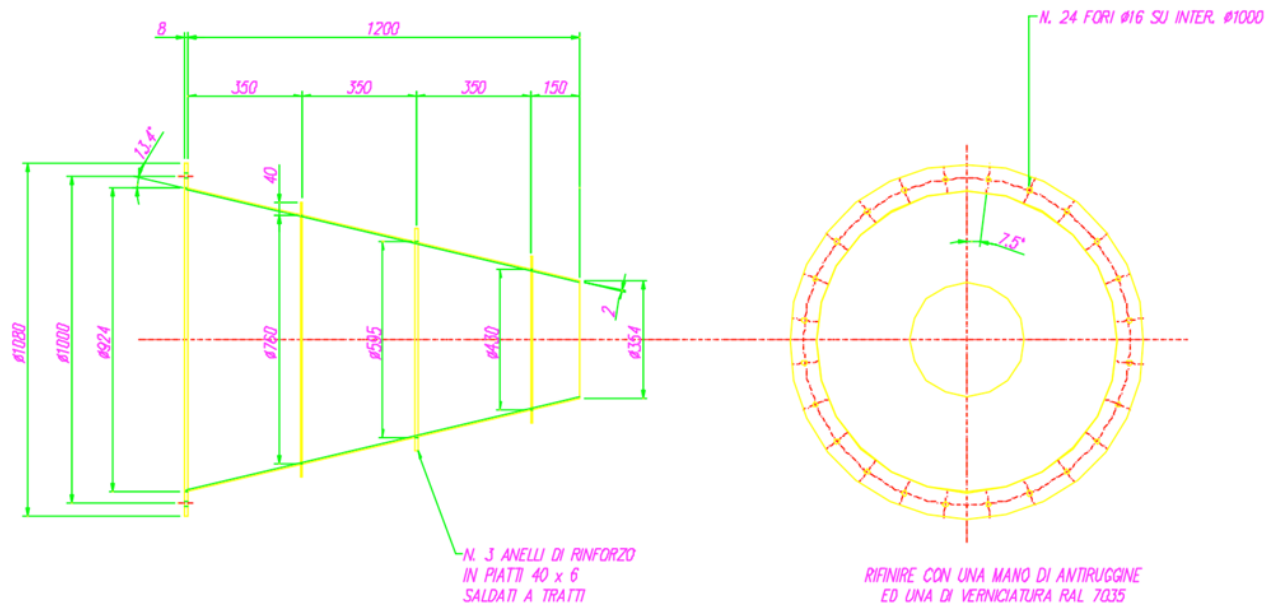


Table 2.2. List of directly measured quantities

N.	Quantity	Units	Measure	Note
1	time	s	time	
2	DP-002	kPa	Diff. pressure HX inlet - upper header	
3	DP-003	kPa	Diff. pressure HX upper header - lower header	
4	DP-004	kPa	Diff. pressure HX lower header - drain line	
5	DP-006	kPa	Diff. pressure drain line - 1	
6	DP-Q001	kPa	Diff. pressure HX pool - 1	
7	DP-Q002	kPa	Diff. pressure HX pool - 2	
8	DP-Q003	kPa	Diff. pressure HX pool - 3	
9	DP-Q004	kPa	Diff. pressure HX pool - 4	
10	DP-Q005	kPa	Diff. pressure HX pool - 5	
11	DP-Q006	kPa	Diff. pressure HX pool diaphragm	
12	F-M001	kPa	Diff. pressure pool make-up line	
13	L-P001	kPa	Diff. pressure overall pool	
14	P-B001A	kPa	Absolute pressure HX upper header	
15	F-PQ01 (or Vdc)	kPa or V		Not used
16	F-G1001	kPa		Not used
17	T-Q004	°C	Temperature HX pool	
18	T-Q023	°C	Temperature HX pool	
19	T-Q030	°C	Temperature HX pool	
20	T-Q032	°C	Temperature HX pool	
21	T-Q016	°C	Temperature HX pool	

Table 2.3. List of directly measured quantities (Continued)

N.	Quantity	Units	Measure	Note
22	T-Q007	°C	Temperature HX pool	
23	T-Q006	°C	Temperature HX pool	
24	T-Q031	°C	Temperature HX pool	
25	T-Q024	°C	Temperature HX pool	
26	T-Q009	°C	Temperature HX pool	
27	T-Q013	°C	Temperature HX pool	
28	T-Q015	°C	Temperature HX pool	
29	T-Q034	°C	Temperature HX pool	
30	T-Q036	°C	Temperature HX pool	
31	T-Q022	°C	Temperature HX pool	
32	T-Q033	°C	Temperature HX pool	
33	T-Q010	°C	Temperature HX pool	
34	T-Q008	°C	Temperature HX pool	
35	T-P006	°C	Temperature overall pool	
36	T-Q037	°C	Temperature HX pool	
37	T-P028	°C	Temperature overall pool	
38	T-P007	°C	Temperature overall pool	
39	T-P023	°C	Temperature overall pool	
40	T-P030	°C	Temperature overall pool	
41	T-P008	°C	Temperature overall pool	
42	T-P025	°C	Temperature overall pool	
43	T-P022	°C	Temperature overall pool	
44	T-P021	°C	Temperature overall pool	
45	DX-B009	m/m	Strain HX upper header	
46	DX-B010	m/m	Strain HX upper header	Not used
47	DX-B013	m/m	Strain HX upper header	
48	DX-B015	m/m	Strain HX upper header	Not used
49	DX-D001	m/m	Strain HX lower header	
50	DX-C013	m/m	Strain HX pipe	
51	DX-D003	m/m	Strain HX upper header	
52	DX-B012	m/m	Strain HX upper header	
53	DX-C003	m/m	Strain HX pipe	
54	DX-C006	m/m	Strain HX pipe	
55	DX-D004	m/m	Strain HX lower header	
56	DX-D002	m/m	Strain HX lower header	
57	DX-C005	m/m	Strain HX pipe	
58	DX-B014	m/m	Strain HX upper header	Not used
59	DX-C011	m/m	Strain HX pipe	
60	DX-C004	m/m	Strain HX pipe	
61	DX-B011	m/m	Strain HX upper header	

Table 2.4. List of directly measured quantities (Continued)

N.	Quantity	Units	Measure	Note
62	DX-B016	m/m	Strain HX upper header	
63	CJTEMP	°C		Not used
64	T-A004	°C	Temperature steam supply line	
65	T-A005	°C	Temperature HX inlet	
66	T-B001	°C		Not used
67	T-D001	°C	Temperature HX lower header	
68	T-E001	°C	Temperature drain line (HX outlet)	
69	T-N001	°C	Temperature overall pool to HX pool line	
70	TW-C004	°C	Wall temperature HX pipe	
71	TW-C002	°C	Wall temperature HX pipe	
72	TW-C005	°C	Wall temperature HX pipe	
73	TW-D001	°C	Wall temperature HX lower header	
74	TW-C003	°C	Wall temperature HX pipe	
75	TW-C001	°C	Wall temperature HX pipe	
76	TW-C011	°C	Wall temperature HX pipe	
77	TW-C006	°C	Wall temperature HX pipe	
78	TW-C008	°C	Wall temperature HX pipe	
79	TW-C007	°C	Wall temperature HX pipe	
80	TW-B007	°C	Wall temperature HX upper header	
81	TW-B005	°C	Wall temperature HX upper header	
82	TW-C009	°C	Wall temperature HX pipe	
83	TW-C010	°C	Wall temperature HX pipe	
84	TW-D002	°C	Wall temperature HX lower header	
85	TW-B008	°C	Wall temperature HX upper header	
86	TW-B006	°C	Wall temperature HX upper header	
87	DP-S002	kPa	Diff. pressure steam duct	
88	DP-S001	kPa	Diff. pressure steam duct siphon	
89	DP-J001	kPa	Diff. pressure steam duct injector	
90	DP-J002	kPa	Diff. pressure steam duct injector	
91	DP-028	kPa	Diff. pressure steam duct injector-overall pool	
92	P-Q001	kPa	Relative pressure HX pool top	
93	DP-020	kPa	Diff. pressure HX upper header - 2A tube	
94	P-I001	kPa	Absolute pressure vessel	
95	DP-008	kPa	Diff. pressure drain line - 2	
96	DP-011	kPa	Diff. pressure drain line - 3	
97	DP-012	kPa	Diff. pressure drain line - 4	
98	DP-010	kPa	Diff. pressure vessel outlet - drain line	
99	DP-001	kPa	Diff. pressure vessel outlet - HX inlet	
100	F-A001a	kPa	Diff. pressure steam supply line	

Table 2.5. List of directly measured quantities (Continued)

N.	Quantity	Units	Measure	Note
101	L-101	kPa	Diff. pressure vessel (lower)	
102	F-E001a	kPa	Diff. pressure drain line	
103	DP-030	kPa	Diff. pressure drain line vent	
104	T-A002	°C	Temperature steam supply line	
105	T-1003	°C	Temperature vessel mixer	
106	T-E002	°C	Temperature drain line	
107	L-1305	kPa	Diff. pressure vessel (upper)	

Source: Ferri, Achilli and Gandolfi, 2002[1].

Table 2.6. List of derived quantities

N.	Quantity	Units	Measure	Derived by	Note
108	L_VQ	m	Level HX pool	DP-Q005, T-Q013, T-Q015, (P = 110 kPa imposed)	
109	L_VP	m	Level overall pool	L-P001, T-P028, T-P023, T-P025, T-P021, (P = 110 kPa imposed)	
110	L_DPH	m	Level HX pool diaphragm	DP-Q006, (P = 101.3 kPa imposed)	
111	L_SPH	m	Level steam duct siphon	DP-S001, (P = 101.3 kPa imposed)	
112	F_M001	kg/s	Flowrate pool make-up line	F-M001	
113	W_I	kW			Not used
114	H-E001	kJ/kg	Enthalpy of condensate	F_E001, T-E002	
115	H-A001	kJ/kg	Enthalpy of steam	F_A001, T-A002	
116	W_IC	kW	Power heat exchanger	H-A001, F_A001, H_E001, F_E001	
117	L_101	m	Level pressure vessel (lower)	L-101, P-I001	
118	L_1305	m	Level pressure vessel (upper)	L-1305, P-I001	
119	F_A001	kg/s	Flowrate steam supply line	F-A001a, T-A002, P-I001	
120	F_E001	kg/s	Flowrate steam supply line	F-E001a, T-E002, P-I001	
121	DPsum	kPa	Primary loop diff. press. sum	DP-002, DP-003, DP-004, DP-006, DP-001, DP-008, DP-011, DP-012, DP-010	
122	F_POOL	kg/s	Flowrate Ov. pool to HX pool line	L_VQ, T-Q016	
123	F_028	kg/s	Flowrate vacuum breaker air	DP-028, (P= 100 kPa and T = 20°C imposed)	
124	DX_B009	m/m	Strain	DX-B009, TW-B005	
125	DX_B011	m/m	Strain	DX-B011, TW-B005	
126	DX_B013	m/m	Strain	DX-B013, TW-B007	
127	DX_C003	m/m	Strain	DX-C003, TW-C003	

Table 2.7. List of derived quantities (Continued)

N.	Quantity	Units	Measure	Derived by	Note
128	DX_C004	m/m	Strain	DX-C004, TW-C003	
129	DX_C005	m/m	Strain	DX-C005, TW-C004	
130	DX_C006	m/m	Strain	DX-C006, TW-C004	
131	DX_C011	m/m	Strain	DX-C011, TW-C001	
132	DX_C013	m/m	Strain	DX-C013, TW-C001	
133	DX_D001	m/m	Strain	DX-D001, TW-D001	
134	DX_D002	m/m	Strain	DX-D002, TW-D001	
135	DX_D003	m/m	Strain	DX-D003, TW-D002	
136	DX_D004	m/m	Strain	DX-D004, TW-D002	

Source: Ferri, Achilli and Gandolfi, 2002[1].

Table 2.8. PERSEO main components material

Component	Material
Heat exchanger	Inconel-600
Condensate drain line in pool	Stainless steel 316
Condensate drain line out of pool	Carbon steel
Steam line	Carbon steel
Steam line vertical final part (after T-A004)	Stainless steel 316 + Rockwool + Stainless steel 316
Steam line tubes to upper header	Stainless steel 316
Pools connection line	Carbon steel
HXP	Stainless steel 304 and outer reinforcement structure in carbon steel
OP	Fiberglass
Steam duct	Fiberglass
Injector	Stainless steel 316
Vessel	Carbon steel

PERSEO, which as previously underlined was not designed to simulate a specific passive system of a particular reactor, is a SETF-Component that has the target of the thermal-hydraulic characterisation of the operation, performance and efficiency of a new in-pool heat exchanger for DHR, implementing natural circulation. The system is an evolution of the previous CEA-ENEA proposal (thermal valve device) which moved the generic IC primary side drain line valve to the low pressure pool side.

The main innovation in PERSEO facility is the presence of two pools connected by a line with a triggering valve. In this way it is possible to fill the pool where the heat exchanger is located only when it is needed for safety reasons, by using the water stored in a second separate pool that could be placed also outside the containment (in this case it should be also verified that the pressure drop in the steam line connecting the HXP and the OP does not limit excessively the natural circulation between the two pools). This system could be used both for BWR and secondary side of PWR reactors allowing the elimination of the triggering valves on the primary side.

Considering as a reference the prototypical new system proposal, these are the main scaling characteristics of the facility:

- time preserving facility;
- full height facility;
- full volume facility;
- full pressure facility;
- prototypical fluid and fluid conditions;
- well imposed boundary condition to simulate the operation of the system but not to capture the integral feedback of the system to the reactor behaviour;
- instrumentation dedicated to characterise all the most relevant thermal-hydraulic parameters (pressure, temperature, pressure drop, flowrate, level).

Considering the prototypical system proposal, the main distortions of the facility are due to the scaling effect of the boundary condition causing a distortion on the interacting phenomena at the facility boundary. It is clear that in order to characterise the operation of the passive system the interaction/feedback from the reactor, during the transient progression, is necessary (scaled-down ITF). Therefore, to have a complete characterisation of the passive system operation are necessary ITF experiments coupled with PERSEO experiment. Considering the general application of the system, the in-vessel circuit of PERSEO does not have any direct scaling relation with any BWR and PWR prototypical pressure drop circuit.

It is important to underline, however, that the new system proposal was only at a preliminary state of design and that the layout has not been optimised for construction, operation and grace time of the reactor in an accident situation.

In relation to the data extrapolation, the data of PERSEO can be used for the full-scale characterisation of heat exchange in in-pool heat exchanger for DHR (implementing natural circulation) in relation to the in-tube and pool side, thermal stratification, natural circulation in-tube side and pool side (large pool convection) and between two coupled pools.

3. Test 7 Part 1 and 2 description

The PERSEO facility is a SETF-Component-Test (NEA, 2017_[8]) and has been designed to characterise a new in-pool heat exchanger for DHR, implementing natural circulation. Therefore, the initial conditions of the transient do not represent a classical steady state condition that can be used to assess the nodalisation in steady condition. In fact, the initial conditions of the facility represent the thermal-hydraulic condition of the prototypical passive system not in operation with the RPV in a stable pressure condition (simulating the steady state condition of the generic RPV of the BWR or the secondary side of the SG in a PWR).

In this condition the system is in the following configuration:

- HXP with a fixed water level and the remaining volume filled with air or steam depending on the test (air in Test 7 Part 1 and steam in Test 7 Part 2);
- OP filled with water;
- pressure vessel at saturation pressure (70 bar for Test 7 Part 1 and 2); this represents a hypothetical steady state condition for the vessel representing or the RPV of a generic BWR or the secondary side of a hypothetical SG;
- no mass flow rate in the steam duct connecting the two pools;
- no mass flow rate in the line connecting the HXP and the OP;
- no heat transfer between the circuit connected with the pressure vessel and therefore no fluid circulation in the pressure vessel circuit.

Considering that the operation of the system determines the decrease of the HXP, a quasi-steady-operation condition is highlighted in order to have an operational point. However, it should be considered that the identification of this quasi-steady-operation phenomenological window is only an abstraction because the facility is in a transient condition.

Pressure drop characterisation is important for any numerical simulation since it is useful to evaluate the correctness of distributed and local pressure drop modelling in the simulation. In PERSEO facility, as already mentioned, the initial conditions do not represent a classical steady state conditions (system not in operation), thus pressure drop characterisation are referred to the quasi-steady-operation phenomenological window identified (the test procedure is described more in detail afterward). Pressure drop measured in PERSEO are total one, therefore considering also the gravitational contribution.

For Test 7 Part 2 it is possible to identify in the central part of the transients a quasi-steady condition. In this temporal window (1 500–2 000 s) it is possible to compute mean pressure drops. Table 3.1 presents the average, minimum and maximum flow rate, pressure and pressure drop values for this time window.

**Table 3.1. Test 7 Part 2 quasi-steady operation condition (1 500 s–
2 000 s)**

Experimental parameter	Mean value	Maximum value	Minimum value
Flowrate steam supply line (F A001) [kg/s]	13.18	13.31	12.96
Flowrate condensate drain line (F E001) [kg/s]	12.80	13.34	12.17
Power heat exchanger (W IC) [MW]	20.10	20.85	19.08
Diff. pressure vessel outlet – HX inlet (DP-001) [kPa]	6.10	6.62	5.58
Diff. pressure HX inlet – upper header (DP-002) [kPa]	14.33	14.83	13.77
Diff. pressure HX upper header – lower header (DP-003) [kPa]	-1.20	-1.01	-1.39
Diff. pressure HX lower header – drain line (DP-004) [kPa]	-8.60	-7.22	-9.84
Diff. pressure drain line 1 (DP-006) [kPa]	-11.78	-10.68	-12.87
Diff. pressure drain line 2 (DP-008) [kPa]	-4.97	-2.96	-6.66
Diff. pressure drain line 3 (DP-011) [kPa]	-38.87	-36.26	-40.11
Diff. pressure drain line 4 (DP-012) [kPa]	10.91	11.99	9.89
Diff. pressure vessel outlet – drain line (DP-010) [kPa]	37.54	40.60	35.20
Diff. pressure HX upper header – 2A tube (DP-020) [kPa]	-0.59	-0.38	-0.82
Absolute pressure vessel (P-I001) [kPa]	7 035	7 054	7 011
Absolute pressure HX upper header (P-B001A) [kPa]	6 985	7 004	6 962
Diff. pressure steam duct injector (DP-J001) [kPa]	7.95	12.28	3.71

Among the four actual tests performed, Test 7 has been chosen for its completeness. In fact, it is a full pressure test (7 MPa) that investigates both the system stability and the long-term cooling capability (system operation) of the system itself. The test is divided into two parts:

- Part 1: stability test to verify the behaviour of the system with two different water levels. Water level increase at 1.4 m and 3.5 m in the HXP.
- Part 2: test to verify the long-term cooling capability of the system. In this part the water level reduction in the pool is accelerated by opening a dedicated valve to drain water from the OP (instead of the depletion of water due to evaporation resulting from the heat transferred in the HX).

Test 7 is devoted to investigating the following items:

- the system actuation and the trend of power removed with a low HXP level (Part 1);
- the presence of instabilities due to steam condensation at the interface between water and steam in the injector (in the OP) (Part 1 and 2);
- the system re-actuation consequent to the HXP filling-up and reaching of the thermal regime in both the pools (Part 1);
- the effectiveness of the injector in mixing the OP water (Part 1 and 2);
- the power and flow regime variation after the OP level decreases below the injector outlet (Part 2);
- the trend of power as a function of the water level in the pools, decreasing for the loss of mass through the boil-off (Part 2).

Heat losses are not measured during the test, so reference values are not available. However, considering the full-scale dimensions with respect to the prototypical passive system, the relatively high power (around 20 MW) and the low transient duration (less than 6 000 s) their effect is not expected to significantly affect the test and, therefore, the calculation results. Considering the increase and decrease of level and the consequent

power removal, the importance of the metal masses for the thermal inertia of the system must be underlined.

3.1. Test 7 Part 1

This test is characterised by three phenomenological windows:

1. 10 000 s – 11 260 s (maximum level in the HXP): Increase of level in two steps in the HXP with a consequent increase of the exchanged power. Relevant thermal-hydraulic aspects are:
 - 1) HXP level increase;
 - 2) OP level decrease;
 - 3) mass flow increase in-tube side;
 - 4) power removed increase;
 - 5) progressive covering of the HX in the pool side;
 - 6) system instability with cold water – steam interface at the injector (strong condensation shocks).
2. 11 260 s – 11 845 s (HX power around 20 MW, the ending time of the PhW is when the HX power decreases under 20 MW): Quasi-steady-operation starting from the HXP level of 3.4 m. Relevant thermal-hydraulic aspects are:
 - 1) quasi-steady power removed;
 - 2) quasi-steady flow rate in-tube side;
 - 3) initial boil-off in the HXP;
 - 4) mixing of the OP water due to the acceleration of the steam in the injector.
3. 11 845 s – 14 784 s: Boil-off in the HXP with a consequent level reduction. Therefore, reduction of power removed (no accelerated level decrease by opening of the pool discharge valve). Relevant thermal-hydraulic aspects are:
 - 1) Boil-off in the HXP;
 - 2) Reduction of HXP level;
 - 3) Increase of OP level due to steam condensation;
 - 4) Reduction of removed power;
 - 5) Reduction of flow rate in-tube side;
 - 6) Progressive uncovering of the HX in the pool side;
 - 7) Thermal stratification in the OP due to the reduction of mixing for the decrease of steam accelerated in the injector.

This test is performed at 7 MPa; the primary side pressure is shown in Figure 3.1.

After the beginning of the transient, at time 10 475 s, valve F045 begins to be opened slowly then it is completely closed at 10 608 s. At time 10 621 s a further opening is actuated and the valve is completely closed at 10 655 s. This sequence of F045 valve opening and closure represents the first phase of water injection. The injection water flowrate between the pools (derived by the HXP level) for the first phase of injection is reported in figure 3.2 (Water level increase 1.1). Initially the HXP contains superheated air; the HXP level begins to increase at time 10 483 s and at about 10 683 s, the HXP

reaches the level of about 1.41 m (then it decreases slowly down to about 1.40 m) Figure 3.4.

The OP level decreasing is observed during the first water pour-off towards the HXP, Figure 3.4. After the first phase of water pour-off, power exchanged⁵ from the primary to the pool side slightly increase (around 3.5 MW, Figure 3.5) together with steam and condensate flow rate (Figure 3.6). This small increase of power removed is due to the low water level increase in the HXP. The data regarding the opening and closure rate of valve F045 and the normalised flow area associated to each opening are not available.

After this first phase of water injection, due to the low level reached in the HXP, the steam production is limited and not sufficient to maintain the HXP pressure high enough to drive the fluid circulation between the pool through the steam duct and the injector. An interface between cold water and steam is present in the injector, and strong condensation shocks take place. This determines that the HXP pool relative pressure dumps down to negative values till air inlet through the vacuum breaker valve is sufficient to recover the pressure, Figure 3.15.

The HXP fluid temperatures are shown in Figures 3.7 to 3.14. Before the water injection, the air contained in the pool is hot, due to the high temperature of the HX. Then the temperature decreases slowly for the steam production in the HXP after the first phase of water injection.

The second phase of water injection occurs between 11 039 and 11 260 s when F045 valve is opened at 11 039 s and completely closed at 11 260 s. The injection water flowrate between the pools (derived by the HXP level) for the second phase of injection is reported in Figure 3.3. At time 11 050 s, HXP level reaches the maximum value of 3.4 m, following the second water injection. The OP level is reported in Figure 3.4. Level decreasing is observed during the two water pour-off towards the HXP. The HXP fluid temperatures decrease rapidly due to the progressive covering of the HXP (some thermocouples are wetted by the fluid).

After the F045 valve is opened for the second injection and power begins to be exchanged heavily from the primary to the pool side, the primary side pressure decreases rapidly, so it is manually increased in order to compensate the pressure decreasing due to the heat removal. After about 550 s, the pressure average value returns to 7 MPa, Figure 3.1.

While in the first phase of water pour-off, power exchanged from the primary to the pool side is quite low (around 3.5 MW), because of the low water level in the HXP, it increases by increasing the level up to reaching the maximum value of about 21 MW (Figure 3.5). The steam flowrate entering the HX and the condensate flowrate exiting the HX increase and are shown in Figure 3.6.

When the maximum level of the HXP is reached (3.4 m) the quasi-steady-operation of the system begins. In this case the triggering valve F-045 is closed during the quasi-steady-operation, thus the window related to the maximum removed power (around 21 MW) is relatively short (around 600 s). In the Test 7 Part 2, the triggering valve remains opened so this window last for a longer time (around 1 500 s).

The maximum steam flowrate condensed in the HX is around 13 kg/s (quasi-steady flowrate 2.2) Figure 3.6. In the HXP saturation is reached early and temperature stabilises around 104°C, corresponding to the saturation at the pressure in the HXP, Figure 3.15. The production of steam is higher and the steam circulation in the steam duct is detected, so

5. The HX power is obtained as $W = F_S \cdot H_S - F_L \cdot H_L$ where F is the mass flow rate, H the enthalpy and the subscript S and L are referred to the steam and condensate respectively.

limiting the thermal stratification in the OP at least until about 12 500 s. The OP temperatures are shown in Figure 3.16 to Figure 3.21.

After 11 845 s, due to the reduction of the HXP level (for the boil-off) and the progressive HX uncovering, the removed power starts to decrease sensibly. Correspondingly also the steam and condensate flow rate reduce. The boil-off in the HXP brings to a level increase in the OP.

In Figure 3.22 it is possible to notice the thermal stratification in the OP starting from 12 500 s when the steam flow rate from the injector is no longer sufficient to promote mixing.

The trend of the HX outer wall temperatures on the headers during the test is reported in Figure 3.23 and Figure 3.24. It is possible to observe the temperature fall consequent to the HXP flooding and later the temperature rising when the HX pool dries out. For the upper header the considered wall temperature (TW-B005) is placed in the lower part of the header, while for the lower header the considered wall temperature (TW-D001) is placed in the upper part of the header.

Table 3.2 summarises the opening and closing time of the valve that controls the transient.

Table 3.3 shows the main relevant thermal-hydraulic aspect related to Test 7 Part 1.

Table 3.2. Test 7 Part 1 valve events timing

Event	Time [s]
Triggering valve (F-045) first opening	10 475
Triggering valve (F-045) first closure	10 608
Triggering valve (F-045) second opening	10 621
Triggering valve (F-045) second closure	10 655
Triggering valve (F-045) final opening	11 039
Triggering valve (F-045) final closure	11 260

Source: Ferri, Achilli and Gandolfi, 2002[1].

Table 3.3. Main relevant thermal-hydraulic aspect related to the Test 7 Part 1

Relevant thermal-hydraulic aspects	Time [s]	Quantity
Triggering valve (F045) opening and closure	10 475 – 10 608	
Triggering valve (F045) re-opening and re-closure	10 621 – 10 655	
Maximum level in the HX pool for the first filling step	10 683	1.41 m
Small Heat removal from the primary side	10 600 – 11 000	3.5 MW
Slow water consumption in the HX pool	11 049	From 1.41 m to 1.4 m
Instabilities for steam condensation in the injector	10 930 – 11 290	Negative HXP relative pressure
Triggering valve (F045) opening and closure	11 039 – 11 260	
Maximum level in the HX pool	11 050	3.4 m
Maximum exchanged power	11 260 – 11 845	21.5 MW
HX pool minimum level	14 800	1.25 m
OP average temperature	13 000	around 55°C

Source: Ferri, Achilli and Gandolfi, 2002[1].

Figure 3.1. Test 7 Part 1 - Primary side pressure

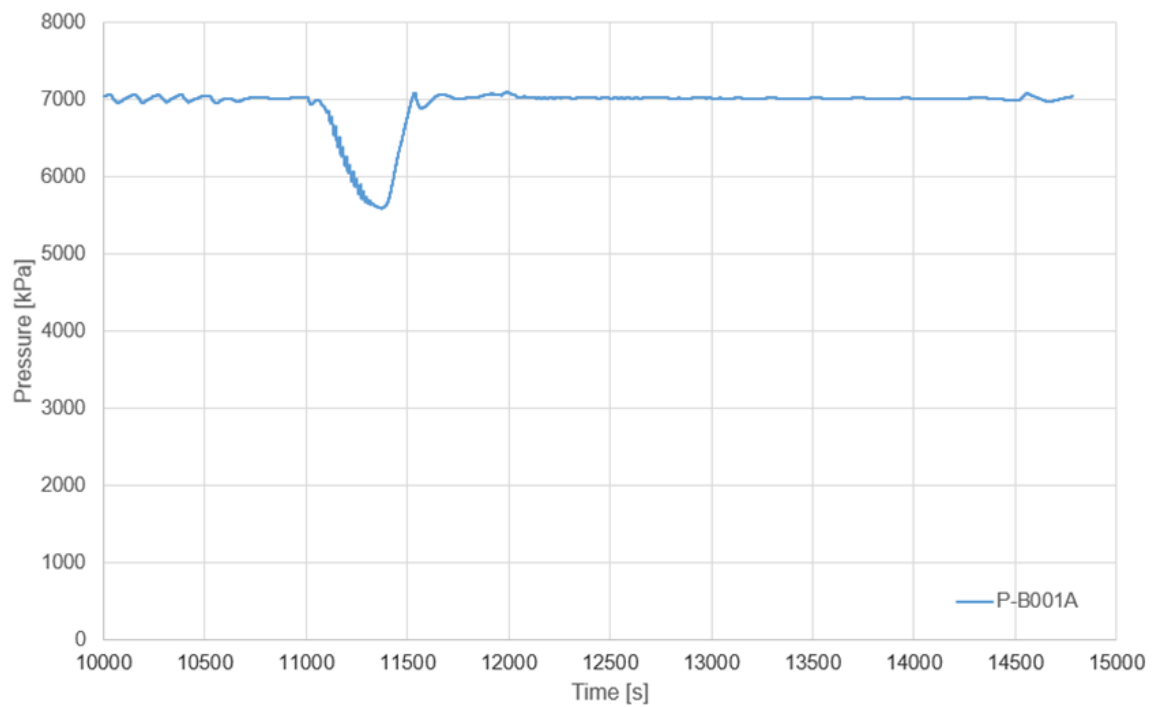
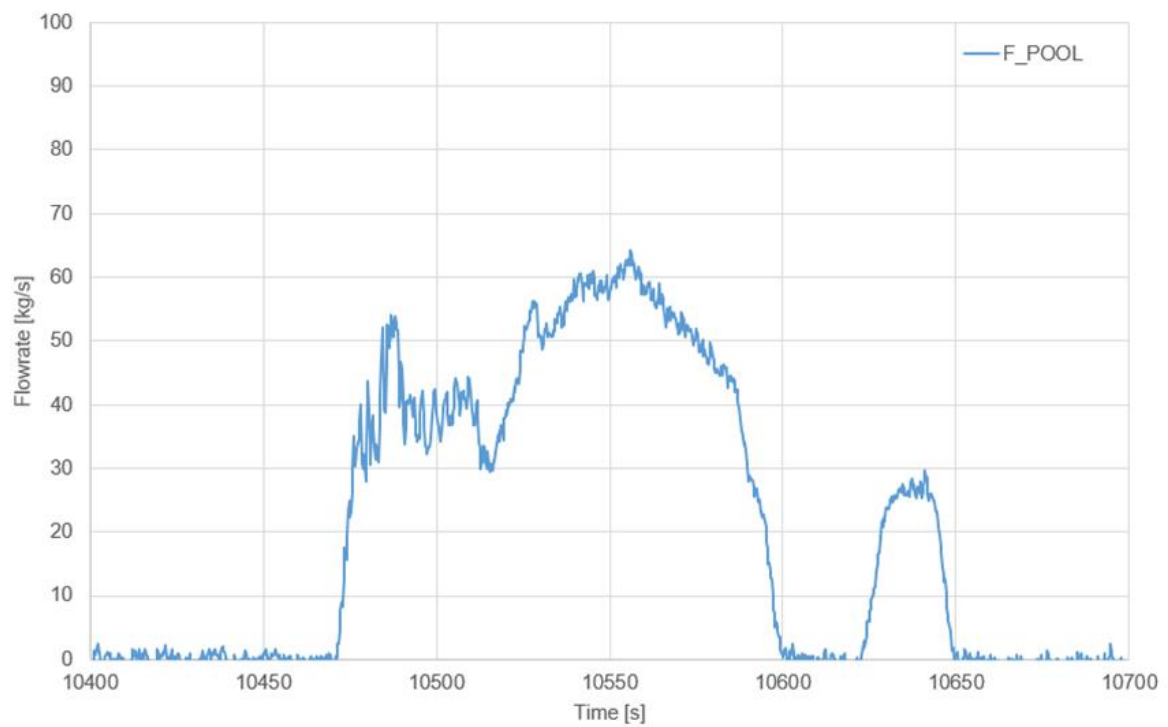


Figure 3.2. Test 7 Part 1 - Water flowrate between the pools (initial HX pool filling)



**Figure 3.3. Test 7 Part 1 - Water flowrate between the pools
(complete HX pool filling)**

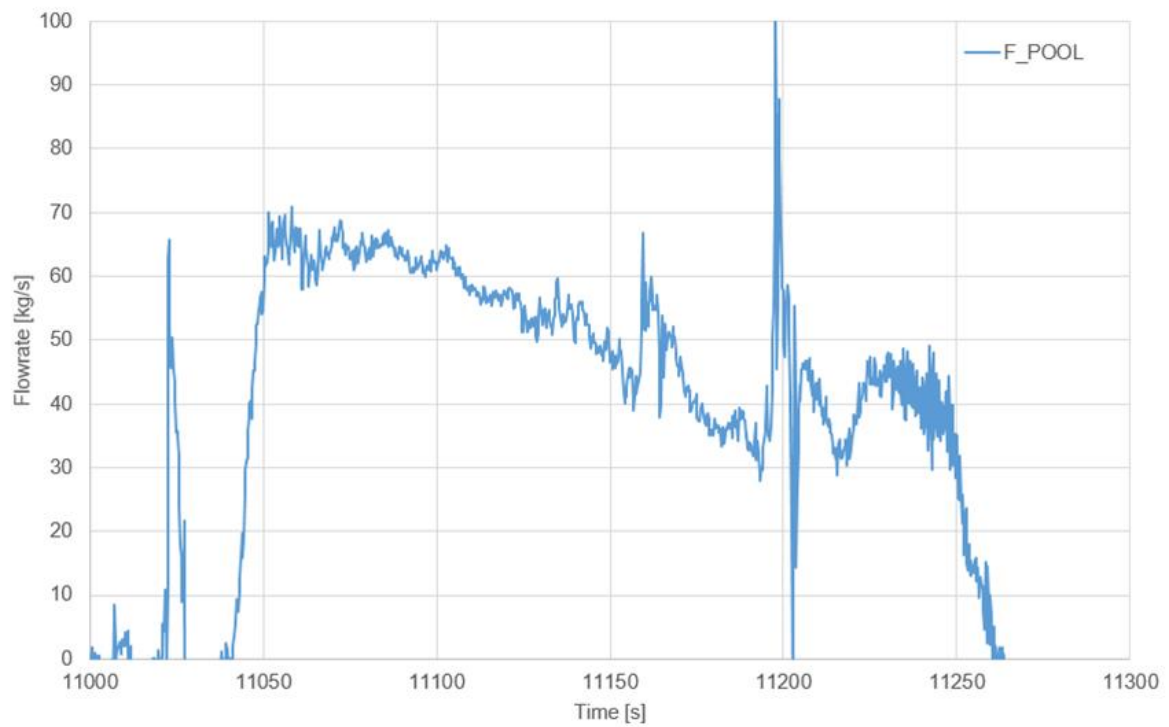


Figure 3.4. Test 7 Part 1 - HX pool and overall pool level

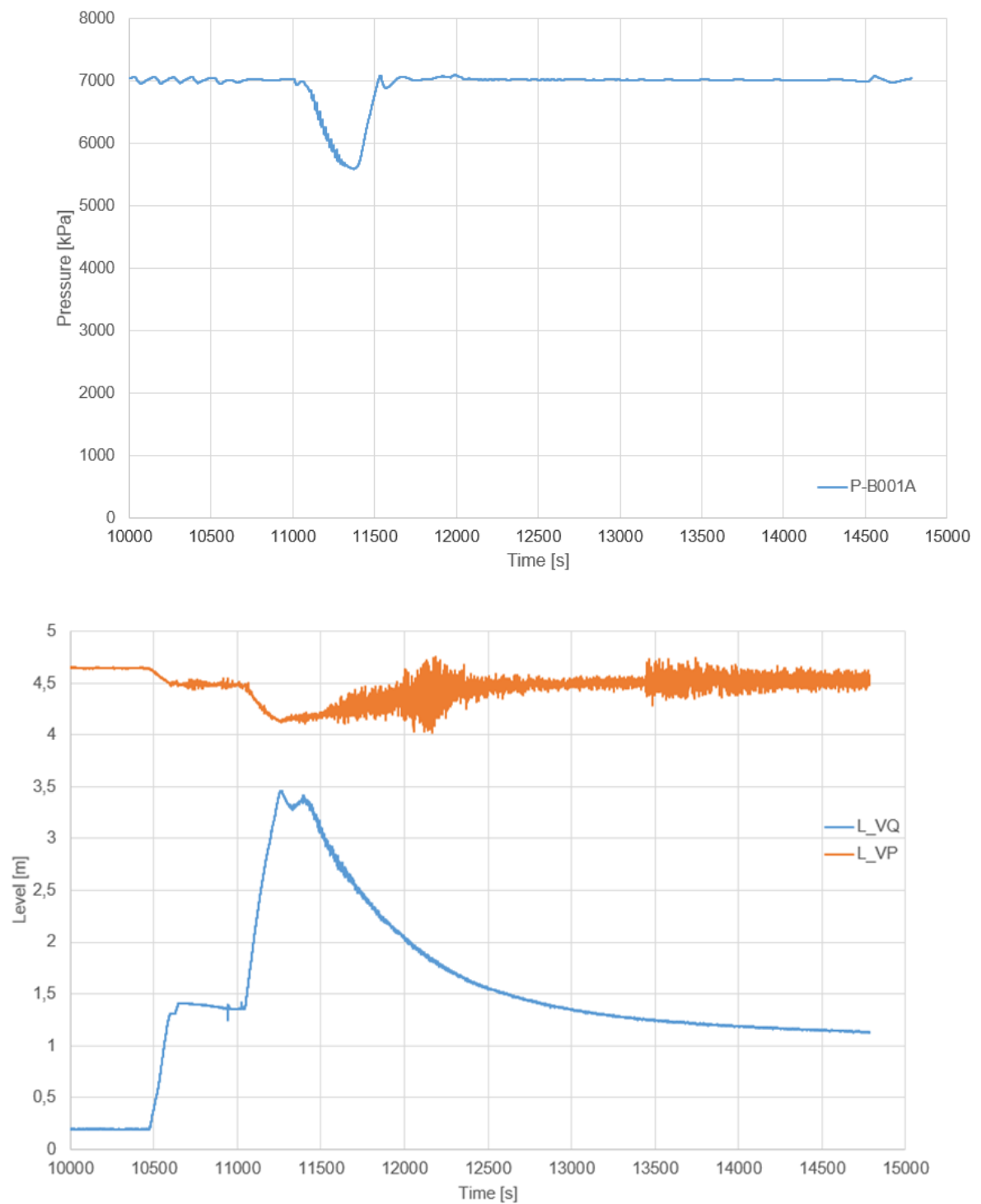


Figure 3.5. Test 7 Part 1 - HX exchanged power

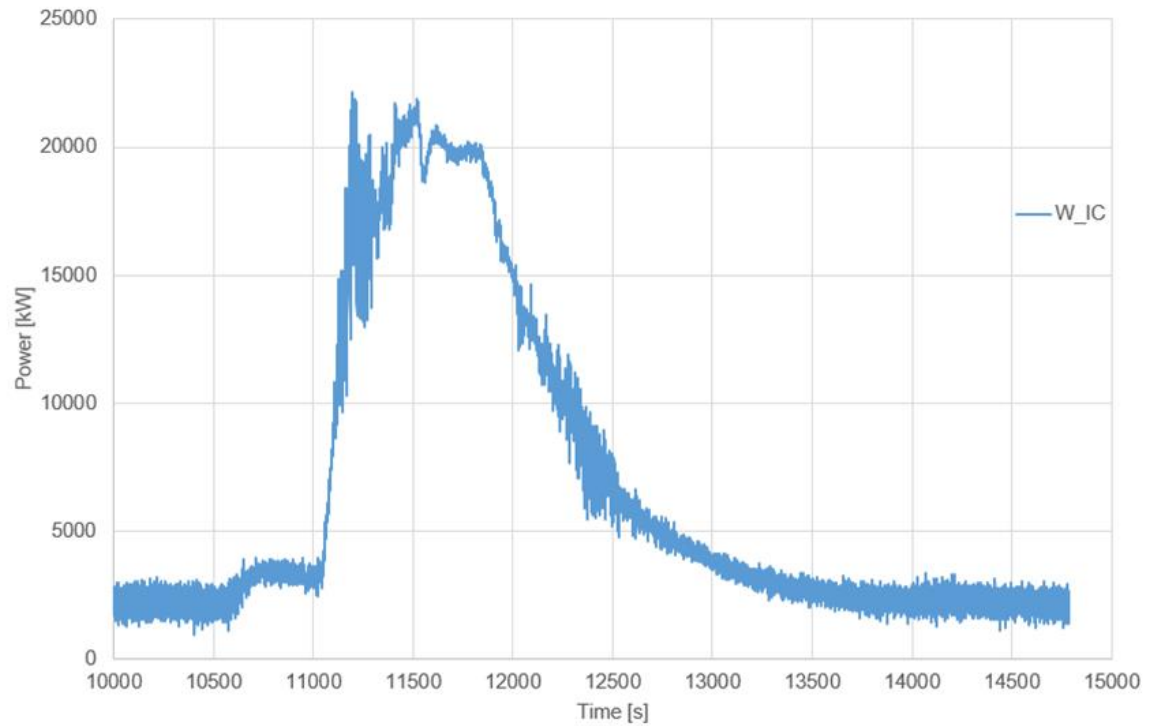


Figure 3.6. Test 7 Part 1 - Steam and condensate flow rate

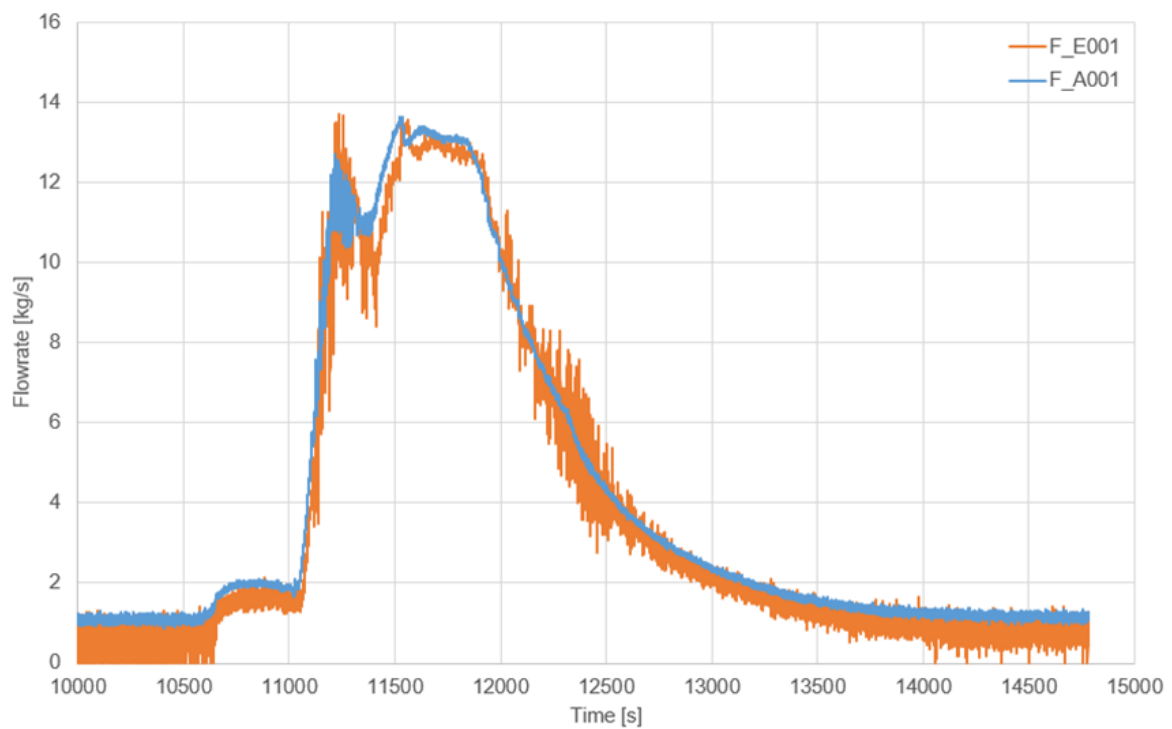


Figure 3.7. Test 7 Part 1 - HX pool temperatures (level 1)

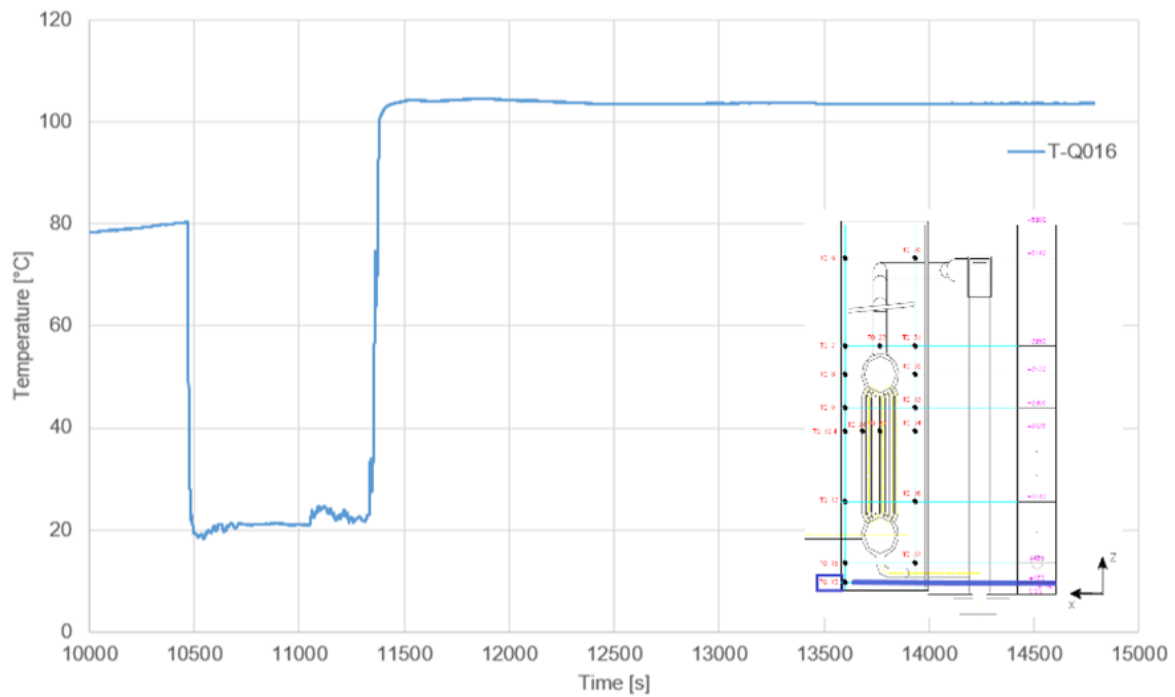


Figure 3.8. Test 7 Part 1 - HX pool temperatures (level 2)

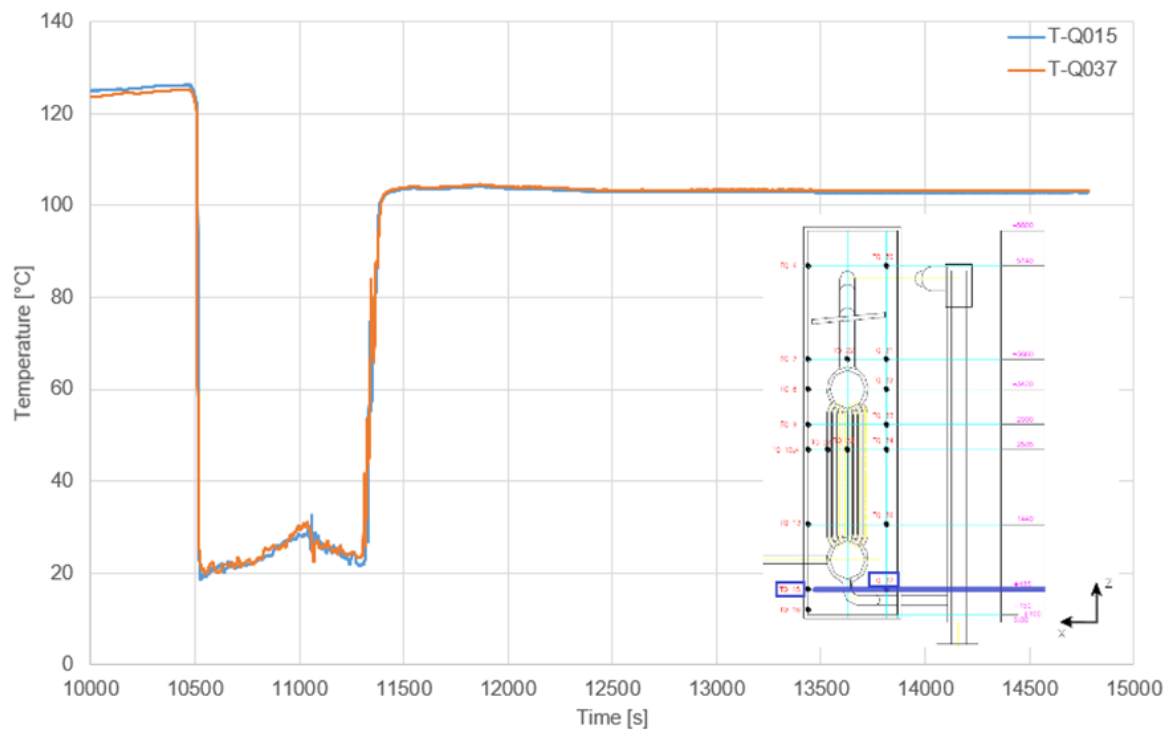


Figure 3.9. Test 7 Part 1 - HX pool temperatures (level 3)

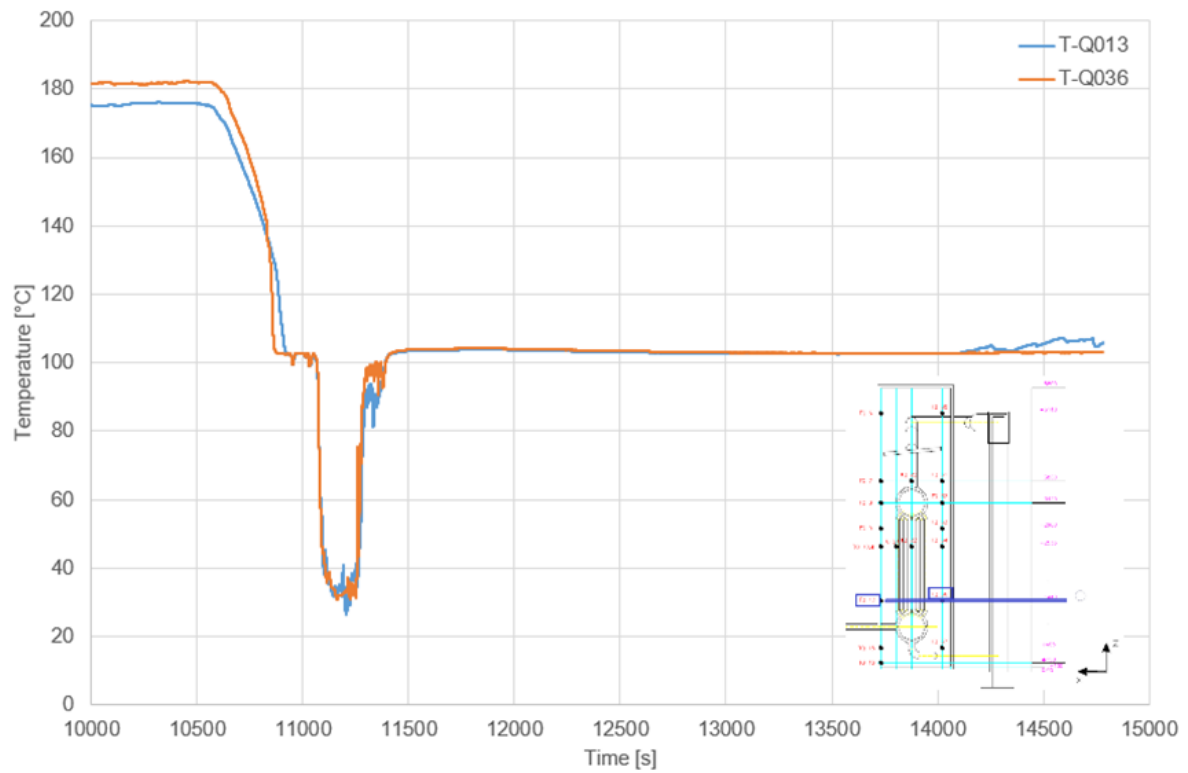


Figure 3.10. Test 7 Part 1 - HX pool temperatures (level 4)

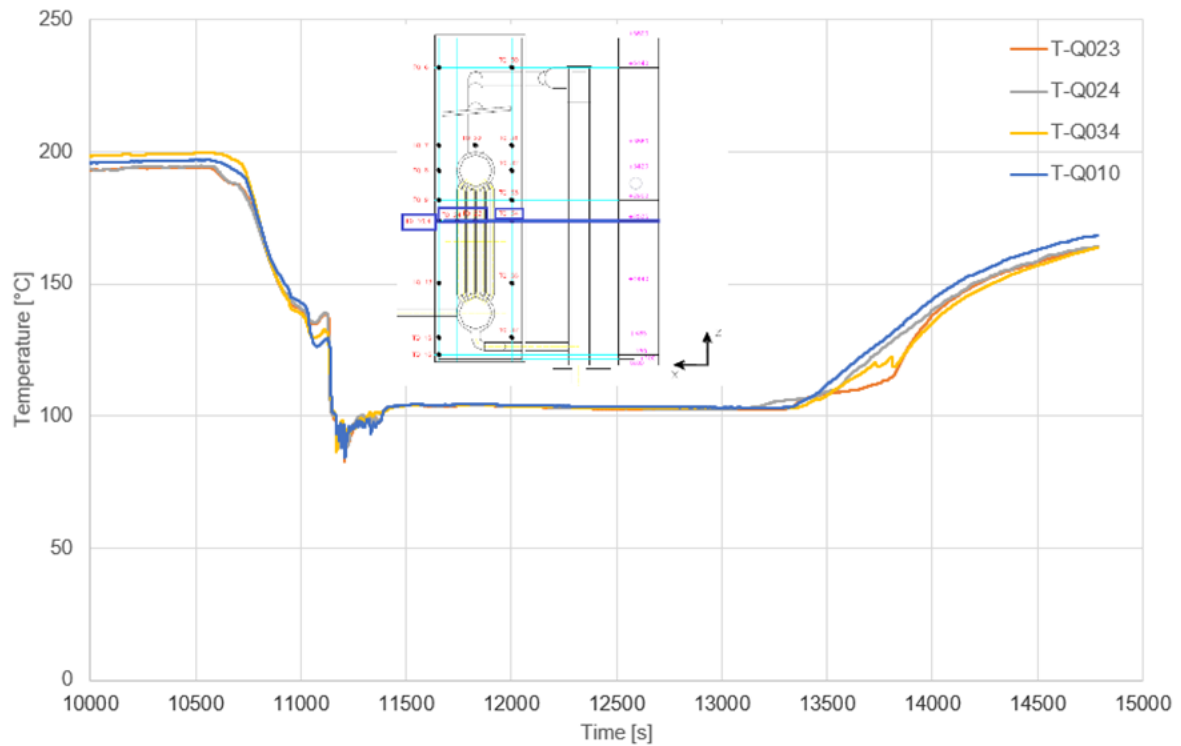


Figure 3.11. Test 7 Part 1 - HX pool temperatures (level 5)

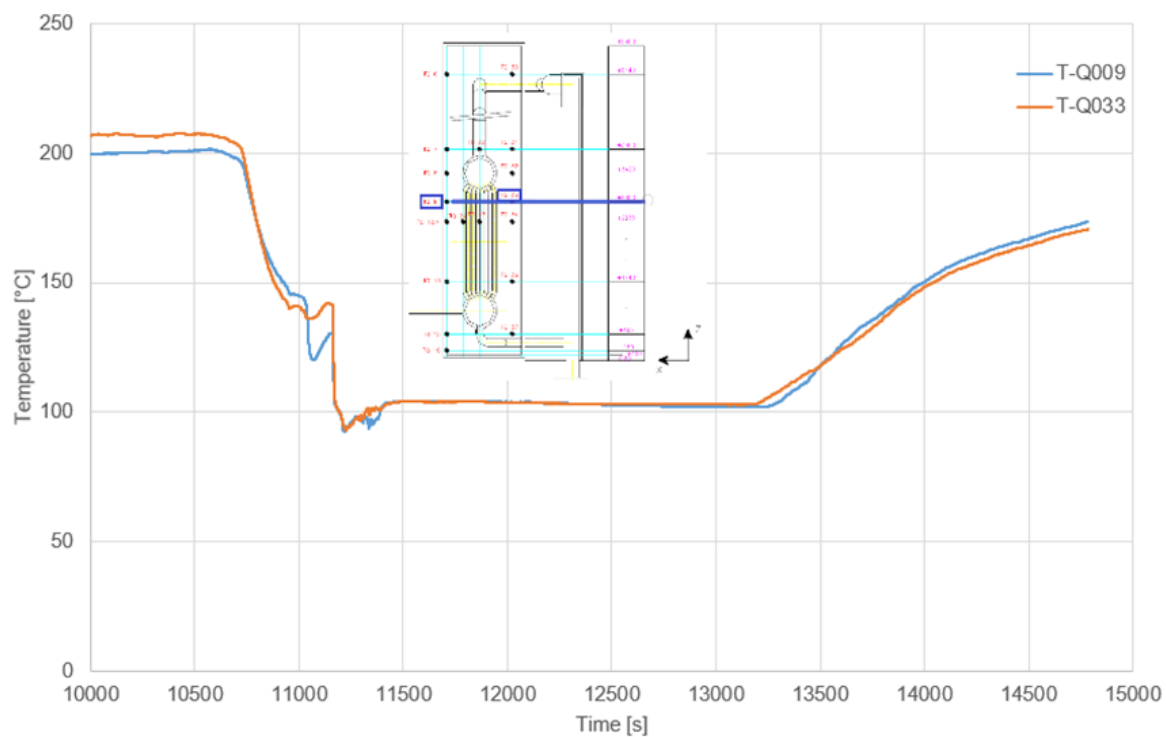


Figure 3.12. Test 7 Part 1 - HX pool temperatures (level 6)

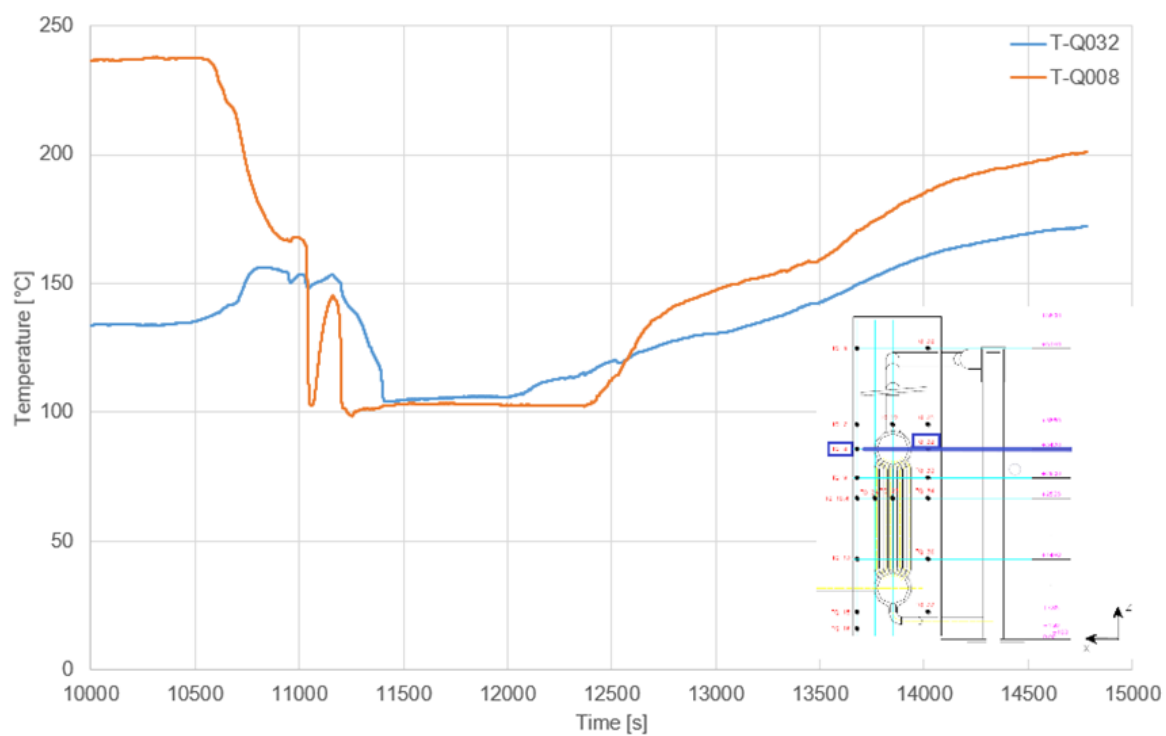


Figure 3.13. Test 7 Part 1 - HX pool temperatures (level 7)

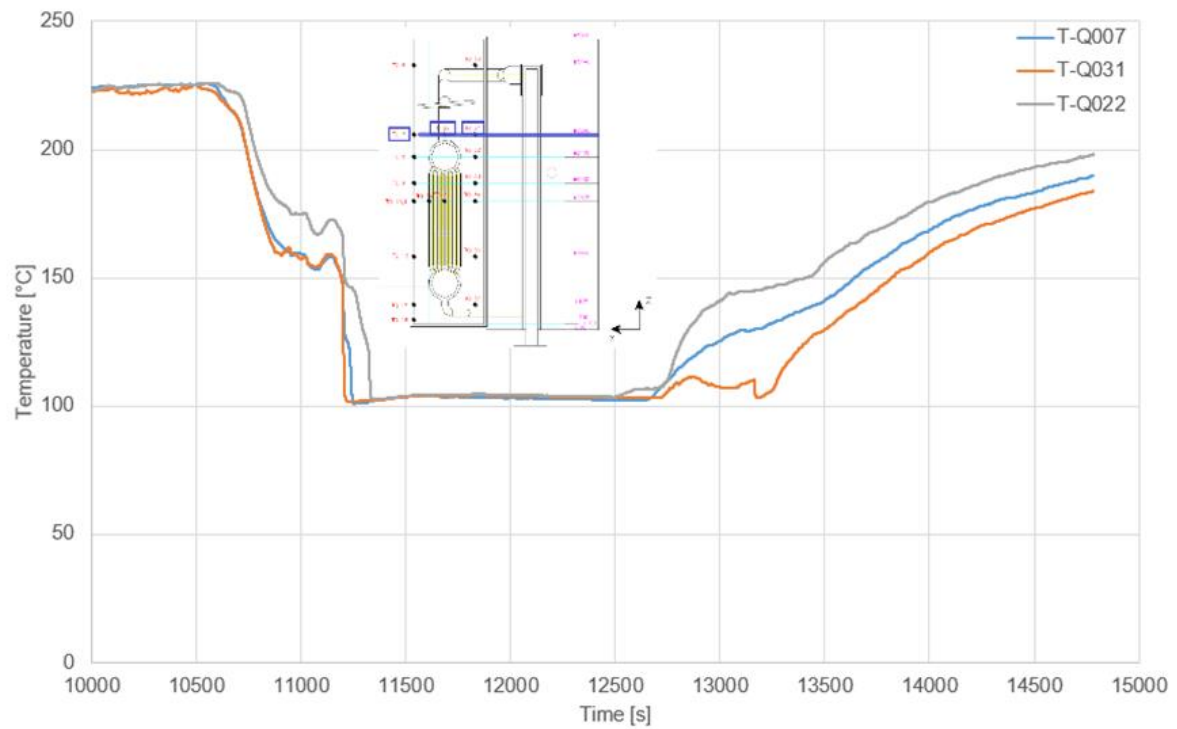


Figure 3.14. Test 7 Part 1 - HX pool temperatures (level 8)

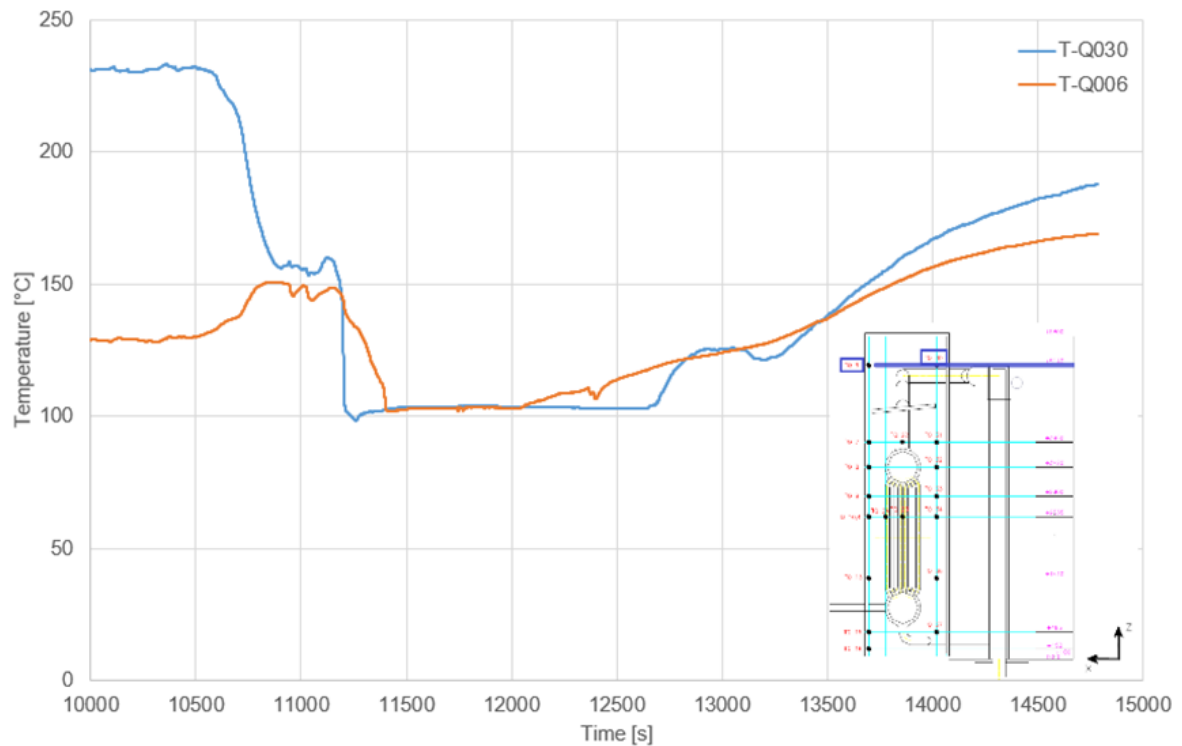


Figure 3.15. Test 7 Part 1 - HX pool relative pressure

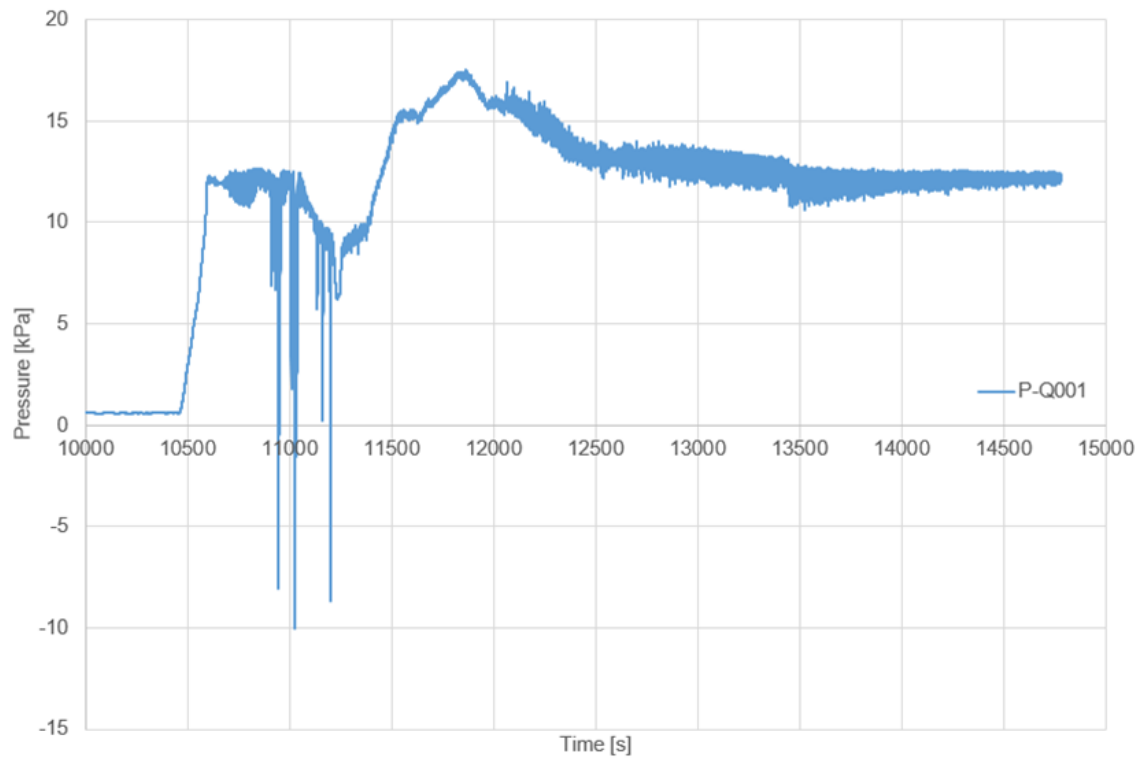


Figure 3.16. Test 7 Part 1 - Overall pool temperatures (level 1)

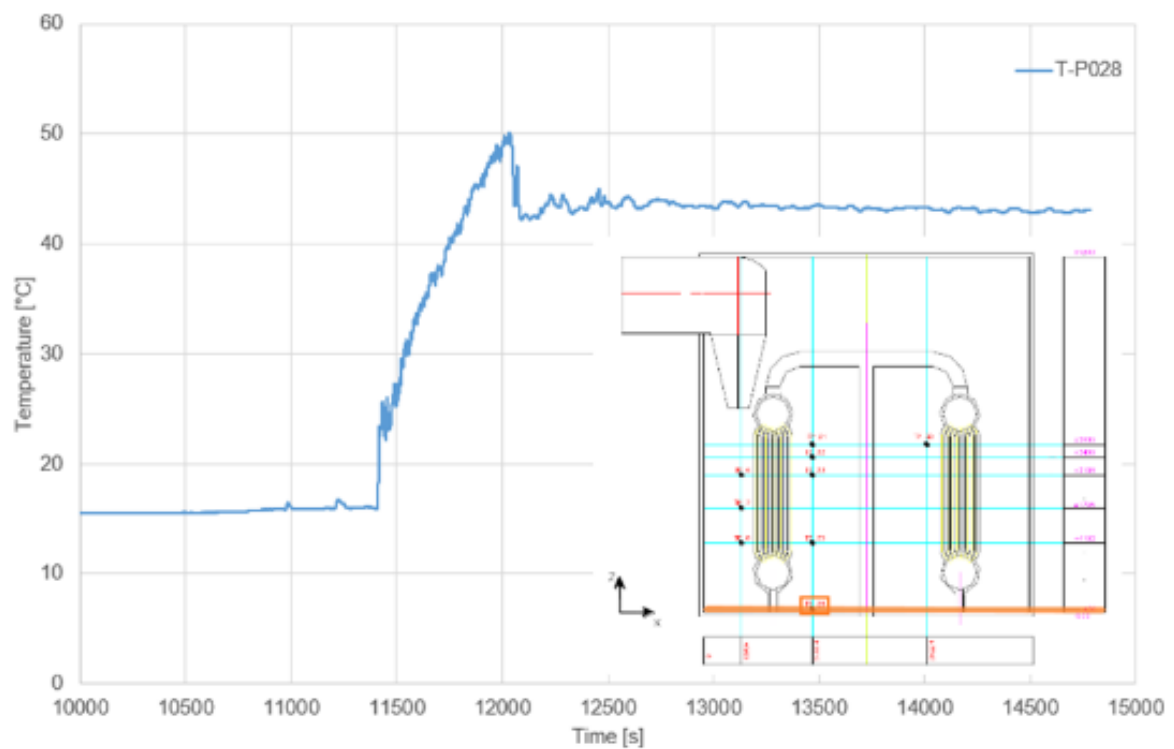


Figure 3.17. Test 7 Part 1 - Overall pool temperatures (level 2)

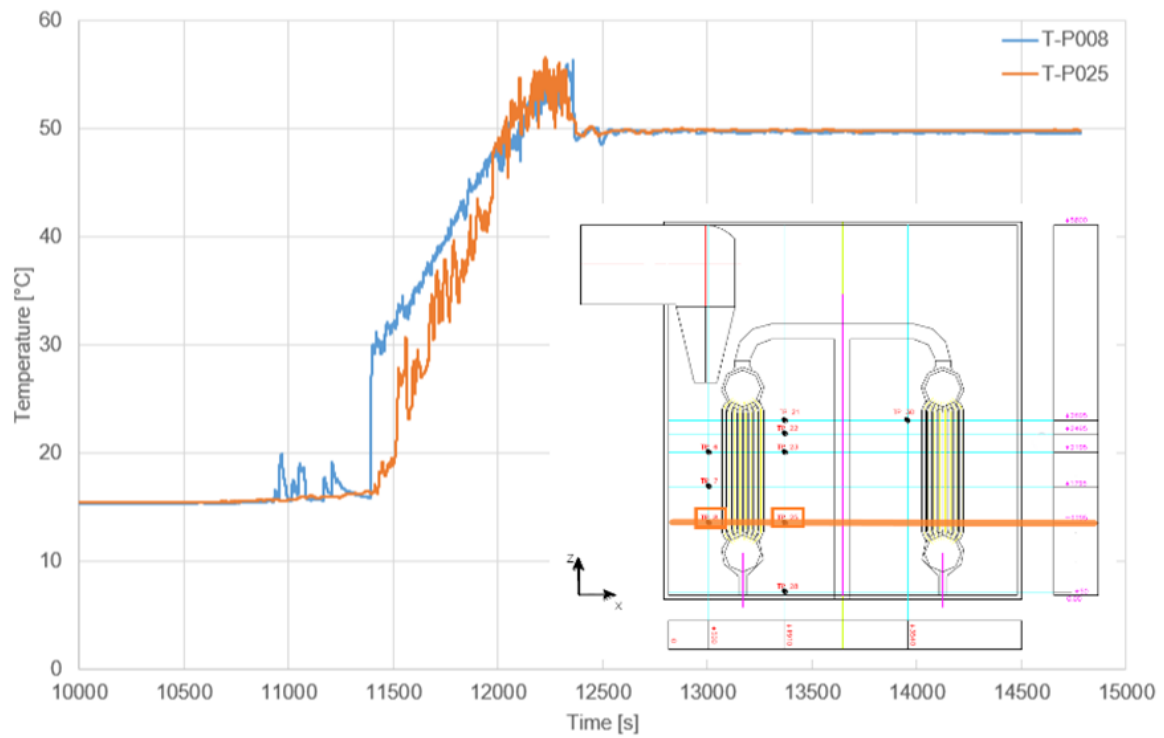


Figure 3.18. Test 7 Part 1 - Overall pool temperatures (level 3)

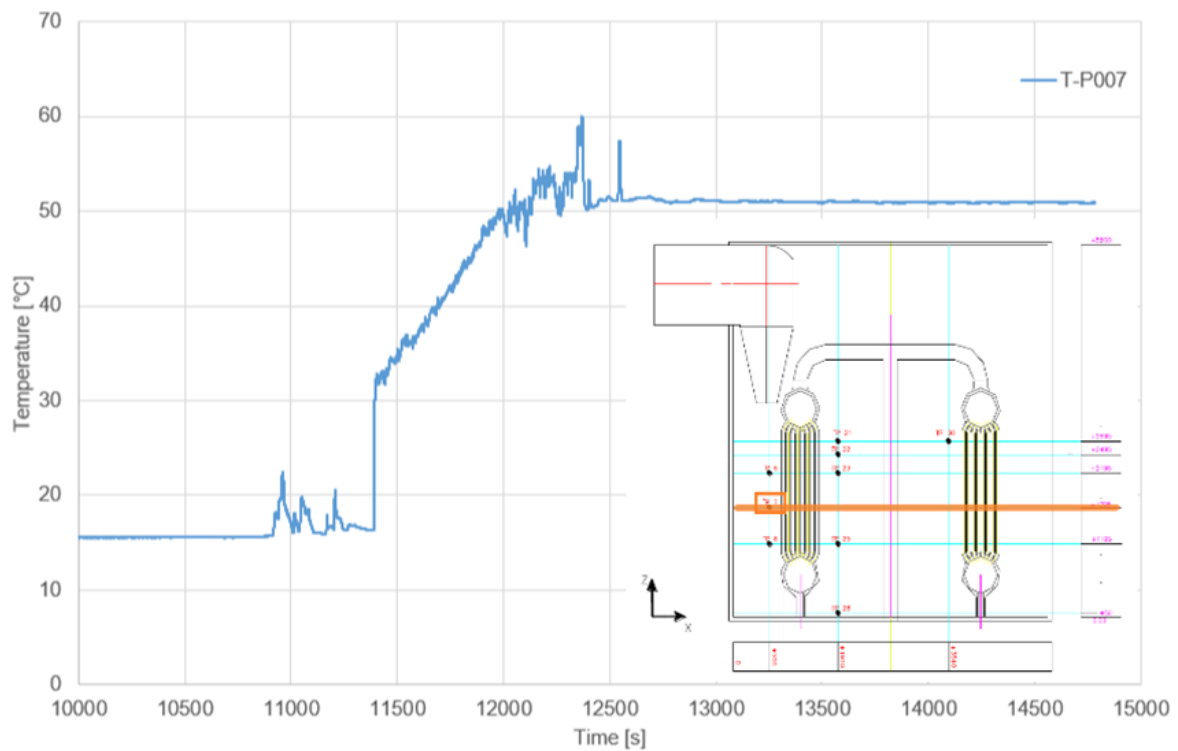


Figure 3.19. Test 7 Part 1 - Overall pool temperatures (level 4)

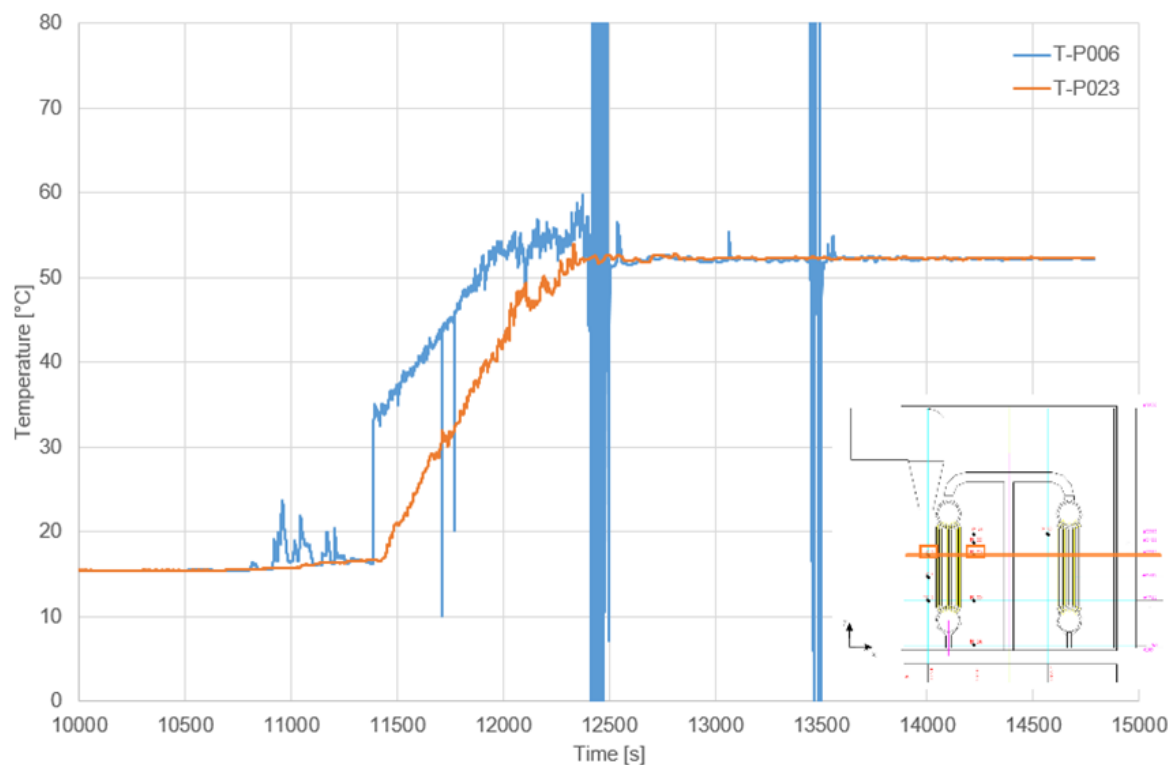


Figure 3.20. Test 7 Part 1 - Overall pool temperatures (level 5)

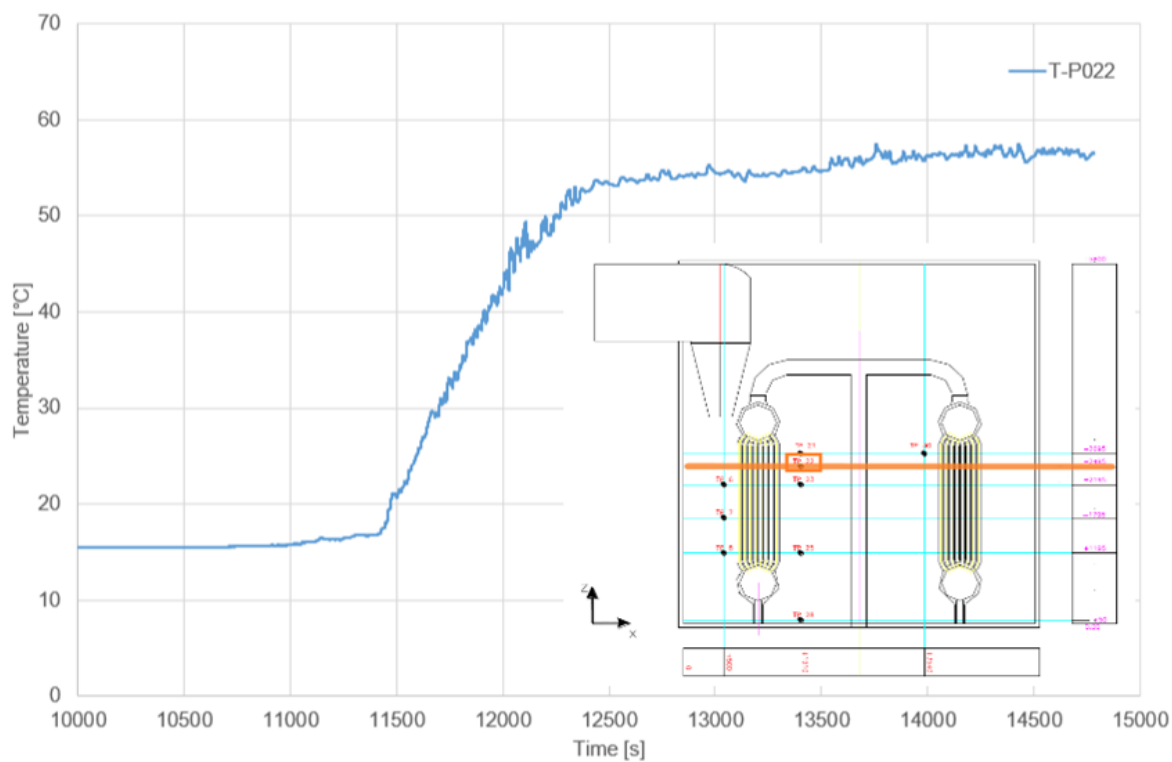


Figure 3.21. Test 7 Part 1 - Overall pool temperatures (level 6)

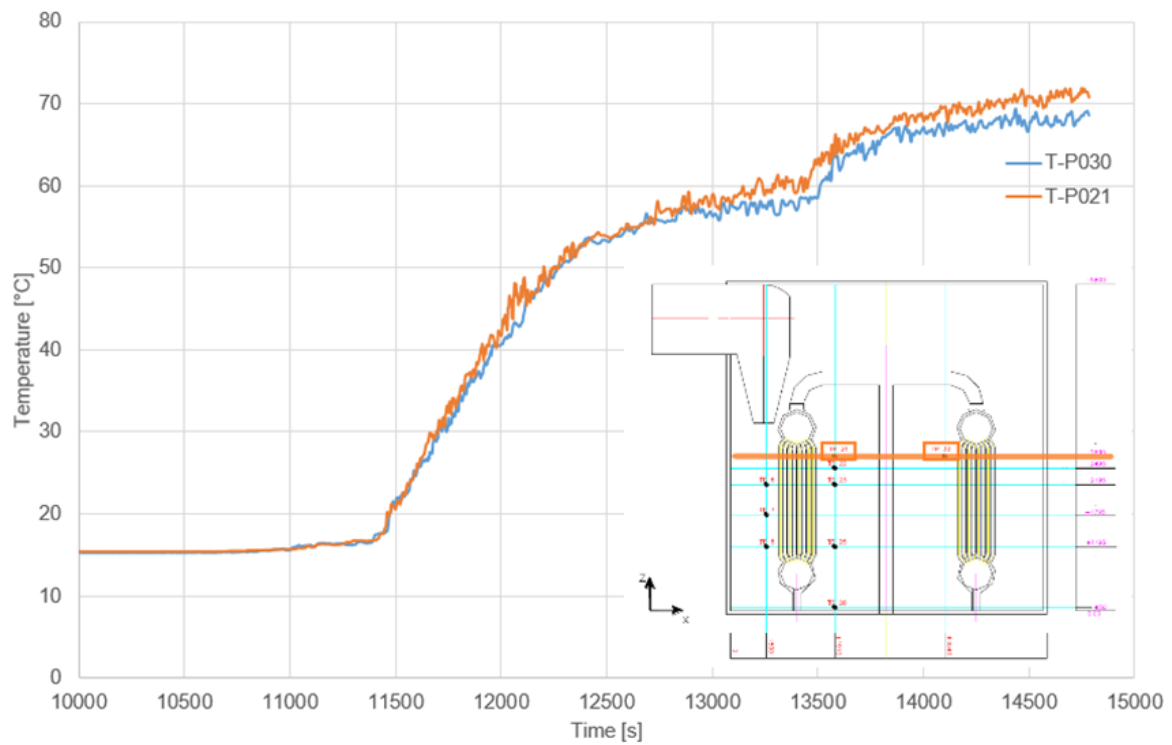


Figure 3.22. Test 7 Part 1 - Overall pool temperatures

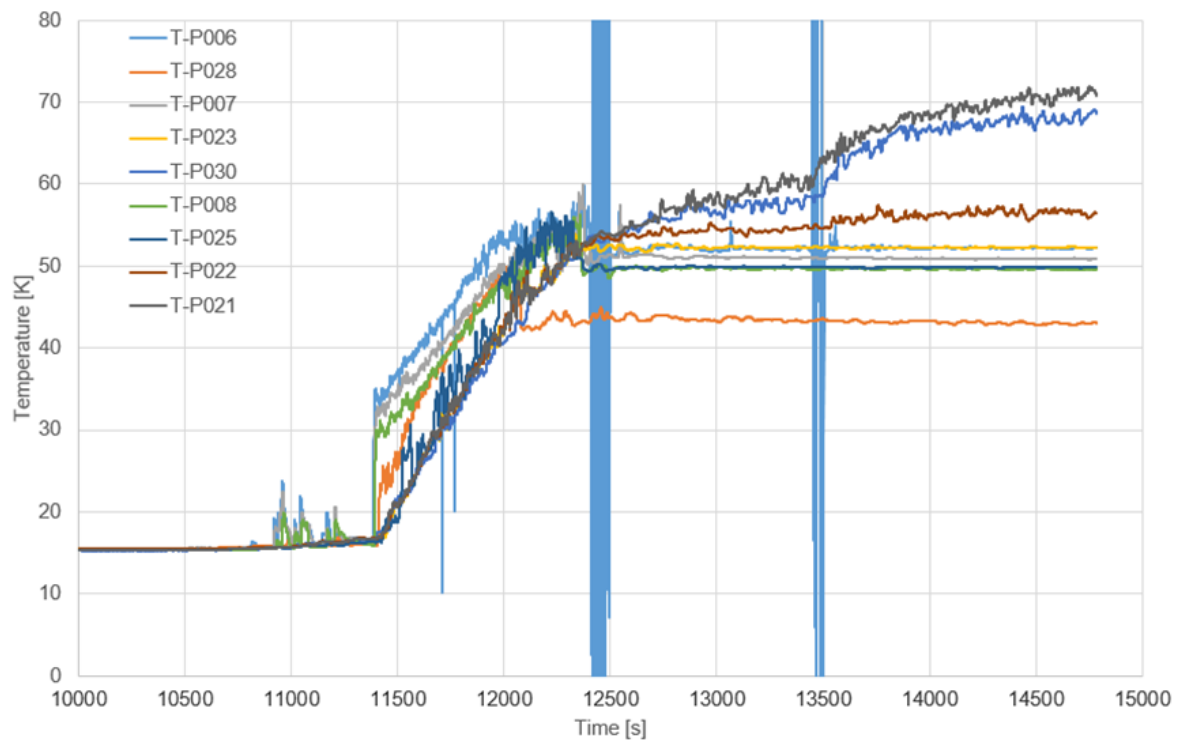


Figure 3.23. Test 7 Part 1 - HX upper header wall temperatures

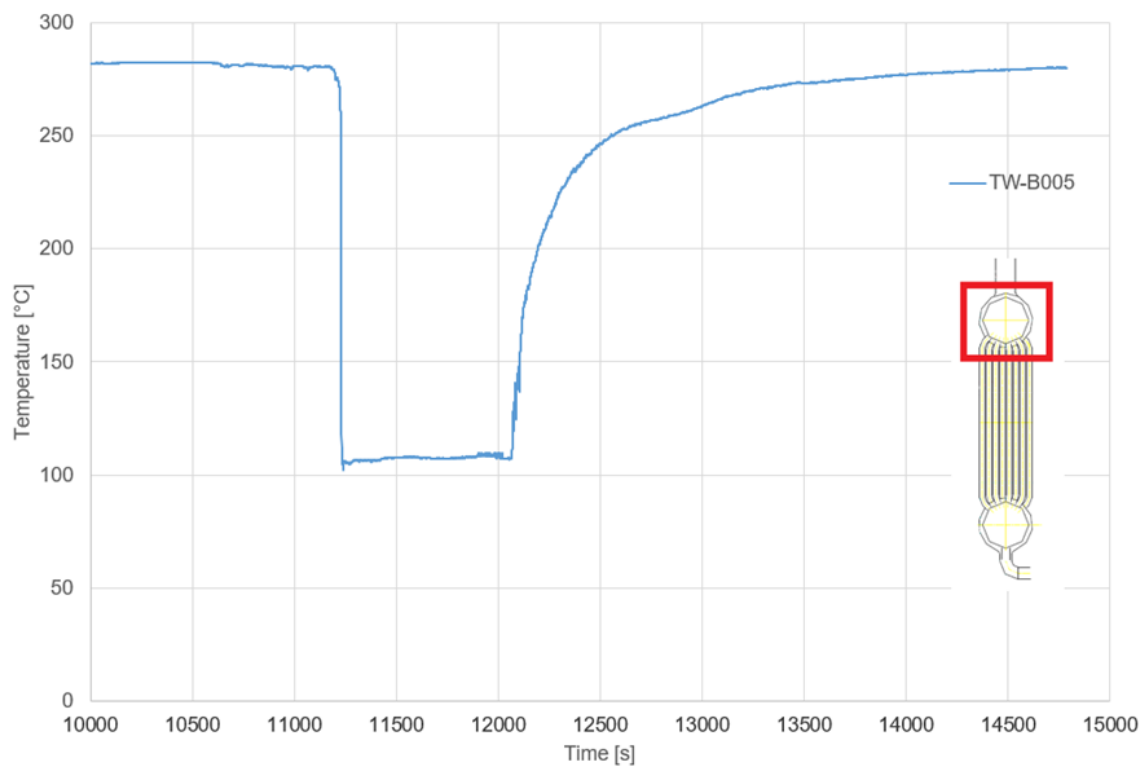
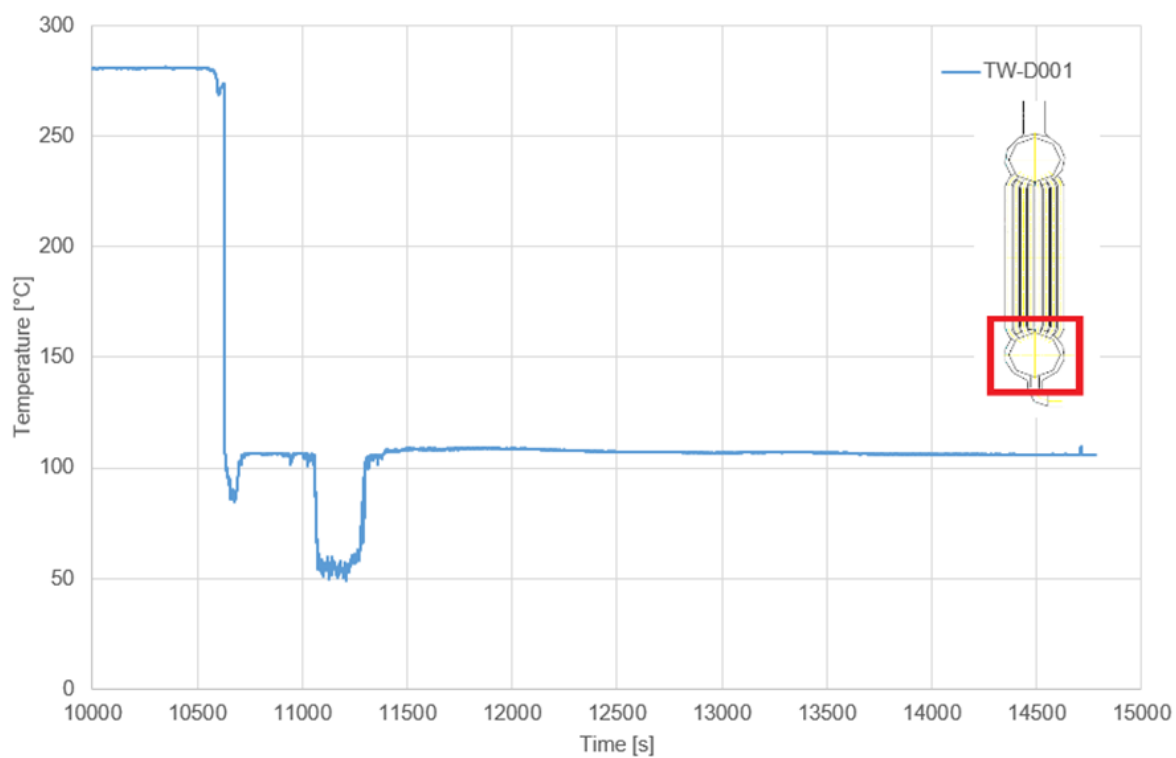


Figure 3.24. Test 7 Part 1 - HX lower header wall temperatures



3.2. Test 7 Part 2

This test is characterised by three phenomenological windows:

1. 0 s – 531 s (maximum level in the HXP): Increase of level in one step in the HXP with a consequent increase of the exchanged power. Relevant thermal-hydraulic aspects are:
 - 1) HXP level increase;
 - 2) OP level decrease;
 - 3) Mass flow increase in-tube side;
 - 4) Power removed increase;
 - 5) Progressive covering of the HX in the pool side.
2. 531 s – 2 282 s (HX power around 20 MW, the ending time of the PhW is when the HX power decreases under 20 MW): Quasi-steady state operation starting from the HXP level of 3.3 m. Relevant thermal-hydraulic aspects are:
 - 1) Quasi-steady state power removed;
 - 2) Quasi-steady state flow rate in-tube side;
 - 3) Initial boil-off in the HXP;
 - 4) Instabilities in the OP water level.
3. 2 282 s – 5 735 s: Boil-off in the HXP with a consequent level reduction. Therefore reduction of power removed (accelerated level decrease by opening of the pool discharge valve). Relevant thermal-hydraulic aspects are:
 - 1) Boil-off in the HXP;
 - 2) Reduction of HXP level and OP level due to the accelerated water draining from the drain valve;
 - 3) Reduction of removed power;
 - 4) Reduction of flow rate in-tube side;
 - 5) Progressive uncovering of the HX in the pool side.

The second part of the test starts with the HXP containing 1.12 m water level in saturation conditions, the OP full of warm water and the in-tube side pressure of 7 MPa. The PV pressure is shown in Figure 3.25.

Valve F045 begins to be opened at time 300 s and it is completely open at 326 s (26 s opening time). The same valve is closed at 3 338 s in 123 s in order to isolate the two pools and investigate the trend of power as a function of the HXP level. The water flowrate between the pools (derived by the HXP level) is reported in Figure 3.26.

The HXP level begins to increase at time 310 s. At time 531 s, the HXP reaches the maximum level of 3.25 m, then oscillations follows until about 1 500 s, Figure 3.27. The OP level is reported in the same figure. After the early OP level decreasing for the water pour-off to the HXP, strong and fast oscillations are observed in the OP level, due to the condensation of steam produced in the HXP and flowing through the injector.

After the F045 valve is opened and power begins to be exchanged from the primary to the pool side, the primary side pressure is manually increased in order to compensate the pressure decreasing due to the heat removal. After some oscillations, the pressure average

value returns to 7 MPa and it is maintained stable until the depressurisation of the plant is started at 4 685 s, Figure 3.25.

The exchanged power is shown in Figure 3.28. It is possible to observe that the removed power follows the trend of level in the HXP and it is quite stable around 20 MW until the level does not decrease below 2.2 m (about 2 400 s), Figure 3.27.

The HX steam and condensate flowrate are shown in Figure 3.29. The condensed steam flowrate at the maximum exchanged power is about 13 kg/s.

The HXP fluid temperatures are shown in Figure 3.30 to Figure 3.37. Before the water injection, superheated steam is contained in the upper part and subcooled water in the lower one. After the HXP flooding and water boiling, all temperature stabilise around 104 °C, corresponding to the saturation at the pressure in the pool, Figure 3.38. Pressure in the HXP is sufficient to drive steam in the OP through the steam duct and the injector.

Steam, accelerated into the OP by the injector, promotes the water circulation and mixing in the OP. The temperature peaks observed around 650 and 1 040 s are due to level oscillations between the pools and water transfer from the HX to the OP through the water line. All the OP fluid temperatures are shown in Figure 3.44 and it is possible to notice the mixing promoted by the injector and then the reaching of saturation conditions. The OP temperatures are shown in Figure 3.39 to Figure 3.43 (T-P007 is not available for Test 7 Part 2 so Level 3 is not shown).

At time 1 150 s, when the majority of OP temperatures is between 80°C and 90°C, the level decreasing in the pools is accelerated by opening the discharge valve F031. The valve is left open for the remaining part of the test. At this point, the injector outlet is uncovered and steam arriving from the steam duct is discharged through the boil-off pipe.

The data regarding the opening and closure rate of valve F031 and the normalised flow area associated to each opening are not available.

After the F045 valve between the two pools is closed (from 3 338 s to 3 461 s), the HXP level decreases more rapidly and consequently the exchanged power the steam and condensate flow rate.

The trend of the HX wall temperatures on the headers is reported in Figure 3.45, and Figure 3.46. It is possible to observe the temperature fall consequent to the HXP flooding and later the stabilising of the wall temperature about 5°C above the saturation temperature until they are covered by water.

Table 3.4 summarises the opening and closure time of the valves that control the transient.

Table 3.5 shows the main relevant thermal-hydraulic aspect related to the Test 7 Part 2.

Table 3.4. Test 7 Part 2 valve events timing

Event	Time [s]
Triggering valve (F-045) opening (in 26 s)	300
Overall Pool discharge valve (F-031) opening	1 150
Triggering valve (F-045) closure (in 123 s)	3 338

Source: Ferri, Achilli and Gandolfi, 2002[1].

Table 3.5. Main relevant thermal-hydraulic aspect related to the Test 7 Part 2

Relevant thermal-hydraulic aspects	Time [s]	Quantity
Triggering valve (F045) opening	326 (opened in 26 s)	
Maximum level in the HXP	531	3.25 m
Maximum exchanged power	531 – 2 282	21 MW
OP discharge valve F031 opening	1 150	
Triggering valve F045 closure	3 338 (closed in 123 s)	
HX pool level decreasing and loss of mass from the boil-off	2 282 – 5 735	
Primary side depressurisation beginning for end of test	4 685	

Source: Ferri, Achilli and Gandolfi, 2002[1].

Figure 3.25. Test 7 Part 2 - Primary side pressure

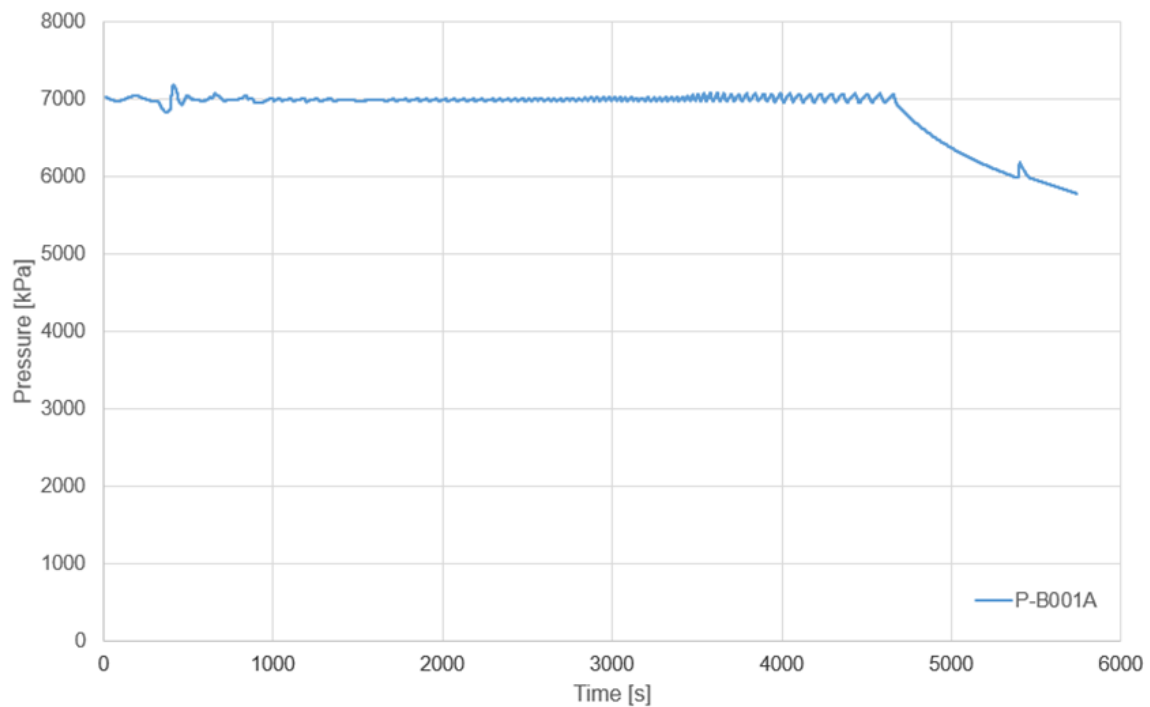


Figure 3.26. Test 7 Part 2 - Water flowrate between the pools

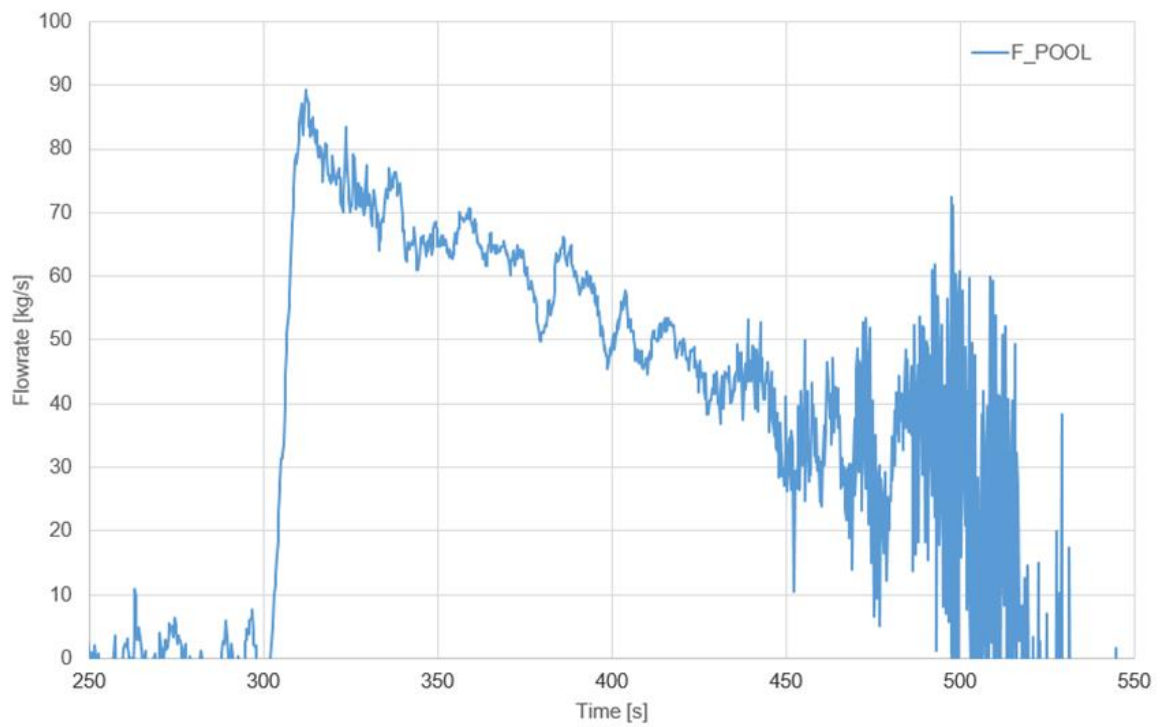


Figure 3.27. Test 7 Part 2 - HX pool and overall pool water level

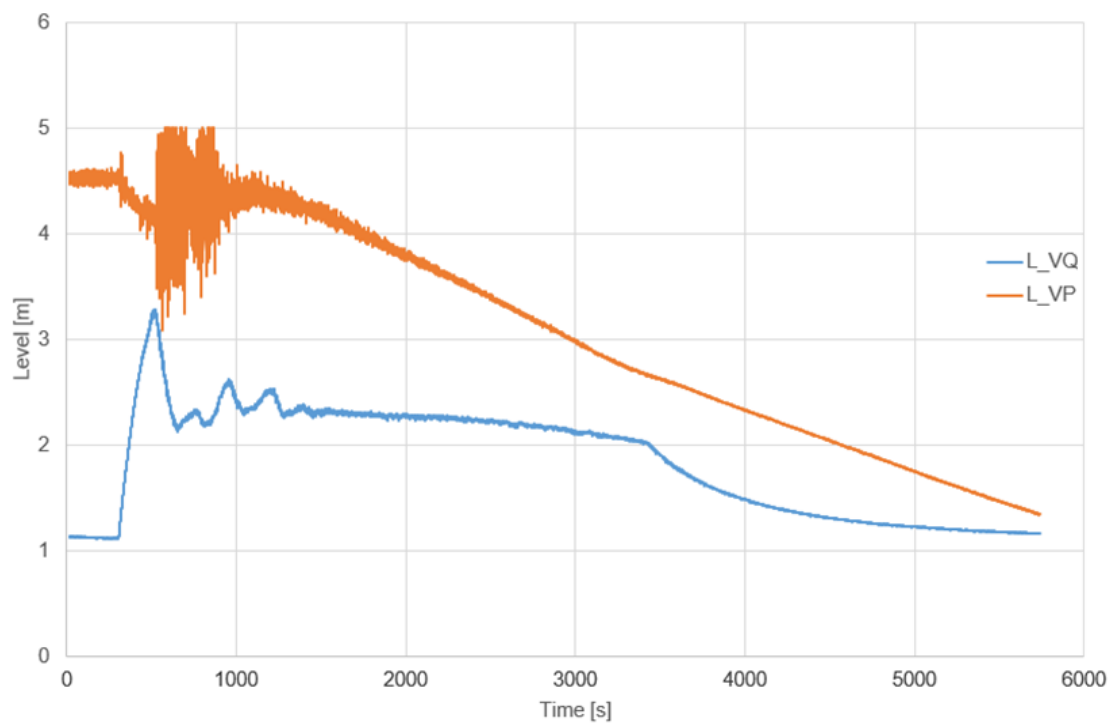


Figure 3.28. Test 7 Part 2 - HX exchanged power

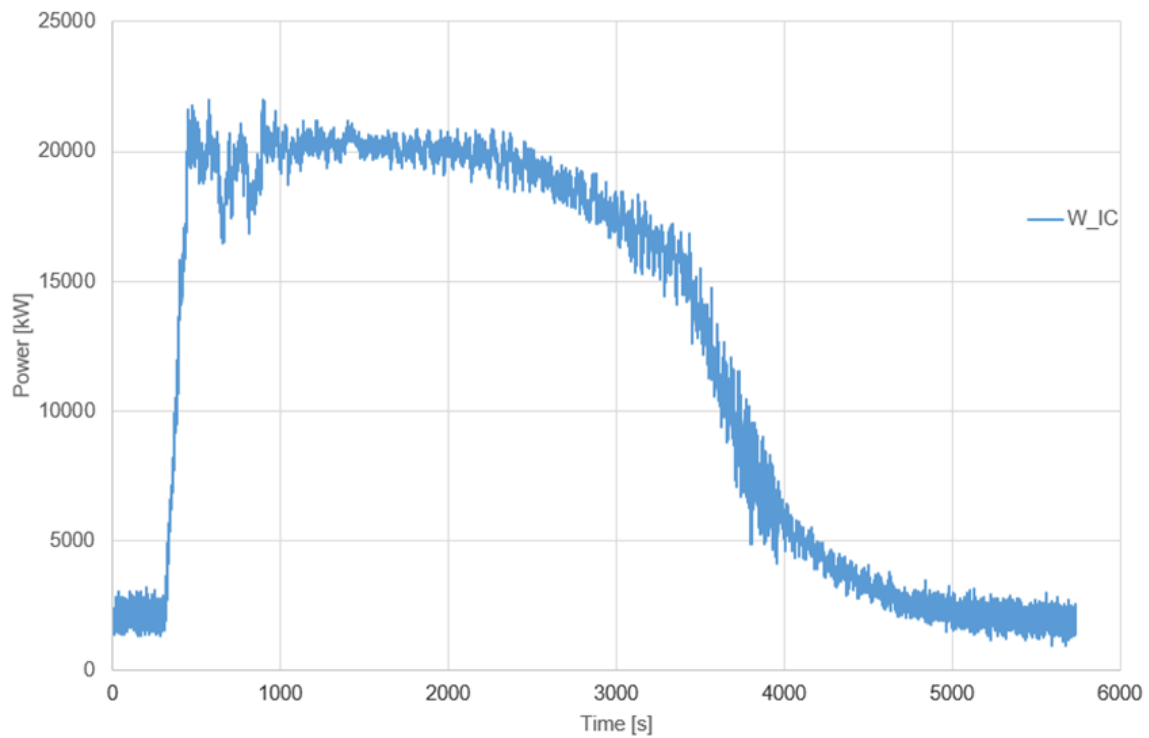


Figure 3.29. Test 7 Part 2 - Steam and condensate flowrate

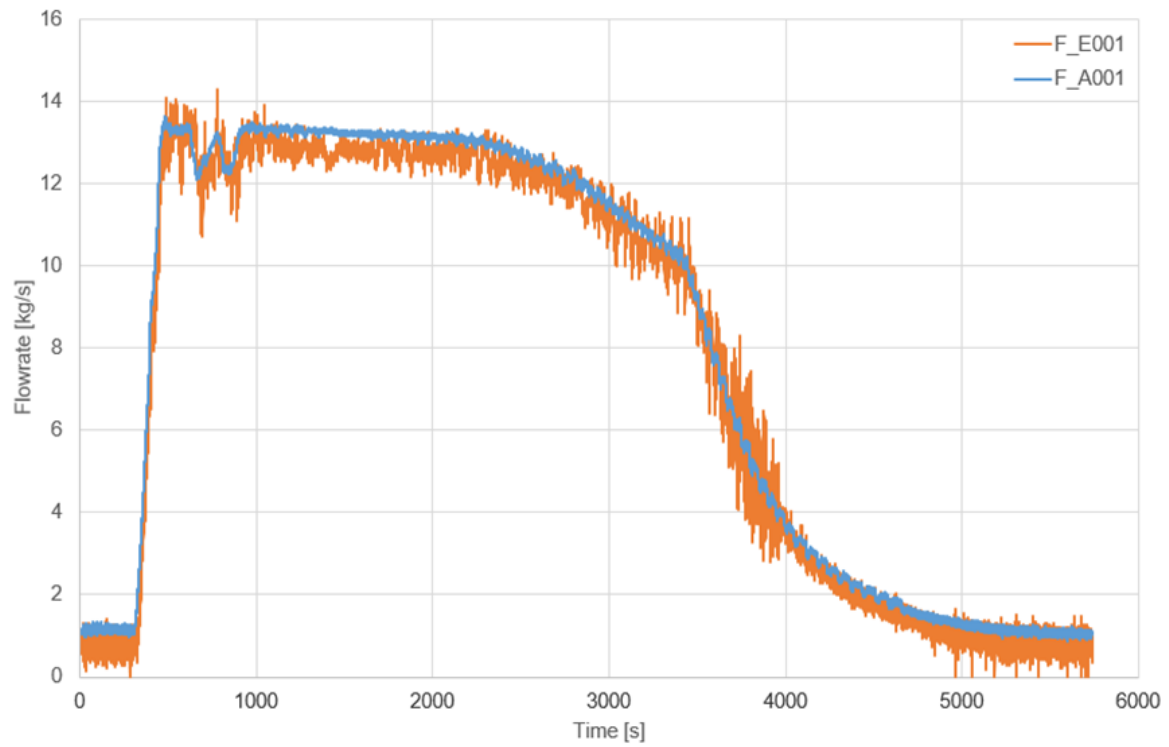


Figure 3.30. Test 7 Part 2 - HX pool temperatures (Level 1)

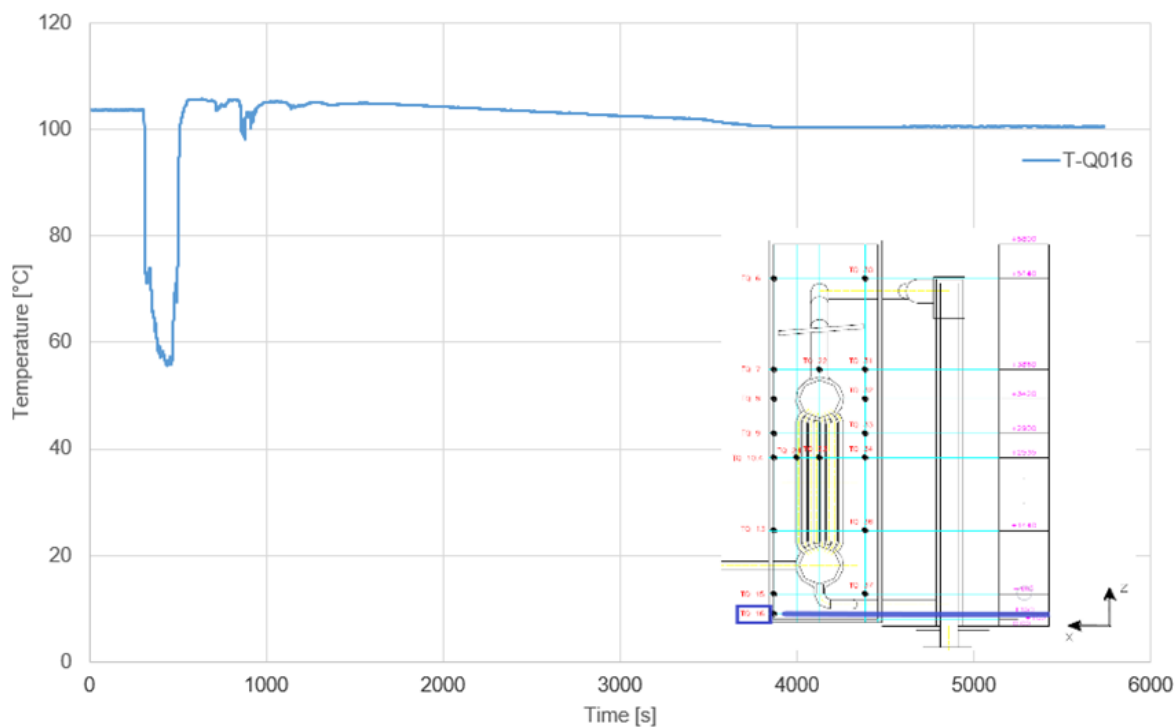


Figure 3.31. Test 7 Part 2 - HX pool temperatures (Level 2)

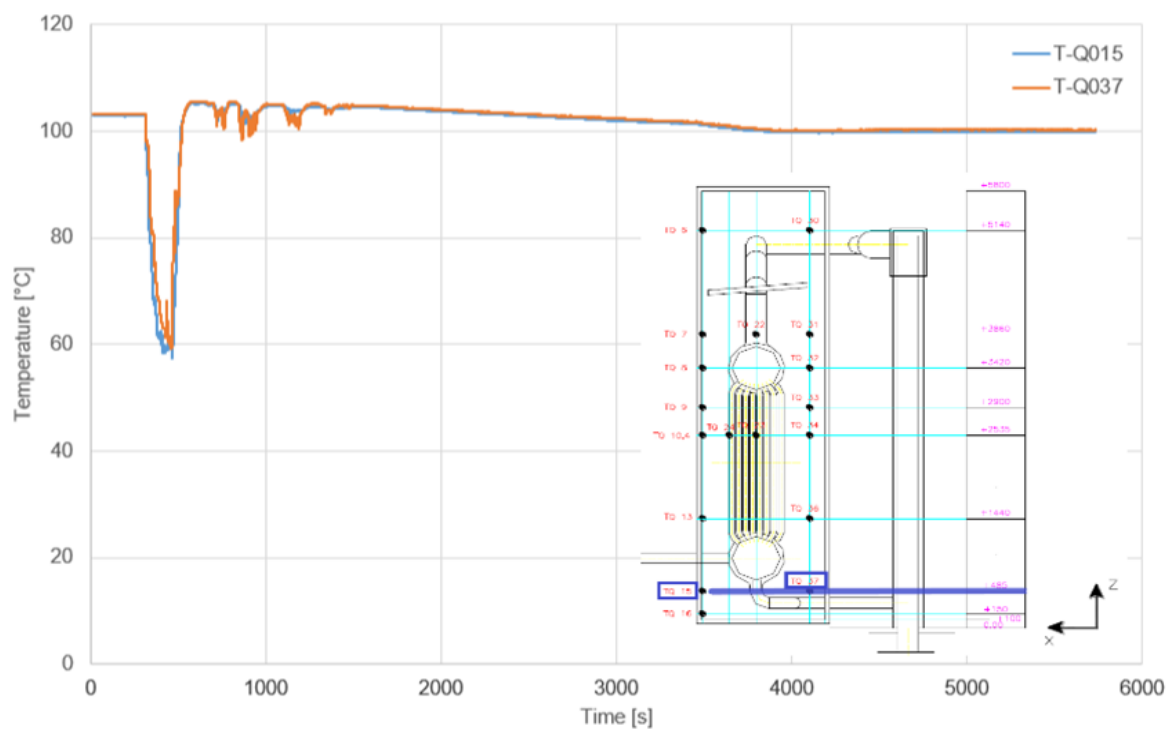


Figure 3.32. Test 7 Part 2 - HX pool temperatures (Level 3)

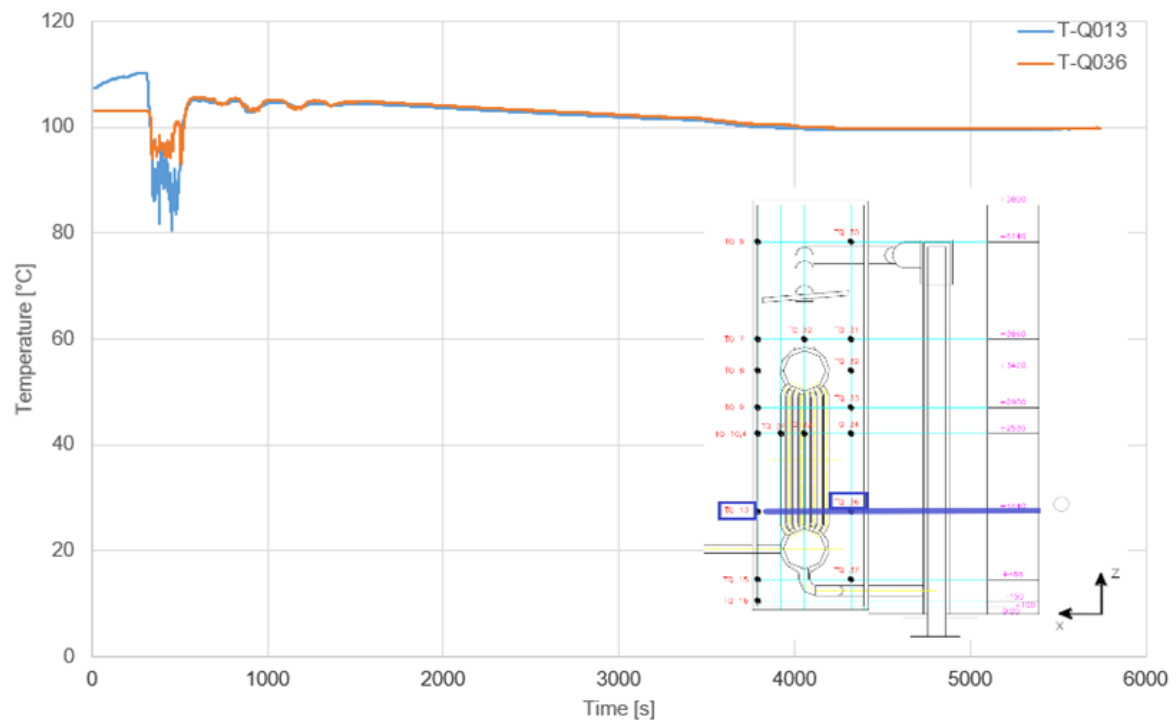


Figure 3.33. Test 7 Part 2 - HX pool temperatures (Level 4)

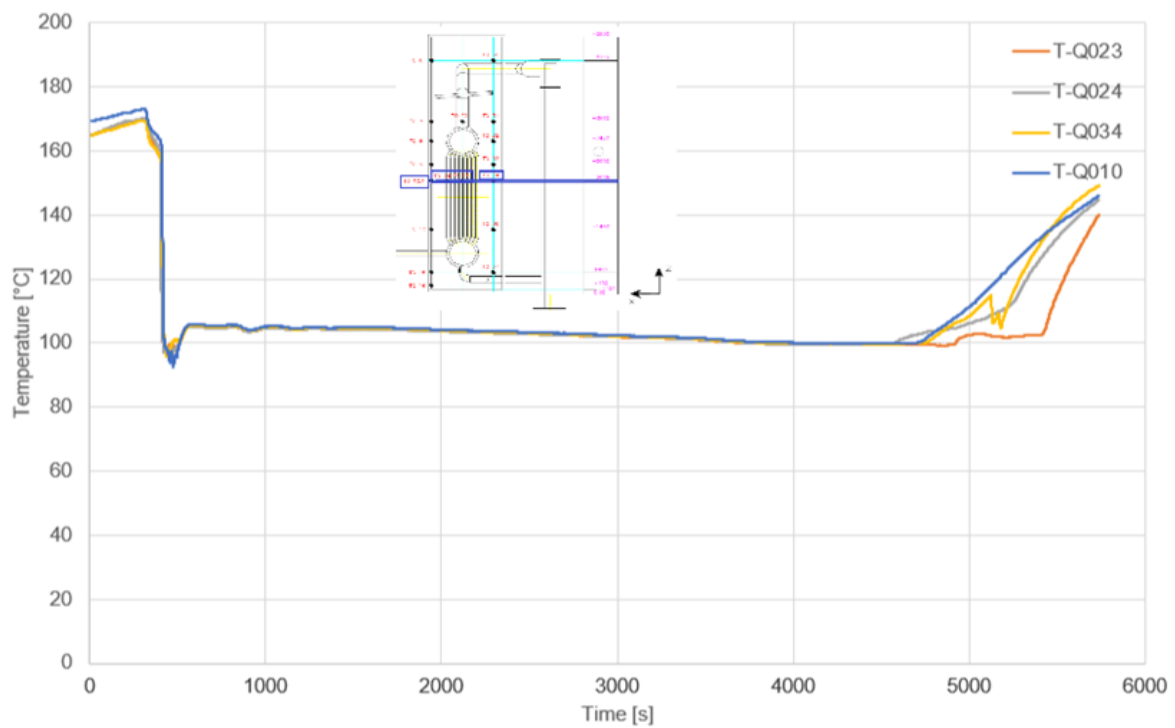


Figure 3.34. Test 7 Part 2 - HX pool temperatures (Level 5)

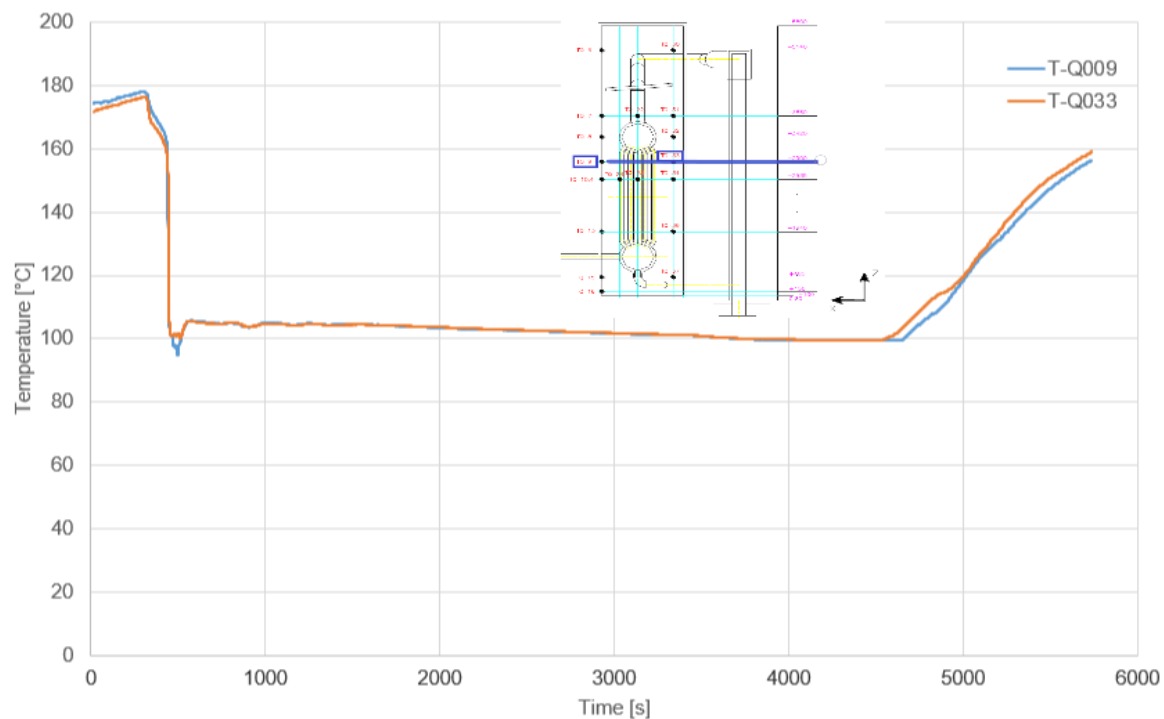


Figure 3.35. Test 7 Part 2 - HX pool temperatures (Level 6)

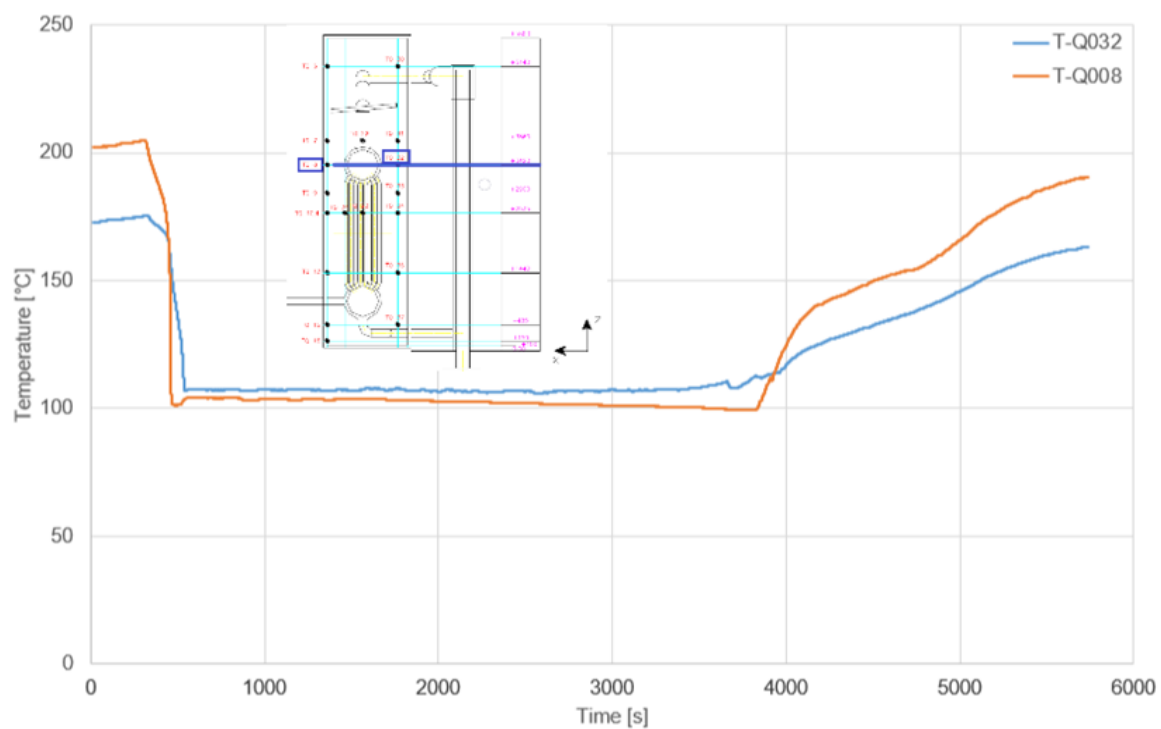


Figure 3.36. Test 7 Part 2 - HX pool temperatures (Level 7)

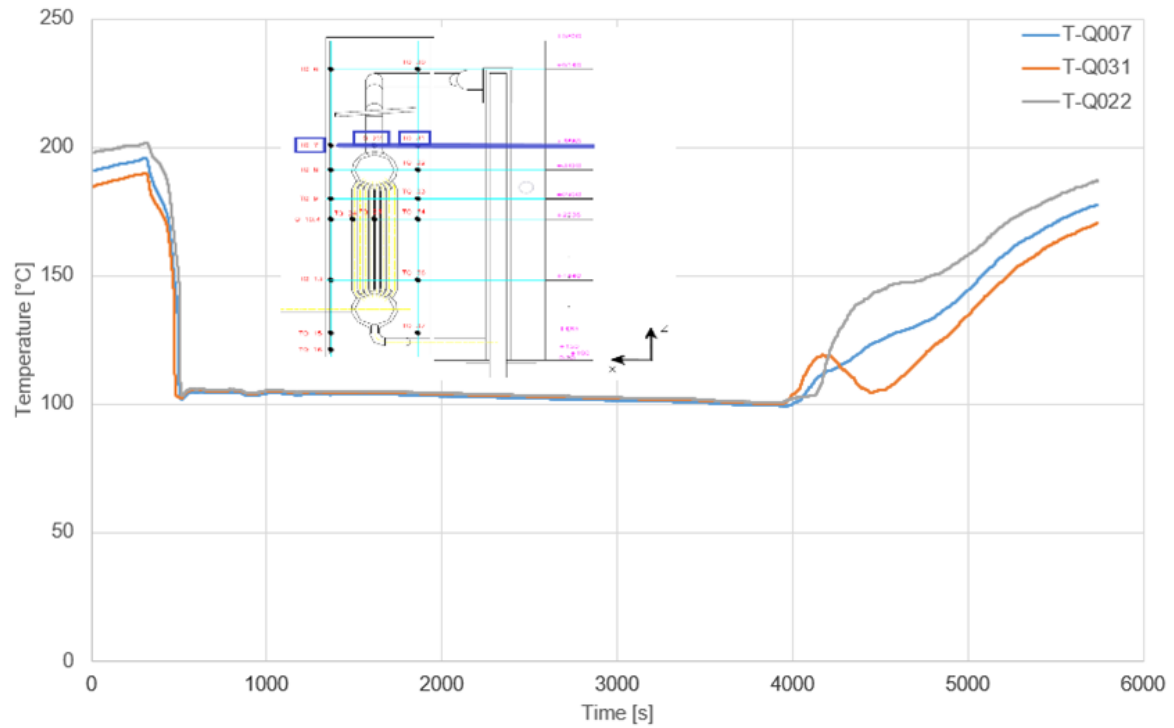


Figure 3.37. Test 7 Part 2 - HX pool temperatures (Level 8)

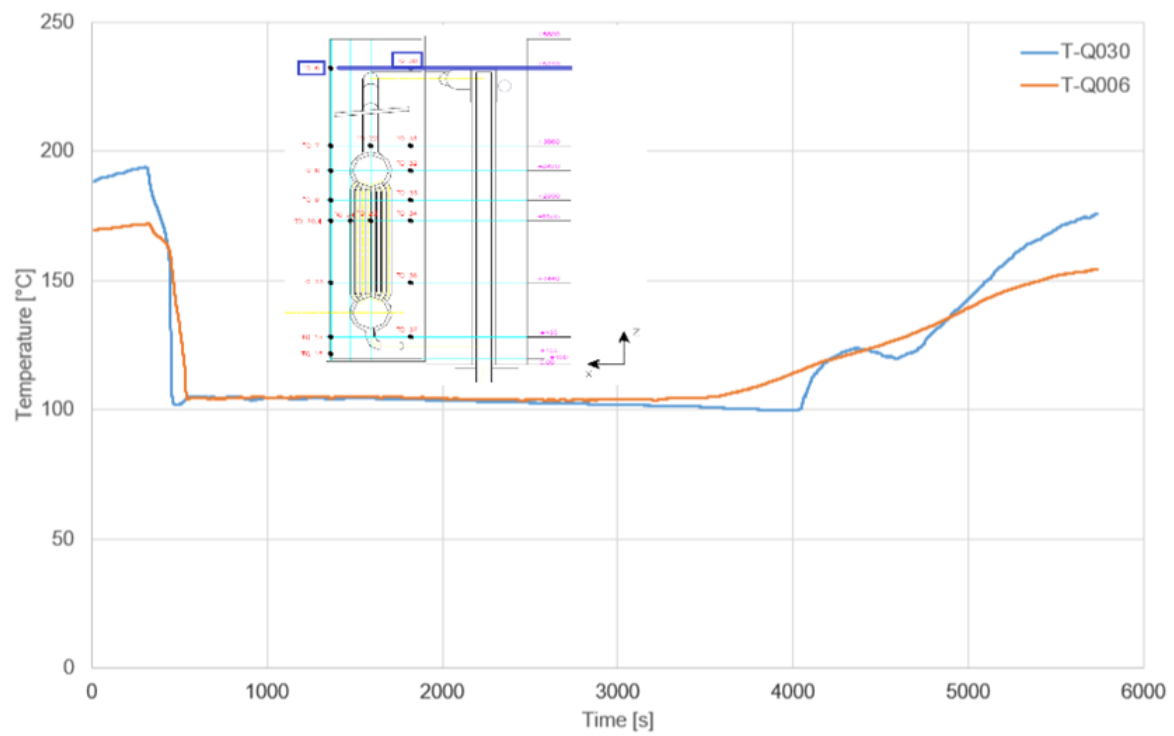


Figure 3.38. Test 7 Part 2 - HX pool relative pressure

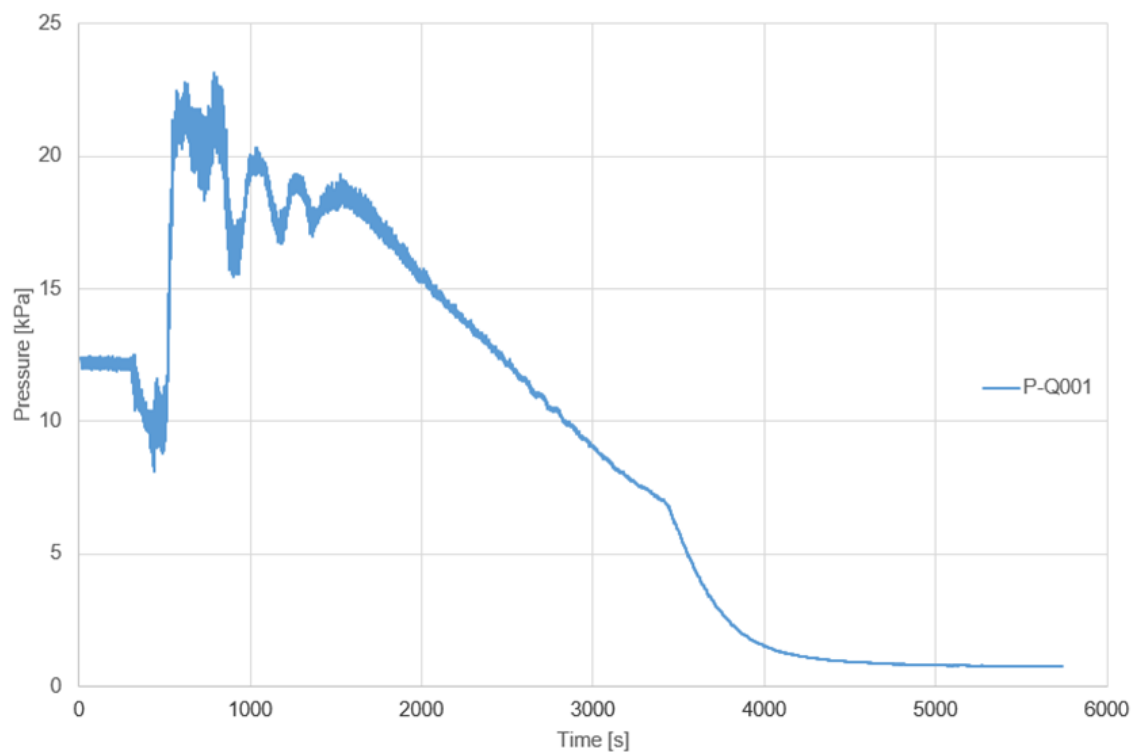


Figure 3.39. Test 7 Part 2 - Overall pool temperatures (Level 1)

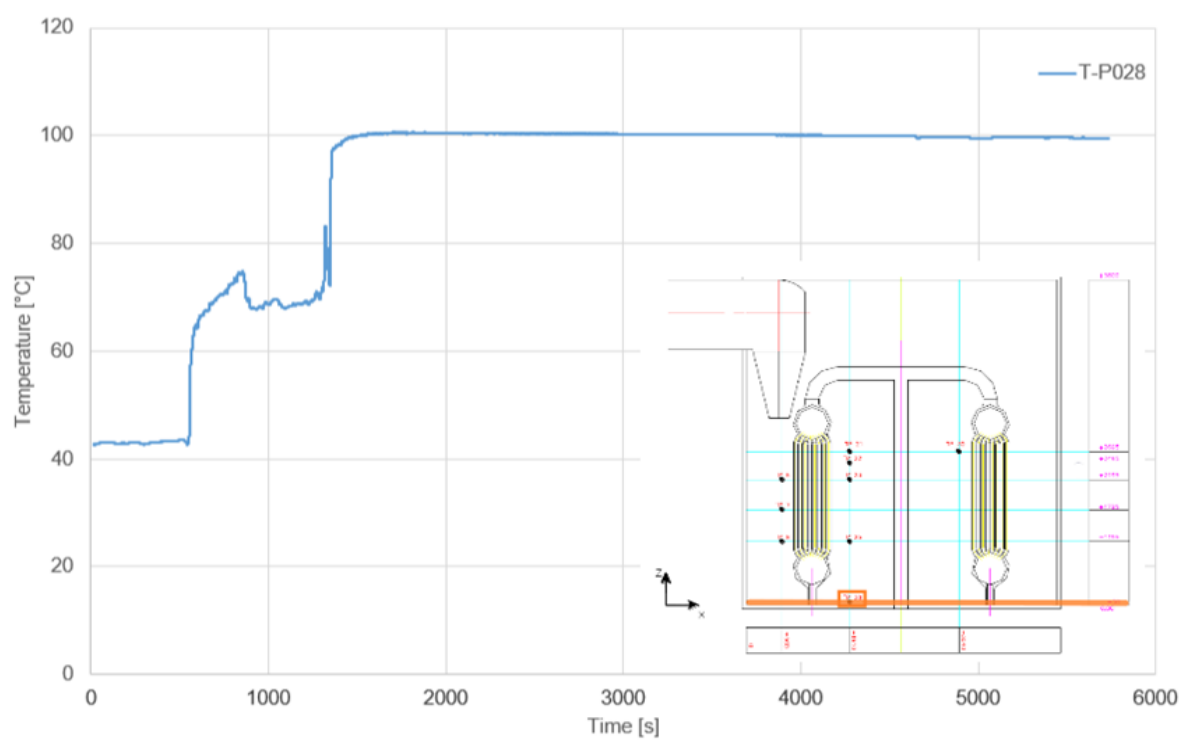


Figure 3.40. Test 7 Part 2 - Overall pool temperatures (Level 2)

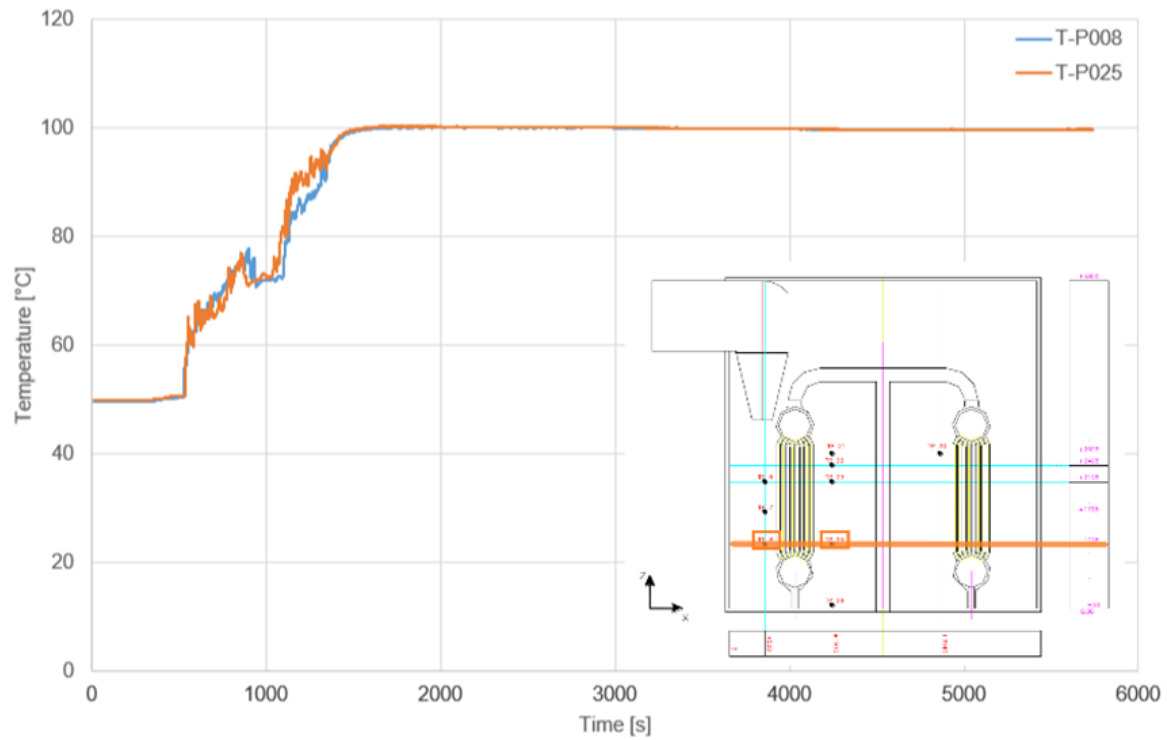


Figure 3.41. Test 7 Part 2 - Overall pool temperatures (Level 4)

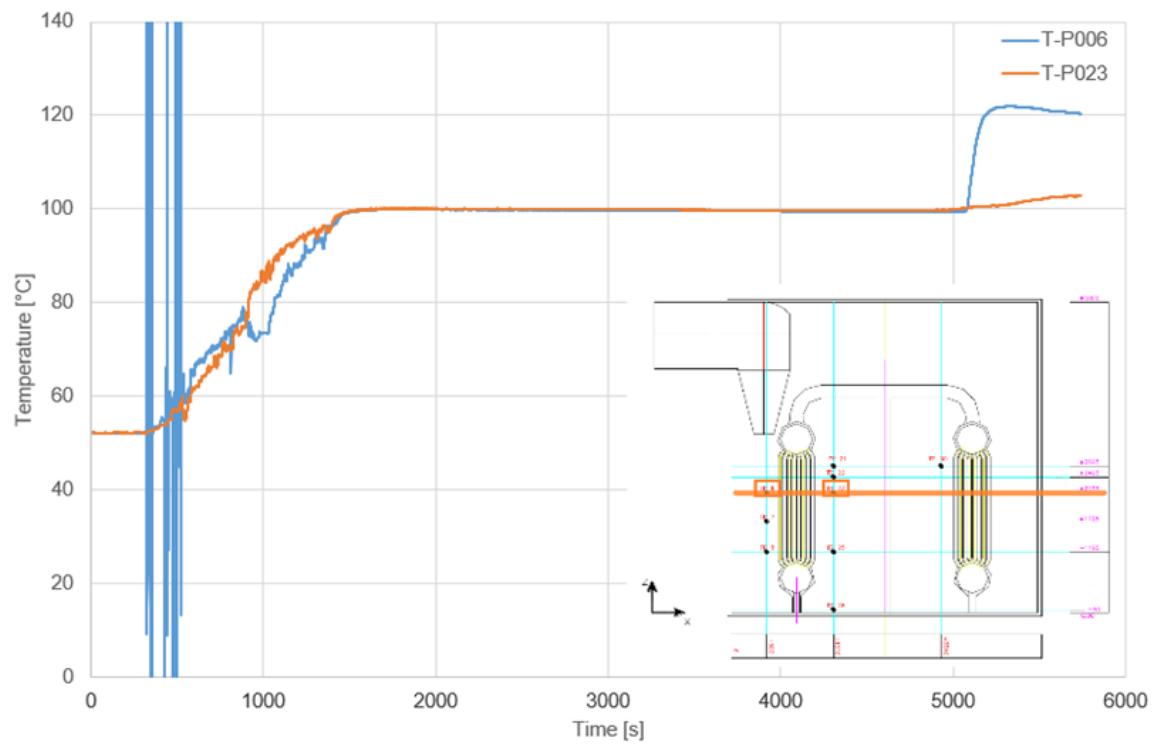


Figure 3.42. Test 7 Part 2 - Overall pool temperatures (Level 5)

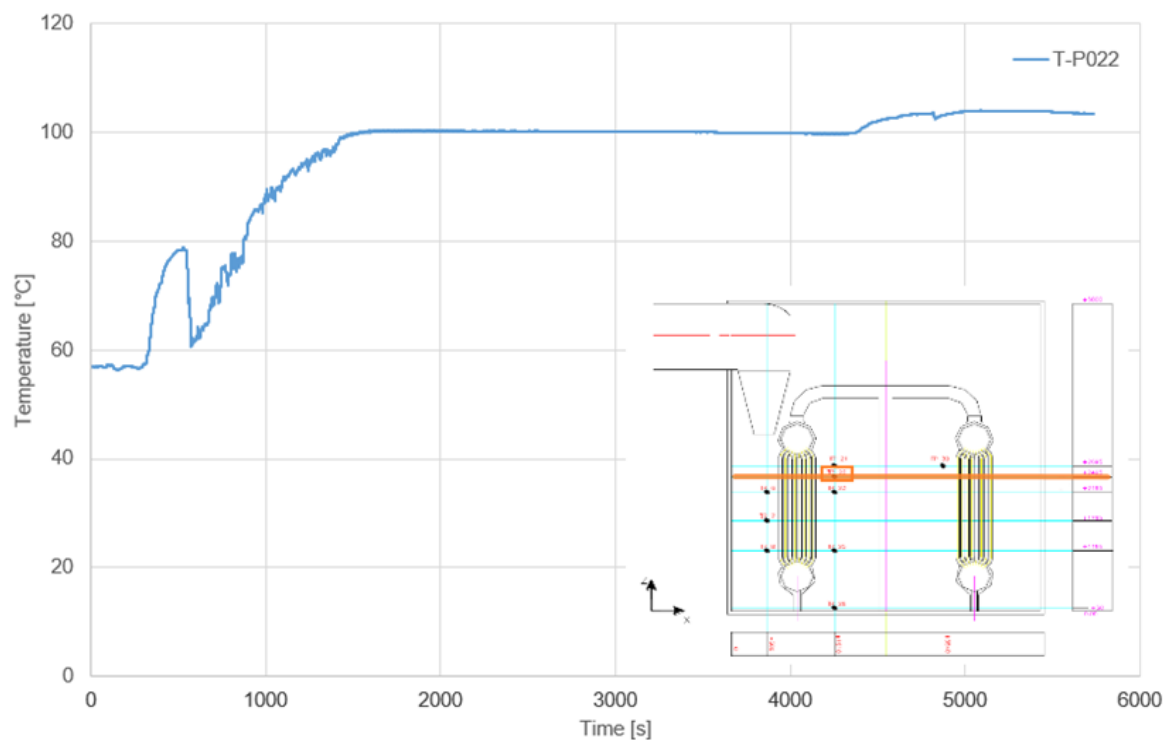


Figure 3.43. Test 7 Part 2 - Overall pool temperatures (Level 6)

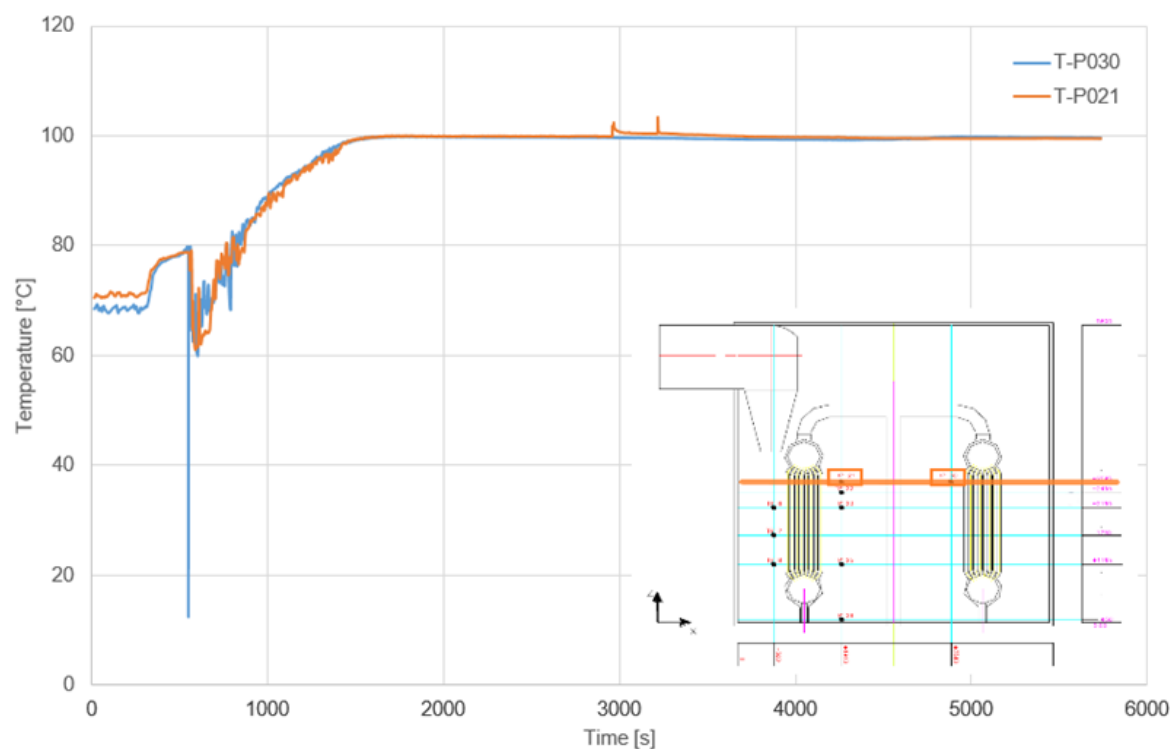


Figure 3.44. Test 7 Part 2 - Overall pool temperatures

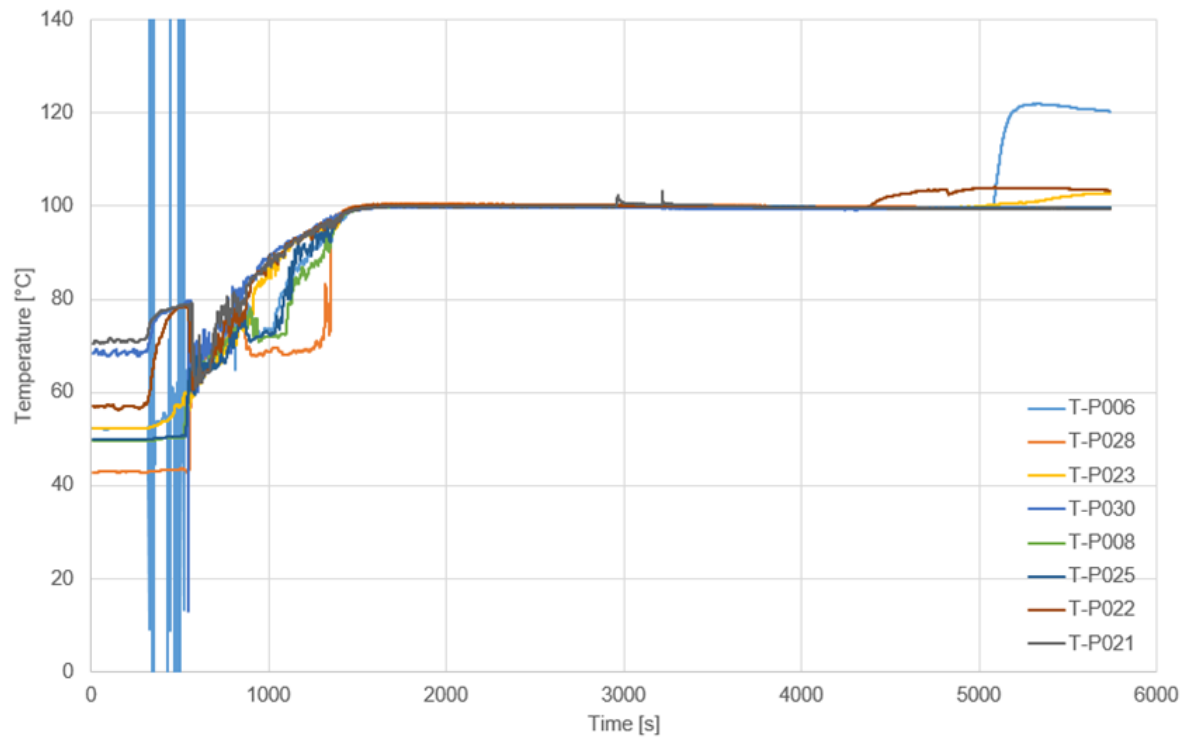


Figure 3.45. Test 7 Part 2 - Heat exchanger upper header wall temperature

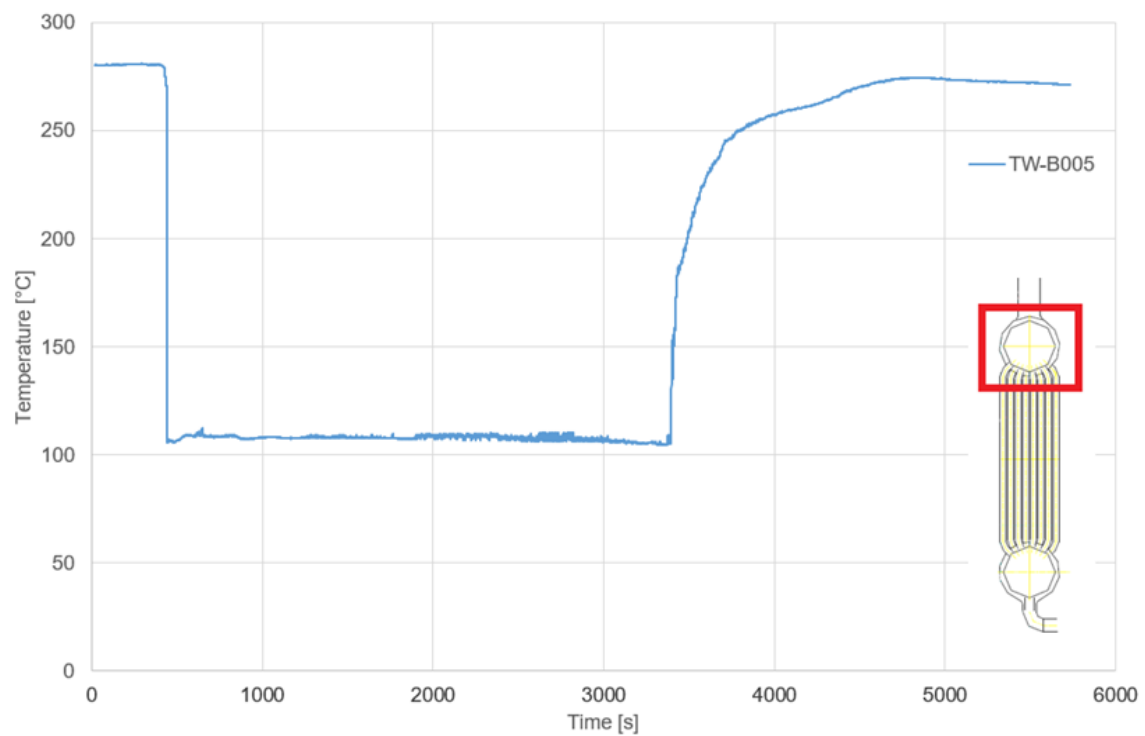
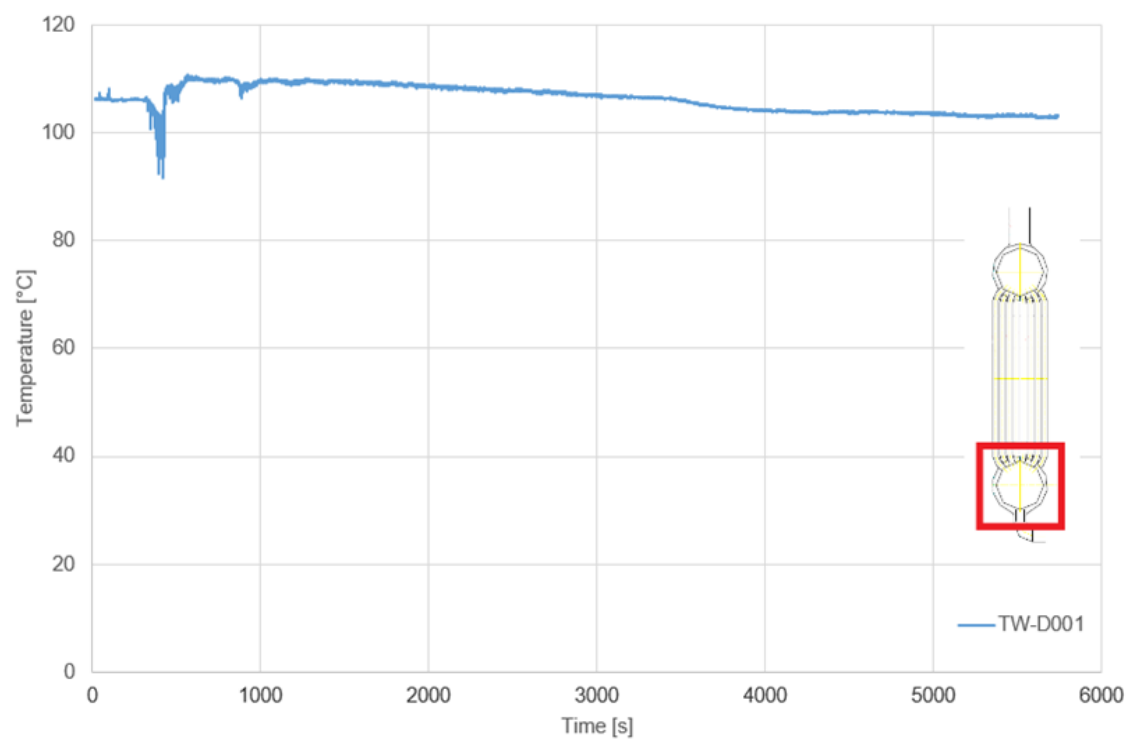


Figure 3.46. Test 7 Part 2 - Heat exchanger lower header wall temperature



4. Qualitative and quantitative accuracy evaluation: Hypothesis, target phenomena, methods

To assess the quality of a code prediction, a code validation process has to be fulfilled; the main parts of the code validation process are the “code internal development”⁶ and “code independent qualification”. The main goal of the “code independent qualification” is to evaluate the code accuracy (Mascari et al., 2015^[17]). Accuracy is connected with the qualitative and quantitative discrepancy in the comparison between measured and calculated trends. This evaluation is done by comparing the “calculated transient” against the “measured transient”.

It should be underlined that the validation of each individually adopted code is responsibility of the different code users and code developers, based on their methodology and acceptance criteria; then it is out of the target of the PERSEO benchmark. Instead, the target of this benchmark is to evaluate the capability of the adopted codes with a common methodology, already used in technical literature (D’Auria, Frogheri and Giannotti, 1999^[18]), and based on a qualitative and quantitative point of view. This permits to identify the main code limitations and new proposals for future further activities that can contribute to the improvement of the safety of current and advanced reactor designs.

The accuracy evaluation of the PERSEO benchmark is performed in two steps (Mascari et al., 2015^[17]) (D’Auria, Frogheri and Giannotti, 1999^[18]):

1. qualitative evaluation;
2. quantitative evaluation.

The qualitative evaluation is performed identifying the “relevant thermal hydraulic phenomena” in the system and the “phenomenological windows” where a relevant physical process occurs. In each phenomenological window the “relevant thermal hydraulic aspects” are then identified and they are used to characterise the phenomena of interest. Finally, it is possible to perform the qualitative analysis of the obtained results by comparison of the measured and calculated trends. Qualitative analysis is based on four subjective judgement marks (Excellent (+), Reasonable (o), Minimal (NA), Unqualified (-)), that is applied to the matrix of the selected phenomena. It is mainly based on a visual observation of the experimental and calculated trends. After the qualitative accuracy analysis, the quantitative evaluation has been performed. This evaluation is important to judge from a quantitative point of view the results of a calculation and properly assure its quality. Considering the subjective nature of the qualitative analysis, qualitative and quantitative accuracy evaluation should be considered complementary and they should be applied together to have a solid accuracy evaluation. The fast Fourier transform based method has been applied to quantitatively evaluate the accuracy of the calculations.

4.1. Qualitative accuracy evaluation

The PERSEO facility is suitable for observing several thermal-hydraulic phenomena such as: natural circulation, the behaviour of large pool of liquid and the performance of the emergency heat exchanger (IAEA-TECDOC-1677, 2012^[14]) (Mascari et al., 2019^[15]).

6. As reported in (Mascari et al., 2015^[17]) the code internal development is constituted by code verification and internal code validation. Therefore, its main target is to qualify the models implemented in the code and the global architecture.

A series of experimental parameters (either directly measured or derived from other quantities) have been selected to characterise the phenomena of interest. A matrix of phenomena observed and related experimental quantity is shown in Table 4.1. The occurrence in the facility of the phenomena of interest is qualitatively evaluated according to Table 4.2. In the same table also the code capability to qualitatively simulate the phenomena is ranked (Mascari et al., 2016^[19]). In Table 4.3 it is summarised the list of the parameters selected for the qualitative accuracy evaluation of the benchmark. The parameters have been proposed by ENEA and then agreed by the benchmark participants at the first passive system group meeting in Karlstein (Germany), 26-27 June 2018.

The phenomenon B “natural circulation in HXP and OP coupled circuit” is typical of this new advanced passive system proposal consisting of two coupled pools. The flow rate between the two pools, even if useful to characterise the natural circulation, has not been considered since it is available only in short time windows.

For phenomenon C, the absolute pressure and the removed power determine the operating conditions of the system; in these operating conditions there is a pressure drop profile. During the test one can identify a time window during which it is possible to fix a quasi-steady-operational point (as already mentioned). For phenomenon D it is important to characterise the in-tube condensation and the adopted correlations in the codes.

In relation to the phenomenon H the steam flow from the HXP to the OP is not available, only the pressure drops in the steam duct and in the injector are available. The consequent thermal stratification is investigated in phenomenon F thus it is not inserted in phenomenon H.

In phenomenon I heat losses are not inserted since they are not measured in the facility and they are expected to have a little effect on the operating conditions and on the simulation results.

Table 4.1. Phenomena characterised in PERSEO tests

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure HX upper-lower header	DP-003	
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
				Power heat exchanger	W IC (der.)	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
F	Behaviour of large pool: Thermal stratification	+	+	Power heat exchanger	W IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature OP (top)	T-P021	
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Power heat exchanger	W IC (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
				Level OP	L VP (der.)	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

** Ph. = phenomenon

Table 4.2. Experimental facility and code qualitative phenomena prediction evaluation

	+	o	NA	-
Experimental data	Phenomenon occurred in the test and it is directly measured	Phenomenon occurred in the test and it is indirectly measured	Phenomenon occurred during the test but there is no instrumentation to detect (lack of instrumentation)	Phenomenon did not occur in the test
Calculated data	Phenomenon is clearly predicted by the code (Excellent/Reasonable)	Phenomenon is partially predicted (i.e. the answer of the code is reasonable but closure relations are not appropriate, etc.)	Models are not appropriate to predict (i.e. nodalisation strategy, etc.) (Minimal)	Phenomenon is not predicted by the code (Unqualified)

Table 4.3. List of parameters selected for the benchmark

	Parameter	Plant code	Unit
1	Flow rate steam supply line	F_A001 (der.)	kg/s
2	Flow rate condensate drain line	F_E001 (der.)	kg/s
3	Power heat exchanger	W_IC (der.)	kW
4	Absolute pressure vessel	P-I001	kPa
5	HX inlet temperature	T-A005	°C
6	HX outlet temperature	T-E001	°C
7	Level HXP	L_VQ (der.)	m
8	Level OP	L_VP (der.)	m
9	Temperature HXP (bottom)	T-Q037	°C
10	Temperature HXP (middle)	T-Q034	°C
11	Temperature HXP (top)	T-Q031	°C
12	Relative pressure HXP top	P-Q001	kPa
13	Temperature OP (bottom)	T-P008	°C
14	Temperature OP (top)	T-P021	°C
15	Differential pressure HX upper-lower header	DP-003	kPa
16	Differential pressure steam duct injector	DP-J001	kPa
17	Wall temperature HX upper header	TW-B005	°C
18	Wall temperature HX lower header	TW-D001	°C

4.2. Quantitative accuracy evaluation

The quantitative accuracy evaluation of the benchmark results is performed applying the FFTBM (briefly described in Annex 1) to 12 selected parameters. The 12 parameters are a subset of the 18 considered in the qualitative evaluation. The parameters selected for the

quantitative accuracy evaluation have been proposed by ENEA and agreed by the benchmark participants at the second passive system group meeting in Tirrenia (Italy), 27 February – 1 March 2019.

The weighting factors adopted for the various parameters are reported in Table 4.4 with some notes regarding some assumptions made with respect to the original methodology (Prošek, D'Auria and Mavko, 2002_[6]) (proposed by ENEA and agreed by the benchmark participants at the second passive system group meeting in Tirrenia (Italy), 27 February – 1 March 2019). The weighting factors reported in the table consider the experimental accuracy (w_{exp}), the safety relevance (w_{saf}) and the parameter contribution to the primary pressure (w_{norm}).

Table 4.4. Weighting factors for the FFTBM application

Parameter	Type	w_{exp}	w_{saf}	w_{norm}	Note
F_A001	Flow rate	0.5	0.8	0.5	
W_IC	Power	0.8	0.8	0.5	Assumed as core power
P-I001	Pressure	1	1	1	Assumed as primary pressure
L_VQ	Collapsed level	0.8	0.9	0.6	
L_VP	Collapsed level	0.8	0.9	0.6	
T-Q034	Fluid temperature	0.8	0.8	2.4	
P-Q001	Pressure	1	0.6	1.1	Assumed as secondary pressure
T-P008	Fluid temperature	0.8	0.8	2.4	
T-P021	Fluid temperature	0.8	0.8	2.4	
DP-003	Pressure drop	0.7	0.7	0.5	
DP-J001	Pressure drop	0.7	0.7	0.5	
TW-B005	Outer wall temperature	0.9	1	1.2	Assumed as cladding temperature

5. Benchmark participants and individual reports

5.1. Benchmark participants and codes

Nineteen organisations worldwide expressed interest in participating in the benchmark. Twelve results from eleven organisations were submitted according to the fixed deadlines, original and extended. The original deadline for submitting the results was fixed for 31 March 2019; considering the interest in the activity, a new deadline (10 January 2020) was proposed and accepted at the last working group meeting (Tirrenia, 11- 13 December 2019). Two late submissions, one updated calculation and a new organisation with a late submission were accepted. Eight organisations withdrew from the benchmark. Noticeably, 7 out of 12 calculations presented in this benchmark report were carried out by code developers. Table 5.1 summarises the participants, the adopted codes and the results received. Afterwards, in Section 5.2, the individual reports of all the benchmark participants are collected.

Table 5.1. Summary of the participants and adopted codes

COUNTRY	INSTITUTION	CODE	RESULTS AND REPORT DELIVERED
Canada	CNSC/CCSN	-	Cancelled
China	SPICRI	-	Cancelled
Croatia	FER	-	Cancelled
Czechia	UJV	RELAP5/MOD3.3Patch05	✓
		MELCOR v2.	Cancelled
		GOTHIC	Cancelled
Finland	VTT	Apros 6.09	✓
France	IRSN	CATHARE	Cancelled
Germany	GRS	ATHLET 3.2	✓
Italy	POLITO	RELAP5-3D v4.3.4	✓
	UNIPI	RELAP5/MOD3.3Patch03	✓
	UNIROMA1	RELAP5-3D	✓
Netherlands	NRG	SPECTRA v3.61	✓
Russia	IBRAE	SOCRAT	✓
Korea	KAERI	MARS-KS v1.4	✓
		SPACE v3.2	✓
	KINS	-	Cancelled
Spain	UPV	-	Cancelled
United States	NuScale	-	Cancelled
	UofU	MELCOR v2.2.11620	✓
	OSU	-	Cancelled
	USNRC	TRACE V5.1175	✓

5.2. Individual benchmark participants report

5.2.1. GRS

SECTION 1: GENERAL INFORMATION

- Organisation: GRS gGmbH (Germany)
- Contact persons/authors: Sebastian Buchholz, Henrique Austregesilo
- Code: ATHLET 3.2
- Computing environment:
 - Operative systems PC Windows 10 Enterprise
 - RAM 16 GB
 - CPU characteristics Intel Core i5-8350U with 4 Cores and HT

SECTION 2: DESCRIPTION OF THE CODE USED

The thermal-hydraulic system code analysis of thermal hydraulics of leaks and transients (ATHLET), part of the GRS code package AC², is being developed for the detailed analysis of the whole spectrum of events from normal operation up to design extension conditions without core degradation. The code is applicable for western reactor light water reactor designs, for Russian VVER and RBMK reactors and has diverse capabilities for reactors with other working fluids. The main code features are:

- advanced thermal hydraulics;
- modular code architecture;
- separation between physical models and numerical methods;
- portability to the prevalent computer platforms.

ATHLET is composed of several basic modules for the simulation of the different phenomena involved in the operation of a light water reactor, i.e. the thermo-fluid dynamics (TFD), the heat transfer and heat conduction (HECU), neutron kinetics (NEUKIN), and the control and balance-of-plant (GCSM), together with the fully implicit numerical time integration method FEBE. Other independent modules (e.g. 3-D neutron kinetics or containment modules) can be coupled by means of a general interface.

The thermo-fluid-dynamic module is based on a six-equation model, with fully separated balance equations for liquid and vapour, complemented by mass conservation equations for up to six different non-condensable gases and by a boron tracking model. Alternatively, a five-equation model, with a mixture momentum equation and a full-range drift-flux formulation for the calculation of the relative velocity between phases is also available. Specific models for pumps, valves, separators, turbines, mixture level tracking, critical flow etc. are also included in ATHLET. The system configuration to be simulated is modelled just by connecting basic thermo-fluid dynamic elements, called thermo-fluid (TF) and heat conduction (HC) objects. Multidimensional processes are simulated by a dedicated 2D/3D TF model in cartesian or cylindrical co-ordinates. Optionally, one-dimensional parallel channels with cross connection flows may also be used.

The range of code applicability has been newly extended to supercritical water, enabling the transition from super- to subcritical fluid states. In addition to light water, further

coolants can be simulated as working fluids: heavy water, helium, sodium, lead and lead-bismuth.

The systematic validation of ATHLET [5.2.1 1] is based on a well-balanced set of integral and separate effects tests derived from the CSNI code validation matrices.

The pool side heat transfer is determined by the modified model of Chen (for subcooled and saturated nucleate boiling) and the model of McAdams (natural convection) [5.2.1 5]. For the tube side, the models of Chen (macroscopic part only, forced convection), Nusselt (laminar condensation) and Carpenter and Colburn (turbulent condensation) [5.2.1 5] have been replaced by the models of Nusselt (laminar condensation), Kutateladze (laminar wavy condensation) and Chen (turbulent condensation) proposed in [5.2.1 3].

The newly implemented correlations enhance the heat transfer coefficient depending on the Reynolds number of the liquid inside the tubes. A comparison of the heat transfer coefficients for PERSEO Test 7 Part 2 at approximately 2 000 s is shown in the following Figure 5.2 (from top to bottom of the pipes with increasing node number). While the heat transfer coefficient is almost constant over the height of the heat exchanger when standard ATHLET 3.2 [5.2.1 2] is used, in the developer version (`_dev`) the coefficient is higher at the same locations. Furthermore, its behaviour depends on the condensation regime: At the top of the tubes, the condensation is laminar and the heat transfer coefficient is decreasing due to an increasing water film thickness at the tube wall. When the condensation becomes turbulent (from node three to seven) the heat transfer coefficients are increasing. This enhancement of the condensation heat transfer coefficient leads to a better prediction of the transferred power over the heat exchanger which is shown in Figure 5.1. Without the additional correlations, the power is underpredicted by ATHLET by approximately 20% (on the base of the experimental data), while including the correlations the difference shrinks to five.

Figure 5.1. HX power before and after AC2 modification

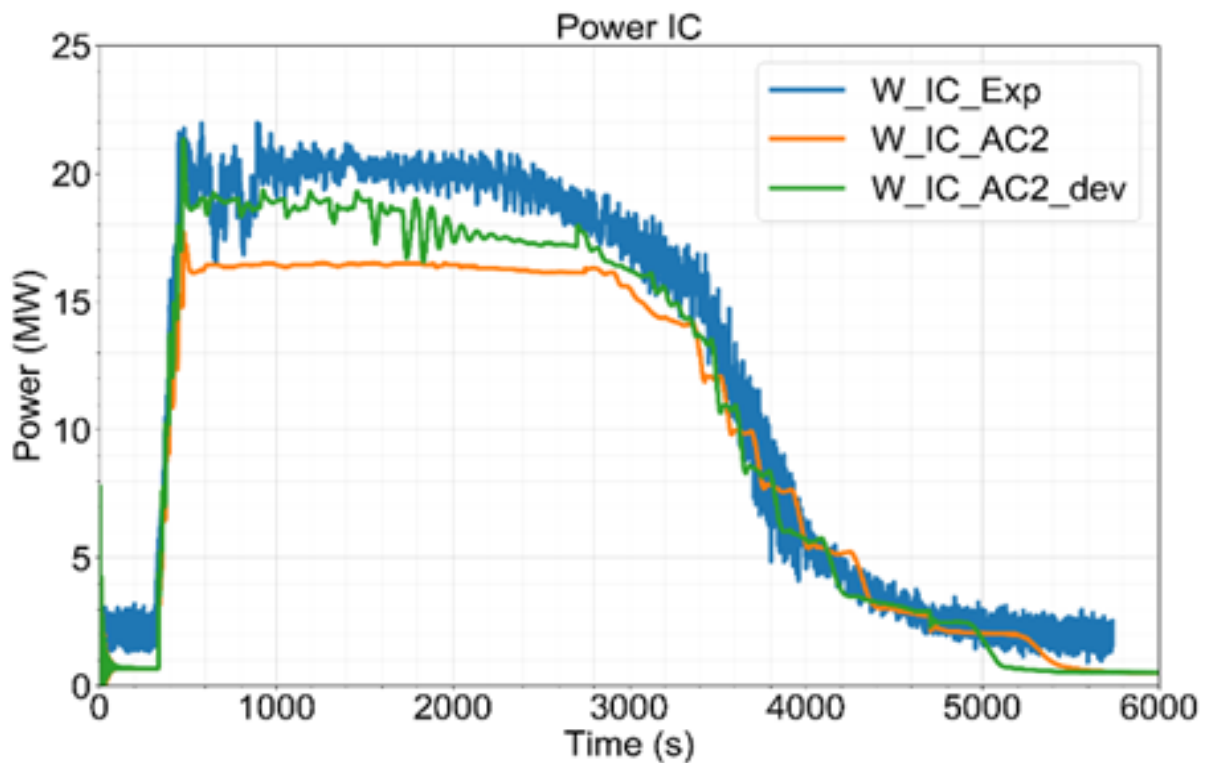
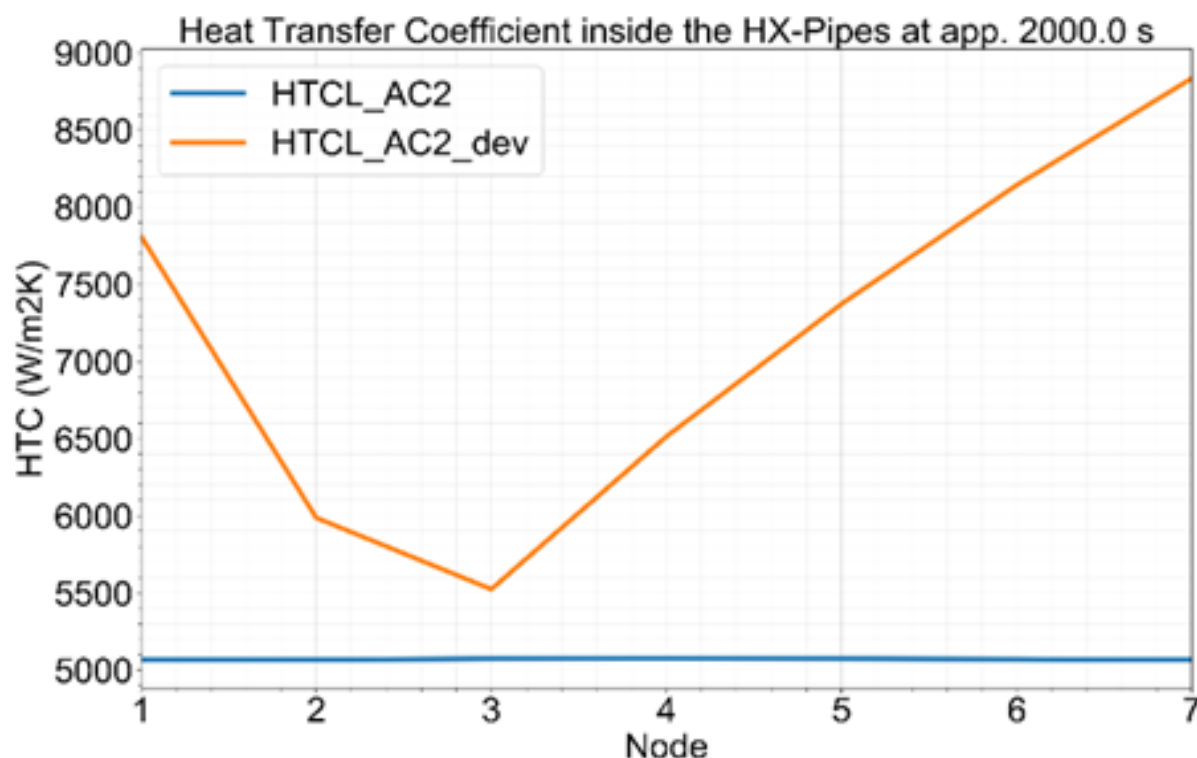


Figure 5.2. Heat transfer coefficient as function of the HX axial nodes



For PERSEO, the six-equation system is mainly used. However, since the mixture level tracking model was needed for the simulation of the mixture levels within the RPV and both water pools, for these objects the five-equation system has been implemented. For wall friction, the Darcy-Weissbach friction factor is calculated with the equations of Hagen-Poiseuille and Colebrook. Furthermore, a two-phase friction multiplier is determined by the Martinelli-Nelson model. Form losses are included by user input.

SECTION 3: DESCRIPTION OF THE NODALISATION

The ATHLET model of PERSEO consists of two fluid dynamic systems. The first one is composed of the pressure vessel, steam line, heat exchanger (including upper and lower header and heat exchanger pipes) and the drain line. Furthermore, a time-dependent volume (pressure and enthalpy boundary object) is defined at the gas/steam region of the pressure vessel, since no data was available concerning the steam injection into the first circuit. The boundary can be disabled by closing a valve which connects the boundary with the vessel. For keeping a constant liquid level inside the vessel, a water drainage has been adopted, modelled as a so-called Fill object. The second fluid dynamic system consists of the two water pools and their connecting lines. Both pools are modelled as a two-channel representation to achieve a mixing of the water inventory of the pools. At the top of the heat exchanger pool, a pressure and enthalpy boundary has been set, which also can be disabled by a valve. A second boundary is given at the end of the boil-off line, which is connected to the top of the overall pool for steam release into the environment. The heat exchanger pool pipe (shell side of the heat exchanger) was implemented with a model option for vertical bundles considering the pitch of the heat exchanger pipes which influences the heat transfer.

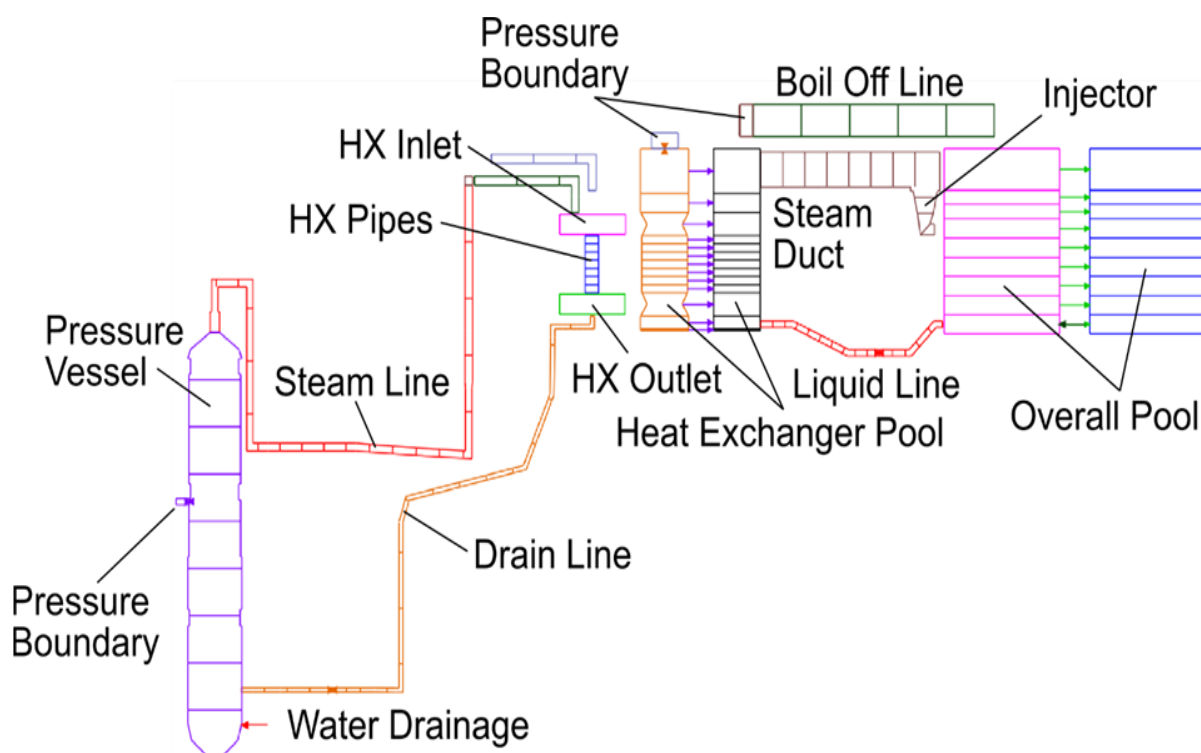
All objects are equipped with wall structures, so-called heat conduction objects, except for the heat exchanger pool channel, which includes the heat exchanger since this one is the

inner channel of the pool. The insulation of the structures has been considered. Material properties were taken from the information provided by the experimenters, except the heat conductivity of INCONEL 600, which differ in the literature (e.g. VDI Wärmeatlas [5.2.1 4]) in a range between $+1 - +2$ W/m K in the temperature range of $100^{\circ}\text{C} - 300^{\circ}\text{C}$ from the provided information and the higher values were taken. Heat losses are modelled by giving a fixed environment temperature and a fixed heat transfer coefficient of $10 \text{ W/m}^2 \text{ K}$ as an outside condition.

Table 5.2. Summary of the main nodalisation characteristics of the PERSEO model

	Number of hydraulic volumes	Number of junctions	Number of heat structures	Overall Volume (m ³)
Vessel	9	9	1	38.58
Steam line	27	29	7	2.398
HX	9	8	5	1.826
Condensate line	20	21	2	0.5402
HXP	26	41	2	26.96
Steam duct	11	12	3	12.95
OP	18	29	4	173.0
Heat transfer area HX (m ²)	Inner area: 42.665, outer area: 46.722			
HX heat structure axial nodes number	11			
HX heat structure radial nodes number	3			

Figure 5.3. GRS nodalisation of PERSEO facility



SECTION 4: RESULTS

TEST 7 Part 1

Calculations of this experiment with the standard ATHLET 3.2 did not lead to suitable and satisfying results. The power of the heat exchanger was underpredicted. For that reason, a developer version of ATHLET 3.2 has been created and the heat transfer models for condensation inside vertical pipes have been exchanged by the models described at the end of Section 2. The following results have been obtained by using the developer version. The newly implemented correlations will be adopted into the main version of ATHLET in such a way, that the user can choose them for special heat transfer objects.

The initial conditions are specified by the user within the corresponding ATHLET input deck on the base of the experimental data. With start of the calculation, ATHLET first performs a so-called steady state calculation, which is needed to ensure steady state conditions of the thermal-hydraulic network to avoid unexpected initial transients.

Initially, the pressure inside the pressure vessel (steam part) is 7.0 821 MPa. The temperature is 286.4°C (saturation temperature) and the collapsed level is -9.42 m. Pressure and enthalpy were fixed by a time-dependent volume connected to the upper part of the pressure vessel. The heat exchanger pool is initially fully filled with air at a pressure of 0.126 MPa and a temperature distribution of 80.3°C to 228.7°C from bottom to top. The collapsed level is at 0.1 m, which is the height of the bottom of the pool (so initially, no water is inside the heat exchanger pool). The overall pool is filled with water (collapsed level: 4.65 m, temperature: 15.4°C). The pressure within the gas region is 0.1 MPa. The gas region is filled with air and steam with the steam partial pressure equal the saturation pressure at 15.4°C. The liquid line connecting both pools is closed by a valve and is filled with water in the overall pool side only.

During the steady state phase, the pressure and enthalpy boundary connected with the upper part of the heat exchanger pool is active to prevent the system from a pressure decrease due to condensation within the vessel. After the steady state phase, the experiment starts at 10 475 s with partially (85%) opening the valve in the liquid line. Consequently, water is flowing from the overall to the heat exchanger pool, indicated by an increase of the water level within the pool (Figure 5.10). Five seconds after opening the valve, the above-mentioned boundary condition is deactivated. At 10 608 s, the valve is closed and reopened (85%) again at 10 621 s. At 10 655 s it is closed again until 11 039 s. At this time point, it is fully opened. It is finally closed at 11 260 s. The opening time for the valve has been set to 5 s.

The resulting behaviour of the pool collapsed levels (L_{VQ} , L_{VP}) (Figure 5.10 and Figure 5.11) are in a good agreement with the experimental data. At the primary side, the mean mass flow rates into and from the heat exchanger are also in good agreement (Figure 5.4 and Figure 5.5), whereas the peak values are not fully reached. Since the transferred power is calculated by the mass flow rates and the corresponding enthalpies of the fluid at the in- and outlet, the calculated transferred power (Figure 5.6) is slightly underestimated (approximately 5%, based on the experimental data). Due to the fixed pressure boundary the pressure within the pressure vessel (Figure 5.7) stays constant as well as the inlet temperature (Figure 5.8), while fluctuations in the pressure and temperature can be observed in the experimental data. The constant pressure has been chosen since no information about the steam injection control system were provided (mass flow rate and enthalpy) and therefore this system could be reproduced in the simulation.

The experimental data regarding the condition within the pressure vessel is not clear: It can be seen that the temperature T-A005 (Figure 5.8) follows the pressure P-I001 (Figure 5.7), which would be the case if the temperature is the saturation temperature to P-I001. For the

mean pressure inside the vessel (7.056 MPa) the saturation temperature is 286.4°C. But in the experimental data, the mean measured temperature is about 291.5°C which corresponds to 7.6 MPa. One possibility could be that not the bulk, but a wall or film temperature is measured. For the calculations the experimental pressure has been considered and therefore also the saturation temperature, which is lower than the experimentally determined temperature.

In the comparisons of the heat exchanger pool temperatures, larger differences between experiment and calculations for the steady state values can be observed for the top and bottom measurements (T-Q031 and T-Q037, Figure 5.12 to Figure 5.14). While the experimental values were put into the input deck correctly, the output values after the steady state calculation are mean values of the corresponding control volumes, which may differ from the initial input values. With start of the heat transfer between 11 100 s and 13 000 s the agreement becomes better, since the temperatures of the water inventory reach saturation conditions.

The mixing of the overall pool water inventory might be underestimated by the code. The temperature at the top (T-P021, Figure 5.17) of the overall pool becomes higher in the simulation than in the experiment, while the temperature at the bottom of the pool (T-P008, Figure 5.16) is lower in the simulation than in the experiment.

The wall temperatures of the upper and lower header (TW-B005, Figure 5.20 and TW-D001, Figure 5.21) are in a qualitatively good agreement with the experimental data. The differences may be due to a coarse nodalisation of the header. The upper and lower header are simulated in ATHLET by a branch object each. Consequently, the heat conduction objects simulating the header walls are also modelled with only one control volume.

The relative pressure within the heat exchanger pool (P-Q001, Figure 5.15) has been set higher in the simulation for the steady state case, since otherwise water from the overall pool would have flowed backwards through the steam duct into the heat exchanger pool during the steady state phase. After starting the experiment with the first opening of the liquid line valve, the calculated relative pressure first agrees well but later it overestimates the experimental data during the main heat transfer phase between 11 100 s and 12 000 s. After that, the agreement is good. The pressure difference between the upper and lower header (DP-003, Figure 5.18) is overestimated (in absolute values) but shows qualitatively the same behaviour. The measurement DP-003 is part of a closed pressure difference chain over the whole primary circuit. The sum of all pressure differences should be zero (value DPsum, Figure 5.22). While in the simulation DPsum is zero, in the experiment it is not. Therefore, a comparison of DP-003 is not reasonable.

The differential pressure over the injector (DP-J001, Figure 5.19) is underestimated by ATHLET between 11 100 s and 12 000 s. One reason for that may be the higher temperature at the top of the overall pool leading to a less high counterpressure above the injector, leading to a lower differential pressure.

A total number of 50 727 time steps have been performed. The CPU time was 3 394 s. Since ATHLET has a variable time step size automatically defined by the error convergence criteria within the implicit integration procedure FEBE in ATHLET, no general time step size can be provided. But the bandwidth in the calculation was between 0.005 s and 0.5 s.

Figure 5.4. Test 7 Part 1 - Steam flow rate

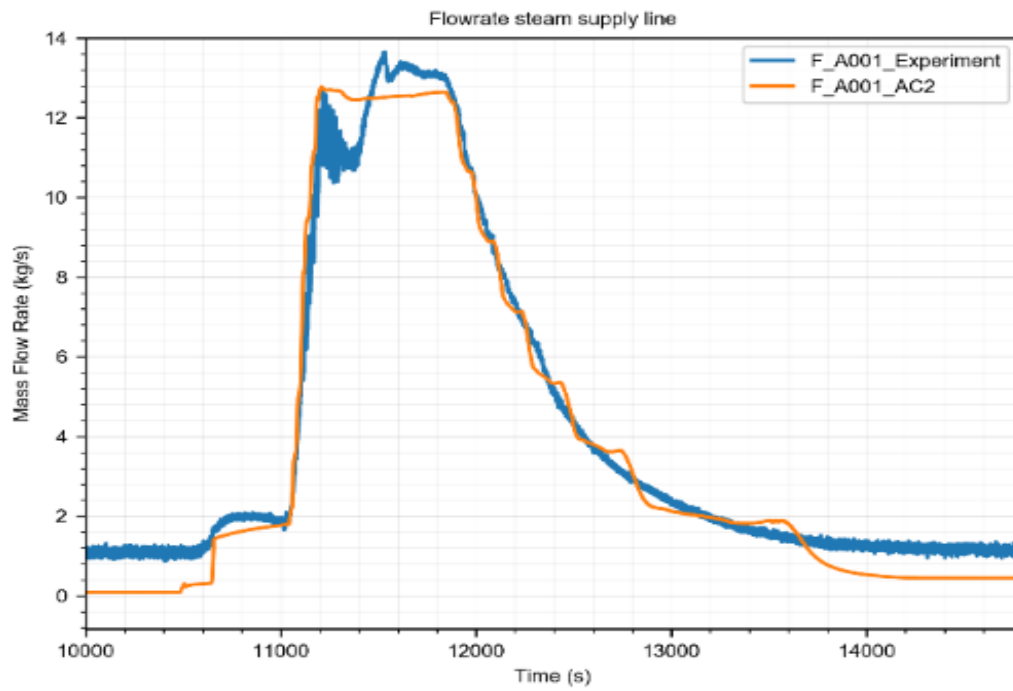


Figure 5.5. Test 7 Part 1 - condensate flow rate

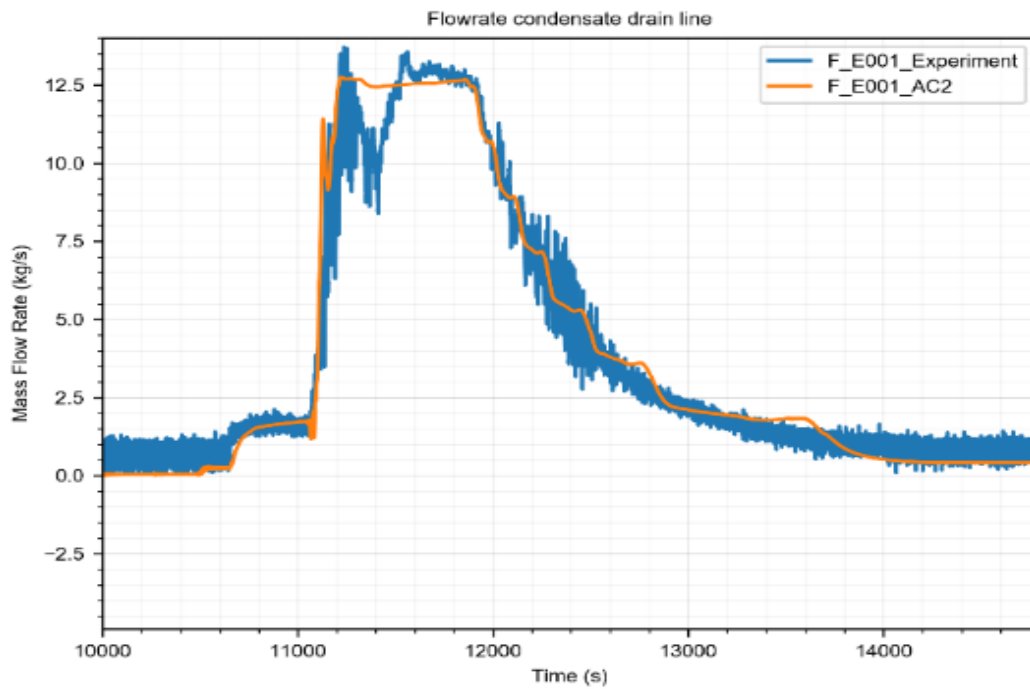


Figure 5.6. Test 7 Part 1 - HX power

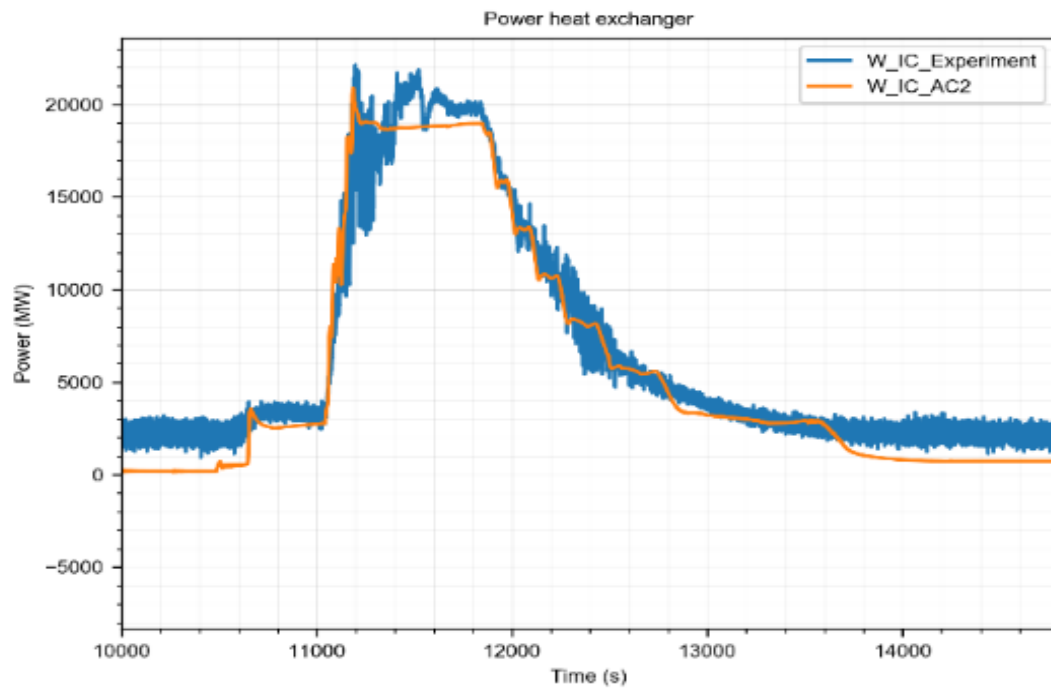


Figure 5.7. Test 7 Part 1 - Primary pressure

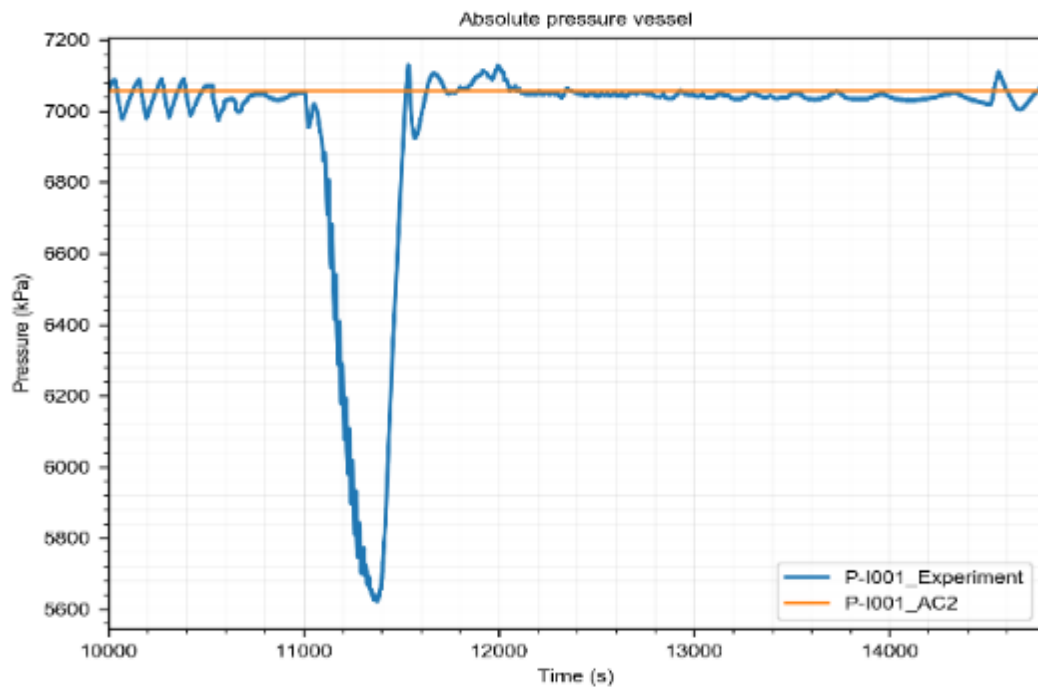


Figure 5.8. Test 7 Part 1 - HX inlet fluid temperature

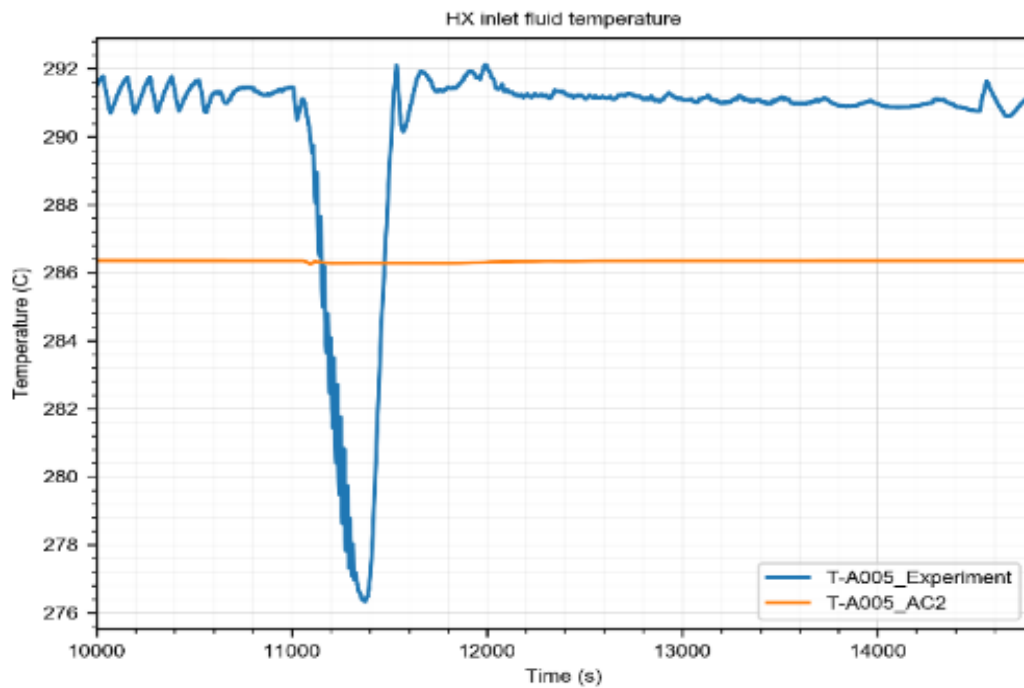


Figure 5.9. Test 7 Part 1 - HX outlet temperature

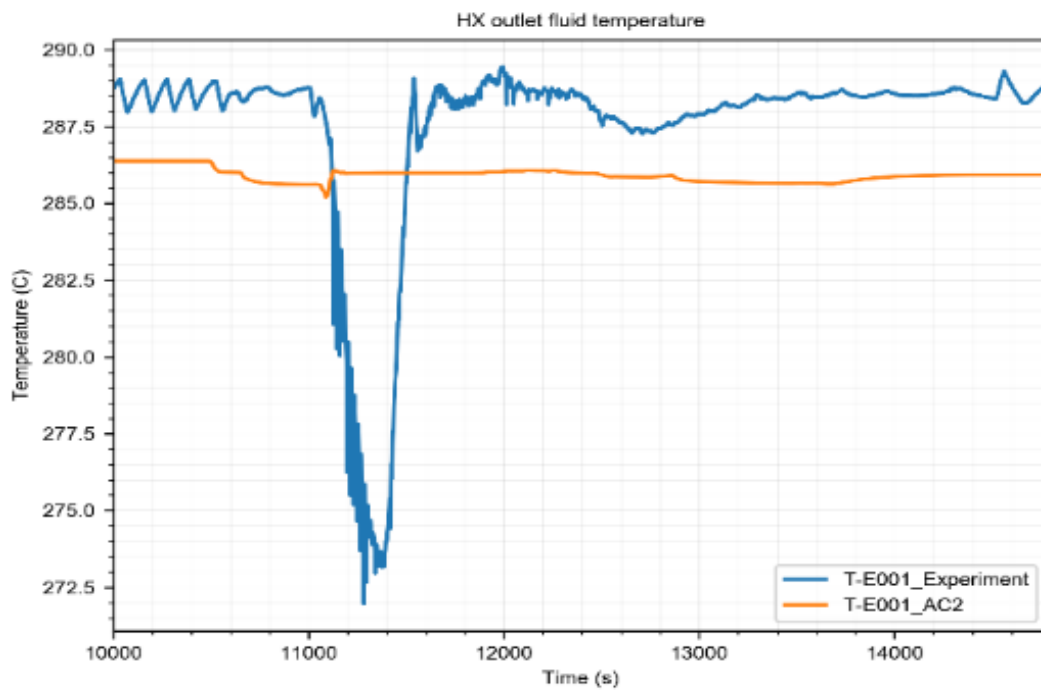


Figure 5.10. Test 7 Part 1 - HXP level

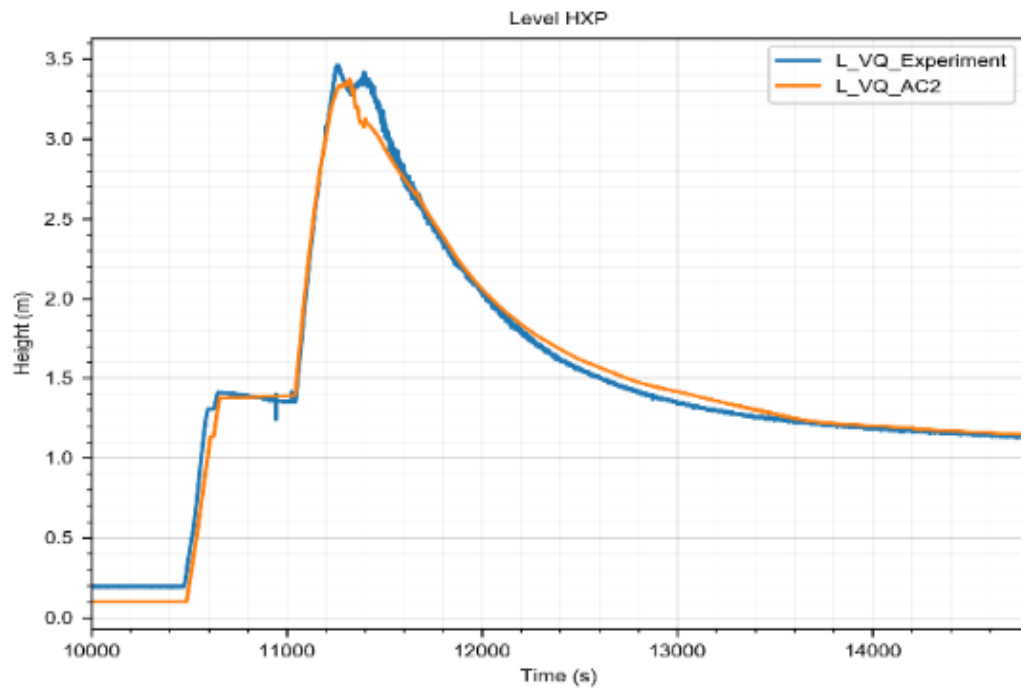


Figure 5.11. Test 7 Part 1 - OP level

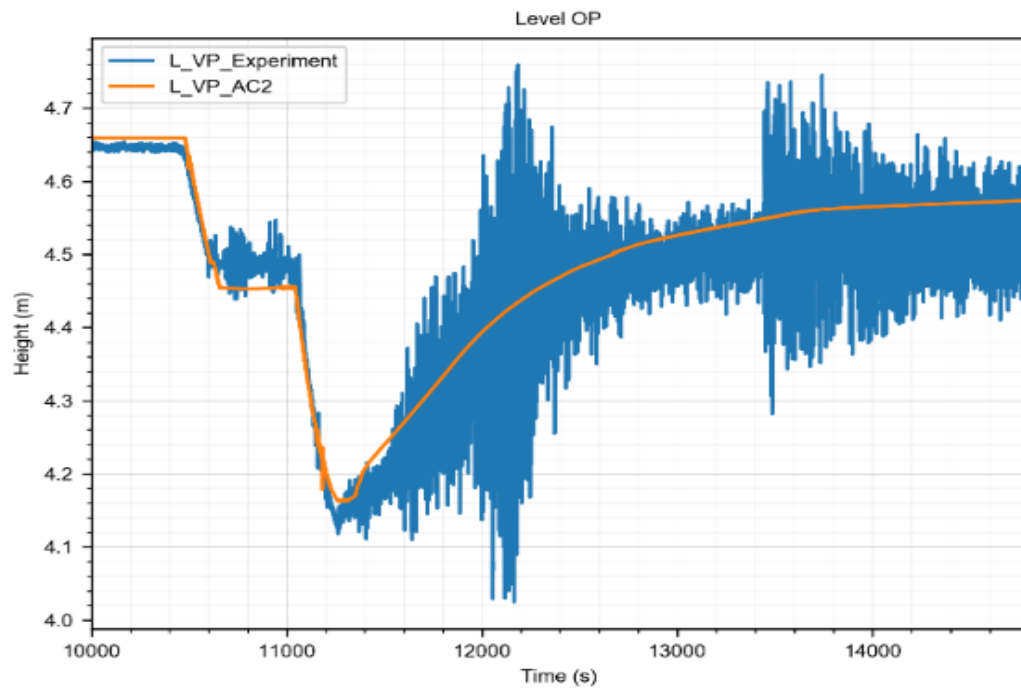


Figure 5.12. Test 7 Part 1 - Fluid temperature HXP (bottom)

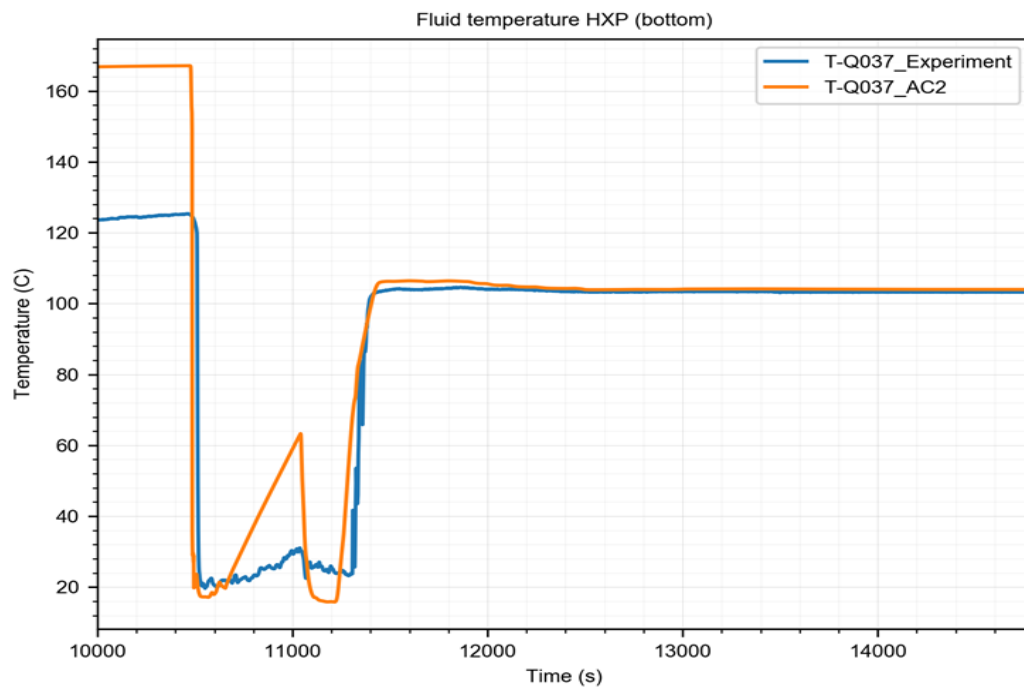


Figure 5.13. Test 7 Part 1 - Fluid temperature HXP (middle)

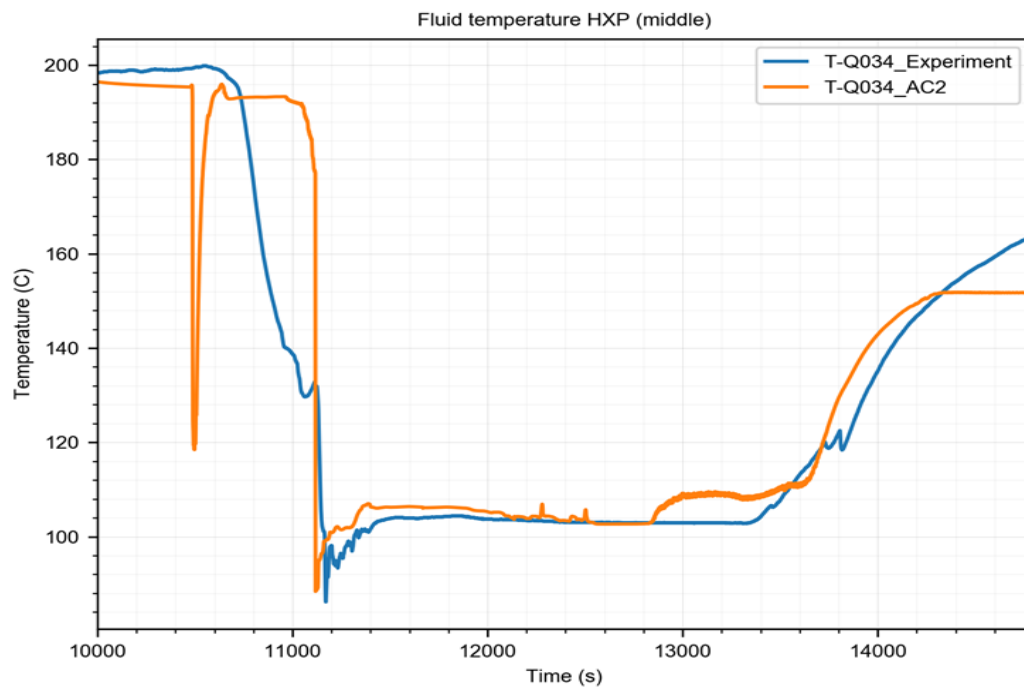


Figure 5.14. Test 7 Part 1 - Fluid temperature HXP (top)

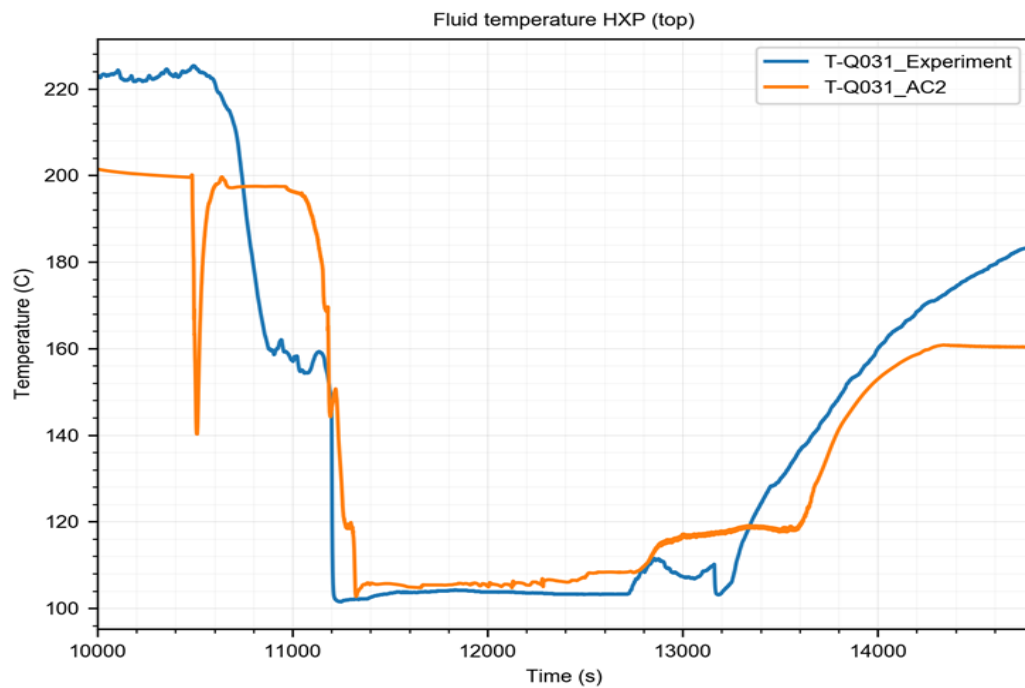


Figure 5.15. Test 7 Part 1 - Relative pressure HXP top

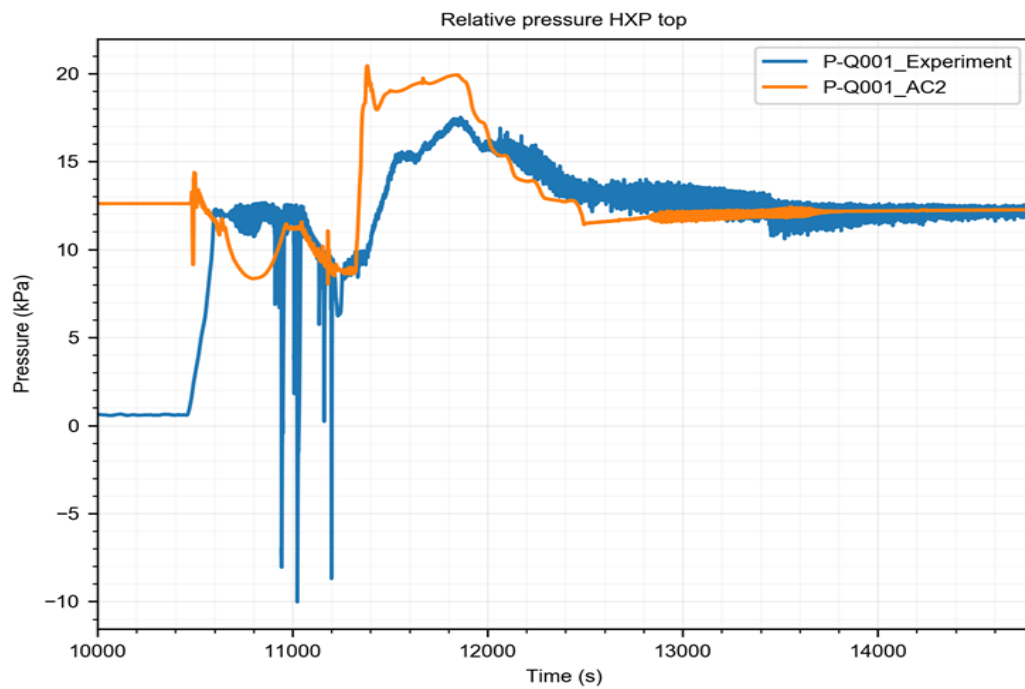


Figure 5.16. Test 7 Part 1 - Fluid temperature OP (bottom)

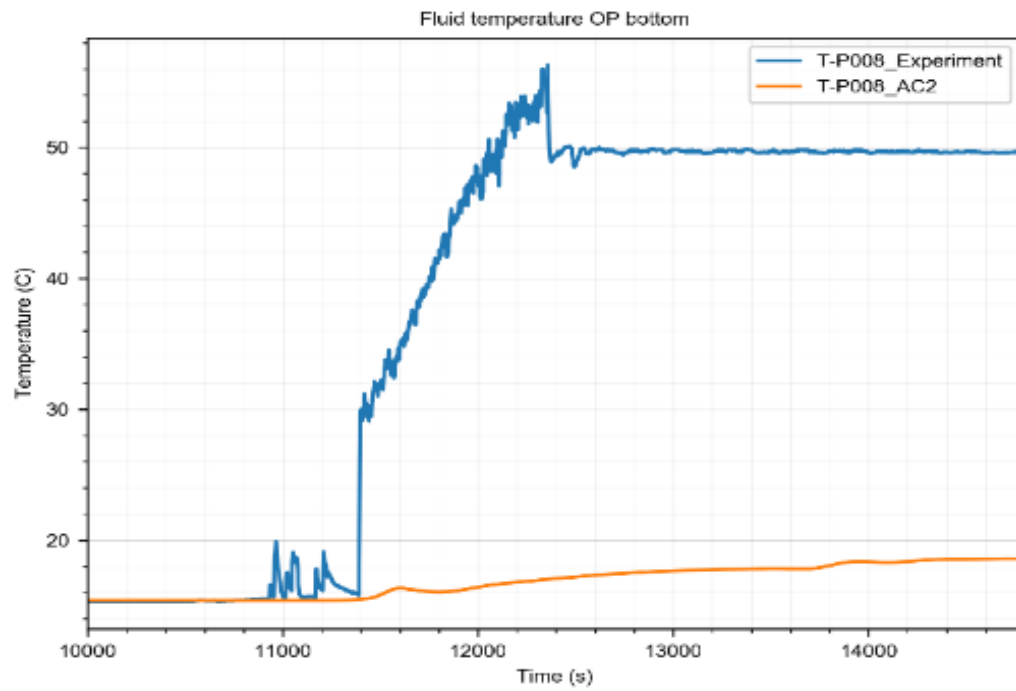


Figure 5.17. Test 7 Part 1 - Fluid temperature OP (top)

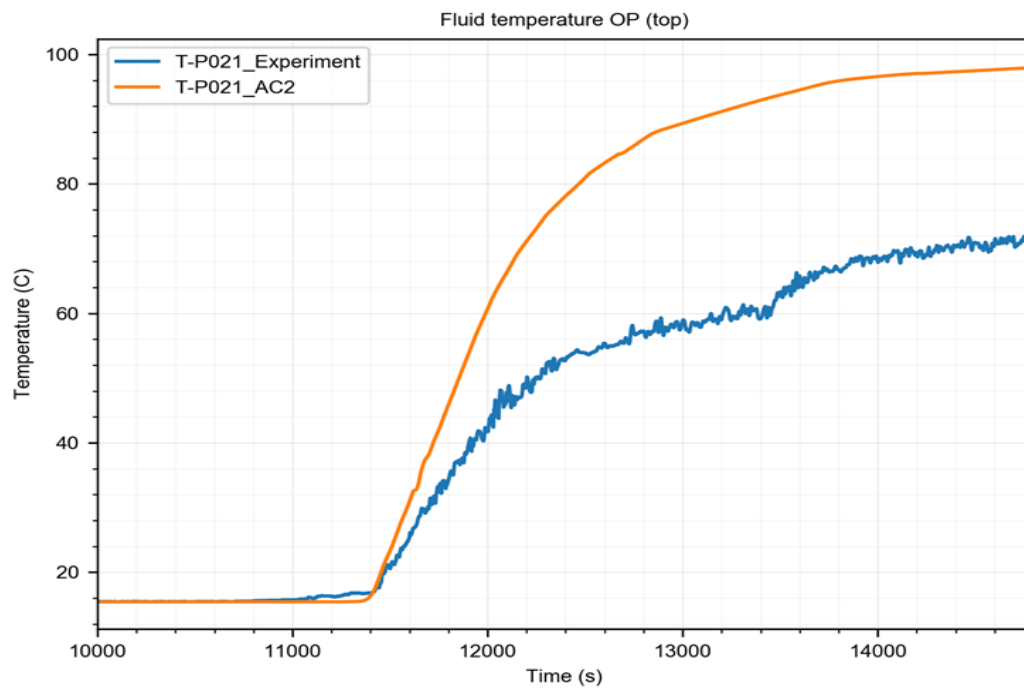


Figure 5.18. Test 7 Part 1 - Differential pressure HX upper-lower header

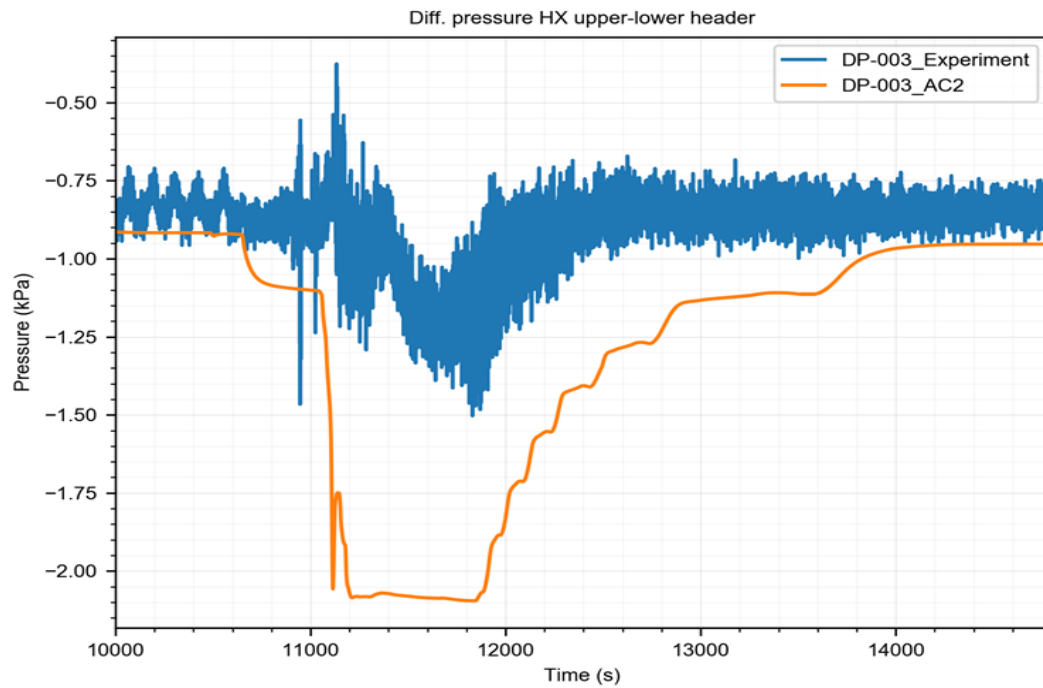


Figure 5.19. Test 7 Part 1 - Differential pressure injector

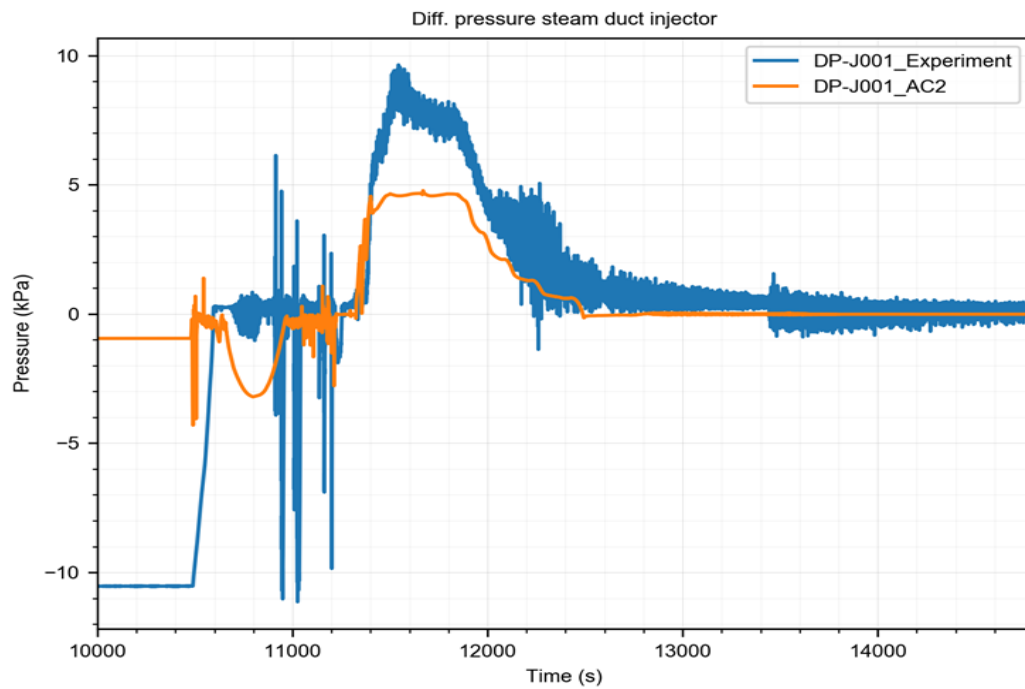


Figure 5.20. Test 7 Part 1 - Wall temperature HX upper header

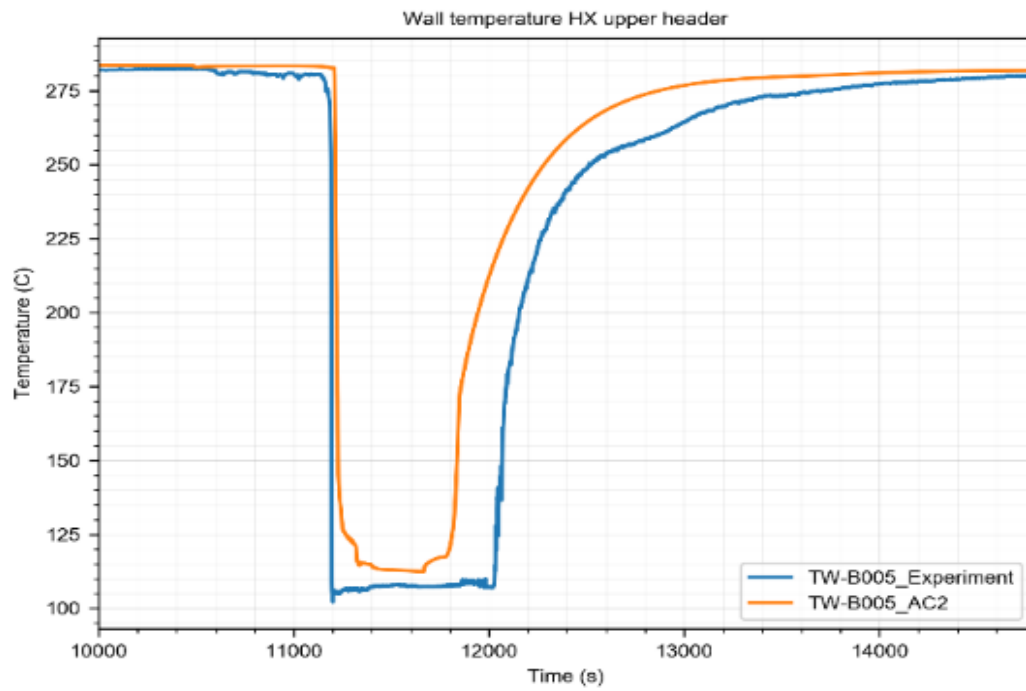


Figure 5.21. Test 7 Part 1 - Wall temperature HX lower header

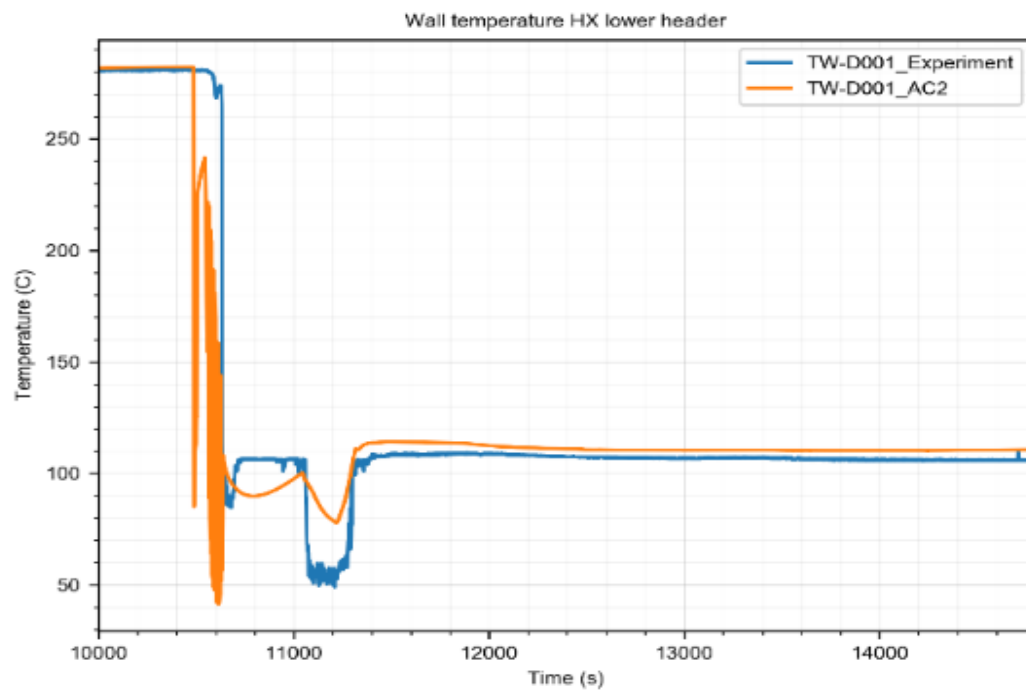


Figure 5.22. Test 7 Part 1 - Primary loop sum of differential pressure

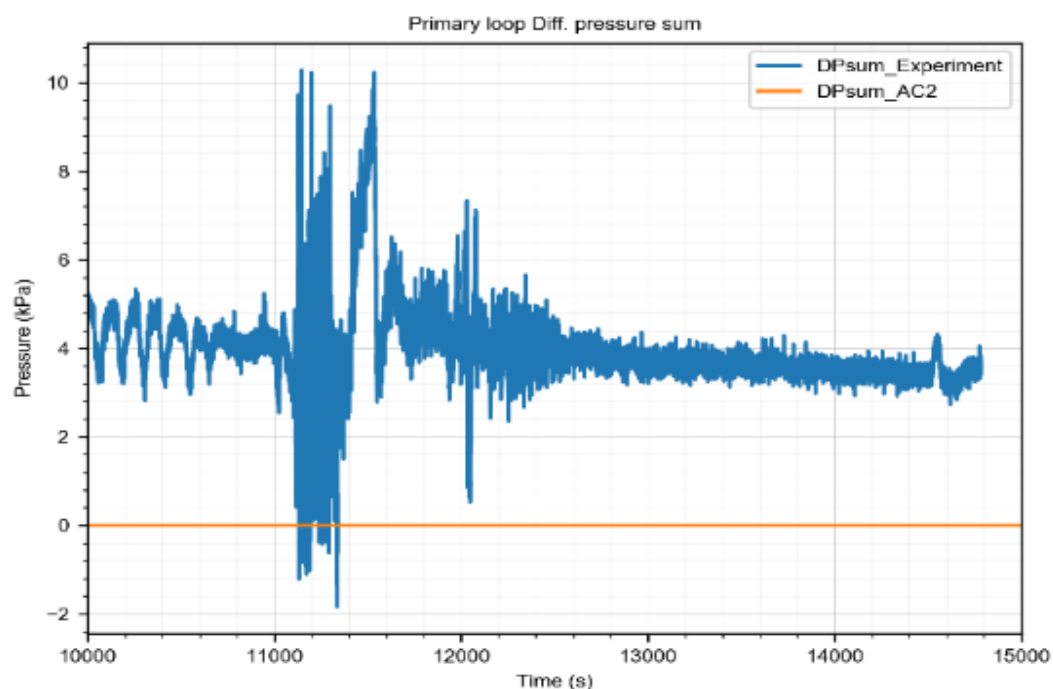


Table 5.3. Main relevant thermal-hydraulic aspects related to the Test 7 Part 1

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	10 475 – 10 608	-
Triggering valve (F045) re-opening and re-closure	10 621 – 10 655	-
Maximum level in the HX pool for the first filling step	11 039	1.39 m
Small heat removal from the primary side	10 665 – 11 039	3 484 – 2 540 kW
Slow water consumption in the HX pool	10 665 – 11 039	$\Delta T \approx 45$ K
Instabilities for steam condensation in the injector	10 475; 11 000	+/- 5 kPa; +/- 4 kPa
Triggering valve (F045) opening and closure	11 039 – 11 260	-
Maximum level in the HX pool	11 325	3.36 m
Maximum exchanged power	11 188	20 844 kW
HX pool minimum level	15 000	1.14 m
OP average temperature	15 000	57°C

The marks adopted in Table 5.4 for the qualitative accuracy evaluation are reported in Table 4.2.

**Table 5.4. PERSEO Test 7 Part 1 versus phenomena, code
prediction versus phenomena**

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	+/-
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	+/-
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure HX upper-lower header	DP-003	+
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	HX inlet temperature	T-A005	+/-
				HX outlet temperature	T-E001	
				Power heat exchanger	W IC (der.)	
				Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (bottom)	T-Q037	o
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
				Diff. pressure steam duct injector	DP-J001	
				Power heat exchanger	W IC (der.)	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP	L VQ (der.)	+
				Level OP	L VP (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L VP (der.)	o
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

** Ph. = Phenomenon

Test 7 Part 2

As with experiment Test 7 Part 1, calculations of Test 7 Part 2 with the standard ATHLET 3.2 did not lead to suitable and satisfying results. The power of the heat exchanger was underpredicted. For that reason, a developer version of ATHLET 3.2 has been created and the heat transfer models for condensation inside vertical pipes have been exchanged by the models described at the end of Section 2. The following results have been obtained by using the developer version.

The initial conditions are specified by the user within the corresponding ATHLET input deck on the base of the experimental data. With start of the calculation, ATHLET first performs a so-called steady state calculation, which is needed to ensure steady state conditions of the thermal-hydraulic network to avoid unexpected initial transients.

Initially, the pressure inside the pressure vessel (steam part) is 7.0 519 MPa. The temperature is 286.4°C (saturation temperature) and the collapsed level is -9.68 m. Pressure and enthalpy were fixed by a time-dependent volume connected to the upper part of the pressure vessel. The heat exchanger pool is fully filled with superheated steam initially at a pressure of 0.12 MPa and a temperature distribution of 103.6°C to 191.3°C from bottom to top. The collapsed level is at 1.12 m. The overall pool is filled with water (collapsed level: 4.52 m, temperature: 42.7°C to 70°C (bottom to top distribution)). The pressure within the gas region is 0.1 MPa. The gas region is filled with air and steam with the steam partial pressure equal the saturation pressure at 70°C. The liquid line connecting both pools is closed by a valve and is filled with water on both sides.

While in Part 1 of Test 7 during the steady state phase, the pressure and enthalpy boundary connected with the upper part of the heat exchanger pool is active, in Part 2, this is not necessary. After the steady state phase, the experiment starts at time point $t = 300$ s with fully opening the valve in the liquid line.

With opening the valve, consequently, water is flowing into the heat exchanger pool from the overall pool (F_POOL, Figure 5.42). This leads to a decreasing water level inside the overall pool (L_VP, Figure 5.30), while the heat exchanger pool level is increasing (L_VQ, Figure 5.29). The pressures at the overall and heat exchanger pool openings of the liquid line (P-LL-OP and P-LL-HP, Figure 5.41) start to equalise and power is transferred over the heat exchanger. This leads to an evaporation inside the heat exchanger pool and an increase of the relative pressure within the gas region (P-Q001, Figure 5.34). Due to this in combination with the increasing water column the pressure P-LL-HP becomes larger than the pressure P-LL-OP and water flows now backwards from the heat exchanger pool to the overall pool. Consequently, the power is slightly decreasing, less water is evaporated and the relative pressure is decreasing so that the pressure difference over the liquid line turns and the water is flowing to the heat exchanger pool again. This phenomenon repeats several times but decays until approximately 1 600 s. Due to the evaporation, the mean liquid levels of both pools are decreasing, which is accelerated by activation of the overall pool drainage at 1 150 s. Unfortunately, the mass flow rate is not known. For the simulation, 18 kg/s were chosen having been tuned on the progress of the overall pool liquid level. At 3 338 s the valve inside the liquid line is closed. This leads to a stronger decrease of the water level inside the heat exchanger pool and a less strong decrease inside the overall pool. The simulation data of the liquid levels and relative pressure inside the heat exchanger pool fit well with the experimental data, although the peak value of 3.3 m height of the liquid level inside the heat exchanger pool is not fully reached. The fluctuations are also captured.

The transferred power (W_IC, Figure 5.25) is slightly underestimated (approximately 2 MW, which is 10% based on the experimentally determined power). But already mentioned as for Part 1, the primary boundary conditions are not fully clear, since the inlet

fluid temperature (T-A005, Figure 5.27), which should be the saturated temperature of the pressure (P-I001, Figure 5.26), is too high. As the power is underestimated, consequently, the mass flow rates of the inlet steam, (F_A001, Figure 5.23) as well as (F_E001, Figure 5.24), are underestimated, too.

At timepoint $t = 4\,685$ s, the pressure vessel is depressurised (see Figure 5.26). This is performed in the simulation by closing the connection to the pressure and enthalpy boundary for the pressure vessel. Therefore, the pressure inside the vessel is decreasing but drops faster in the simulation than in the experiment. One reason for that could be that during this phase in the experiment steam is still injected into the vessel, but with lower power. Unfortunately, no special information about the depressurisation procedure was available. This could explain the deviations in the pressure.

The simulated fluid temperatures in the heat exchanger pool at all heights are in good agreement with the experimental data (see Figure 5.31, Figure 5.32 and Figure 5.33). Differences can be observed in the temperatures inside the overall pool. At the top (T-P021, see Figure 5.36), the temperature increase fits well until 3 830 s. Here the mixture level track of the pool leaves the control volume in which the temperature is determined. Therefore, the temperature signal switches from saturated water to superheated vapour conditions. It is not clear why this behaviour is not seen in the experimental data, since the experimentally determined liquid level of the overall pool reaches at approximately 3 365 s the height of the probe at 2.695 m and falls below this point further on. Maybe the superheated steam flowing through the injector does not reach the probe in the experiment, but due to the applied nodalisation it does in the simulation. Another possibility could be that a water droplet got caught on the temperature probe. This droplet would have had saturation conditions. At the bottom of the pool, the temperature (T-P008, Figure 5.35) in the simulation rises 400 s later than in the experiment but reaches also saturated conditions.

As in Part 1 of the test, the pressure difference between the upper and lower header is overestimated (in absolute values). But also, in this case, DPsum (sum of the complete pressure difference chain, see Figure 5.43) is not zero in the experiment. The pressure difference of the injector is also underestimated (DP-J001, Figure 5.38), although the relative pressure inside the heat exchanger pool fits well with the experimental data.

The wall temperatures of the upper header are not well captured. At the beginning of the experiment, the temperature drops as in the experiment, but it fluctuates further on. In the experiment, the thermo probe TW-B005 is wetted all the time until 3 400 s keeping the temperature low. In the simulations the heat conduction object is wetted only at the peaks of the liquid level progress. Later on, without any fluctuations, the heat conduction object stays dry until the end of the simulation, leading to higher temperatures than in the experiment. The temperature of the lower header shows an offset between experimental data and simulation of approximately 4 K. This difference could also be explained by the coarse nodalisation of the lower header (1 Node) in contrast with the exact location of the thermo probe.

In total, 43 430 time steps were performed and 2 473 s of CPU time were consumed for the simulation of Test 7 Part 2. Since ATHLET has a variable time step size, size automatically defined by the error convergence criteria within the implicit integration procedure FEBE in ATHLET, no general time step size can be provided. But the bandwidth in the calculation was between 0.005 s and 0.5 s.

Figure 5.23. Test 7 Part 2 - Steam flow rate

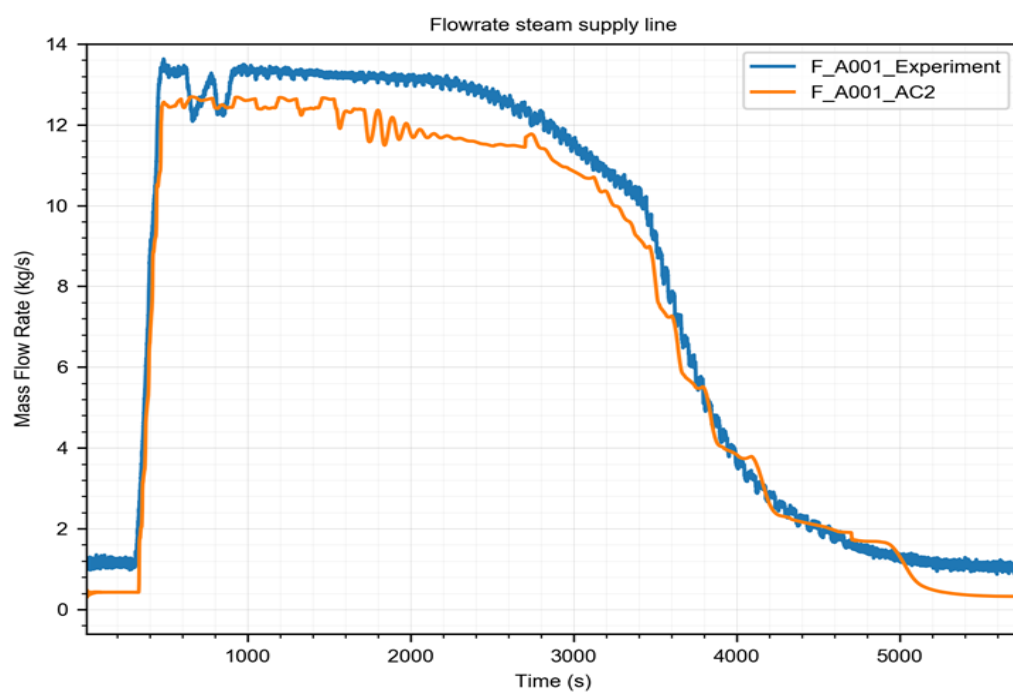


Figure 5.24. Test 7 Part 2 - Condensate flow rate

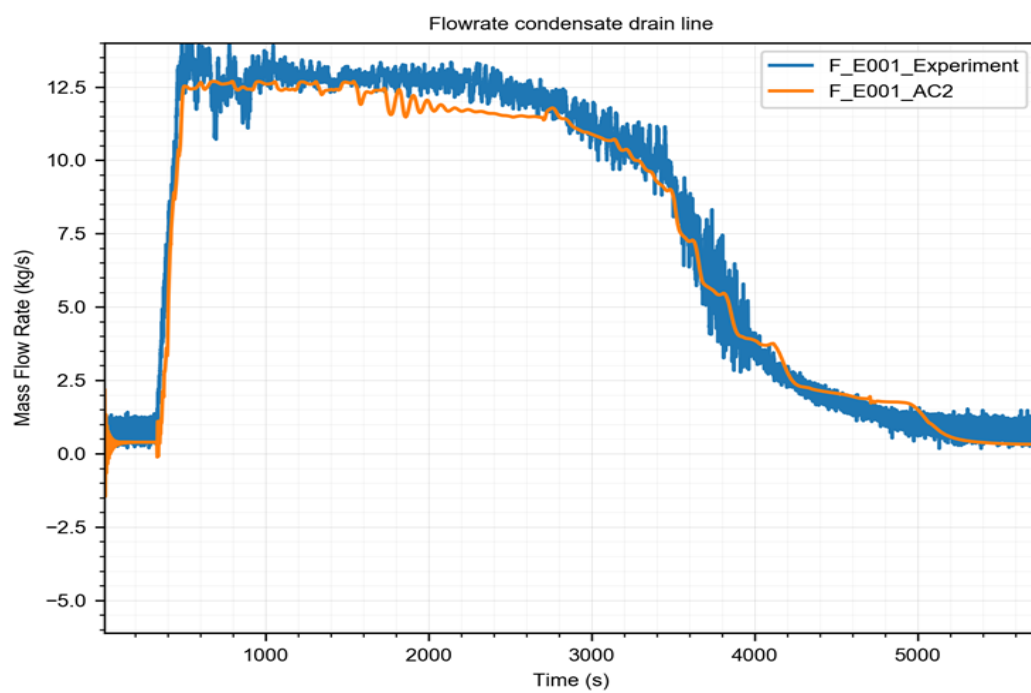


Figure 5.25. Test 7 Part 2 - HX power

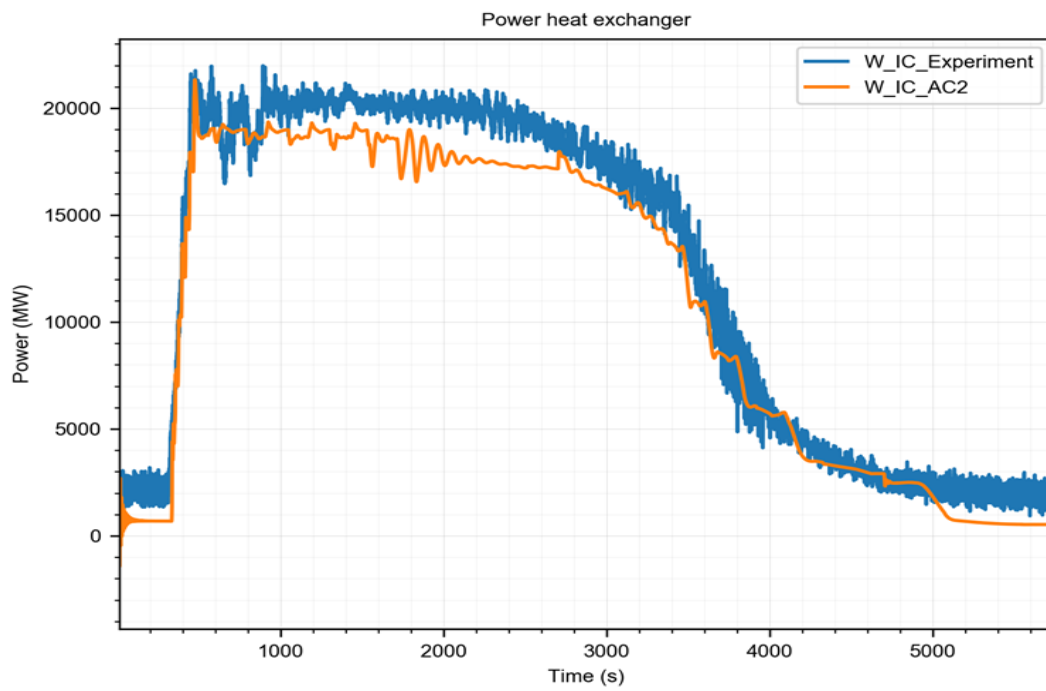


Figure 5.26. Test 7 Part 2 - Primary pressure

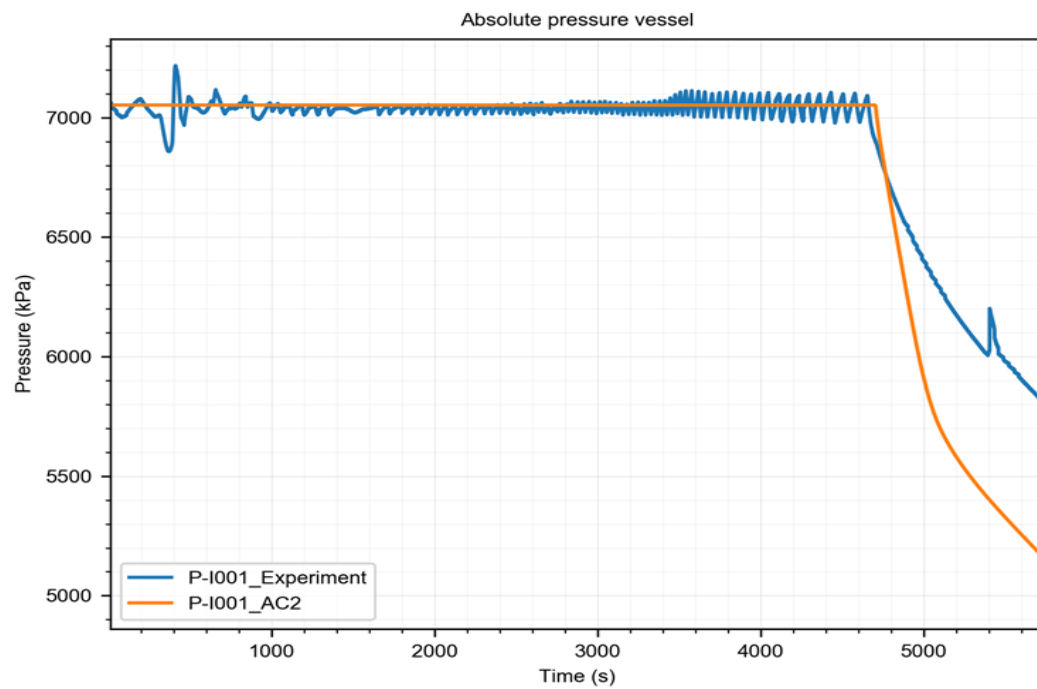


Figure 5.27. Test 7 Part 2 - HX inlet fluid temperature

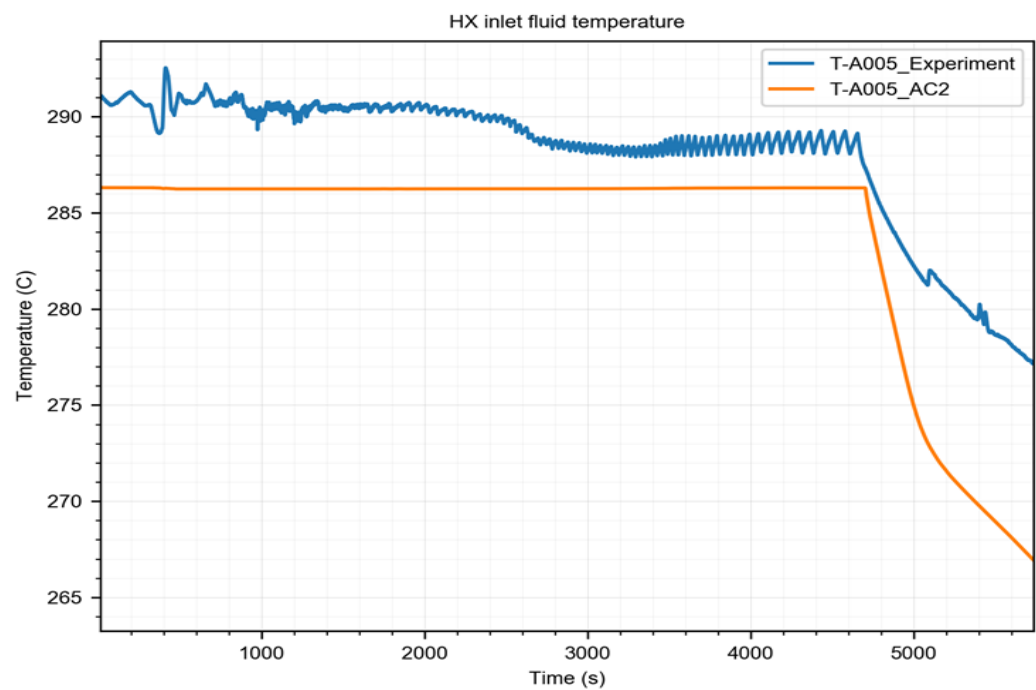


Figure 5.28. Test 7 Part 2 - HX outlet fluid temperature

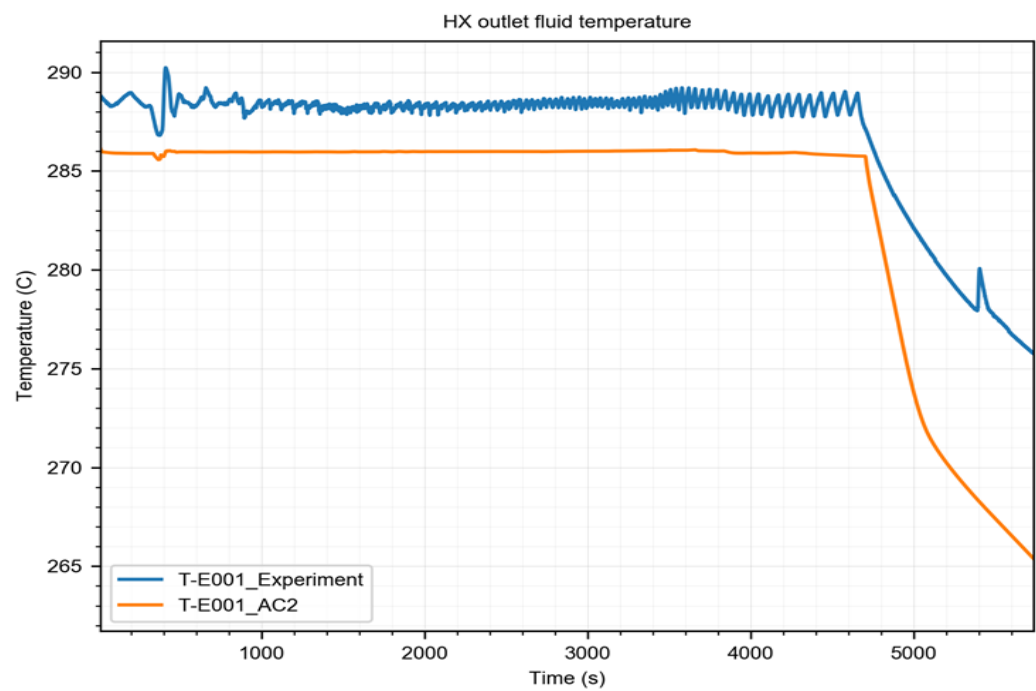


Figure 5.29. Test 7 Part 2 - HXP level

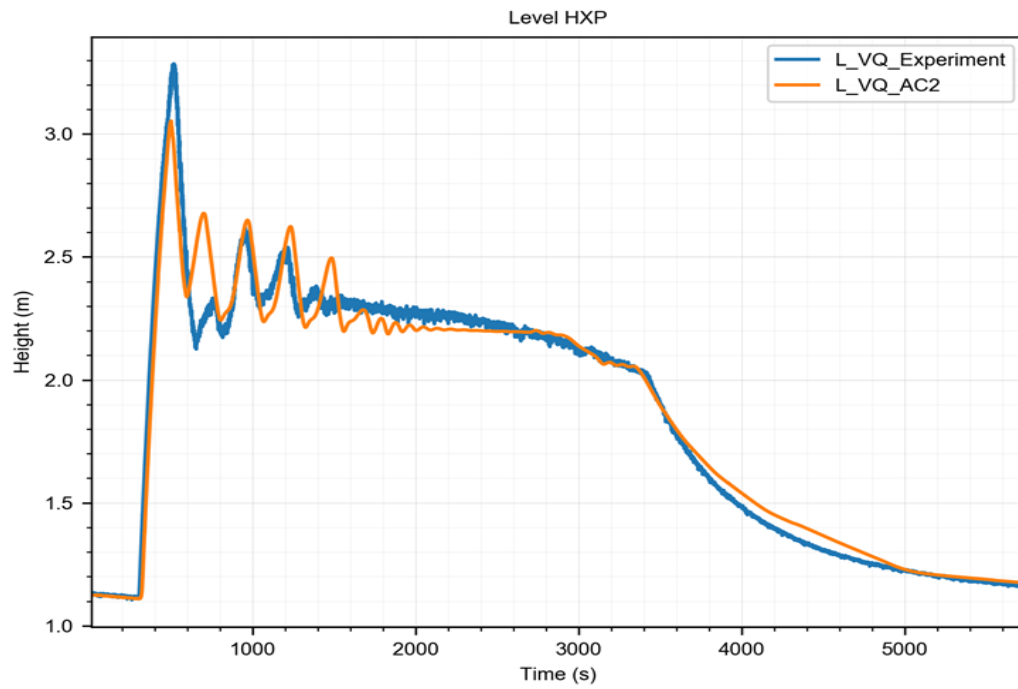


Figure 5.30. Test 7 Part 2 - OP level

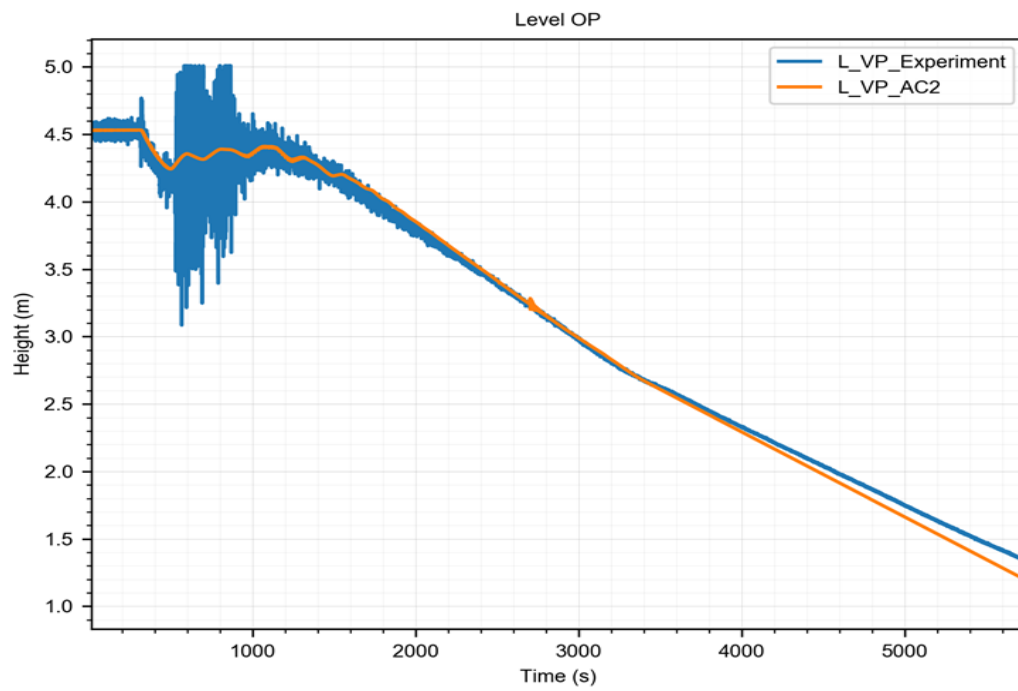


Figure 5.31. Test 7 Part 2 - Fluid temperature HXP (bottom)

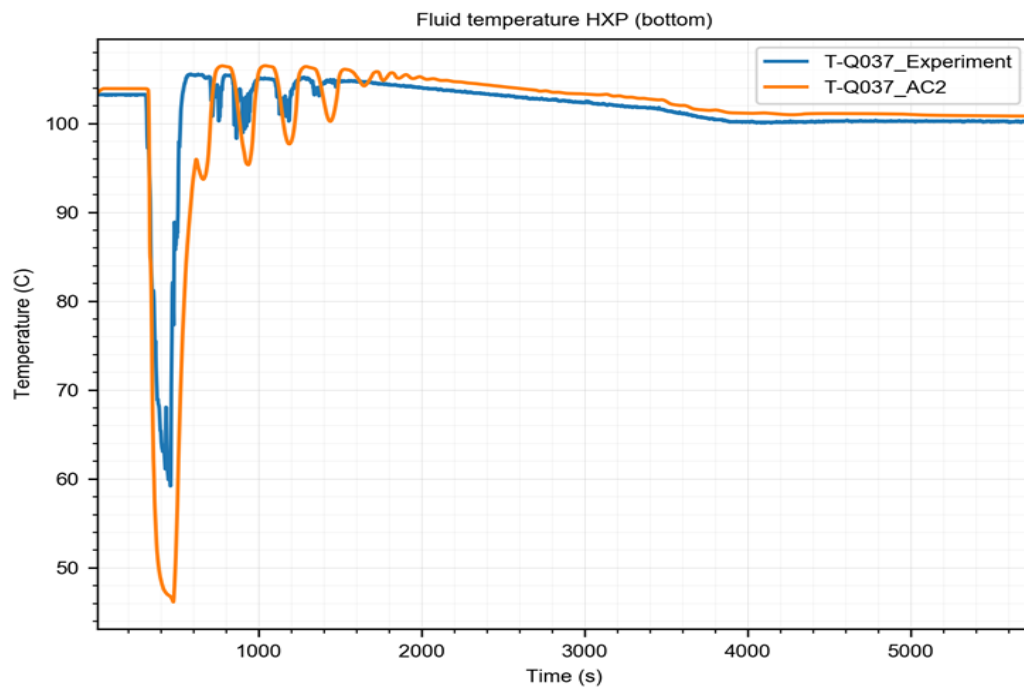


Figure 5.32. Test 7 Part 2 - Fluid temperature HXP (middle)

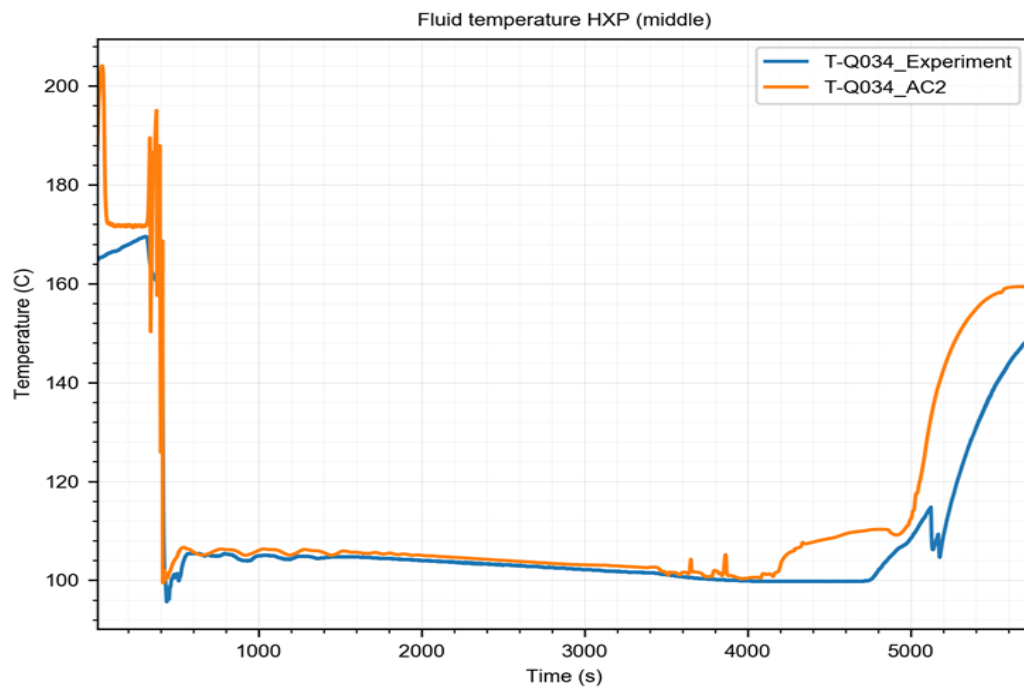


Figure 5.33. Test 7 Part 2 - Fluid temperature HXP (top)

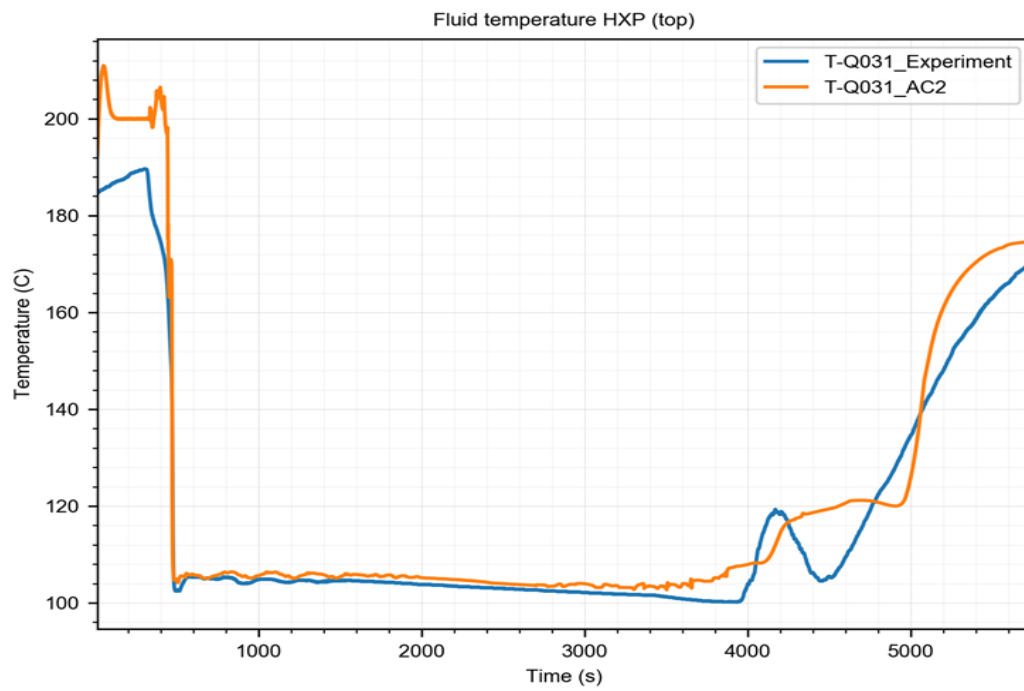


Figure 5.34. Test 7 Part 2 - Relative pressure HXP top

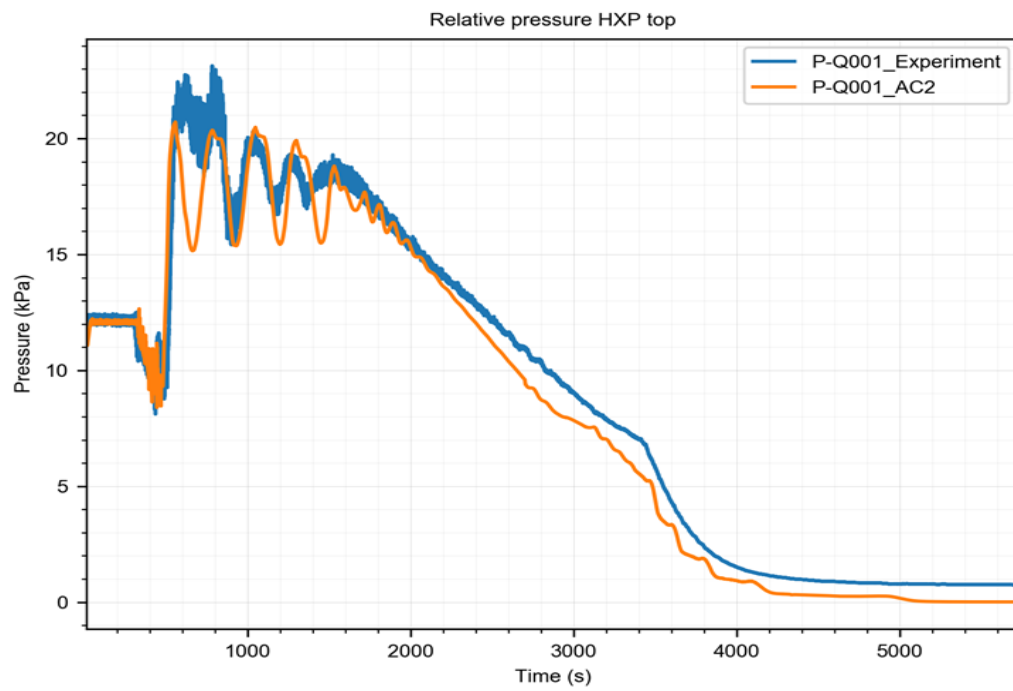


Figure 5.35. Test 7 Part 2 - Fluid temperature OP (bottom)

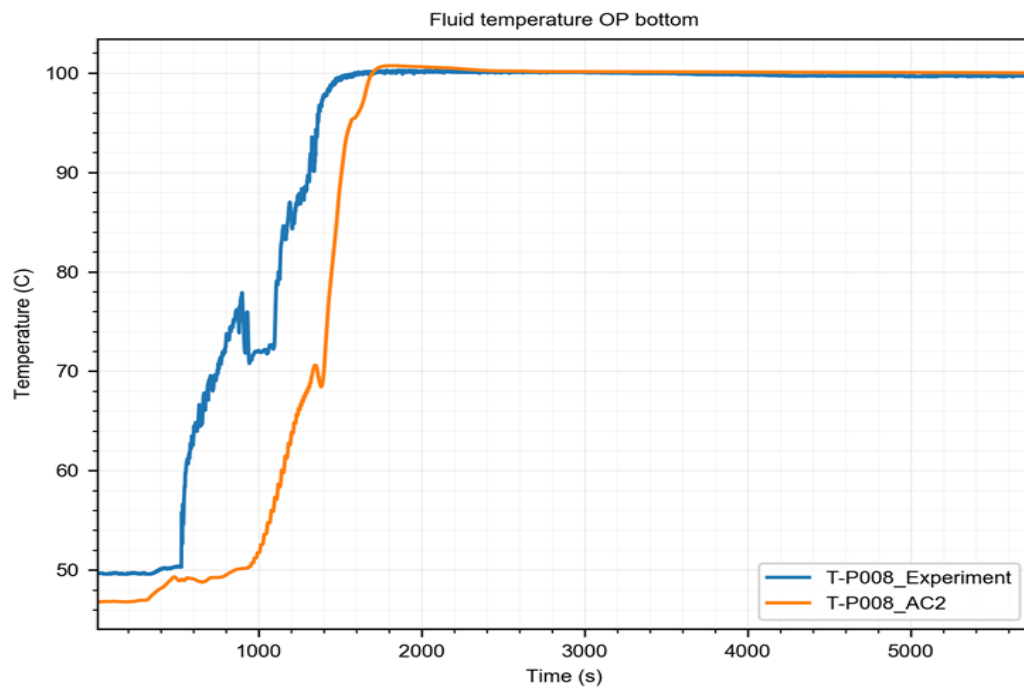


Figure 5.36. Test 7 Part 2 - Fluid temperature OP (top)

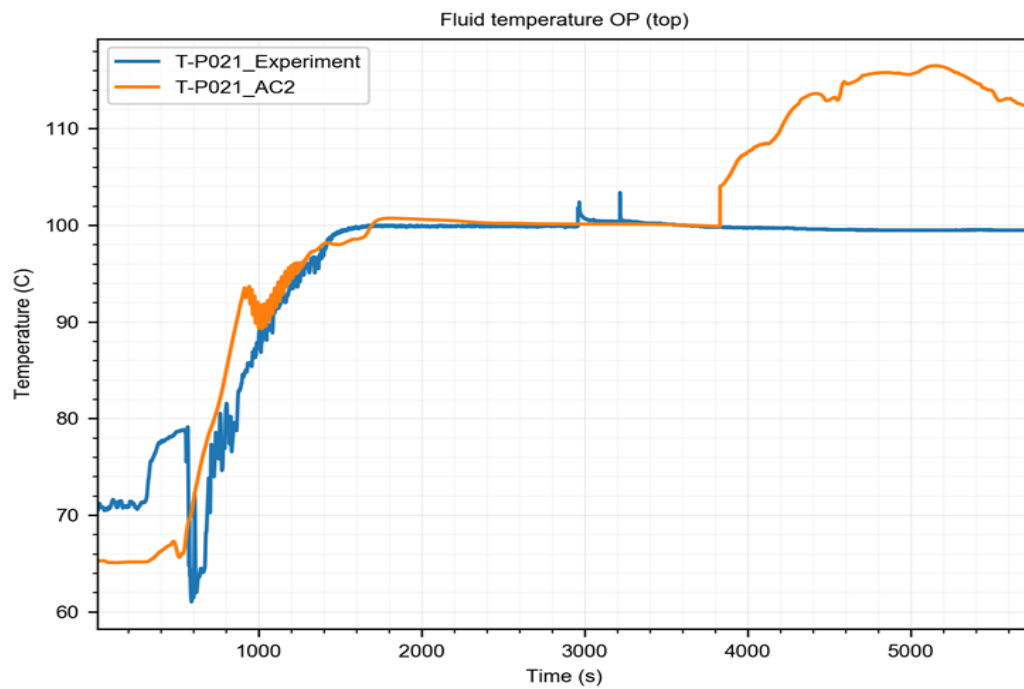


Figure 5.37. Test 7 Part 2 - Differential pressure HX upper-lower header

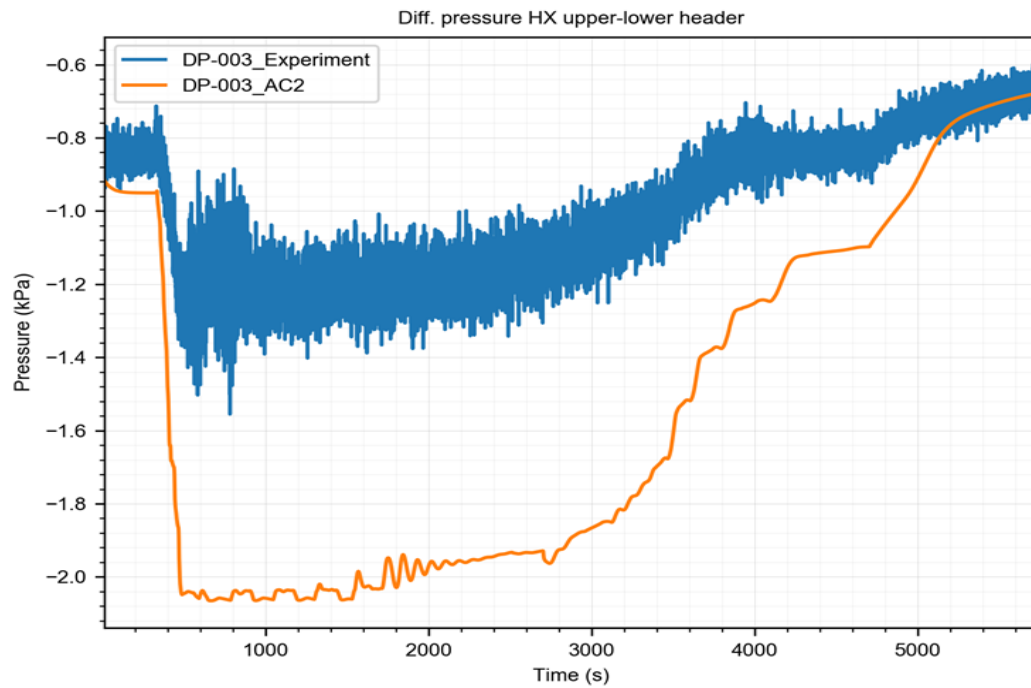


Figure 5.38. Test 7 Part 2 - Differential pressure injector

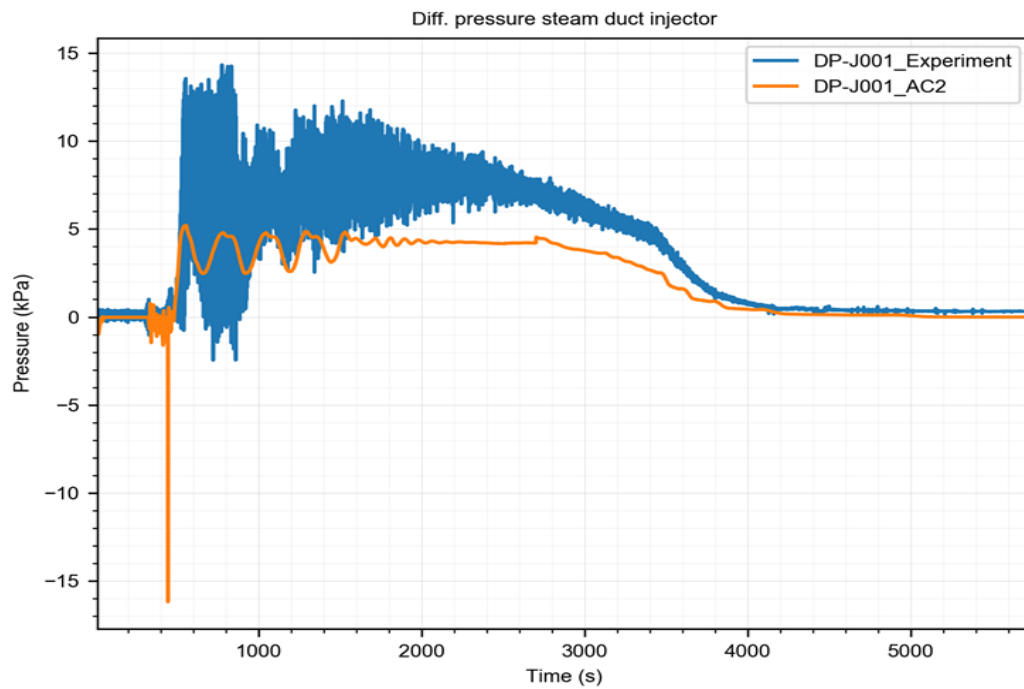


Figure 5.39. Test 7 Part 2 - Wall temperature HX upper header

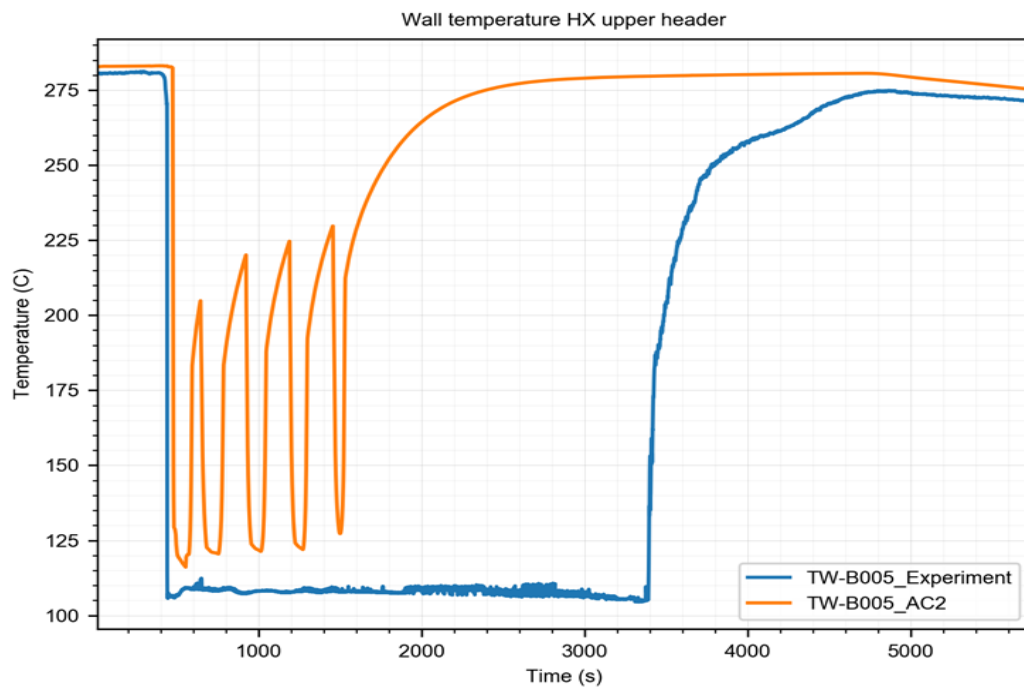


Figure 5.40. Test 7 Part 2 - Wall temperature HX lower header

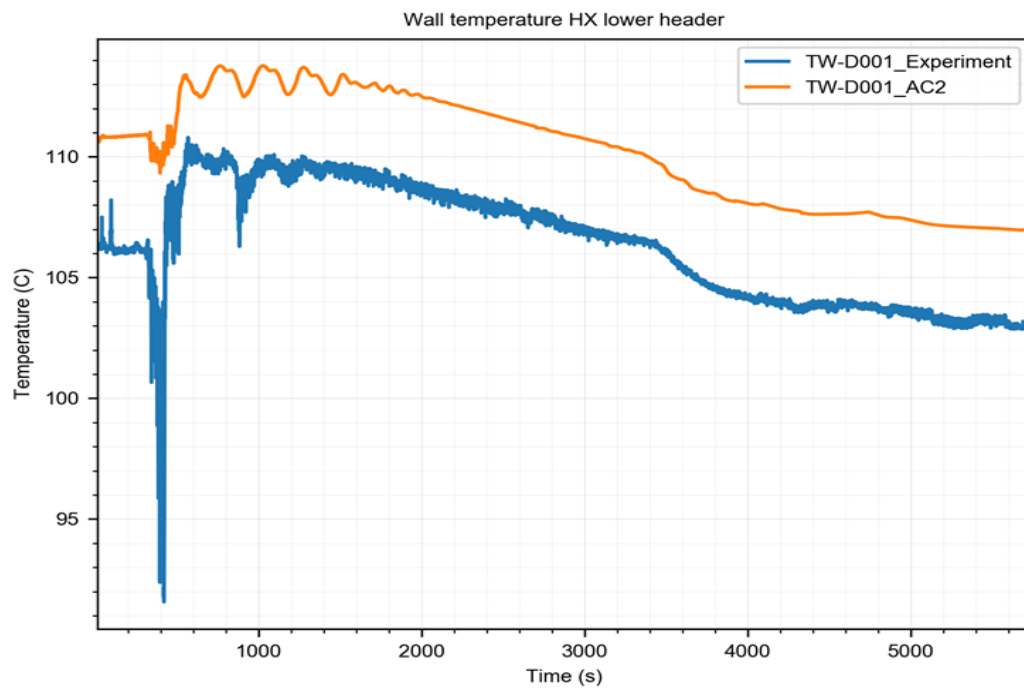


Figure 5.41. Test 7 Part 2 - Pressures liquid line in and out

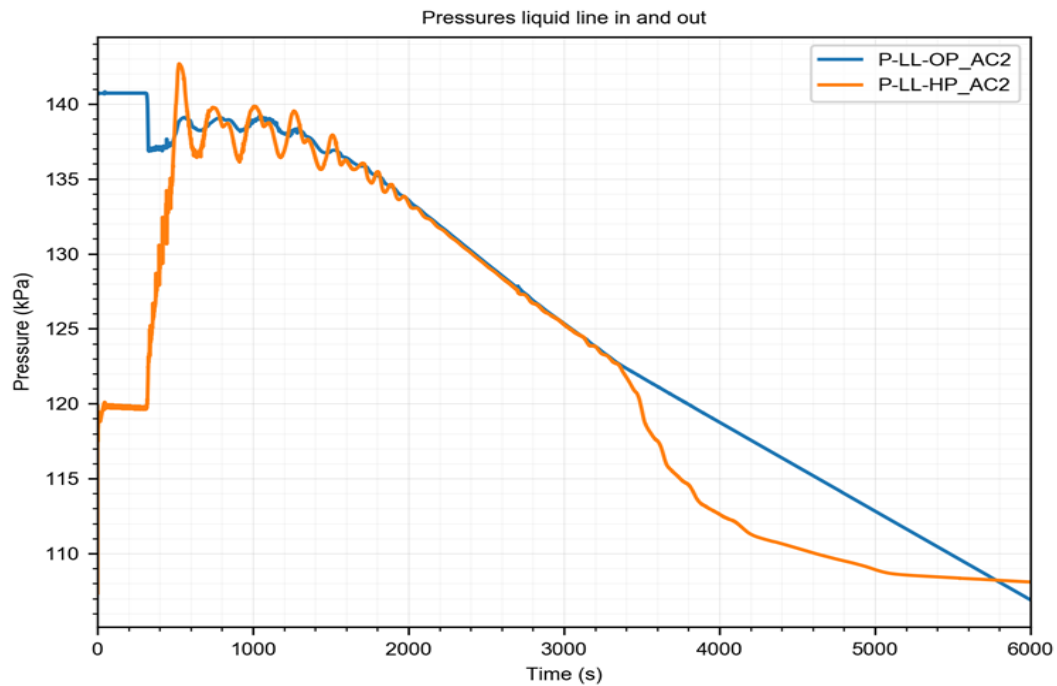


Figure 5.42. Test 7 Part 2 - Water mass flow rate through liquid line

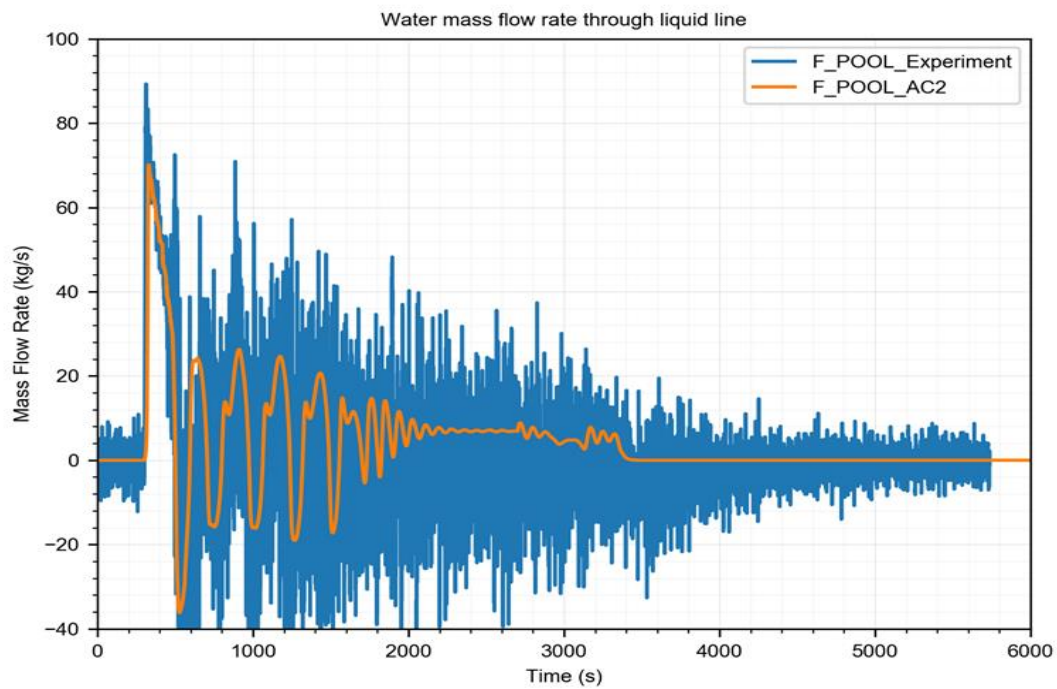


Figure 5.43. Test 7 Part 2 - Primary loop sum of differential pressure

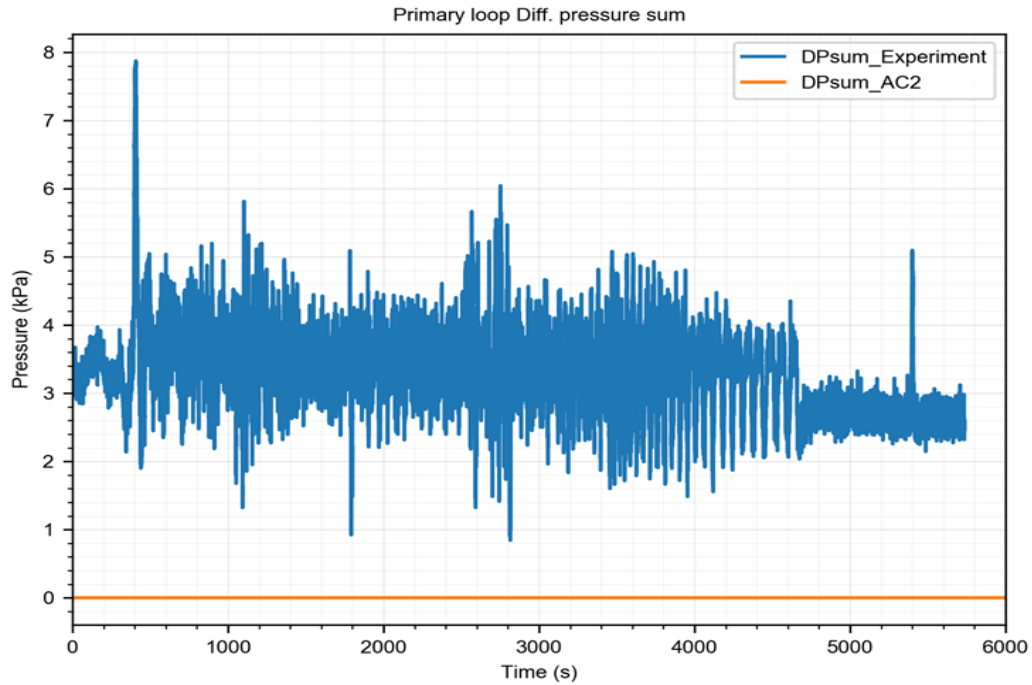


Table 5.5. Main relevant thermal-hydraulic aspect related to the Test 7 Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	300	-
Maximum level in the HXP	501	3.05 m
Maximum exchanged power	475	21 348 kW
OP discharge valve F031 opening	1 150	-
Triggering valve F045 closure	3 338	-
HX pool level decreasing and loss of mass from the boil-off	1 660	-
Primary side depressurisation beginning for end of test	4 710	-

The marks adopted in Table 5.6 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.6. PERSEO Test 7 Part 2 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F_A001 (der.)	+
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W_IC (der.)	+
				Level HXP	L_VQ (der.)	
				Level OP	L_VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	+/o
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure HX upper-lower header	DP-003	+
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	HX inlet temperature	T-A005	+
				HX outlet temperature	T-E001	
				Power heat exchanger	W_IC (der.)	
				Level HXP	L_VQ (der.)	
				Power heat exchanger	W_IC (der.)	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (bottom)	T-Q037	+
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
				Power heat exchanger	W_IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP	L_VQ (der.)	+
				Level OP	L_VP (der.)	
				Power heat exchanger	W_IC (der.)	

Table 5.7. PERSEO Test 7 Part 2 versus phenomena, code prediction versus phenomena (Continued)

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
				Relative pressure HXP top	P-Q001	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L_VP (der.)	+/-o
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	o
				Wall temperature HX lower header	TW-D001	

SECTION 5: CONCLUSIONS

It has been shown that the thermal-hydraulic code ATHLET is able to predict the main phenomena observed in the PERSEO experiments Test 7 Part 1 and 2. While the natural circulation within the primary circuit has been simulated well according to the experimental data, some minor problems have been seen in the circulation and the mixing within the overall pool, especially in the subcooled case (Part 1). To improve the results concerning the temperature distribution within the overall pool, a 3D representation of the pool could be generated and used with the 3D thermal-hydraulic model of ATHLET.

For the calculations, a modified version of ATHLET 3.2 has been used, in which the correlations recommended in ATHLET for determining the condensation inside vertical tubes were replaced by dedicated ones (see Section 2). This issue improved the simulations the most. Therefore, it has to be investigated if and when the new correlations will be included into the main version of ATHLET. Uncertainties within the boundary conditions given by the primary circuit could be the reason for the remaining small deviations of the transferred power. A refinement of the numerical grid of the heat exchanger did not improve the results.

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- [5.2.1 2] Lerchl, G. et al. (2019), *ATHLET 3.2 – User’s Manual*, ATHLET, GRS Publishing.
- [5.2.1 3] Papini, D. and A. Cammi (2010), “Modelling of heat transfer phenomena for vertical and horizontal configurations of in-pool condensers and comparison with experimental data”, *Science and Technology of Nuclear Installations*.
- [5.2.1 4] Verein Deutscher Ingenieure, “VDI-Wärmeatlas”, 11.
- [5.2.1 5] Austregesilo, H. et. al., *ATHLET 3.2.0 Models and Methods*, GRS-P-1 / Vol. 4 Rev. 5, GRS gGmbH.

5.2.2. IBRAE

SECTION 1: GENERAL INFORMATION

- Organisation: IBRAE (Russia)
- Contact person/author: Dmitrii Yu. Tomashchik
- Code: SOCRAT V3 Rev_G4.02 (20.12.18)
- Computing environment (hardware):
 - Intel i7-3 770 K
 - RAM 16 Gb
 - Windows 7 Professional

SECTION 2: DESCRIPTION OF THE CODE USED

System of codes for realistic assessment of severe accidents (SOCRAT) is a computer code intended for a coupled modelling of a wide range of thermo-hydraulic, physico-chemical, thermo-mechanical and aerosol processes at all stages of accident progression, starting from initial event and up to corium release following the reactor vessel failure and consequent ex-vessel processes in containment. The code is essentially developed to model VVER nuclear power plants but it was also applied to simulate the severe accidents at integral-type reactors, RMBK and PWR reactors. SOCRAT is widely validated on experimental data got from integral and separate effect tests, including international standard problems and benchmarks and national experiments.

SOCRAT's field of application includes licensing support, design of safety systems, planning of experiments, PSA support, SAMG development and verification, crisis centres support and education. The main areas of SOCRAT application include estimates of hydrogen source to the containment, and source of corium (mass, energy and composition) from reactor pressure vessel after its melt-through. These data were used for safety system design (hydrogen recombiners, core catcher). During the Fukushima Daiichi accident in 2011, SOCRAT was used as one of numerical tools in support to decision-making about the need for evacuation of Russian population at far-east coast.

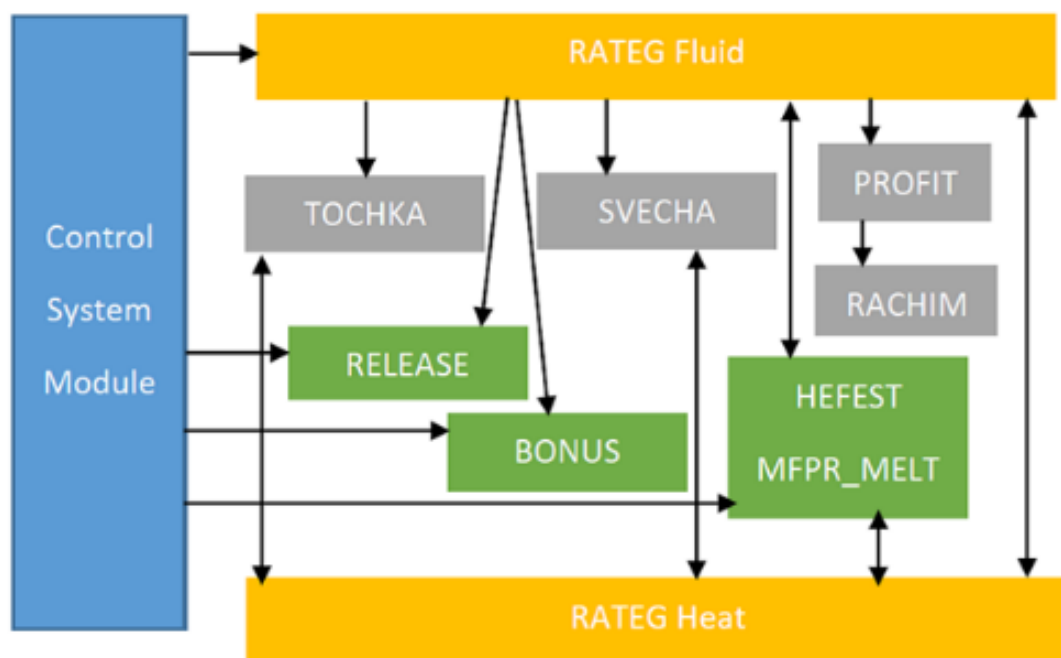
SOCRAT has a modular structure. Each module contains the realistic models of a separate set of physical processes, and interaction between different processes is assured by coupling of modules through the common interface standards. Some of these modules are computer codes developed by different Russian scientific institutes. SOCRAT contains the data base on the thermo-physical properties of different materials.

The main modules are as follows:

- **RATEG** - full circuit two-fluid thermal dynamics and heat transfer in solid body.
- **SVECHA** - in-core physical-chemical processes in severe accident conditions up to full core degradation.
- **HEFEST** - thermal processes in the lower plenum, degradation of reactor pressure vessel.
- **BONUS** - accumulation of FP in the fuel during normal operation of the reactor.
- **RELEASE** - FP release from the fuel to the gas gap of the fuel rod.

- **PROFIT** - for modelling the FP and structural materials transport.
- **MFPR_MELT** - FP release from the molten corium in the lower plenum.
- **RACHIM** - chemical and radioactive transmutations of FP during their mass transport in the reactor and calculation of FP activities from their masses.
- **TOCHKA** - calculation of the neutron power and decay heat power of the core in point approximation and calculation of the reactivity insertion with account for feedback from thermal-hydraulic parameters.
- **HEFEST-EVA** - module for modelling corium behaviour in core catcher, molten corium-concrete interaction, FP and structural materials release into containment.

Figure 5.44. Structural diagram of SOCRAT code



In the calculations of the PERSEO tests only the RATEG module was used.

The RATEG module is intended for simulation of thermal-hydraulic behaviour of the primary and secondary circuits. It contains models for different elements such as channels, chambers, pumps, valves and models for control and instrumentation systems allowing development of the full-scale nodalisation schemes for complex thermal-hydraulic systems.

To model the coolant flow in RATEG, a two-fluid two-phase hydraulic heterogeneous approach is used. The coolant is assumed to be in a liquid or gaseous phases. Each phase is characterised by its own volume, velocity and temperature and may include several components. For example, liquid phase may contain water and dissolved boric acid or non-condensable gases, gaseous phase contains steam and non-condensable gases. Interphase interactions (heat and mass transfer, friction) and heat transfer to solid structures depend upon flow regime (convection, bubble or film boiling, condensation, etc.). This approach

allows simulation of different flow regimes under normal operation and accident conditions.

The basic thermal-hydraulic variables are pressure, void fraction, phasic enthalpies, non-condensable qualities (nitrogen, hydrogen, oxygen) defined in control volume centres, and phasic velocities determined in boundary between successive control volumes. The total number of equations is $6+N_{\text{gas}}$. In case of 2D flow, two additional phasic velocities for cross-flow ($8+N_{\text{gas}}$ equations) are used.

The basic equations are approximated using a linear semi-implicit finite-difference scheme allowing violation of the Courant limit. Spatial approximation of mass continuity and energy conservation equations is based on control volumes method with donor formulation for flux terms. The momentum conservation equations are approximated in a non-divergent form using upstream formulation for convective derivatives. Linearisation of finite-difference equations is made using either Newton or lagging coefficients method. To solve the system of equations direct Hauss-type solver is used.

Heat transfer in solid structures (fuel rods, SG tubes, barrel, shrouds, RCS walls etc.) can be modelled either in one-dimensional or two-dimensional approaches. Two-dimensional heat conduction equation is approximated using linear implicit splitting scheme.

Figure 5.45. Algorithm of choice of heat exchange with wall used in SOCRAT

P>P _{crit}		Supercritical heat transfer (100)				
P<P _{crit}	T _w <T _s	T _w <T _{sv}	α<0.05	Convection /water/ (1)		
			0.05≤α<0.1	Transition (17)		
			α≥0.1	Condensation (7)		
		T _w ≥T _{sv}	Convection /mixture/ (8)			
	T _w ≥T _s	α≥0.9999	Convection /gas/ (4)			
		α<0.99	T _w <T _{chf}	Xe<0	Subcooled boiling (2)	
				Xe≥0	Nucleate boiling (3)	
		T _w >T _{chf}	T _w >T _{film}	Film boiling (6)		
			T _w ≤T _{film}	Transition boiling (5)		
		0.99≤α<0.9999	T _w <T _{chf}	Xe<0	Transition (24)	
				Xe≥0	Transition (34)	
			T _w >T _{chf}	T _w >T _{film}	Transition (64)	
				T _w ≤T _{film}	Transition (54)	

CHECKING CONDITIONS

SOCRAT use next correlations for heat transfer and wall friction in heat exchanger:

For Pool side heat transfer: CHEN correlation for boiling [5.2.2 1],[5.2.2 2].

For Tube side condensation SOCRAT use next list of correlations (no non-condensable gases, vertical tubes):

turbulent flow

$$\Delta = 0.9086 \left(\mu_F \mu_F^2 \frac{Re_F}{g \rho_F (\rho_F - \rho_G)} \right)^{1/3}, \quad \alpha_{t,cond} = \frac{\lambda_F \alpha_G}{\max(\Delta, 0.00001)} (1 + 0.02 Re_F^{0.2} + 0.0009 Re_F^{0.85} Pr_F^{0.65})$$

laminar flow

$$\Delta = 5 \frac{\lambda_G}{c_{pG} \rho_G}, \quad Sh_G = \left(\frac{\mu_G}{\rho_G \Delta} \right)^{1/3}, \quad \alpha_{lam,cond} = Sh_G \Delta \rho_g \frac{H_{VS} - H_{FS}}{50 D_{hydr}}$$

Condensation heat transfer coefficient

$$\alpha_{cond} = \max(\alpha_{t,cond}, \alpha_{lam,cond})$$

Pressure drop in 1-phase and 2-phase flow: phasic Darcy-Weisbach wall friction coefficients [5.2.2 3].

SECTION 3: DESCRIPTION OF THE NODALISATION

Table 5.8. General description of the SOCRAT nodalisation for PERSEO Test 7 Part 1 and 2

	Number of hydraulic volumes	Number of junctions	Number of heat structures	Overall Volume (m ³)
Vessel	36	10	4	n/a*
Steam Line	19	11	2	n/a
HX	15	4	3	n/a
Condensate line	21	9	3	n/a
HXP	42	10 +18 (2D)	5	n/a
Steam duct	11	5	1	n/a
OP	21	30	-	n/a
Heat Transfer Area HX (m ²)	34.47 m ² (HE tubes), 8.4+8.4 m ² (HE collectors)			
HX heat structure axial nodes number	13 (HE tubes), 1 (HE collectors)			
HX heat structure radial nodes number	5 (HE tubes), 8 (HE collectors)			

*User input is: area, length and multiplicity

Figure 5.46. Vessel, steam supply and drain lines nodalisation

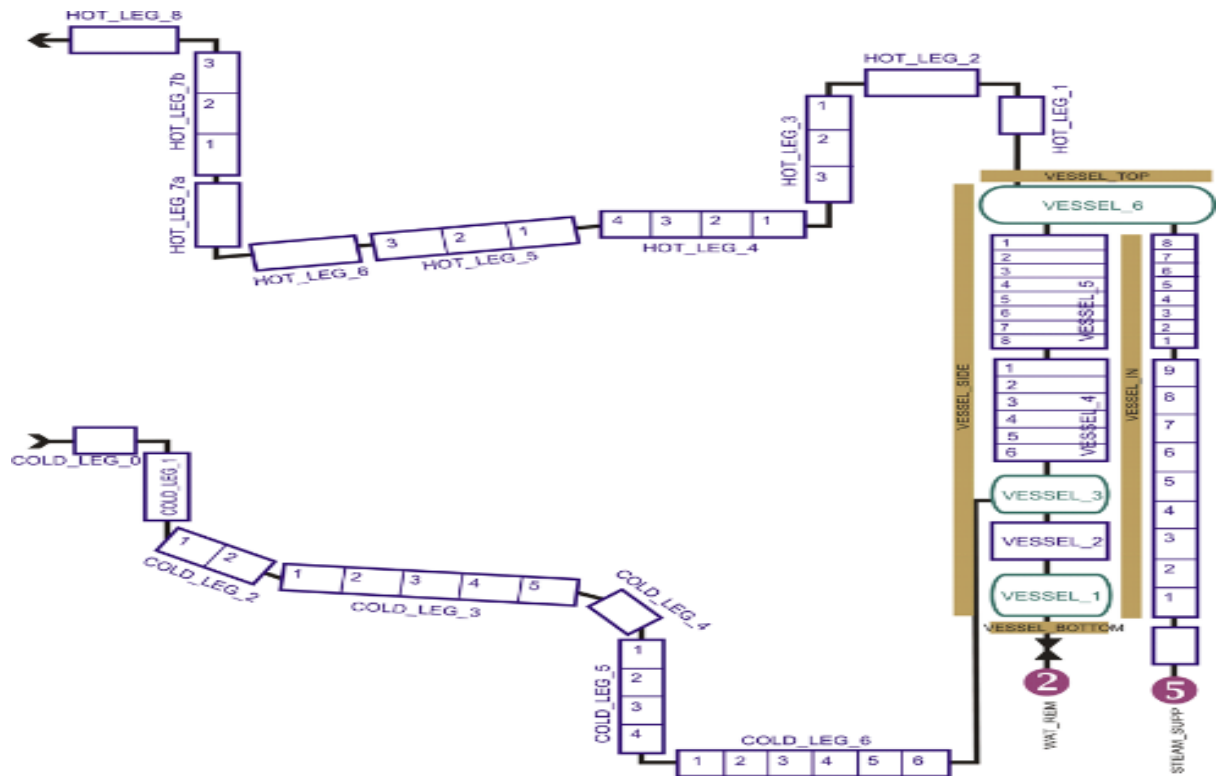
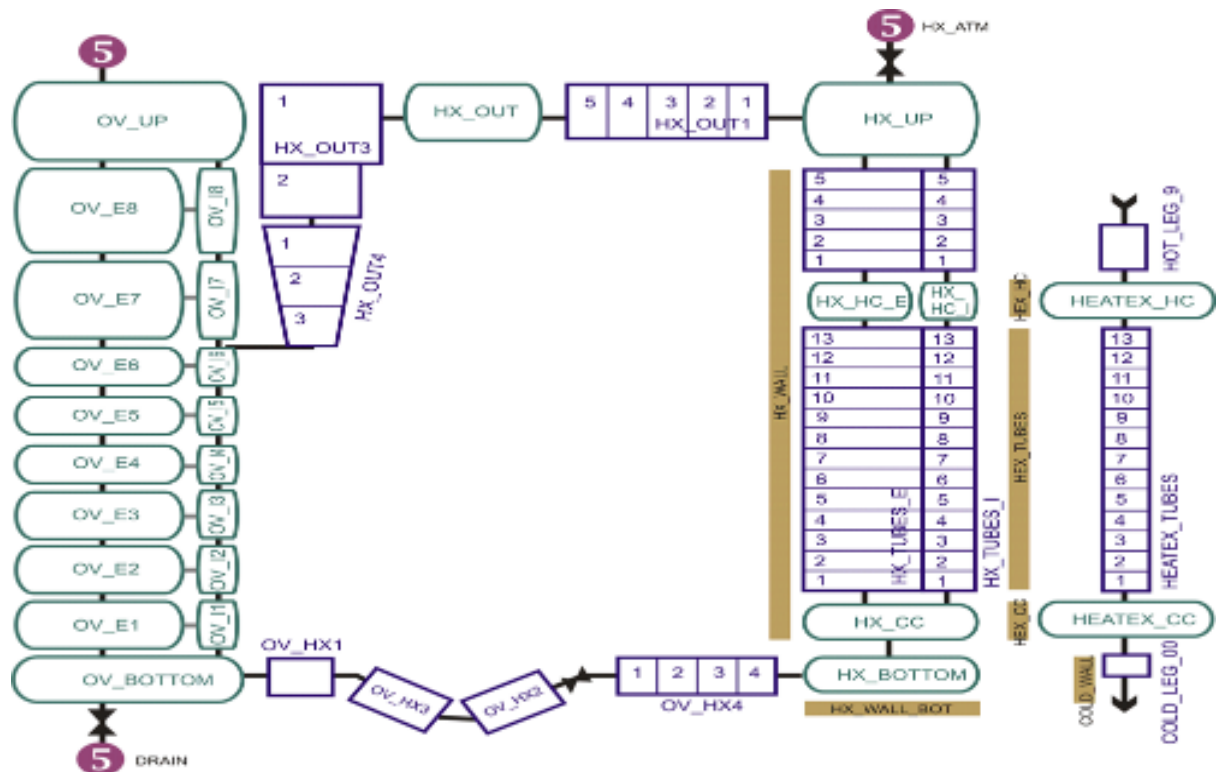


Figure 5.47. Heat exchanger, HX pool and overall pool nodalisation



Modelling assumptions:

- Heat losses from vessel, steam line, condensate line are calculated by third kind of BC with $HTC=2 \text{ W/m}^2\text{K}$ and $T=300 \text{ K}$.
- Heat losses HX pool are calculated by third kind of BC with $HTC=15 \text{ W/m}^2\text{K}$ and $T=300 \text{ K}$.
- No heat losses from steam duct and overall pool.
- Form loss coefficient for coolant flow 90° turn is taken equal to 0,5.
- Primary side pressure is not calculated by SOCRAT but set in BC (STEAM_SUPP, Figure 5.46) accordingly to Table 5.8.
- Multidimensional components are used for HE pool side. Additional momentum equations applied to hydraulic channels HX_TUBES_E/HX_TUBES_I (Figure 5.47) and elements in HX above it.
- Vertical stratification model for HE pool side HTC is on (Averaging heat flux to pool then level cross cell boundaries, Figure 5.48).
- Nodalisation is no- slicing, levels I elements OV_* is not the same as in HX_TUBES_*(Figure 5.47).
- F045 open area multiplayer is presented in Table 5.9 total area is equal to tube area.
- HE heat flux calculated not through enthalpy and flow rate but from HE area and flux density.

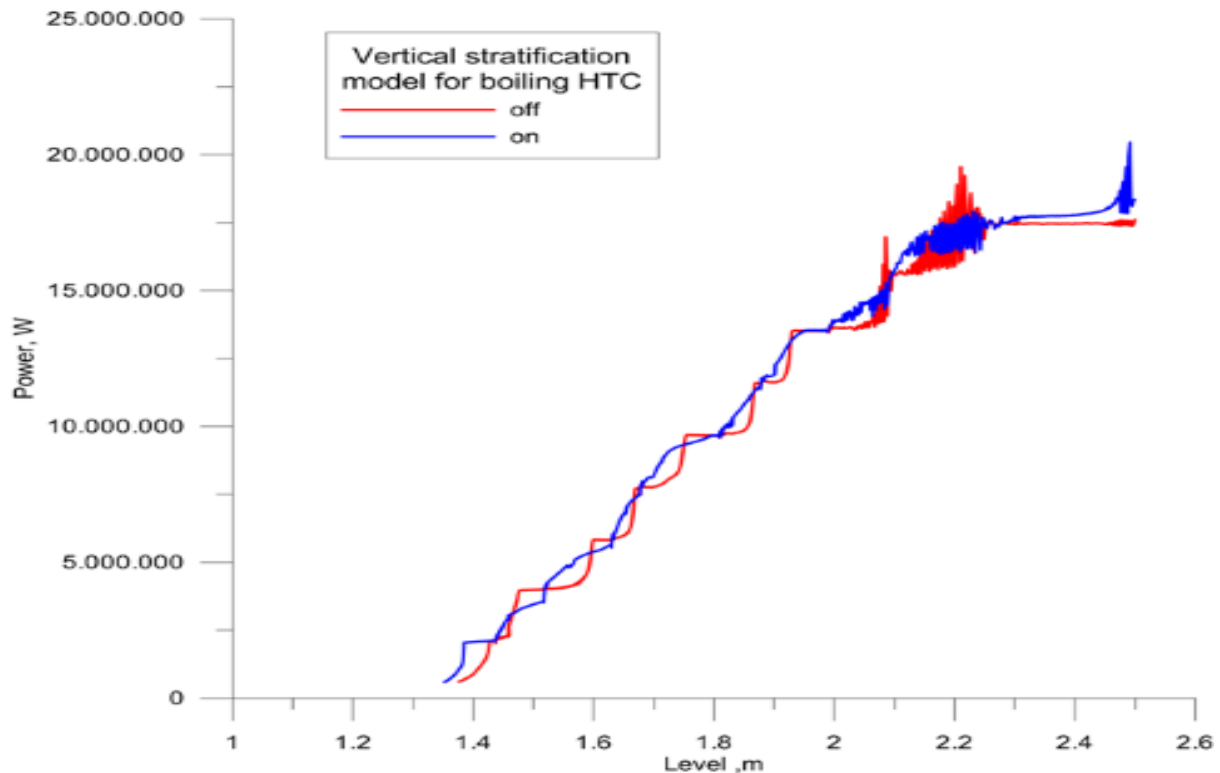
Table 5.9. Steam pressure for Test 7

Time, s	Primary pressure, Pa	Time, s	Primary pressure, Pa
Test 1		Test 2	
9 900	7.04E6	0	7.04E6
11 100	7.04E6	4 700	7.04E6
11 300	5.8E6	5 000	6.4E6
11 350	5.7E6	5 800	5.8E6
11 500	7.1E6		
12 100	7.1E6		
12 200	7.04E6		
15 000	7.04E6		

Table 5.10. F045 open area fraction

Time, s	Fraction	Time, s	Fraction
Test 1		Test 2	
9 000	0.0	0	0.0
10 470	0.0	300	0.0
10 480	0.04	326	0.5
10 490	0.20	3 338	0.5
10 590	0.23	3 460	0.0
10 600	0.0		
10 621	0.0		
10 625	0.11		
10 645	0.11		
10 650	0.0		
11 020	0.0		
11 022	0.3		
11 025	0.0		
11 039	0.0		
11 049	0.44		
11 250	0.52		
11 260	0.0		

Figure 5.48. HE heat flux vs coolant mass level in HXP, vertical stratification model for pool side HTC



SECTION 4: RESULTS

TEST 7 Part 1

Calculation start time for Test 7 Part 1 is 9 500 s, until 9 990 s vacuum breaker is open; simulation of Test 2 starts at 15 000 s (one run). Valve F045 position (open area) is presented in Table 5.9. Non-derivative parameters (Table 5.10, column “EXP”) are set as initial for start time = 9 500 s.

During Test 7 Part 1 there is at least three circulation contours in PERSEO facility (Figure 5.49). Circulations, marked purple, are modelled by SOCRAT with 2D (HXP) and pseudo-2D (OP) nodalisation. Circulation, marked red (steam-air mixture), is not modelled due to 1D approach.

It is required to use circulation contours in HXP during water filling. In case of 1D model (Figure 5.50a) one can see temperature gradient in injected water with saturation condition and strong boiling near gas-water boundary. Pressure of HXP top became overpredicted and it leads to stop filling. Mixing with possible subcooling boiling (Figure 5.50b) improves results of calculations.

Figure 5.51 and Figure 5.52 show that at ~11 050 s after double opening of the vacuum breaker, sensor DP_S001 shows presence of water. About 150 s after valve F045 close one can see L_VQ increasing due to water drain from steam duct. It is not modelled by SOCRAT code; the distance between the HXP top and the vacuum breaker is set to a very low value and there are no significant pressure drops in the steam duct.

Data in Table 5.11 show the main relevant thermal-hydraulic aspects relevant to Part 1 of Test 7.

Figure 5.53 to Figure 5.70 show calculated and experimental proposed parameters. Calculated results qualitatively and in most cases quantitatively reproduce the experimental data. The average difference in HE power and pool levels is less than 10%

The integration timesteps for SOCRAT code are from 0.01 s (1st HXP filling) to 0.02 s. The calculation time is 2 250 s for Part 1.

Table 5.11. Initial condition for Test 7 Part 1

	PARAMETER	LABEL	EXP	SOCRAT	(%) DISCREPANCIES	NOTE
1	Flowrate steam supply line (kg/s)	F_A001 (der.)	1.10	0.11	90	Flowmeter calibration?
2	Flowrate condensate drain line (kg/s)	F_E001 (der.)	0.59	0.10	83	Flowmeter calibration?
3	Power heat exchanger (kW)	W_IC (der.)	2 320	25	100	W/O heat loss from RCS
4	Absolute pressure vessel (kPa)	P-I001	7 056	7 037	<1	User input tabulated value
5	HX inlet fluid temperature (°C)	T-A005	291.4	286.1	2	TC calibration?
6	HX outlet fluid temperature (°C)	T-E001	288.7	286.2	<1	
7	Level HXP (m)	L_VQ (der.)	0.19	0.20	5	Less than measurement accuracy

	PARAMETER	LABEL	EXP	SOCRAT	(%) DISCREPANCIES	NOTE
8	Level OP (m)	L_VP (der.)	4.65	4.64	<1	
9	Fluid temperature HXP (bottom) (°C)	T-Q037	123.6	137.5	11	
10	Fluid temperature HXP (middle) (°C)	T-Q034	198.3	202.4	2	
11	Fluid temperature HXP (top) (°C)	T-Q031	222.7	202.6	10	
12	Relative pressure HXP top (kPa)	P-Q001	0.61	0.007	99	
13	Fluid temperature OP (bottom) (°C)	T-P008	15.3	15.4	<1	
14	Fluid temperature OP (top) (°C)	T-P021	15.4	15.5	<1	
15	Diff. pressure HX upper-lower header (kPa)	DP-003	-0.87	-0.91	5	
16	Diff. pressure steam duct injector (kPa)	DP-J001	-10.5	-10.2	1	
17	Wall temperature HX upper header (°C)	TW-B005	282.01	285.9	1	
18	Wall temperature HX lower header (°C)	TW-D001	280.48	284.5	1	

Figure 5.49. Circulation contours in PERSEO Test 7

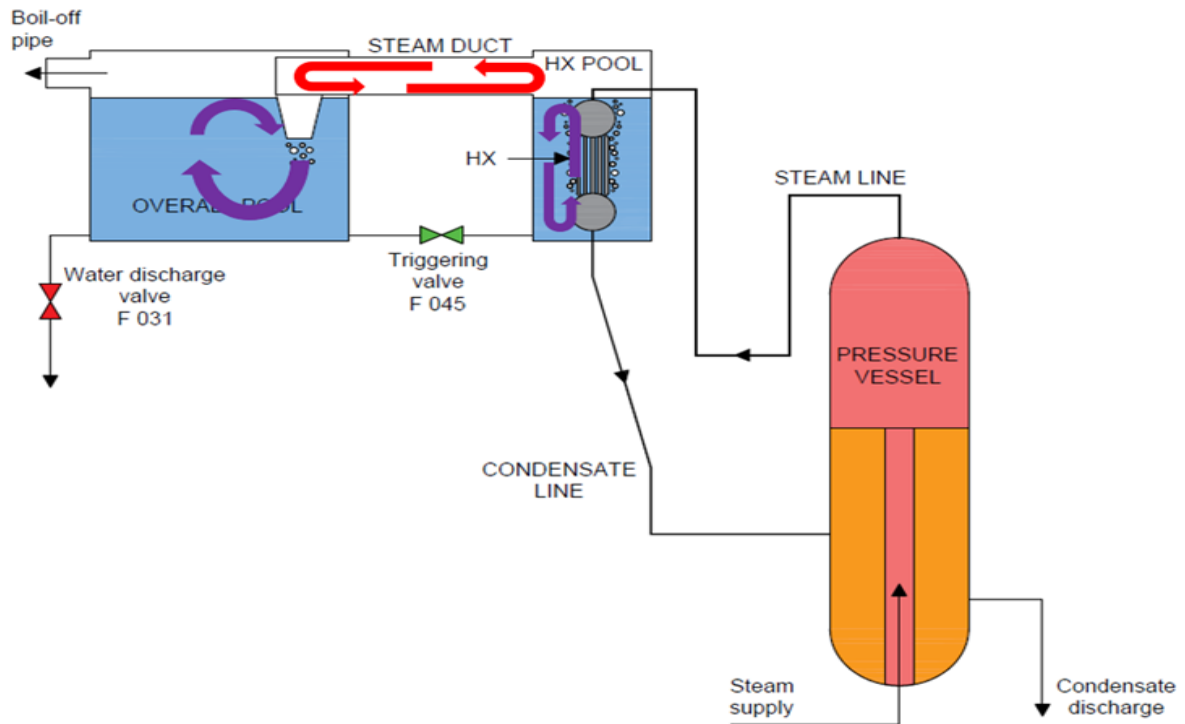


Figure 5.50. HXP level for 1D and 2D models

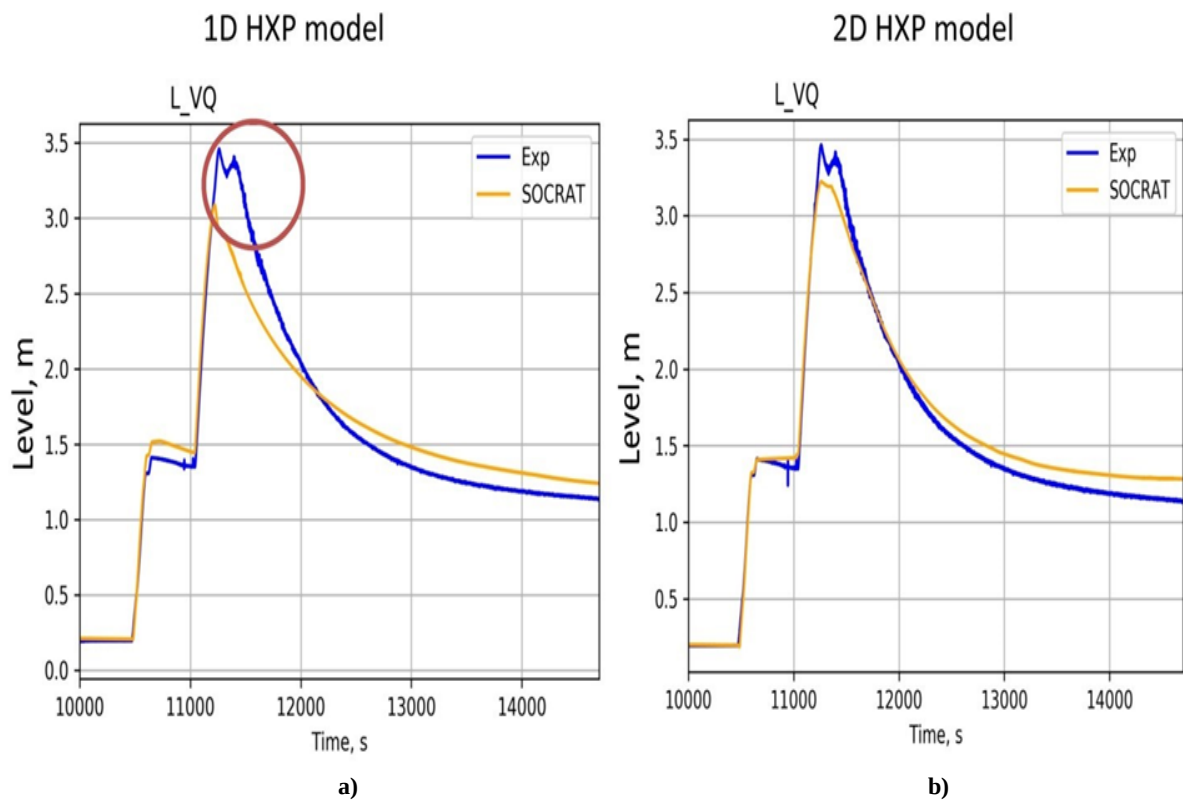


Figure 5.51. HXP level and pressure

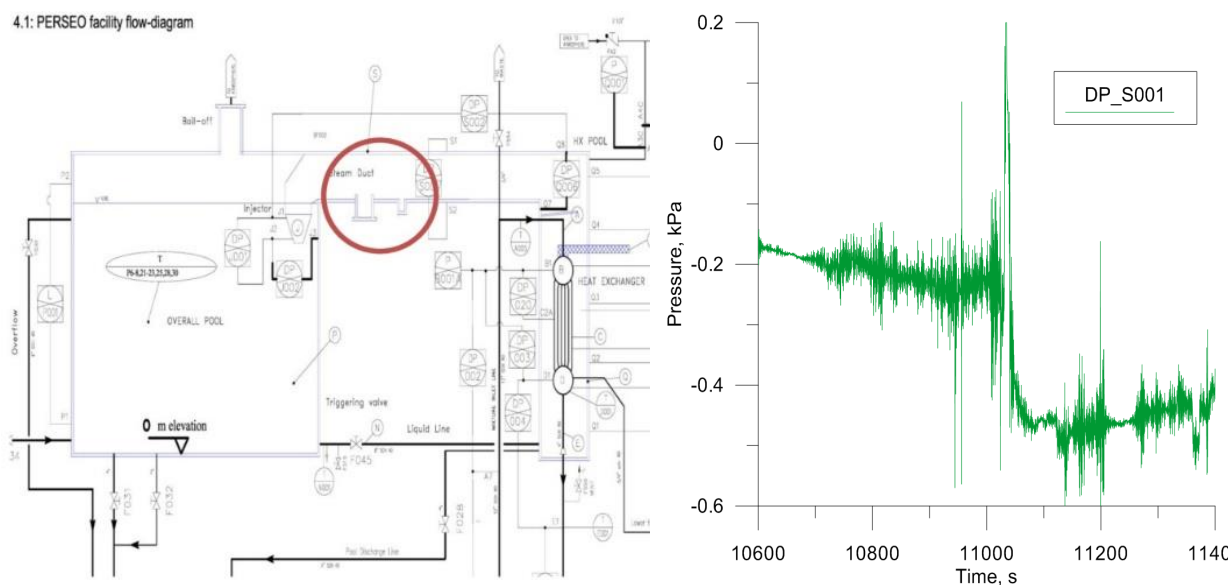


Figure 5.52. Water coming from OP to HXP through steam duct

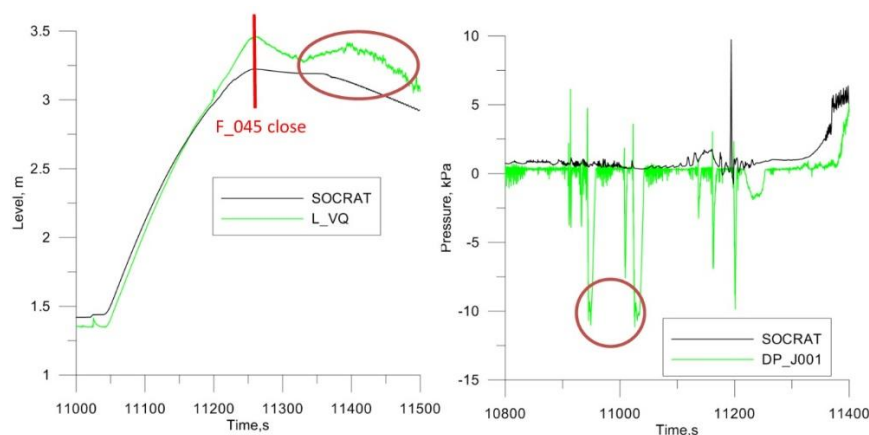


Table 5.12. Main relevant thermal-hydraulic aspect related to the Test 7 Part 1 (SOCRAT code)

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	10 470-10 600	20% average
Triggering valve (F045) re-opening and re-closure	10 621-10 650	11% average
Maximum level in the HX pool for the first filling step	10 650	1.41 m
Small Heat removal from the primary side	10 590	1 100 kW*
Slow water consumption in the HX pool	10 600-11 000	0.06 kg/s steam duct flow
Instabilities for steam condensation in the injector	10 500	Negative HXP pressure
Triggering valve (F045) opening and closure	11 020-11 025; 11 039-11 260	-
Maximum level in the HX pool	11 255	3.22 m
Maximum exchanged power	11 094	33 000 kW*
HX pool minimum level	11 260	4.21 m
OP average temperature	13 500	47 C

*Calculated from heat flux density through HE tubes and collectors

Figure 5.53. Flowrate steam supply line for Test 7 Part 1

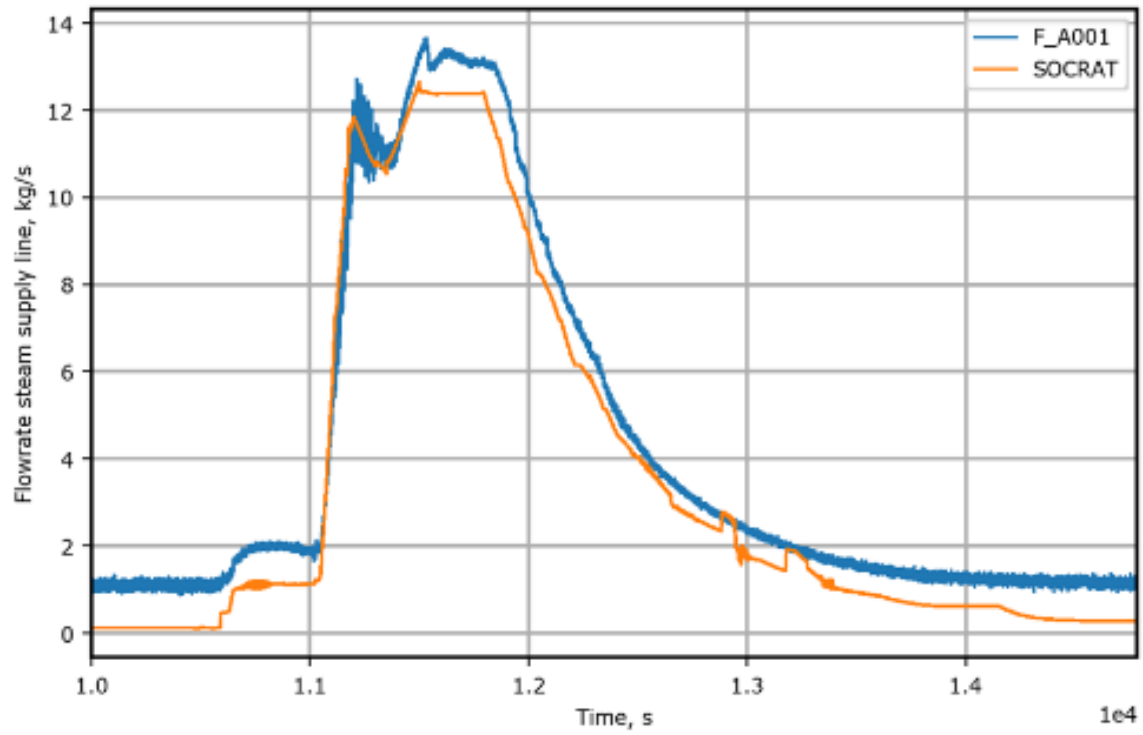


Figure 5.54. Flowrate condensate drain line for Test 7 Part 1

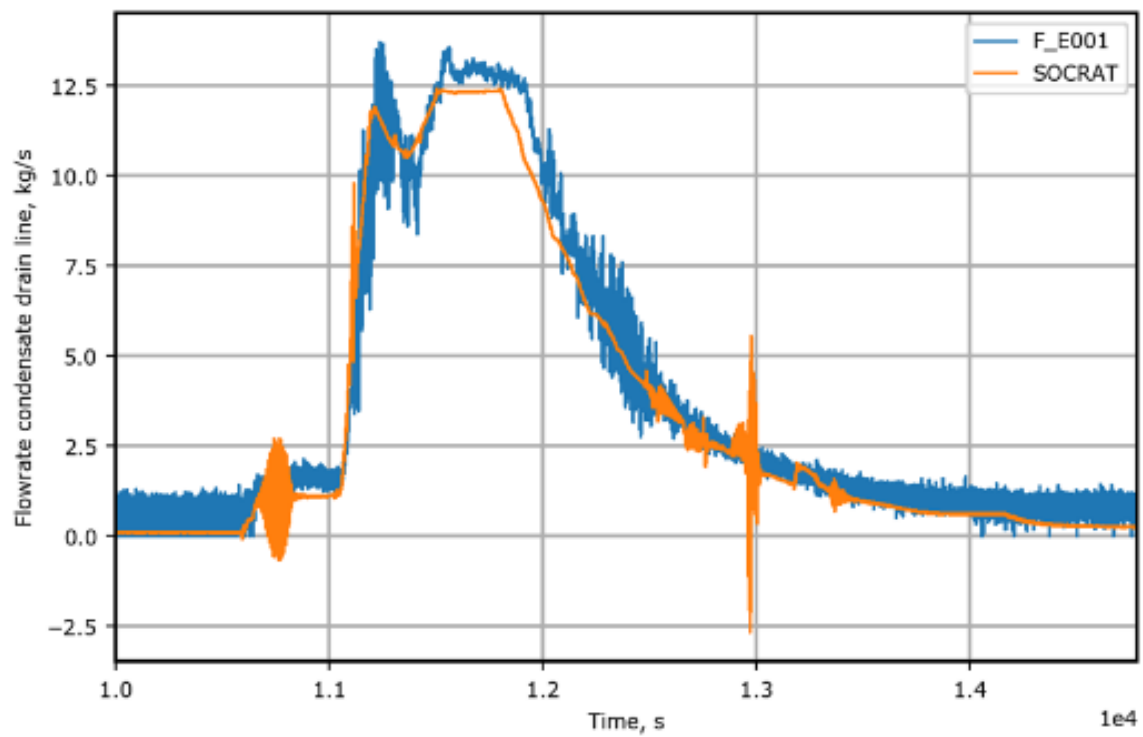


Figure 5.55. Power heat exchanger for Test 7 Part 1

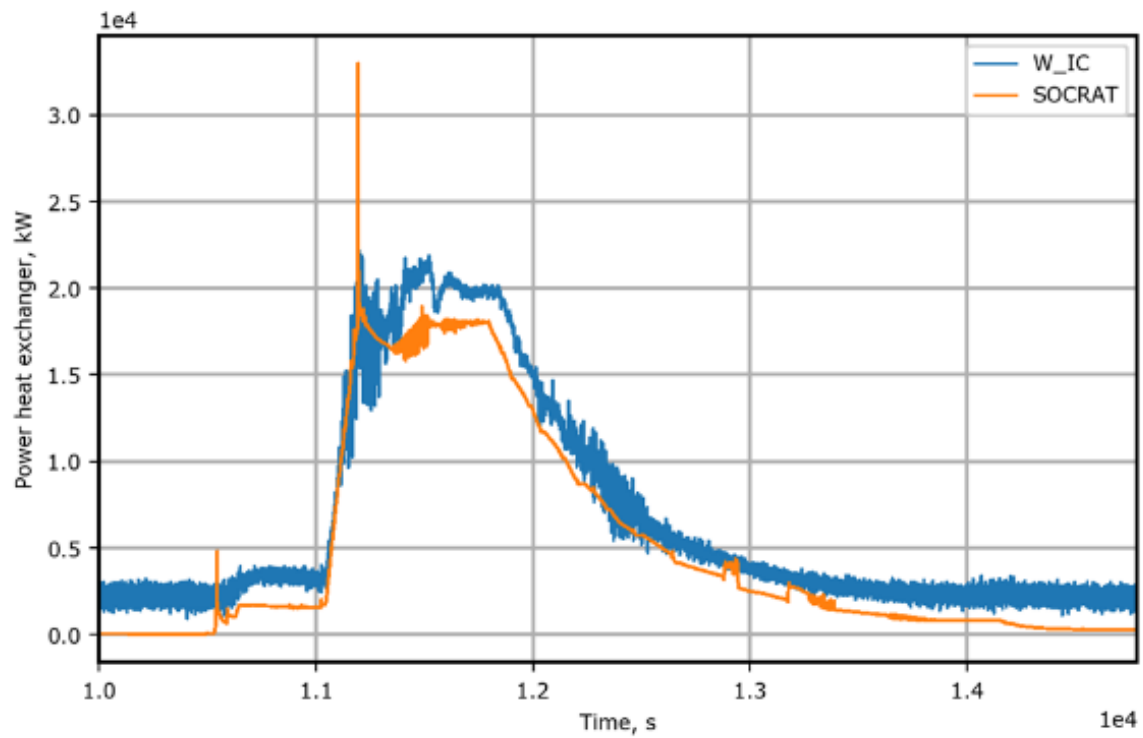


Figure 5.56. Absolute pressure vessel for Test 7 Part 1

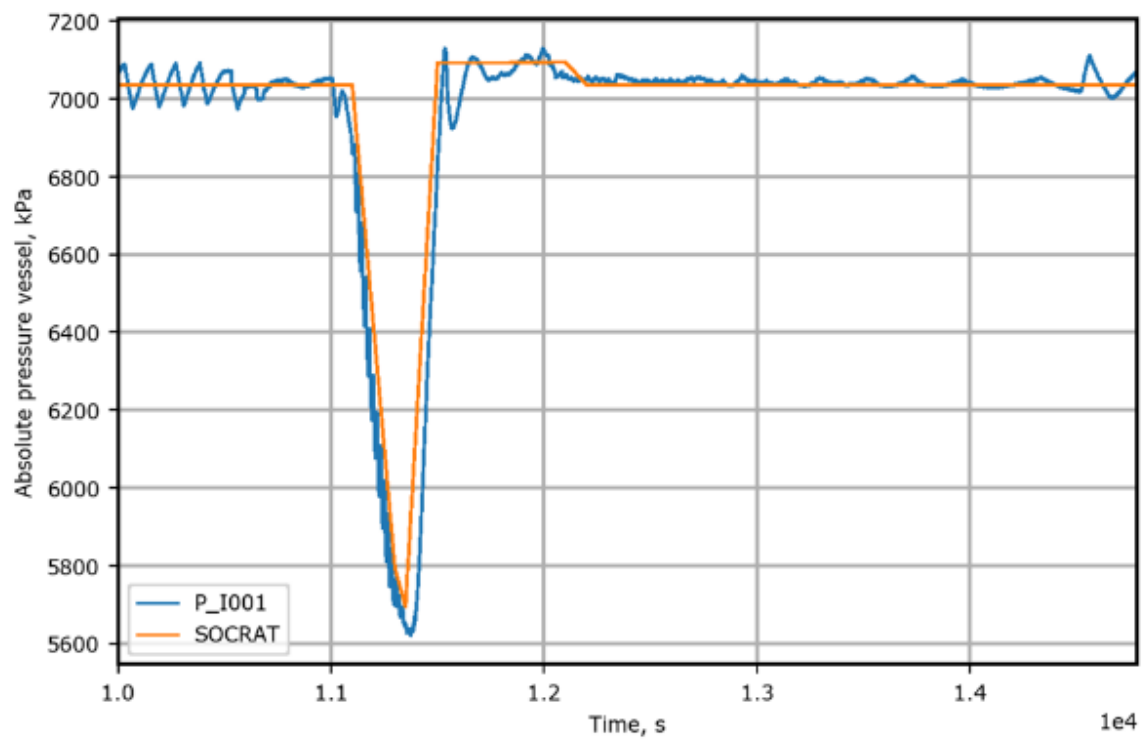


Figure 5.57. HX inlet fluid temperature for Test 7 Part 1

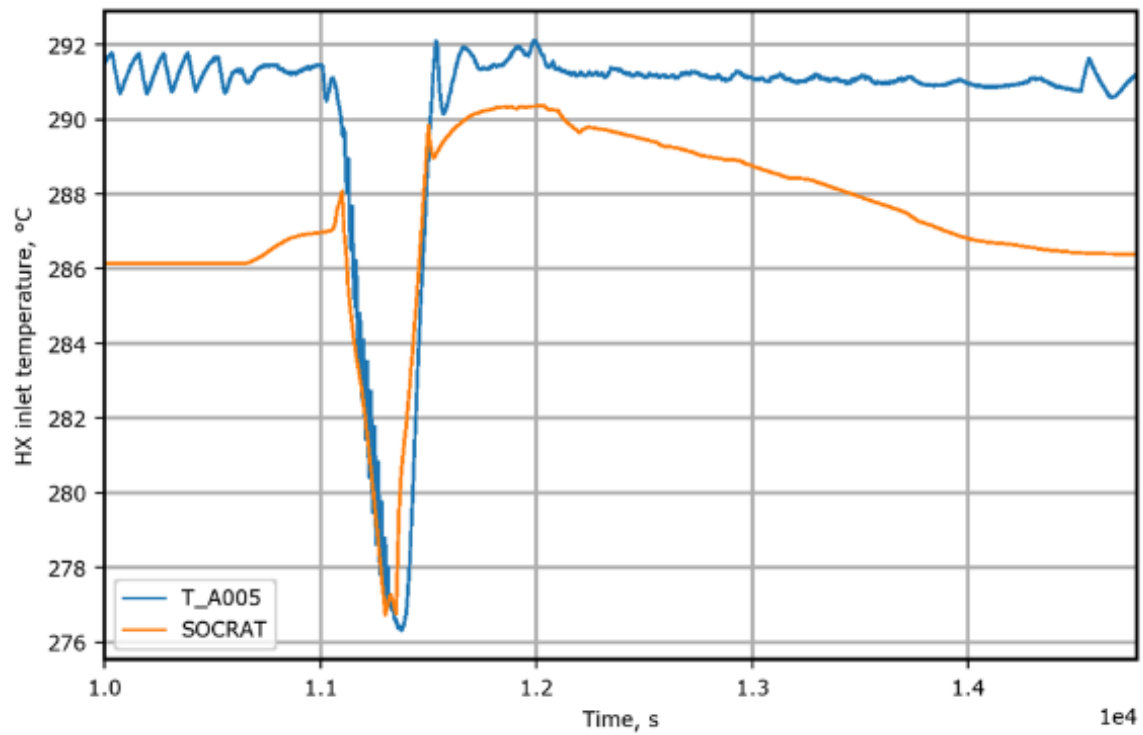


Figure 5.58. HX outlet fluid temperature for Test 7 Part 1

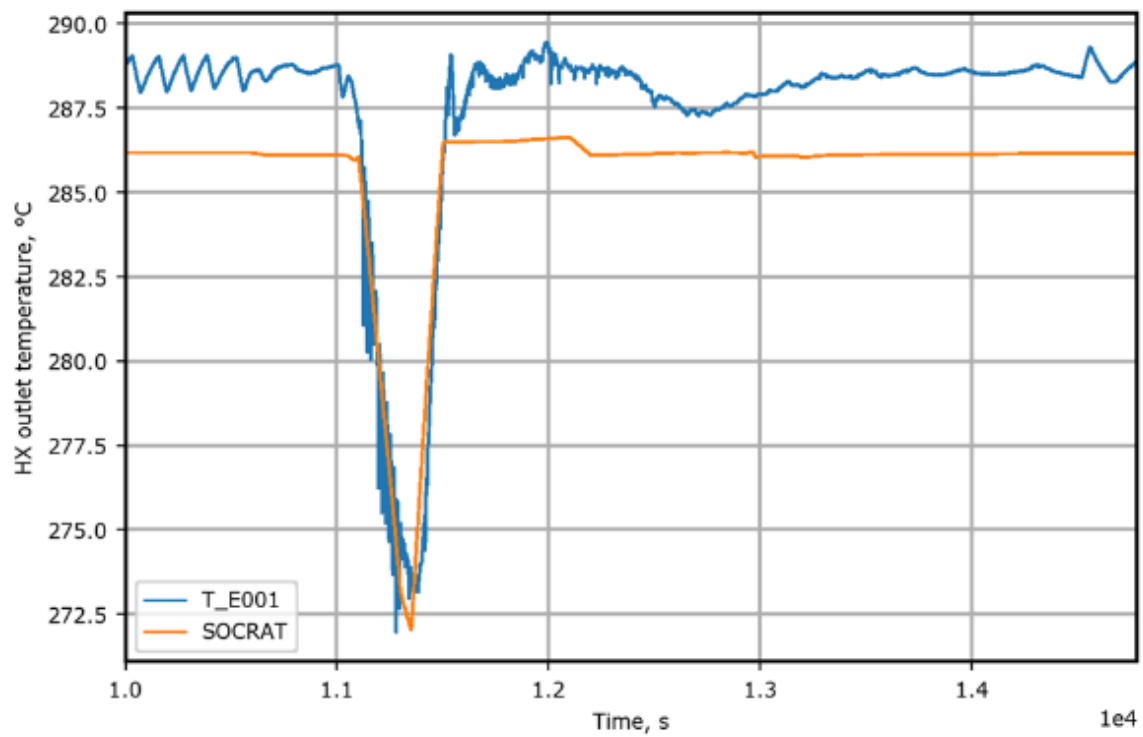


Figure 5.59. Level HXP for Test 7 Part 1

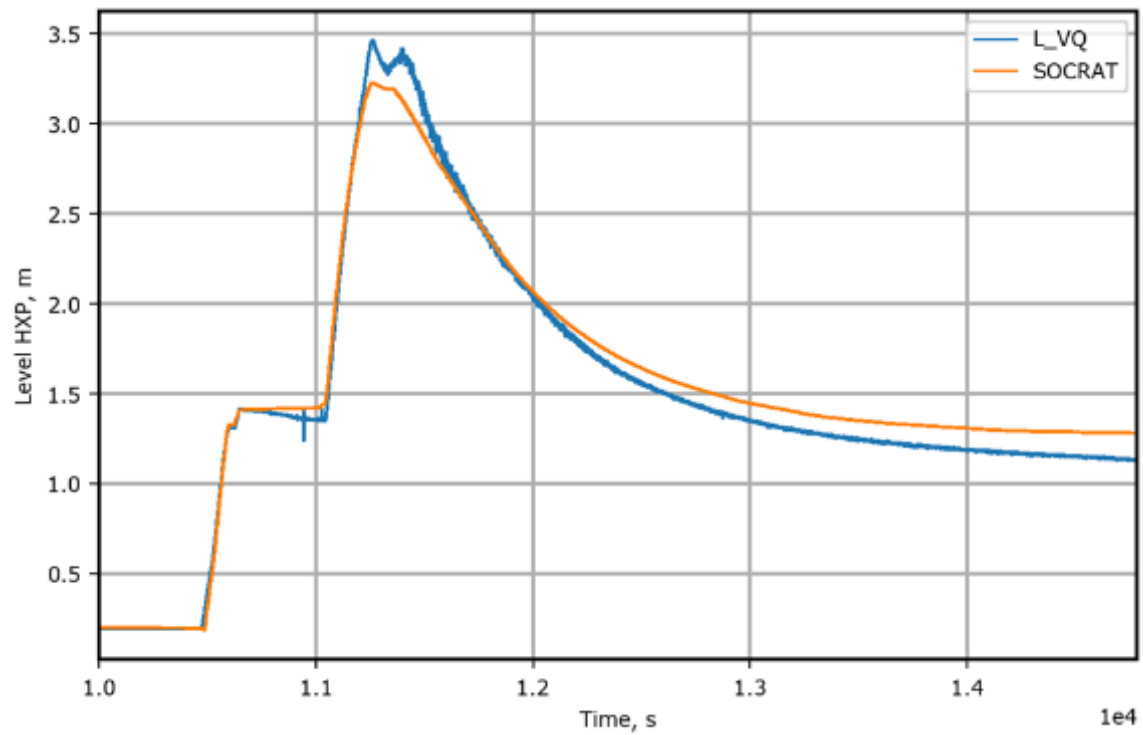


Figure 5.60. Level OP for Test 7 Part 1

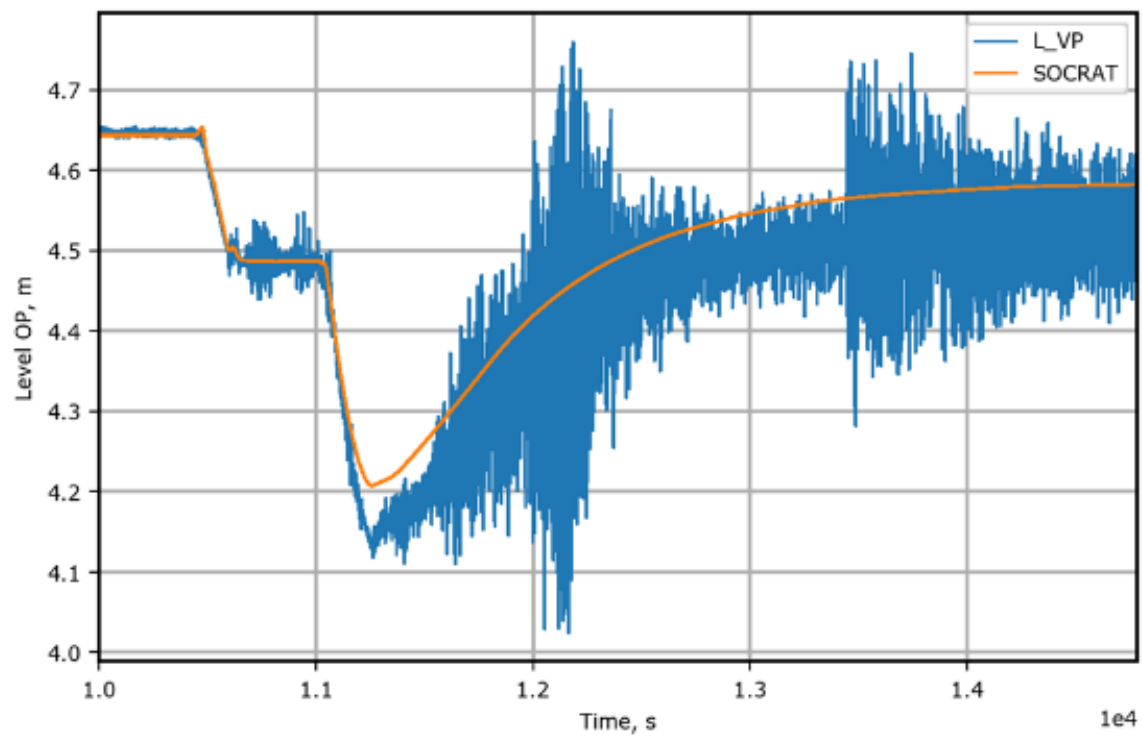


Figure 5.61. Fluid temperature HXP (bottom) for Test 7 Part 1

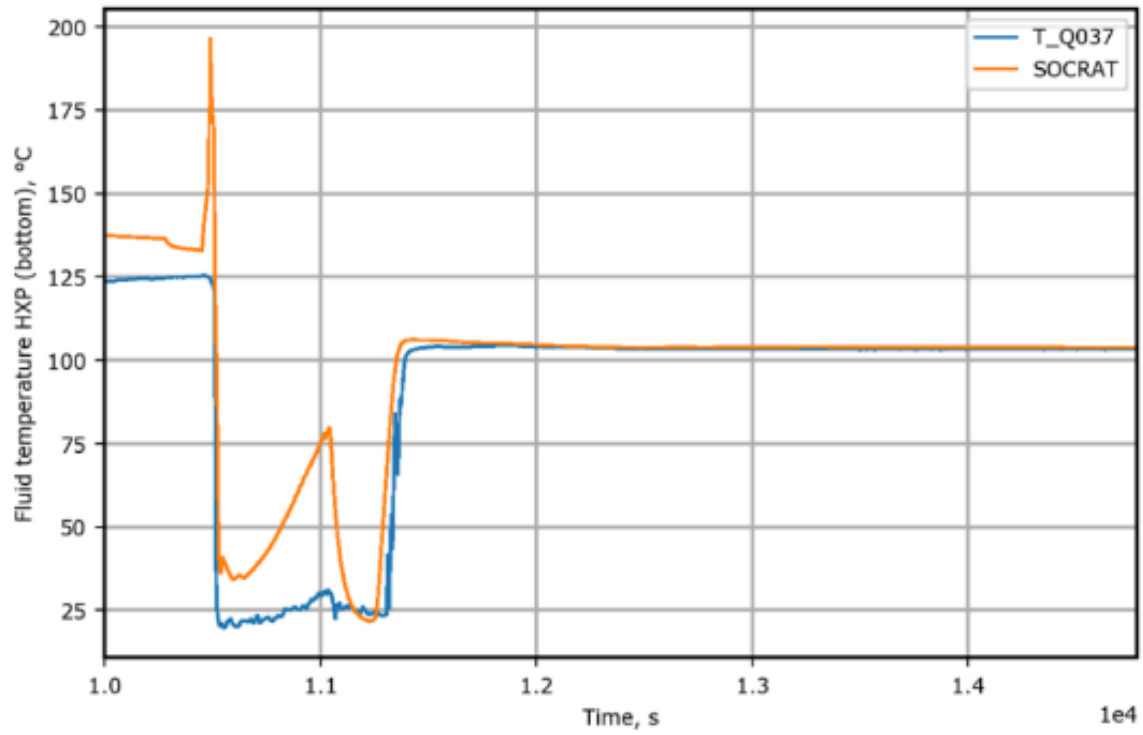


Figure 5.62. Fluid temperature HXP (middle) for Test 7 Part 1

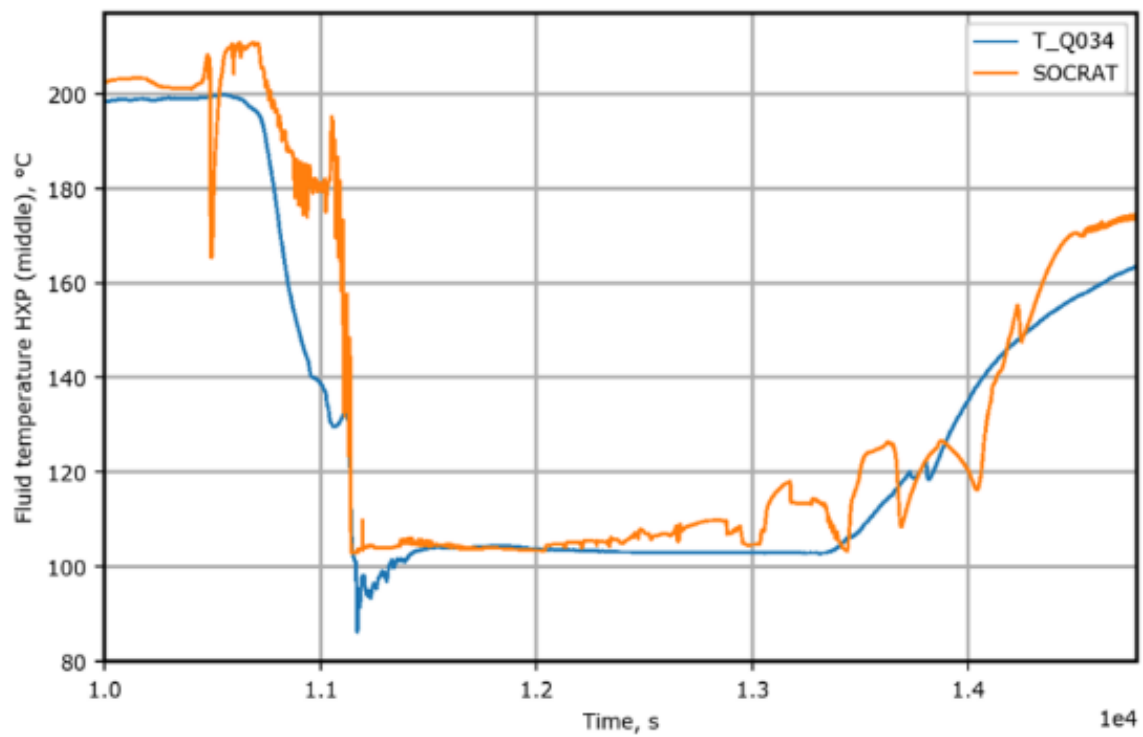


Figure 5.63. Fluid temperature HXP (top) for Test 7 Part 1

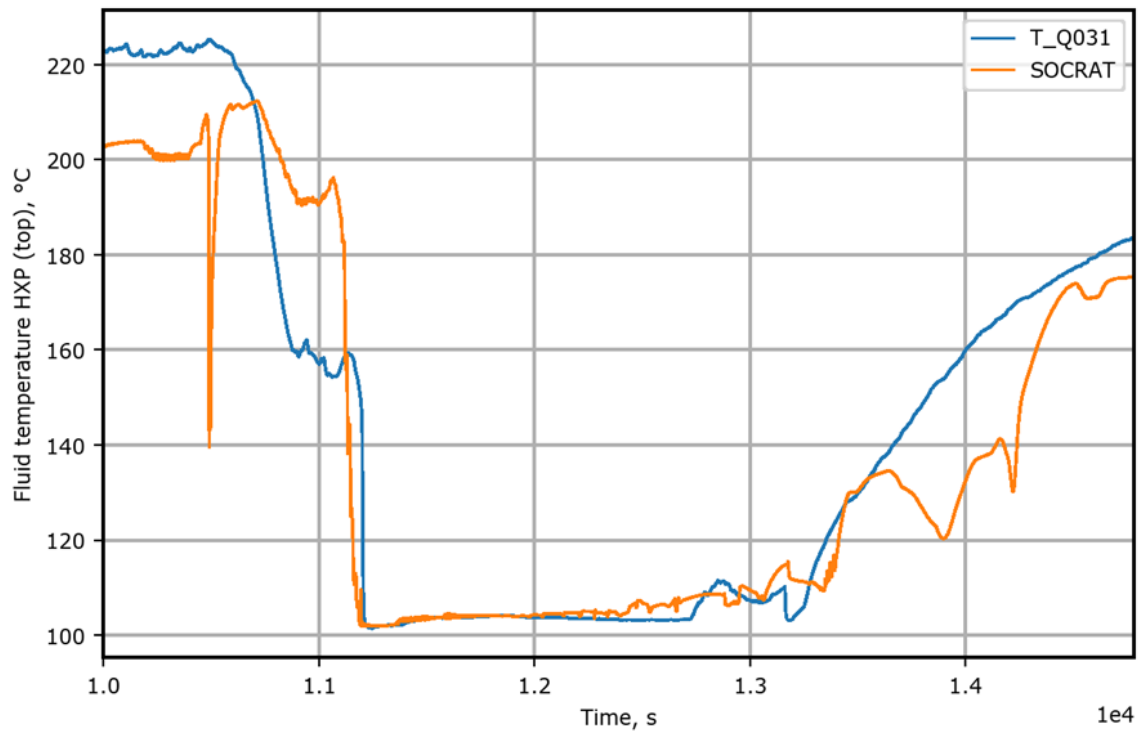


Figure 5.64. Relative pressure HXP top for Test 7 Part 1

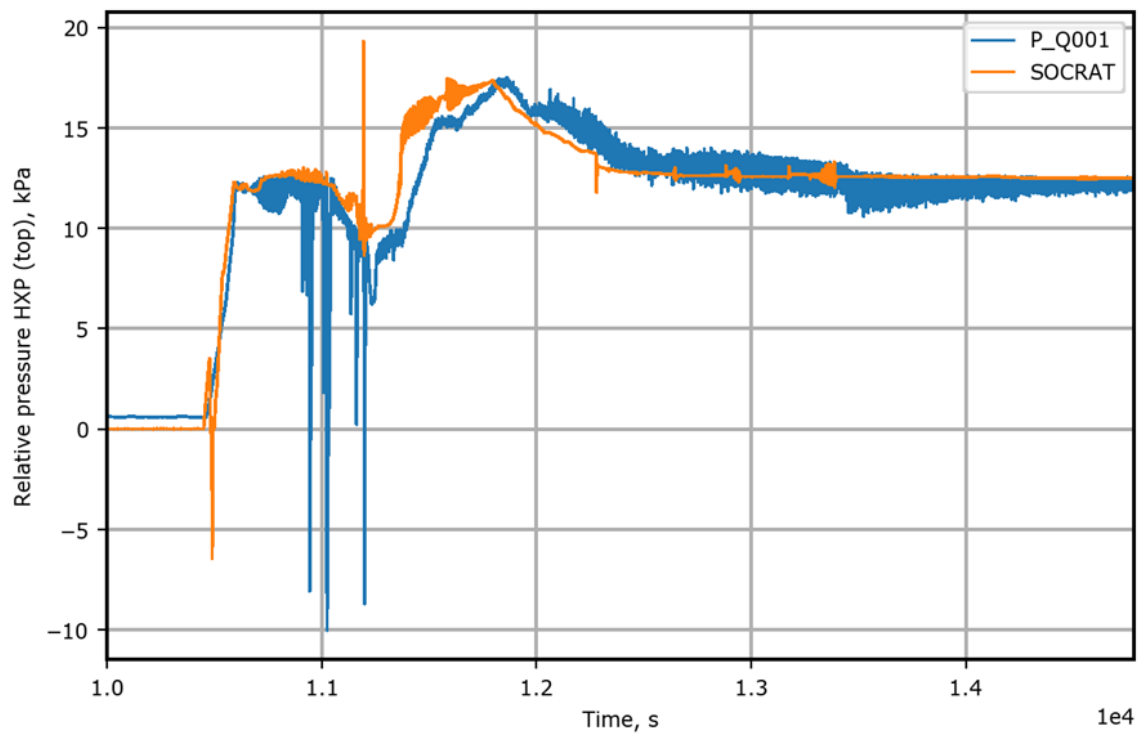


Figure 5.65. Fluid temperature OP (bottom) for Test 7 Part 1

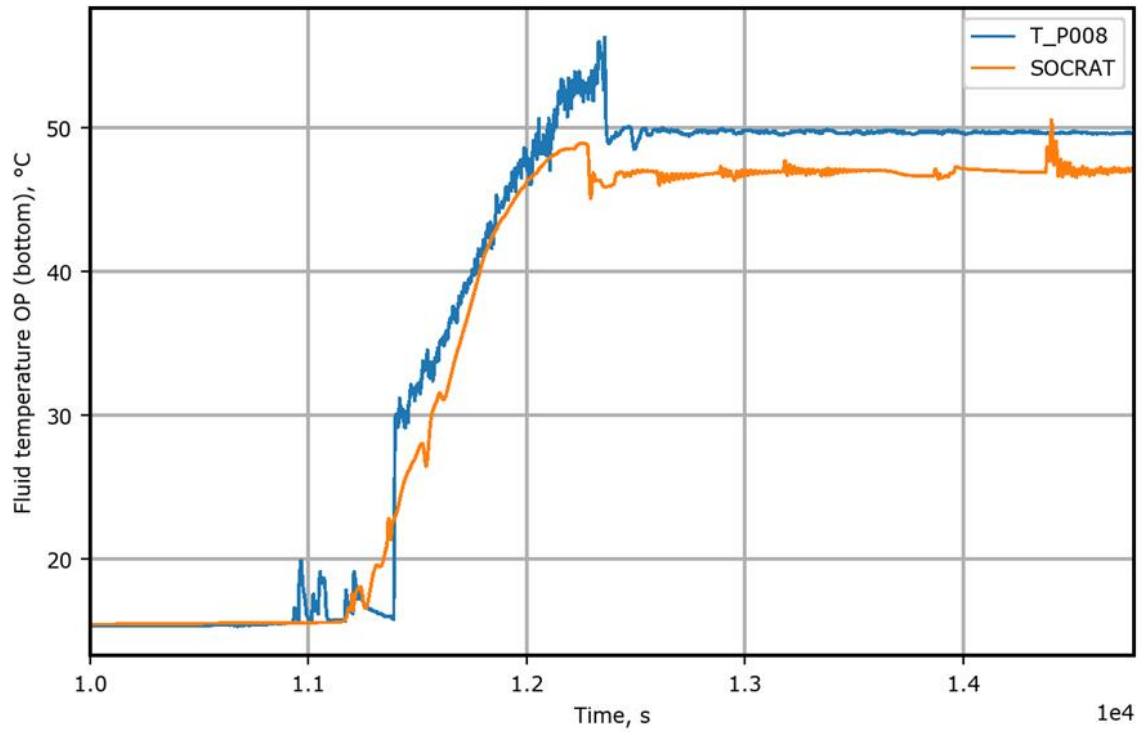


Figure 5.66. Fluid temperature OP (top) for Test 7 Part 1

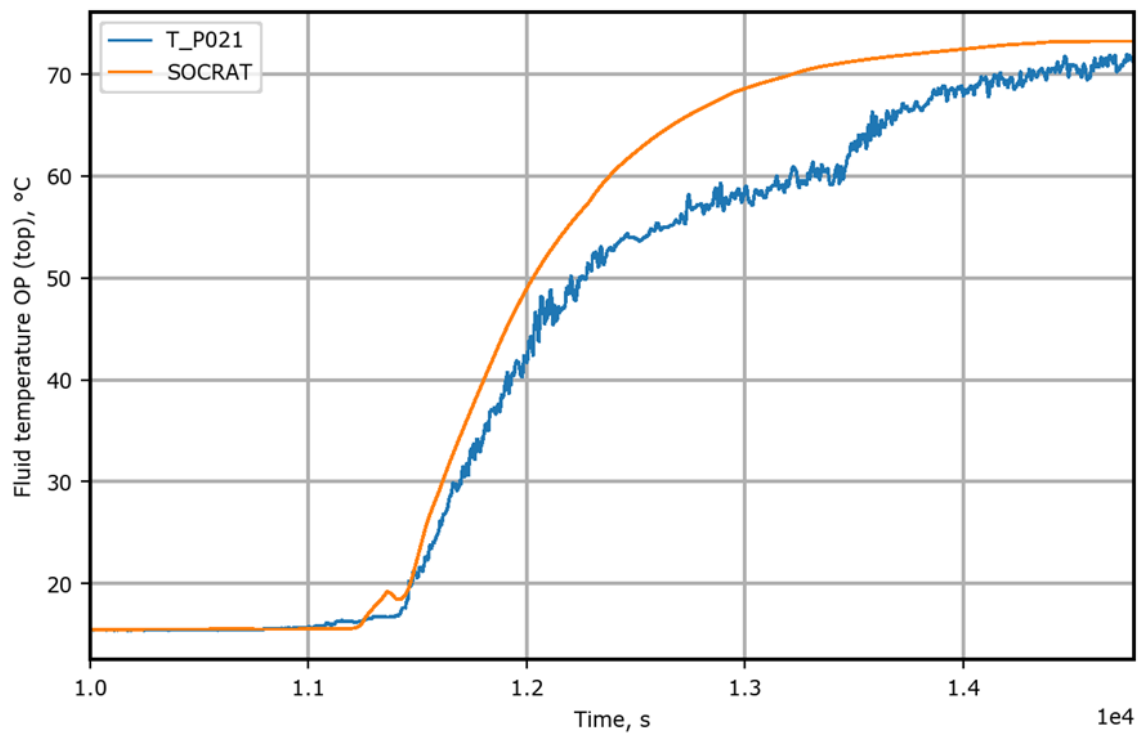


Figure 5.67. Diff. pressure HX upper-lower header for Test 7 Part 1

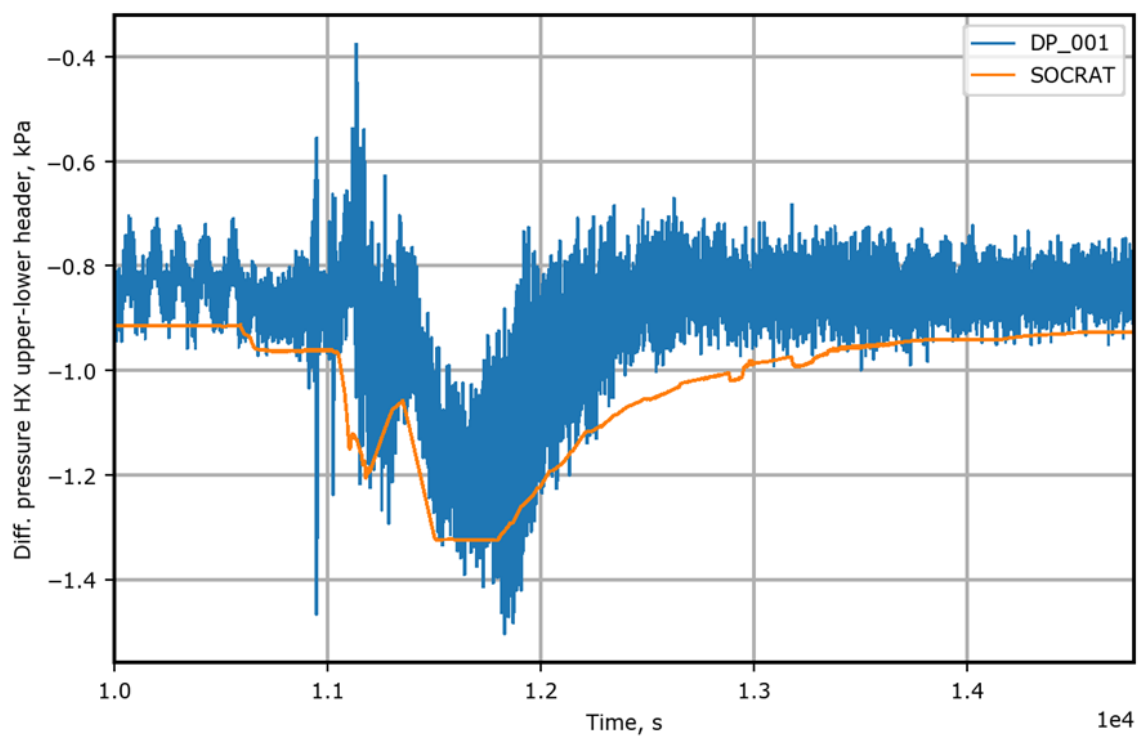


Figure 5.68. Diff. pressure steam duct injector for Test 7 Part 1

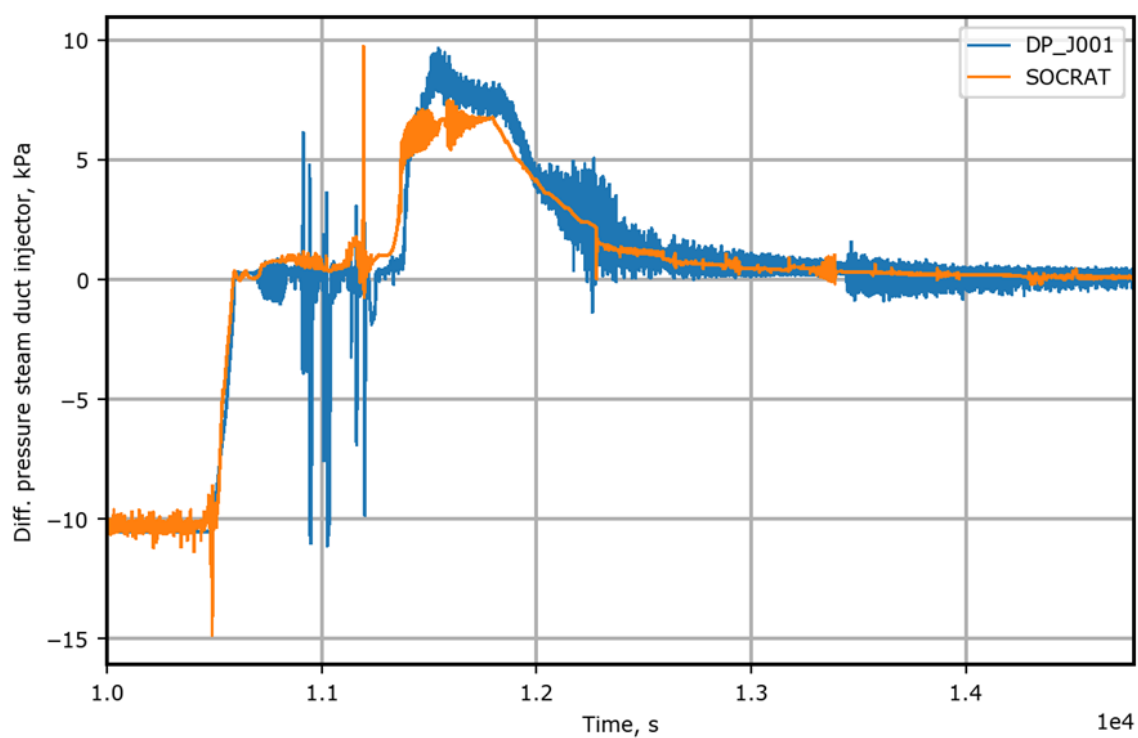


Figure 5.69. Wall temperature HX upper header for Test 7 Part 1

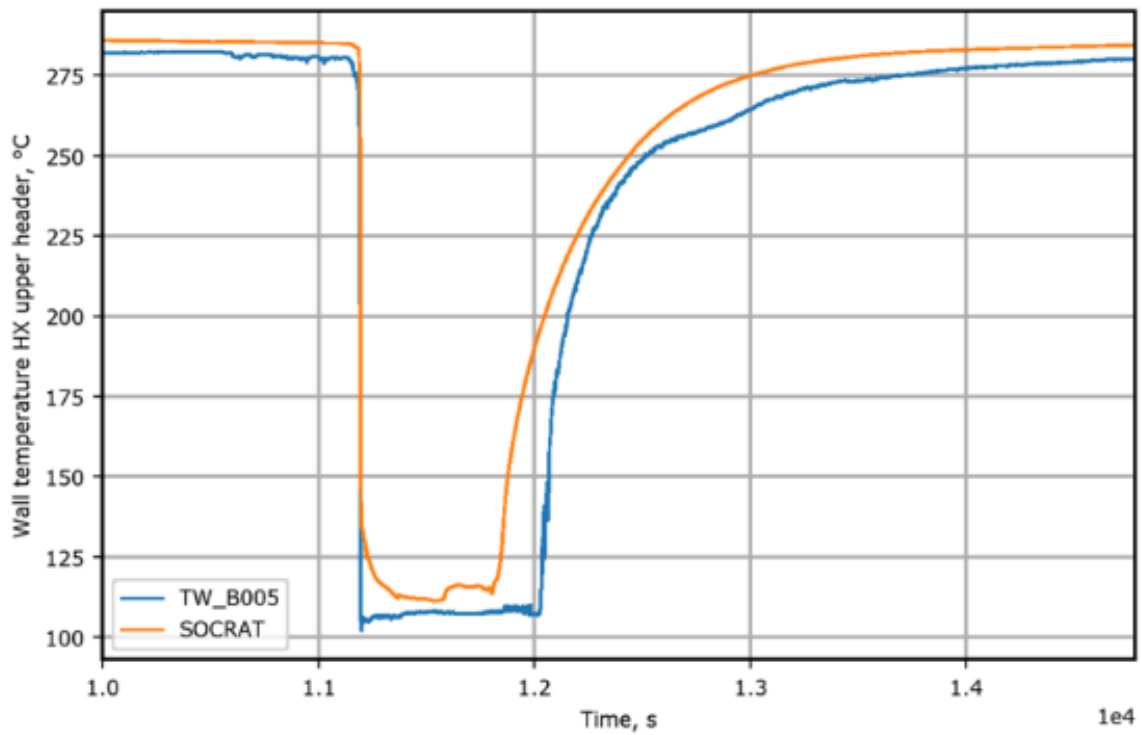
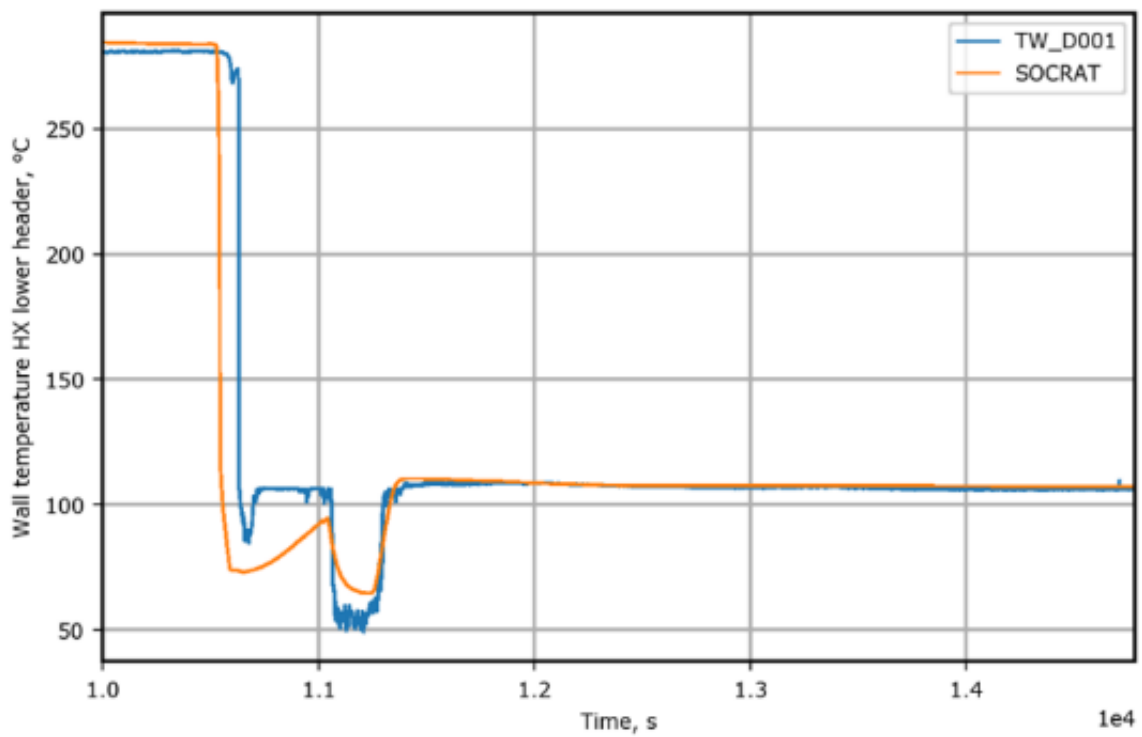


Figure 5.70. Wall temperature HX lower header for Test 7 Part 1



The marks adopted in Table 5.12 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.13. PERSEO Test 7 Part 1 versus phenomena, SOCRAT code prediction

	Phenomenon	Experiment				SOCRAT
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F_A001 (der.)	+
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W_IC (der.)	+
				Level HXP	L_VQ (der.)	
				Level OP	L_VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	+
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure HX upper-lower header	DP-003	+
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	HX inlet temperature	T-A005	+
				HX outlet temperature	T-E001	
				Power heat exchanger	W_IC (der.)	
				Level HXP	L_VQ (der.)	
				Power heat exchanger	W_IC (der.)	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (bottom)	T-Q037	+
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
				Diff. pressure steam duct injector	DP-J001	
				Power heat exchanger	W_IC (der.)	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP	L_VQ (der.)	+/o
				Level OP	L_VP (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L_VP (der.)	+/o
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

** Ph. = Phenomenon

Test 7 Part 2

The calculation start time for Test 7 Part 2 is 0 s (=15 000 s for Part 1); there is no special tuning of the system parameters – they are “as is” after finishing Part 1 (see Table 5.13).

Data in Table 5.14 show the main relevant thermal-hydraulic aspects relevant to Part 2 of Test 7.

Figure 5.71 to Figure 5.88 show calculated and experimental proposed parameters. The calculated results qualitatively and in most cases quantitatively reproduce the experimental data. The average difference in the heat exchanger power and pool levels is less than 10%. The water drain flowrate from OP is matched to fit L_{VP} data.

Table 5.14. Initial condition for Test 7 Part 2

	PARAMETER	LABEL	EXP	SOCRAT	(%) DISCRPANCIES	NOTE
1	Flowrate steam supply line (kg/s)	F_A001 (der.)	1.13	0.27	76	All data from the end of part 1
2	Flowrate condensate drain line (kg/s)	F_E001 (der.)	0.75	0.25	67	
3	Power heat exchanger (kW)	W_IC (der.)	2 161	273	87	W/O heat loss from RCS
4	Absolute pressure vessel (kPa)	P-I001	7 052	7 034	<1	User input tabulated value
5	HX inlet fluid temperature (°C)	T-A005	291.1	286.3	2	
6	HX outlet fluid temperature (°C)	T-E001	288.7	286.2	<1	
7	Level HXP (m)	L_VQ (der.)	1.12	1.27	13	
8	Level OP (m)	L_VP (der.)	4.52	4.58	1	
9	Fluid temperature HXP (bottom) (°C)	T-Q037	103.2	103.8	<1	
10	Fluid temperature HXP (middle) (°C)	T-Q034	165.0	175.8	7	
11	Fluid temperature HXP (top) (°C)	T-Q031	184.8	175.9	5	
12	Relative pressure HXP top (kPa)	P-Q001	12.2	12.5	2	
13	Fluid temperature OP (bottom) (°C)	T-P008	49.7	47.1	5	
14	Fluid temperature OP (top) (°C)	T-P021	70.7	73.2	4	
15	Diff. pressure HX upper-lower header (kPa)	DP-003	-0.83	-0.93	12	
16	Diff. pressure steam duct injector (kPa)	DP-J001	0.19	0.04	79	
17	Wall temperature HX upper header (°C)	TW-B005	280.5	284.5	1	
18	Wall temperature HX lower header (°C)	TW-D001	106.3	107.2	<1	

Table 5.15. Main relevant thermal-hydraulic aspect related to the Test 7 Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	300	-
Maximum level in the HXP	482	3.0 m
Maximum exchanged power	460	26 000 kW*
OP discharge valve F031 opening	1 150	-
Triggering valve F045 closure	3 450	-
HX pool level decreasing and loss of mass from the boil-off	1 120	-
Primary side depressurisation beginning for end of test	4 700	-

Figure 5.71. Flowrate steam supply line for Test 7 Part 2

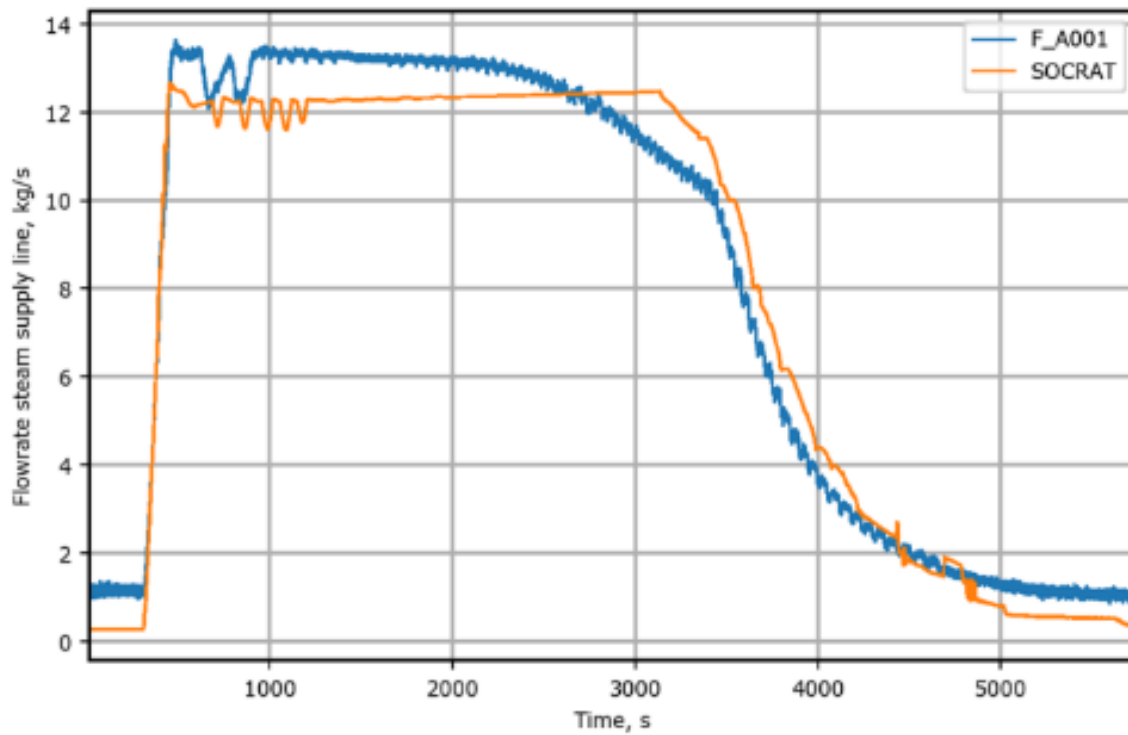


Figure 5.72. Flowrate condensate drain line for Test 7 Part 2

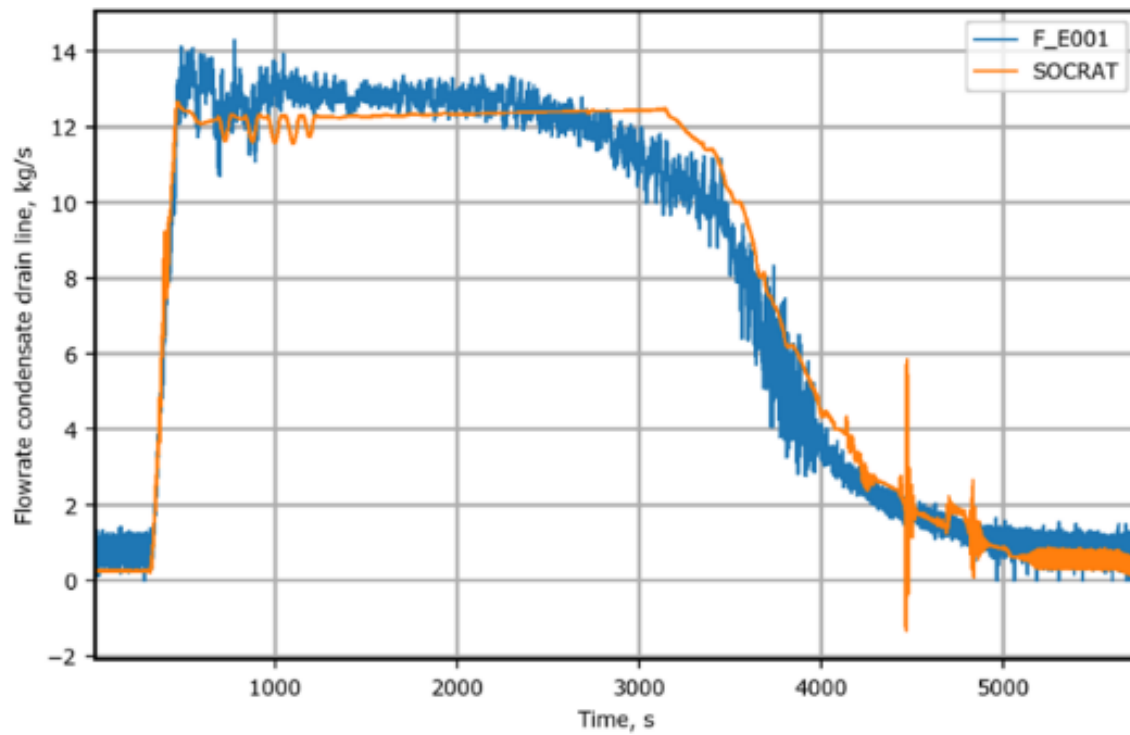


Figure 5.73. Power heat exchanger for Test 7 Part 2

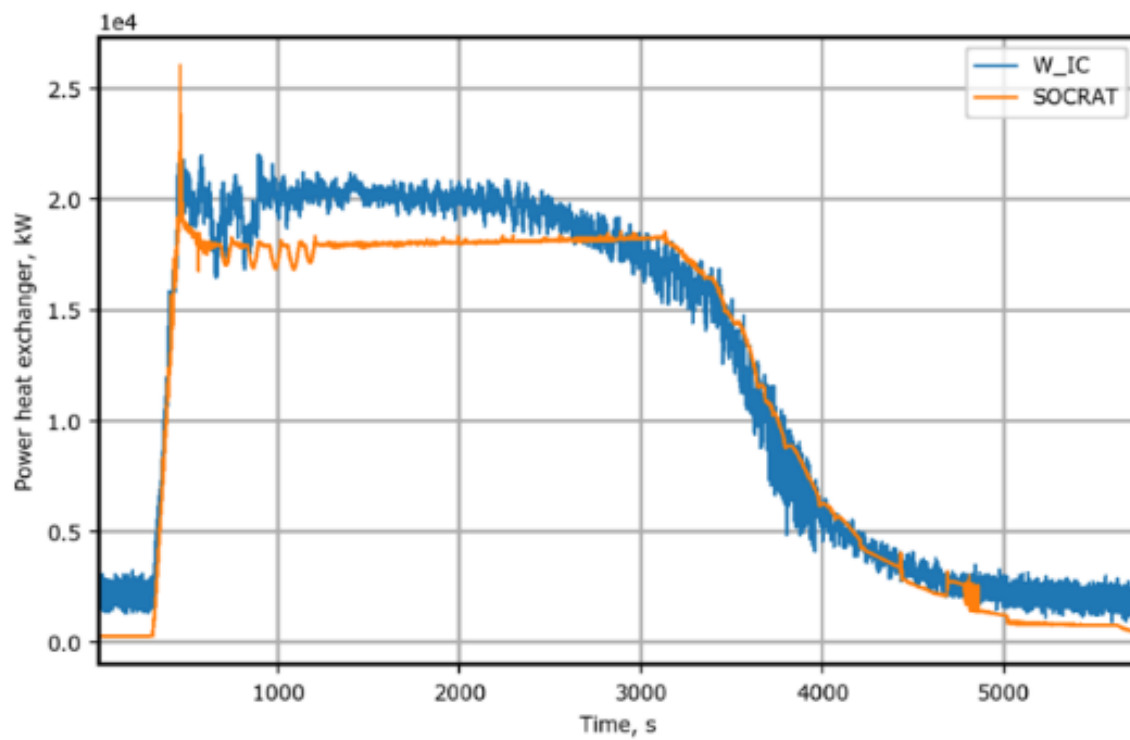


Figure 5.74. Absolute pressure vessel for Test 7 Part 2

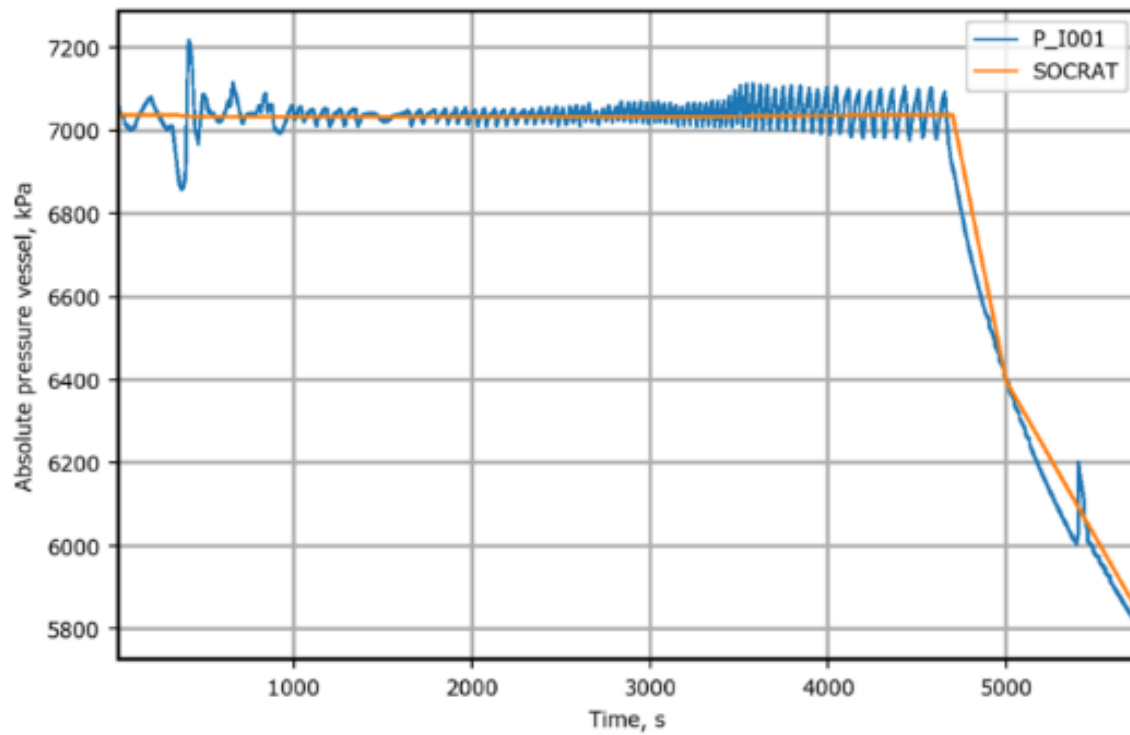


Figure 5.75. HX inlet fluid temperature for Test 7 Part 2

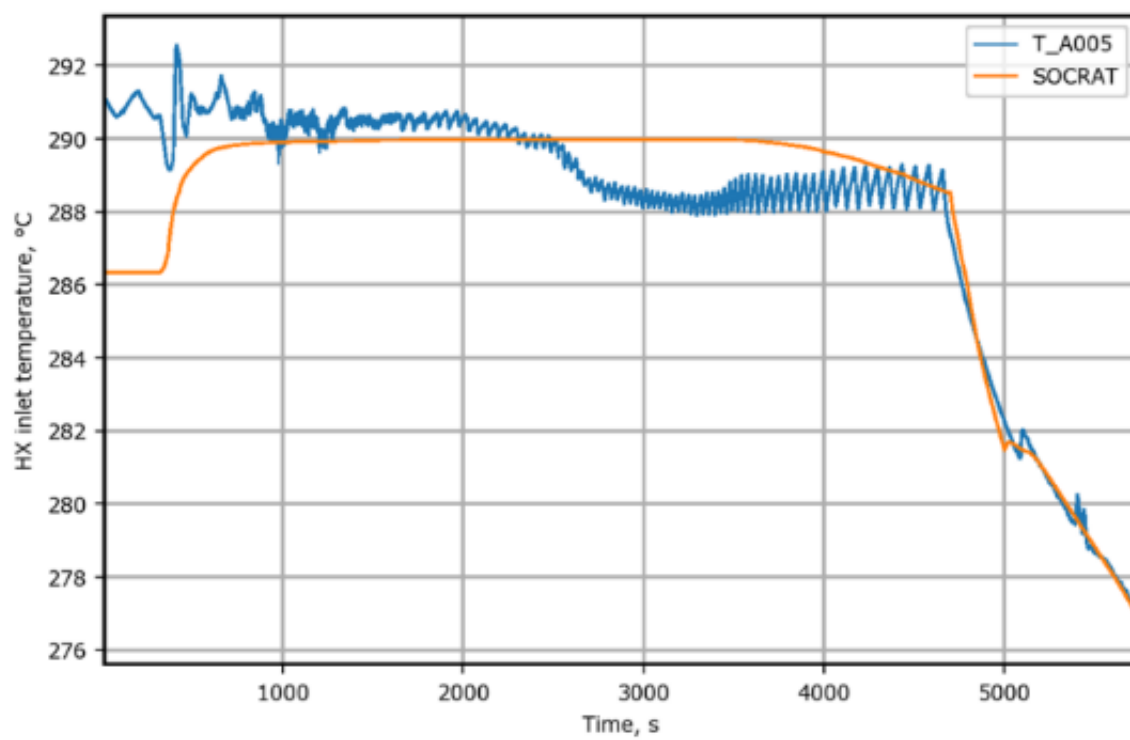


Figure 5.76. HX outlet fluid temperature for Test 7 Part 2

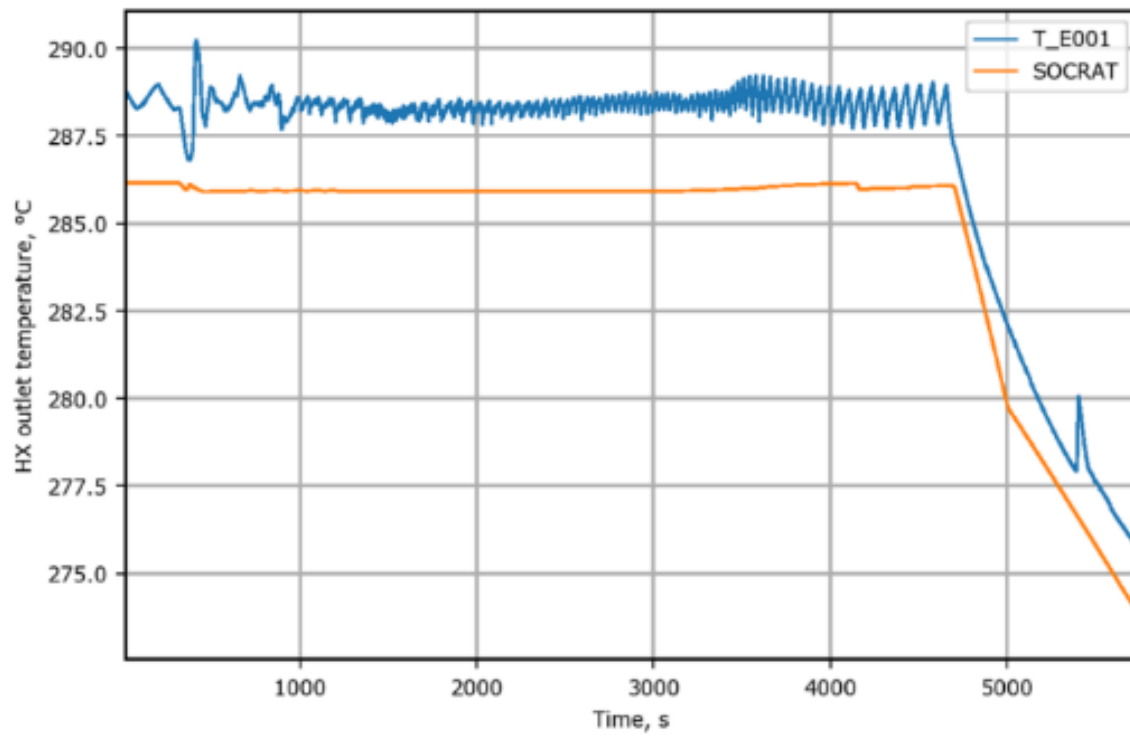


Figure 5.77. Level HXP for Test 7 Part 2

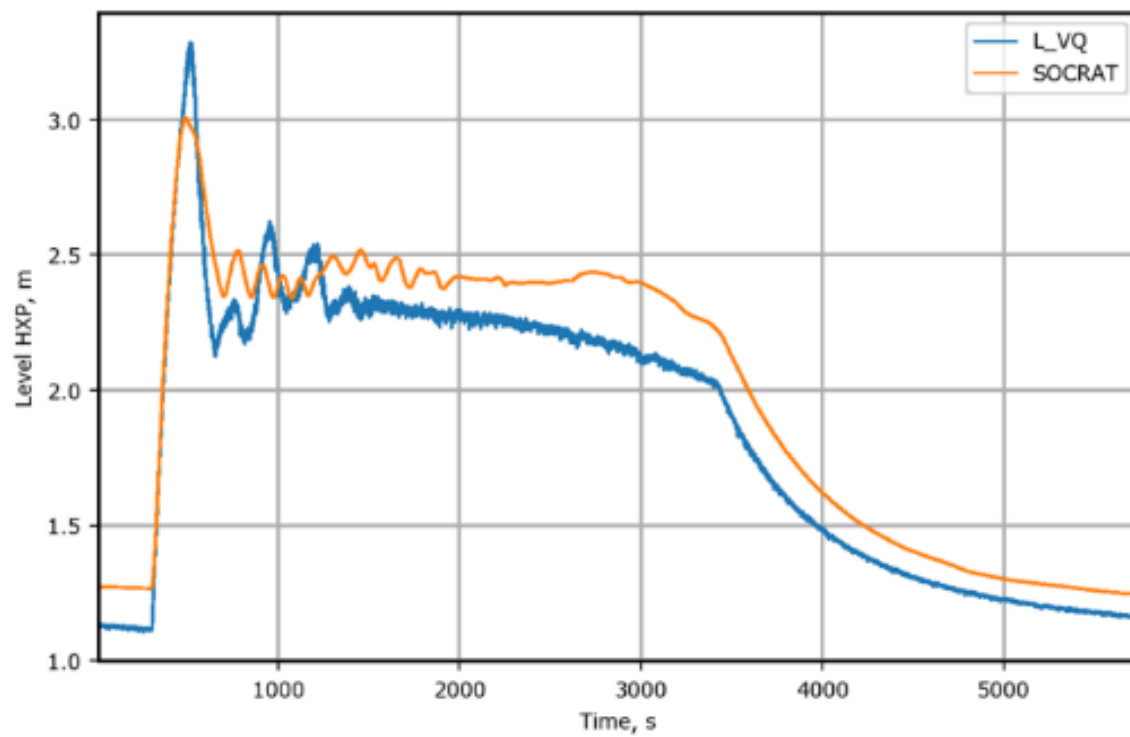


Figure 5.78. Level OP for Test 7 Part 2

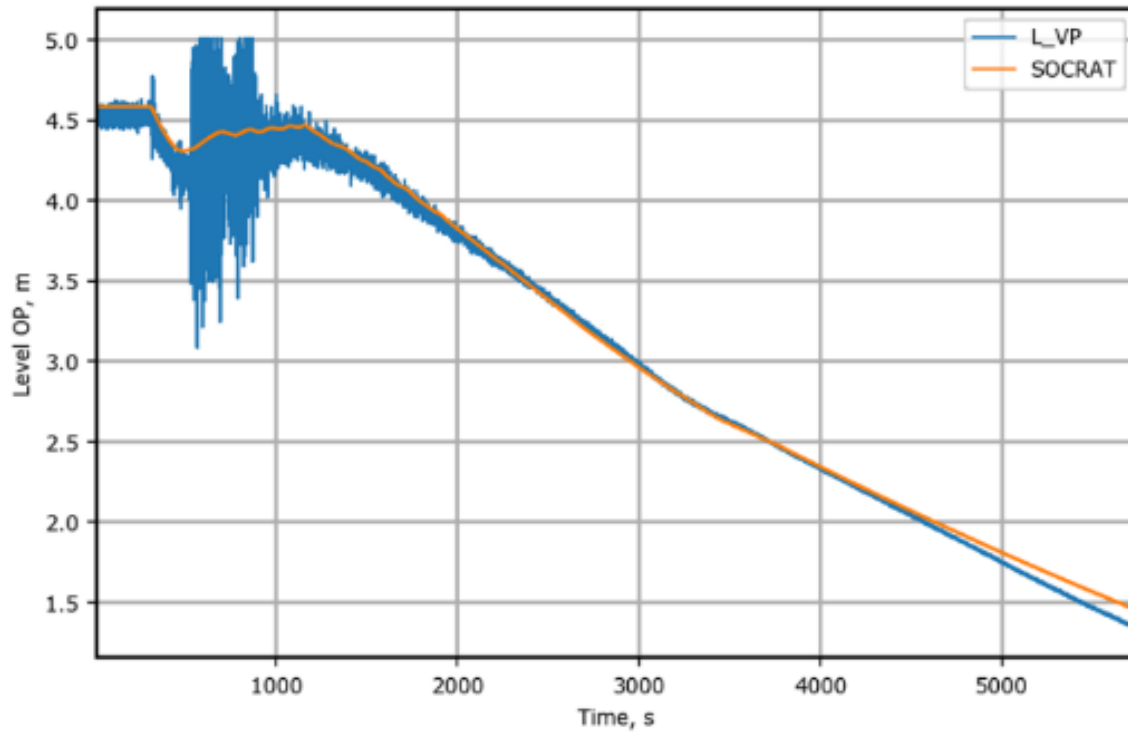


Figure 5.79. Fluid temperature HXP (bottom) for tTest 7 Part 2

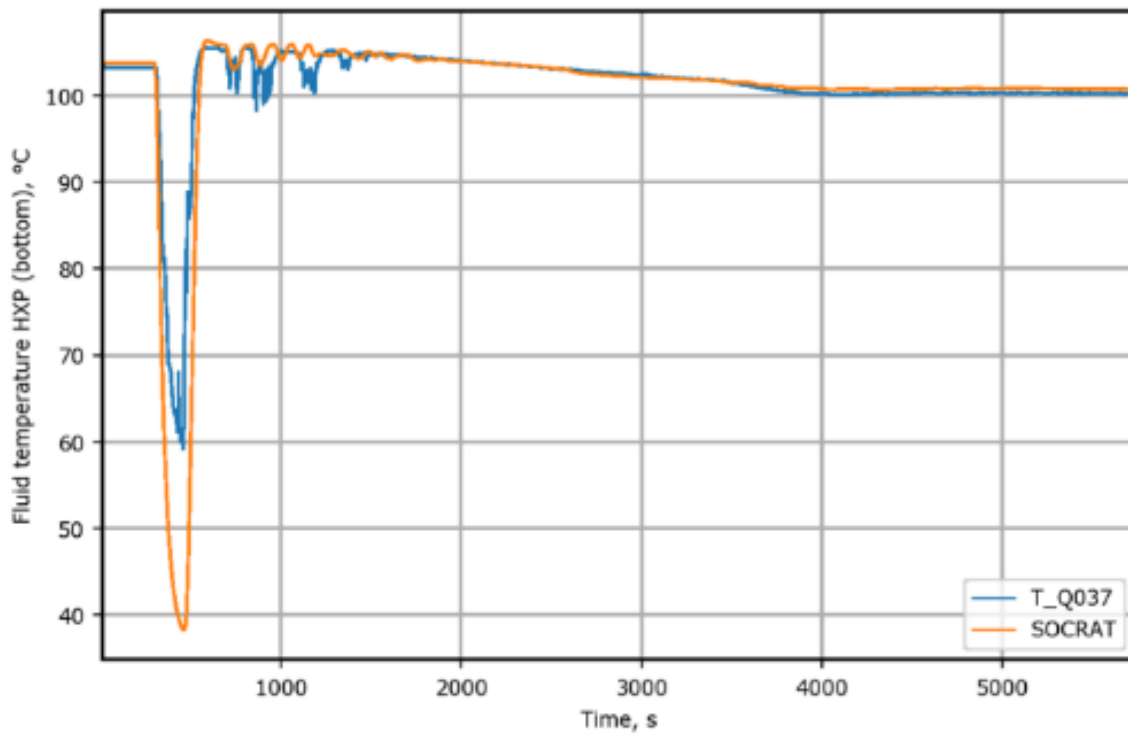


Figure 5.80. Fluid temperature HXP (middle) for Test 7 Part 2

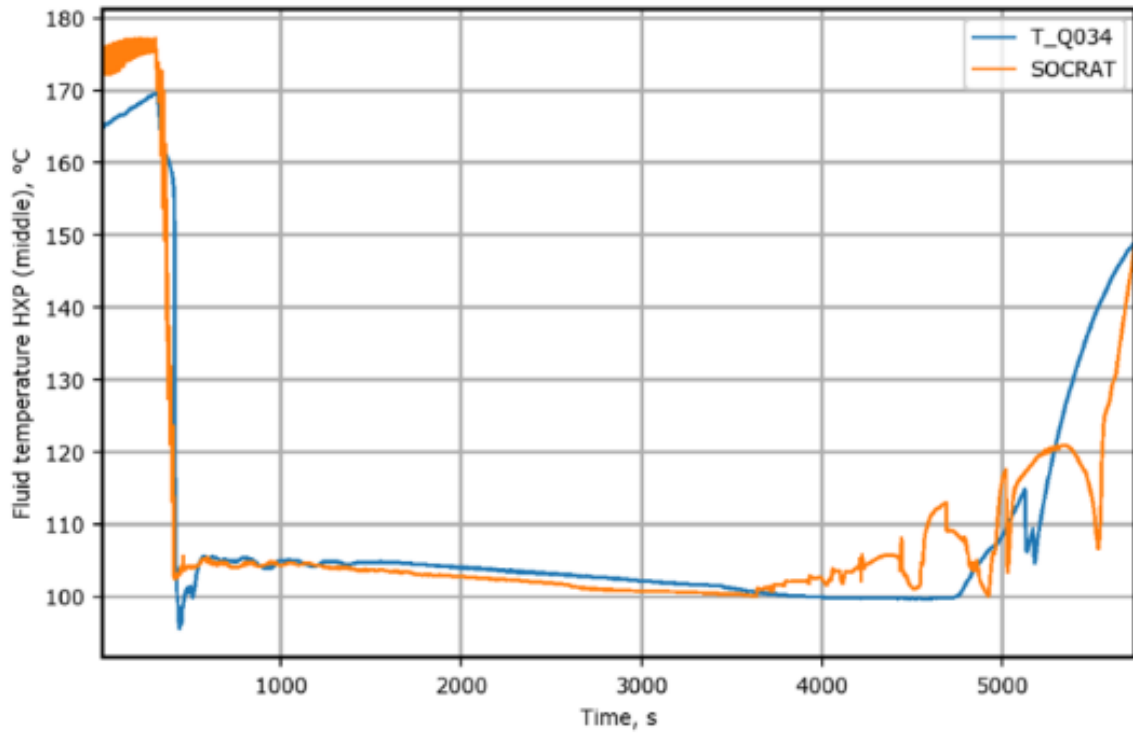


Figure 5.81. Fluid temperature HXP (top) for Test 7 Part 2

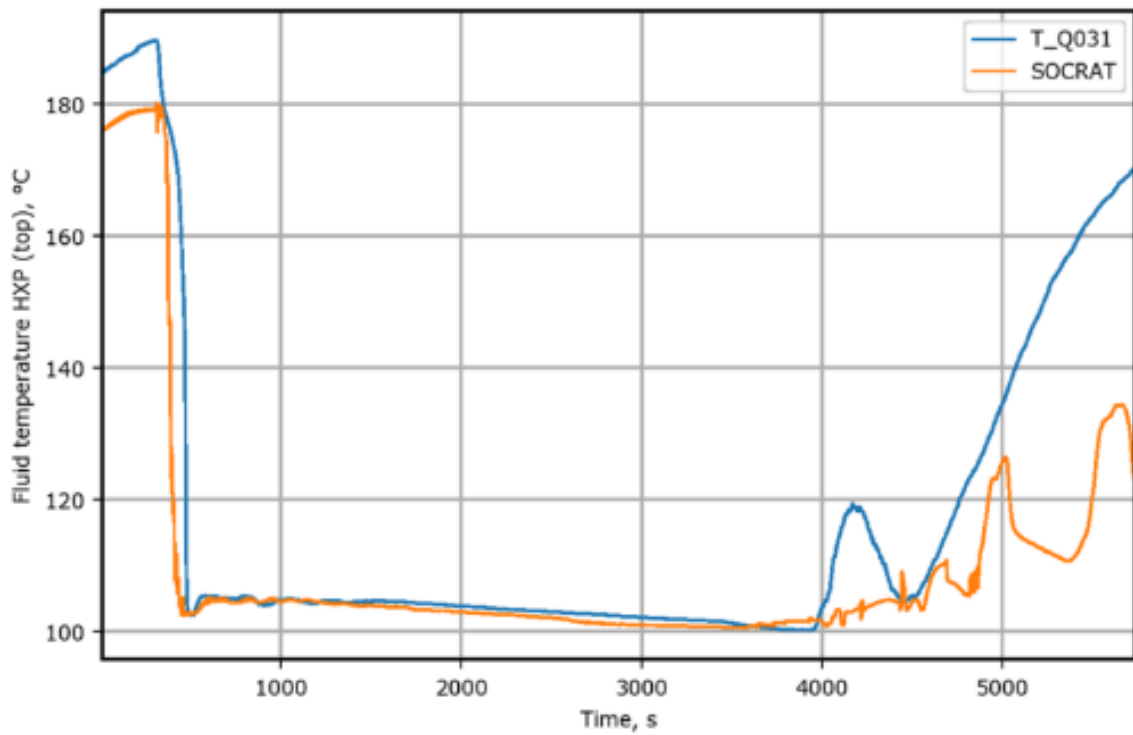


Figure 5.82. Relative pressure HXP top for Test 7 Part 2

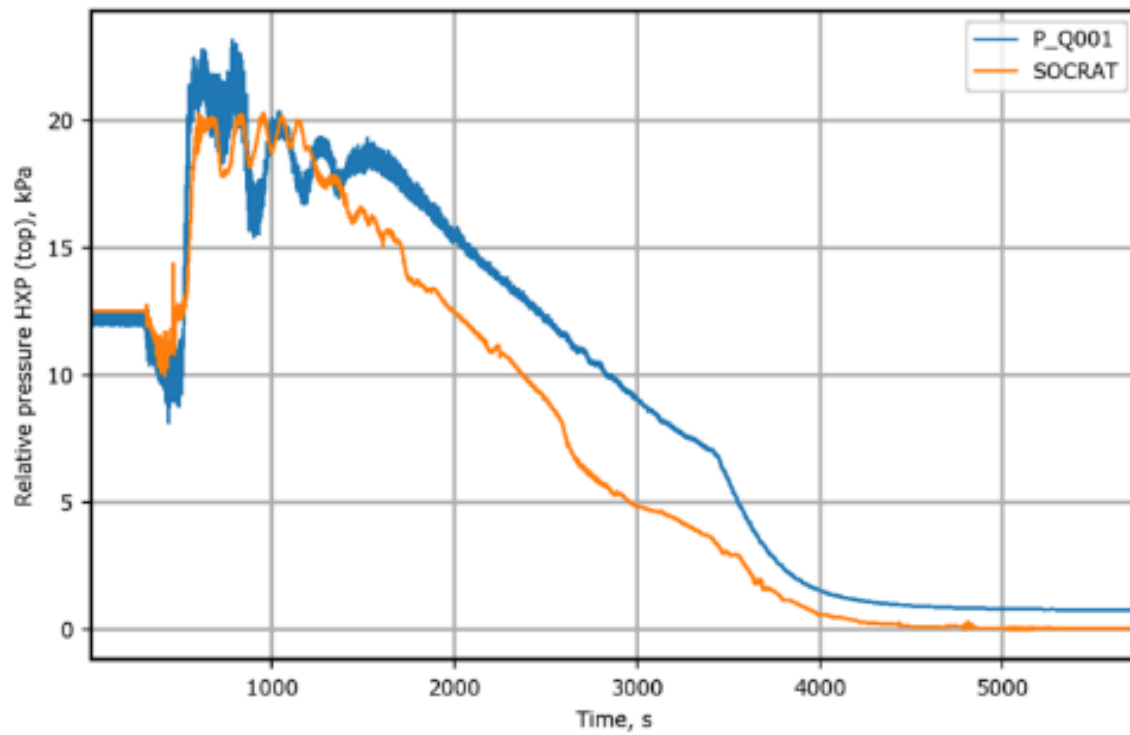


Figure 5.83. Fluid temperature OP (bottom) for Test 7 Part 2

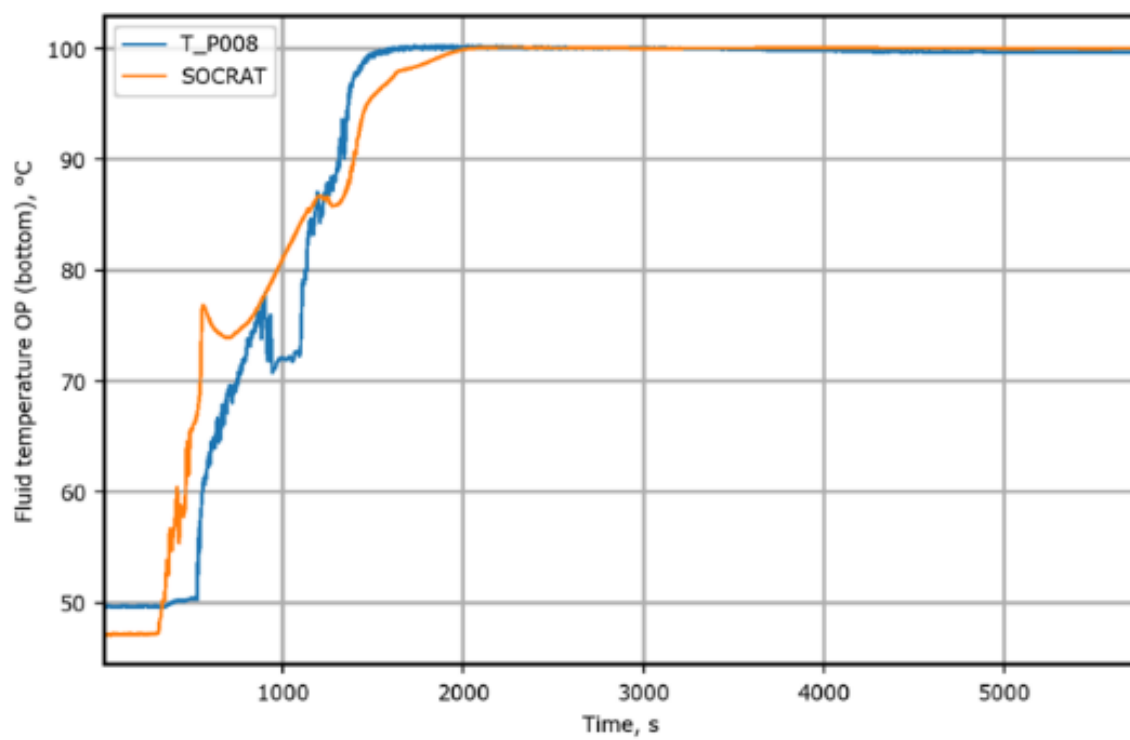


Figure 5.84. Fluid temperature OP (top) for Test 7 Part 2

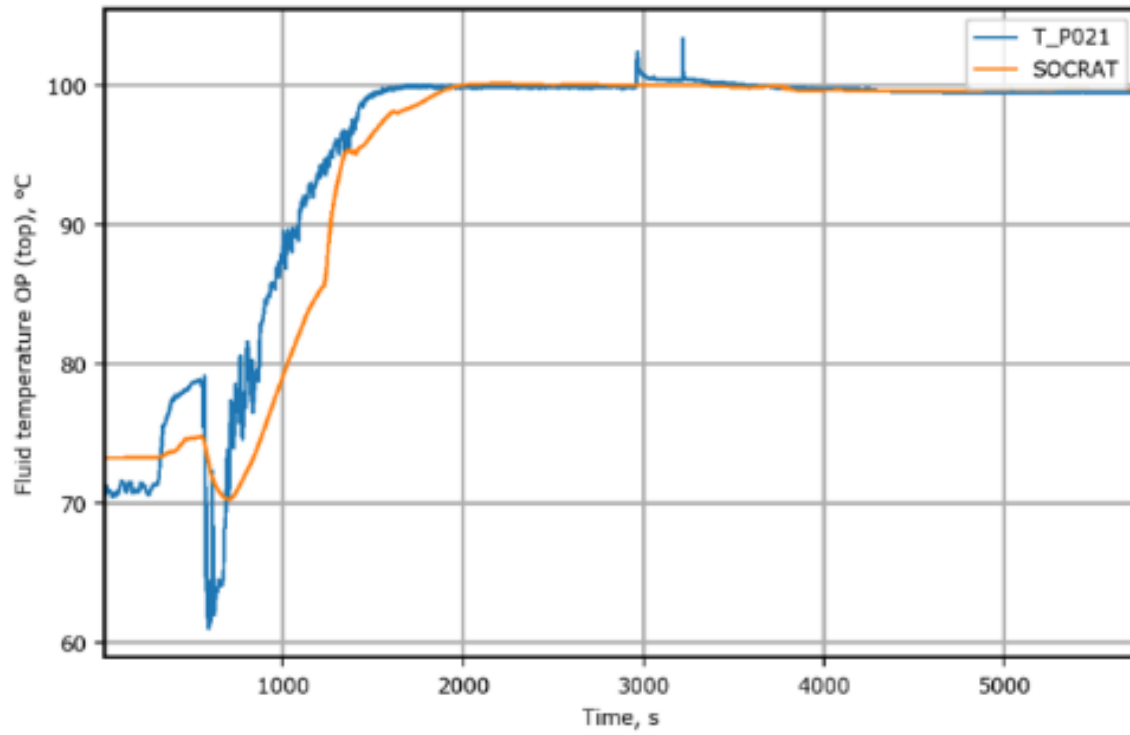


Figure 5.85. Diff. pressure HX upper-lower header for Test 7 Part 2

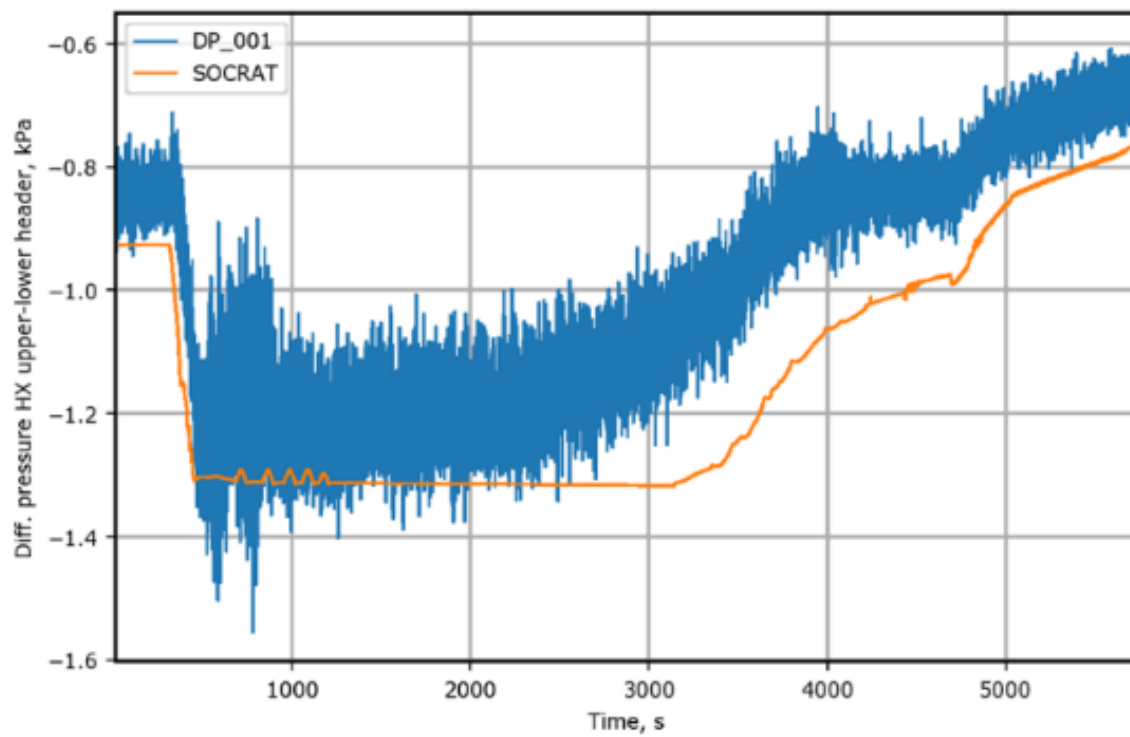


Figure 5.86. Diff. pressure steam duct injector for Test 7 Part 2

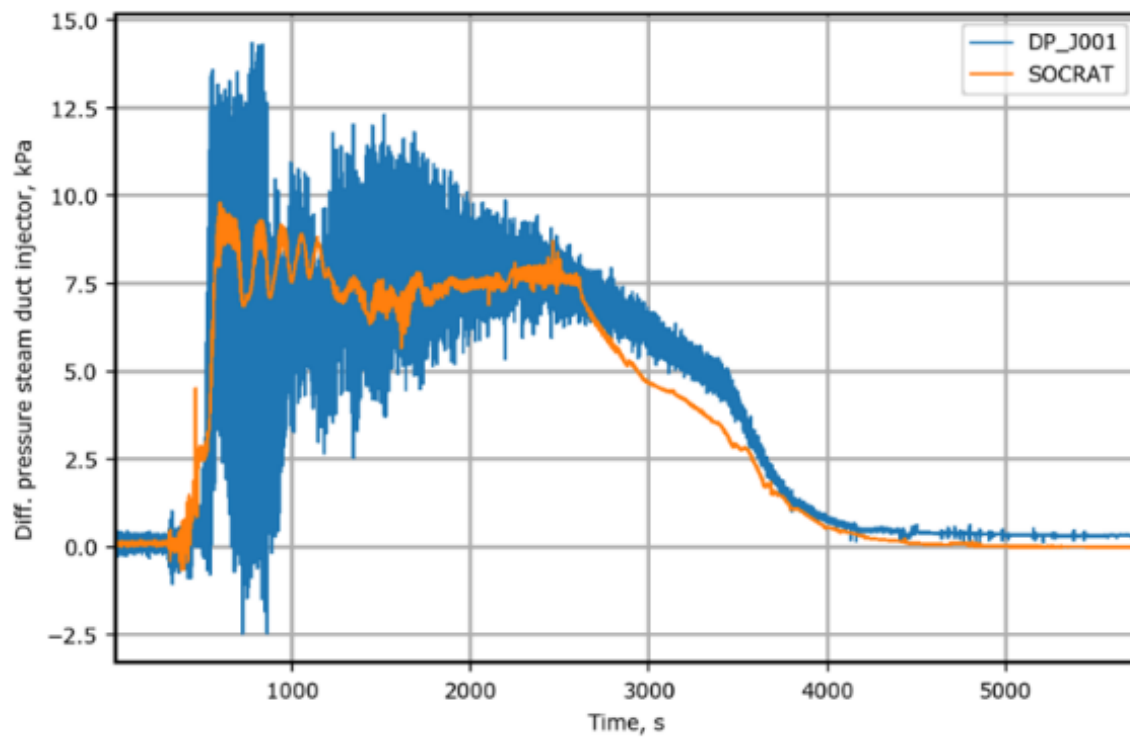


Figure 5.87. Wall temperature HX upper header for Test 7 Part 2

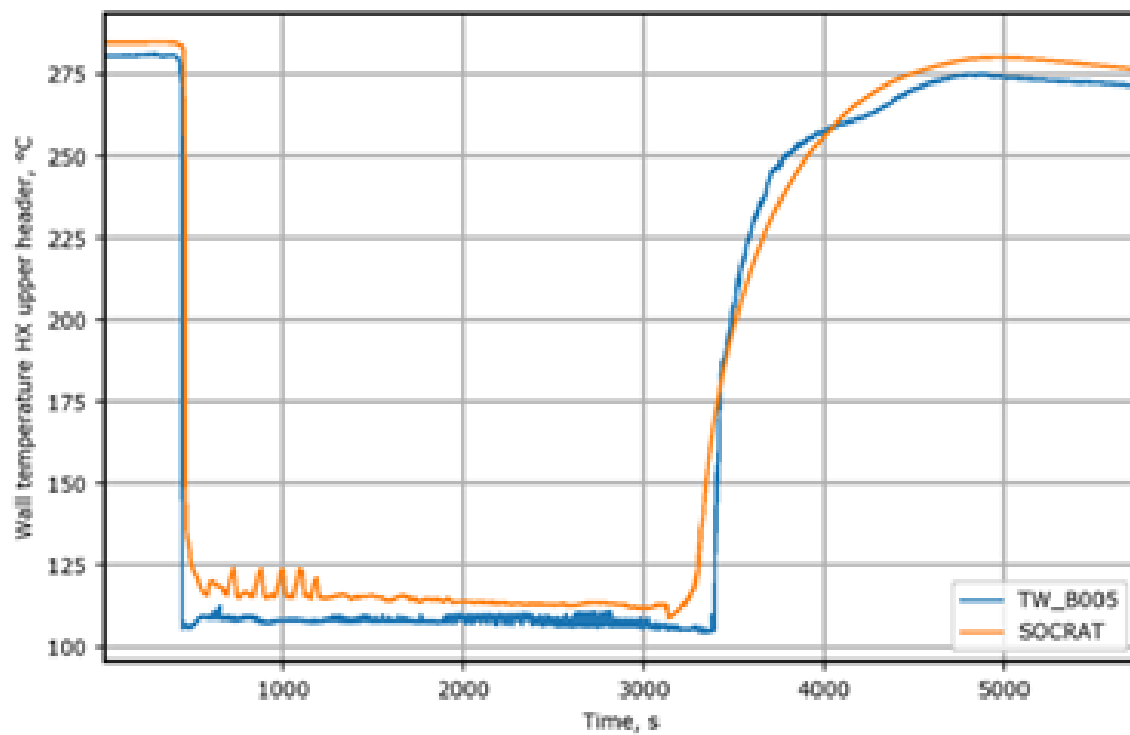
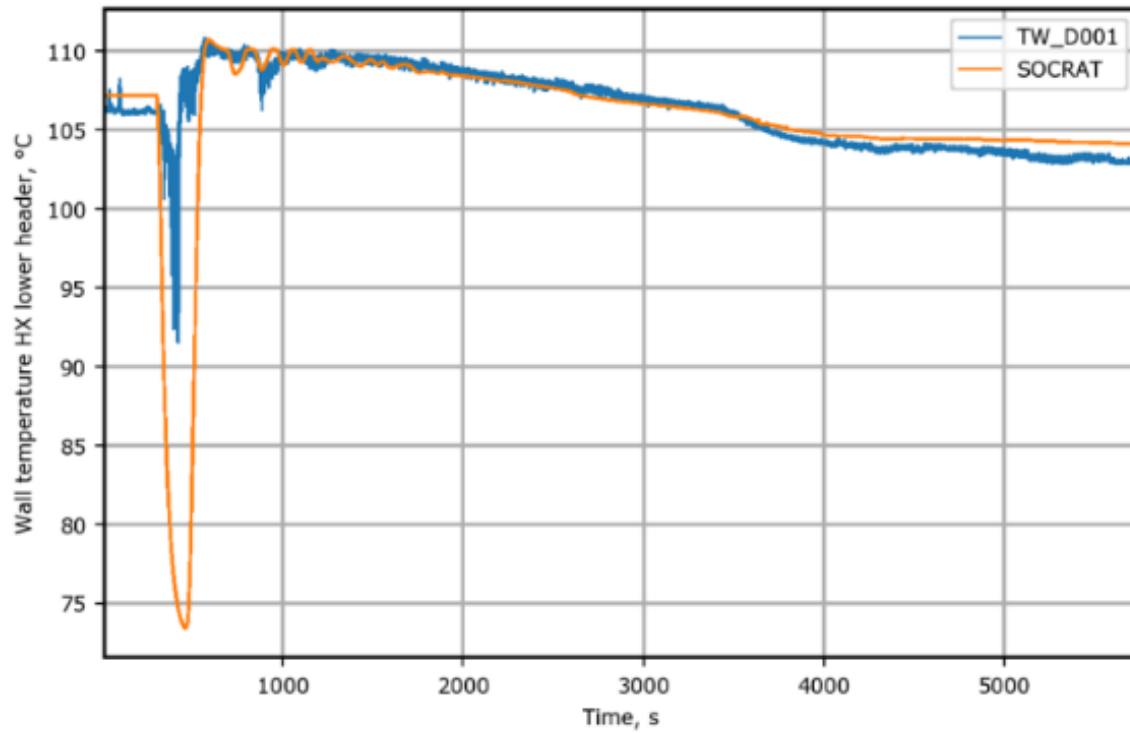


Figure 5.88. Wall temperature HX lower header for Test 7 Part 2



The marks adopted in Table 5.15 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.16. PERSEO Test 7 Part 2 versus phenomena, SOCRAT code prediction

	Phenomenon	Experiment				SOCRAT
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F_A001 (der.)	+
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W_IC (der.)	+
				Level HXP	L_VQ (der.)	
				Level OP	L_VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	

**Table 5.15. PERSEO Test 7 Part 2 versus phenomena, SOCRAT
code prediction (Continued)**

	Phenomenon	Experiment				SOCRAT
		Ph.	Measurement			Ph.
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Absolute pressure vessel	P-I001	+
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
				Diff. pressure HX upper-lower header	DP-003	
				Diff. pressure steam duct injector	DP-J001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Flowrate steam supply line	F_A001 (der.)	+
				Flowrate condensate drain line	F_E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
				Power heat exchanger	W_IC (der.)	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Level HXP	L_VQ (der.)	+
				Power heat exchanger	W_IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
F	Behaviour of large pool: Thermal stratification	+	+	Power heat exchanger	W_IC (der.)	+
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
Temperature OP (top)	T-P021					
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP	L_VQ (der.)	+/o
				Level OP	L_VP (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L_VP (der.)	+/o
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

SECTION 5: CONCLUSIONS

The SOCRAT code is able to “catch” practically all phenomena observed in natural circulation loops and in pools at low pressure in the PERSEO facility, with limitations in case of steam-air-water mixing in large horizontal pipes due to limited validation.

The main lessons learnt from the PERSEO data relate to:

- Modelling of pool fast filling with an immersed heat exchanger.
- Modelling of steam discharge in OP.

REFERENCES

- [5.2.2 1] Chen, J. C. (1966), “A correlation for boiling heat transfer to saturated fluids in convective flow”, *Process Design and Development*, Vol. 5, pp. 322-327.
- [5.2.2 2] Chen, J. C., R. K. Sundaram, and F. T. Ozkaynak (1977), *A Phenomenological Correlation for Post-CHF Heat Transfer*, NUREG-0237.
- [5.2.2 3] RELAP3.3 MOD3.3 Code Manual Volume IV: Models and Correlations, NUREG/CR-5535/Rev P3-Vol IV (2006).
- [5.2.2 4] Bolshov, L. K., S. Dolganov, A. E. Kiselev and V. F. Strizhov (2019), “Results of SOCRAT code development, validation and applications for NPP safety assessment under severe accidents,” *Nuclear Engineering and Design*, Vol. 341, pp. 326-345.

5.2.3. KAERI_a

SECTION 1: GENERAL INFORMATION

- Organisation: KAERI (Korea)
- Contact persons/authors: Byong-Guk Jeon , Kyoung-Ho Kang , Hyun-Sik Park
- Code: MARS-KS version 1.4
- Computing environment:
 - Operative systems: Windows 10
 - RAM: 16 GB
 - CPU characteristics: Intel Core™ i7-4 770 CPU @ 3.40 GHz

SECTION 2: DESCRIPTION OF THE CODE USED

- General description of the code used:
 - developed by KAERI;
 - for multidimensional and multipurpose TH analysis;
 - based on RELAP5 mode 3.2.1.2 and COBRA-TF;
 - written by FORTRAN 90;
 - numerical solving scheme;
 - first-order, finite-difference method;
 - 1-dimensional model;
 - staggered-grid mesh;
 - donor-cell scheme;
 - semi-implicit scheme.
- Basic differential equations and approach (6 equations, 5 equations...):
 - Six equations (two continuity, two momentum, two energy) + one continuity for non-condensable gas.

- Implemented models relevant for PERSEO conditions:
 - pool side heat transfer; Chen;
 - tube side condensation; Max (Nusselt, Shah);
 - pressure drop in 1-phase and 2-phase flow.
Wall: Colebrook-White correlation,
Interphase: Depending on the flow regime.

SECTION 3: DESCRIPTION OF THE NODALISATION

Two systems: 1) One enclosed loop comprised of pressure vessel, HX, and connecting pipes; 2) Two tanks connected by a steam duct and a water line. TDV: Boundary pressure and temperature of supplied steam.

TDJ: Flowrate of supplied steam.

Heat losses, how the pressure vessel is modelled: No heat loss is imposed. Steam is injected at the upper space of the pressure vessel using a time-dependent volume and time-dependent junction.

Nodalisation strategies (e.g. slicing nodalisation); 1 m per node for pipes. 0.2 m per node for HX and HX pool.

0.5 m per node for overall pool.

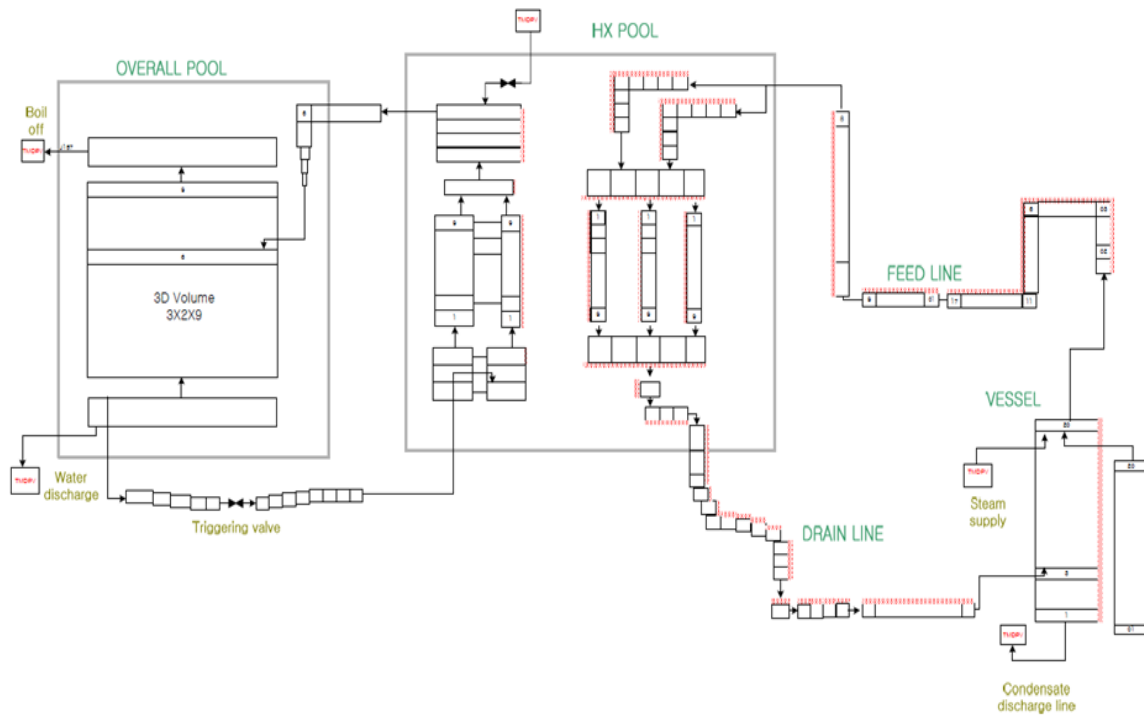
Eventual tuning by the user; heat transfer coefficient in the HX was multiplied by 2.4.

Use of multidimensional components and description of 3D components for overall pool tank. 3D representation of HX pool was tried but failed because of unstable calculation.

Table 5.17. Summary of the main nodalisation characteristics of the PERSEO model

	Number of hydraulic volumes	Number of junctions	Number of heat structures	Overall volume (m ³)
Vessel	20	19	1	46.0
Steam line	50	49	5	1.65
HX	27	24	3	0.36
Condensate line	29	28	5	0.49
HXP	29	40	0	23.5
Steam duct	10	9	0	12.5
OP	58	111	0	170
Heat transfer area HX (m ²)	34.47			
HX heat structure axial nodes number	9			
HX heat structure radial nodes Number	4			

Figure 5.89. KAERI_a nodalisation of PERSEO facility



SECTION 4: RESULTS

TEST 7 Part 1

A time-dependent volume was connected to the top of the overall pool to reach the steady state.

The pressure trend, water levels, and temperature trend were reasonably predicted.

The heat transfer coefficient was artificially multiplied by 2.4.

Figure 5.90. Test 7 Part 1 - Steam flow rate

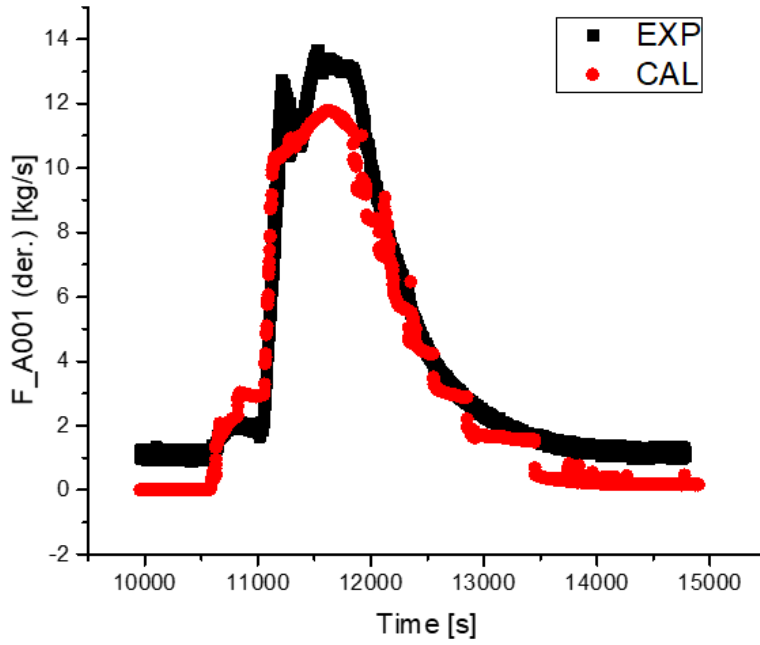


Figure 5.91. Test 7 Part 1 - Condensate flow rate

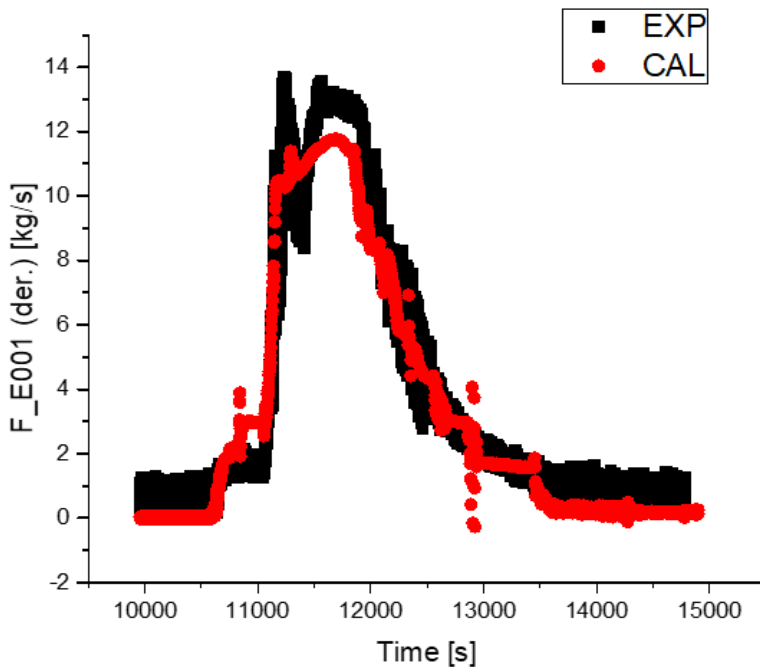


Figure 5.92. Test 7 Part 1 - HX power

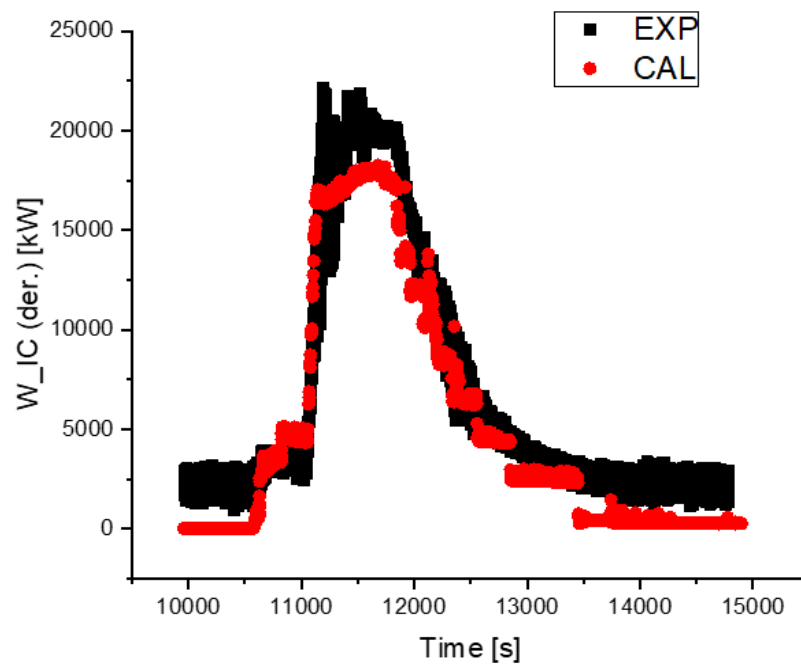


Figure 5.93. Test 7 Part 1 - Primary pressure

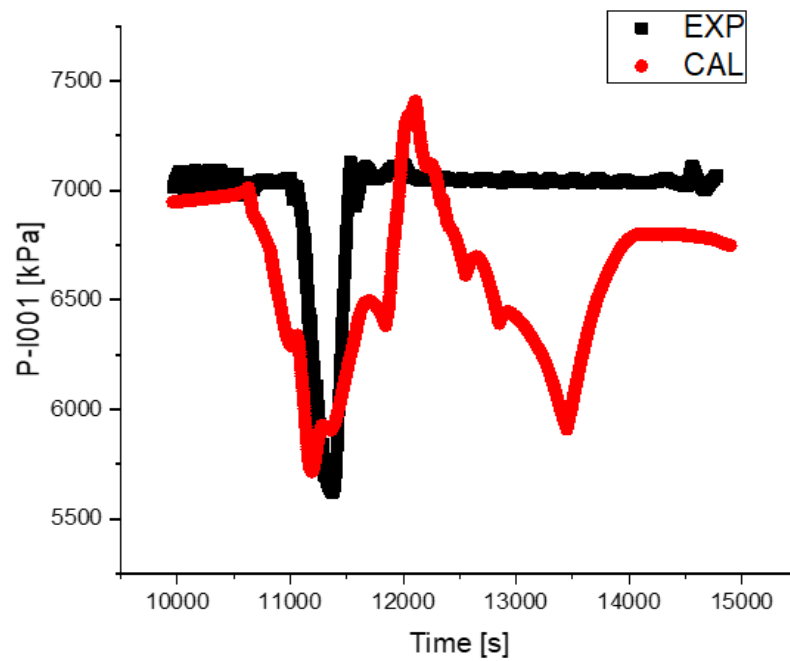


Figure 5.94. Test 7 Part 1 - Steam temperature

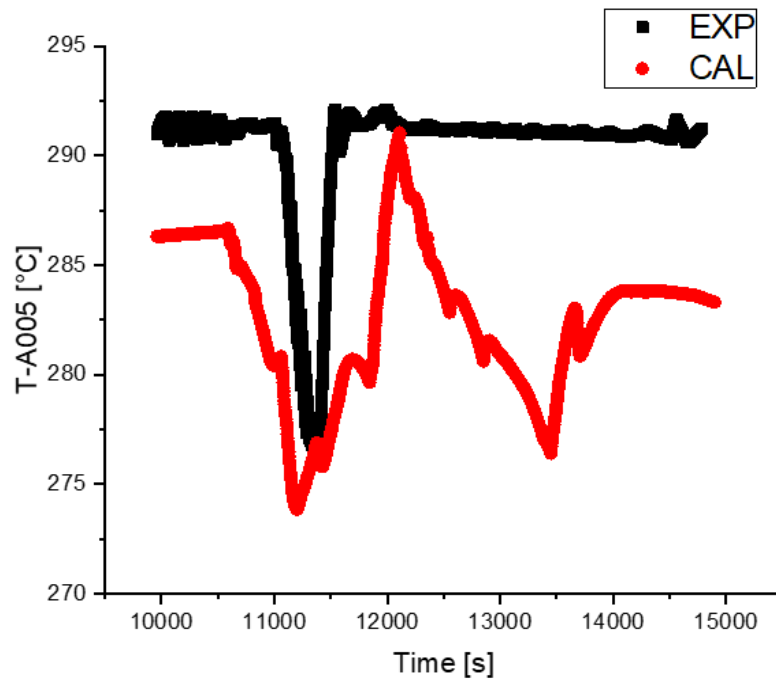


Figure 5.95. Test 7 Part 1 - Condensate temperature

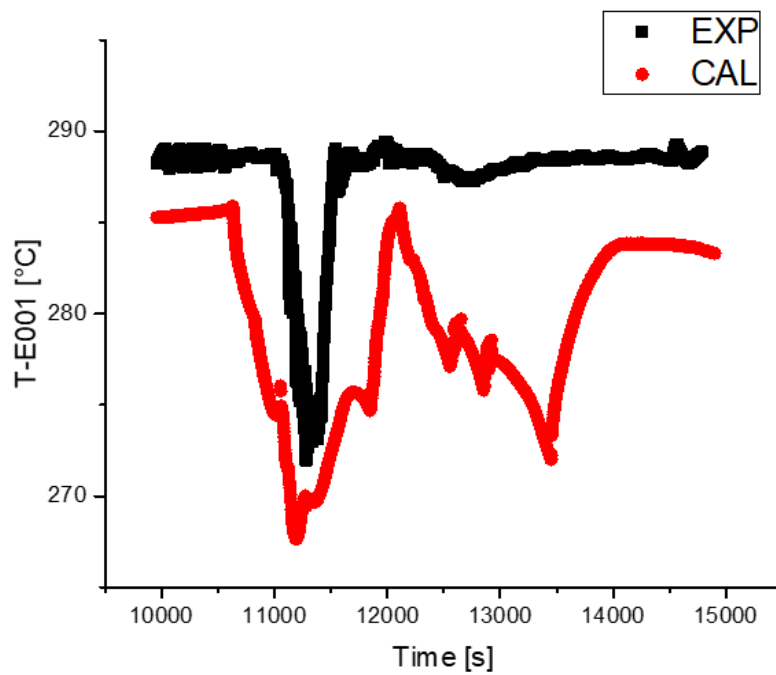


Figure 5.96. Test 7 Part 1 - HXP level

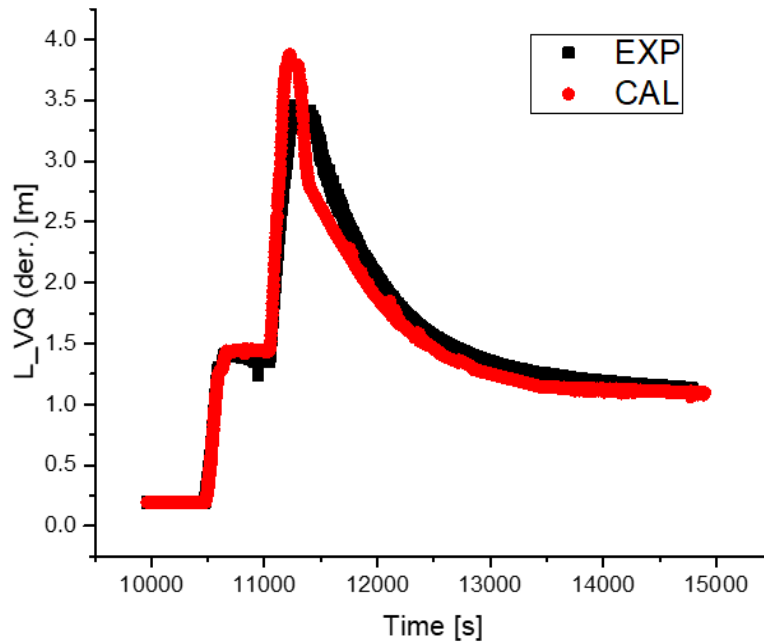


Figure 5.97. Test 7 Part 1 - OP level

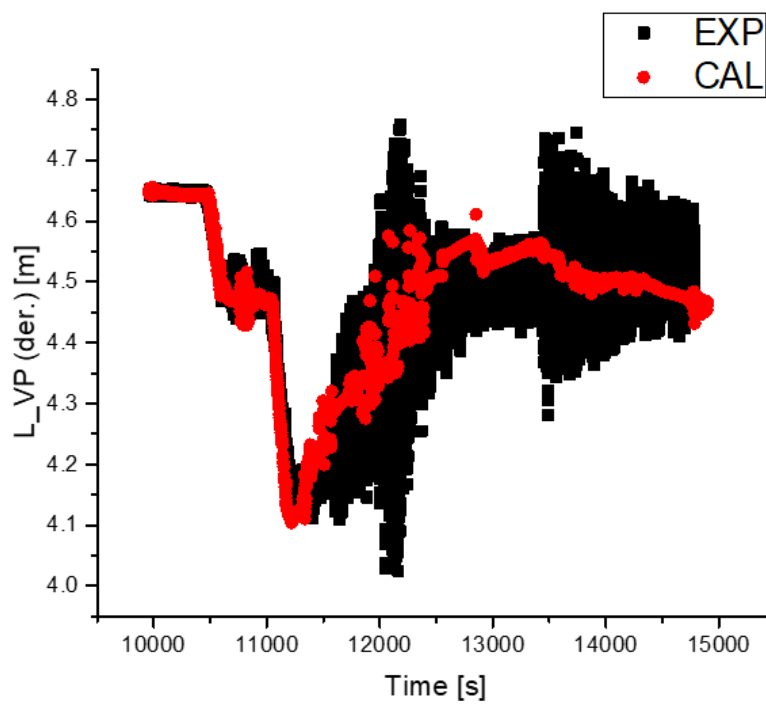


Figure 5.98. Test 7 Part 1 - HXP temperature T-Q037

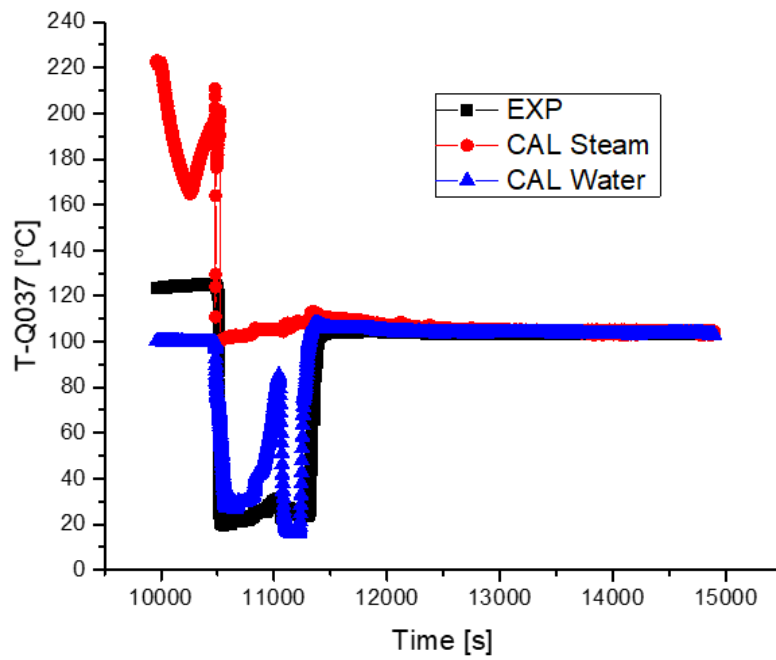


Figure 5.99. Test 7 Part 1 - HXP temperature T-Q034

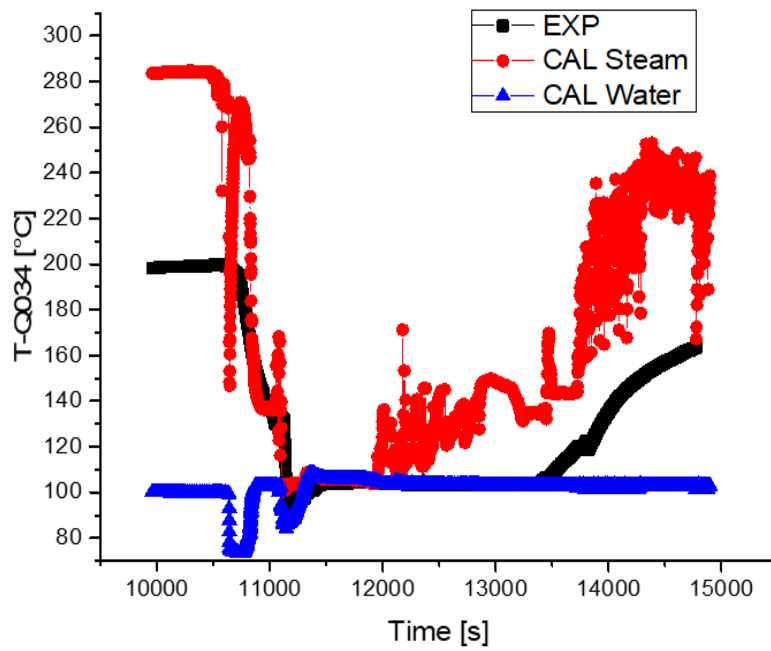


Figure 5.100. Test 7 Part 1 - HXP temperature T-Q031

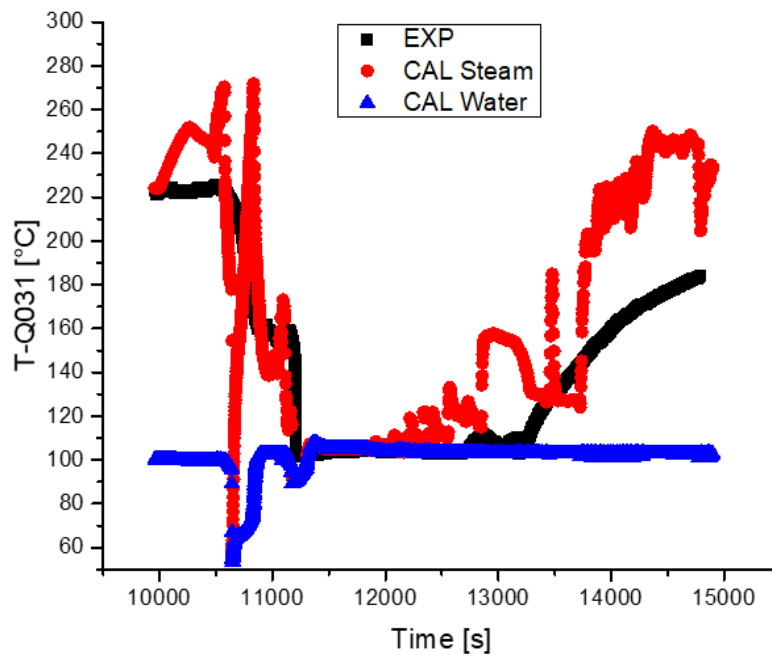


Figure 5.101. Test 7 Part 1 - HXP relative pressure

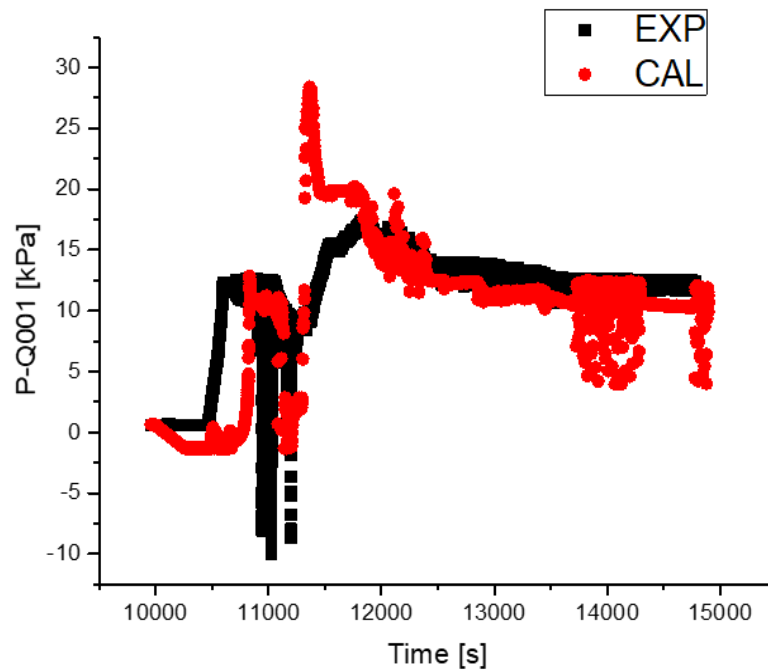


Figure 5.102. Test 7 Part 1 - OP temperature T-P008

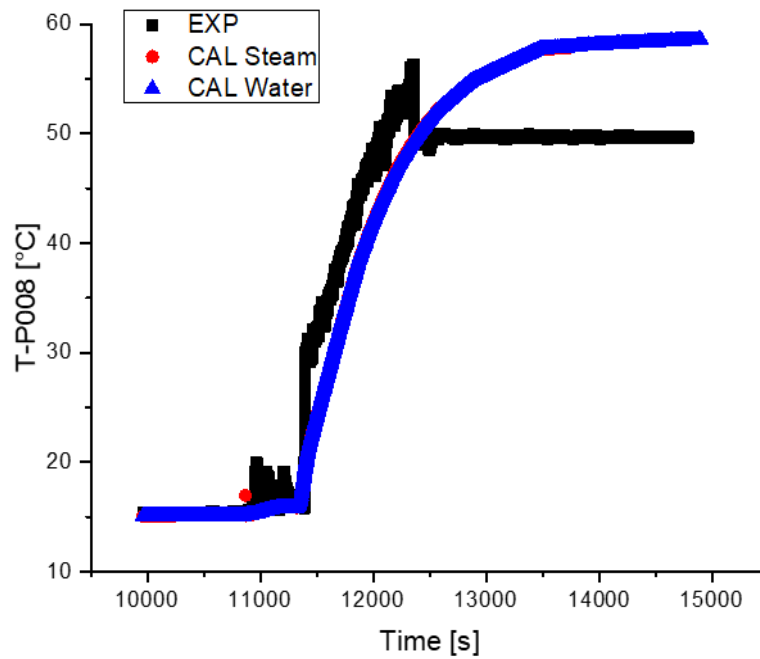


Figure 5.103. Test 7 Part 1 - OP temperature T-P021

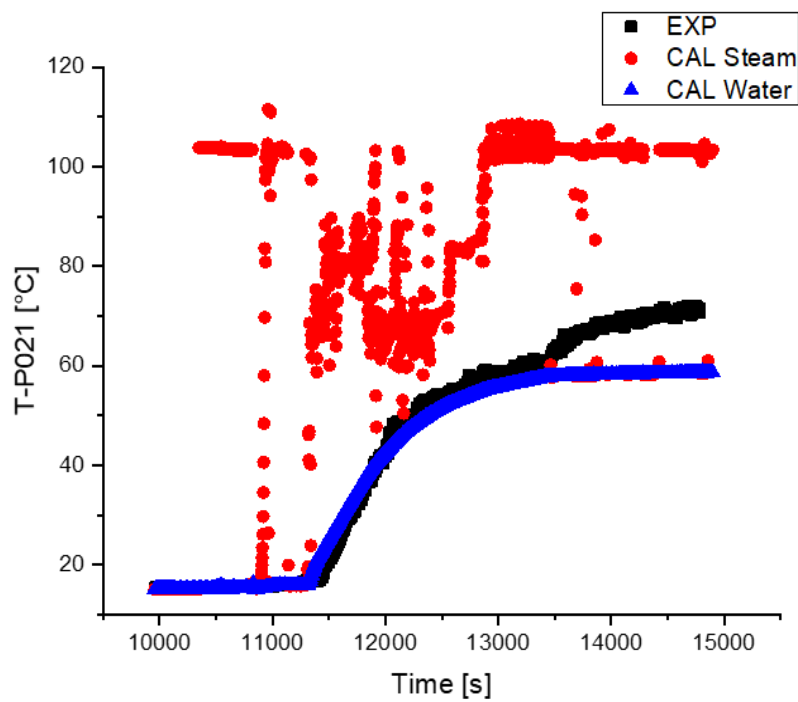


Figure 5.104. Test 7 Part 1 - HX differential pressure

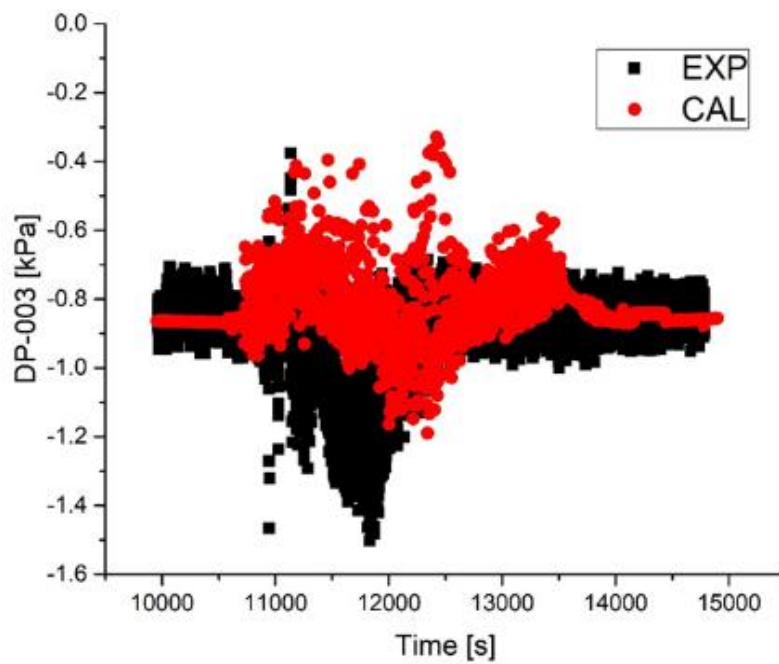


Figure 5.105. Test 7 Part 1 - Injector differential pressure

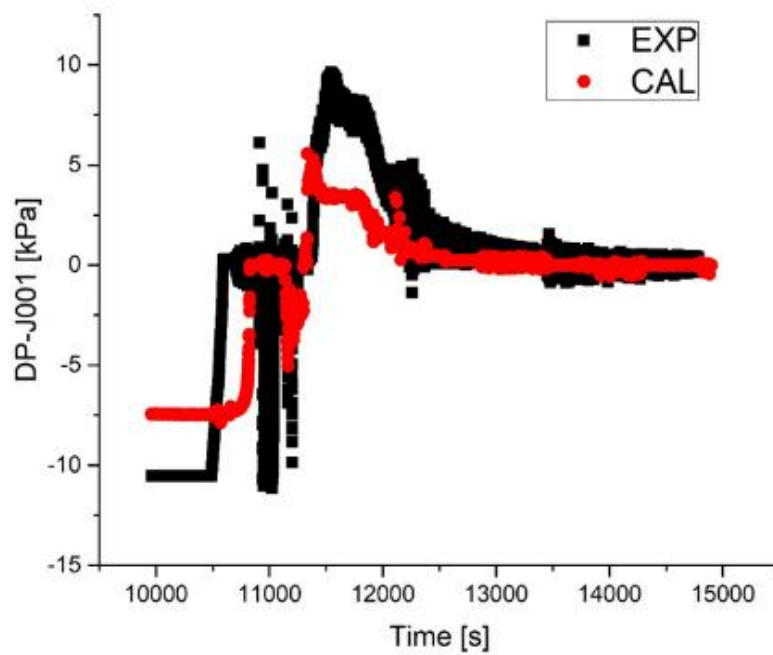


Figure 5.106. Test 7 Part 1 - HX upper header wall temperature

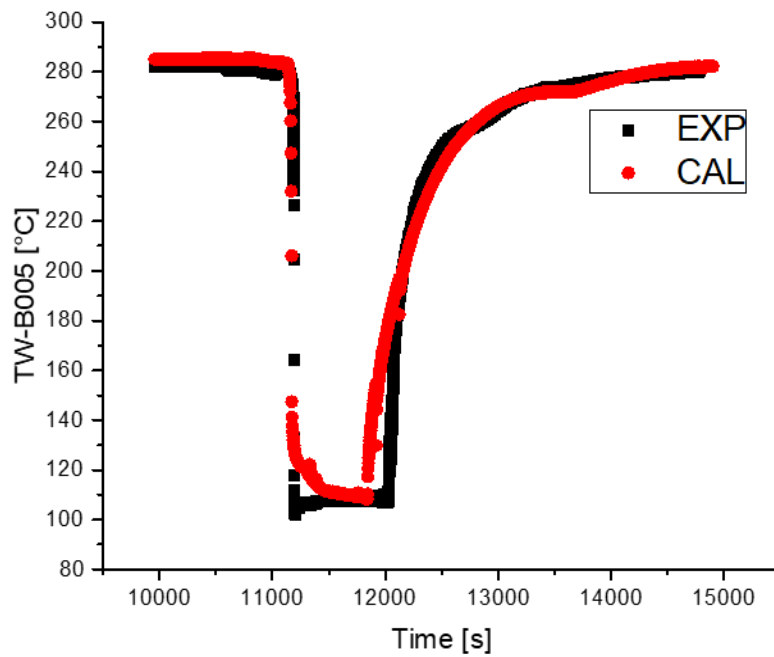
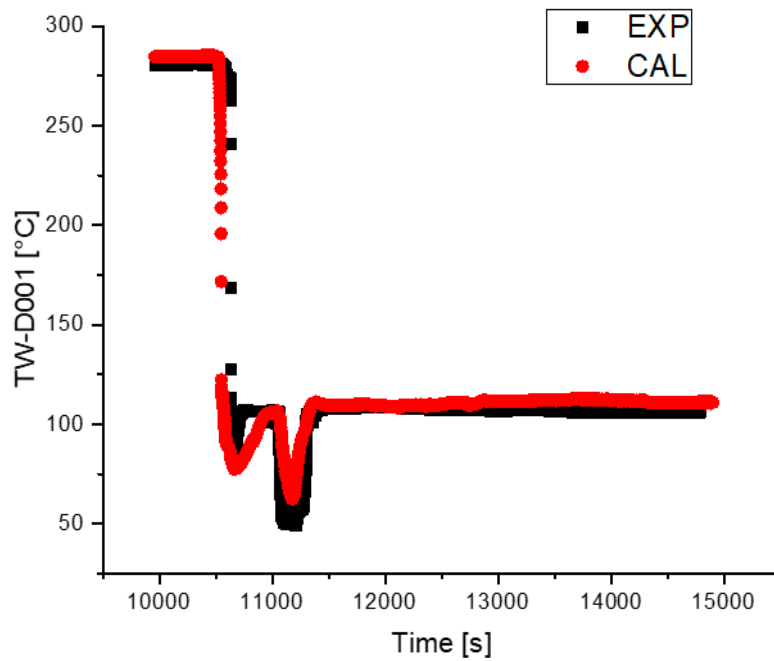


Figure 5.107. Test 7 Part 1 - HX lower header wall temperature



Time Step Control:

Mass error controls the time step

Hydrodynamic time step same as heat conduction time step.

Computation Time: 20 min.

Table 5.18. Main Relevant thermal-hydraulic aspect related to the Test 7 Part 1

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	10 475/10 608	-
Triggering valve (F045) re-opening and re-closure	10 621/10 665	-
Maximum level in the HX pool for the first filling step	10 663 – 11 052	1.44 m
Small heat removal from the primary side	10 721 – 11 055	3.2-4.7 MW
Slow water consumption in the HX pool	-	
Instabilities for steam condensation in the injector	-	
Triggering valve (F045) opening and closure	11 039/11 270	-
Maximum level in the HX pool	11 222	3.86 m
Maximum exchanged power	11 500-11 700	18.0 MW
HX pool minimum level	14 800	1.13 m
OP average temperature	14 800	Around 59 °C

Table 5.19. PERSEO Test 7 Part 1 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	+
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	o
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure HX upper-lower header	DP-003	o
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	HX inlet temperature	T-A005	o
				HX outlet temperature	T-E001	
				Power heat exchanger	W IC (der.)	
				Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (bottom)	T-Q037	o
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Power heat exchanger	W IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature HXP (top)	T-Q031	o
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
				Level HXP	L VQ (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L VP (der.)	o
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	o
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

●** Ph. = Phenomenon

Test 7 Part 2

A time-dependent volume was connected to the top of the overall pool to reach the steady state.

The pressure trend, water levels, and temperature trend were reasonably predicted.

As in the Part 1 calculation, the heat transfer coefficient was artificially multiplied by 2.4.

The HX pool water level was sensitive to the form loss coefficient at the steam duct injector.

Figure 5.108. Test 7 Part 2 - Steam flow rate

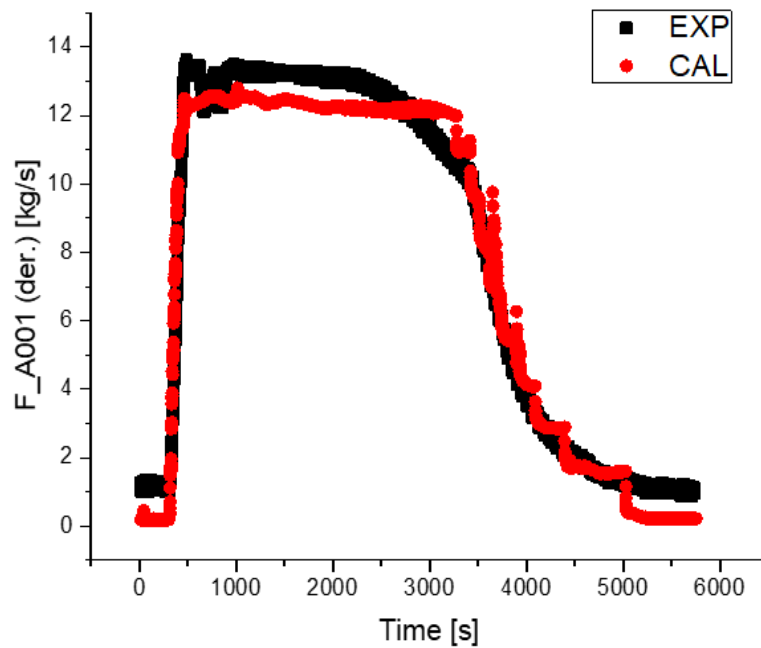


Figure 5.109. Test 7 Part 2 - Condensate flow rate

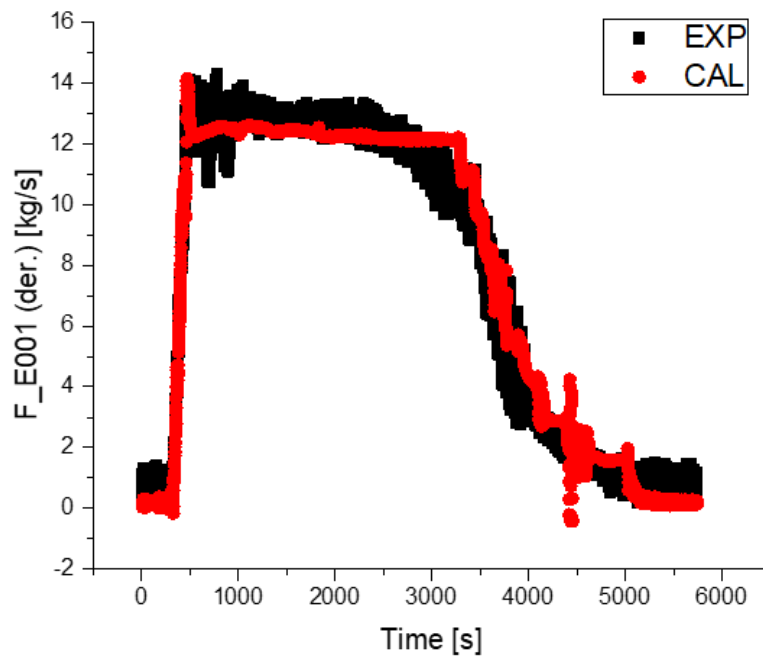


Figure 5.110. Test 7 Part 2 - HX power

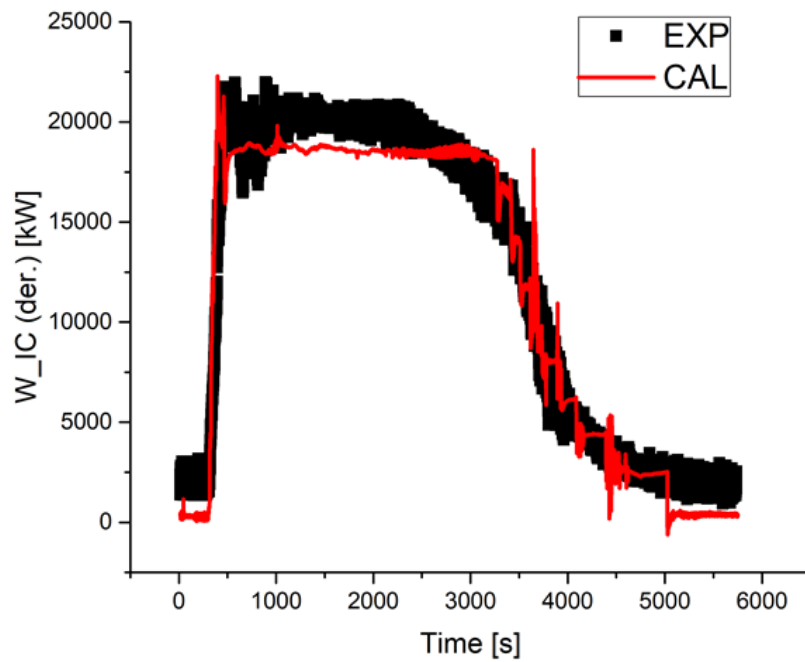


Figure 5.111. Test 7 Part 2 - Primary pressure

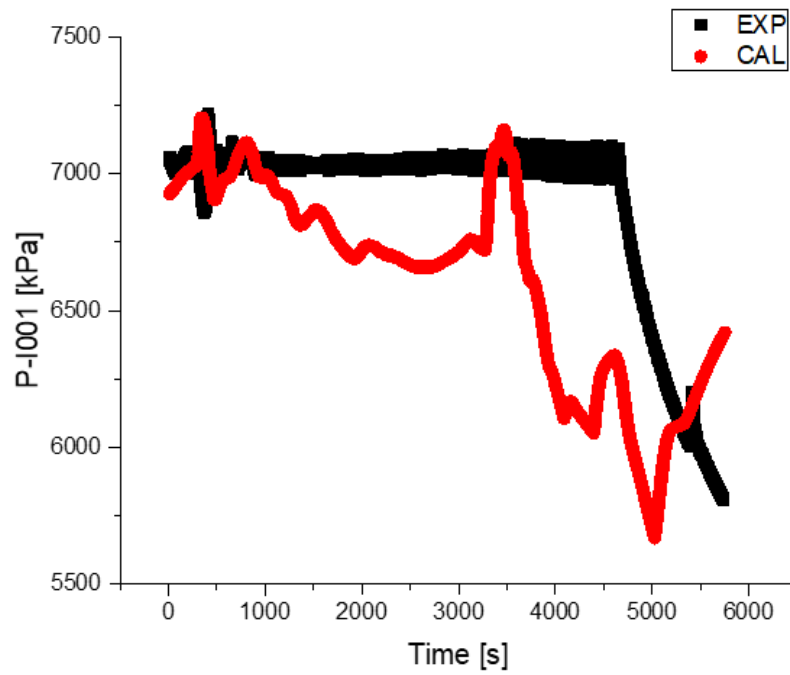


Figure 5.112. Test 7 Part 2 - Steam temperature

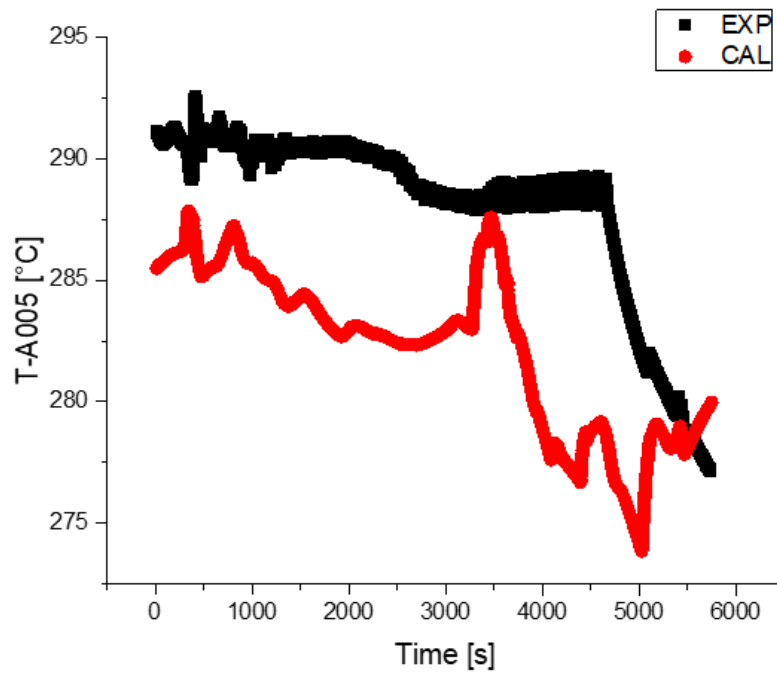


Figure 5.113. Test 7 Part 2 - Condensate temperature

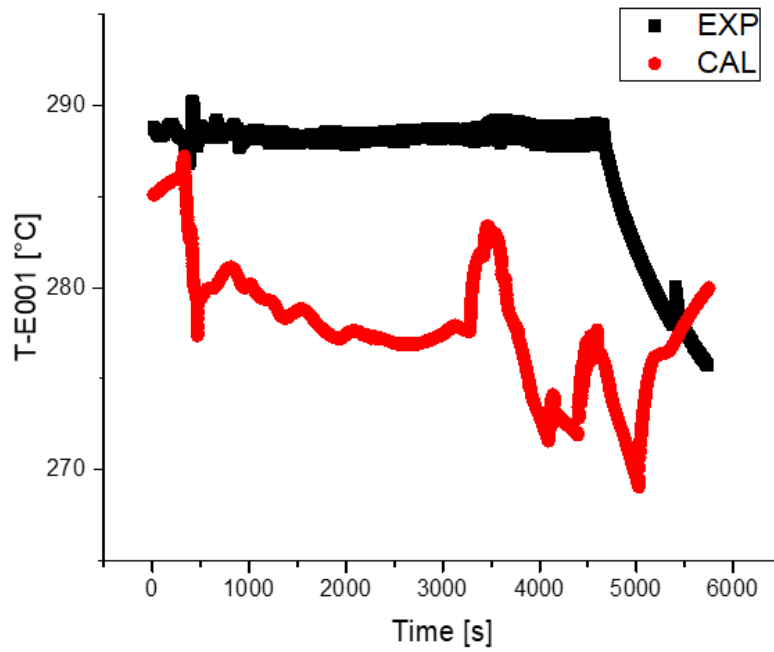


Figure 5.114. Test 7 Part 2 - HXP level

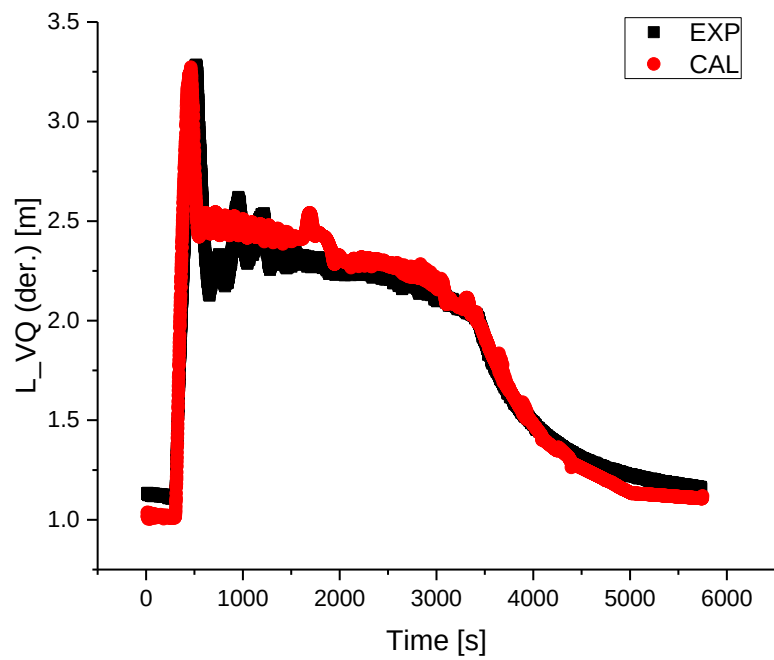
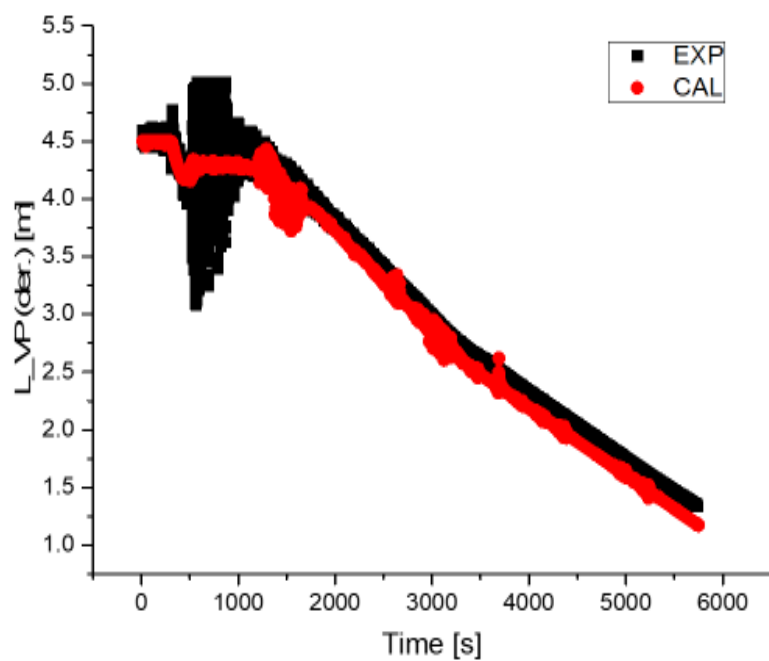


Figure 5.115. Test 7 Part 2 - OP level



8

Figure 5.116. Test 7 Part 2 - HXP temperature T-Q037

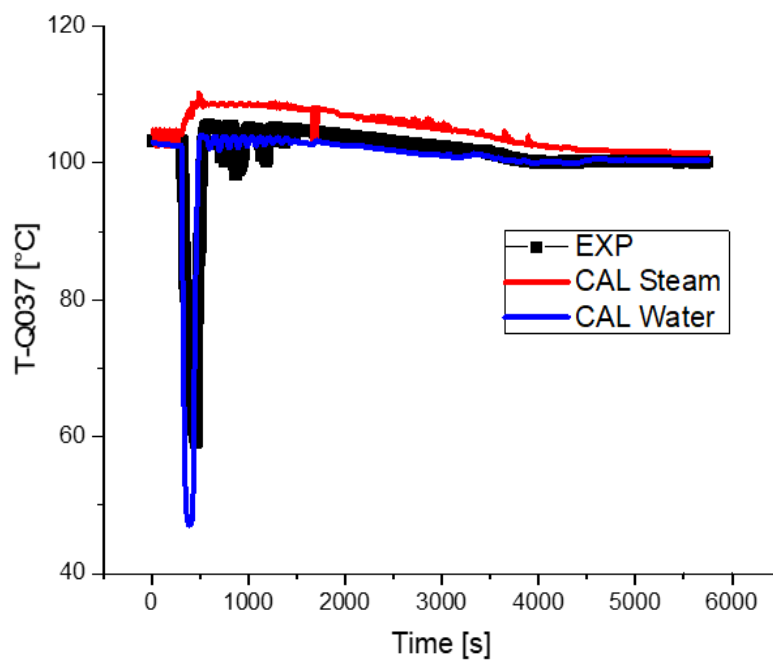


Figure 5.117. Test 7 Part 2 - HXP temperature T-Q034

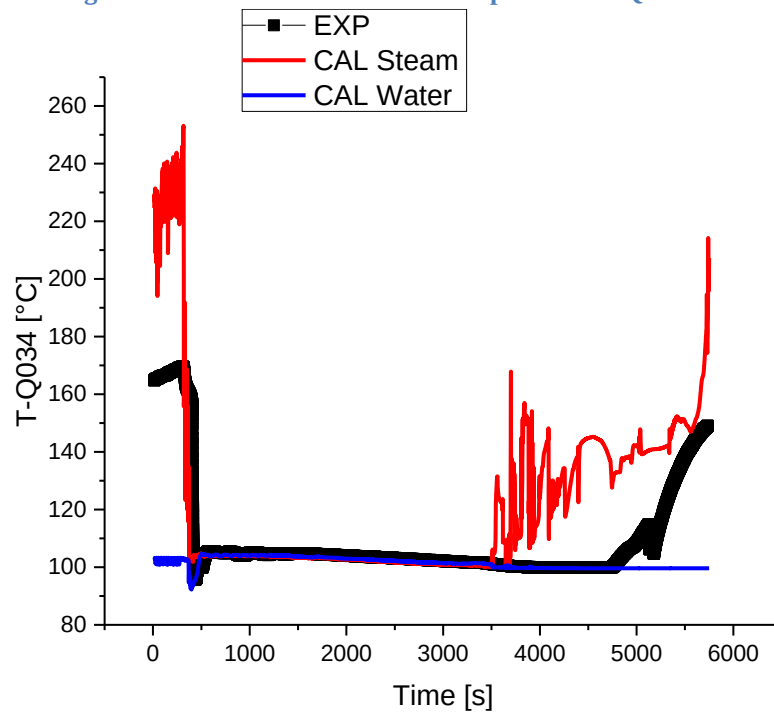


Figure 5.118. Test 7 Part 2 - HXP temperature T-Q031

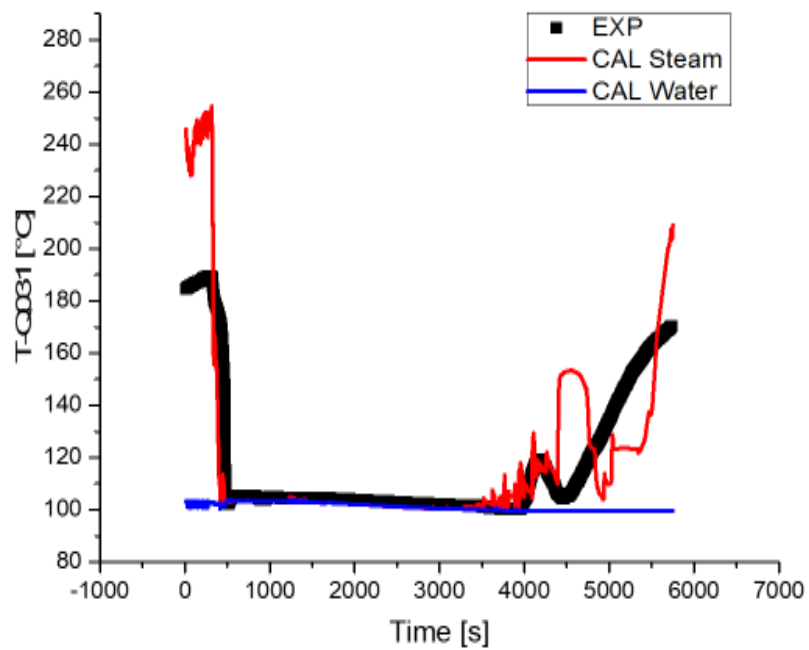


Figure 5.119. Test 7 Part 2 - HXP relative pressure

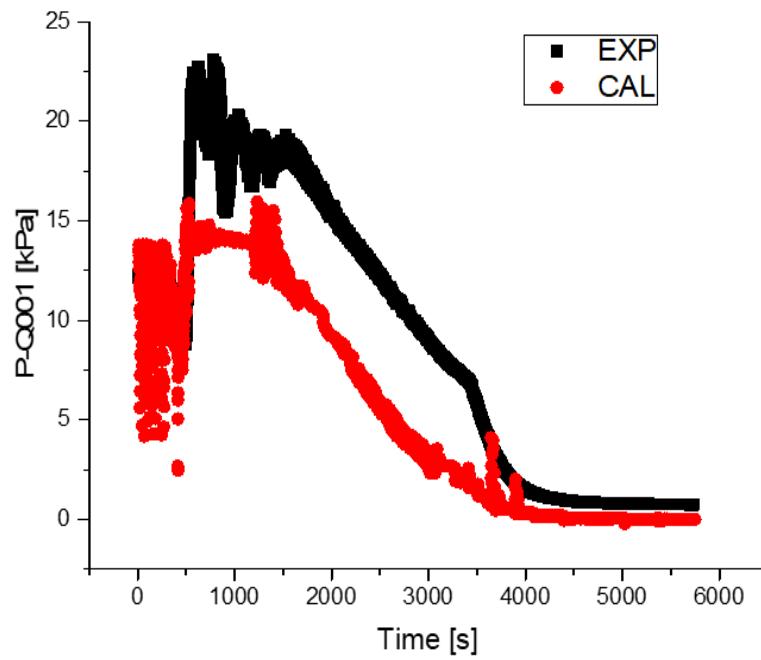


Figure 5.120. Test 7 Part 2 - OP temperature T-P008

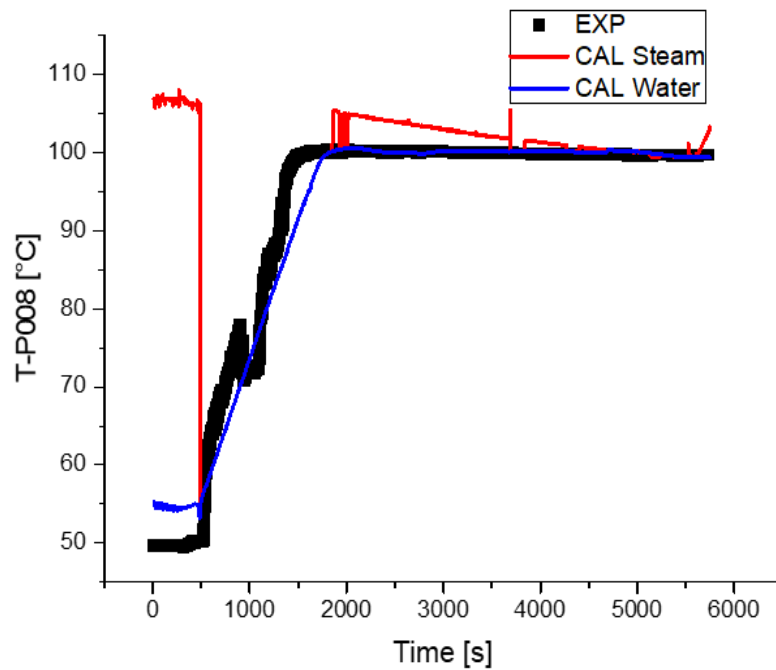
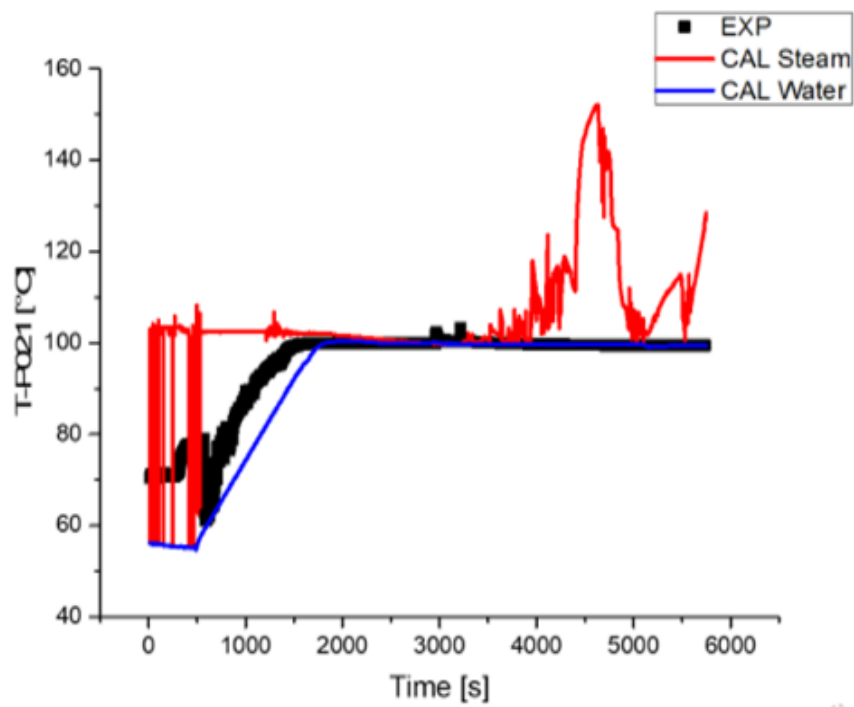


Figure 5.121. Test 7 Part 2 - OP temperature T-P021



13

Figure 5.122. Test 7 Part 2 - HX differential pressure

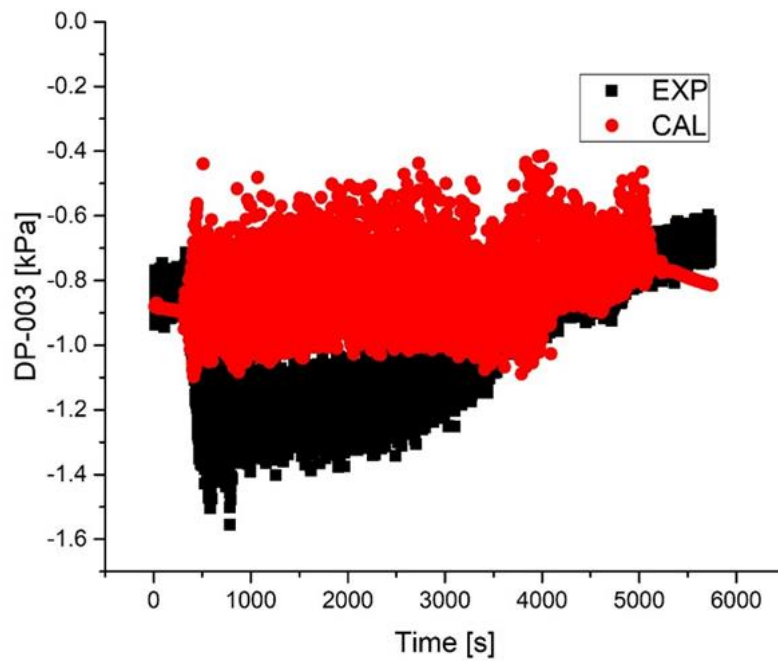


Figure 5.123. Test 7 Part 2 - Injector differential pressure

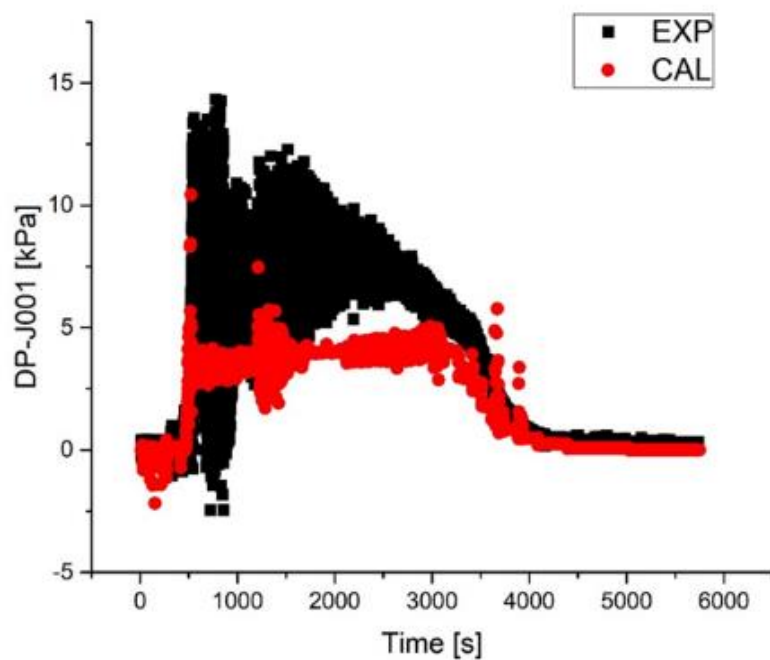


Figure 5.124. Test 7 Part 2 - HX upper header wall temperature

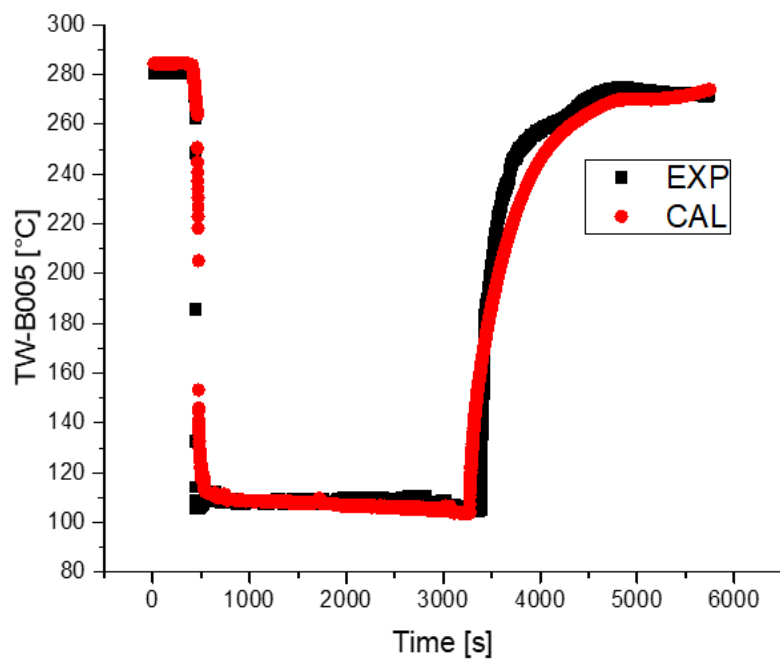


Figure 5.125. Test 7 Part 2 - HX lower header wall temperature

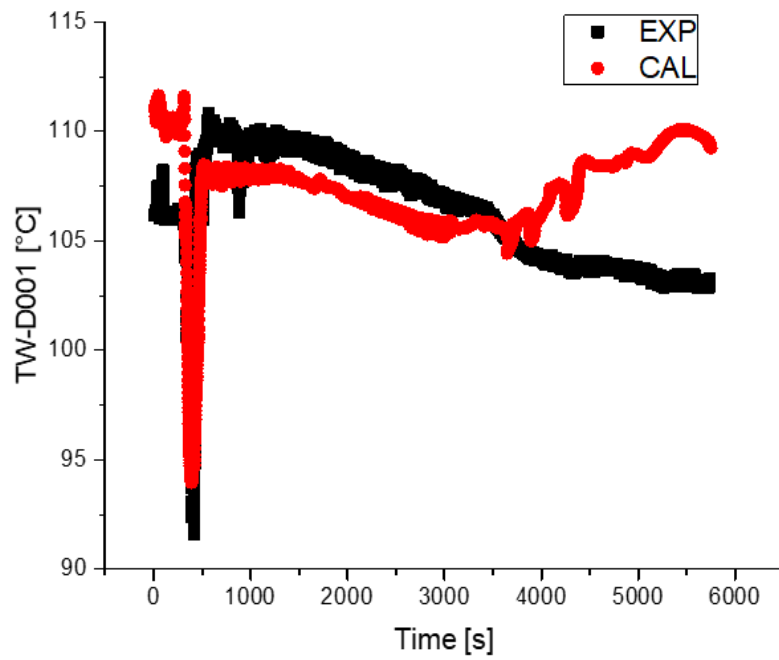
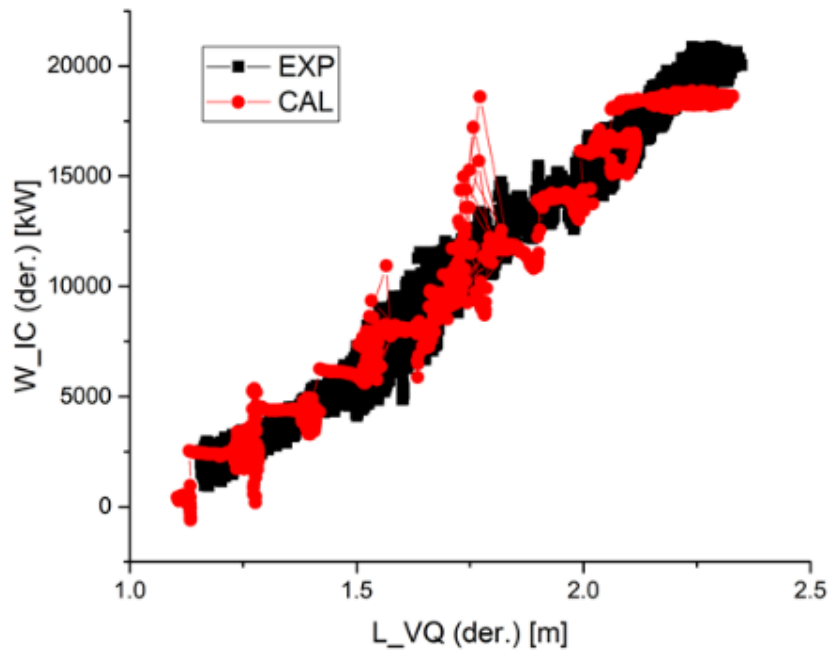


Figure 5.126. HX power as function of the HXP level



The overall trend is similar. In calculation, because of discontinuous injection of steam, the trend is not as smooth as the experiment.

Time Step Control:

Mass error controls the time step

Hydrodynamic time step same as heat conduction time step.

Computation Time: 1 hr.

Table 5.20. Main relevant thermal-hydraulic aspects related to Test 7 Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	300	-
Maximum level in the HXP	463	3.3 m
Maximum exchanged power	385-3 040	19.6 MW
OP discharge valve F031 opening	1 150	-
Triggering valve F045 closure	3 338	-
HX pool level decreasing and loss of mass from the boil-off	3 370-5 770	-
Primary side depressurisation beginning for end of test	-	-

The marks adopted in Table 5.20 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.21. PERSEO Test 7 Part 2 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.		Measurement		Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	o
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	o
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
				Diff. pressure HX upper-lower header	DP-003	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure steam duct injector	DP-J001	o
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Power heat exchanger	W IC (der.)	o
				Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (top)	T-Q031	o
				Power heat exchanger	W IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature OP (top)	T-P021	o
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Power heat exchanger	W IC (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Relative pressure HXP top	P-Q001	o
				Level OP	L VP (der.)	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	o
				Wall temperature HX lower header	TW-D001	

SECTION 5: CONCLUSIONS

The overall trends could be predicted well by the code.

The nodalisation effect was small.

The user effect can exist, depending on the pool and steam duct representation.

Boiling and condensation heat transfer coefficient models need to be further examined.

REFERENCES

- [5.2.3 1] Jeong, J.J., K.S. Ha, B.D. Chung, W.J. Lee (1999), “Development of a multi-dimensional thermal-hydraulic system code, MARS 1.3.1”, *Annals of Nuclear Energy*, Vol. 26, issue 18, pp. 1611-1642.

5.2.4. KAERI_b

SECTION 1: GENERAL INFORMATION

- Organisation: KAERI (Korea)
- Contact persons/authors: Chiwoong Choi, Kwiseok Ha , Kyungdoo Kim
- Code: SPACE version 3.2
- Computing environment:
 - Operative systems: Windows 10
 - RAM: 32 GB
 - CPU characteristics: Intel Core™ i9-7920X CPU @ 2.9 GHz

SECTION 2: DESCRIPTION OF THE CODE USED

- General description of the code used [5.2.4 1]:
 - Developed by KAERI
 - For multidimensional and multipurpose TH analysis
 - Written by C++
 - Numerical solving scheme
 - First-order, finite-difference method
 - One-dimensional model
 - Staggered-grid mesh
 - Donor-cell scheme
 - Semi-implicit scheme
 - Basic differential equations and approach (six equations)
 - Two Phases (gas and liquid), three fields (continuous liquid, gas, and droplet) equations
 - Nine equations (three continuities, three momenta, three energy) + one continuity for non-condensable gas
 - Implemented models relevant for PERSEO conditions:
 - Single Phase: Dittus-Boelter model
 - Nucleate boiling: Chen model
 - Condensation: maximum value of Shah and Nusselt models
 - Pressure drop in one-phase and two-phase flow
 - Wall: Colebrook-White correlation
 - Interphase: Depending on the flow regime

SECTION 3: DESCRIPTION OF THE NODALISATION

Two loops are modelled; one is a primary loop including the vessel and the heat exchanger. The other is a secondary loop including the HXP and the OP. The heat exchanger is modelled with averaged single tube represents 120 heat transfer tubes. The HXP and OP are modelled with separated two volumes and cross connections for each volume. The injector is connected to the OP volume with side junction. In the Part-2, the HXP and the

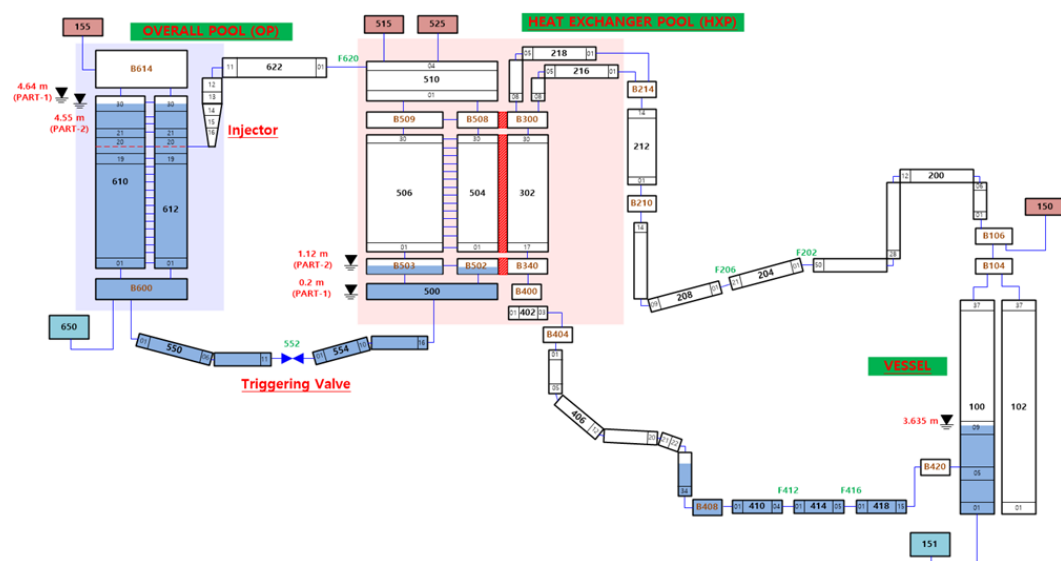
OP are not modelled with the separated two volumes and cross junctions, since the calculation is failed.

- Heat losses, how the pressure vessel is modelled: No heat loss is imposed. Steam is injected at the upper space of the pressure vessel, which is controlled experimentally measured pressure using a pressure boundary TFBC component in SPACE.
- Nodalisation strategies (e.g. slicing nodalisation, etc.); 1 m per node for pipes. 0.1 m per node for HX and HX pool.
- 0.4 m ~ 0.5 m per node for overall pool.
- Eventual tuning by the user; heat transfer coefficients for the nucleate boiling and condensation was multiplied by 3.0.
- Use of multidimensional components and description. None.

Table 5.22. Summary of the main nodalisation characteristics of the PERSEO model

	Number of hydraulic volumes	Number of junctions	Number of heat structures	Overall Volume (m ³)
Vessel	94	95	0	45.02
Steam line	130	129	130	3.22
HX	32	32	22	1.83
Condensate line	65	64	65	0.53
HXP	69	102	0	26.34
Steam duct	16	15	0	12.05
OP	62	94	0	168.24
Heat transfer area HX (m ²)	34.47			
HX heat structure axial nodes number	30			
HX heat structure radial nodes Number	11			

Figure 5.127. PERSEO nodalisation for SPACE code



SECTION 4: RESULTS

TEST 7 Part 1

During the initial period before starting the valve opening, the pressure boundary (TFBC) is connected to the top of the HXP and maintained constant pressure (101 kPa). And null transient is calculated for initial 1 000 s. All pool levels are set to initial values. The vessel level is controlled with the flow boundary condition.

The pressure trend, water levels, and temperature trend were reasonably predicted.

When the injector is connected to the OP with y-direction, the calculation becomes stable.

The subcooled and saturated nucleate boiling and condensation heat transfer coefficients are tentatively multiplied by 3.0.

It is difficult to predict the initial pool temperature distribution for the appropriate initial condition.

Various sensitivity tests were conducted including HXP pool size, OP pool size, alternative heat transfer models, initial pool temperatures, and so on. The cross-sectional area ratio of the HXP pools is modelled with 7:3 based on the sensitivity test. In addition, the form loss in the HXP pool are increased based on the sensitivity test. Some errors were found in the single-phase heat transfer during initial region. The single vapour phase heat transfer is overestimated due to wrong selection among laminar, turbulent, natural circulation regions. However, it is not sensitive to the overall transient; this has not yet been corrected in this report.

Figure 5.128. Part 1-SPACE Result: 1-Flowrate in steam supply line

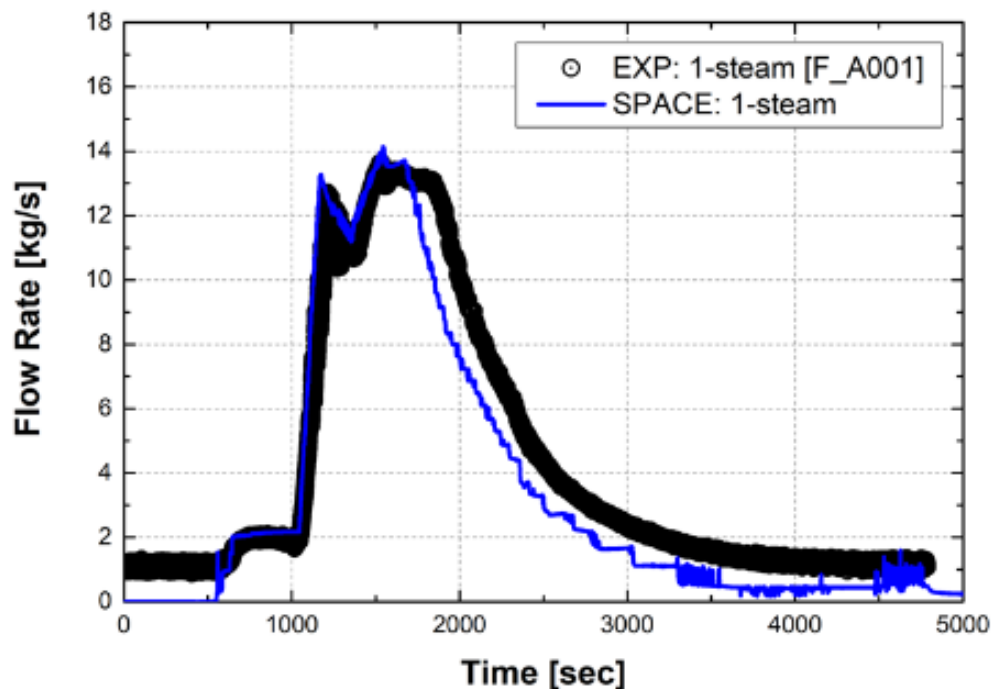


Figure 5.129. Part 1-SPACE Result: 2-Flowrate in condensate drain line

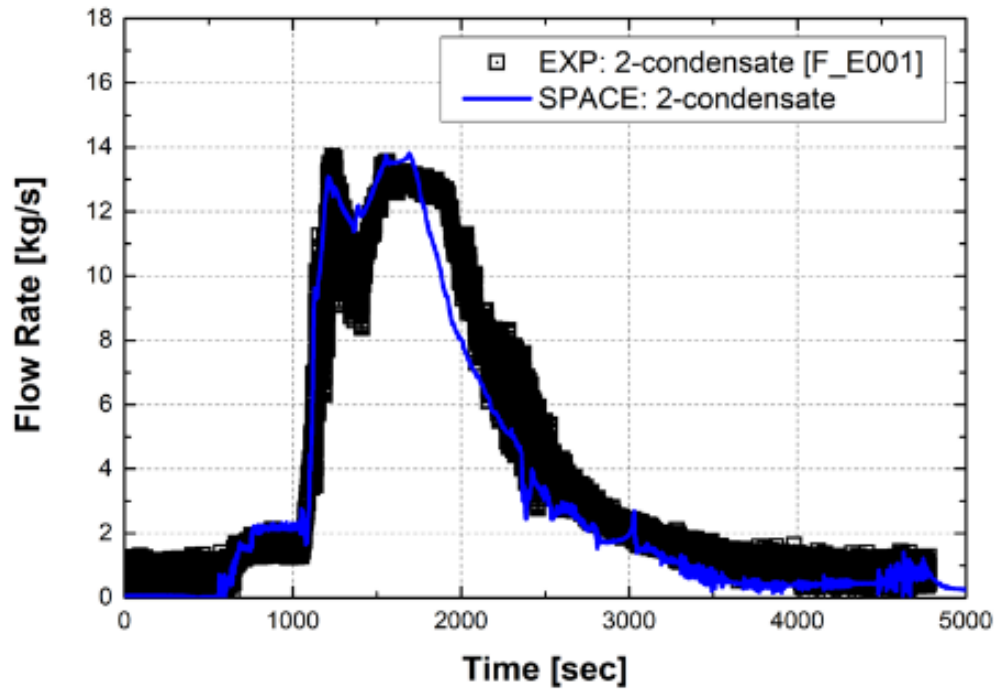


Figure 5.130. Part 1-SPACE Result: 3-Power heat exchanger

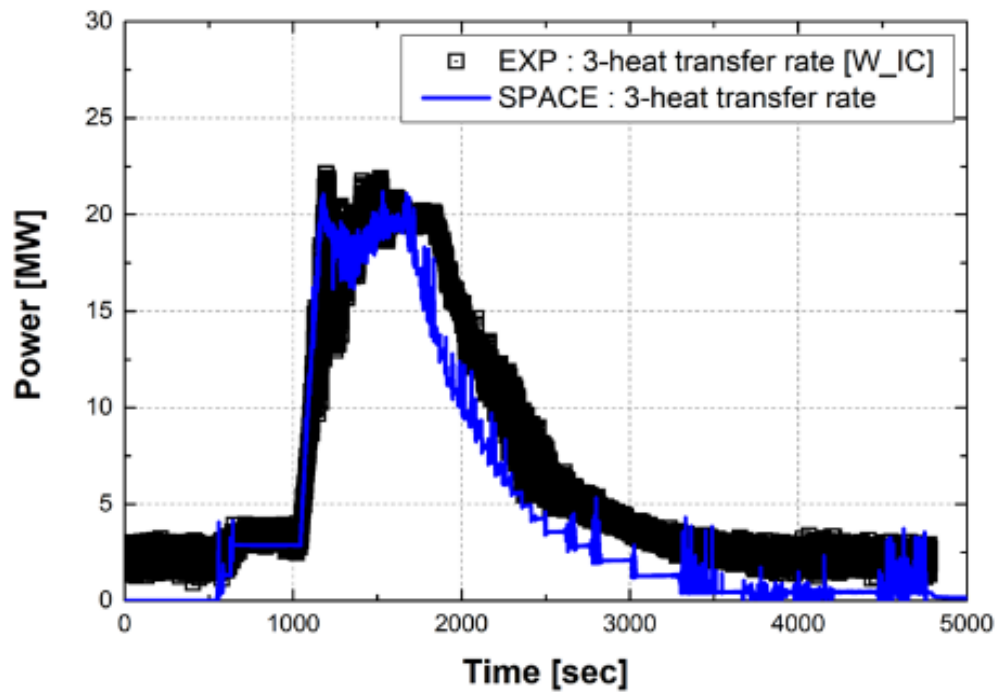


Figure 5.131. Part 1-SPACE Result: 4-Absolute pressure vessel

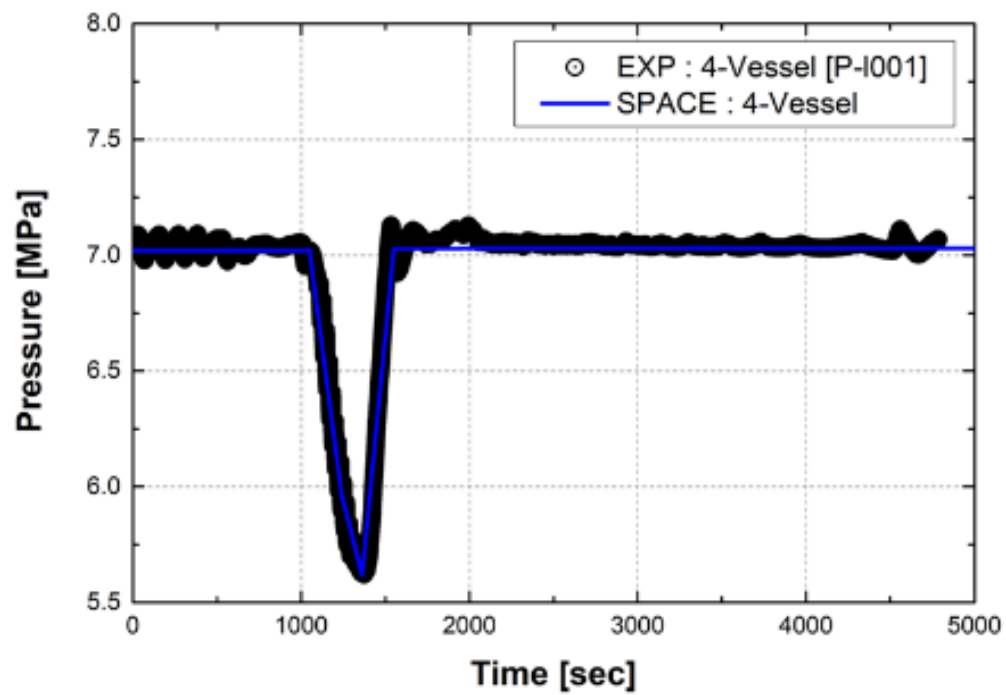


Figure 5.132. Part 1-SPACE Result: 5-HX inlet temperature

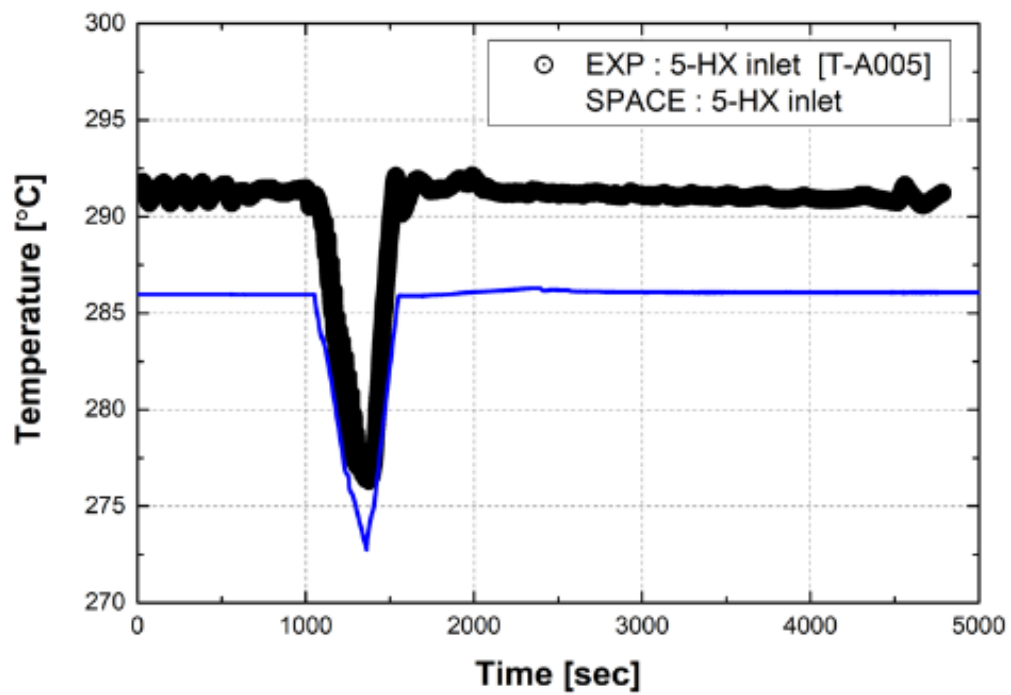


Figure 5.133. Part 1-SPACE Result: 6-HX outlet temperature

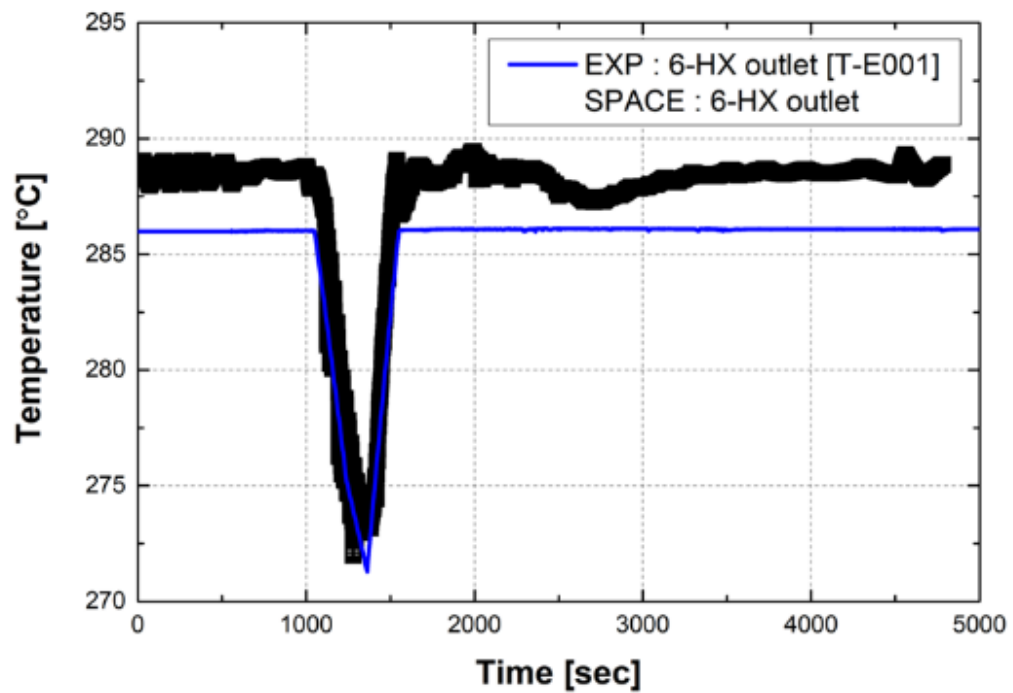


Figure 5.134. Part 1-SPACE Result: 7-Level HXP

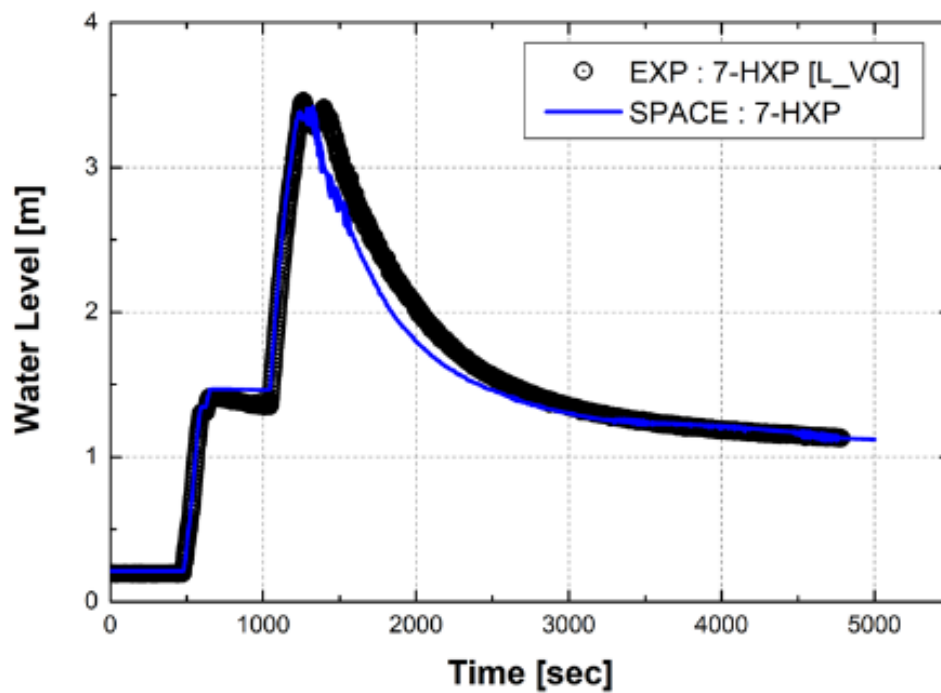


Figure 5.135. Part 1-SPACE Result: 8-Level OP

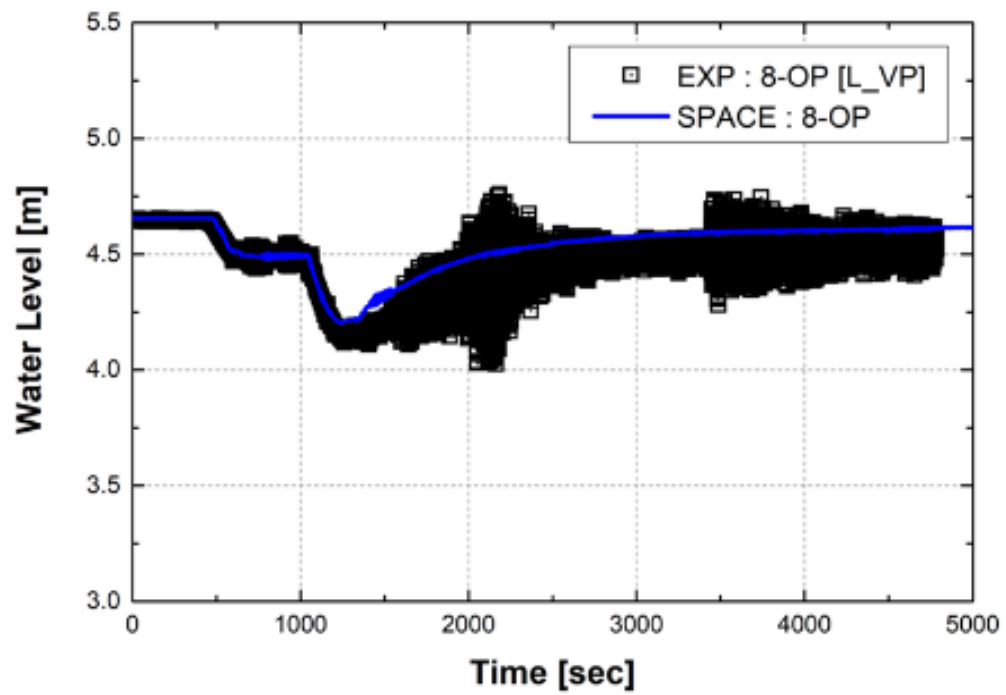


Figure 5.136. Part 1-SPACE Result: 9-Temperature HXP (bottom)

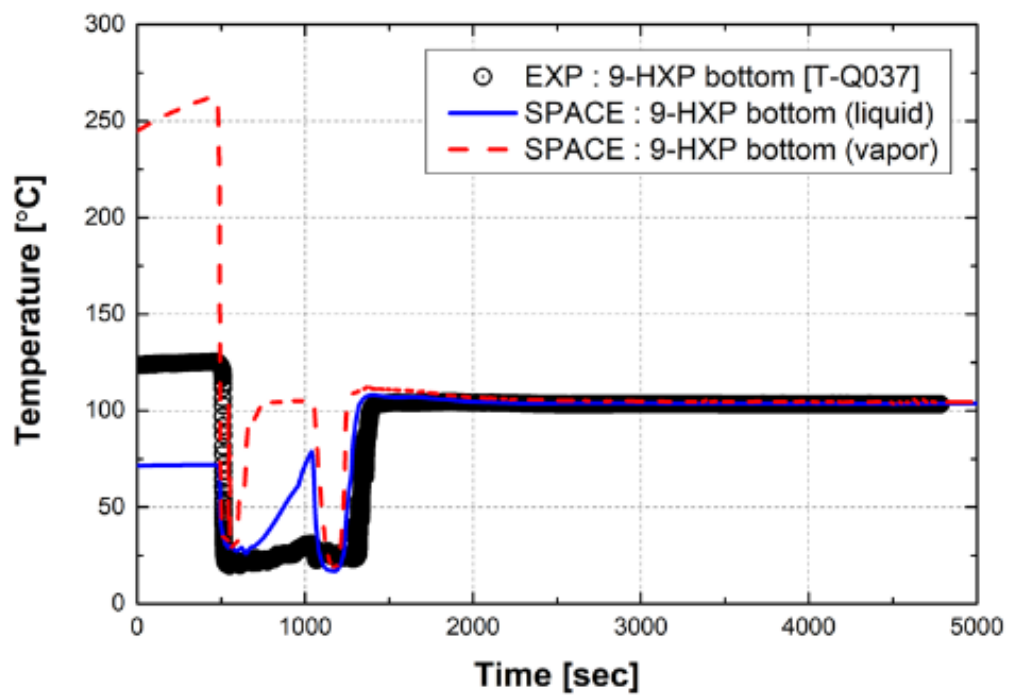


Figure 5.137. Part 1-SPACE Result: 10-Temperature HXP (middle)

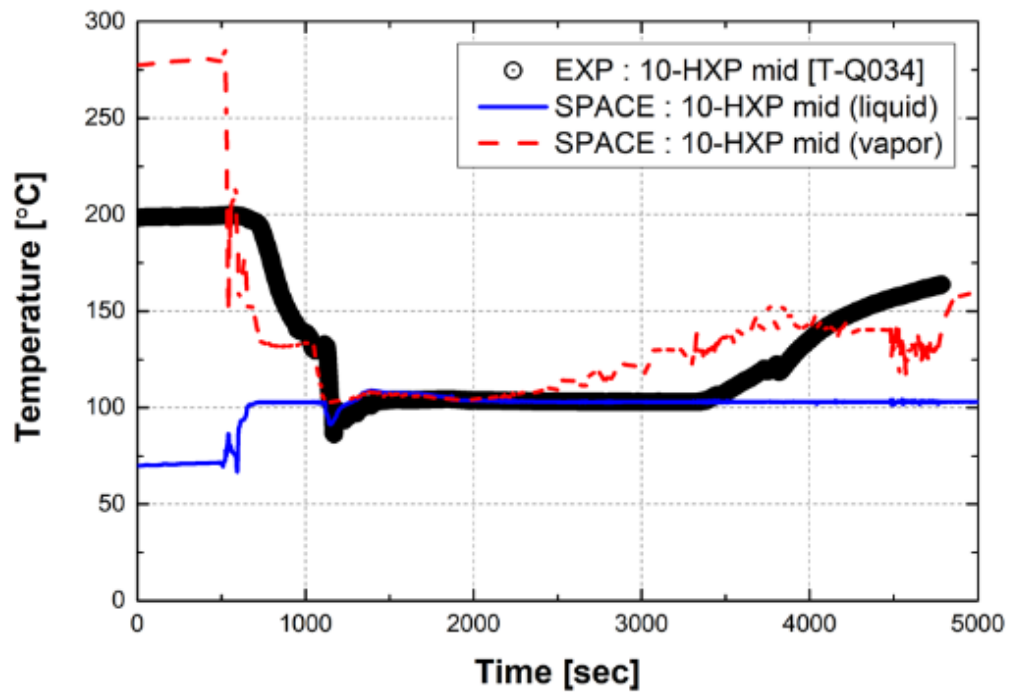


Figure 5.138. Part 1-SPACE Result: 11-Temperature HXP (top)

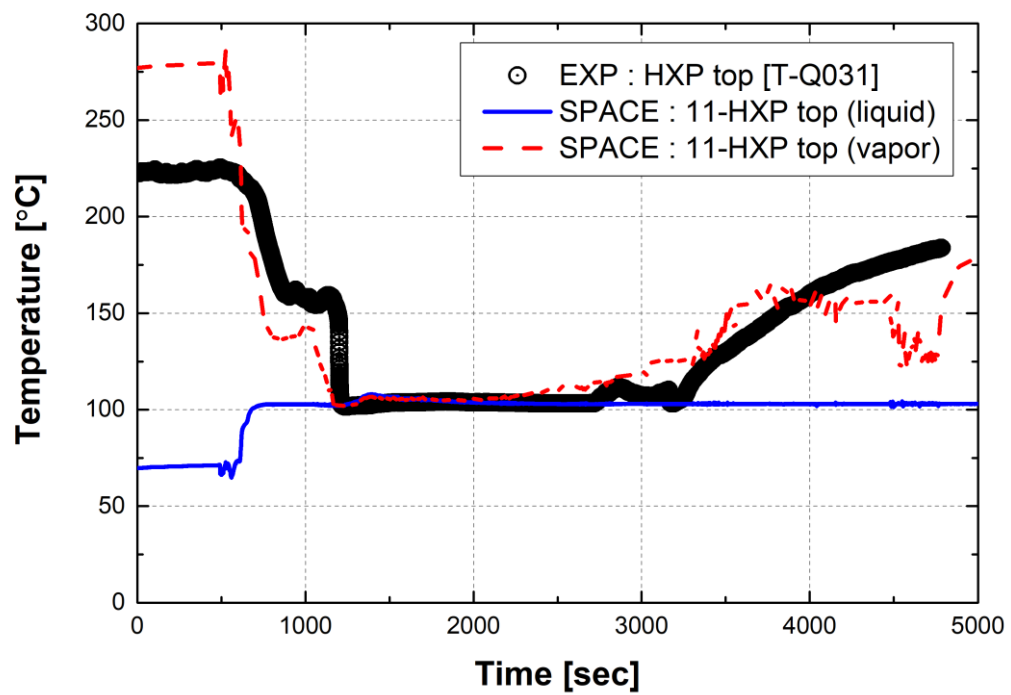


Figure 5.139. Part 1-SPACE Result: 12-Relative pressure HXP (top)

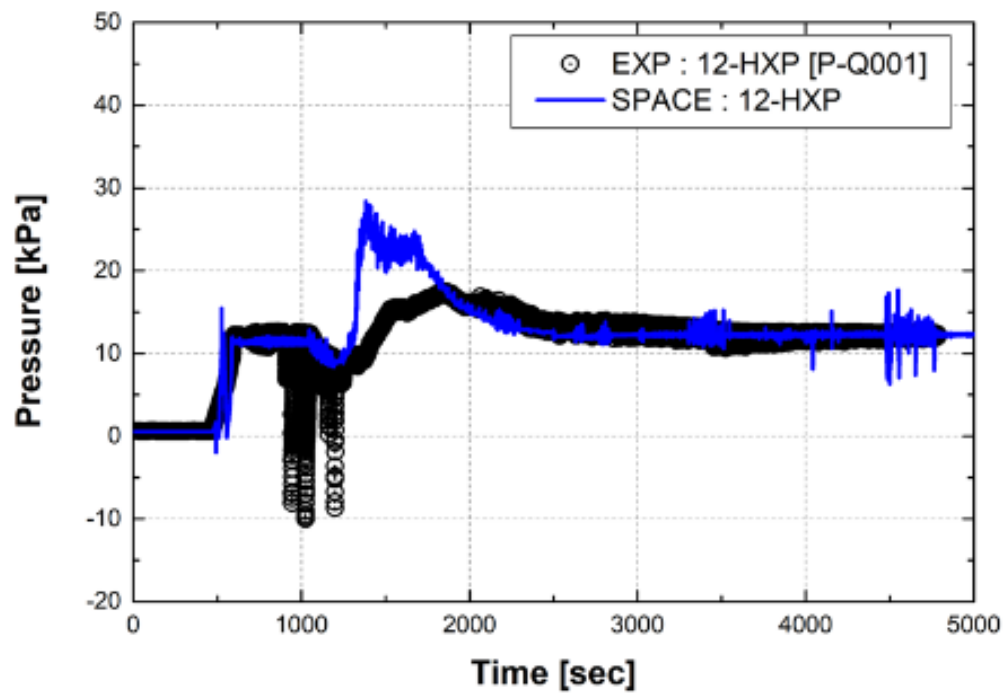


Figure 5.140. Part 1-SPACE Result: 13-Temperature OP (bottom)

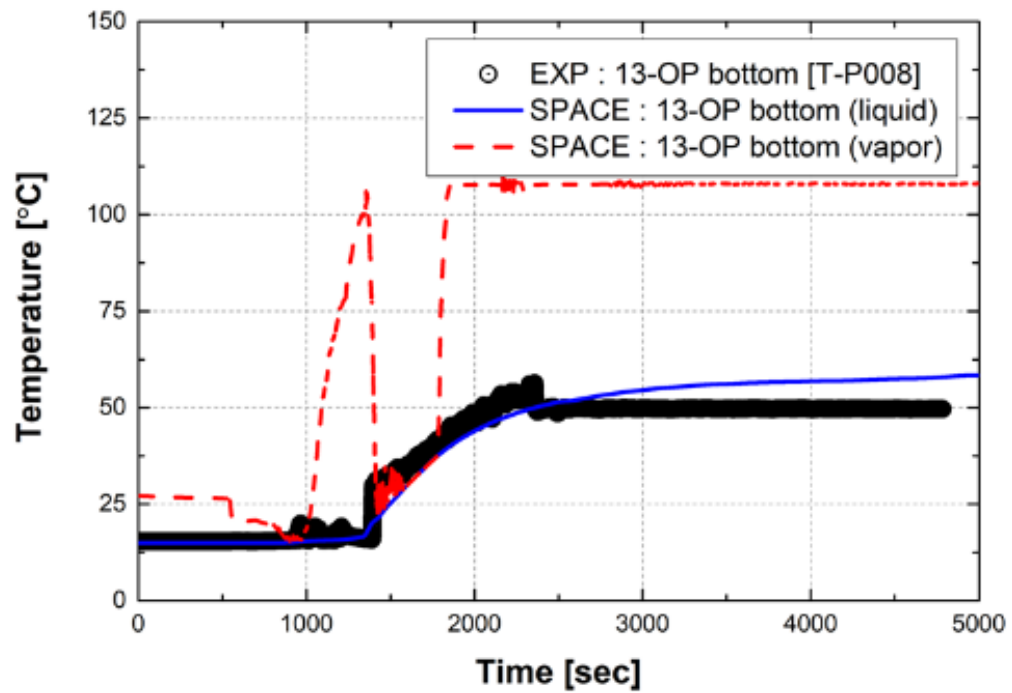


Figure 5.141. Part 1-SPACE Result: 14-Temperature OP (top)

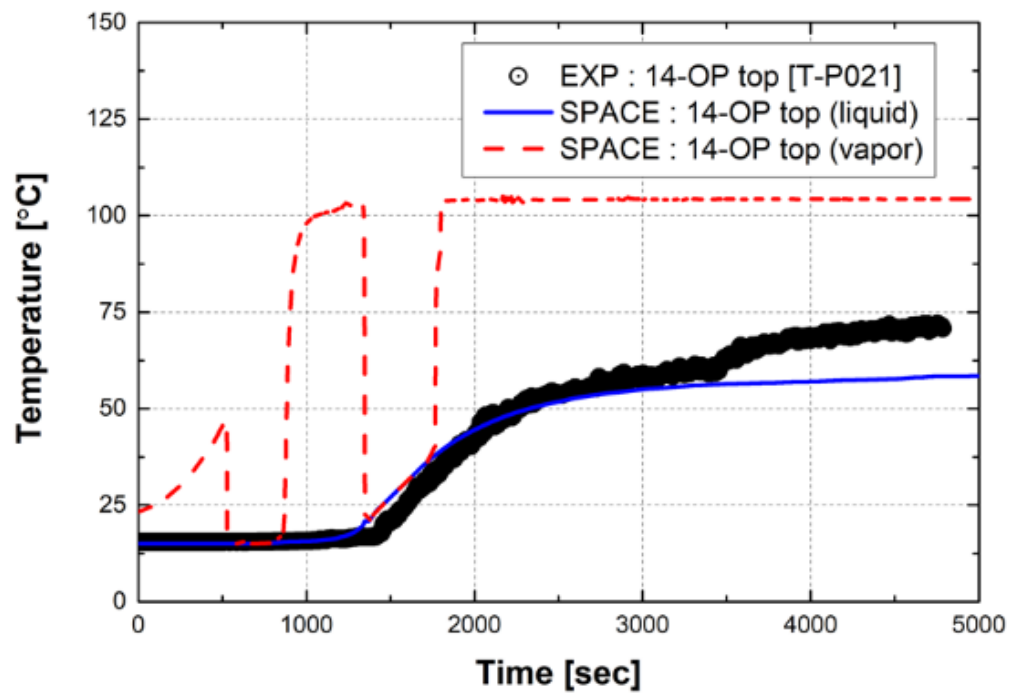


Figure 5.142. Part 1-SPACE Result: 15-Differential pressure HX upper-lower header

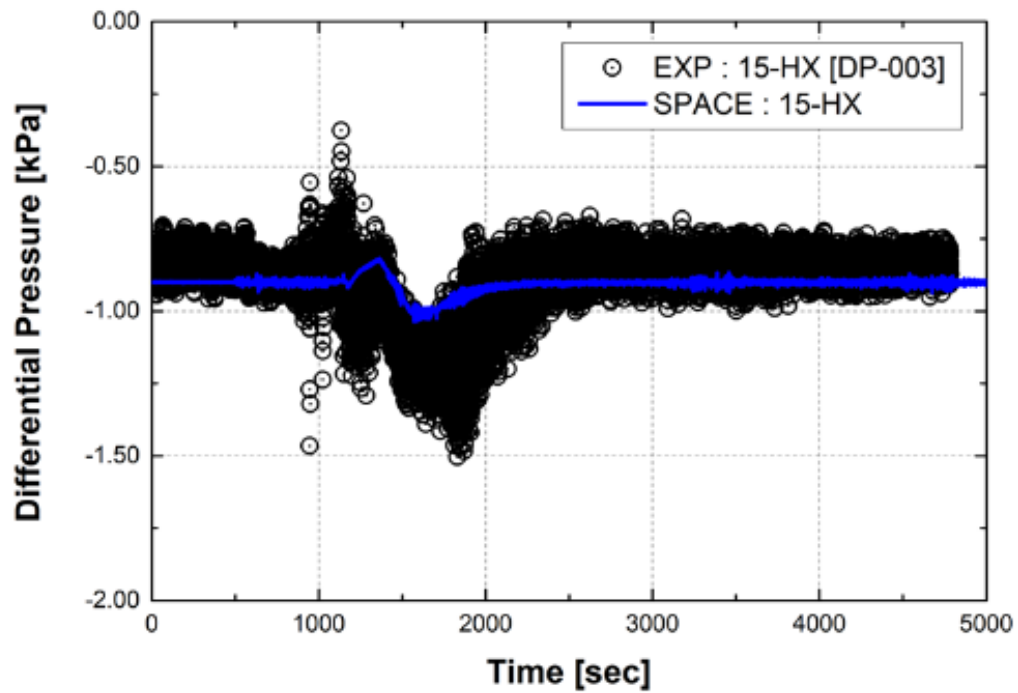


Figure 5.143. Part 1-SPACE Result: 16-Differential pressure steam duct injector

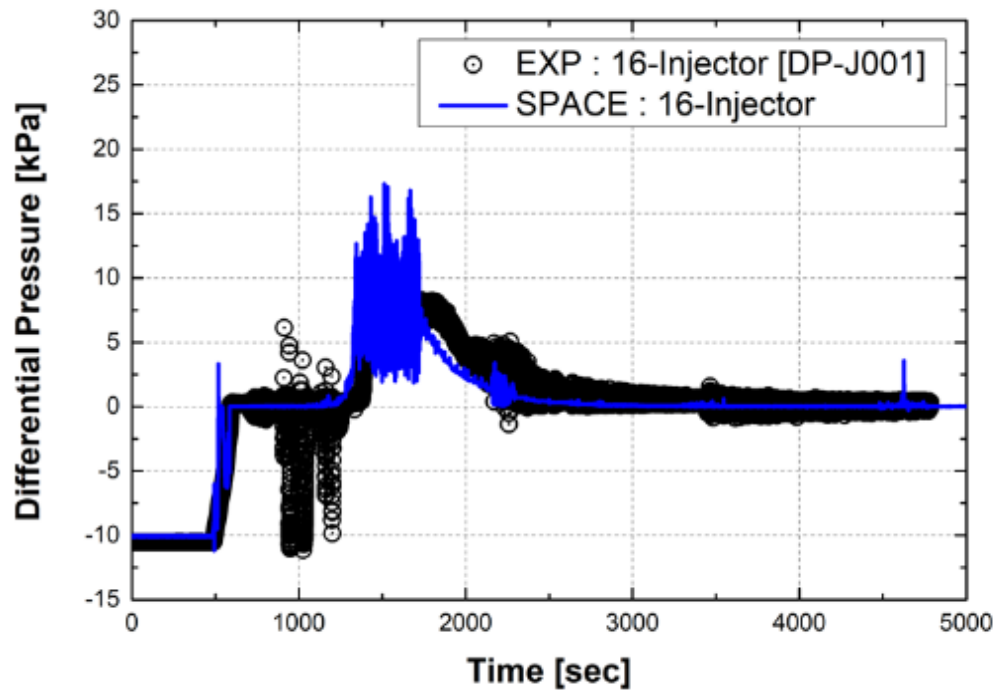


Figure 5.144. Part 1-SPACE Result: 17-Wall temperature HX upper header

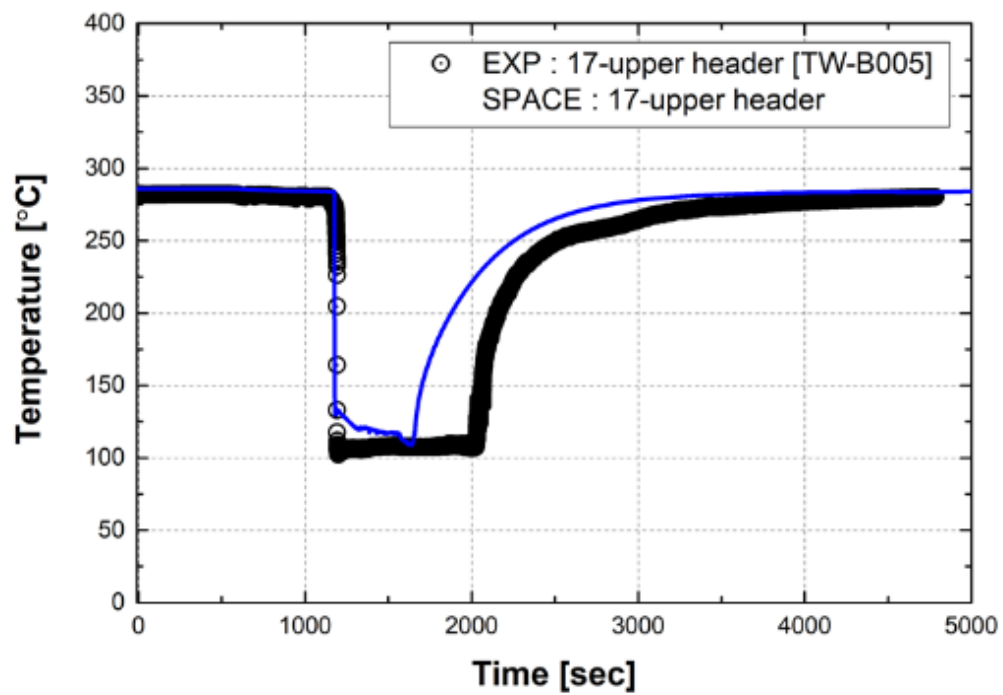
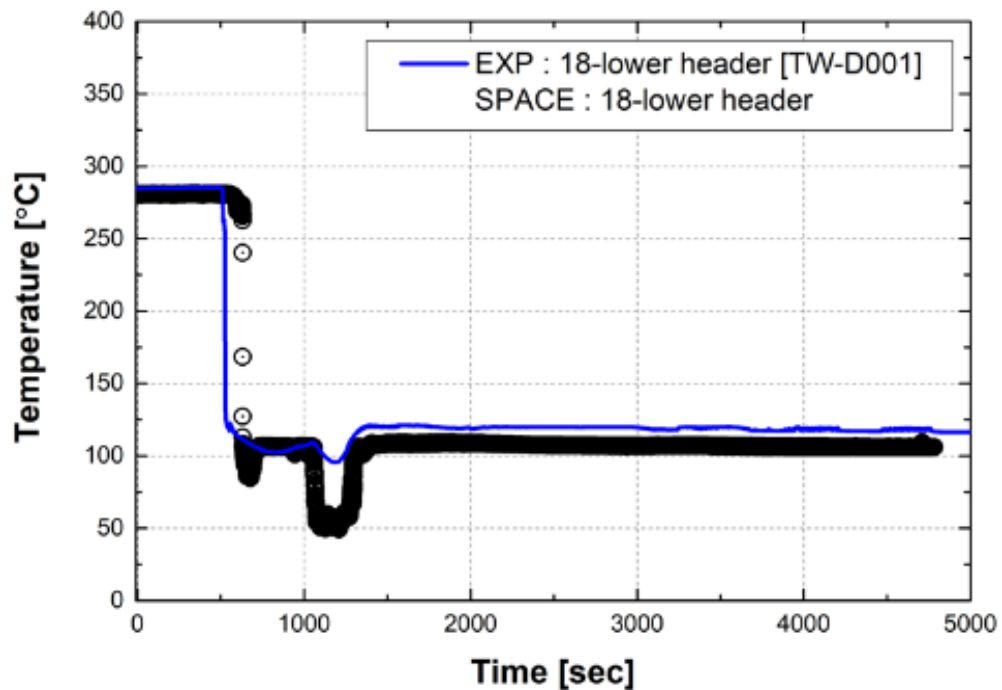


Figure 5.145. Part 1-SPACE Result: 18-Wall temperature HX lower header



- Time Step Control:

Mass error controls the time step

Hydrodynamic time step same as heat conduction time step.

- Computation Time: approximately 12 hours

Table 5.23. Main relevant thermal-hydraulic aspects related to Test 7 Part 1

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	475/600	-
Triggering valve (F045) re-opening and re-closure	621/655	-
Maximum level in the HX pool for the first filling step	652	1.44 m
Small heat removal from the primary side	700 – 1 000	~ 3.7 MW
Slow water consumption in the HX pool	-	
Instabilities for steam condensation in the injector	-	
Triggering valve (F045) opening and closure	1 039/1 260	-
Maximum level in the HX pool	1 335	3.53 m
Maximum exchanged power	1 500-2 030	~ 20.5 MW
HX pool minimum level	5 000	0.87 m
OP average temperature	14 800	Around 59°C

The marks adopted in Table 5.23 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.24. PERSEO Test 7 Part 1 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	+
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	o
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure HX upper-lower header	DP-003	o
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	HX inlet temperature	T-A005	o
				HX outlet temperature	T-E001	
				Power heat exchanger	W IC (der.)	
				Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (bottom)	T-Q037	o
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Power heat exchanger	W IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature HXP (top)	T-Q031	o
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
				Level HXP	L VQ (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L VP (der.)	o
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	o
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

** Ph. = Phenomenon

Test 7 Part 2

In the PART-2, the HXP pressure is initially higher than the OP pressure. So, there is initial steam flow. I think that makes the setting of the initial conditions difficult. In our case, when the HXP and OP modelling with the two separated volumes is applied, the calculations are failed. Therefore, all 1-D modelling for the HXP and OP are applied to enforce the initial temperatures.

Overall prediction is reasonable.

Nodalisation strategies/tuning: same as Part-1

Initially, when the injector in the OP is uncovered, non-physical sudden drop occurred during transient. Some error was found in the interfacial drag when the vertical stratified flow regime and corrected. No non-physical behaviour occurred after resolving this issue.

Same modifications to the Part-1 are applied. In addition, the form loss in the injector is slightly reduced to obtain the better water level in the HXP.

Figure 5.146. Part 2-SPACE Result: 1-Flowrate in steam supply line

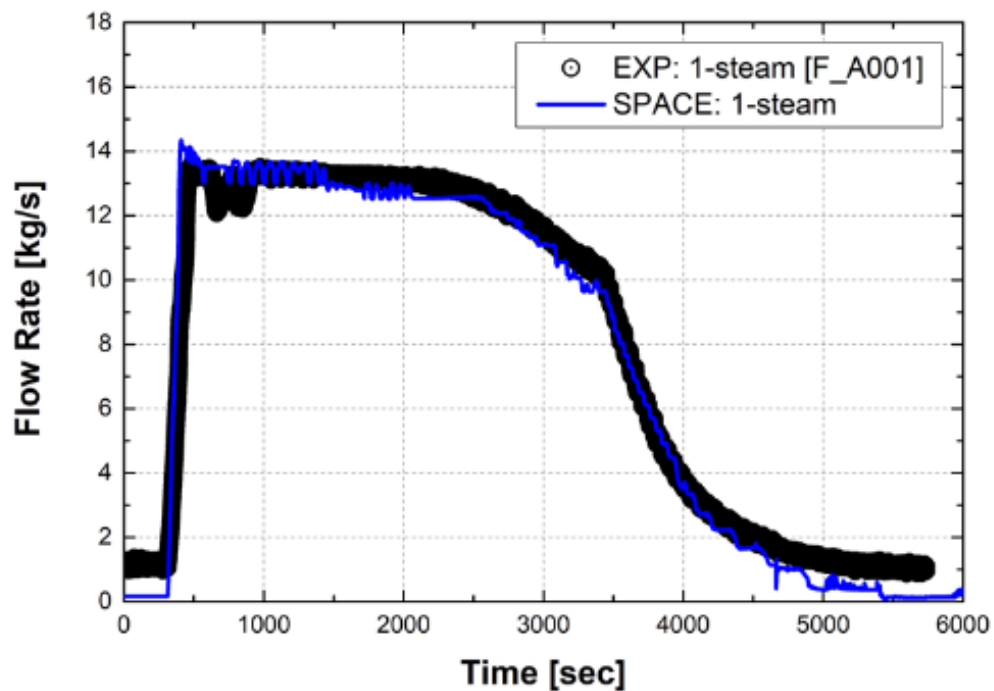


Figure 5.147. Part 2-SPACE Result: 2-Flowrate in condensate drain line

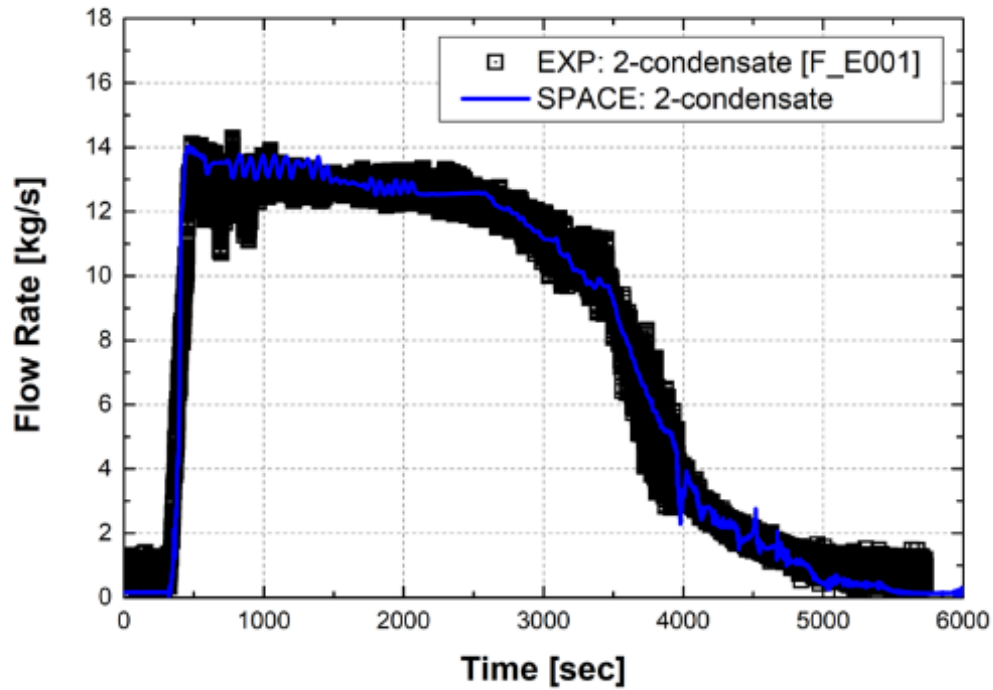


Figure 5.148. Part 2-SPACE Result: 3-Power heat exchanger

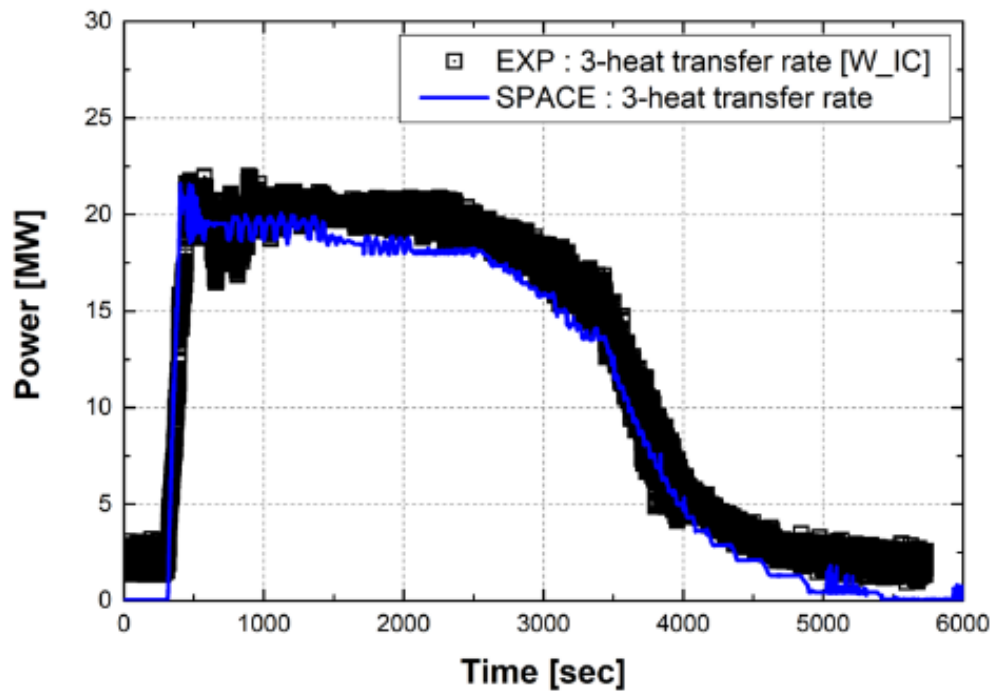


Figure 5.149. Part 2-SPACE Result: 4-Absolute pressure vessel

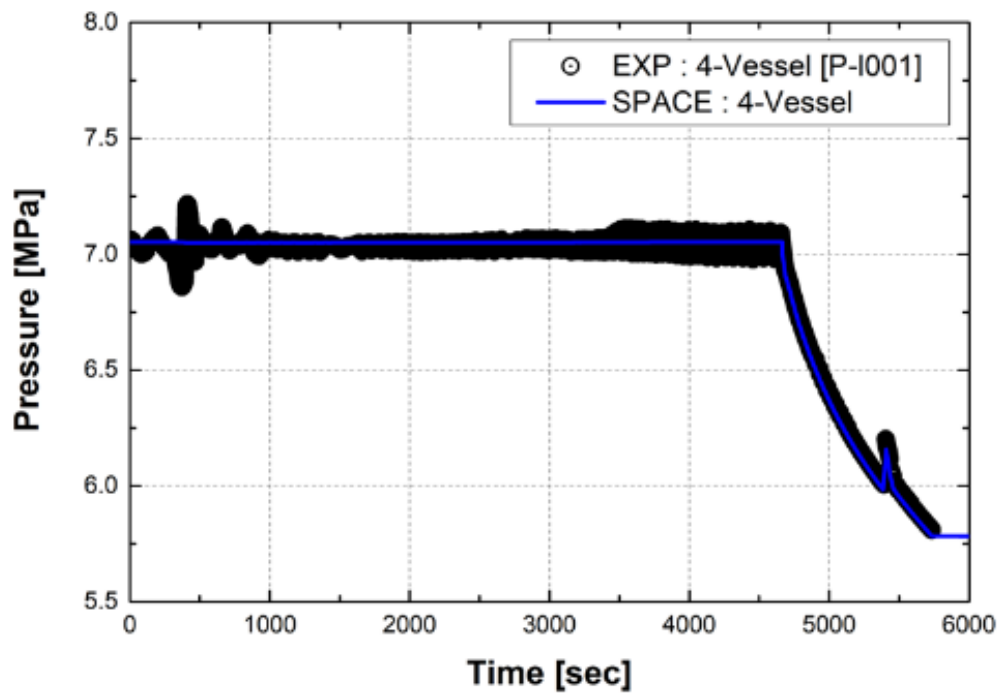


Figure 5.150. Part 2-SPACE Result: 5-HX inlet temperature

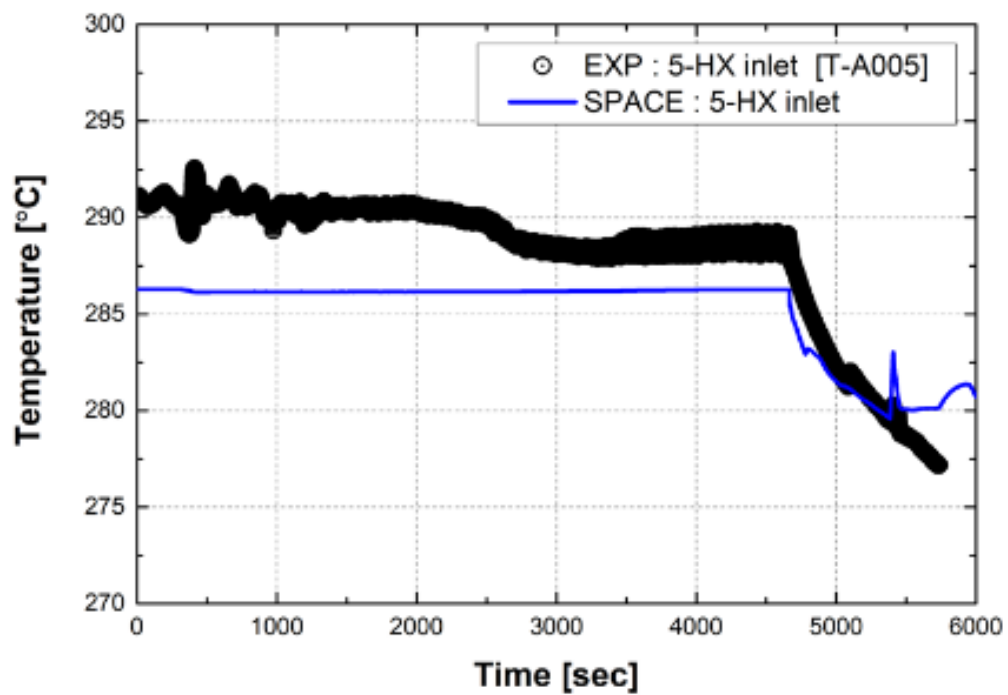


Figure 5.151. Part 2-SPACE Result: 6-HX outlet temperature

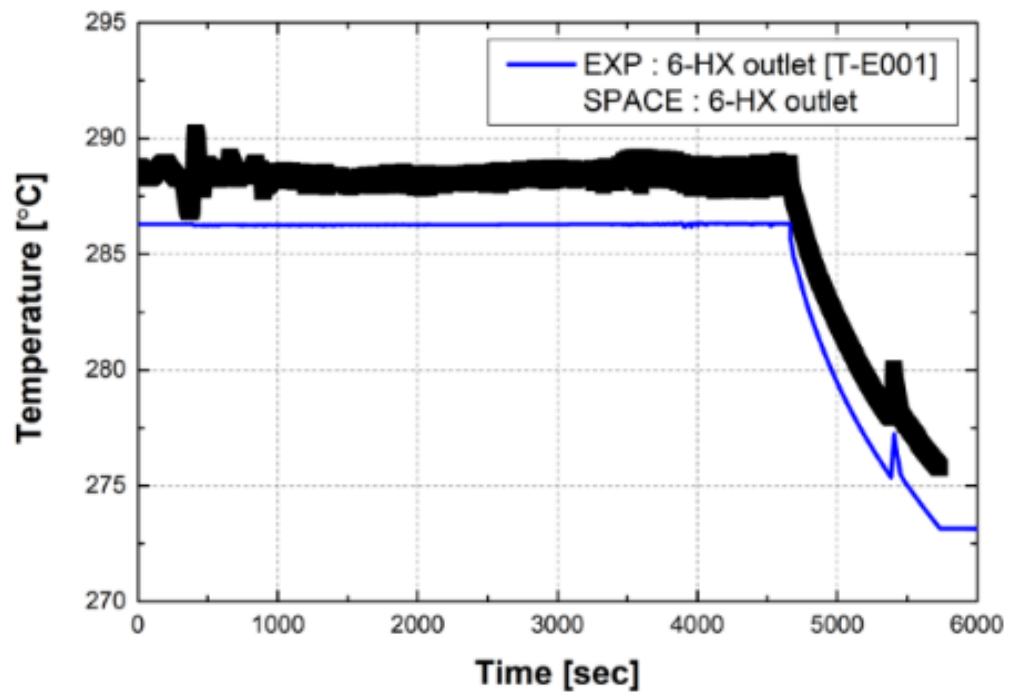


Figure 5.152. SPACE Result: 7-Level HXP

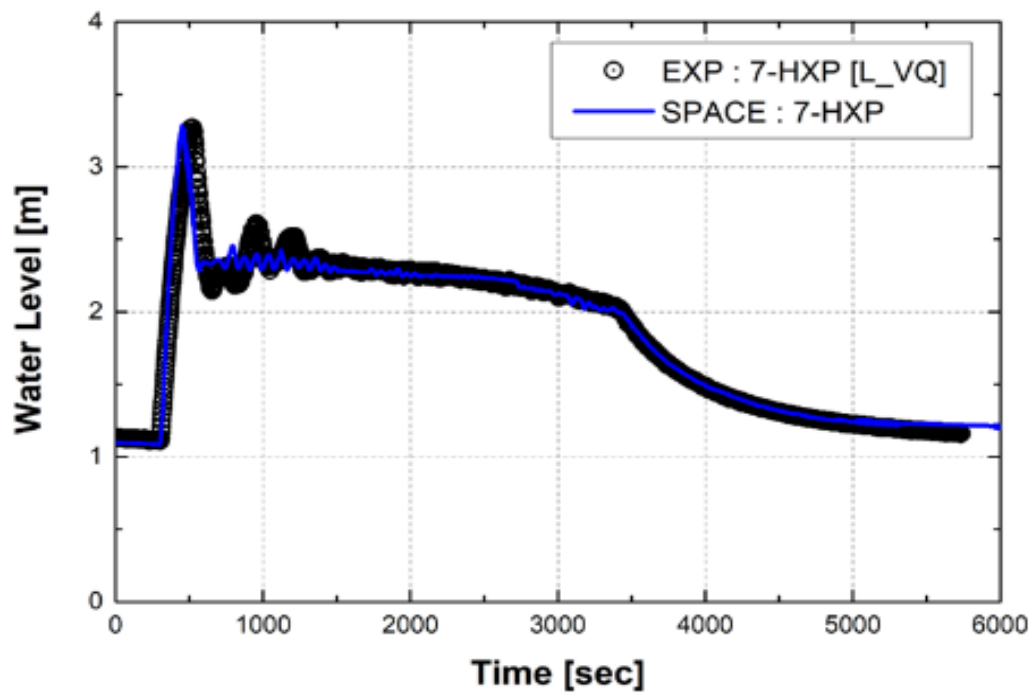


Figure 5.153. Art2-SPACE Result: 8-Level OP

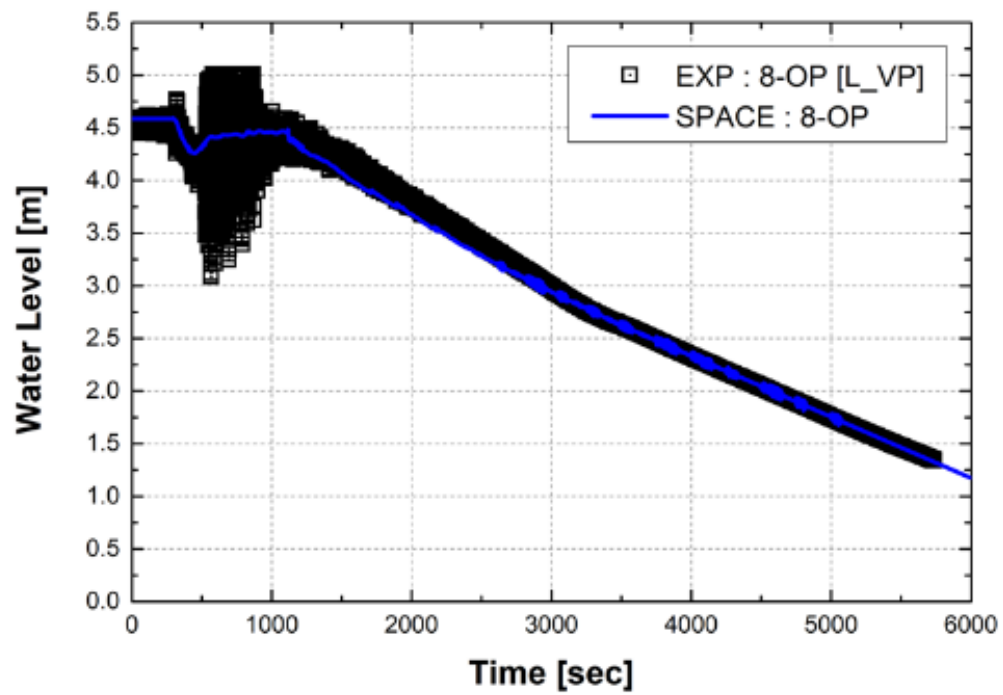


Figure 5.154. Part 2-SPACE Result: 9-Temperature HXP (bottom)

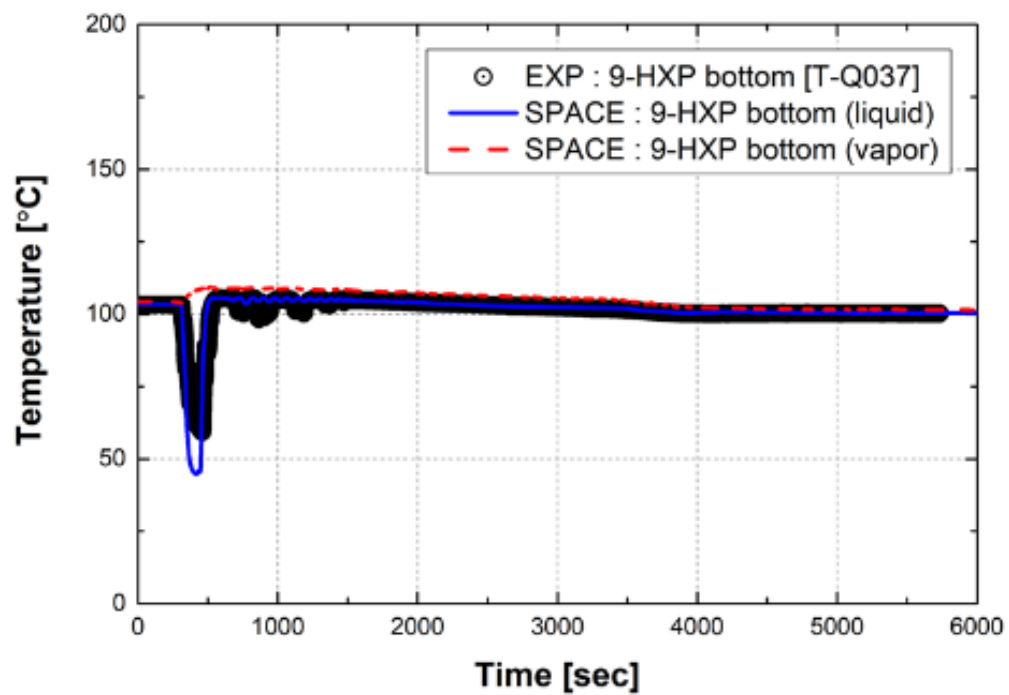


Figure 5.155. Part 2-SPACE Result: 10-Temperature HXP (middle)

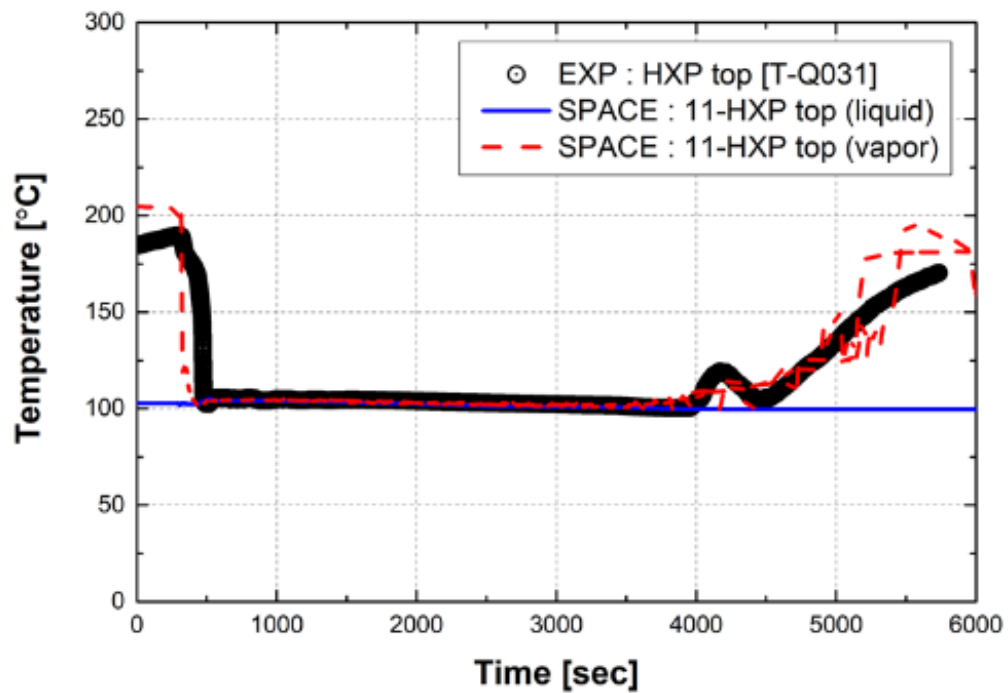


Figure 5.156. Part 2-SPACE Result: 11-Temperature HXP (top)

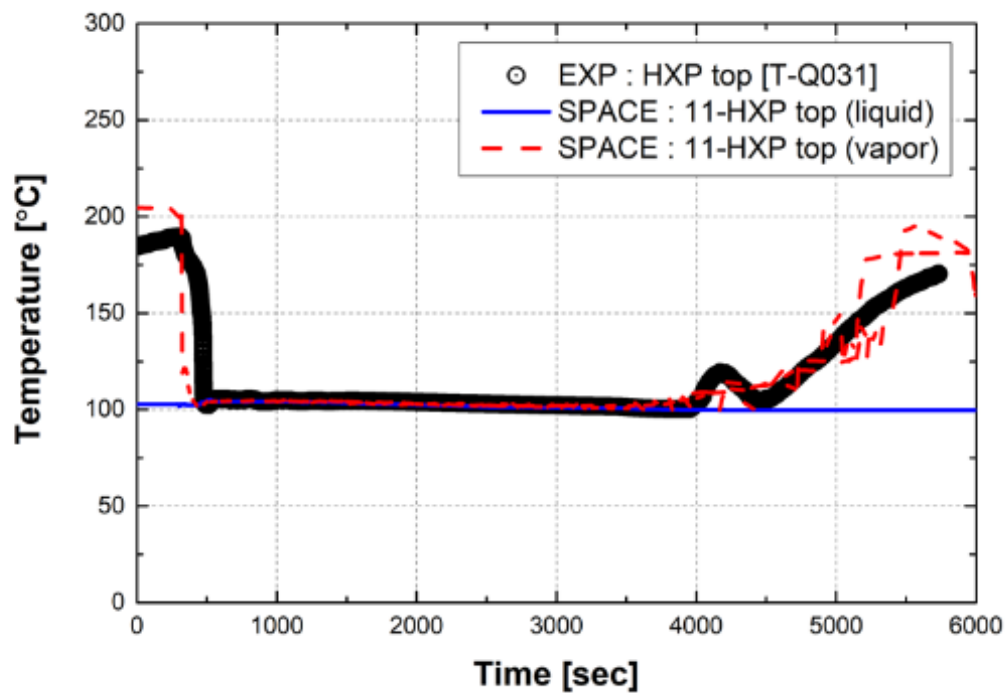


Figure 5.157. Part 2-SPACE Result: 12-Relative pressure HXP (top)

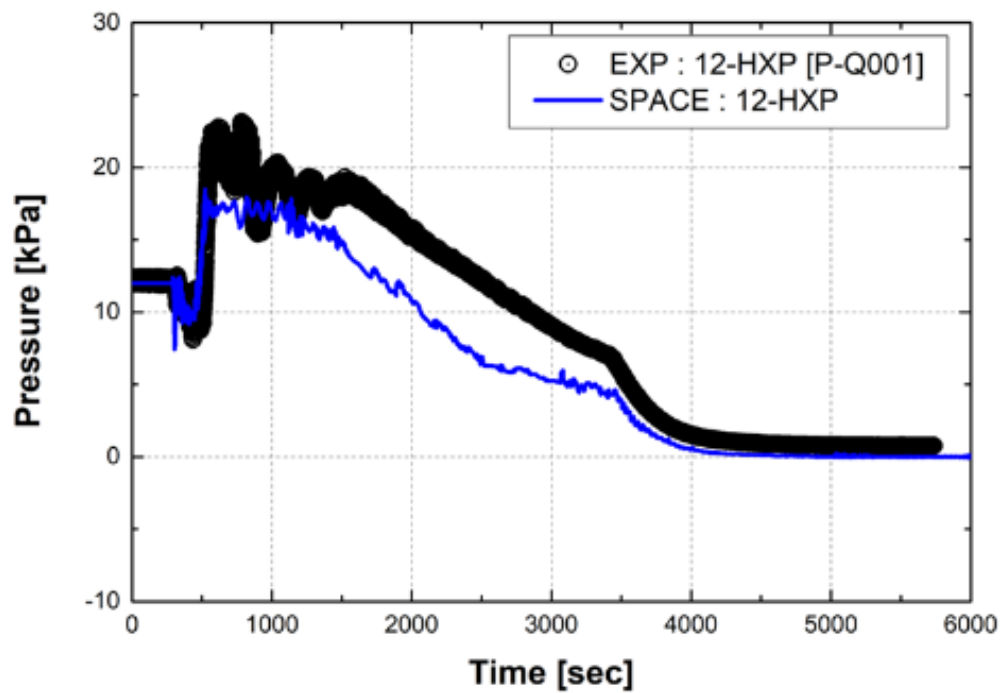


Figure 5.158. Part 2-SPACE Result: 13-Temperature OP (bottom)

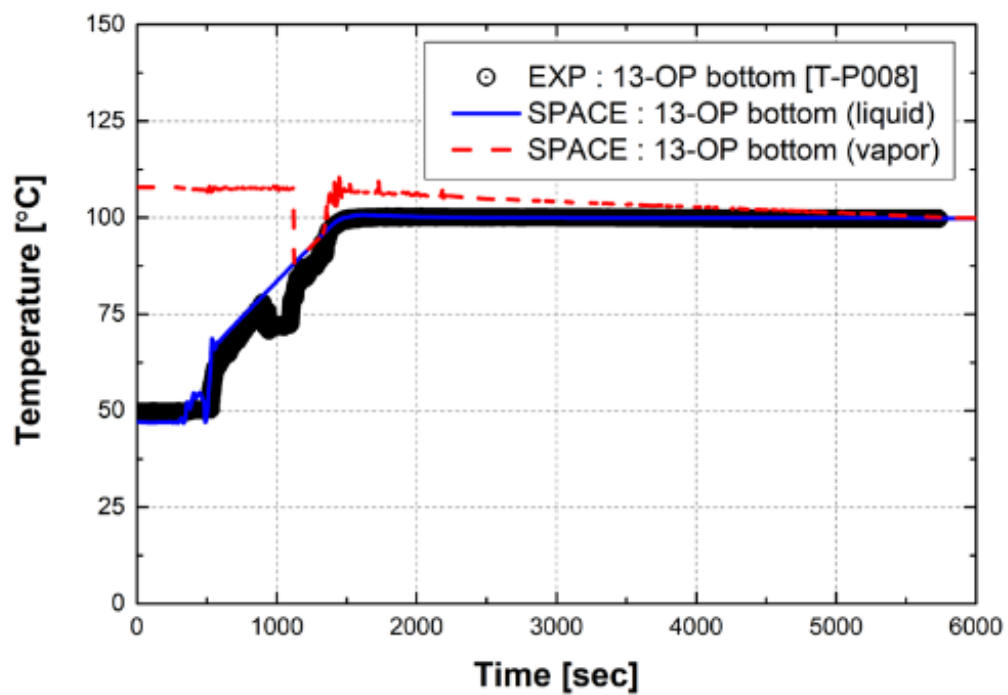


Figure 5.159. Part 2-SPACE Result: 14-Temperature OP (top)

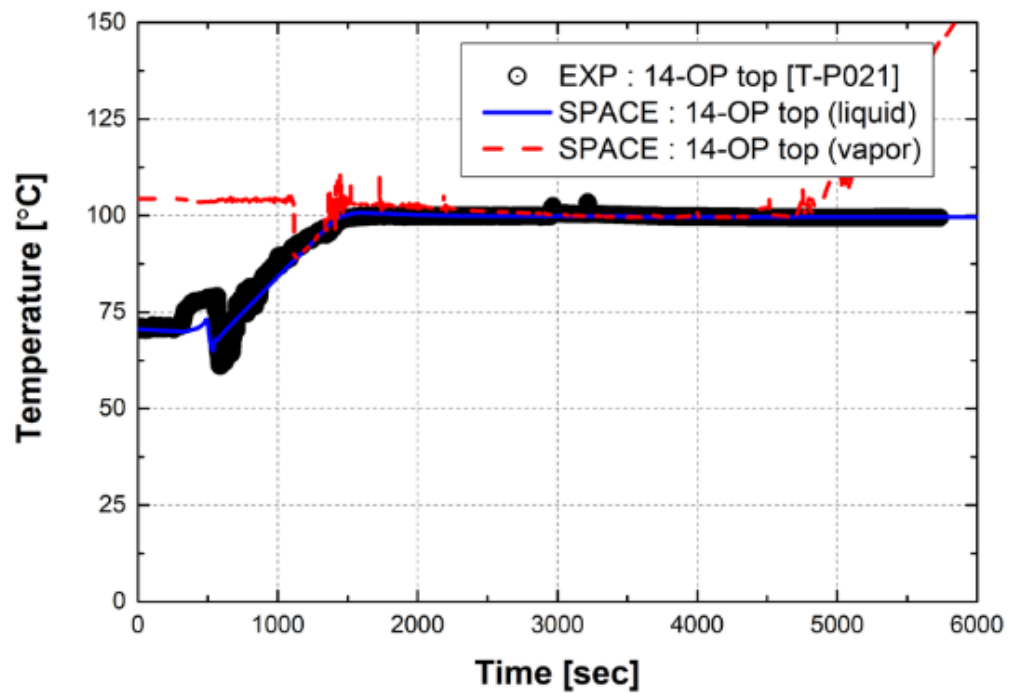


Figure 5.160. Part 2-SPACE Result: 15-Differential pressure HX upper-lower header

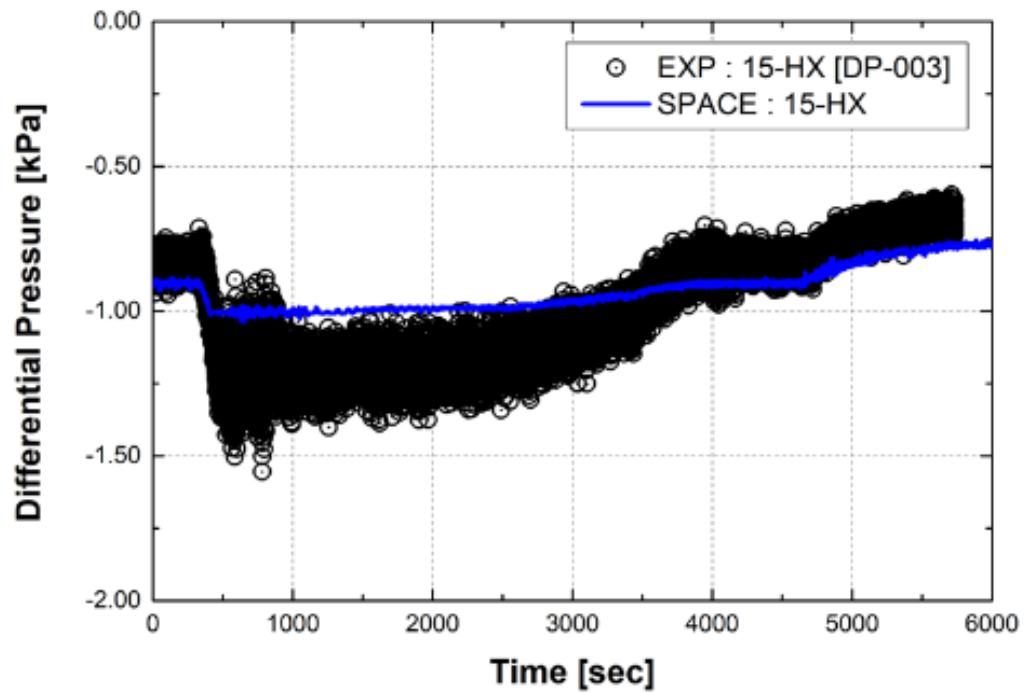


Figure 5.161. Part 2-SPACE Result: 16-Differential pressure steam duct injector

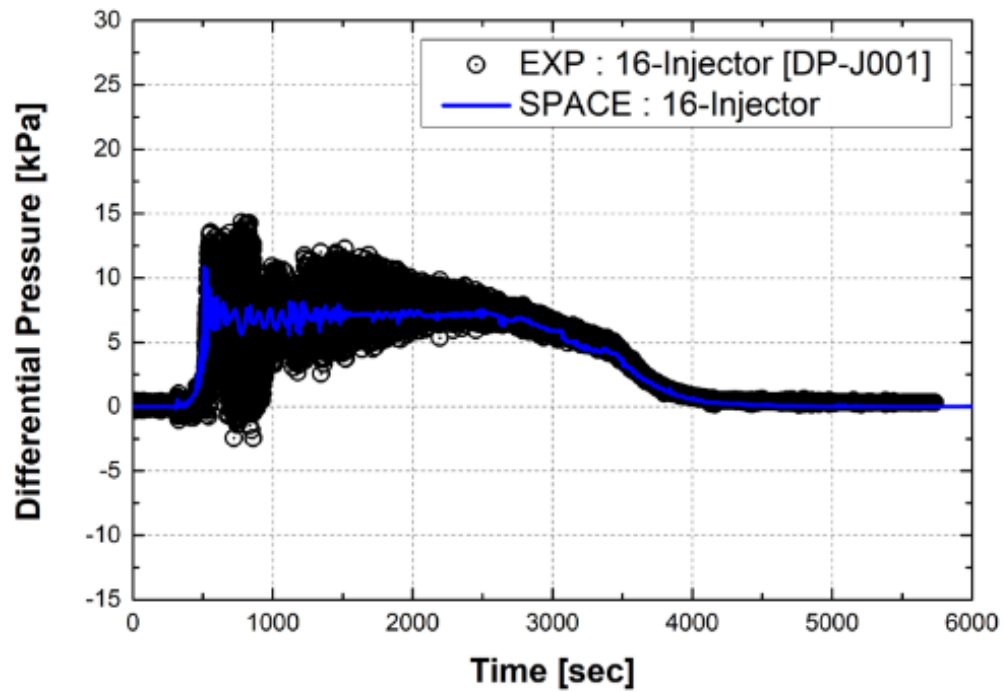


Figure 5.162. Part 2-SPACE Result: 17-Wall temperature HX upper header

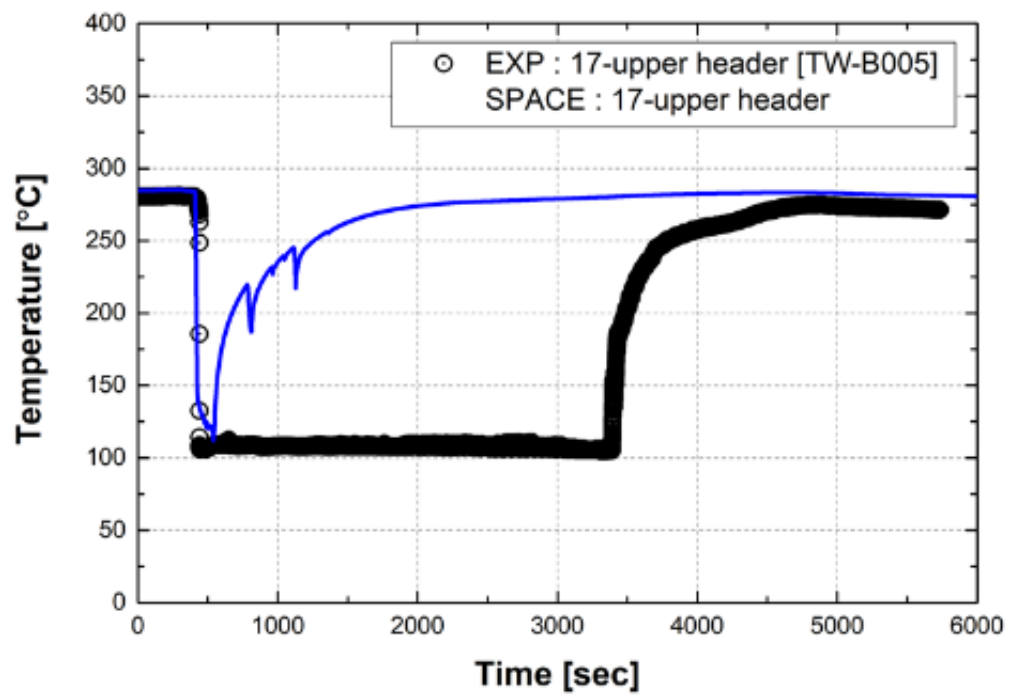


Figure 5.163. Part 2-SPACE Result: 18-Wall temperature HX lower header

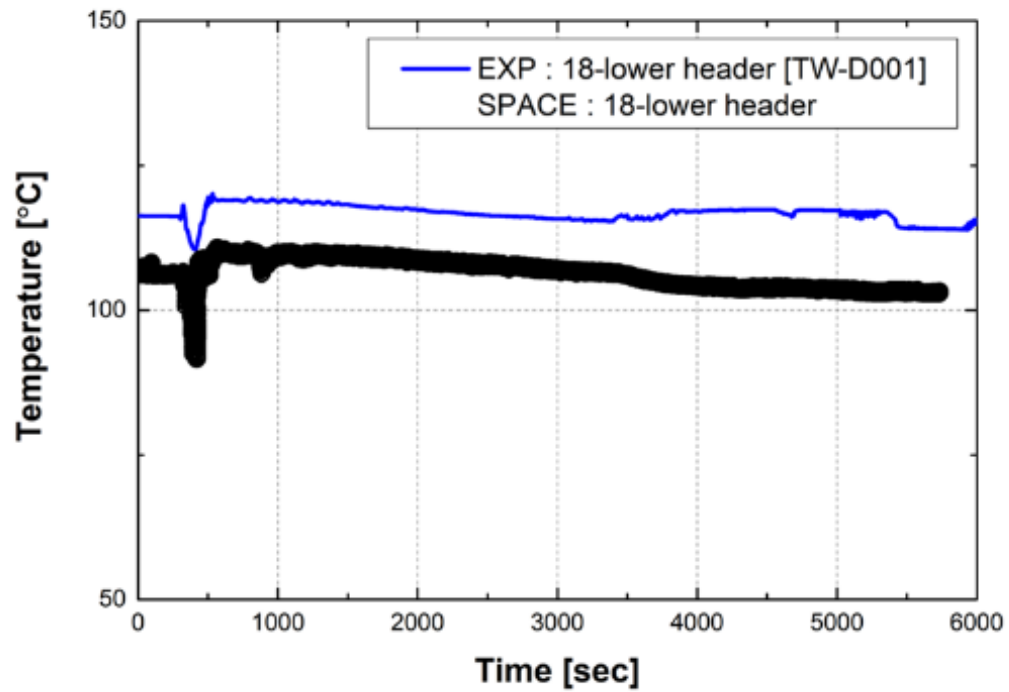
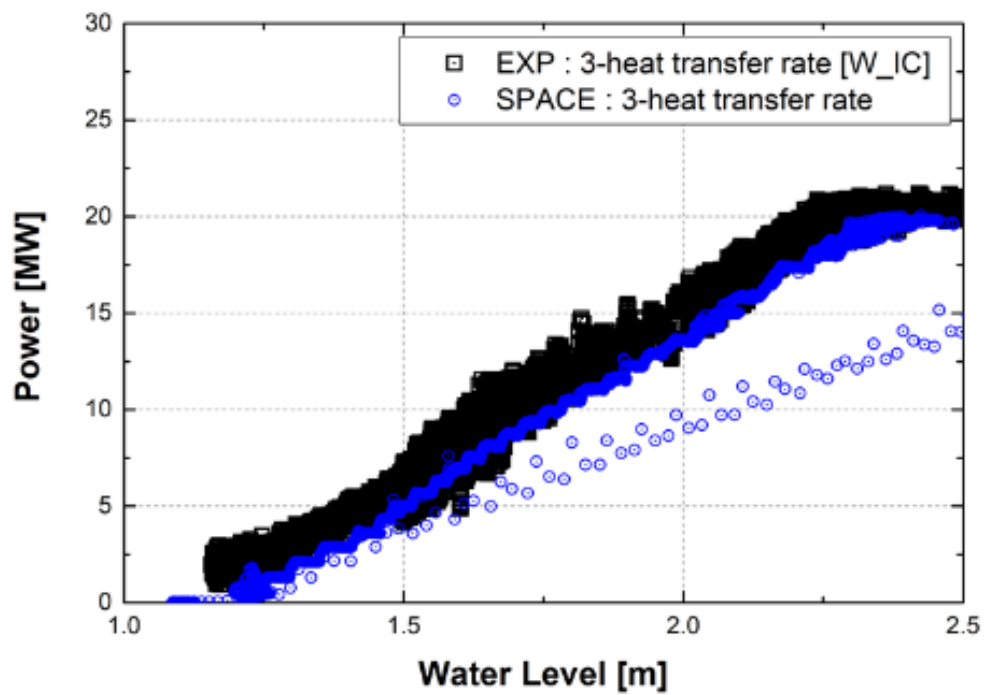


Figure 5.164. Part 2-SPACE Result: Relation between HX power and HXP water level (1 000 sec – 5 736 sec)



Time step control:

- Mass error controls the time step.
- Hydrodynamic time step same as heat conduction time step.

Computation Time: approximately 15 hr.

Table 5.25. Main relevant thermal-hydraulic aspects related to Test 7 Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	326 (opened in 26 sec)	-
Maximum level in the HXP	416	~ 2.6 m
Maximum exchanged power	400 – 2 200	~ 19.8 MW
OP discharge valve F031 opening	1 150	-
Triggering valve F045 closure	3 338 (closed in 123 sec)	-
HX pool level decreasing and loss of mass from the boil-off	2 000-5 735	-
Primary side depressurisation beginning for end of test	-	-

The marks adopted in Table 5.25 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.26. PERSEO Test 7 Part 2 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.		Measurement		Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	o
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	o
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
				Diff. pressure HX upper-lower header	DP-003	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure steam duct injector	DP-J001	o
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Power heat exchanger	W IC (der.)	o
				Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (top)	T-Q031	o
				Power heat exchanger	W IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature OP (top)	T-P021	o
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Power heat exchanger	W IC (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Relative pressure HXP top	P-Q001	o
				Level OP	L VP (der.)	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	o
				Wall temperature HX lower header	TW-D001	

SECTION 5: CONCLUSIONS

PART-2 results show reasonable prediction.

The nucleate boiling and condensation heat transfer models underestimate performance of this kind of heat exchanger.

The nodalisation effect can be influential for the pool modelling.

The user effect can exist, especially when setting the initial conditions.

One of the most important parameters was form loss in the HXP and injector. Based on the sensitivity tests, reasonable values for the form loss coefficients were selected.

REFERENCES

[5.2.4 1] SPACE 3.0 manual vol.I Theory Manual, TR-KHNP-0032

5.2.5. NRG

SECTION 1: GENERAL INFORMATION

- Institution: NRG (Netherlands)
- Contact: Dr Fabio Alcaro, Dr Marek Stempniewicz
- Code: SPECTRA v3.61
- Computing environment:
 - OS: Red Hat Enterprise Linux Server release 6.10 (Santiago)
 - RAM: 64 GB
 - CPU: 2 NUMA nodes with 2 Intel Xeon CPUs E5-2670 v3 @ 2.30GHz

SECTION 2: DESCRIPTION OF THE CODE USED

- **General description.** SPECTRA is a thermal-hydraulic system code developed at NRG. SPECTRA is designed for thermal-hydraulic analyses of nuclear power plants. The code main applicability is the area of light water reactors, high temperature reactors, liquid metal fast reactors, molten salt reactors, as well as conventional plants and chemical reactors. The code can be used for analysing accident scenarios, including loss-of-coolant accidents (LOCAs), operational transients, and other accident scenarios in nuclear power plants. The code structure is based on packages, which contain models on a given topic.
- **Details about the code.** The modelling concepts are similar to those used for example in RELAP5 or MELCOR. Two options are available:
 - Homogeneous control volumes (RELAP-type). Each control volume is assumed to be a mixture of gas and liquid phase. Mass, energy and momentum conservation equations are solved assuming non-equilibrium between phases.
 - Heterogeneous control volumes (MELCOR-type). Each control volume is assumed to consist of a pool (liquid) and atmosphere (gas) phase. Bubbles may exist in the pool and droplets may exist in the atmosphere. Transport of the continuous components (pool, atmosphere) is modelled using the momentum equation. Dispersed components (bubbles, droplets) are transported using the drift-flux model. Mass and energy conservation equations are solved assuming non-equilibrium between the four components.

The gas phase may consist of steam and an arbitrary number of non-condensable gases. Six gases are built in (H₂, He, steam, N₂, O₂, CO₂). An arbitrary number of user-defined gases may be added. The liquid phase consists of a single liquid. Built-in properties for water exist. The user may define an alternative liquid (e.g. liquid metal, molten salt, etc.) as coolant.

Pressure drops are calculated using single-phase friction models and two-phase multipliers. Friction factors are calculated for rough wall correlations (Colebrook-White or Prandtl-Nikuradse model) with the user-defined wall roughness and local loss factors for forwards and reverse flow defined by the user. The two-phase multipliers are applied for wall friction (Hancox-Nicoll or Levy model) as well as local loss factors (Griffith-Rohsenow model). Note that the latter is seldom used in the codes (e.g. in RELAP).

Heat conduction is calculated by the 1-D and 2-D solid heat conductors, using a general transient heat conduction equation. The heat transfer at the boundaries of the solid heat conductors is obtained from the heat and mass transfer package, which provides models for natural and forced convection, condensation with and without non-condensable gases, nucleate boiling (Chen or Rohsenow model), critical heat flux, transition boiling, Leidenfrost transition, film boiling, heat transfer in two-phase flow, as well as non-equilibrium boiling and condensation (“flashing” and “fogging”). Other important models include:

- Thermal radiation (grey enclosure);
- Point reactor kinetics, including standard reactivity feedbacks, as well as isotope concentrations (Xe poisoning, etc.);
- Radioactivity transport, release of fission products, aerosol transport, deposition, and resuspension.

Control systems - general-purpose tabular and control functions can be applied to model reactor control system, safety systems, provide boundary conditions, etc.

A fully implicit numerical scheme is used, which involves all packages (similar as in MELCOR). Compared to MELCOR, also the control function may be included in the implicit solution scheme, if the user so wishes.

Models relevant for PERSEO conditions:

- Pool side heat transfer;
- Tube side condensation; (a drawback of the condensation model is lack of the condensate film tracking - this model should be implemented in the future);
- Pressure drop in 1-phase and 2-phase flow.

SECTION 3: DESCRIPTION OF THE NODALISATION

- The rationale behind the construction of the computational model was to limit the complexity to the maximum possible extent. For this reason, the vessel model is simplified. The HX is modelled as a single tube of 18 uniform axial nodes (10 cm height) with multiplicity of 120, connected to the headers on the top and bottom. A one-to-one axial correspondence is adopted for the control volumes inside the HX tubes, the tube heat structures and the volumes outside the tubes. Both the HX pool and the overall pool are modelled with a pseudo-2D mesh. The steam duct and the pools-connecting line are modelled as 1D pipes. No gravitational change is accounted for in the pools-connecting line. The overall pool is connected to the environment (fixed-conditions control volume) by a junction at the top, and to the drainage line by a valve at the bottom. During the Test 7–Part 2, a user-defined table is adopted to impose the drain flow rate. Additionally:
 - Perfect insulation is assumed for the HX pool, the overall pool, the steam duct and the pools-connecting line. The vessel is not modelled: only the steam and condensate lines are modelled as fixed-condition volumes where respectively inlet (steam temperature and flow rate) and outlet (pressure) boundary conditions are imposed.
 - A 1D nodalisation is adopted for the HX inner (high pressure) side, the steam duct and the pools-connecting line. The HX pool and the overall pool are modelled with a pseudo-2D mesh without sliced approach. In the HX pool, the

inner region surrounds the HX and is in contact with the headers and tubes walls. In the overall pool, the inner region represents the place where the steam from the HX pool is discharged. The horizontal area occupied by the inner region is ~30% of the total. In both pools the outer regions are in contact with the corresponding pool walls, though heat losses are not modelled.

- No multidimensional components are adopted.

Table 5.27. Summary of the main nodalisation characteristics of the PERSEO model

	Number of hydraulic volumes	Number of junctions	Number of heat structures	Overall Volume (m ³)
Vessel	NA	NA	NA	NA
Steam Line	1	1	0	NA
HX	20	19	38	1.826
Condensate line	1	1	0	NA
HXP	76	112	40	24.79
Steam duct	10	13	0	1.141
OP	58	85	31	173.1
Heat transfer area HX ⁷ (m ²)	40.23 (including headers), 34.47 (only tubes)			
HX heat structure axial nodes number	28 (including headers), 18 (only tubes)			
HX heat structure radial nodes number	Headers: uniform mesh with 6 cells, $\Delta x = 1.0$ cm Tubes: uniform mesh with 4 cells, $\Delta x = 0.575$ mm			

7. Calculated at the outer surface level.

Figure 5.165. Nodalisation scheme adopted for the HX (one tube with multiplicity of 120).

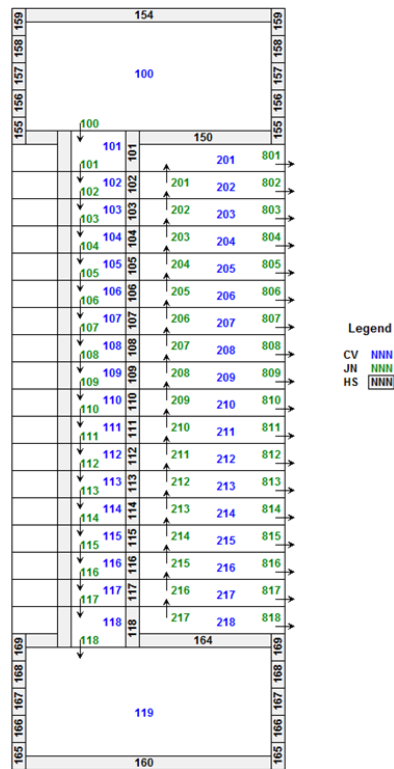


Figure 5.166. Nodalisation scheme adopted for the HX pool

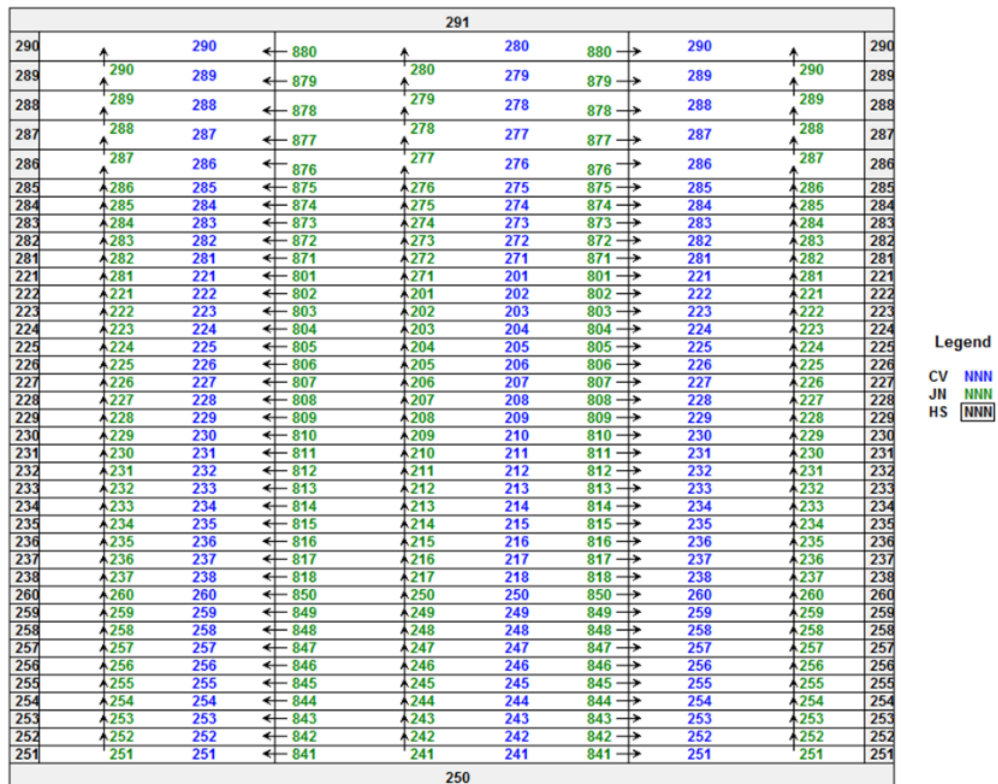


Figure 5.167. Nodalisation scheme adopted for the overall pool

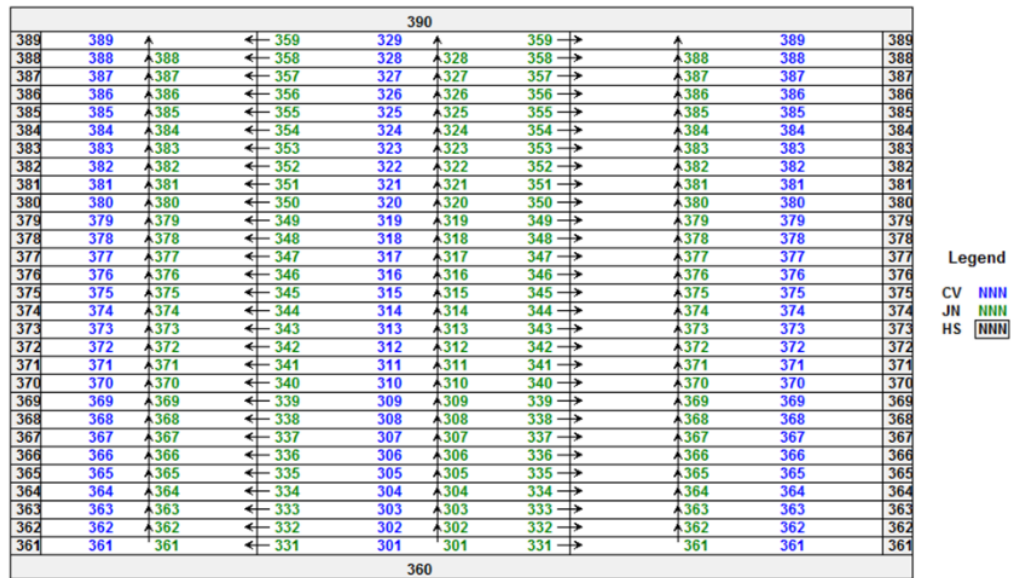
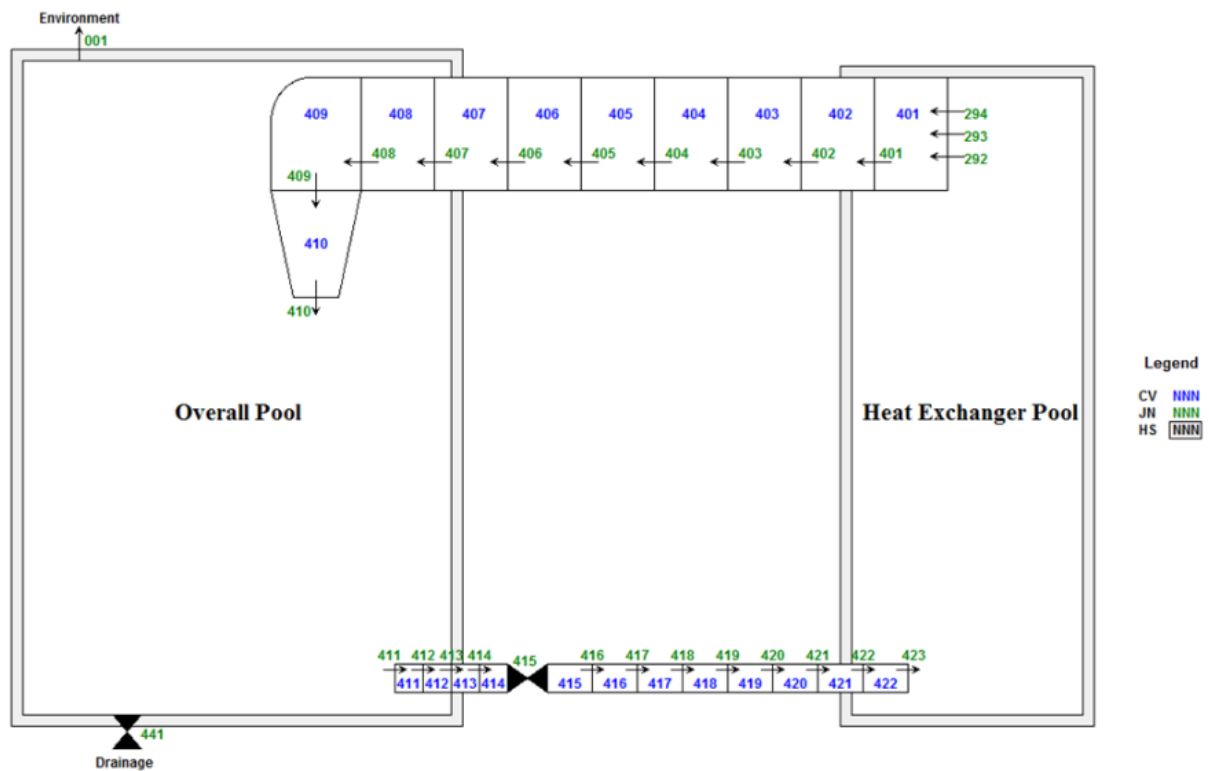


Figure 5.168. Nodalisation scheme adopted for the steam duct and pools-connecting line



SECTION 4: RESULTS

TEST 7 Part 1

- Initial conditions are set in the model by implementing the available measured data in the input deck in the most accurate way, given the nodalisation scheme adopted. Steam and water temperature distributions as well as structures wall temperature are initialised in the corresponding initial condition cards. Stable conditions are observed about ten seconds from the start of the simulation, after an initial short phase of pressure equilibration in the pools. The start of the SPECTRA simulation occurs at 10 400 s in order to reduce the duration of the whole transient.
- The results obtained with the SPECTRA model are qualitatively in agreement with the experimental data. Some discrepancies occurring at specific stages of the transient can be observed. During the first phenomenological window, the HX pool level increase profile is in perfect agreement with data, along with the OP level decrease, the HX power and the corresponding condensate flow rate. No relevant instabilities due to strong condensation of steam in the OP are observed macroscopically, but rather at a computational level (time step size reduction). During the second phenomenological window the HXP level progression differs from data as soon as the maximum value is reached, which is at the level of the lower surface of the upper header and is some 35 cm lower than the experiment (Figure 5.175). Consequently, the minimum value of the OP level is higher (Figure 5.176). This is explained by the occurrence of HXP pressurisation in the SPECTRA simulation (Figure 5.180) between 11 250 s and 11 750 s. This phenomenon is probably due to the lack of HXP water mixing and therefore the slight depressurisation observed in the experiment, likely caused by steam condensation on the water surface front, is not experienced in the SPECTRA simulation. In this stage the quasi-steady operation of the HX has a short extent and the HXP boil-off is significant. The maximum HX power observed is about 19 MW. During the third phenomenological window the qualitative behaviour of the SPECTRA simulation is in agreement with the data, although the main thermal-hydraulic phenomena occurs slightly ahead of time compared to the data (consequently of the what discussed in the second Ph. window). The HX power rate is slightly lower in the SPECTRA simulation, and so is the HXP level decrease rate (conversely for what concerns the OP level). The HX power reduction exhibits the typical stepwise change due to the HX tube nodalisation scheme (Figure 5.171). The thermal stratification in the OP is visible only in few nodes below the steam injector junction (Figure 5.182). The bottom part results unaltered (Figure 5.181). In summary:
 - Results from the SPECTRA simulation of the transient qualitatively reproduce the experimental data.
 - It is observed that the SPECTRA model generally underestimates the HX power, though by a small extent. One possible explanation is that SPECTRA has no active level tracking capability, therefore the film condensation phenomenon inside the HX tubes is not modelled with the highest accuracy. The heat transfer coefficient on the tube condensing side, which is the limiting phenomenon that drives the heat transfer when the HX is operating, is determined by the supply of a characteristic dimension for film condensation in the input deck. A possible improvement can be the tuning of such characteristic dimension to better match the HX power. A different nodalisation for the HX pool might be considered investigating with the aim of improving water mixing during the stages when the triggering valve is open.

This might likely improve the behaviour of the model during the second phenomenological window stage of the transient.

- The effect of the pool wall heat losses might need be investigated, especially in connection to the HXP depressurisation during the second phenomenological window.
- The time step size was Courant-limited during the whole transient. The occurrence of sudden steam condensation in pool and high rate of boiling had the effect of frequently reducing the time step size. The total computation time was $7.89\text{E}+05$ seconds (about 219 hours).
- The SPECTRA model calculates the HXP and OP temperatures (i.e. T-Q037, T-Q034, T-Q031, T-P008 and T-P021) in the following way: if the corresponding hydraulic has a void fraction smaller than 95%, the pool temperature is considered otherwise the steam temperature is recorded. The sudden jumps observed for instance in Figure 5.178 and Figure 5.179 are caused by the change of the parameter recorded (from pool to steam temperature).

In the following, all the selected parameters for the benchmark are plotted comparing the SPECTRA computed values with experimental data. The mass flow rate in the triggering valve (F_POOL) is also provided in Figure 5.187 and Figure 5.188.

Figure 5.169. Test 7 – Part 1, profile of the mass flow rate of steam in the vessel supply line

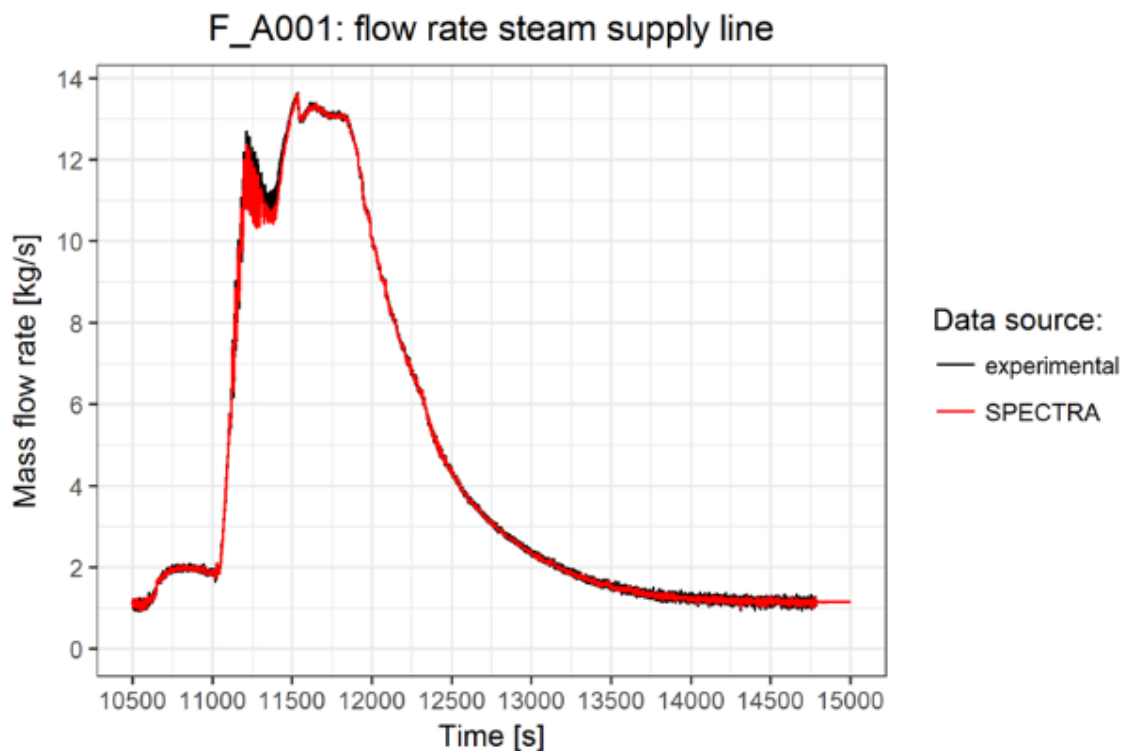


Figure 5.170. Test 7 – Part 1, profile of the mass flow rate of water in the vessel condensate line

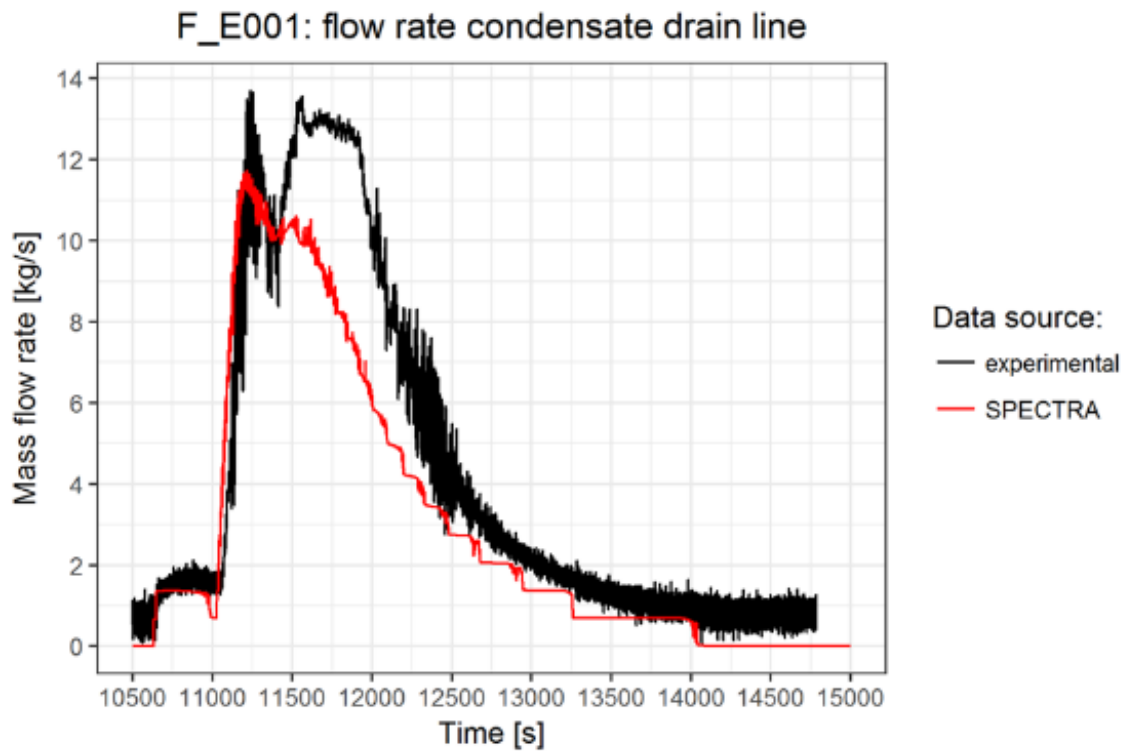


Figure 5.171. Test 7 – Part 1, profile of the HX power

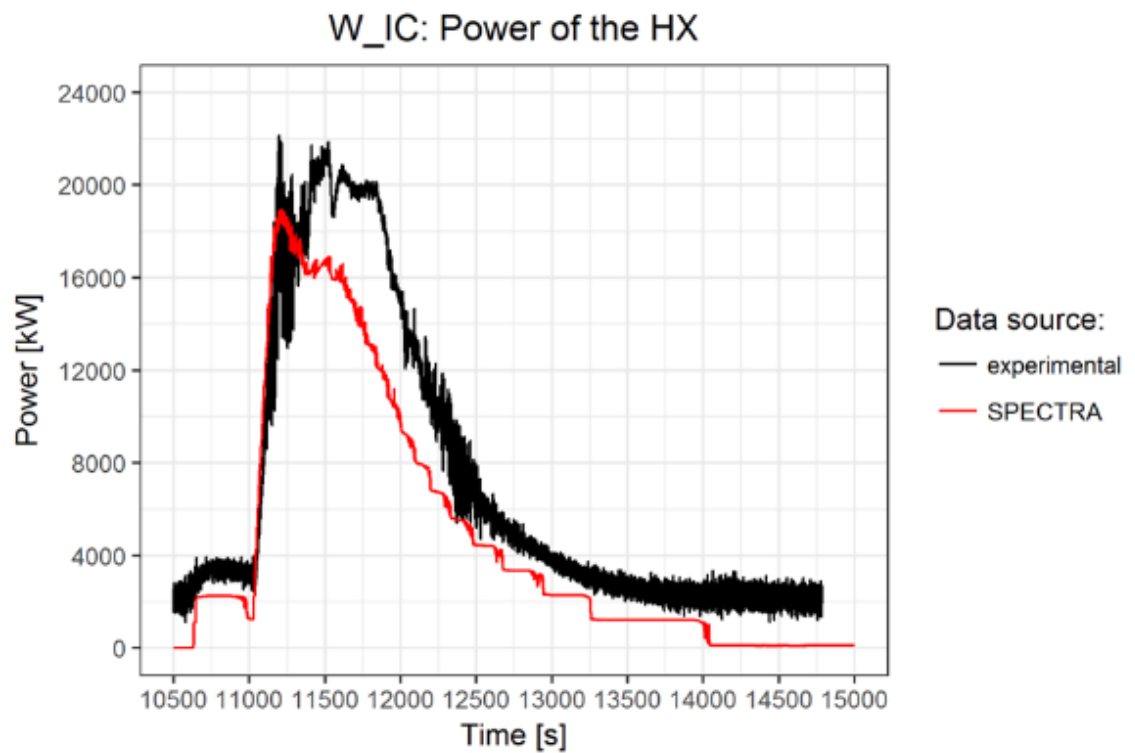


Figure 5.172. Test 7 – Part 1, profile of the absolute pressure in the vessel

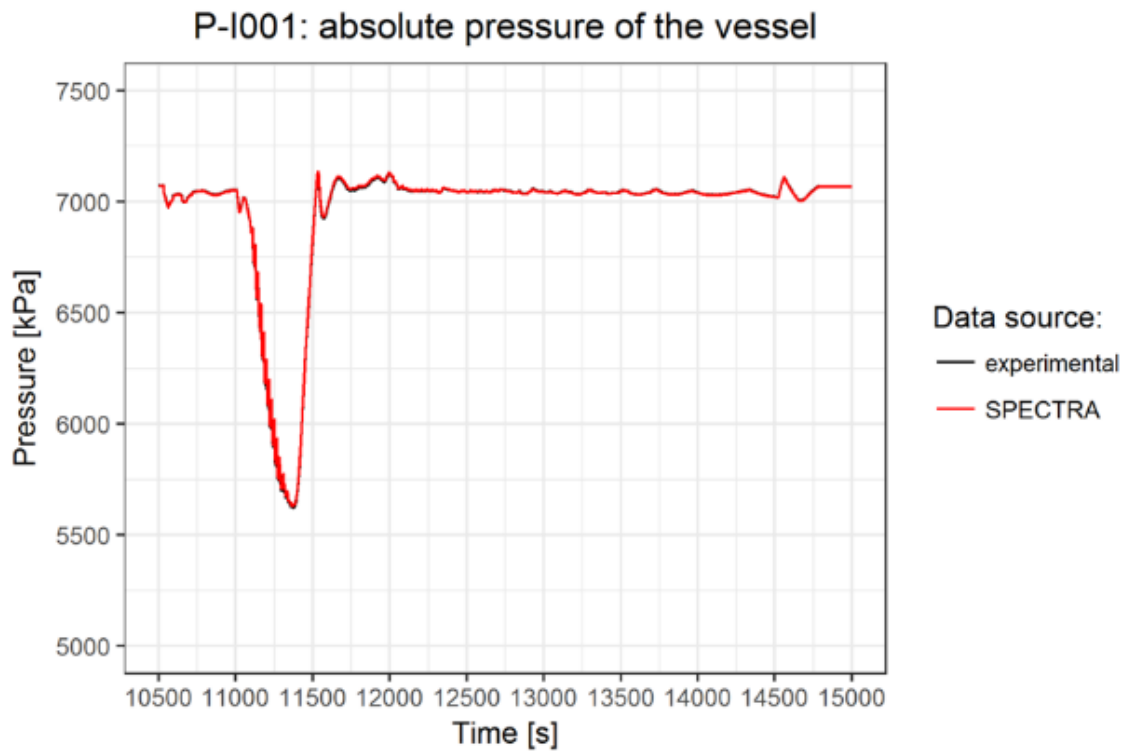


Figure 5.173. Test 7 – Part 1, profile of the steam inlet temperature in the HX

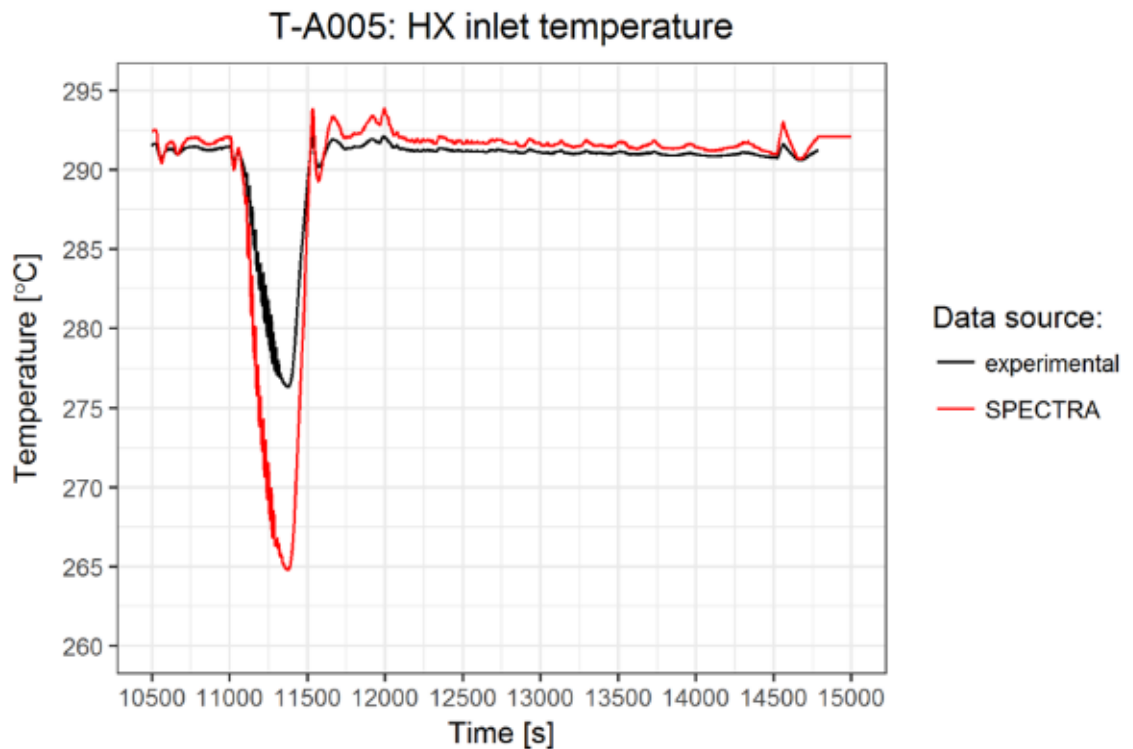


Figure 5.174. Test 7 – Part 1, profile of the steam outlet temperature in the HX

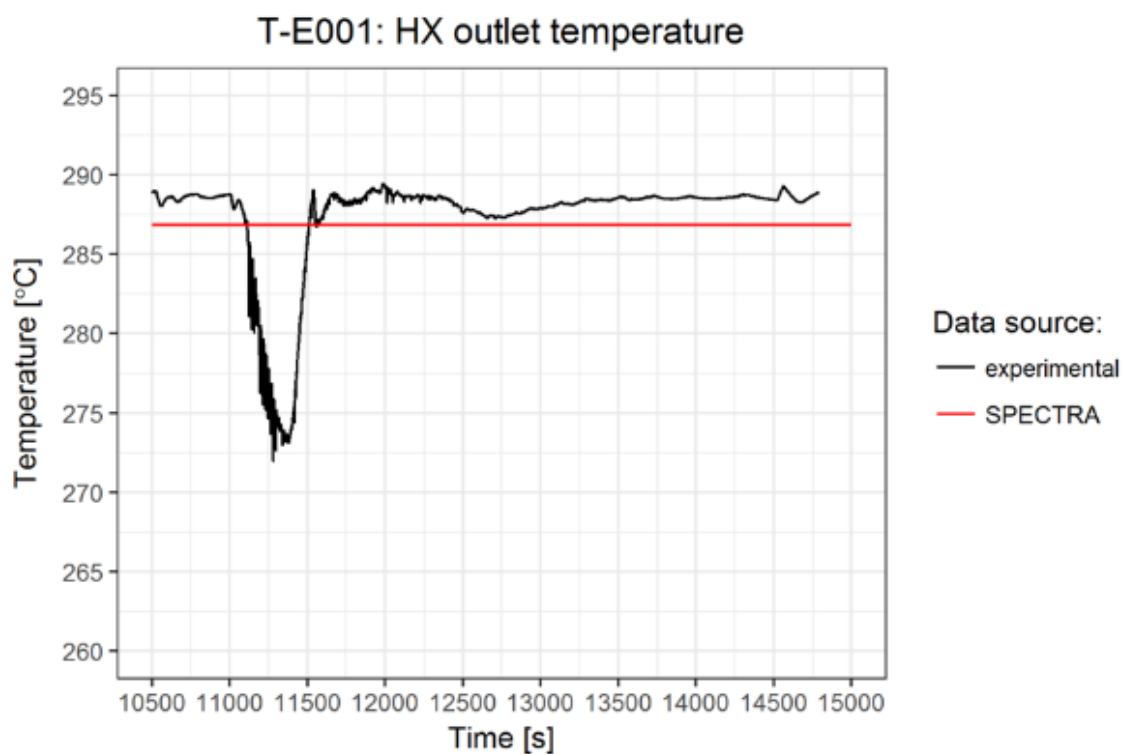


Figure 5.175. Test 7 – Part 1, profile of the HX pool level

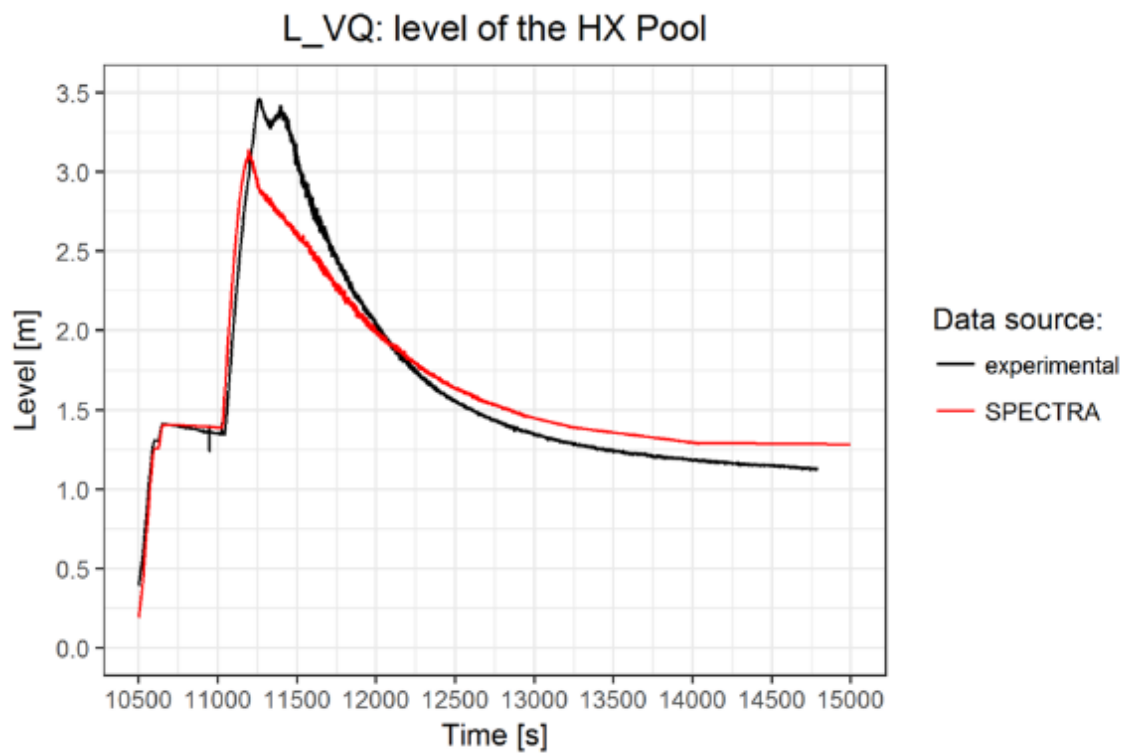


Figure 5.176. Test 7 – Part 1, profile of the overall pool level

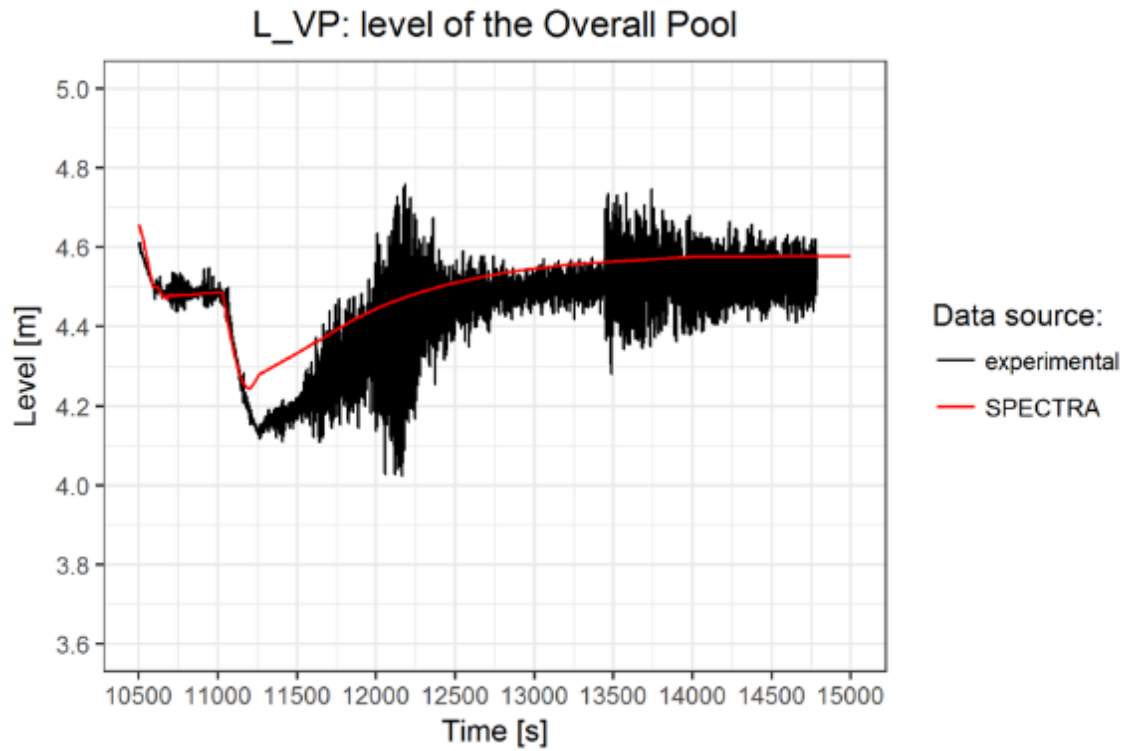


Figure 5.177. Test 7 – Part 1, profile of the HX pool temperature (0.485 m from the HX pool floor)

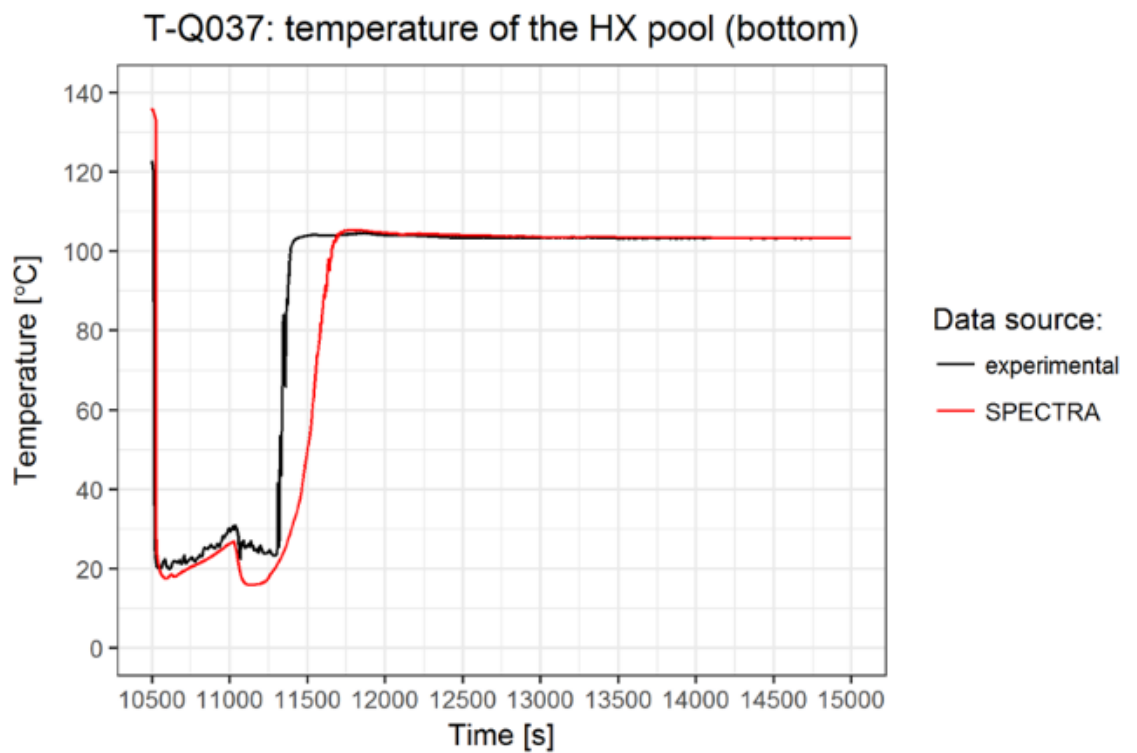


Figure 5.178. Test 7 – Part 1, profile of the HX pool temperature
(2.535 m from the HX pool floor)

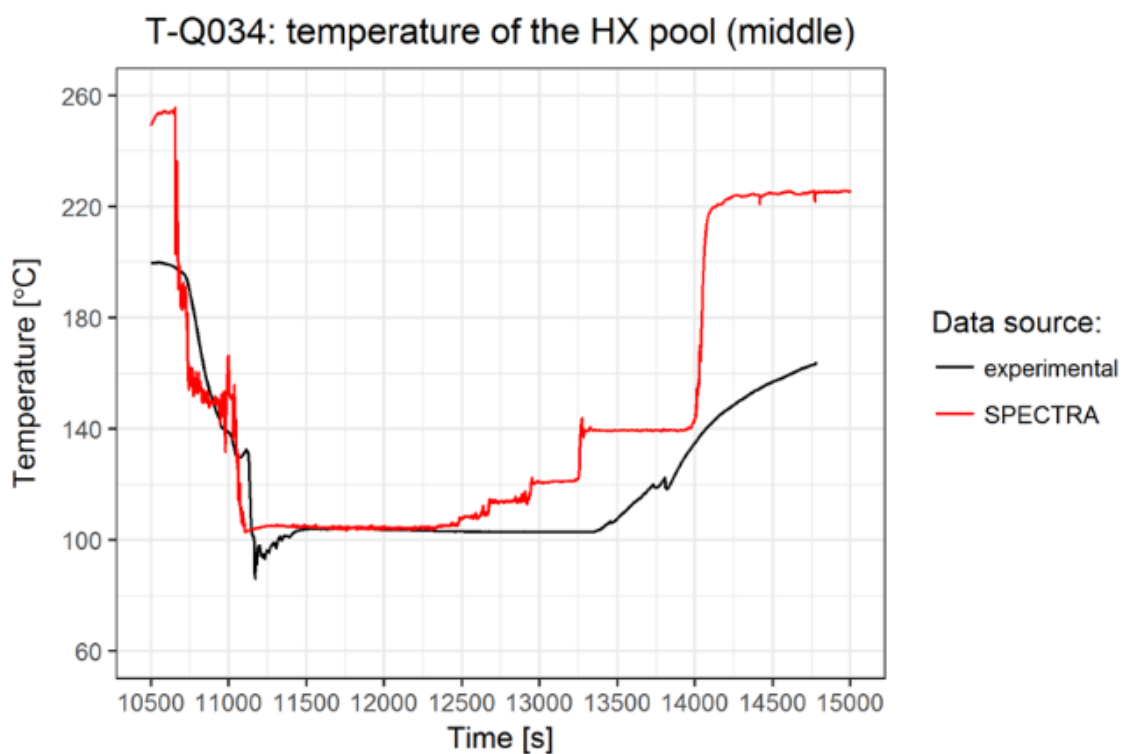


Figure 5.179. Test 7 – Part 1, profile of the HX pool temperature
(3.860 m from the HX pool floor).

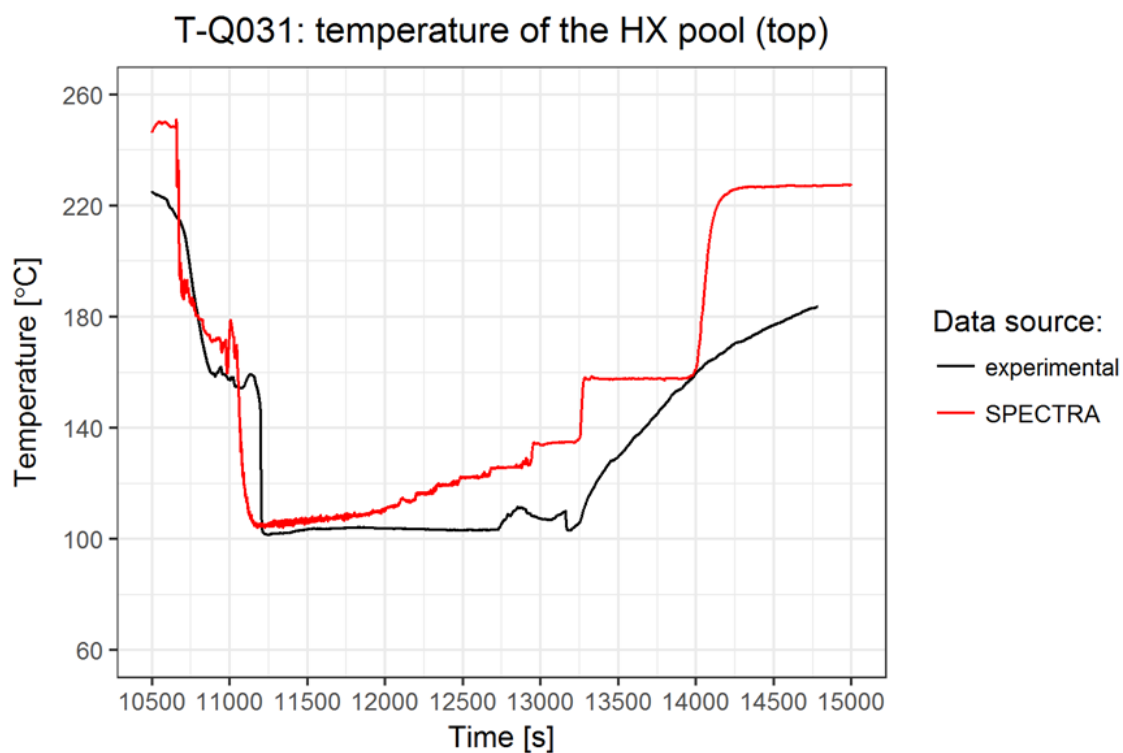


Figure 5.180. Test 7 – Part 1, profile of the HX pool relative pressure

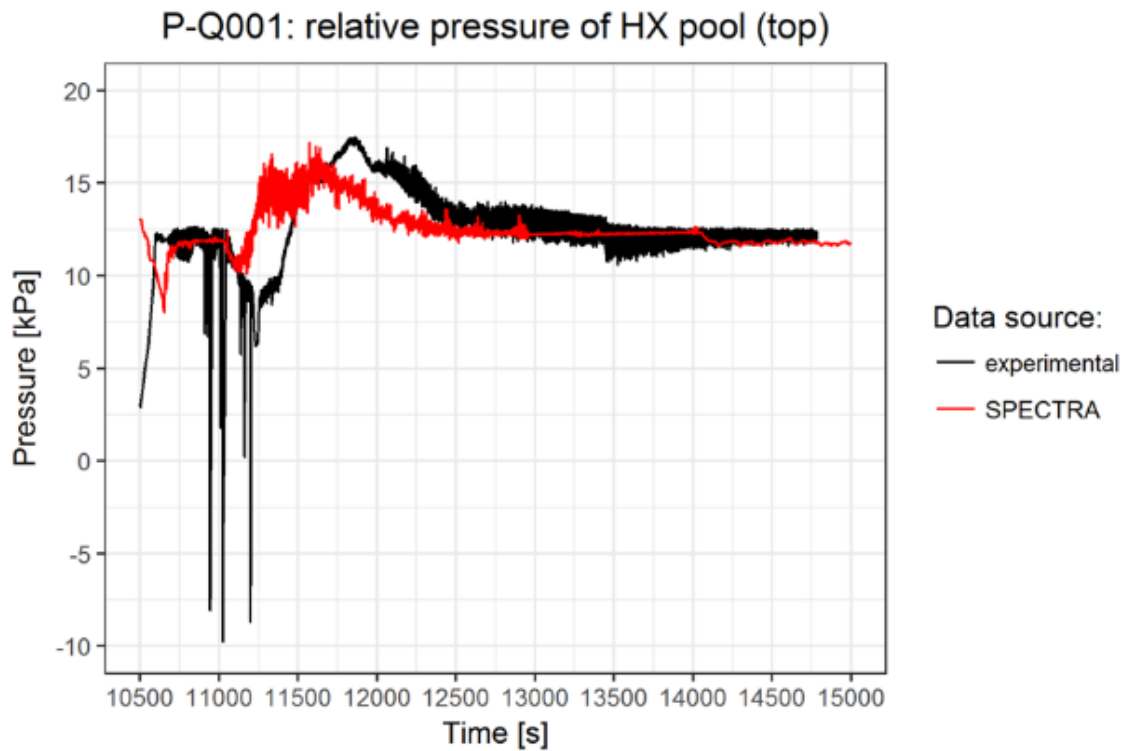


Figure 5.181. Test 7 – Part 1, profile of the overall pool temperature (1.195 m from the OP floor)

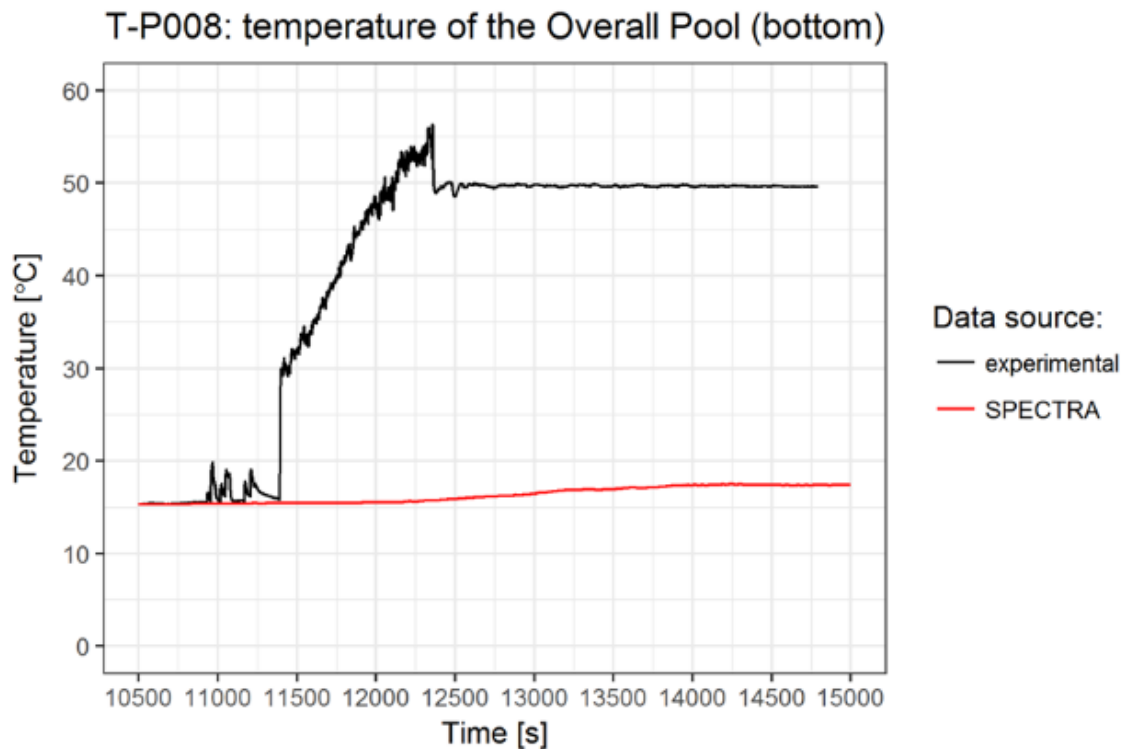


Figure 5.182. Test 7 – Part 1, profile of the overall pool temperature (2.695 m from the OP floor)

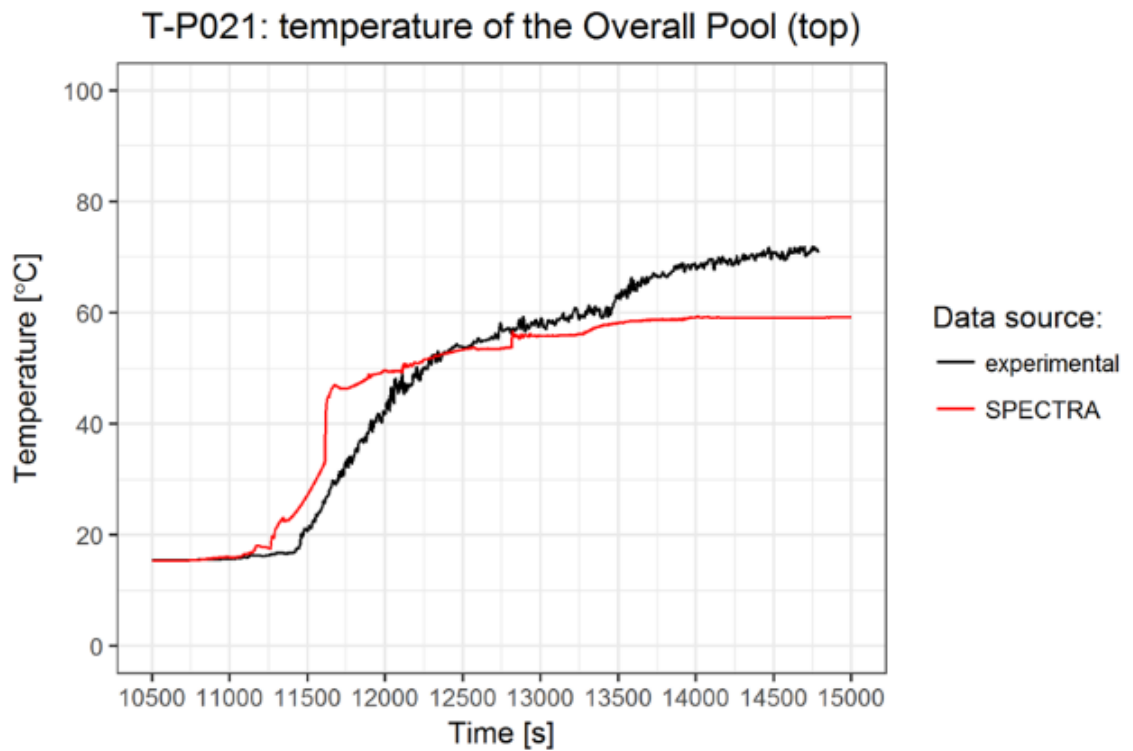


Figure 5.183. Test 7 – Part 1, profile of the differential pressure between the upper and lower HX headers

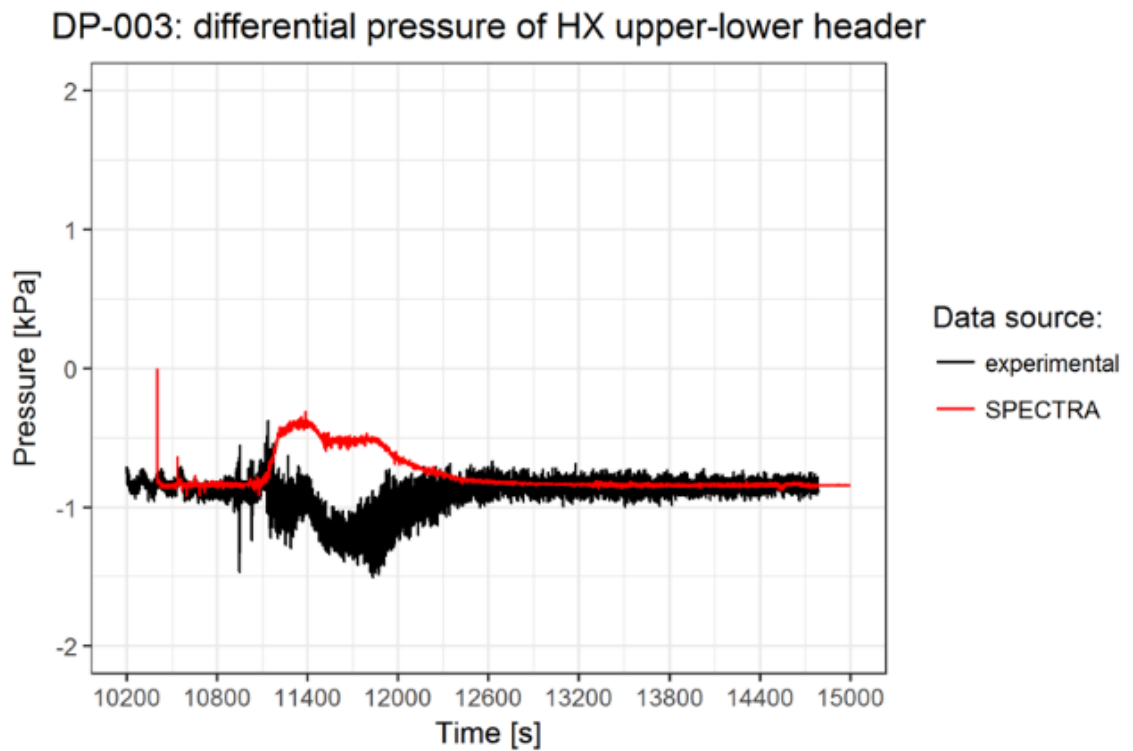


Figure 5.184. Test 7 – Part 1, profile of the differential pressure in the steam injector

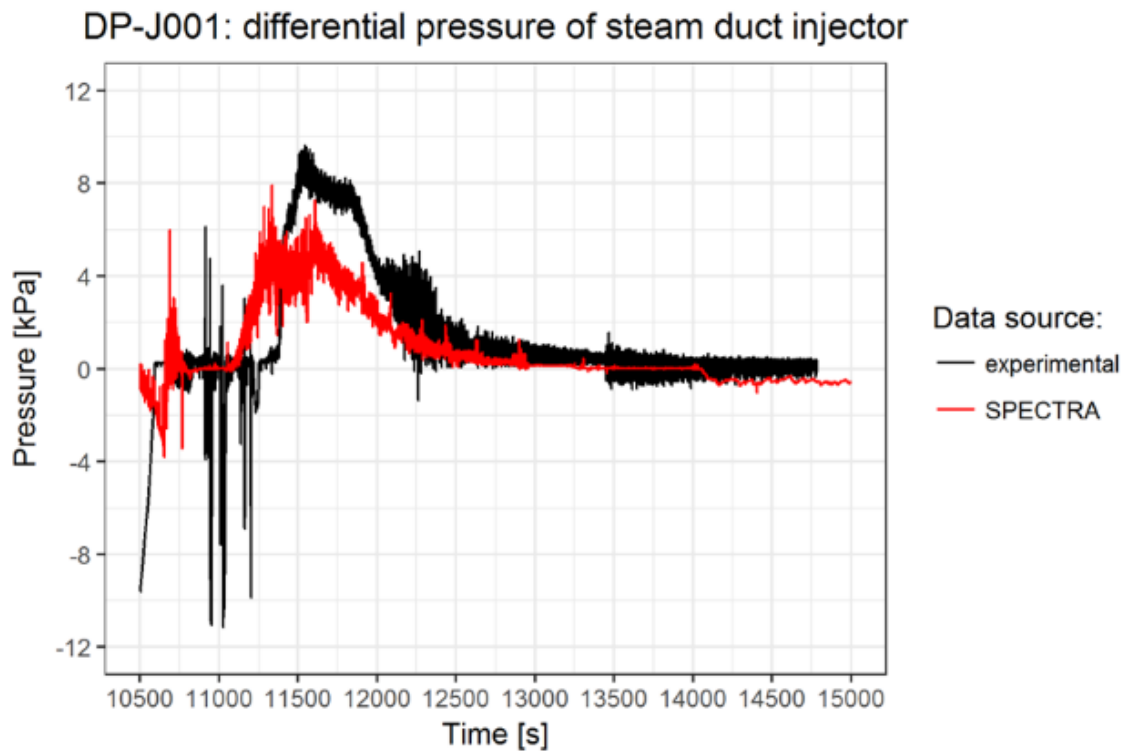


Figure 5.185. Test 7 – Part 1, profile of the wall temperature of the HX upper header (lower part)

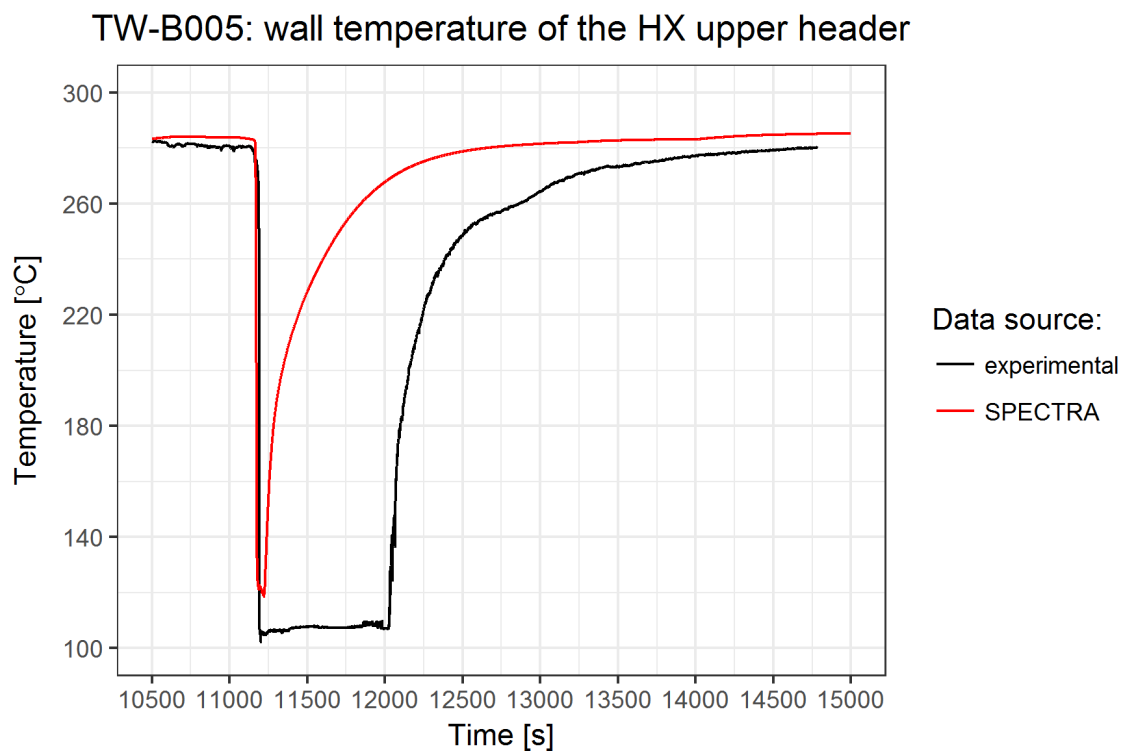


Figure 5.186. Test 7 – Part 1, profile of the wall temperature of the HX lower header (upper part)

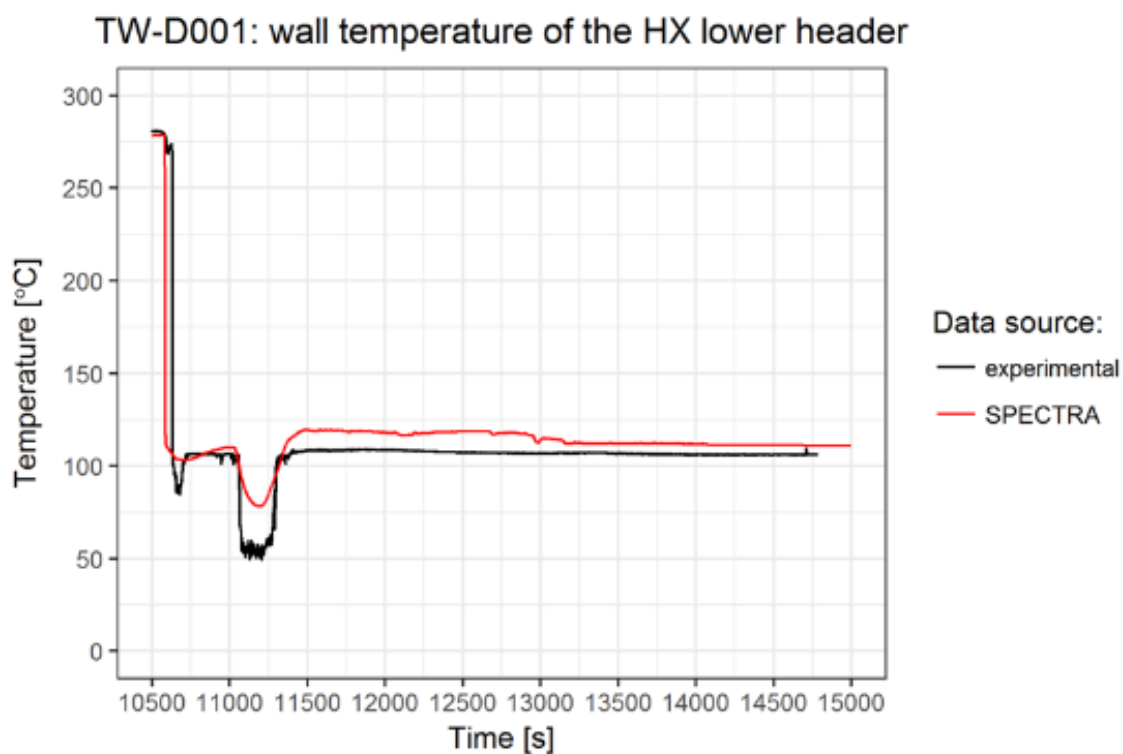


Figure 5.187. Test 7 – Part 1, profile of the mass flow rate in the pools-connecting line

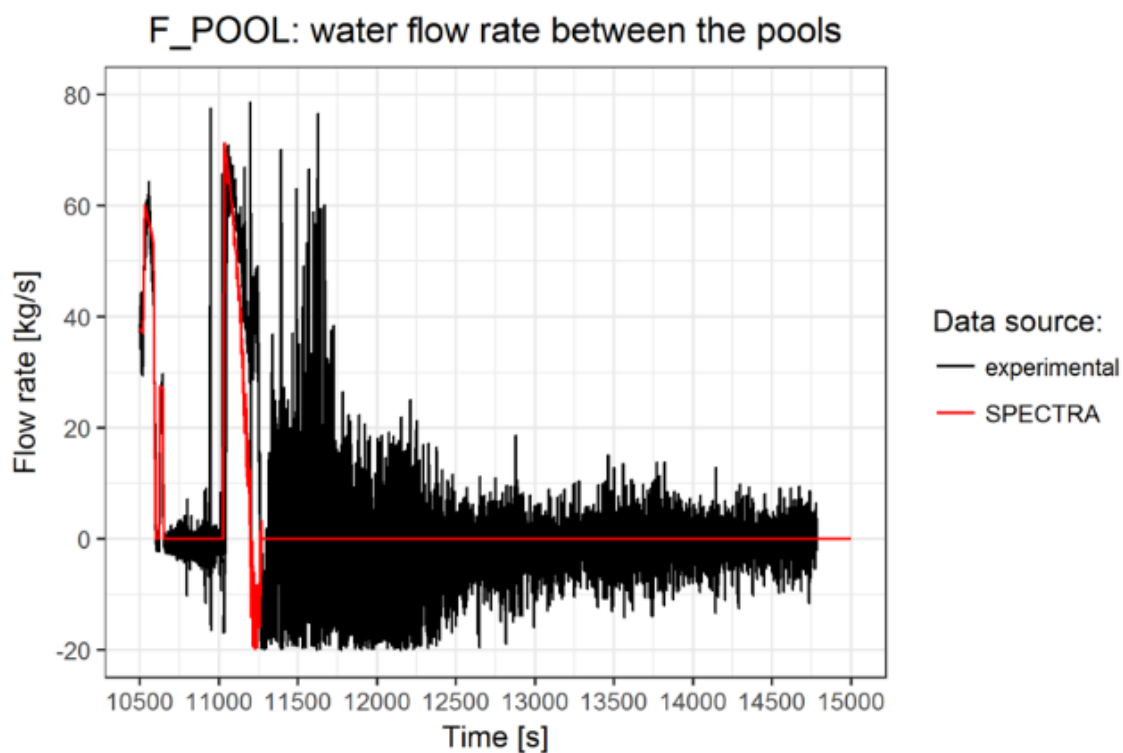


Figure 5.188. Test 7 – Part 1, profile of the mass flow rate in the pools-connecting line (during the first 1 000 seconds)

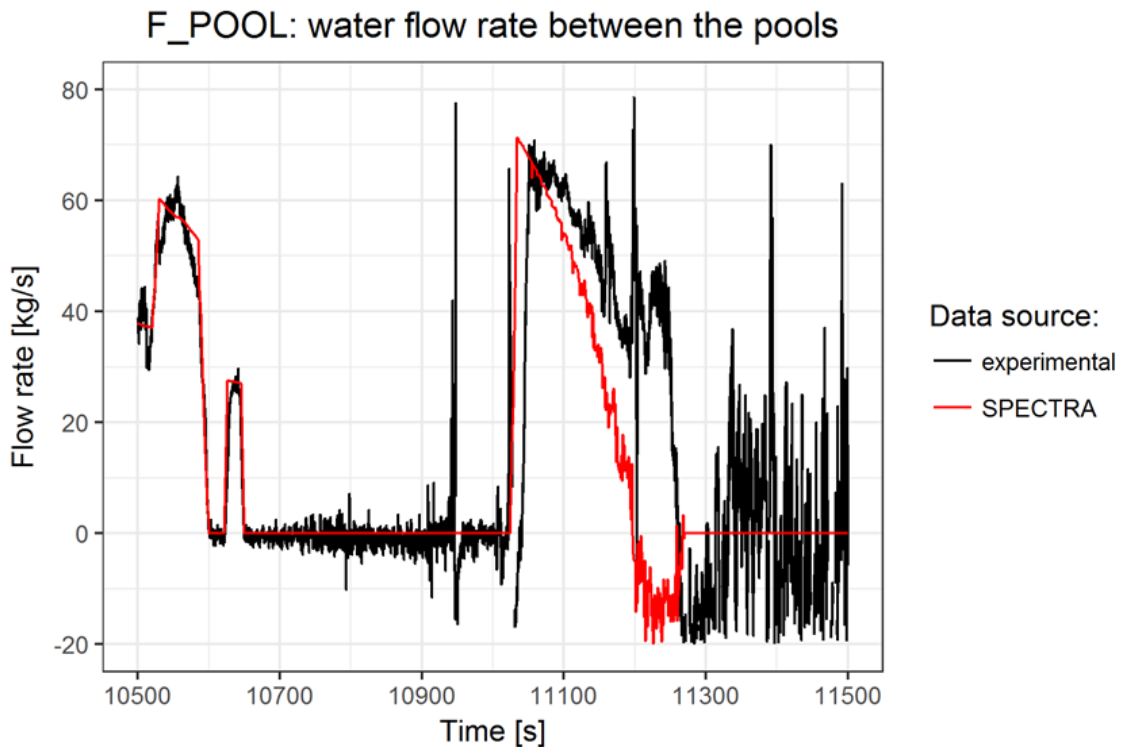


Table 5.28. Main relevant thermal-hydraulic aspects related to Test 7 Part 1

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	10 475 – 10 525 10 525 – 10 600	40% 60%
Triggering valve (F045) re-opening and re-closure	10 621 – 10 650	35%
Maximum level in the HX pool for the first filling step	10 650	1.41 m
Small heat removal from the primary side	10 650 – 10 980	2.2 MW
Slow water consumption in the HX pool	10 650 – 11 023	1.41 m – 1.39 m
Instabilities for steam condensation in the injector	NA	
Triggering valve (F045) opening and closure	11 024 – 11 034 11 034 – 11 270	0% – 80% 80% – 100%
Maximum level in the HX pool	11 193	3.14 m
Maximum exchanged power	11 214	19.0 MW
HX pool minimum level	14 784	1.28 m
OP average temperature	13 000	~ 56°C

The marks adopted in Table 5.28 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.29. PERSEO Test 7 Part 1 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.		Measurement		Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	-
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	o
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	o
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure HX upper-lower header	DP-003	o
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	HX inlet temperature	T-A005	o
				HX outlet temperature	T-E001	
				Power heat exchanger	W IC (der.)	
				Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (bottom)	T-Q037	NA
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Power heat exchanger	W IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature HXP (top)	T-Q031	o
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
				Level HXP	L VQ (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L VP (der.)	o
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

** Ph. = Phenomenon

Test 7 Part 2

- As for the case of the Part 1, initial conditions are set in the model by implementing the measured data available at the initial time in the input deck. Stable conditions are observed about ten seconds from the start of the simulation, after an initial short phase of pressure equilibration in the pools. The start of the SPECTRA simulation occurs at 190 s in order to reduce the duration of the whole transient.
- The results obtained with the SPECTRA model are qualitatively in agreement with the experimental data. The same types of discrepancy with the experimental data highlighted for the Part 1 are observed in this transient, too:

During the first phenomenological window, the HX pool level increase profile is in perfect agreement with data, along with the OP level decrease, the HX power and the corresponding condensate flow rate until $t = 450$ s. After that time, the steam production in the HXP is sufficiently high to pressurise the pool, preventing additional water to enter the HXP from the pools-connecting line.

During the second phenomenological window the boil-off phase is already ongoing. The maximum HXP level (observed in the previous stage at $t = 450$ s) is 2.75 m, which is some 50 cm lower than the experiment (Figure 5.195). For this reason the HX upper header is never flooded, thus the corresponding wall temperature remains approximatively the same throughout the whole transient (Figure 5.205). Instabilities in the OP are not observed (Figure 5.196). The quasi-steady operation stage of the HX is modelled sufficiently accurately, though the average value of the HX power and condensate flow rate is slightly lower (Figure 5.191 and figure 5.190 respectively) for the same considerations described for the transient of Part 1. The maximum HX power observed is about 18.7 MW. Since power removal is slightly smaller than in the experiment, the HXP level at the end of this stage is some 20 cm higher than the experimental data (Figure 5.195).

During the third phenomenological window the qualitative behaviour of the SPECTRA simulation is in reasonable agreement with the data. The rates of reduction of the HXP and OP levels, as well as the rates of reduction of the HX power and condensate mass flow calculated by the model are in perfect agreement with data (respectively Figure 5.195, Figure 5.196, Figure 5.191 and Figure 5.190). The OP drainage is modelled through a user-defined table of the mass flow rate through the drain valve F-031. A value of 16.2 kg/s is adopted when the valve is open. In summary:

- Results from the SPECTRA simulation of the transient qualitatively reproduce the experimental data.
- As for the transient of Part 1, it is observed that the SPECTRA model generally underestimates the HX power by a small extent also in the present case. The same considerations provided for the transient of Part 1 apply for Part 2, too.
- The effect of the pool wall heat losses might need be investigated, especially in connection to the HXP depressurisation during the second phenomenological window.
- The time step size was Courant-limited during the whole transient. The occurrence of sudden steam condensation in pool and high rate of boiling had the effect of frequently reducing the time step size. The total computation time was $8.01\text{E}+05$ seconds (about 222 hours).

In the following, all the selected parameters for the benchmark are plotted comparing the SPECTRA computed values with experimental data. The mass flow rate in the triggering valve (F_POOL) is also provided in Figure 5.207 and Figure 5.208.

Figure 5.189. Test 7 – Part 2, profile of the mass flow rate of steam in the vessel supply line

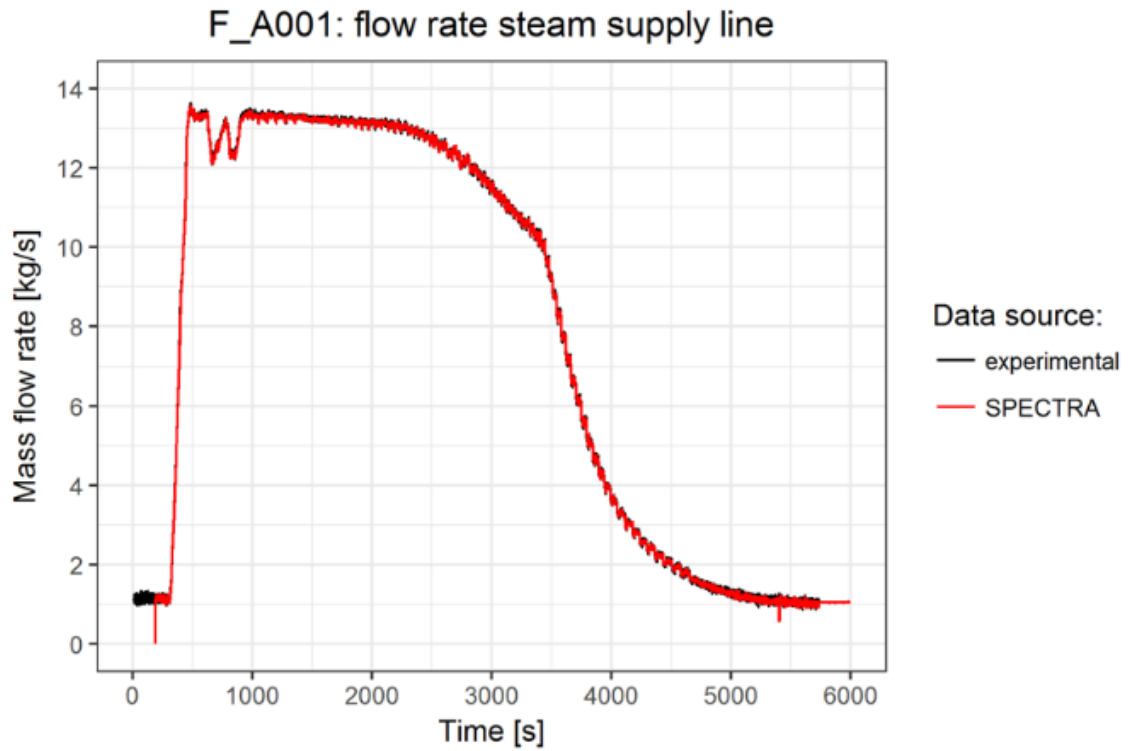


Figure 5.190. Test 7 – Part 2, profile of the mass flow rate of water in the vessel condensate line

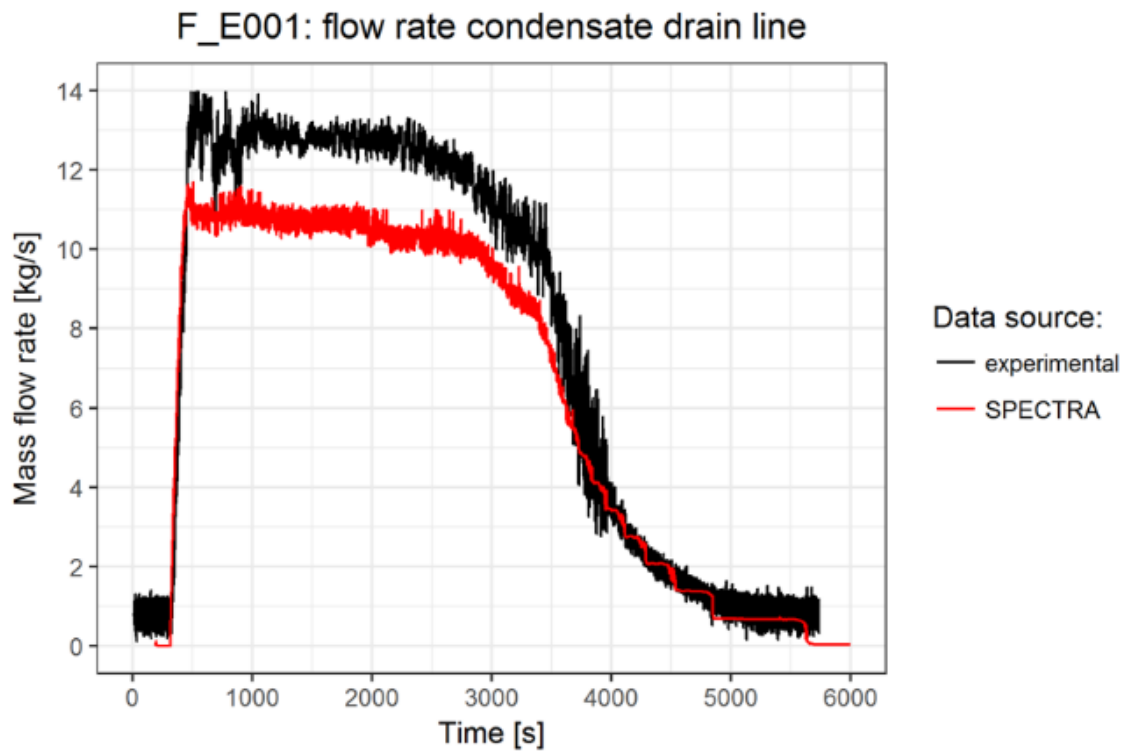


Figure 5.191. Test 7 – Part 2, profile of the HX power

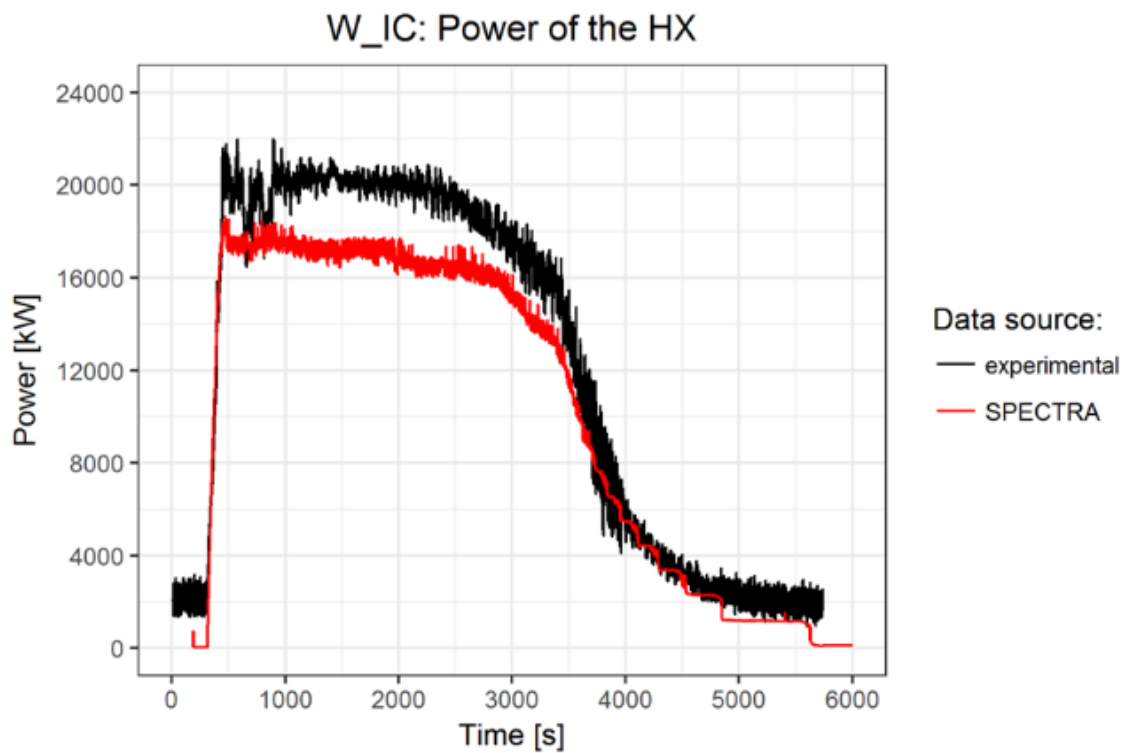


Figure 5.192. Test 7 – Part 2, profile of the absolute pressure in the vessel

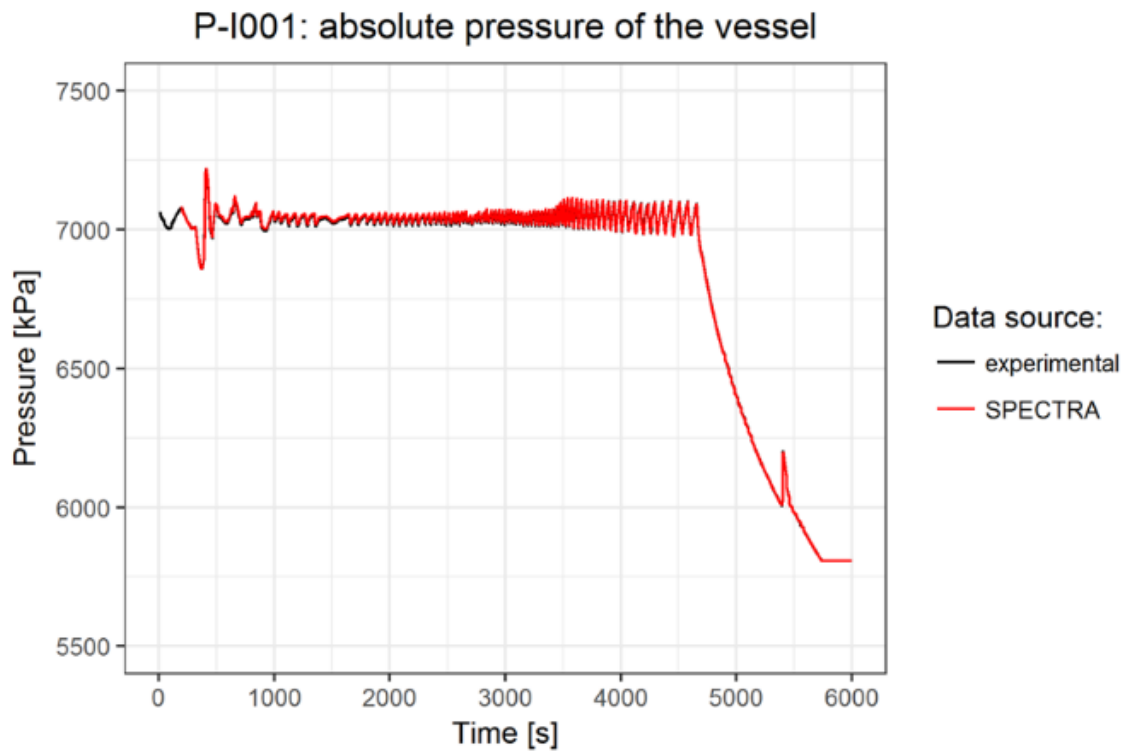


Figure 5.193. Test 7 – Part 2, profile of the steam inlet temperature in the HX

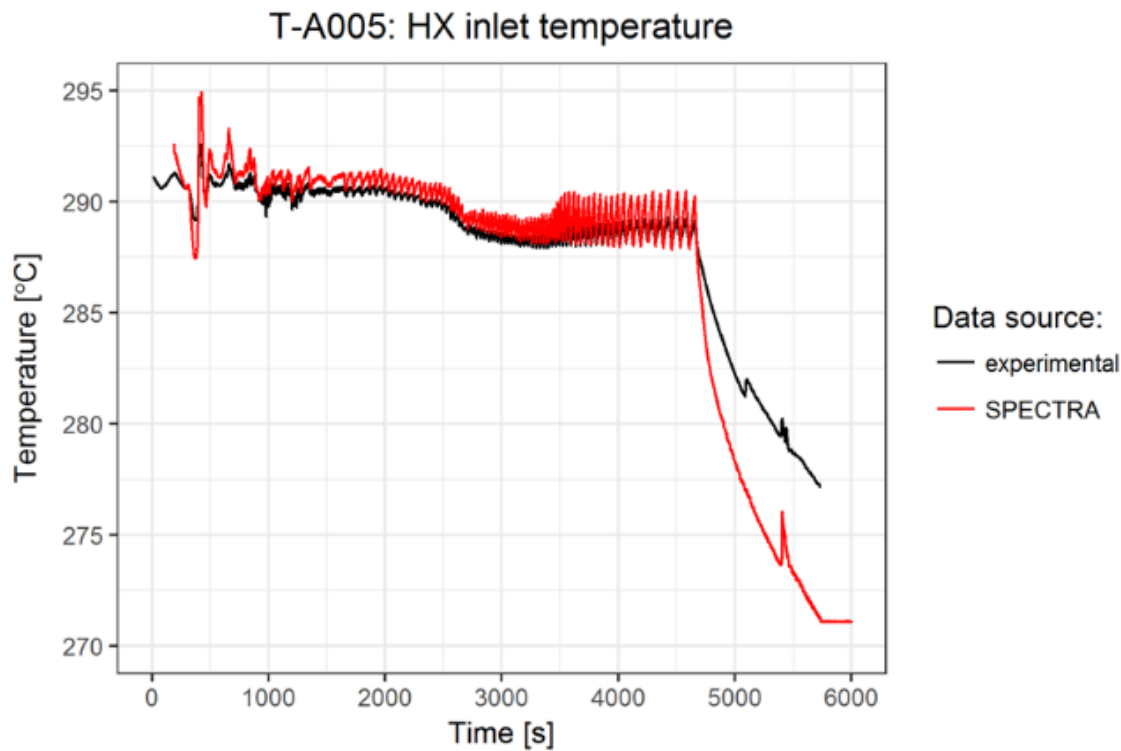


Figure 5.194. Test 7 – Part 2, profile of the steam outlet temperature in the HX

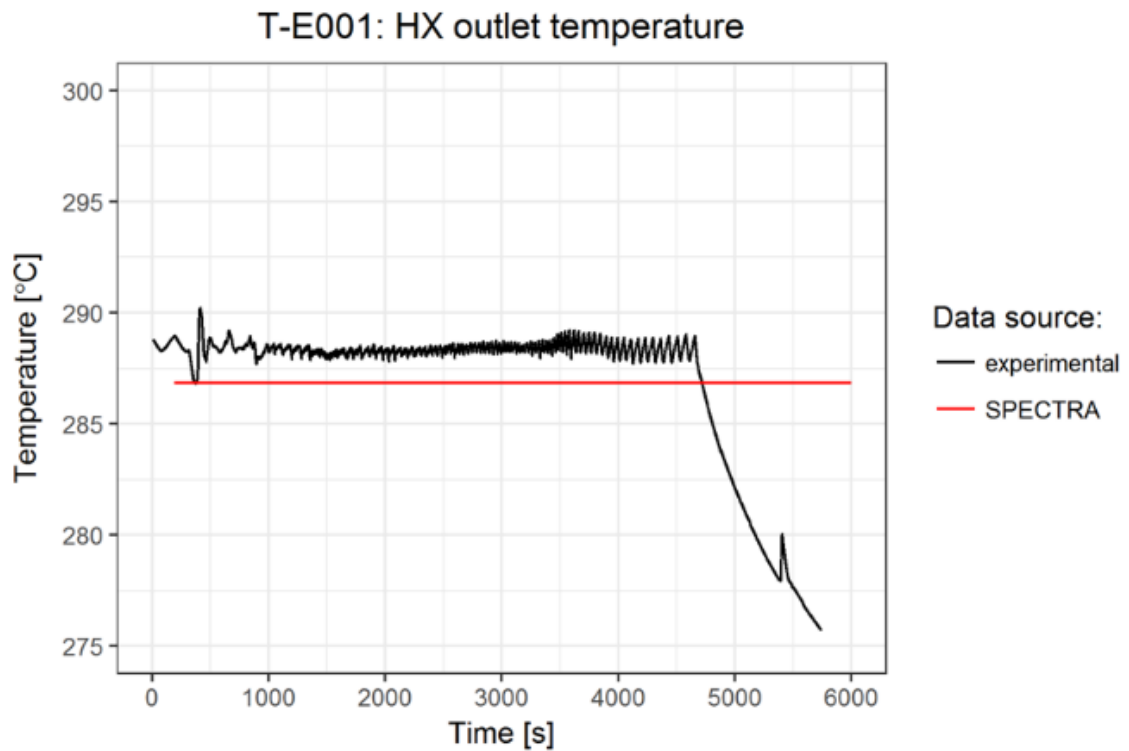


Figure 5.195. Test 7 – Part 2, profile of the HX pool level

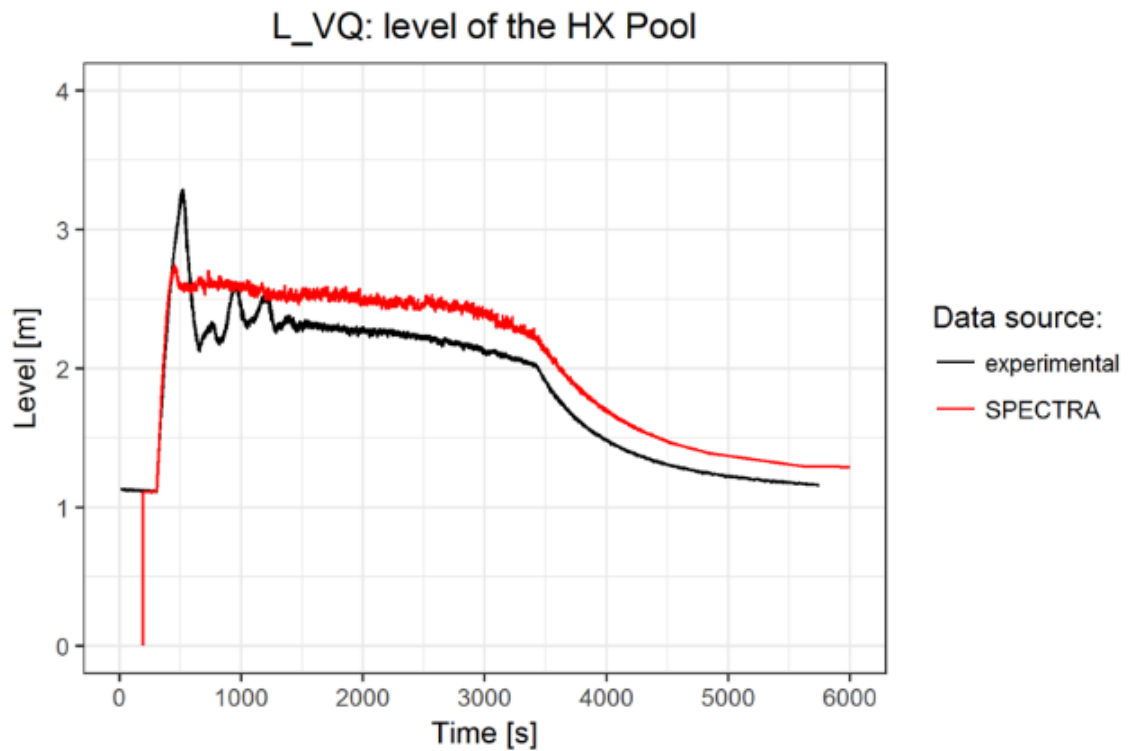


Figure 5.196. Test 7 – Part 2, profile of the overall pool level

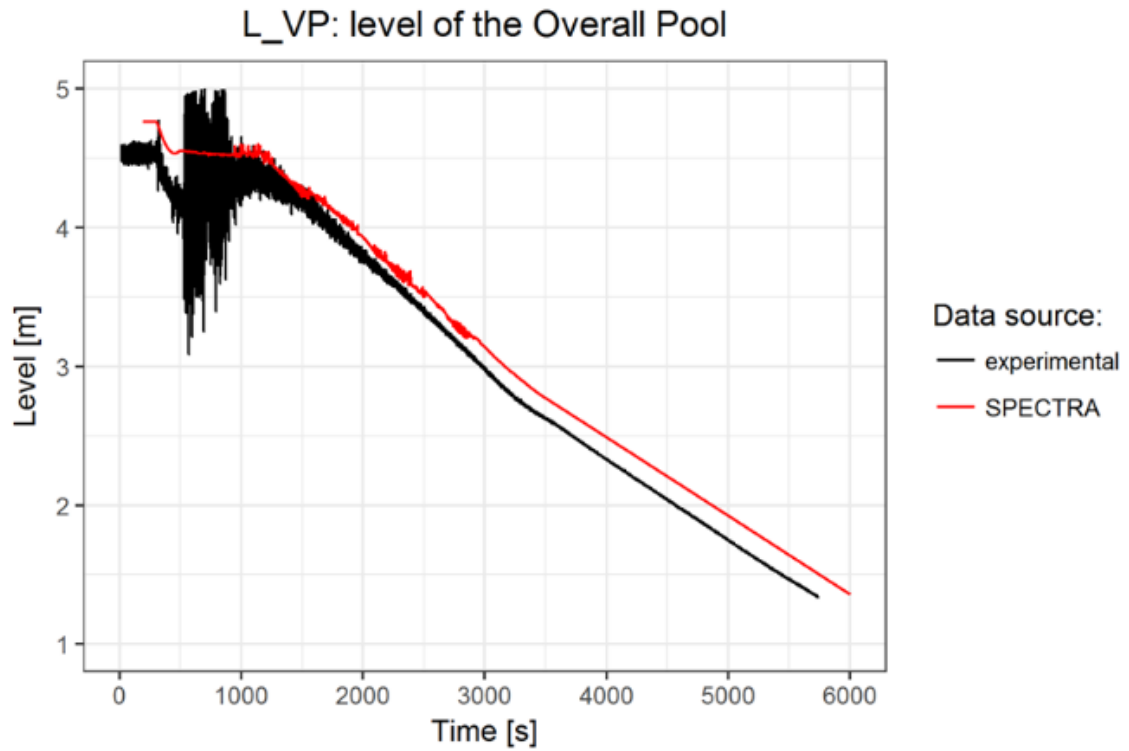


Figure 5.197. Test 7 – Part 2, profile of the HX pool temperature (0.485 m from the HX pool floor)

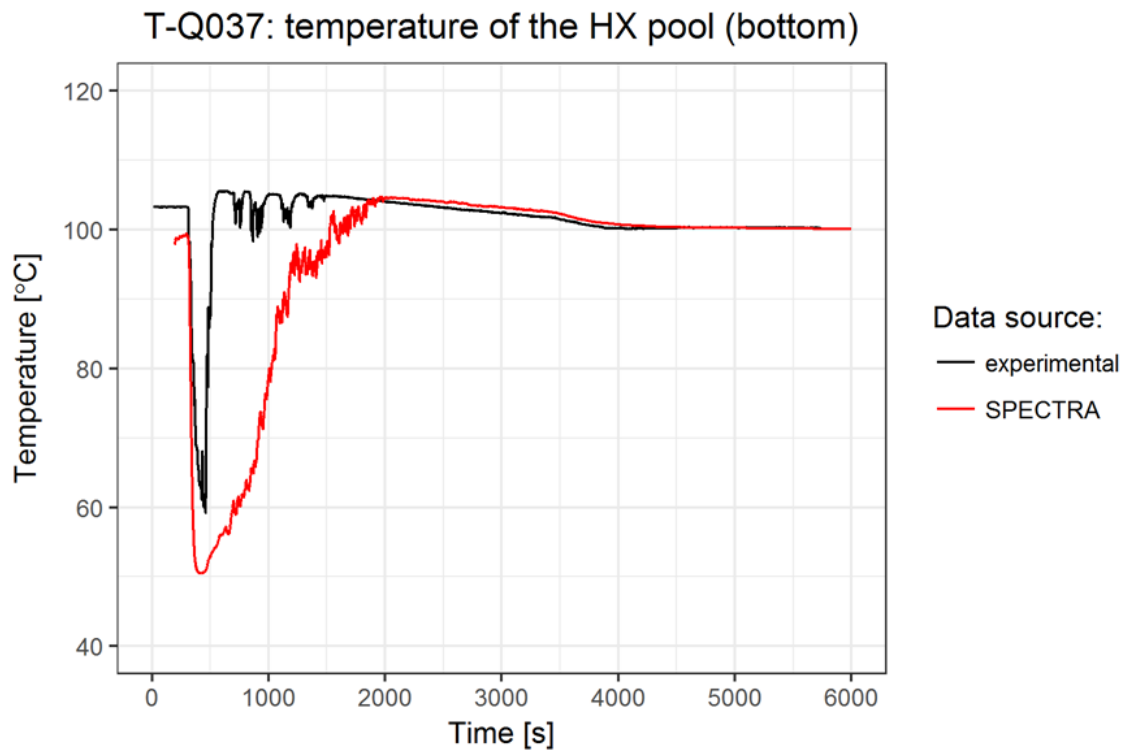


Figure 5.198. Test 7 – Part 2, profile of the HX pool temperature
(2.535 m from the HX pool floor)

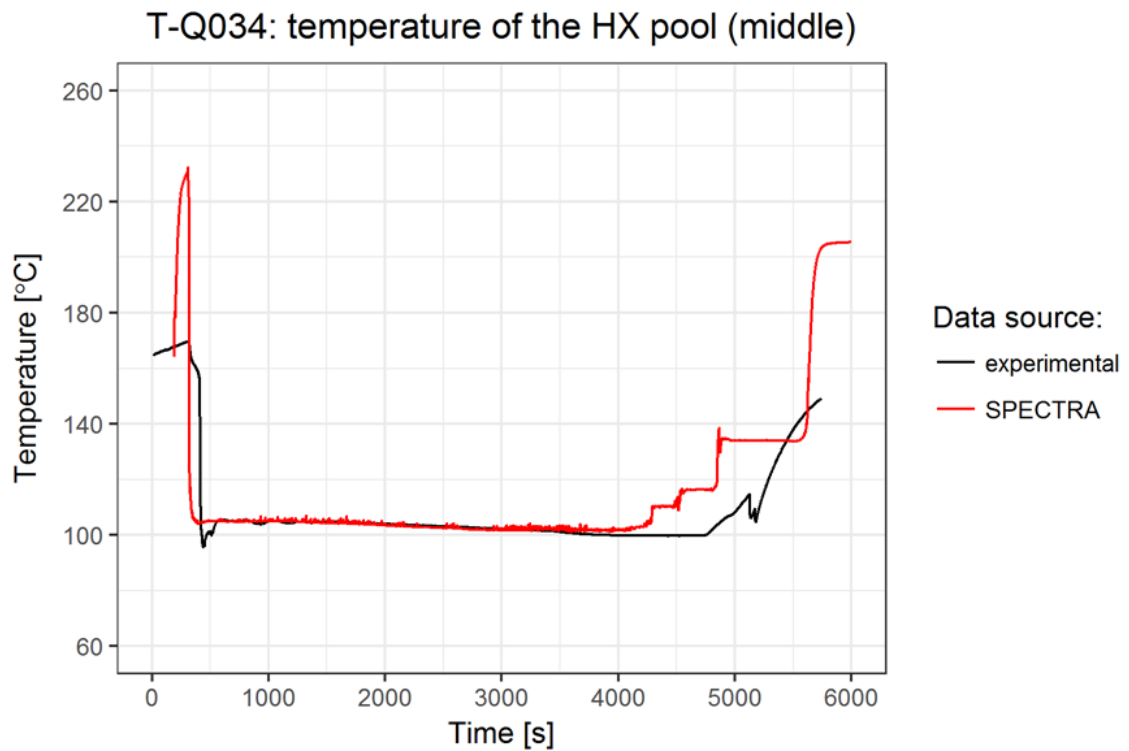


Figure 5.199. Test 7 – Part 2, profile of the HX pool temperature
(3.860 m from the HX pool floor)

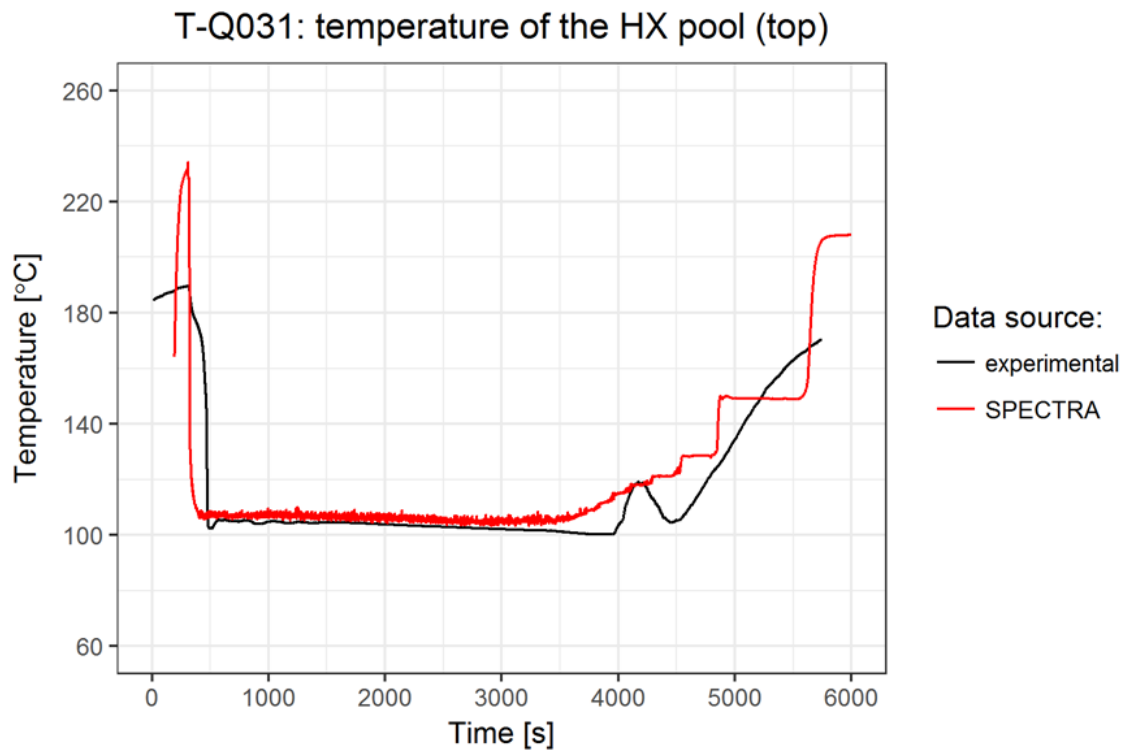


Figure 5.200. Test 7 – Part 2, profile of the HX pool relative pressure

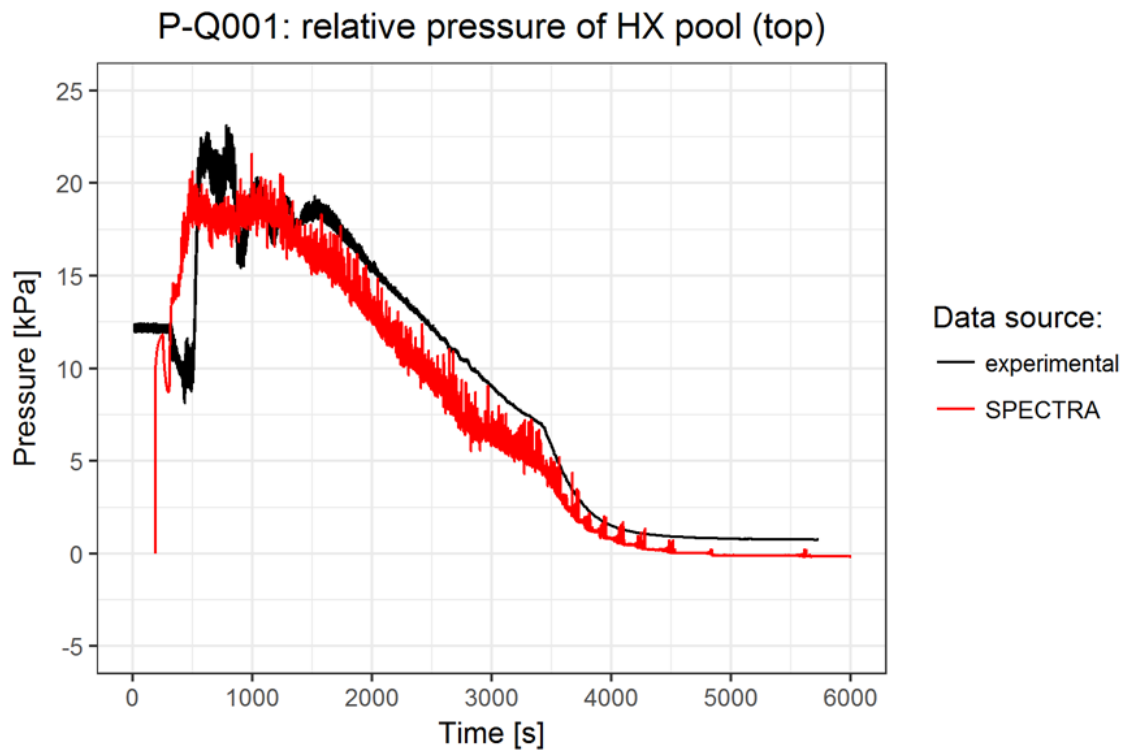
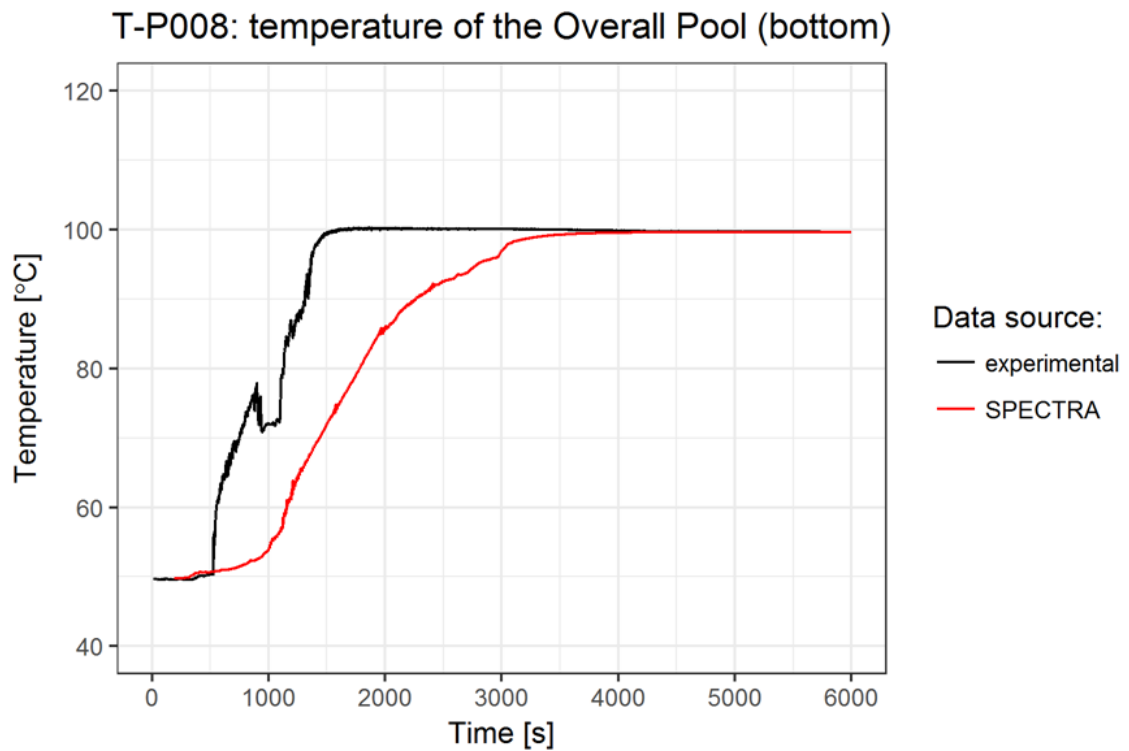
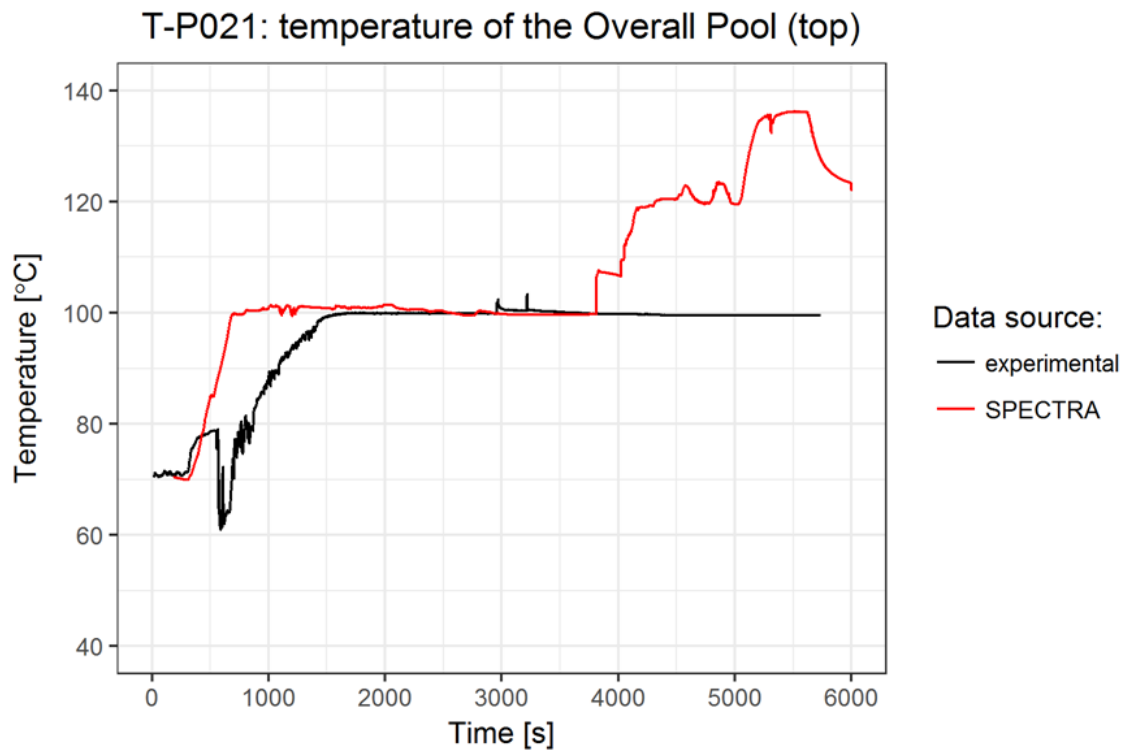


Figure 5.201. Test 7 – Part 2, profile of the overall pool temperature (1 195 m from the OP floor)



**Figure 5.202. Test 7 – Part 2, profile of the overall pool temperature
(2 695 m from the OP floor)**



**Figure 5.203. Test 7 – Part 2, profile of the differential pressure
between the upper and lower HX headers**

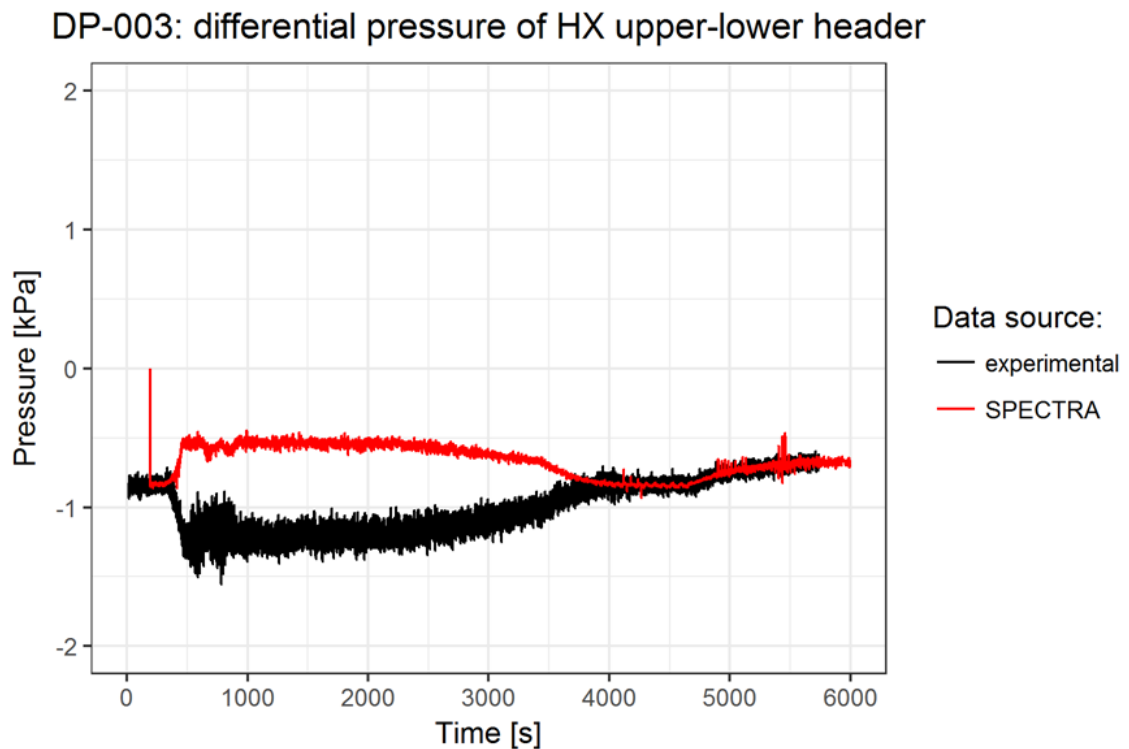


Figure 5.204. Test 7 – Part 2, profile of the differential pressure in the steam injector

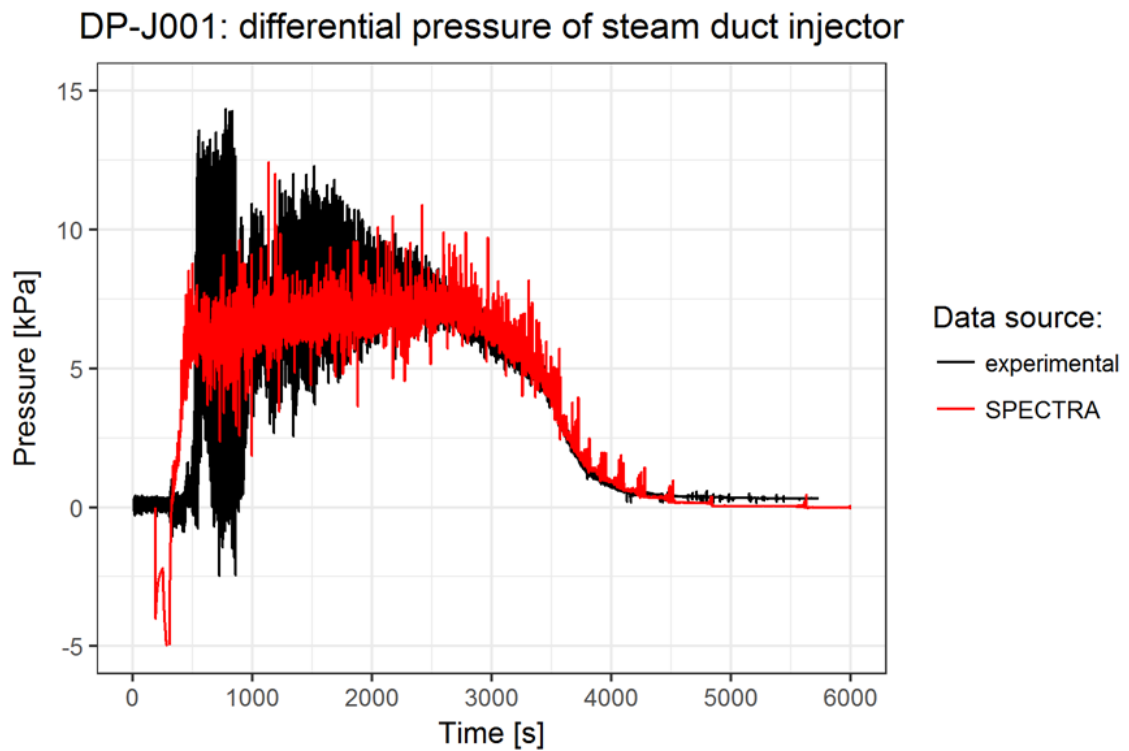


Figure 5.205. Test 7 – Part 2, profile of the wall temperature of the HX upper header (lower part)

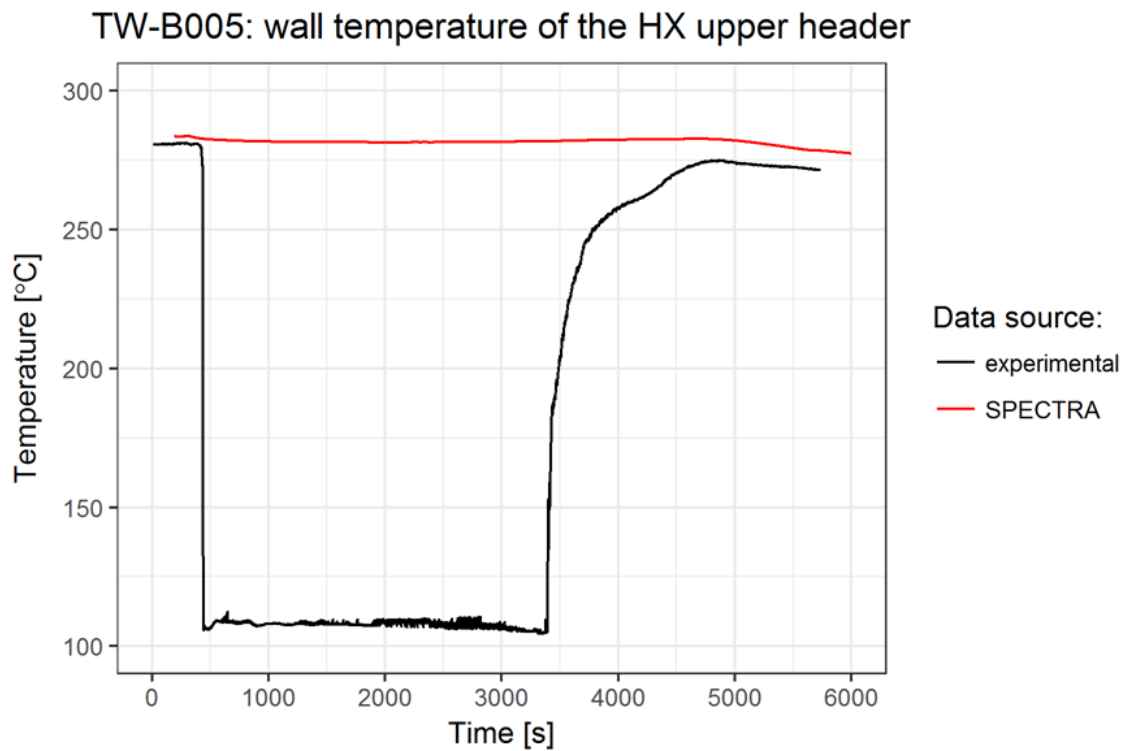


Figure 5.206. Test 7 – Part 2, profile of the wall temperature of the HX lower header (upper part)

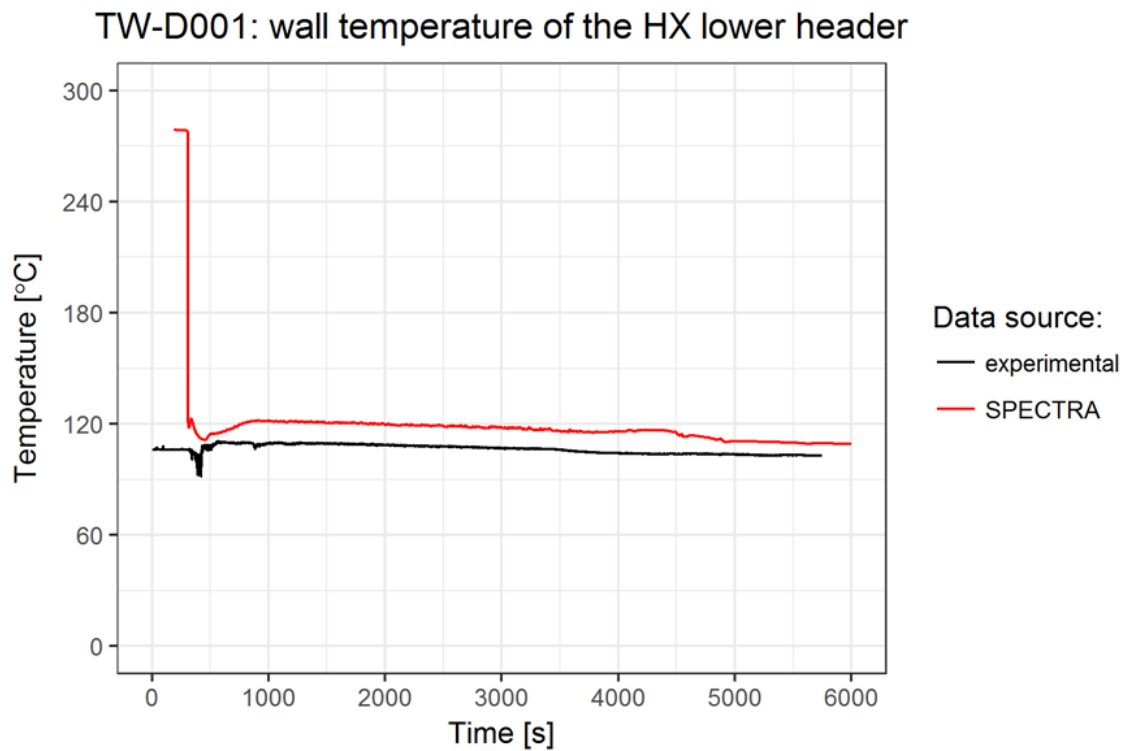


Figure 5.207. Test 7 – Part 2, profile of the mass flow rate in the pools-connecting line

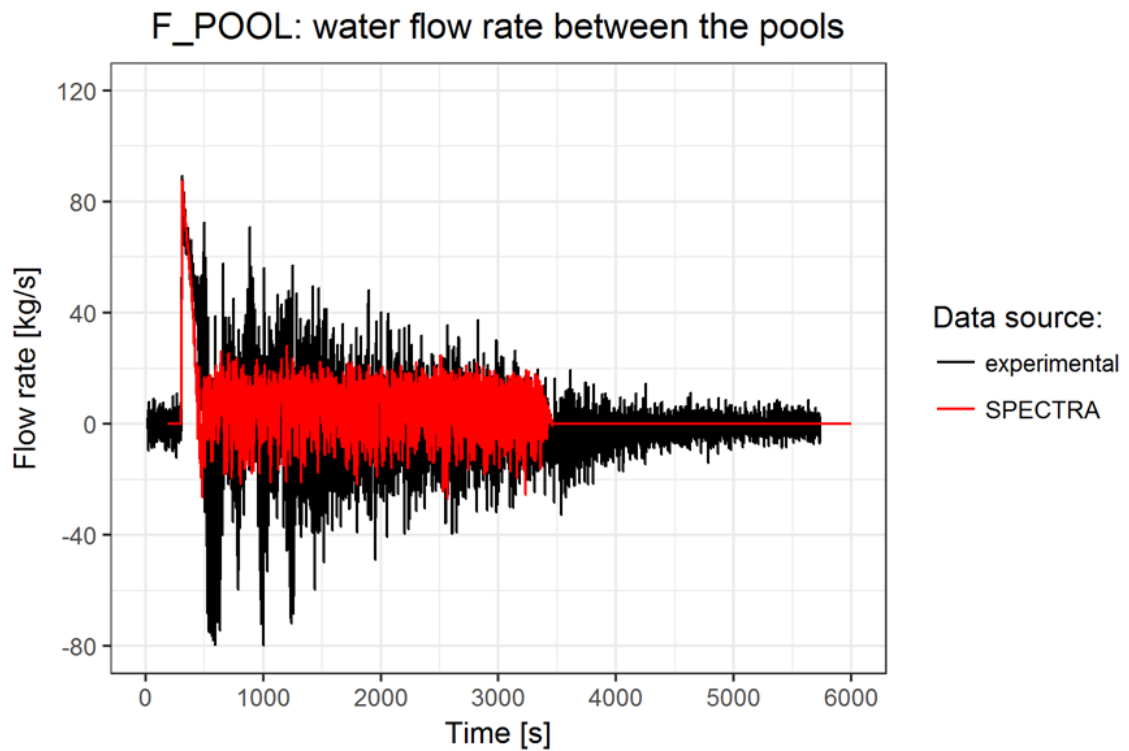


Figure 5.208. Test 7 – Part 2, profile of the mass flow rate in the pools-connecting line (during the first 400 seconds)

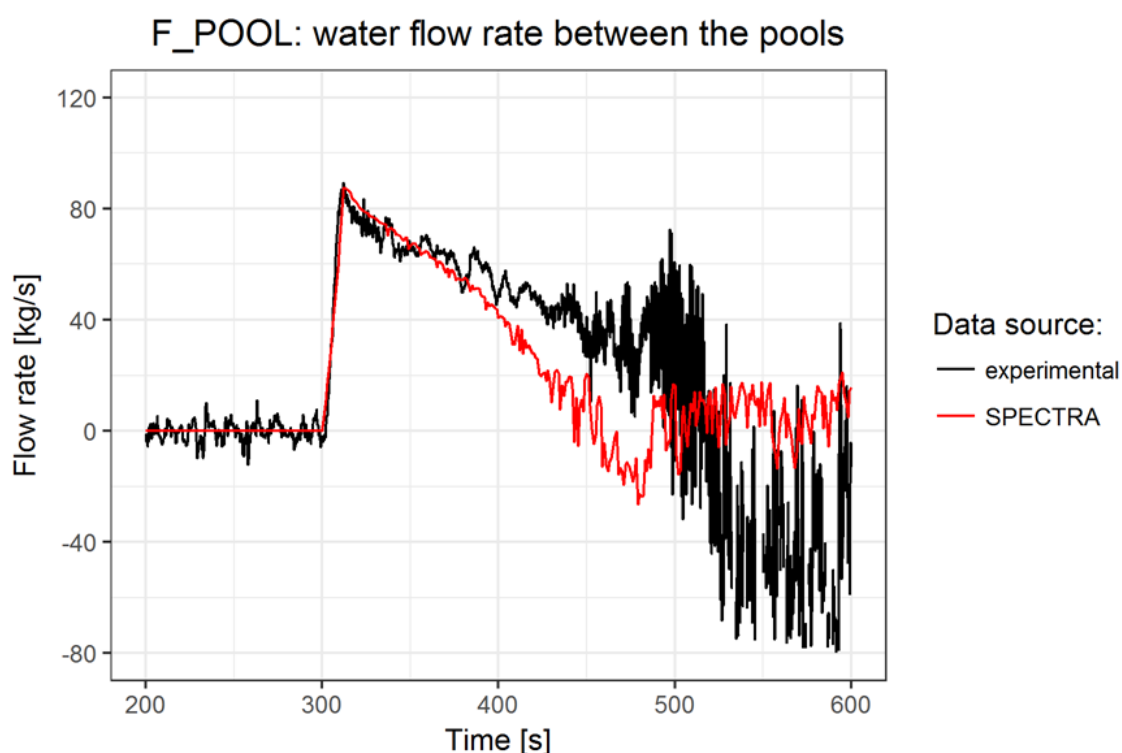


Table 5.30. Main relevant thermal-hydraulic aspects related to Test 7 - Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	300 – 312	0% – 85%
	312 – 600	85% – 100%
Maximum level in the HXP	450	2.75 m
Maximum exchanged power	450 – 2 150	18.7 MW
OP discharge valve F031 opening	1 150	100%
Triggering valve F045 closure	3 338 – 3 461	100% – 0%
HX pool level decreasing and loss of mass from the boil-off	820 – 5 736	2.67 m – 1.29 m
Primary side depressurisation beginning for end of test	4 685 – 5 736	70.9 bar – 58.1 bar

The marks adopted in Table 5.30 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.31. PERSEO Test 7 - Part 2 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.		Measurement		Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	-
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	o
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	o
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
				Diff. pressure HX upper-lower header	DP-003	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure steam duct injector	DP-J001	o
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Power heat exchanger	W IC (der.)	o
				Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (top)	T-Q031	NA
				Power heat exchanger	W IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature OP (top)	T-P021	o
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Power heat exchanger	W IC (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Relative pressure HXP top	P-Q001	o
				Level OP	L VP (der.)	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

SECTION 5: CONCLUSIONS

- The results presented in this document showed that the SPECTRA model of PERSEO was capable of describing the relevant thermal-hydraulic phenomena that occurred during the test scenarios proposed for the benchmark:
 - Good agreement with the experimental data was observed for the following thermal-hydraulic phenomena:
 - Natural circulation in HXP and OP coupled circuit;
 - Thermo-fluid dynamics and pressure drops in various geometrical configurations;
 - HX pool side convection heat transfer;
 - Thermal stratification in pools;
 - Natural convection within a pool;
 - Direct contact condensation of steam in pool water.
 - The nodalisation scheme adopted to model the HX system (HX, HXP, OP, steam duct and liquid line) proved to be appropriate to deliver rather accurate results of the transient scenarios proposed. The “non-sliced” nodalisation approach adopted to model the pools revealed some weak points, in particular:
 - In the OP, when the HX is fully operating a strong steam jet comes from the steam duct. Such steam mainly condenses in the hydraulic volume directly connected to the injector outlet. A thermal stratification effect is thus visible only in few nodes below the injector, therefore water mixing in the OP occurred only in the middle-upper part of the pool leaving the bottom part almost unchanged. This phenomenon was more evident in Part 1 of the test.
 - In the HXP, the water mixing occurring when the triggering valve is open was not propagated towards the surface of the HXP. This phenomenon is likely responsible of the absence of the HXP depressurisation phase during the HXP filling in the SPECTRA model.

As a consequence, a “sliced” nodalisation approach might be investigated. In particular, a coarser axial nodalisation might be adopted for the pool volumes.

- The following are the main lesson learnt from the project:
 - In general, the nodalisation strategy adopted can greatly affect the model of transient scenarios where the typical thermal-hydraulic phenomena occurring in the Test 7 of PERSEO are present (specifically: natural circulation in the pool circuit, interaction from direct contact of steam-water, film condensation, thermal stratification and natural convection in a pool). Nevertheless, it is difficult to design an STH model a priori, that is suitable for all possible conditions of operation for a system like PERSEO.
 - Concerning specifically the SPECTRA code, the lack of capability of tracking water level in contact with a set of structures stacked vertically (as was the case of the HX tubes) may result a not very accurate estimation of the power exchanged under dynamic conditions of the liquid level on the opposite side of the structures.

- As a final remark of the results presented, the model of heat losses in the pools should be investigated.

REFERENCES

[5.2.5 1] Stempniewicz, M.M. (2019), *SPECTRA Computer Code Manuals*, Version 3.61.

5.2.6. *POLITO*

SECTION 1: GENERAL INFORMATION

- Organisation: Politecnico di Torino (Italy)
- Contact persons/authors: Andrea Bersano, Nicolò Falcone, Cristina Bertani, Mario De Salve
- Code: RELAP5-3D v 4.3.4
- Computing environment:
 - Operative system Windows 10 Pro (v 1803)
 - RAM: 32 GB
 - CPU characteristic: Intel(R) Core^(TM) i7-7700 CPU @3.6 GHz

SECTION 2: DESCRIPTION OF THE CODE USED

Reactor excursion and leak analysis programme (RELAP5-3D) is a thermal-hydraulic code developed by Idaho National Laboratory (INL). It is an evolution of the RELAP5 code series that implements several new fluids, new thermodynamic properties for water, an integrated multidimensional thermal-hydraulic and neutron kinetic modelling capability and other minor improvements. The code has been initially developed to analyse transients in light water reactors (LWRs) but it can be applied to a variety of thermal-hydraulic transients both in nuclear and non-nuclear systems.

The code adopts a partially implicit numerical solving scheme and it is based on a non-homogeneous and non-equilibrium model for the two phases [5.2.6 1]; it is based on 6 equations: the mass, energy and momentum conservation equation for both phases. Closure equations are used for interphase mass and energy transfer, interphase drag, wall energy transfer, wall friction and flow regime models. Additional models for specific phenomena are also present in the code (abrupt area change, choked flow, countercurrent flow limitation, etc.). The code can account for the presence of non-condensable gases in the gas phase and the presence of boron. The desired system can be simulated combining a variety of different component (pipe, junction, pump, etc.) having their own typical models. The code was developed based on a 1D geometry, but it can also model 2D or 3D geometries with the newly introduced multidimensional component.

Regarding the phenomena relevant to PERSEO conditions, condensation is expected in the inner side of the HX tubes and nucleate boiling on the outer side. RELAP5-3D condensation correlations for tubes are the ones derived by Nusselt (laminar regime), Shah (turbulent regime) and Colburn-Hougen (for the diffusion of non-condensable gases if present) [5.2.6 1]; in boiling regime the code uses Chen correlation for nucleate and transition boiling and Bromley for film boiling. Concerning pressure drop, two-phase multipliers according to the Lockhart-Martinelli approach are used if two-phase flow is present [5.2.6 1].

Considering the expected phenomena [5.2.6 2], it has been evaluated that the code is suitable to simulate the experimental transients performed with the PERSEO facility.

SECTION 3: DESCRIPTION OF THE NODALISATION

The nodalisation adopted for the simulation is presented in Figure 5.209. Two main sub-systems are present: the primary loop and the pools for heat removal. The initial and the boundary condition adopted are the ones reported in the Test 7 report distributed to the benchmark participants [5.2.6 2]. The vessel has been simulated by a pipe (330) and two time-dependent volumes (300 and 340) have been used to maintain the desired steam pressure and to drain the condensate. The steam line and the drain line have been simulated by a series of pipes (510, 520, 530 and 540 for the steam line, and 450 and 460 for the drain line). The HX headers have been simulated with branch components (420 and 440), while for the tubes a single pipe (430) has been used with the total flow area of the 120 HX tubes.

In the modelling of the pools it has been evaluated the possibility to use mono-dimensional or multidimensional components to reproduce the relevant phenomena. In fact, in large and complex components with a low length over diameter ratio multidimensional phenomena could be present; however, it has been assumed that, due to the configuration of the system, the flow has a dominant net vertical component, in particular in the HXP: in fact, water enters at the bottom and steam exits from the top. For this reason, mono-dimensional components have been adopted (branch and pipe) but, in order also to model possible recirculation within the pools, they have been nodalised as two vertical stacks of pipes and branch laterally connected with cross-flow junctions. Even if this nodalisation only uses 1D components the result is a quasi-2D configuration since also transversal flow can occur. Slicing nodalisation between the two pools has been applied to reduce unphysical oscillations when the triggering valve is open. This nodalisation technique should be applied in the modelling of parallel channels and consists in the placement of the centre of corresponding volumes at the same height.

The HXP is connected to a time-dependent volume through a servo valve (195) that opens if the pressure in the pool becomes lower than the atmospheric one and it simulates the vacuum breaker. The upper part of the OP is connected to a time-dependent volume (680) simulating the atmosphere and, on the lower part, to another time-dependent volume (602) through a servo valve (601) that models the water discharge from the OP. The steam duct and the injector have been simulated using two pipes (710 and 720 respectively). The pipe that models the injector has volumes with different flow area to account for its conical shape.

Tuning of the nodalisation was necessary to correctly reproduce some experimental parameters. The major tuning is the application of a multiplication factor for the heat transfer coefficients on the inner and outer side of the HX heat structure. This multiplication factor, called fouling factor in RELAP5-3D has been set equal to 2.4. Without this modification, the heat transfer between the HX and the HXP would be highly underestimated. The value has been derived considering similar studies available in literature [5.2.6 3], [5.2.6 4] and preliminary sensitivity calculations reported in Annex 5.2.6 A. The increase of heat transfer by a multiplicative factor applied to the heat transfer coefficient is possible since the dominant thermal resistance is the convective one on the inner side of the tubes determined by the condensation heat transfer coefficient.

Inside the HX tubes, the heat transfer mode predicted by RELAP5-3D is condensation, while in the HXP it is nucleate boiling where the tubes are flooded. The underestimation of the heat transfer coefficient may be due to the fact that in this case the Shah correlation is applied outside of its validity range [5.2.6 5]. In particular, the correlation is valid for steam velocities higher than 3 m/s while, considering the central part of Test 7 Part 2 (phenomenological window two) when the heat transfer is maximum, the steam velocity in the HX tubes is around 1.8 m/s (considering the total flow rate equally divided in the HX tubes). In addition, the HX tubes have a relatively low length over diameter ratio

(lower than 40), so, for a significant portion of the tubes, the flow is not fully developed. Regarding the HX tubes outer side, it should be mentioned that Chen correlation used for the computation of boiling heat transfer coefficient [5.2.6 6] has been derived for flow boiling condition, while in this case it is applied to pool boiling condition. Shah and Chen correlation are reported in Annex 5.2.6 B.

As regards all the components exposed to the ambient, heat losses have been simulated imposing an external heat transfer coefficient of 10 W/m²K for the bare components and 2 W/m²K for the insulated ones. However, heat losses have been simulated mainly for completeness, since it is expected that they have a minor effect on the transient due to the size of the facility.

Since the code provides the temperature of the liquid or gas phase separately, a mixture temperature has been computed in the volumes where both phases are expected during the transient (e.g. the HXP before and after the flooding).

Since no detailed information on the actual regulation system is available, the primary pressure has been imposed as a boundary condition of the calculation for both Part 1 and 2, so a good agreement between experimental and calculated results has been found, as will be shown in Section 4. The pressure behaviour has been derived by graphical comparison with the experimental data available. However, when low amplitude pressure oscillations or variation were present in the experimental data, an average value has been used; the pressure value imposed as boundary condition for the simulation is reported in Annex 5.2.6 C. Experimental pressure oscillations lead to oscillations in other parameters, mainly on the primary side (temperature, flow rate and power), that are not captured by the code since the imposed pressure values are obtained by linear interpolation of the values reported in Annex 5.2.6 C.

Table 5.31 shows the number of hydraulic volumes, junctions and heat structures adopted to model each part of the facility. In the nodalisation six time-dependent volumes, and the related junctions, are present; the number of volumes and junctions reported in Table 5.31 also takes them into account. However, the volume of the time-dependent volumes has not been considered in the volume calculation for each component. Table 5.32 reports the code calculated parameter used for the comparison with the experimental data.

Table 5.32. Nodalisation details

	Number of hydraulic volumes	Number of junctions	Number of heat structures	Overall volume (m³)
Vessel	12	11	0	43.3
Steam Line	21	21	23	1.9
HX	20	19	20	1.9
Condensate line	17	18	18	0.6
HXP	49	69	26	27.7
Steam duct	15	16	15	11.4
OP	54	62	27	173.0
Line connecting pools	15	16	14	0.5
Heat transfer area HX (m ²)	47.93 m ² (outer surface, considering the HX tubes and the headers, covers included)			
HX heat structure axial nodes number	20, 18 for the tubes, 1 for the upper header and 1 for the lower header			
HX heat structure radial nodes number	5			

Figure 5.209. Sketch of the adopted nodalisation

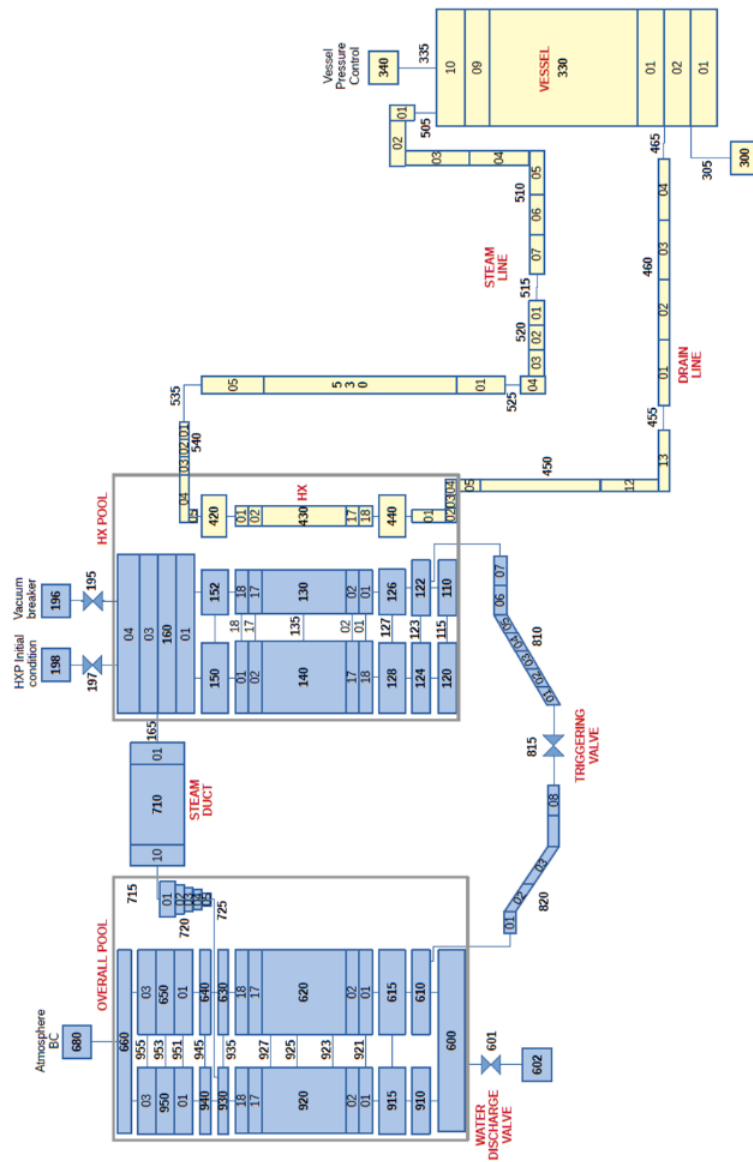


Table 5.33. Code calculated parameter used for the comparison with the experimental data

Experimental parameter	Code parameter
F_A001	mflowj-515 000 000
F_E001	mflowj-455 000 000
W_IC	cntrlvar, sum of the power (q) of the HX volumes
P-I001	p-510 030 000
T-A005	tempg-540 030 000
T-E001	cntrlvar, mixture temperature in volume 450 060 000
L_VQ	cntrlvar, collapsed level in the HXP
L_VP	cntrlvar, collapsed level in the OP
T-Q037	cntrlvar, mixture temperature in volume 124 010 000
T-Q034	cntrlvar, mixture temperature in volume 140 060 000
T-Q031	cntrlvar, mixture temperature in volume 160 010 000
P-Q001	cntrlvar, difference between p-160 040 000 and atmospheric pressure
T-P008	tempf-91 5010 000
T-P021	cntrlvar, mixture temperature in volume 620 150 000
DP-003	cntrlvar, difference between p-420 010 000 and p-440 010 000
DP-J001	cntrlvar, difference between p-720 010 000 and p-720 050 000
TW-B005	httemp-42 010 0105
TW-D001	httemp-440 100 105

SECTION 4: RESULTS

TEST 7 Part 1

In this section the results for Test 7 Part 1 are presented considering the phenomenological windows identified in the report distributed to the benchmark participants [5.2.6 2]. The main relevant thermal-hydraulic aspects resulted from the performed simulation are summarised in Table 5.33. The capability of the code to predict the phenomena occurred in the test is evaluated in Table 5.34 according to the evaluation marks proposed in Table 4.2. The mark “+” has been used for the phenomena correctly predicted by the code, the mark “o” has been used for the phenomena predicted by the code but with the need of major tuning and the mark “-” has been adopted for the unpredicted phenomena.

- Phenomenological window 1 (10 000 – 11 260 s)

In the first phenomenological window (PhW) the first activation of the system occurs, with the HXP filled up to around 1.4 m. In the initial part of the PhW the code cannot predict some parameters, in particular the steam and condensate flow rate, the power (Figure 5.210 to Figure 5.212) and the temperatures in the HXP (Figure 5.218 to Figure 5.220). The discrepancies on the flow rate are reflected on the HX power, since it is experimentally derived from the flow rate and the inlet and outlet enthalpies. The error on the HXP temperatures is due to the presence of thermal stratification in the HXP at the beginning of the transient. The code does not correctly reproduce thermal stratification in due to its numerical solving scheme. In fact RELAP5-3D uses a first-order upwind differencing scheme that has considerable numerical diffusion, which causes significant artificial mixing of the fluid [5.2.6 1]. However, it should be noted that for this transient, the missing prediction of the thermal stratification does not affect the main operation of the system, since this phenomenon is present mainly when the system is inactive.

Also the steam and condensate temperatures present discrepancies (approximately 5°C for the steam and 3°C for the condensate) between the experimental and calculated values

(Figure 5.214 and Figure 5.215). The steam in the primary system should be at saturation condition but the experimental results show a slight superheating that is the cause of the discrepancy between the experimental and calculated results. With the available experimental data, it has been verified that the steam temperature T-A002, which is the nearest to the vessel available, is close to the saturation temperature. Thus, it is possible that the detected superheating could be due to some uncertainty in the measurement. This occurs during all the PhWs of both part of the test.

When the triggering valve is opened, the level in the HXP starts to increase (Figure 5.216) and the OP level to decrease (Figure 5.217). This is correctly reproduced by the code together with the small power transferred in the HX, the flow rate circulating in the primary system, the initial pressurisation of the HXP (Figure 5.224) and the drop of the temperature in the HX lower header (Figure 5.227). In the second part of PhW 1 the experimental HXP decreases, but this is not predicted by the code.

- Phenomenological window 2 (11 260 – 11 845 s)

PhW 2 consists in the time period when the HXP reaches the maximum value and the maximum power is transferred from the HX to the HXP. The HXP temperatures drop to the saturation value and the OP temperatures start to increase due to the steam conveyed to the OP by the steam duct. All the considered parameters are qualitatively well predicted by the code, with the exception of the steam and condensate flow rate.

The correct prediction of the exchanged power, and subsequently of all the other parameters connected to it, is possible if a fouling factor is applied to the HX heat structures to increase the heat transfer coefficient, as previously discussed.

- Phenomenological window 3 (11 845 – 14 784 s)

The last PhW consists in the level reduction in the HXP and the subsequent reduction of heat transfer from the HX to the HXP and therefore also the flow rate on the primary circuit. While all these aspects are qualitatively correctly reproduced by the code, the thermal stratification in the HXP and in the OP is missed, as at the beginning of the transient. This is the main lack presented by the code in the simulation of this particular transient, together with the underestimation of the heat transfer in the HX. This could be improved by applying the thermal stratification model available in the code. Unfortunately, the thermal stratification model can be applied only to volumes linked to a maximum of two junctions. Since in the developed nodalisation several volumes in the pools also have cross-flow junctions, the number of junctions is greater than two, and, therefore the thermal stratification model cannot be applied.

The HX power, and the steam and condensate flow rate that are strongly correlated, show a stepwise variation in the last part of the transient. This can be attributed to the nodalisation adopted for the HX and, in particular to the choice of the volumes height; this effect could be probably reduced using shorter volumes to simulate the HX and the HXP (and the OP since slicing nodalisation is applied), but the computational time would increase excessively. Since the global trend of the parameter is well predicted, it has been evaluated that the chosen nodalisation is an acceptable tradeoff between accuracy and computational time.

The maximum timestep is set to 0.002 s; the computational time is 1 h 15 min.

**Table 5.34. Main relevant thermal-hydraulic aspects related to Test
7 - Part 1**

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	10 475 – 10 608	-
Triggering valve (F045) re-opening and re-closure	10 621 – 10 655	-
Maximum level in the HX pool for the first filling step	654	1.43 m
Small heat removal from the primary side	10 655 – 11 025	2.7 MW
Slow water consumption in the HX pool	Not observed	-
Instabilities for steam condensation in the injector	10 950 – 11 150	-
Triggering valve (F045) opening and closure	11 039 – 11 260	-
Maximum level in the HX pool	11 285	3.44 m
Maximum exchanged power	11 520 – 12 050	19.7 MW
HX pool minimum level	14 784	1.10 m
OP average temperature	13 500	Around 60°C

**Table 5.35. Qualitative accuracy evaluation for PERSEO Test 7 -
Part 1**

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	+
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	+
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure HX upper-lower header	DP-003	o
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	HX outlet temperature	T-E001	o
				Power heat exchanger	W IC (der.)	
				Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
				Temperature HXP (bottom)	T-Q037	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (middle)	T-Q034	-
				Temperature HXP (top)	T-Q031	
				Power heat exchanger	W IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature OP (bottom)	T-P008	+
				Temperature OP (top)	T-P021	
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Power heat exchanger	W IC (der.)	+
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

** Ph. = Phenomenon

Figure 5.210. Test 7 - Part 1 - Steam flow rate

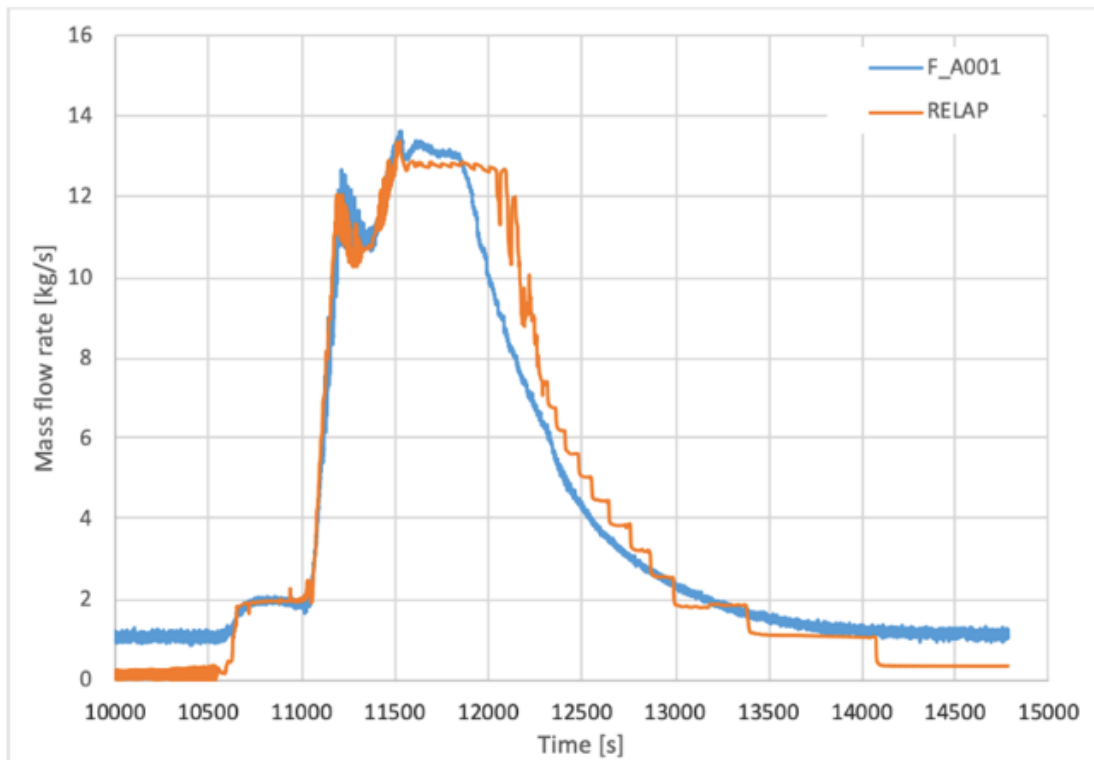


Figure 5.211. Test 7 - Part 1 - Condensate flow rate

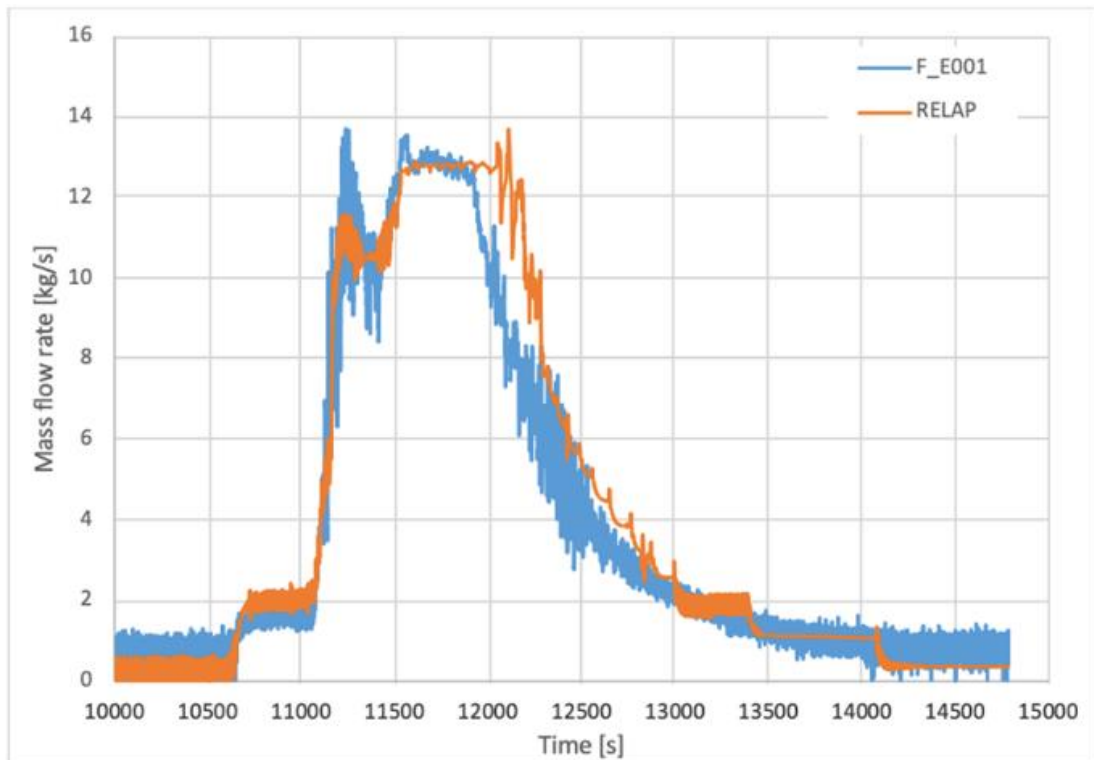


Figure 5.212. Test 7 - Part 1 - HX power

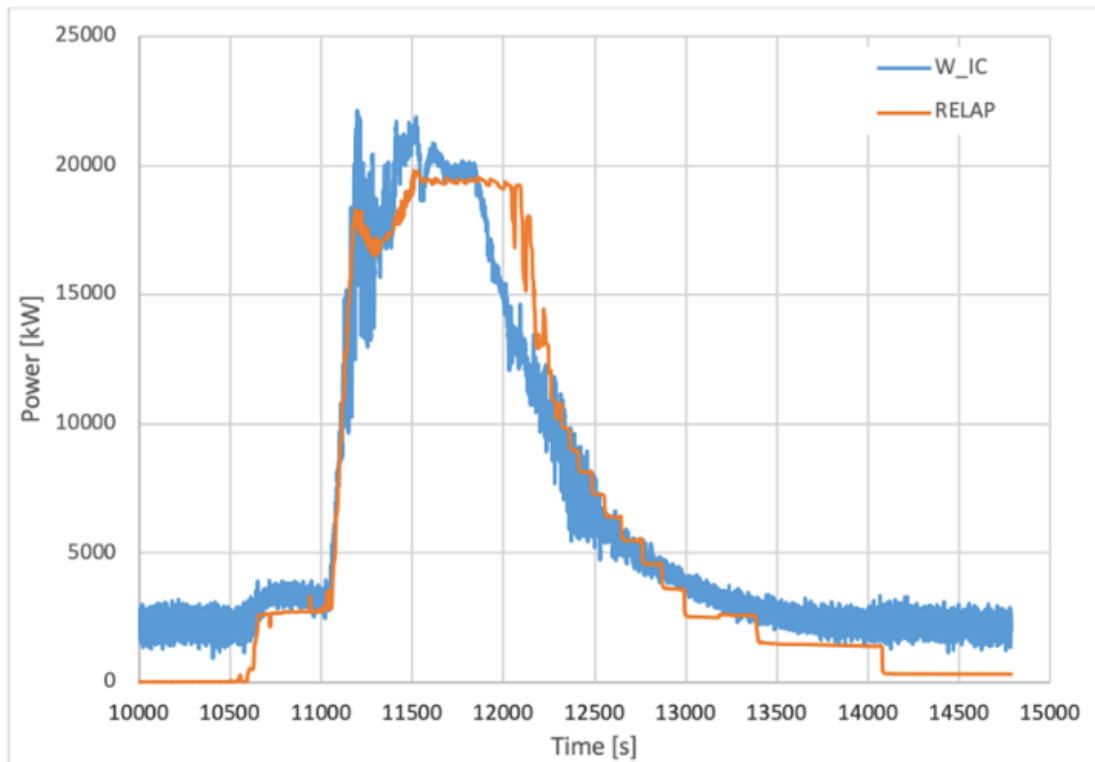


Figure 5.213. Test 7 - Part 1 - Primary pressure

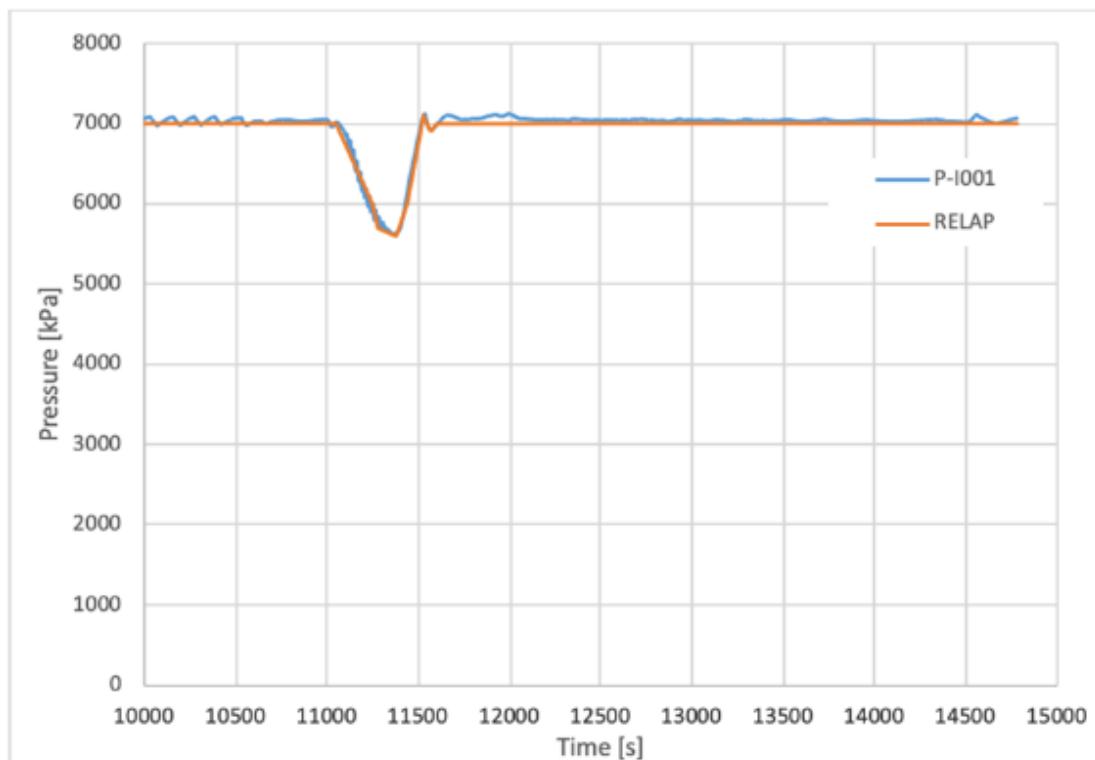


Figure 5.214. Test 7 - Part 1 - Steam temperature

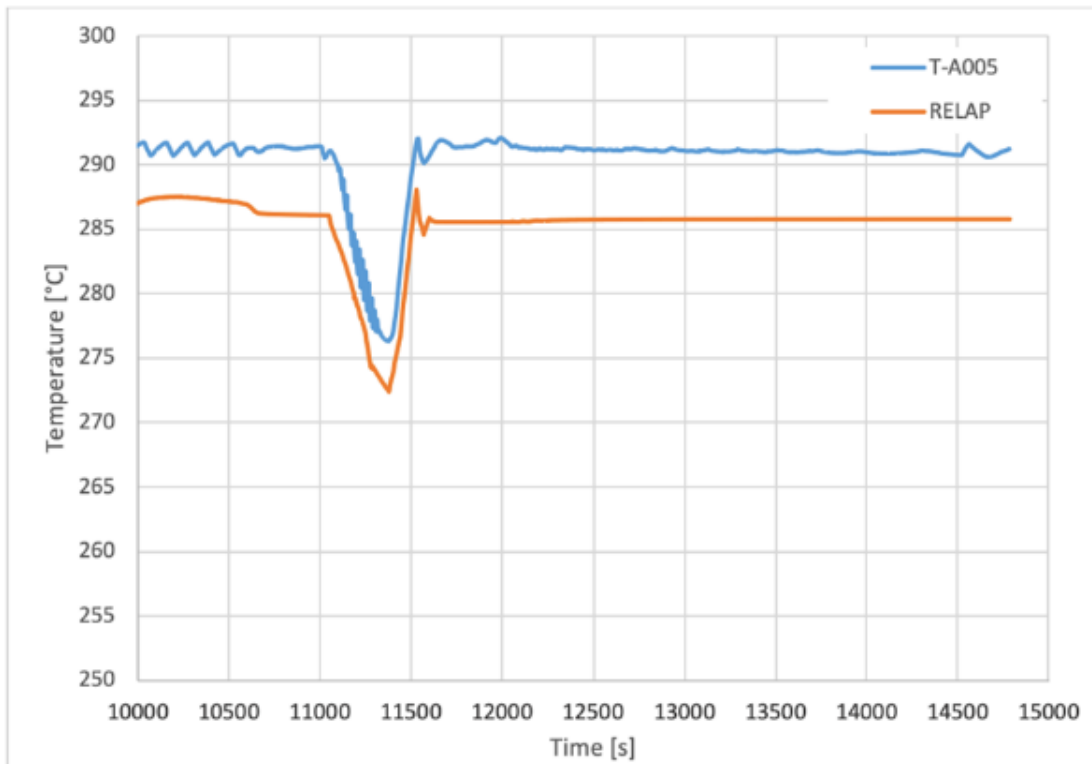


Figure 5.215. Test 7 - Part 1 - Condensate temperature

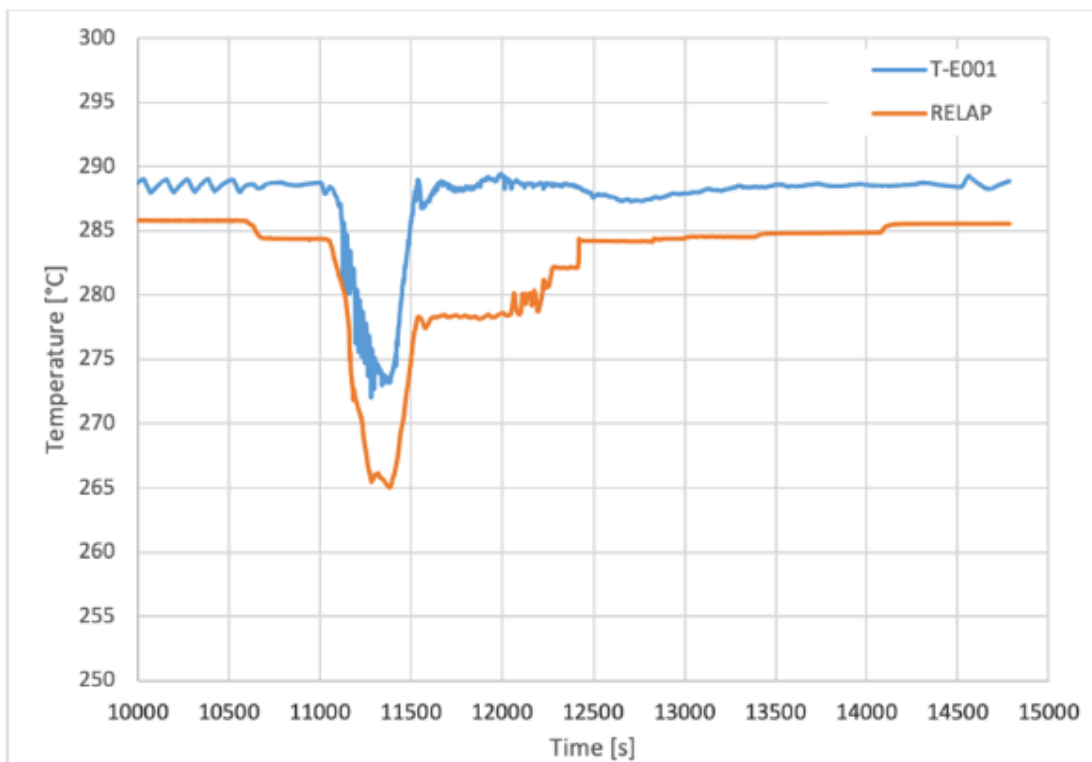


Figure 5.216. Test 7 - Part 1 - HXP level

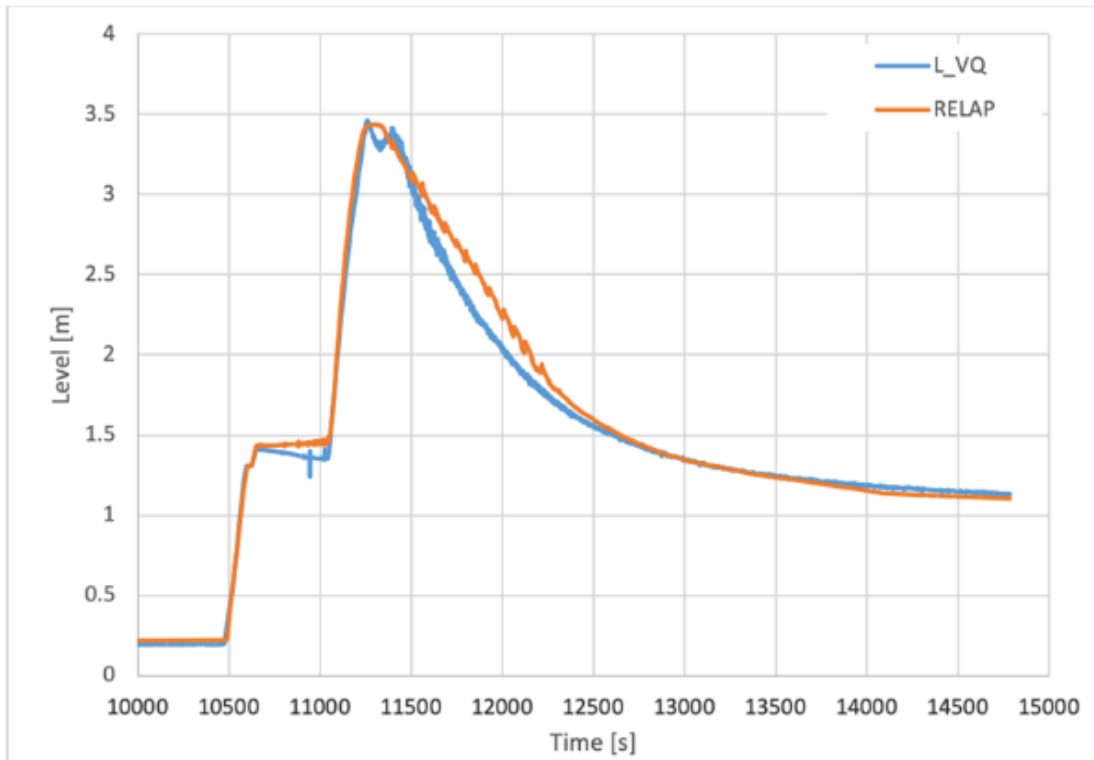


Figure 5.217. Test 7 - Part 1 - OP level

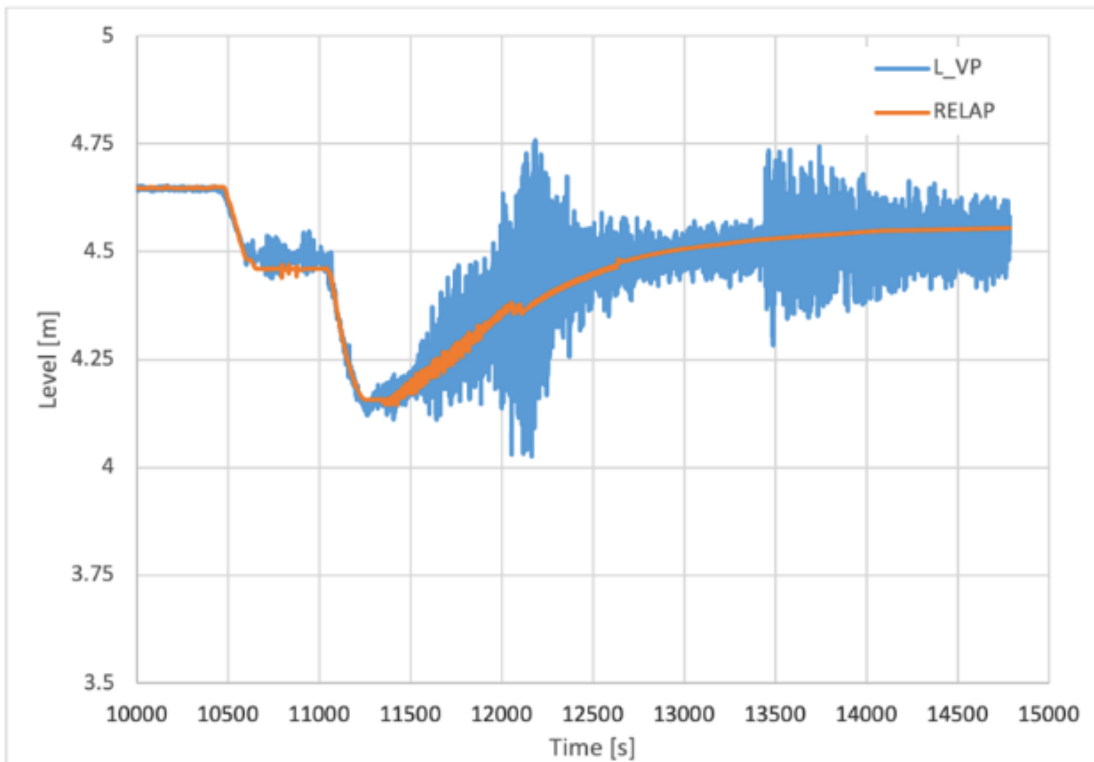


Figure 5.218. Test 7 Part 1 - HXP temperature T-Q037

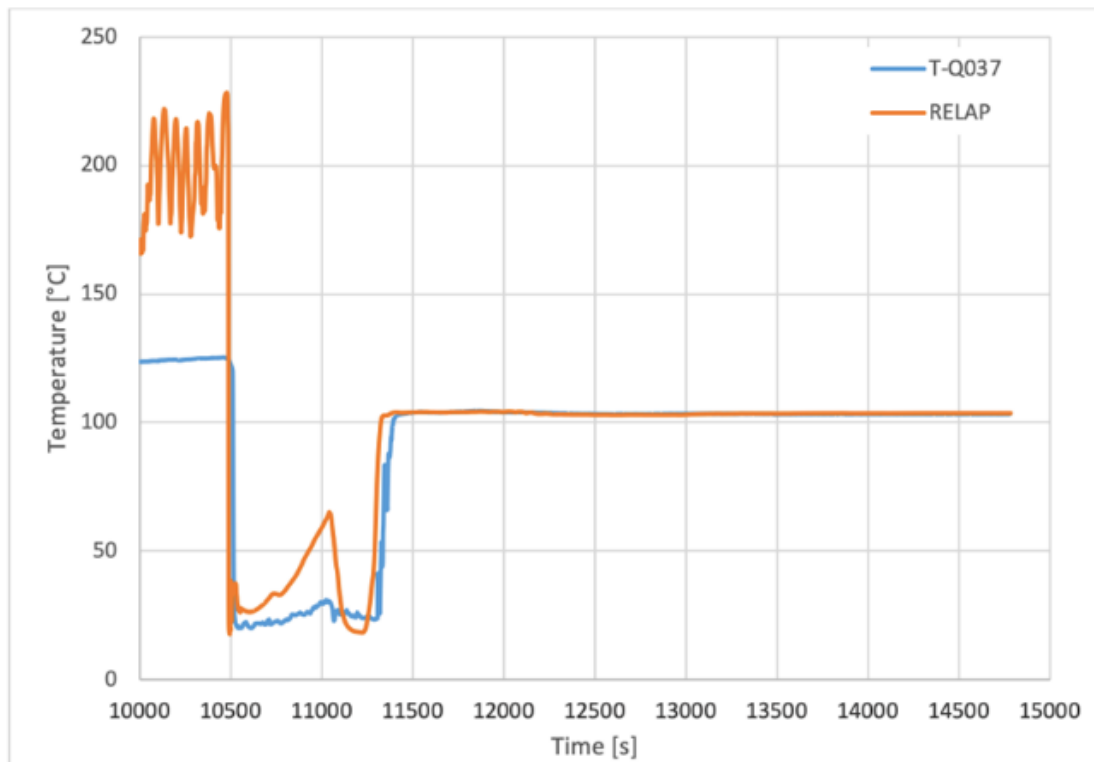


Figure 5.219. Test 7 - Part 1 - HXP temperature T-Q034

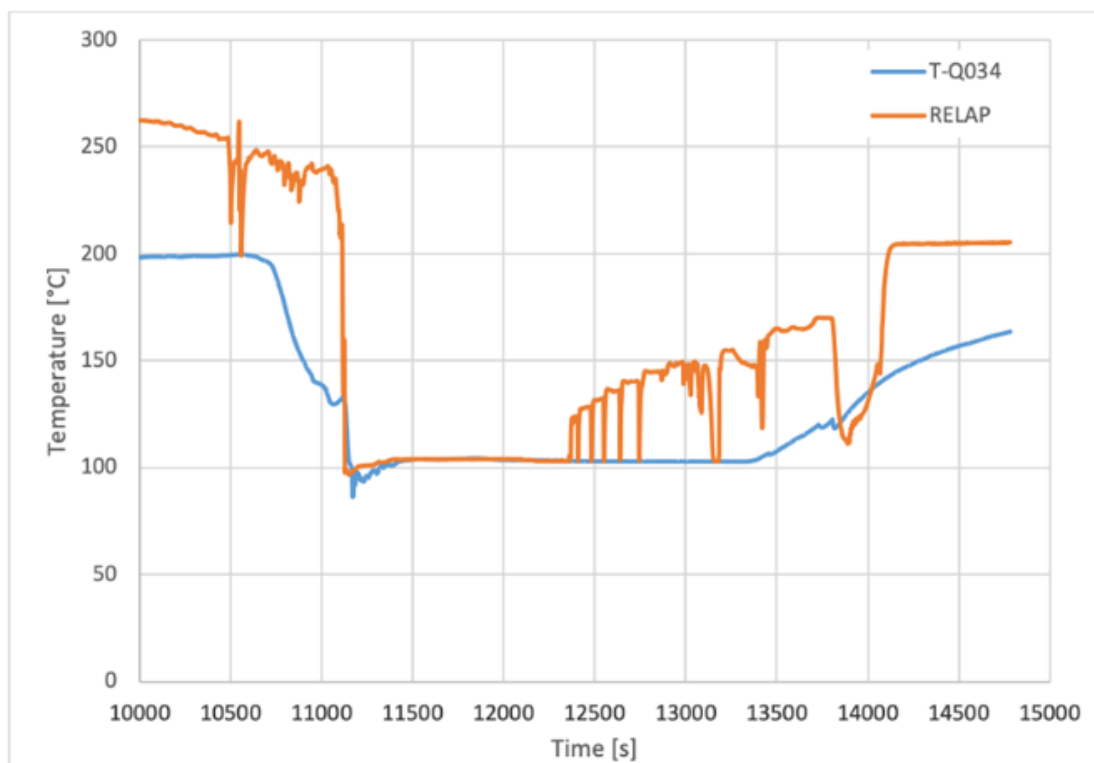


Figure 5.220. Test 7 - Part 1 - HXP temperature T-Q031

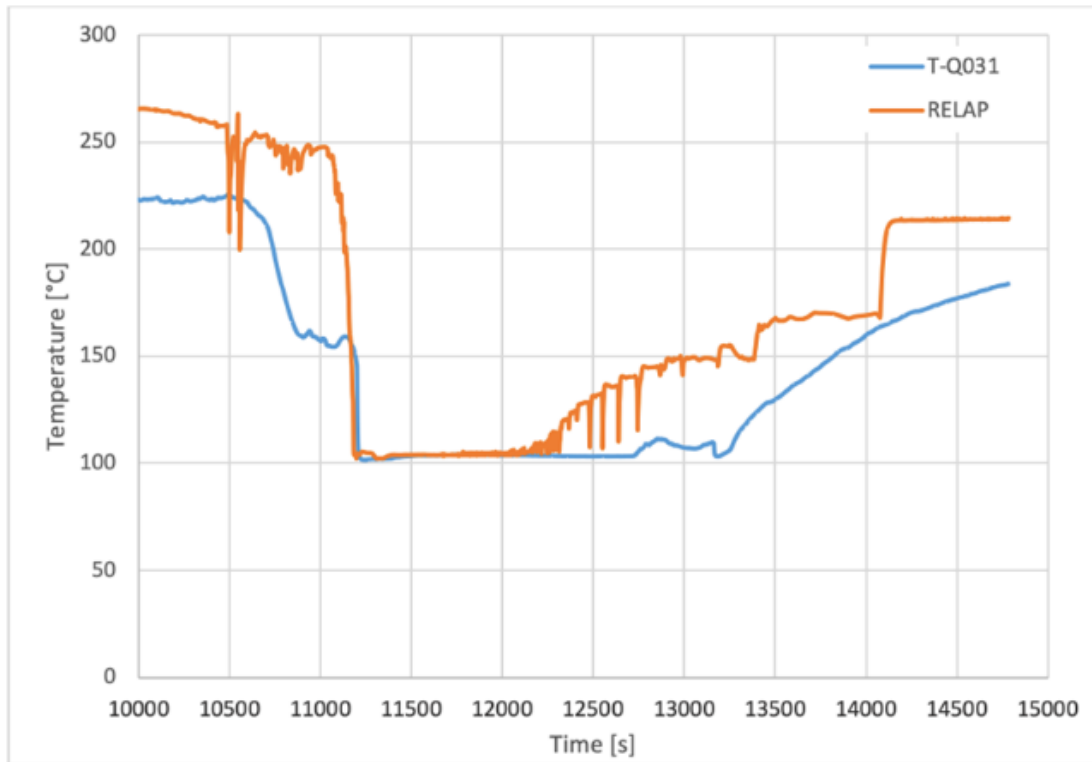


Figure 5.221. Test 7 - Part 1 - HXP relative pressure

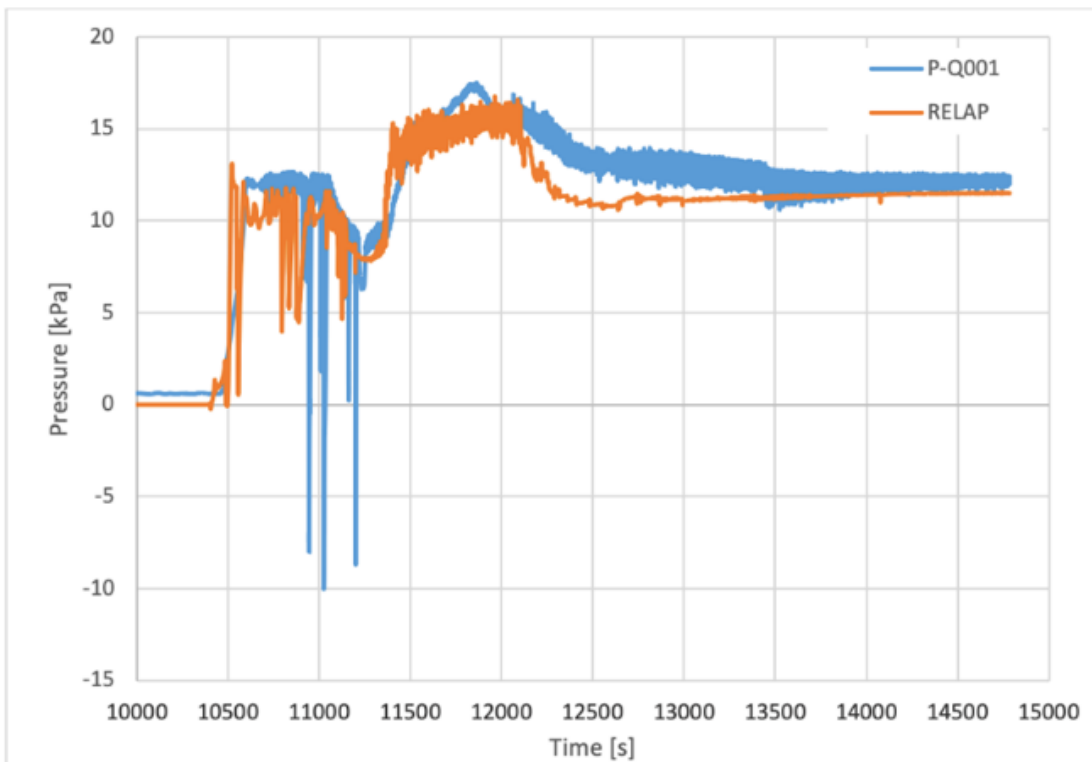


Figure 5.222. Test 7 - Part 1 - OP temperature T-P008

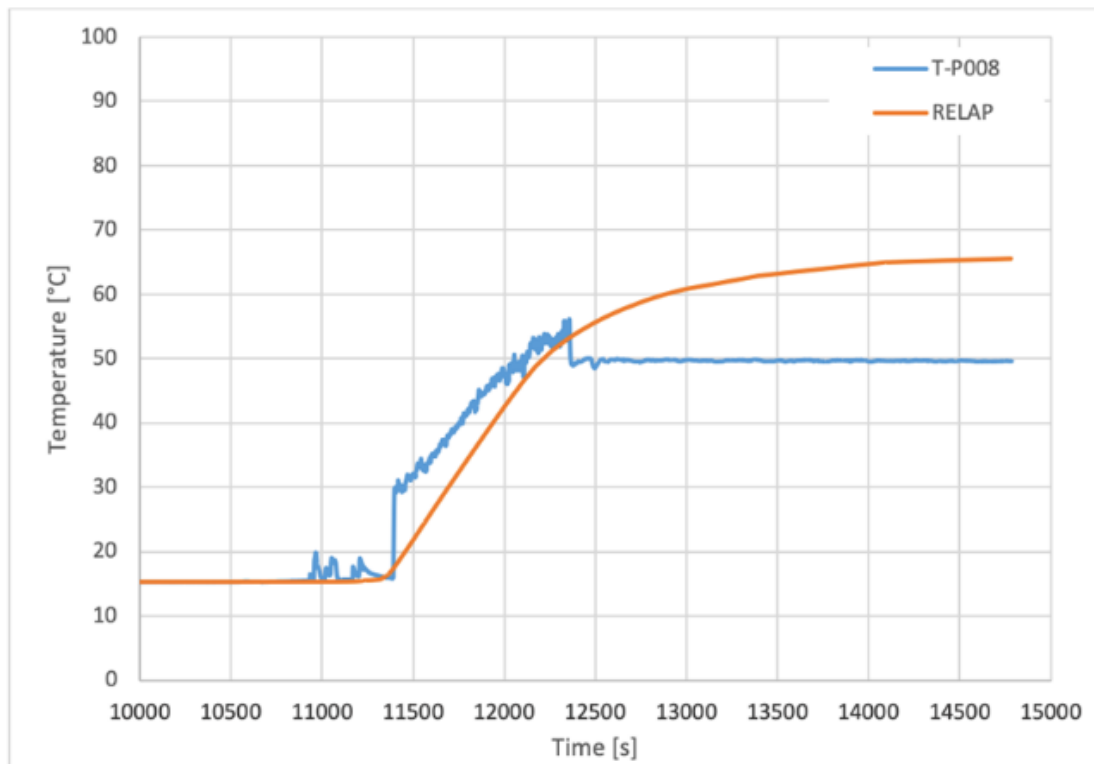


Figure 5.223. Test 7 - Part 1 - OP temperature T-P021

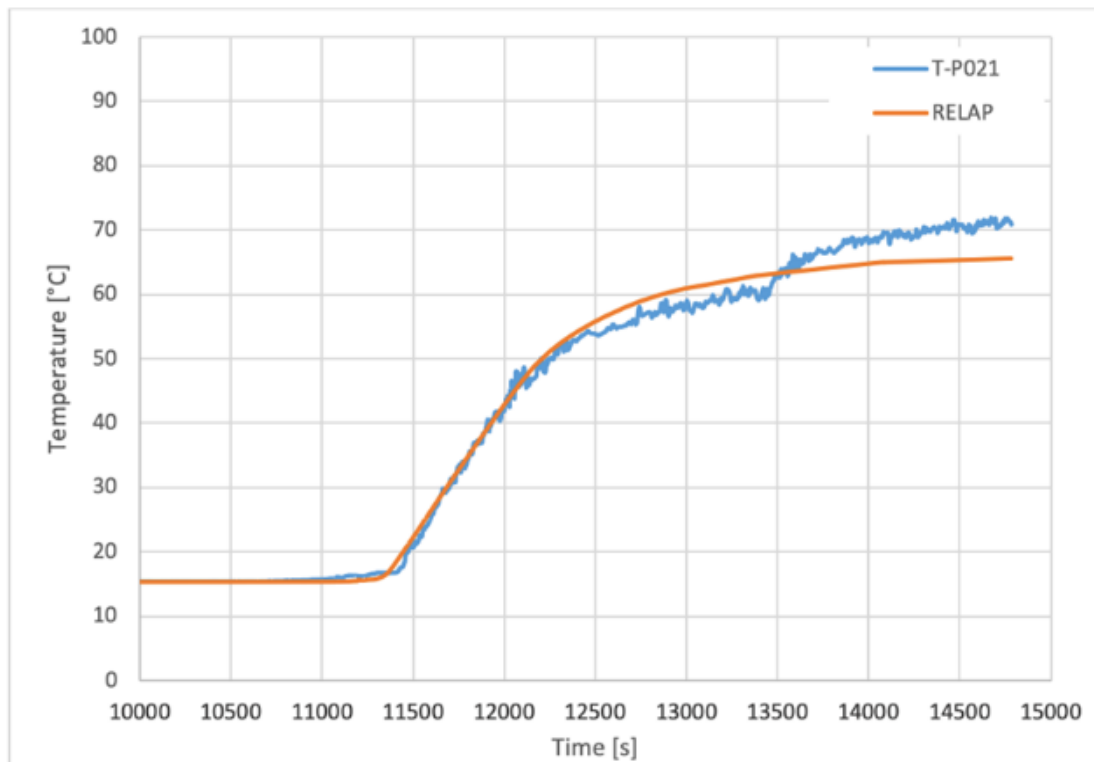


Figure 5.224. Test 7 - Part 1 - HX pressure drop

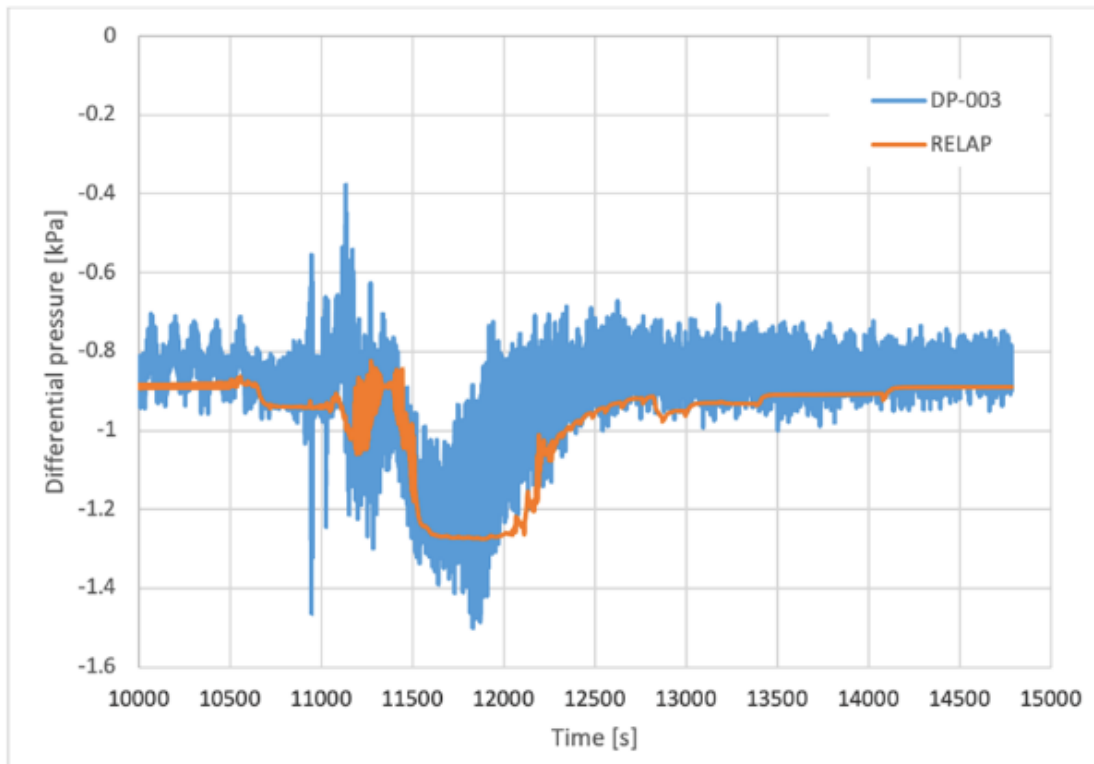


Figure 5.225. Test 7 - Part 1 - Injector pressure drop

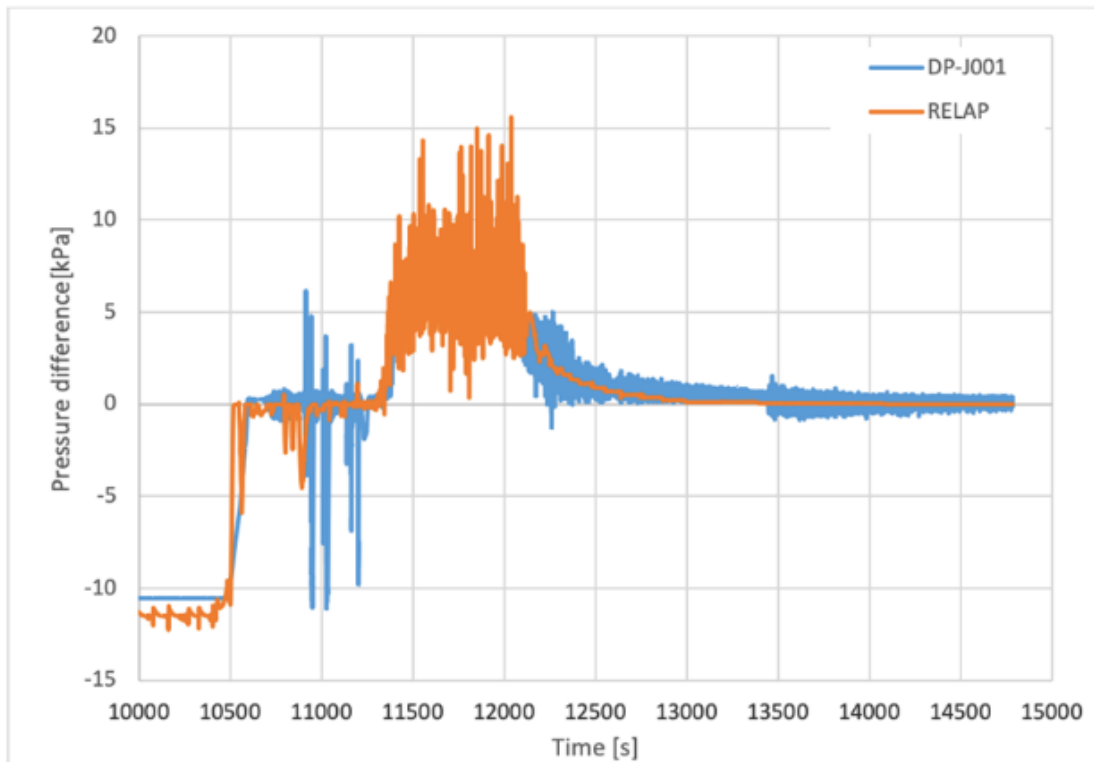


Figure 5.226. Test 7 - Part 1 - HX upper header outer wall temperature

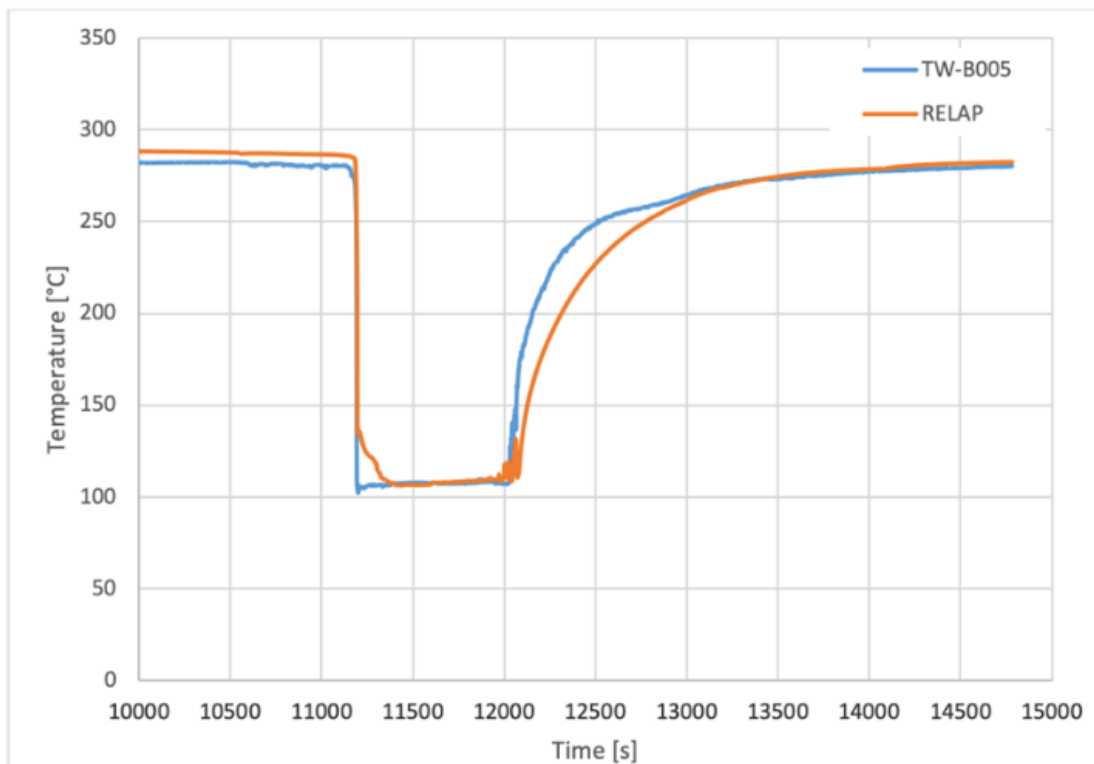
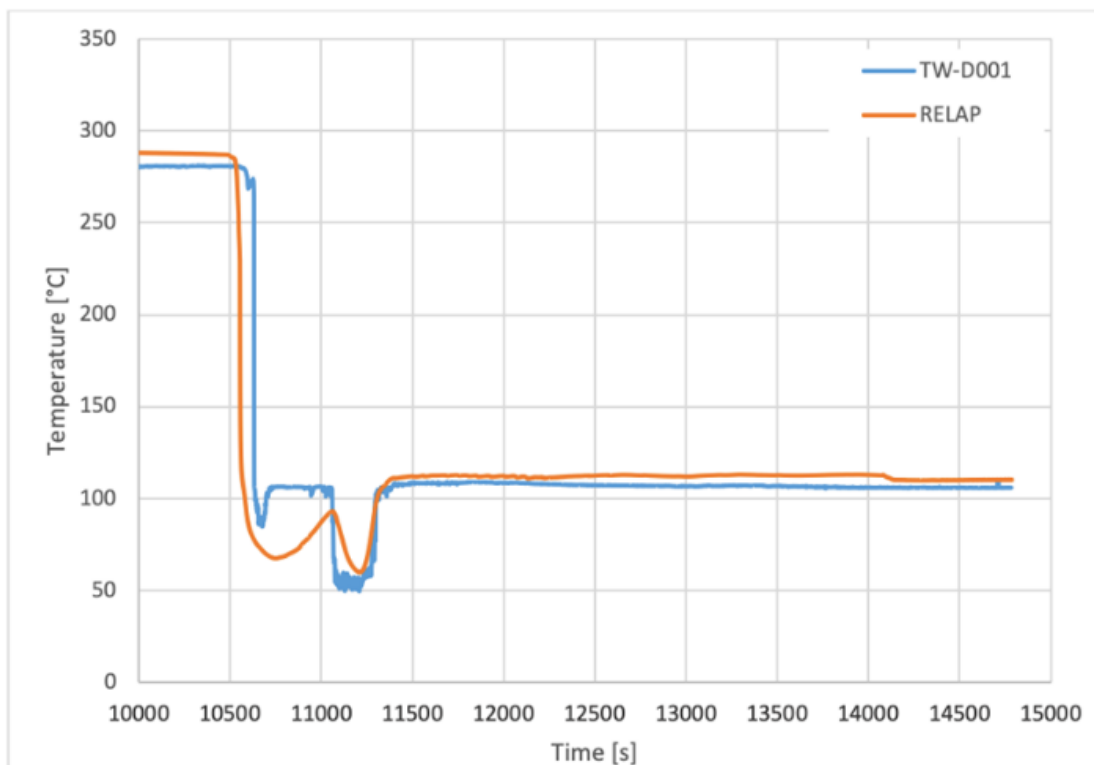


Figure 5.227. Test 7 - Part 1 - HX lower header outer wall temperature



Test 7 Part 2

In this section the results for Test 7 Part 2 are presented considering the phenomenological windows identified in the report distributed to the benchmark participants [5.2.6 2]. The main relevant thermal-hydraulic aspects that resulted from the performed simulation are summarised in Table 5.35. The capability of the code to predict the phenomena that occurred in the test is evaluated in Table 5.36, again according to the evaluation marks proposed in Table 4.2. Also in this case, the mark “+” has been used for the phenomena correctly predicted by the code, the mark “o” has been used for the phenomena predicted by the code but with the need of major tuning and the mark “-” has been adopted for the unpredicted phenomena.

- Phenomenological window 1 (0 – 531 s)

The second part of the test starts at the end of Part 1. In the first PhW, the HXP filling and system activation occurs. The deficiencies of the code are the same highlighted in Part 1: the thermal stratification in the HXP (Figure 5.236, Figure 5.237 and Figure 5.238) and OP (Figure 5.240 and Figure 5.241) is not correctly predicted. However, this does not have a significant impact on the remaining part of the transient since, when the triggering valve is opened, the predicted HXP and OP level (Figure 5.234 and Figure 5.235) and the exchanged power (Figure 5.230) are correct; the HXP level peak is anticipated of around 50 s. The opening of the OP discharge valve brings to a gradual reduction of the OP level (Figure 5.235) that is correctly simulated.

Also the increase of the primary side flow rate (Figure 5.228 and Figure 5.229) is well reproduced after the system activation. As in Test 7 Part 1, there are slight discrepancies in the primary steam and condensate temperature (Figure 5.232 and Figure 5.233); this can be attributed to the fact that the experimental steam temperature shows a small superheating (around 5°C), while in the simulation saturation conditions are present.

When the HXP is flooded, the temperatures in the upper part of the HXP drop to the saturation temperature (Figure 5.237 and Figure 5.238) while, in the lower part, due to the income of colder water from the OP, the temperature reaches 60°C in the experiment and 67°C in the simulation (Figure 5.236). After around 540 s, also the temperature in the lower part of the HXP reaches saturation conditions. The temperature drop and the condensation of the steam initially present in the HXP produces a slight pressure decrease in the HXP itself (Figure 5.239); then the pressure rises fast due to the massive steam production. The HXP maximum pressure is underestimated in the calculation (16 kPa instead of 22 kPa as in the experiment).

- Phenomenological window 2 (531 – 2 282 s)

This PhW represents the quasi-steady system operation; in fact, after the initial peak, the HXP level stabilises at around 2.4 m (Figure 5.234) and the HX power and primary side flow rates remain around their maximum values around 19.5 MW and 13 kg/s respectively. The condensation in the HX tubes produces a condensate level that reduces the total pressure difference across the HX, due to the gravitational contribution of the liquid level, from around -0.8 kPa to around -1.2 kPa (Figure 5.242).

The HXP level presents oscillations of around 30 cm that are not predicted by the code and the temperatures are at saturation condition. Due to significant steam formation, the HXP relative pressure remains between 17 and 22 KPa, with a slight underestimation considering the calculated results. Also the OP level presents strong oscillations in the experiment that are not predicted by the calculation (Figure 5.235). At 1 150 s the OP

discharge valve is opened leading to an OP gradual level reduction that is correctly predicted by the code.

The steam produced in the HXP is directed to the OP through the steam duct and the injector; this causes an increment of the pressure drop across the injector (Figure 5.243) that is correctly predicted by the code, even if the experimental oscillations are reproduced only between 750 s and 1 250 s. The steam is condensed in the OP, causing the increment of the OP temperatures (Figure 5.240 and Figure 5.241) that reach the saturation value at around 1 500 s. The HX upper and lower header temperature is around 113°C, around 10°C above the saturation temperature of the HXP.

In this central PhW the steam and the condensate temperatures are underestimated in the calculation of around 5°C and 10°C respectively (Figure 5.232 and Figure 5.233). This is probably due to the fact that experimental temperatures are not in saturation condition as expected, but the steam is superheated by around 5°C.

- Phenomenological window 3 (2 282 – 5 735 s)

In the last PhW of Test 7 Part 2 the deactivation of the system is investigated. The opening of the OP discharge valve produces a reduction of the OP and HXP levels, and after around 2 300 s the power transferred from the HX to the HXP begins to reduce (Figure 5.230). This leads to a reduction of the primary steam and condensate flow rate (Figure 5.228 and Figure 5.229). The injector in the OP is uncovered after around 2 600 s and the steam produced in the HXP that enters in the OP is vented through the boil-off pipe. The reduction of the HX power causes also a decrease of the condensate level in the HX tubes leading to a higher pressure difference across the HX because of the reduction of the gravitational contribution of the liquid level (Figure 5.242).

At 3 338 s the triggering valve is closed and the level in the HXP starts to reduce significantly since water is no longer reintegrated from the OP (Figure 5.234). The HX power is reduced together with the steam production in the HXP. This also leads to a reduction of the HXP pressure (Figure 5.239) and of the injector differential pressure (Figure 5.243), since less steam is directed to the OP. The lower part of the HXP is always flooded and the fluid temperature remains at saturation condition (Figure 5.236), while the progressive uncovering of the upper part causes the formation of superheated steam (Figure 5.237 and Figure 5.238). As at the beginning of the transient, the thermal stratification that occurs in the HXP at the end of the transient is not correctly simulated by the code. The uncovering of the HXP also causes the temperature rise in the HX upper header (Figure 5.244), while the lower one is always flooded (Figure 5.245).

At around 4 660 s, the primary pressure (Figure 5.231) reduces due to the beginning of the primary side depressurisation in the test; as a consequence, also the steam and the condensate temperature decrease (Figure 5.232 and Figure 5.233).

The HX power as function of the HXP level for Test 7 Part 2 is presented in Figure 5.246, showing a reasonable agreement between the experimental data and the RELAP5-3D prediction.

The maximum time step is set to 0.002 s; the computational time is 1 h 44 min.

Table 5.36. Main relevant thermal-hydraulic aspects related to Test 7 Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	300	-
Maximum level in the HXP	453	3.22 m
Maximum exchanged power	470 – 2 870	19.9 MW
OP discharge valve F031 opening	1 150	-
Triggering valve F045 closure	3 338	-
HX pool level decreasing and loss of mass from the boil-off	2 850 – 5 736	-
Primary side depressurisation beginning for end of test	4 670	-

Table 5.37. Qualitative accuracy evaluation for PERSEO Test 7
Part 2

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F_A001 (der.)	+
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W_IC (der.)	+
				Level HXP	L_VQ (der.)	
				Level OP	L_VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	+
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
				Diff. pressure HX upper-lower header	DP-003	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure steam duct injector	DP-J001	o
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Power heat exchanger	W_IC (der.)	o
				Level HXP	L_VQ (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
F	Behaviour of large pool: Thermal stratification	+	+	Power heat exchanger	W_IC (der.)	-
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP	L_VQ (der.)	+
				Level OP	L_VP (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	

**Table 5.36. Qualitative accuracy evaluation for PERSEO Test 7
Part 2 (Continued)**

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L VP (der.)	+
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

Figure 5.228. Test 7 Part 2 - Steam flow rate

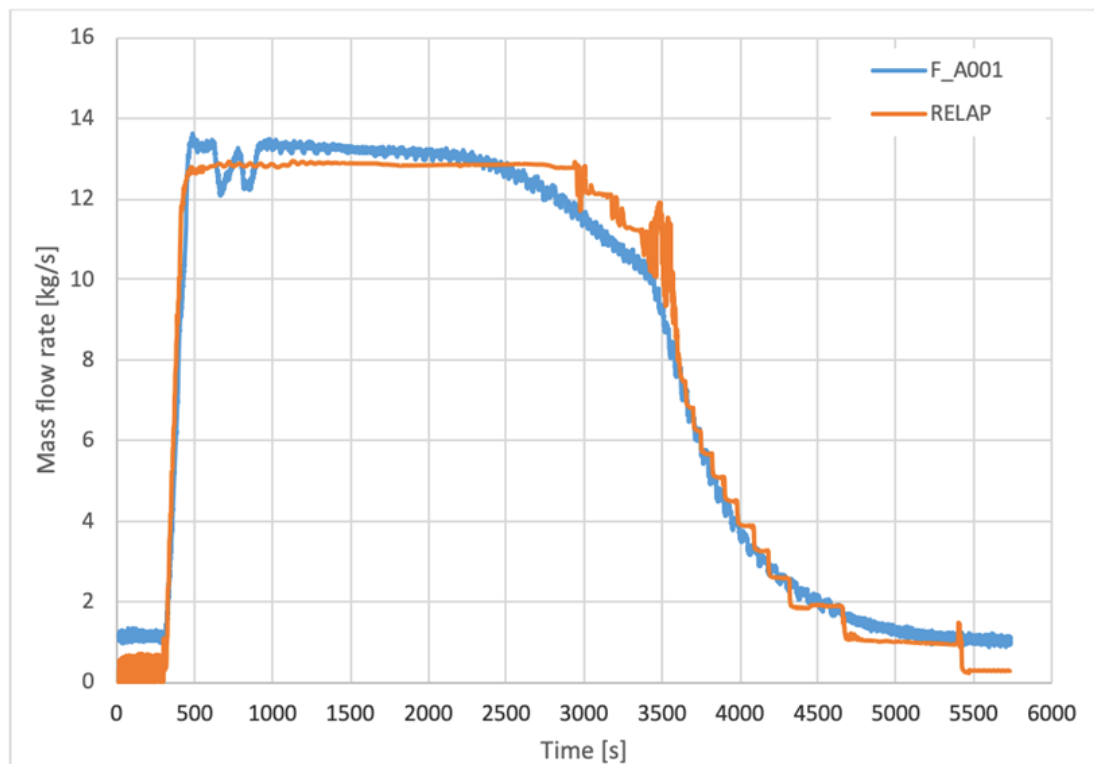


Figure 5.229. Test 7 Part 2 - Condensate flow rate

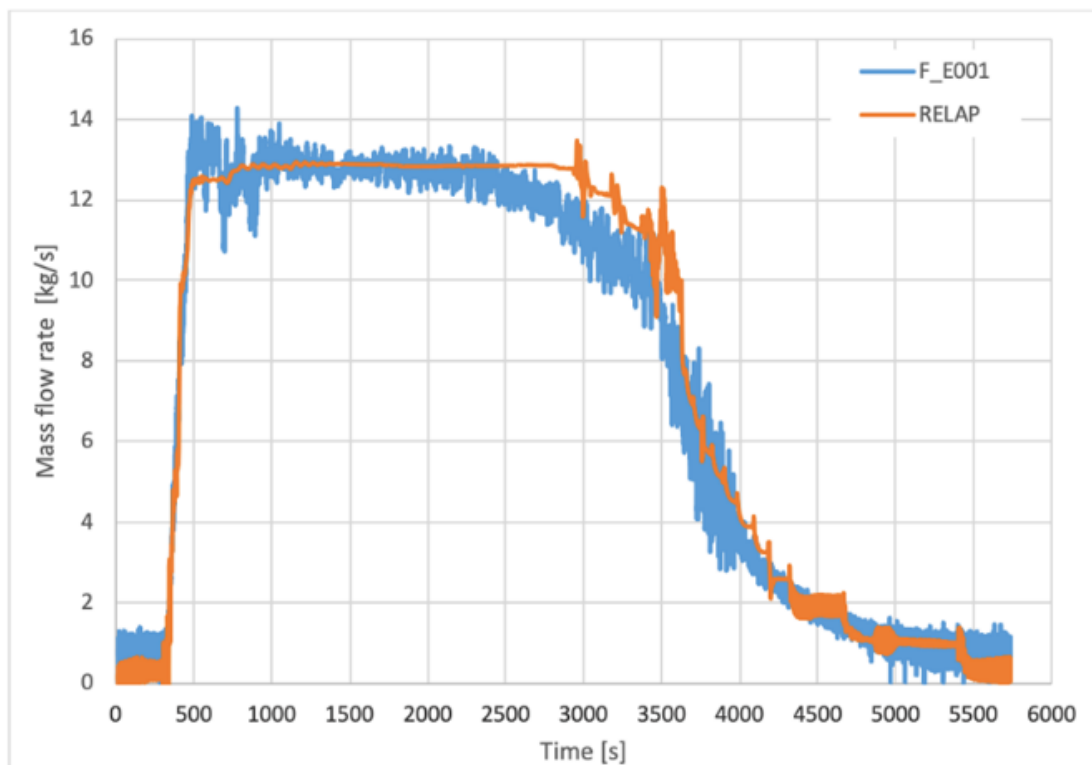


Figure 5.230. Test 7 Part 2 - HX power

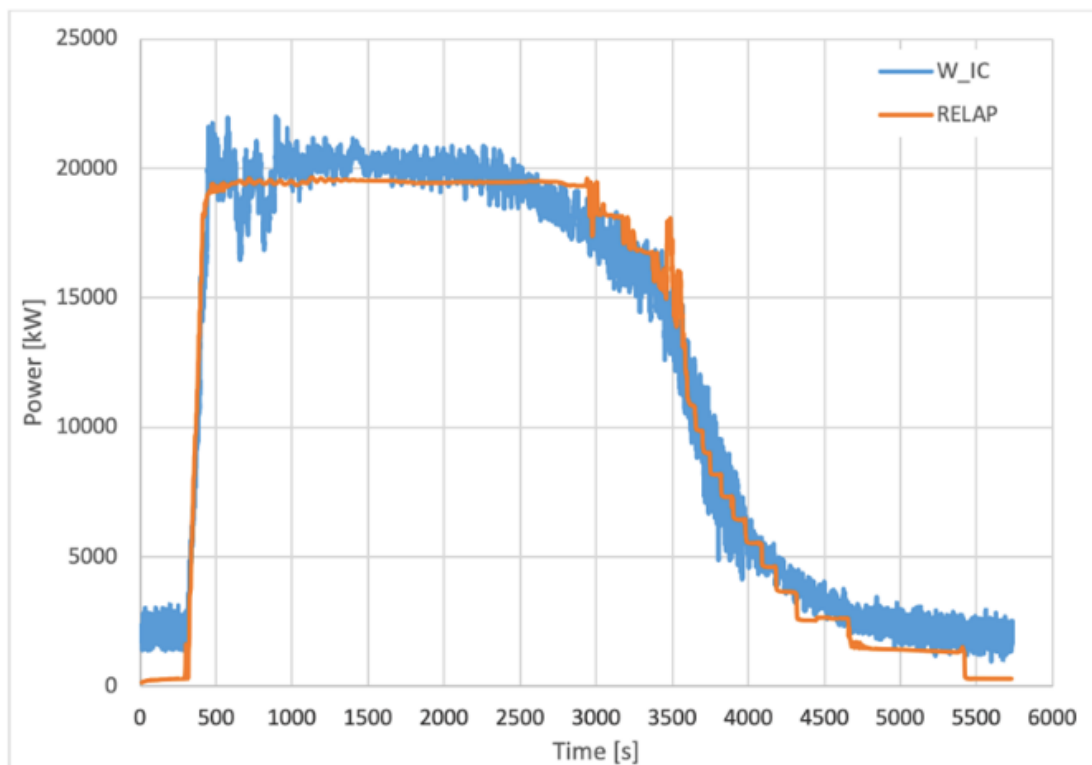


Figure 5.231. Test 7 Part 2 - Primary pressure

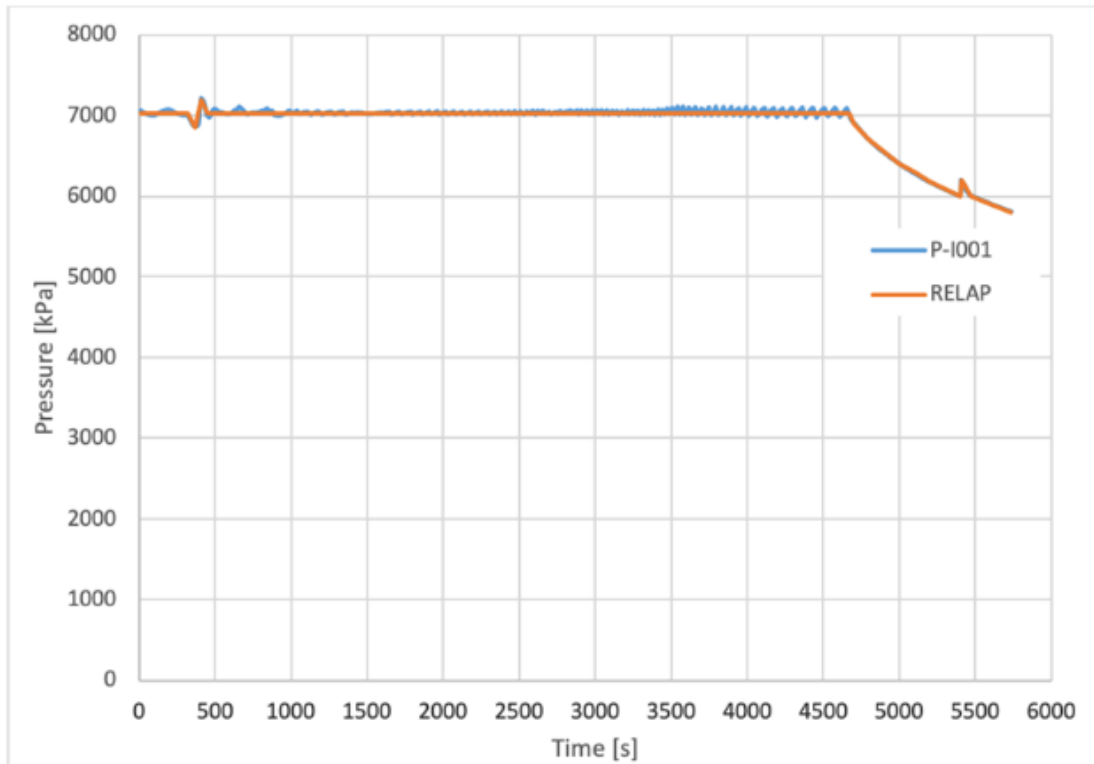


Figure 5.232. Test 7 Part 2 - Steam temperature

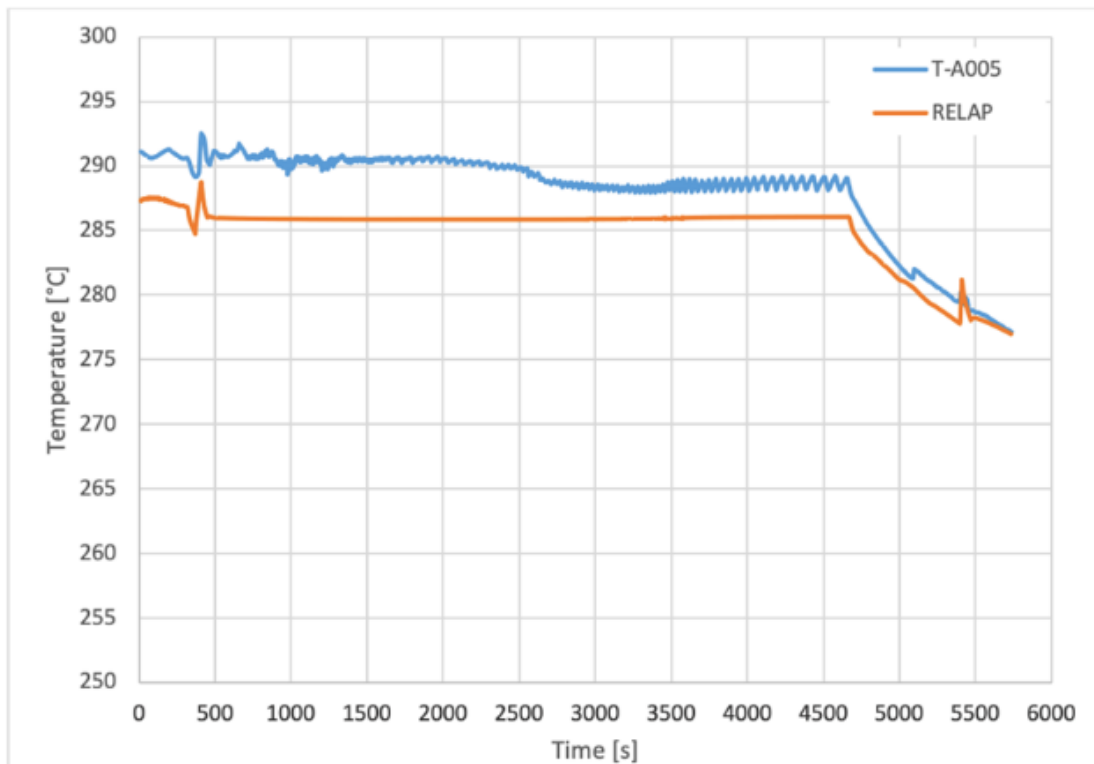


Figure 5.233. Test 7 Part 2 - Condensate temperature

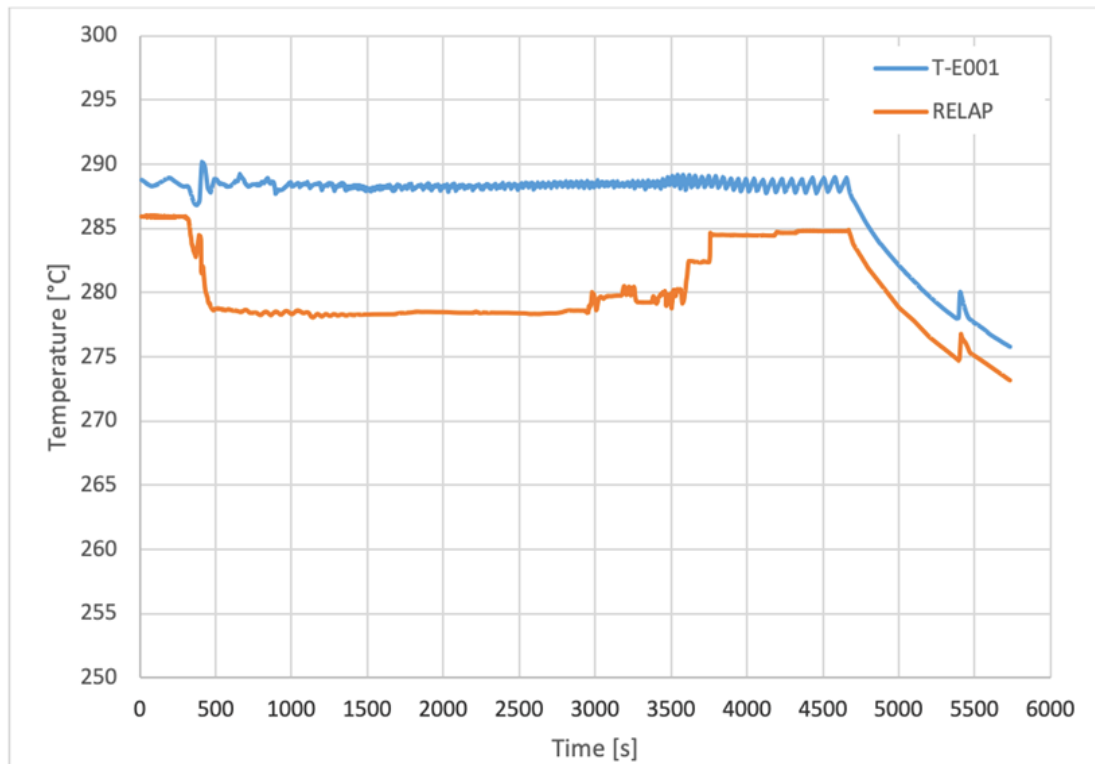


Figure 5.234. Test 7 Part 2 - HXP level

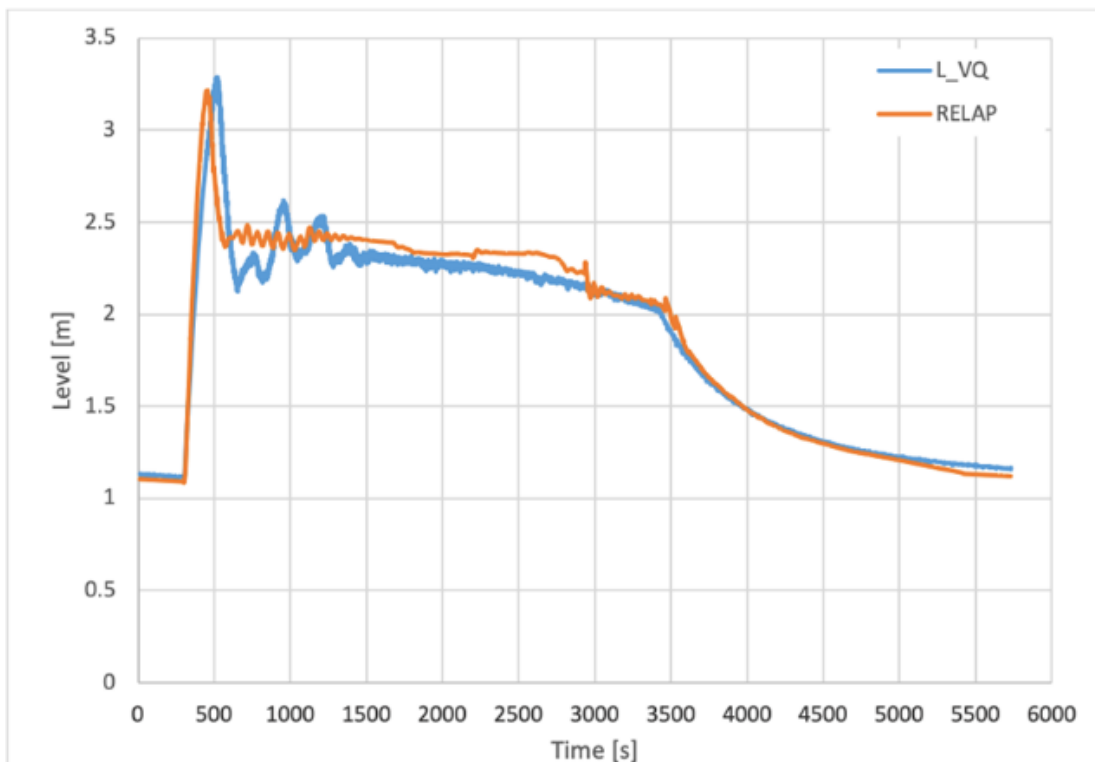


Figure 5.235. Test 7 Part 2 - OP level

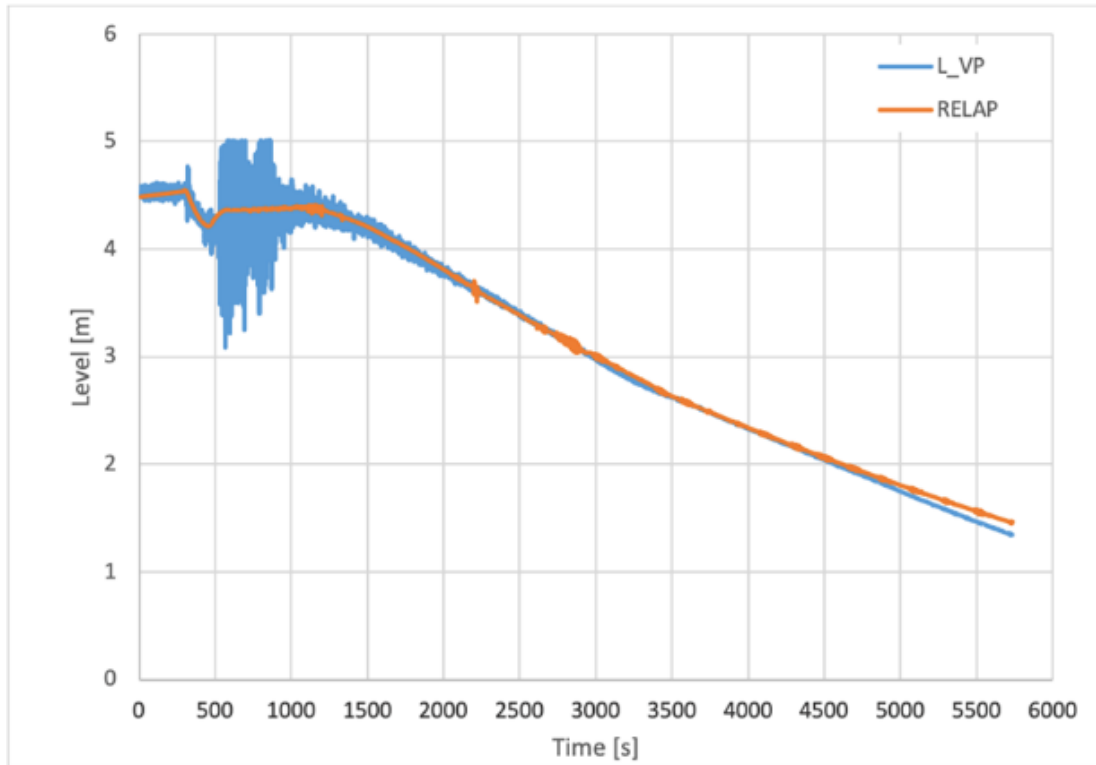


Figure 5.236. Test 7 Part 2 - HXP temperature T-Q037

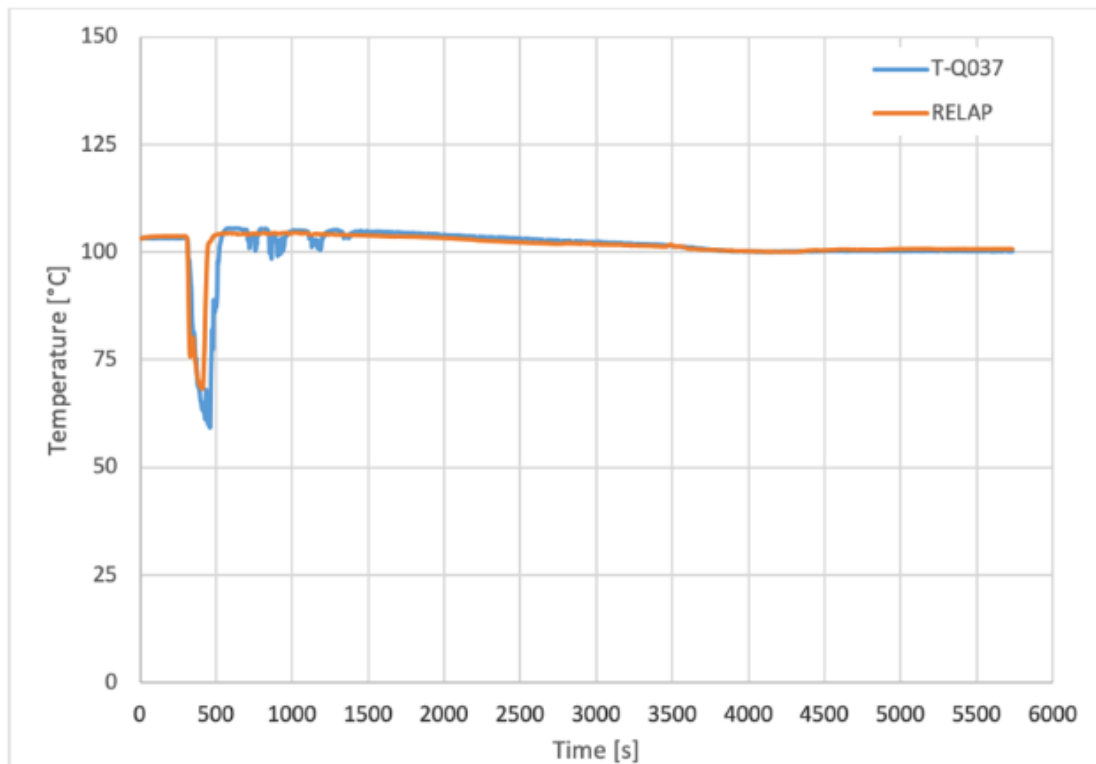


Figure 5.237. Test 7 Part 2 - HXP temperature T-Q034

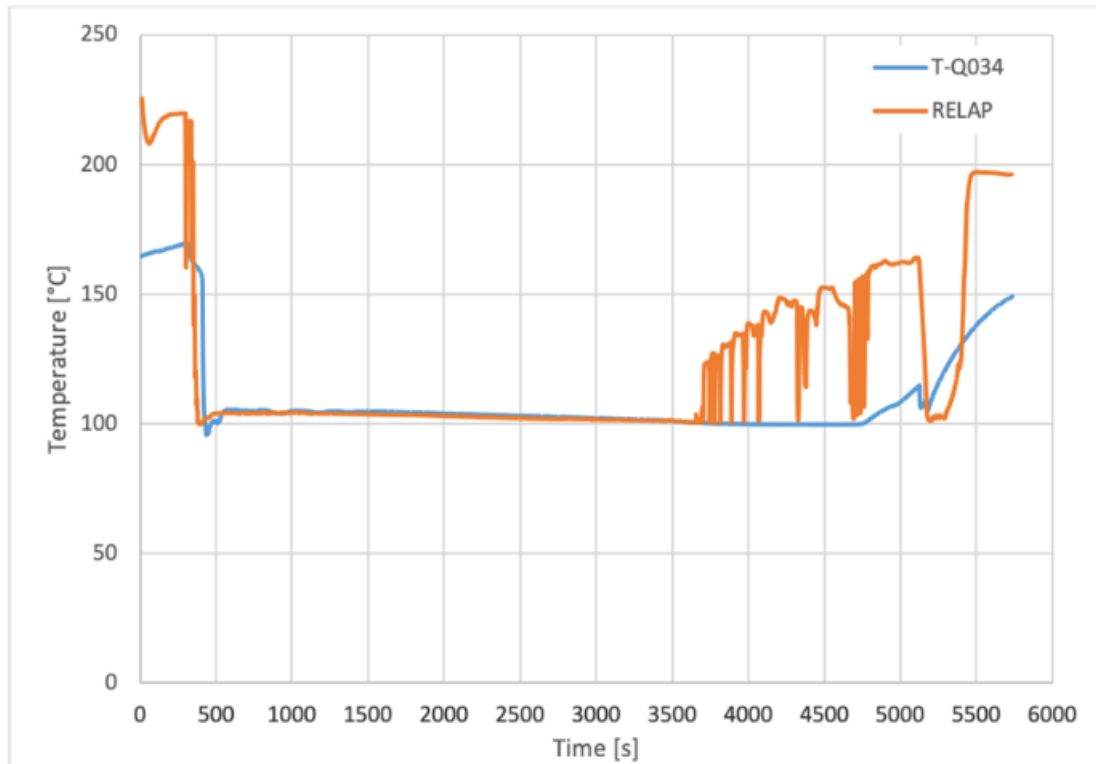


Figure 5.238. Test 7 Part 2 - HXP temperature T-Q031

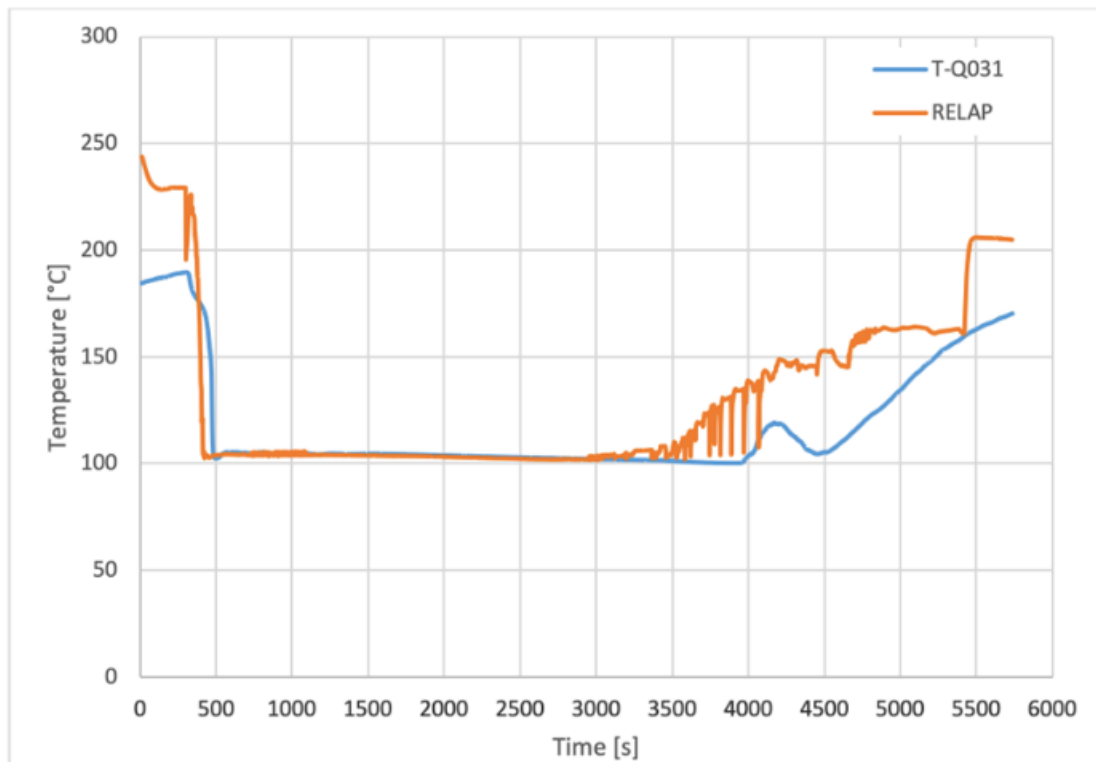


Figure 5.239. Test 7 Part 2 - Relative pressure HXP

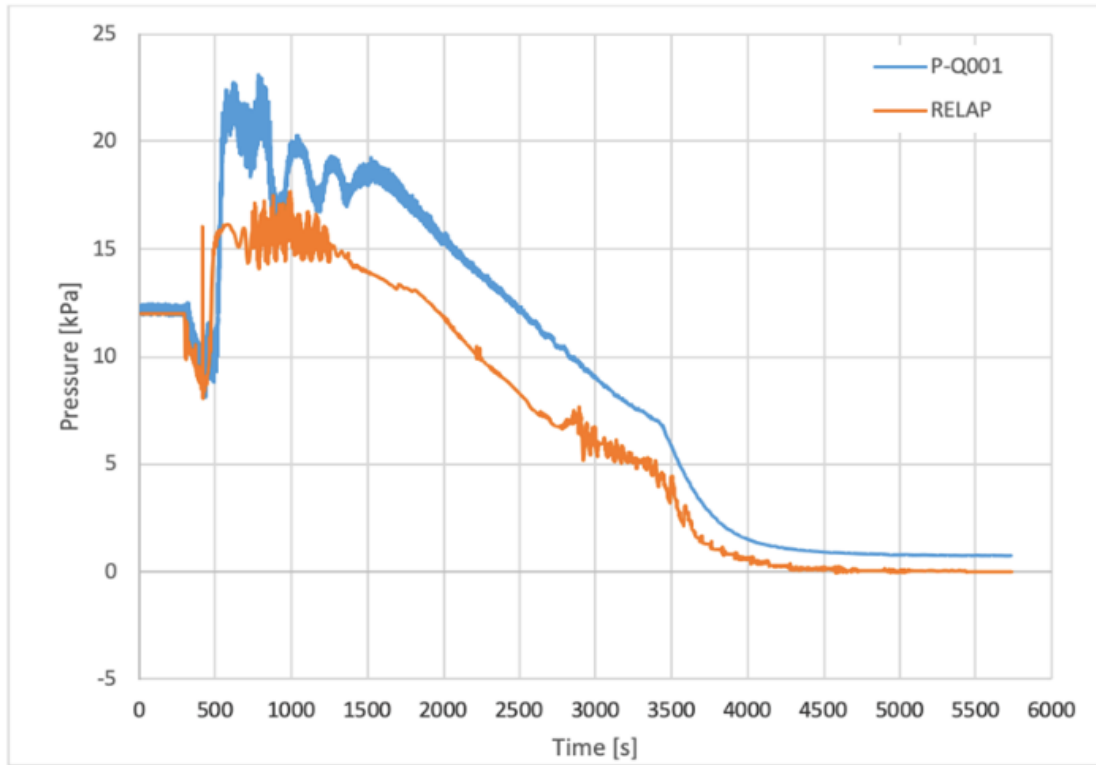


Figure 5.240. Test 7 Part 2 - OP temperature T-P008

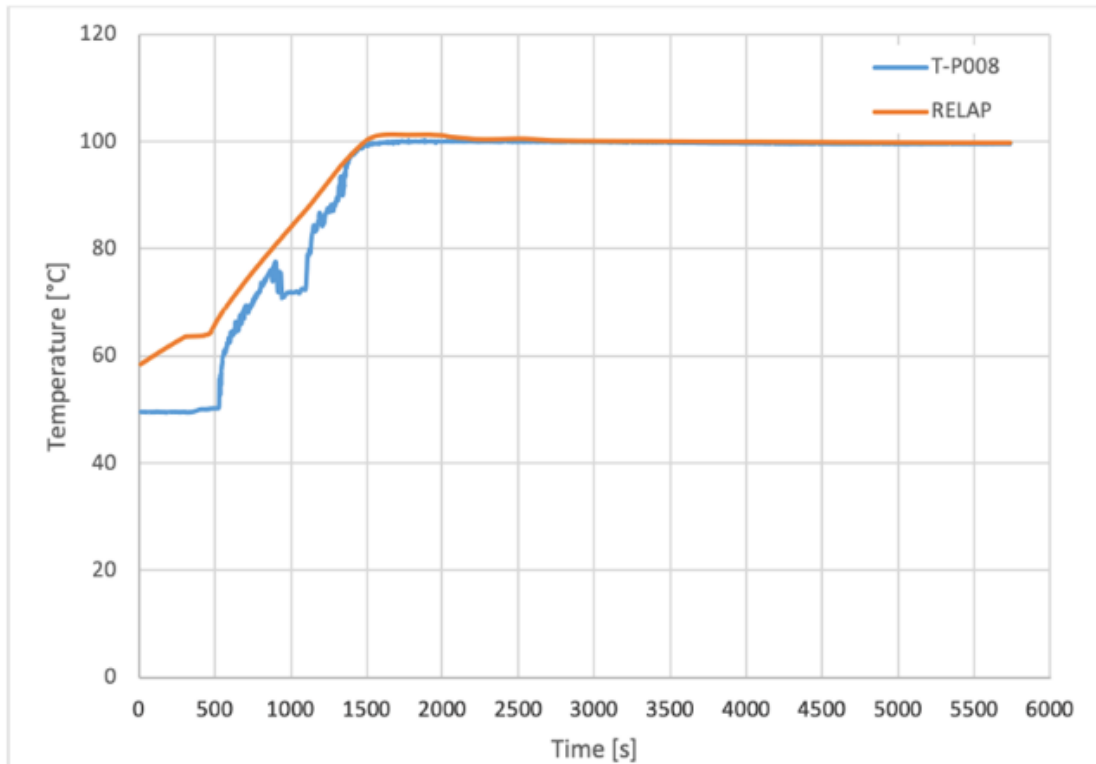


Figure 5.241. Test 7 Part 2 - OP temperature T-P021

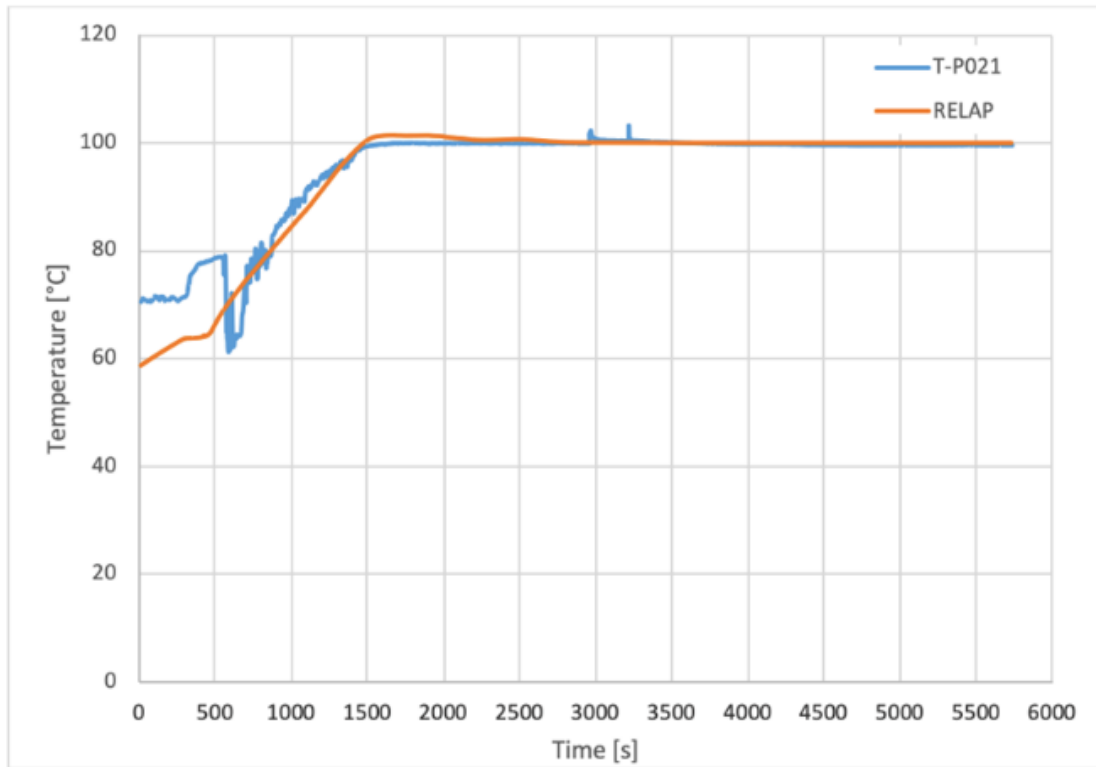


Figure 5.242. Test 7 Part 2 - HX differential pressure

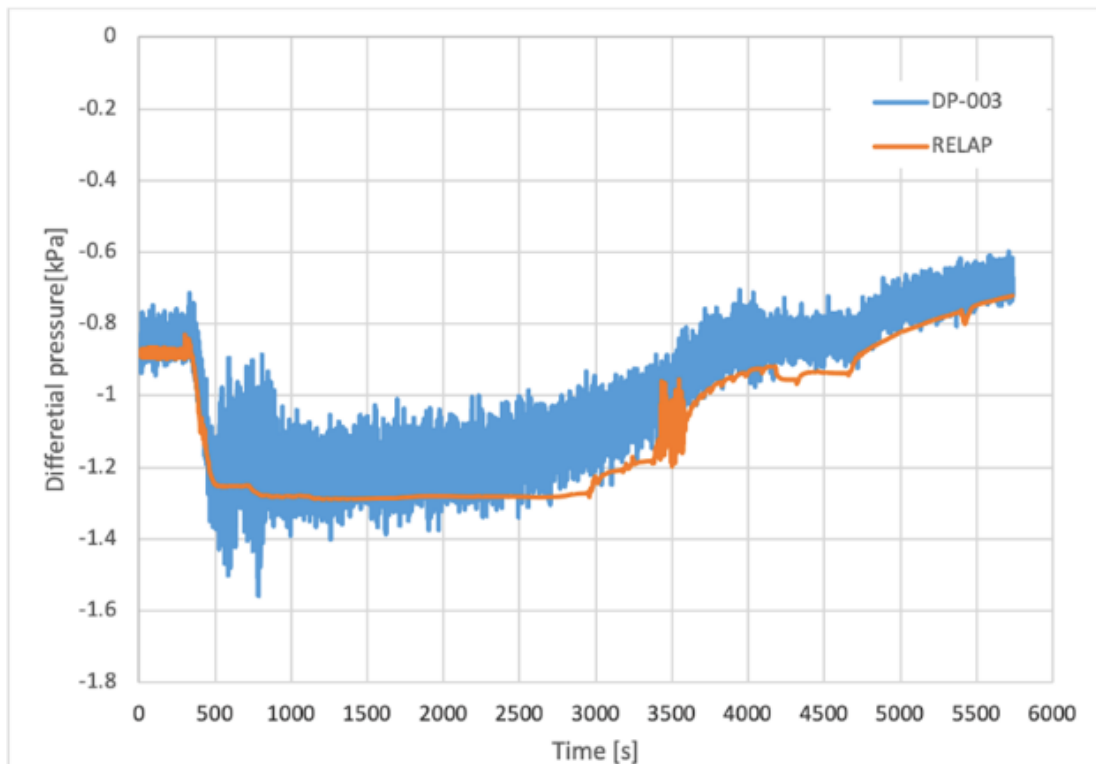


Figure 5.243. Test 7 Part 2 - Injector differential pressure

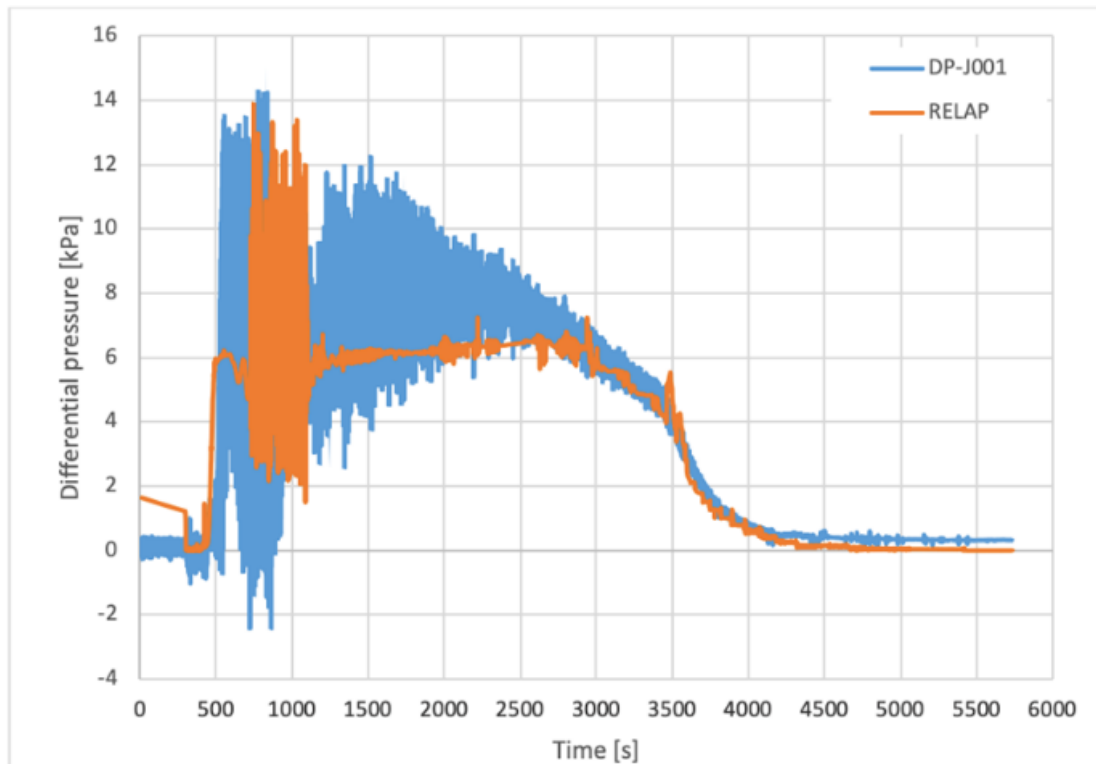


Figure 5.244. Test 7 Part 2 - HX upper header outer wall temperature

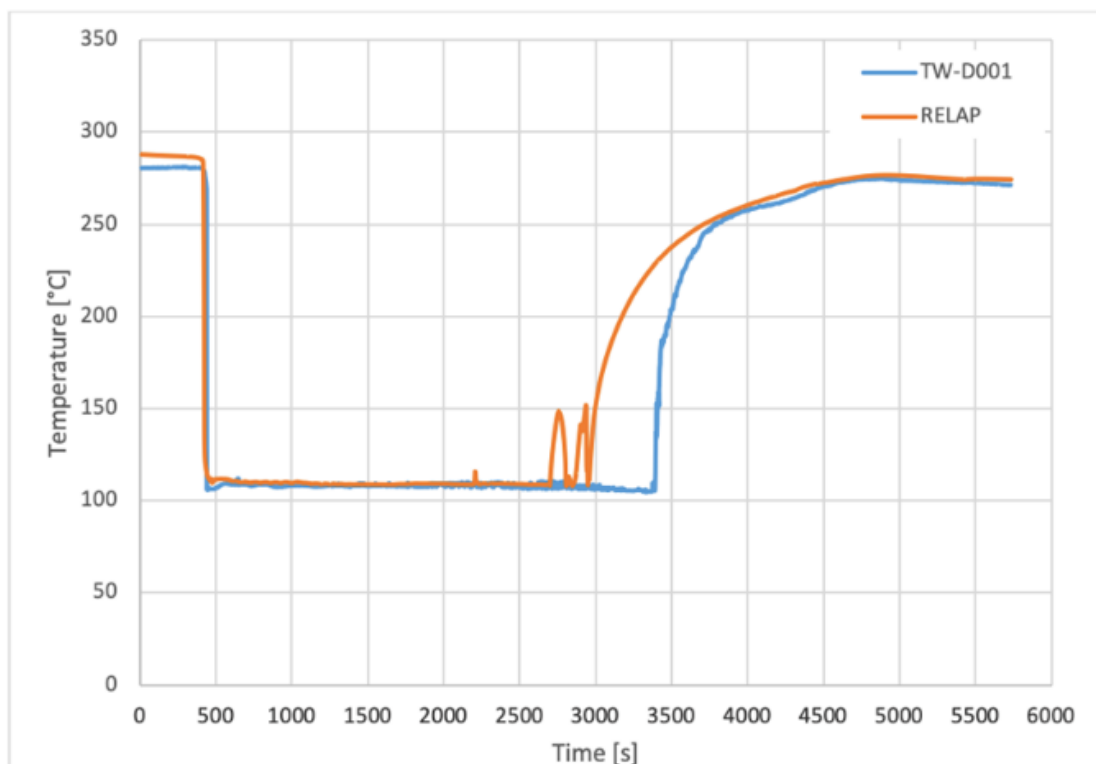


Figure 5.245. Test 7 Part 2 - HX lower header outer wall temperature

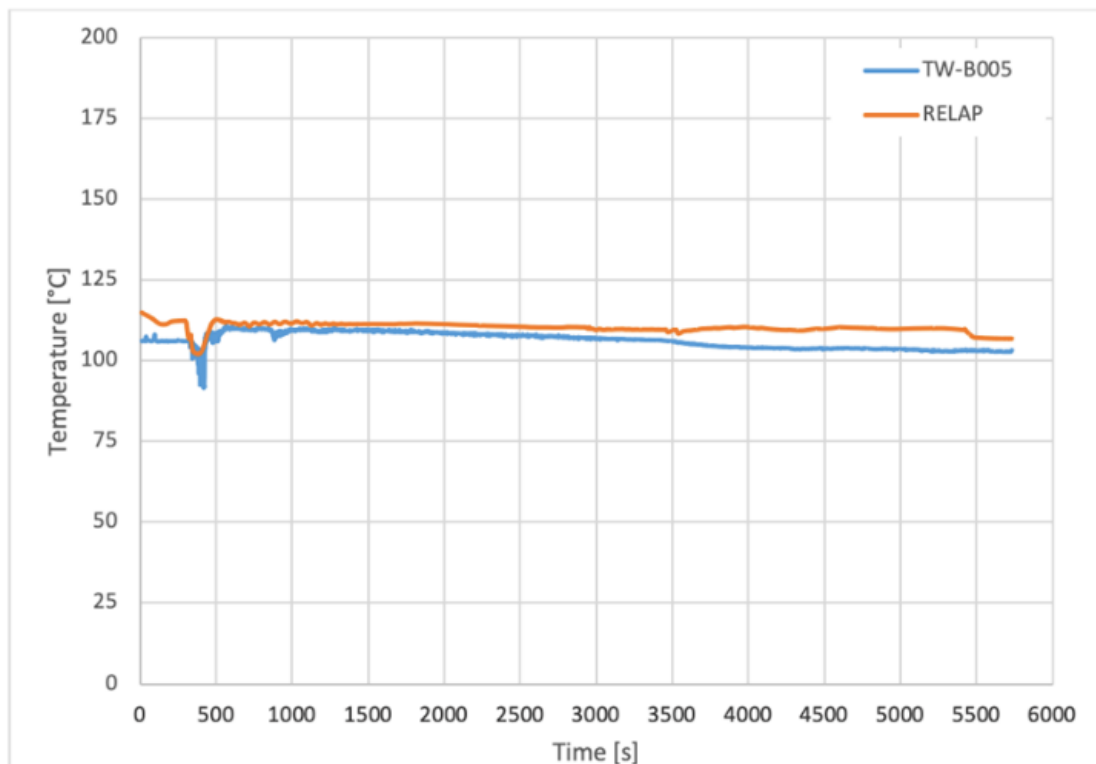
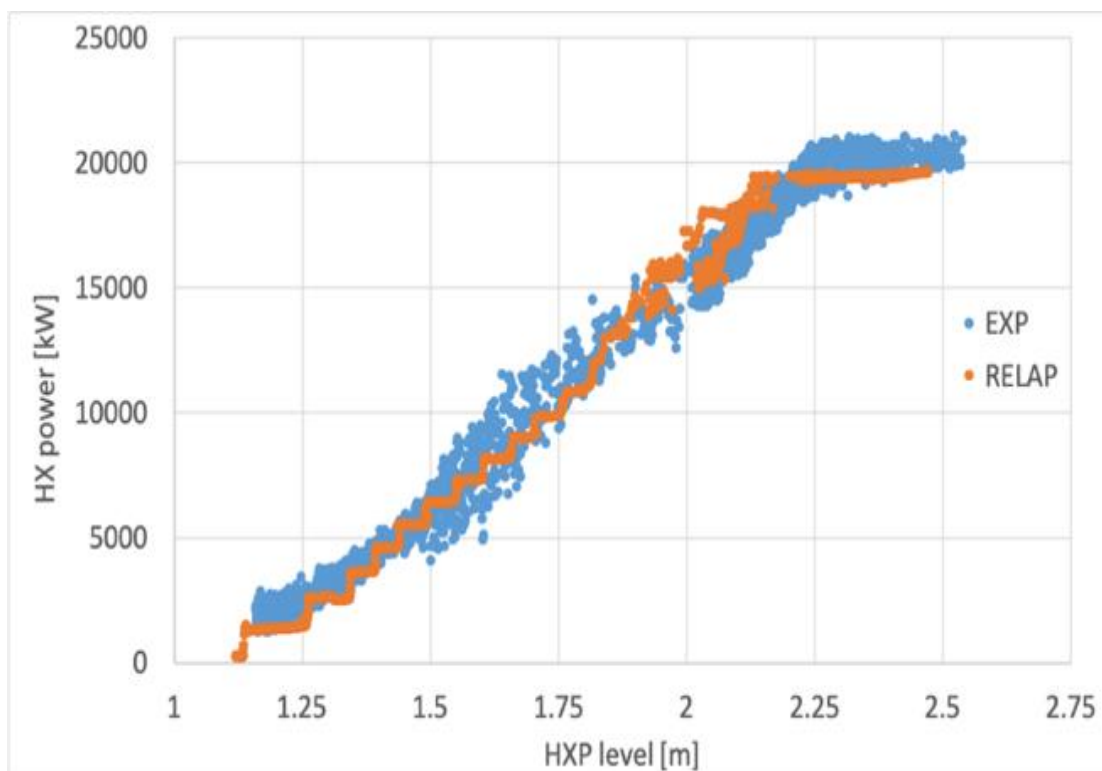


Figure 5.246. Test 7 Part 2 - HX power as function of the HXP level



SECTION 5: CONCLUSIONS

All the main phenomena occurring in PERSEO Test 7 Parts 1 and 2 were reasonably predicted by RELAP5-3D with the exception of thermal stratification in the pools.

The heat transfer between the HX and the HXP was initially strongly under predicted. To improve the code prediction, a heat transfer multiplication coefficient (called fouling factor in RELAP5-3D) was applied to the HX heat structures. The optimum value for PERSEO Test 7 Parts 1 and 2 of the fouling factor resulted to be 2.4.

ANNEX 5.2.6 A: SENSITIVITY RESULTS FOR THE CHOICE OF THE FOULING FACTOR

This Appendix presents a summary of the sensitivity analysis performed to choose the fouling factor for the HX heat structures. After having completed the nodalisation of the PERSEO facility without considering a fouling factor on the HX (corresponding to having a fouling factor of 1.0), a strong underestimation of the HX power (Figure 5.247) and steam and condensate flow rate (Figure 5.248 and Figure 5.249) has been observed. This has been attributed to an underestimation of the heat transfer coefficients on the inner and outer side of the HX, as already found in previous studies [5.2.6 3], [5.2.6 4], caused by the adoption of heat transfer correlation outside their validity domain. This has been corrected with the use of a fouling factor on the inner and outer side of the HX heat structure. The value of the fouling factor that allows to get the correct results has been derived with a sensitivity analysis considering the HX power and the steam and condensate mass flow rates to find the optimum value. For this analysis the second phenomenological window of Test 7 Part 2 has been considered, where there is an almost steady power transfer from the HX to the HXP and primary system flow rates. As shown in Figure 5.247, Figure 5.248 and Figure 5.249 a value of the fouling factor that gives better results is 2.4.

Figure 5.247. HX power as function of the fouling factor

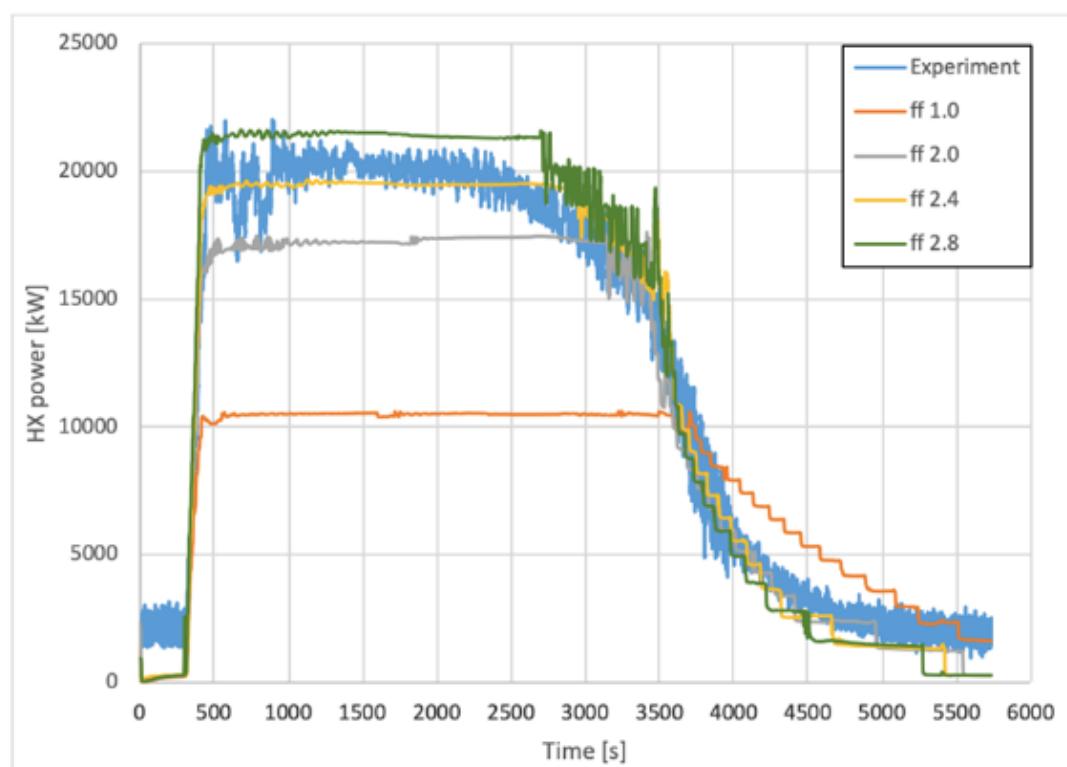


Figure 5.248. Steam mass flow rate as function of the fouling factor

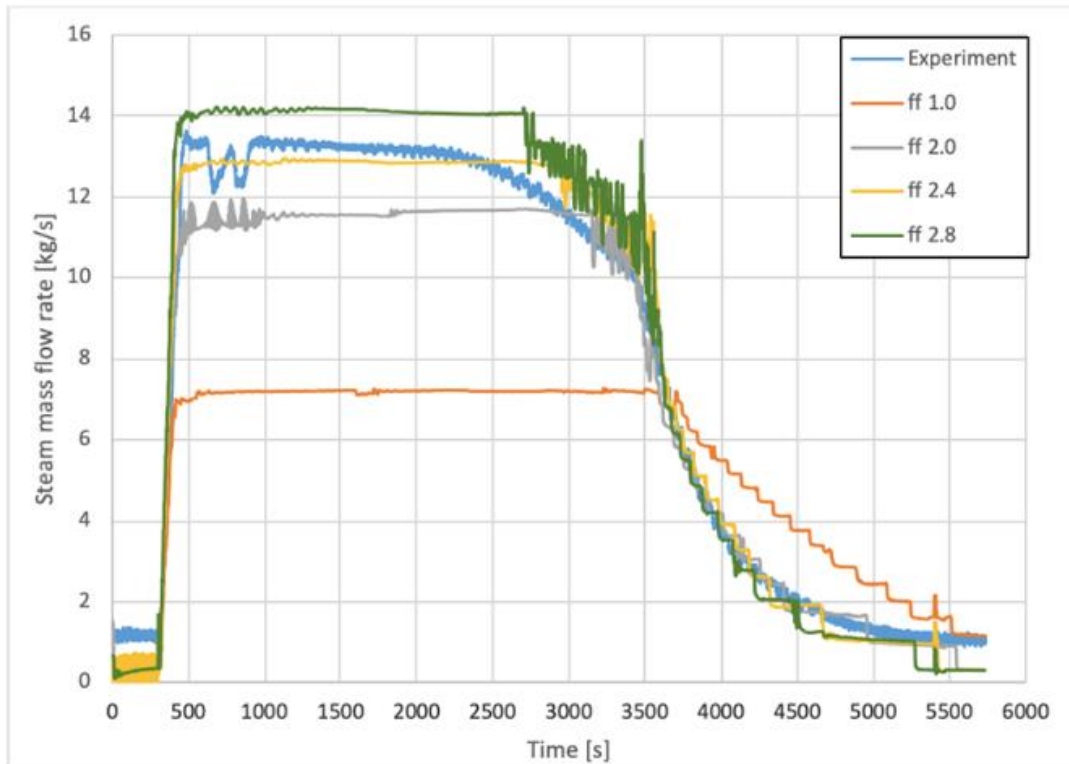
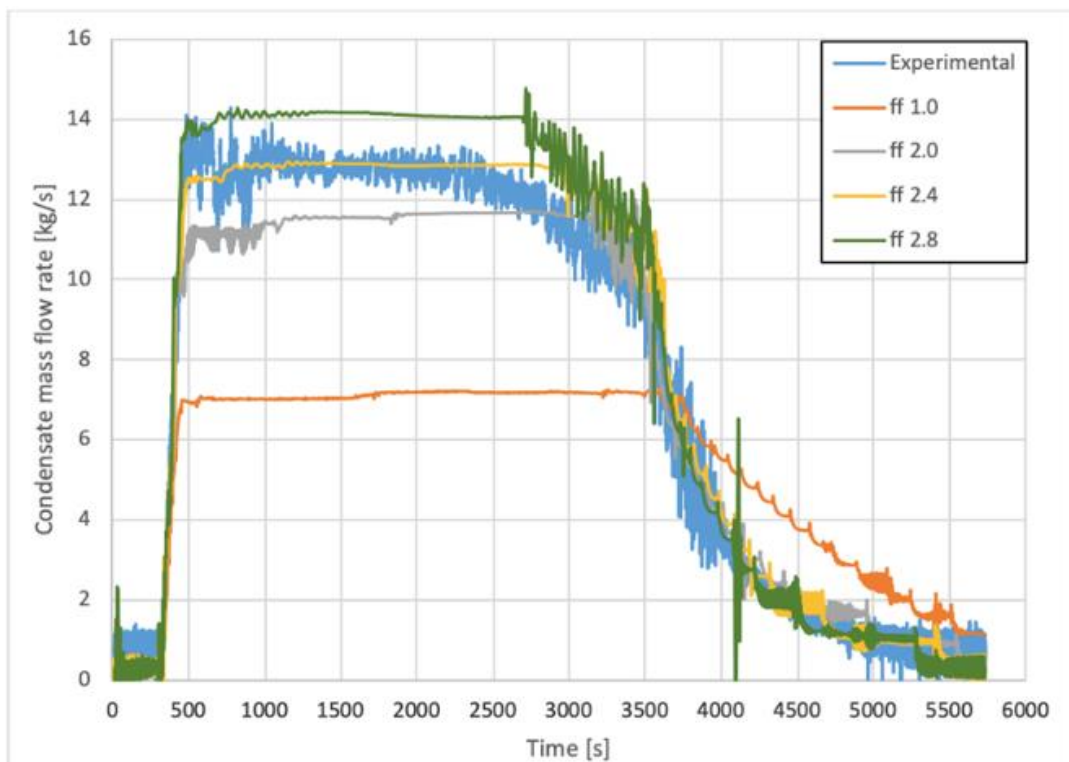


Figure 5.249. Condensate mass flow rate as function of the fouling factor



ANNEX 5.2.6 B: SHAH AND CHEN CORRELATIONS

Shah correlation

Shah correlation for the computation of condensation heat transfer coefficient in RELAP5-3D is expressed as [5.2.6 5], [5.2.6 7]:

$$h_{Shah} = h_{sf} \left(1 + \frac{3.8}{Z^{0.95}} \right)$$

where

$$Z = \left(\frac{1}{X} - 1 \right)^{0.8} P_{red}^{0.4}$$

where X is the static quality and P_{red} the reduced pressure ($=P/P_{crit}$, with P_{crit} the critical pressure). h_{sf} is the superficial heat transfer coefficient computed as:

$$h_{sf} = h_l (1 - X)^{0.8}$$

with h_l the heat transfer coefficient computed with the Dittus-Boelter correlation assuming that all the fluid is in liquid phase.

The correlation has been derived with experimental data on water, R-11, R-12, R-22, R-113, methanol, ethanol, benzene, toluene, and trichloroethylene condensing in horizontal, vertical, and inclined pipes with:

- Pipe diameter from 7 to 4 mm;
- Reduced pressure from 0.002 to 0.44;
- Saturation temperature from 21 to 310°C;
- Vapour velocities from 3 to 300 m/s;
- Vapour qualities from 0 to 100%;
- Mass flux from 39 000 to 758 000 kg/m²h;
- Heat flux from 158 to 1 893 000 W/m²;
- All liquid Reynolds number from 100 to 63 000;
- Liquid Prandtl number from 1 to 13.

Chen correlation

Chen correlation [5.2.6 6] is adopted in RELAP5-3D for subcooled and saturated nucleate boiling even if the correlation was derived for saturated condition [5.2.6 7]. The equation consists in the sum of two terms: macroscopic convection and microscopic boiling. The macroscopic convection is computed according to Dittus-Boelter equation multiplied by a Reynolds number factor F (the ratio of the two-phase Reynolds number to the Reynolds number considering only the liquid phase) while the microscopic boiling is obtained from Forster-Zuber equation multiplied by a suppression factor S (defined as the ratio of the effective superheating for the bubble formation to the total superheating of the wall [5.2.6 6]). The correlation was tested with data for water and organic fluids.

The heat flux according to Chen can be expressed as:

$$q'' = h_{mac}(T_w - T_{spt})F + h_{mic}(T_w - T_{spt})S$$

where T_w is the wall temperature and T_{spt} the saturation temperature based on the total pressure. h_{mac} is the macroscopic heat transfer coefficient computed with Dittus-Boelter correlation (considering the Reynolds number, the Prandtl number and the thermal conductivity referred to the liquid phase) and h_{mic} the microscopic boiling term according to Forster-Zuber:

$$h_{mic} = 0.00122 \left(\frac{k_f^{0.79} C_{pf}^{0.45} \rho_f^{0.49} g_c^{0.25}}{\sigma^{0.5} \mu_f^{0.29} h_{fg}^{0.24} \rho_g^{0.24}} \right) \Delta T_w^{0.24} \Delta P^{0.75}$$

Where:

- k is the thermal conductivity;
- C_p is the specific heat at constant pressure;
- ρ is the density;
- g_c the gravitational conversion factor (in unit systems where force is a primary unit, like in British units, g_c is not equal to 1 as in SI units);
- σ is the surface tension;
- μ is the viscosity;
- h_{fg} is the latent heat of vapourisation;
- $\Delta T_w = T_w - T_{spt}$;
- $\Delta P = P(at T_w) - P$;
- The subscript f is referred to the liquid and g to the vapour/gas.

The factor F was reported by Chen in graphical form; in RELAP it is coded with the curve fit from Butterworth [5.2.6 7] as:

$$F = 2.35(\chi_{tt}^{-1} + 0.213)^{0.736}$$

where χ_{tt} is the Lockhart-Martinelli factor whose inverse is:

$$\chi_{tt}^{-1} = \left(\frac{G_g}{G_f} \right)^{0.9} \left(\frac{\rho_f}{\rho_g} \right)^{0.5} \left(\frac{\mu_g}{\mu_f} \right)^{0.1}$$

being G the mass flux.

For the microscopic boiling term, the suppression factor S is needed since the Forster-Zuber correlation has been derived for the case of pool boiling. Similarly to the factor F , also the factor S was proposed by Chen in a graphical form while in RELAP it is coded according to Butterworth curve fitting as reported by Bjornard and Griffith [5.2.6 8]:

$$S = \begin{cases} (1 + 0.12 Re_{tp}^{1.14})^{-1} & Re_{tp} < 32.5 \\ (1 + 0.42 Re_{tp}^{0.78})^{-1} & 32.5 \leq Re_{tp} < 70 \\ 0.0797 & Re_{tp} \geq 70 \end{cases}$$

where

$$Re_{tp} = 10^{-4} Re_f F^{1.25}$$

being Re_f the Reynolds number of the liquid:

$$Re_f = \frac{G_f D}{\mu_f}$$

For $Re_{ip} \geq 70$, the suppression factor S is 0.0797 instead of 0.1, as reported by Bjornard and Griffith [5.2.6 8], to avoid a discontinuity.

For subcooled nucleate boiling the equation is the same as for saturated nucleate boiling with modification proposed by Bjornard and Griffith [5.2.6 7], [5.2.6 8]: $F=1$ and use of the total mass flux in the Reynolds number. In addition, in the macroscopic convection term, the liquid temperature is used instead of the saturation temperature. The correlation has been tested with some fluids finding a large data scattering (+180% to -60%) with a general underestimation of the data.

ANNEX 5.2.6 C: PRESSURE BOUNDARY CONDITION IN THE SIMULATIONS

This annex presents the pressure boundary condition adopted for the simulations (in time-dependent volume 340) for both Part 1 (Table 5.37) and 2 (Table 5.38). It is given in a table form, as in the RELAP5-3D input, and linear interpolation is performed between the reported values.

Table 5.38. Pressure in time-dependent volume 340 for Test 7 Part 1

Time [s]	Pressure [bar]
9 900	70
11 050	70
11 250	60
11 280	57
11 380	56
11 440	60
11 530	71
11 570	69
11 600	70
15 000	70

Table 5.39. Pressure in time-dependent volume 340 for Test 7 Part 1

Time [s]	Pressure [bar]
0	70.3
320	70.3
370	68.5
410	72
450	70.3
4 670	70.3
4 700	69
4 800	67
4 900	65.5
5 000	64
5 100	63
5 200	61.8
5 300	60.9
5 400	60
5 410	62
5 470	60
5 800	57.5

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- [5.2.6 1] INL/MIS-15-36723 (2015), *The RELAP5-3D© Code Development Team, RELAP5-3D© Code Manual Volume I: Code Structure, System Models and Solution Methods*, Revision 4.3.
- [5.2.6 2] Mascari, F., A. Bersano, F. Ferri, C. Lombardo and L. Burgazzi, “Description of PERSEO Test n 7”.
- [5.2.6 3] Bandini, G., P. Meloni, M. Polidori and C. Lombardo (2011), “Validation of CATHARE V2.5 thermal-hydraulic code against full-scale PERSEO tests for decay heat removal in LWRs”, *Nuclear Engineering and Design*, Vol. 241, pp. 4662-4671.
- [5.2.6 4] Bianchi, F., P. Meloni, R. Ferri and A. Achilli (2004), “Assessment of RELAP5 mod3.3 and CATHARE 2 v1.5A against a full scale test of PERSEO device”, *Proceedings of ICONE12: 12th International Conference on Nuclear Engineering*, 25-29 April 2004, Arlington, Virginia, United States.
- [5.2.6 5] Shah, M.M. (1979), “A general correlation for heat transfer during film condensation inside pipes”, *International Journal of Heat and Mass Transfer*, Vol. 22, Issue 4, Pages 547-556.
- [5.2.6 6] Chen, J.C. (1966), “A Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow”, *Industrial & Engineering Chemistry Process Design and Development*, Vol. 5 (3), pp 322–329.
- [5.2.6 7] The RELAP5-3D© Code Development Team (2015), *RELAP5-3D© Code Manual Volume IV: Models and Correlations*, INL/MIS-15-36723, Revision 4.3.
- [5.2.6 8] Bjornard, T.A. and P. Griffith (1977), *PWR Blowdown Heat Transfer*, *ASME Winter Annual Meeting, Atlanta, GA, 27 November – 2 December 1977*, in: Jones, O. C. and S. G. (1977), *Bankoff, Thermal and Hydraulic Aspects of Nuclear Reactor Safety - Volume I: Light Water Reactors*, New York: ASME, pp. 17-41.

5.2.7. UJV

SECTION 1: GENERAL INFORMATION

- Organisation: ÚJV Řež, a. s. (Czechia)
- Contact persons/authors: František Lahovský, Zbyněk Parduba , Radim Meca
- Code: RELAP5/MOD3.3Patch05
- Computing environment:
 - Operative systems: Windows 7 Professional
 - RAM: 16 GB
 - CPU: Intel Core i7-3 770 K

SECTION 2: DESCRIPTION OF THE CODE USED

The light water reactor transient analysis code, RELAP5, was developed at the Idaho National Engineering Laboratory (INEL) under sponsorship of the US Nuclear Regulatory Commission (NRC). The MOD3 version of RELAP5 has been developed jointly by the NRC and a consortium consisting of several countries and domestic organisations that were members of the international code assessment and applications programme (ICAP) and its successor organisation, code applications and maintenance programme (CAMP).

RELAP5 is a highly generic code that, in addition to calculating the behaviour of a reactor coolant system during a transient, can be used for simulating a wide variety of hydraulic and thermal transients in both nuclear and non-nuclear systems involving mixtures of steam, water, non-condensable, and solute.

The RELAP5/MOD3.3 equation set gives a two-fluid system simulation using a non-equilibrium, non-homogeneous, six-equation representation. The presence of boron and non-condensable gases is also simulated using separate equations for each. Constitutive models represent the interphase drag, the various flow regimes in vertical and horizontal flow, wall friction, and interphase mass transfer. The code has a point kinetics model to simulate neutronics. The code also has the capability to simulate the presence of slabs of material adjacent to the fluid. Thus, energy transfer to and from stationary slabs of material can be simulated. Control systems and component models permit simulations of equipment controllers, balance-of-plant equipment (e.g. turbines, pumps, and condensers), and lumped-node representations of various processes (e.g. heat transfer from one volume to another).

The two-fluid equations of motion that are used as the basis for the RELAP5 hydrodynamic model are formulated in terms of volume and time-averaged parameters of the flow. Phenomena that depend upon transverse gradients, such as friction and heat transfer, are formulated in terms of the bulk properties using empirical transfer coefficient formulations. The system model is solved numerically using a semi-implicit finite-difference technique. The user can select an option for solving the system model using a nearly-implicit finite-difference technique, which allows violation of the material Courant limit.

SECTION 3: DESCRIPTION OF THE NODALISATION

The RELAP5 nodalisation diagram is shown in Figure 5.250.

The pressure vessel is modelled as a vertical pipe with ten volumes. A steam is supplied to the upper volume by means of a time-dependent volume (saturated steam; pressure corresponds to the measured one) and check valve. A constant water level is kept by means of the time-dependent junction.

The heat exchanger (HX) consists of tubes, headers, and pool. The headers are modelled as branches. 120 tubes are simulated by means of one vertical pipe divided into 18 nodes (each node has a length of 0.1 m). Except the top and bottom, the pool is simulated by two parallel channels to enable circulation. Channels are connected by cross-flow junctions. To consider the diaphragm, the channel containing tubes is not connected to the upper branch.

The vacuum breaker is connected to the HX pool upper volume.

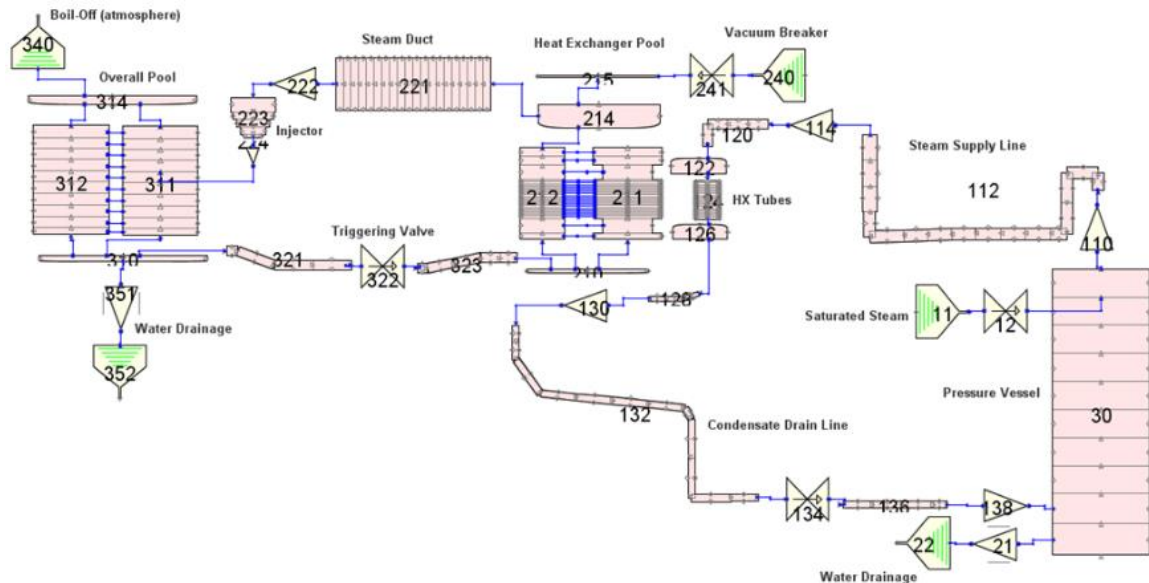
The overall pool (OP) is modelled similarly to the HX pool – the top and bottom are simulated by means of branches, the middle part is modelled as two parallel channels connected by cross-flow junctions. The upper volume is connected to the atmosphere (air; 100 kPa). Discharge of water during the Test 7 Part 2 is simulated by a time-dependent junction connected to the bottom.

Heat structures are modelled on the base of available data. Some dimensions have been estimated. Heat losses were not evaluated; they should have insignificant effect.

Table 5.40. Nodalisation parameters

	Number of hydraulic volumes	Number of junctions	Number of heat structures	Overall volume (m³)
Vessel	10	12	10	43.0
Steam Line	20	20	20	1.85
HX (tubes + headers)	20	20	20	1.83
Condensate line	19	19	19	0.45
HXP	49	73	29	26.11
Steam duct	25	25	25	11.23
OP	22	34	38	165.27
Heat transfer area HX (m ²)	46.16 (tubes + headers; outer surface)			
HX heat structure axial nodes number	20			
HX heat structure radial nodes number	3			

Figure 5.250. RELAP5 nodalisation for PERSEO Test 7



SECTION 4: RESULTS

TEST 7 Part 1

To sufficiently stabilise initial conditions, especially temperatures in the heat exchanger, Test 7 Part 1 was initiated after 4 000 s of a steady state calculation. During this time, pressure in the HX pool was kept constant (100.6 kPa).

The significant initial conditions for Test 7 Part 1 are: saturated fluid in the primary circuit; primary pressure, 7.03 MPa; water level in the pressure vessel, 3.9 m from the bottom (it is kept constant within the whole calculation); HX pool is filled with air (water level 0.18 m); HX pool pressure, 100.6 kPa; steam duct is filled with air; injector is filled with water; overall pool water level, 4.65 m; overall pool water temperature, 15.4°C; triggering valve is closed.

Preliminary calculations showed that RELAP5 underestimates heat exchange. To achieve reasonable agreement with the measured data (Figure 5.253), heat transfer were increased by means of a fouling factor (multiplier for heat transfer coefficients) value of 2.2 on both sides of HX tubes (dominant effect has the primary side). A condensation mode (Nusselt-Shah-Coburn-Hougen) is on the primary side. On the secondary side, a nucleate (Chen-Inayatov), transition (Chen), and film (Bromley) modes are dominant.

Natural circulation in the primary circuit is in good agreement with the measured data (Figure 5.251 and Figure 5.252).

The HX pool level (Figure 5.257), HX pool pressure (Figure 5.262) and overall pool level (Figure 5.258) correspond to the measured ones, except period when boiling starts. It is probably caused by more intensive boiling in the calculation.

Although saturated conditions should be in the primary circuit, the measured temperatures are “superheated” (Figure 5.255 and Figure 5.256).

The calculated HX pool initial temperatures are higher than the data (Figure 5.259, Figure 5.260, Figure 5.261). It may be due to a lower heat loss, or due to an overpredicted heat transfer to air, or due to a higher inner circulation, etc. Although the wall temperatures correspond to the measured ones (Figure 5.267 and Figure 5.269; considering the faster

level decrease) the calculated fluid temperatures start rising too early (maybe due to a higher inner circulation).

Concerning the overall pool temperatures (Figure 5.263 and Figure 5.264), contrary to the measured ones, thermal stratification is minimum (maybe due to a higher inner circulation).

The injector differential pressure is in reasonable agreement with the measured data (Figure 5.266). Appropriate loss coefficients were set in the calculation.

The computational time of the Test 7 Part 1 was 45 min. The maximum time step was set to 0.02 s, but it was often reduced by the code.

All important phenomena were clearly predicted by the code, except the HX heat transfer and OP thermal stratification that were predicted partially (Table 5.41).

Table 5.41. Main relevant thermal-hydraulic aspects related to Test 7 Part 1

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	10 475 – 10 608	-
Triggering valve (F045) re-opening and re-closure	10 621 – 10 655	-
Maximum level in the HX pool for the first filling step	10 655	1.40 m
Small heat removal from the primary side	10 660 – 11 040	1.7 – 1.9 MW
Slow water consumption in the HX pool	-	Level is increasing
Instabilities for steam condensation in the injector	10 600 – 11 290	-
Triggering valve (F045) opening and closure	11 039 – 11 260	-
Maximum level in the HX pool	11 300	3.40 m
Maximum exchanged power	11 220 – 11 745	18.5 MW
HX pool minimum level	14 784	1.16 m
OP average temperature	13 500	around 52°C

The marks adopted in Table 5.41 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.42. PERSEO Test 7 Part 1 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	+
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	+
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
				Diff. pressure HX upper-lower header	DP-003	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure steam duct injector	DP-J001	o
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Power heat exchanger	W IC (der.)	o
				Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (top)	T-Q031	o
				Power heat exchanger	W IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature OP (top)	T-P021	+
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Power heat exchanger	W IC (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Relative pressure HXP top	P-Q001	+
				Level OP	L VP (der.)	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

** Ph. = Phenomenon

Figure 5.251. Test 7 Part 1 – Flowrate steam supply line

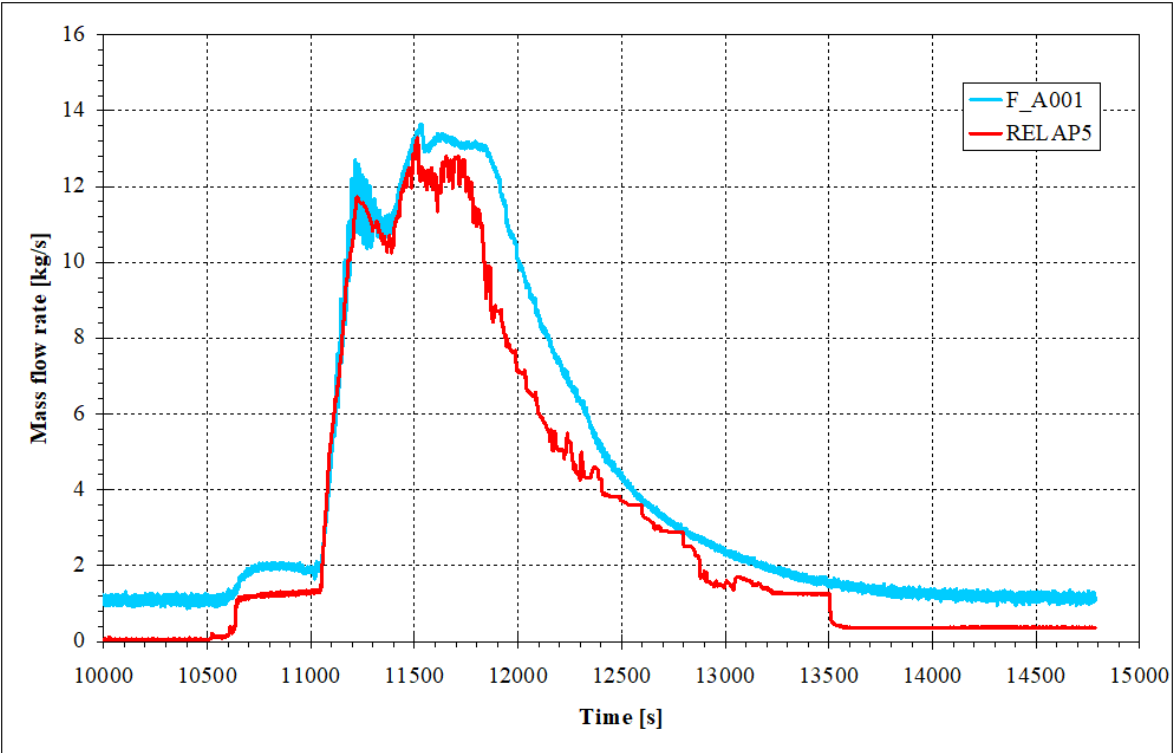


Figure 5.252. Test 7 Part 1 – Flowrate condensate drain line

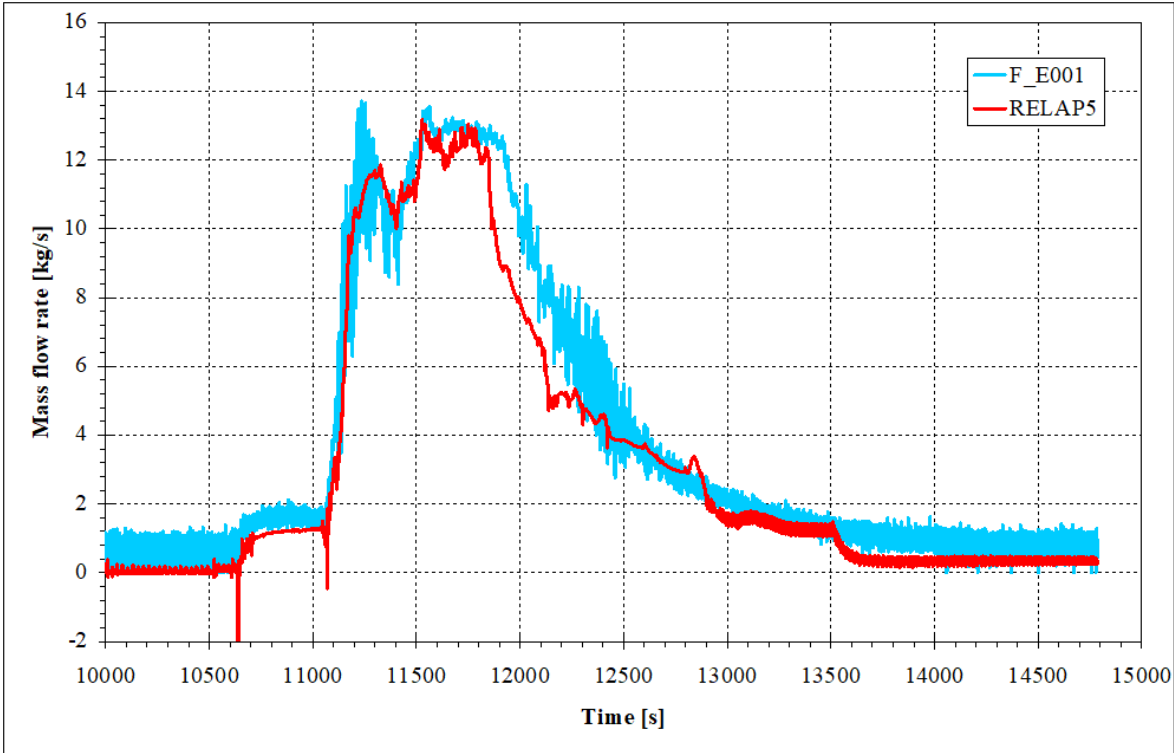


Figure 5.253. Test 7 Part 1 – Power heat exchanger

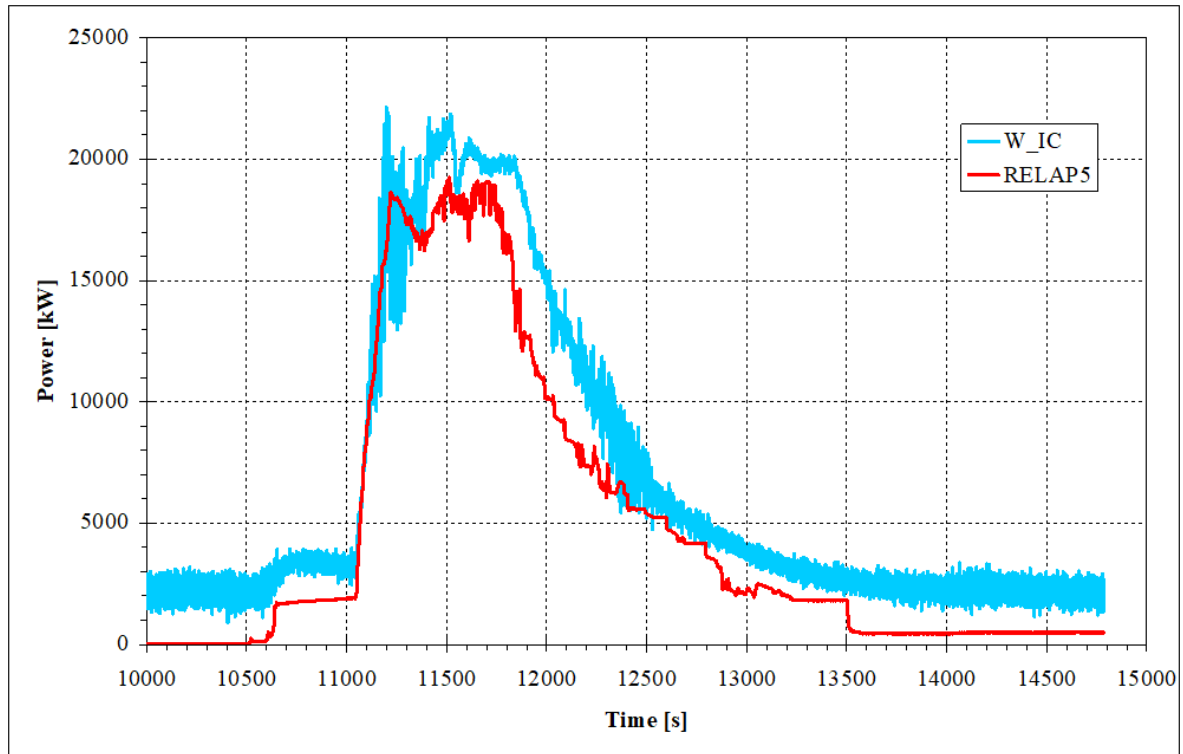


Figure 5.254. Test 7 Part 1 – Absolute pressure vessel

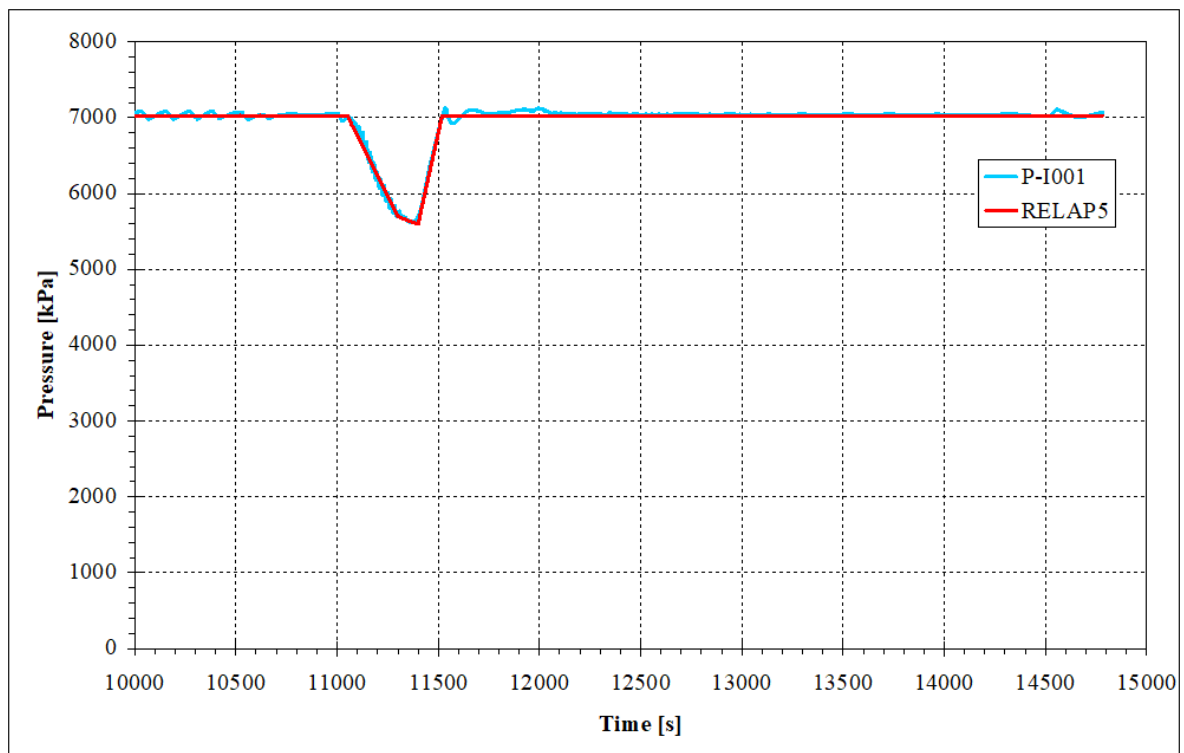


Figure 5.255. Test 7 Part 1 – HX inlet fluid temperature

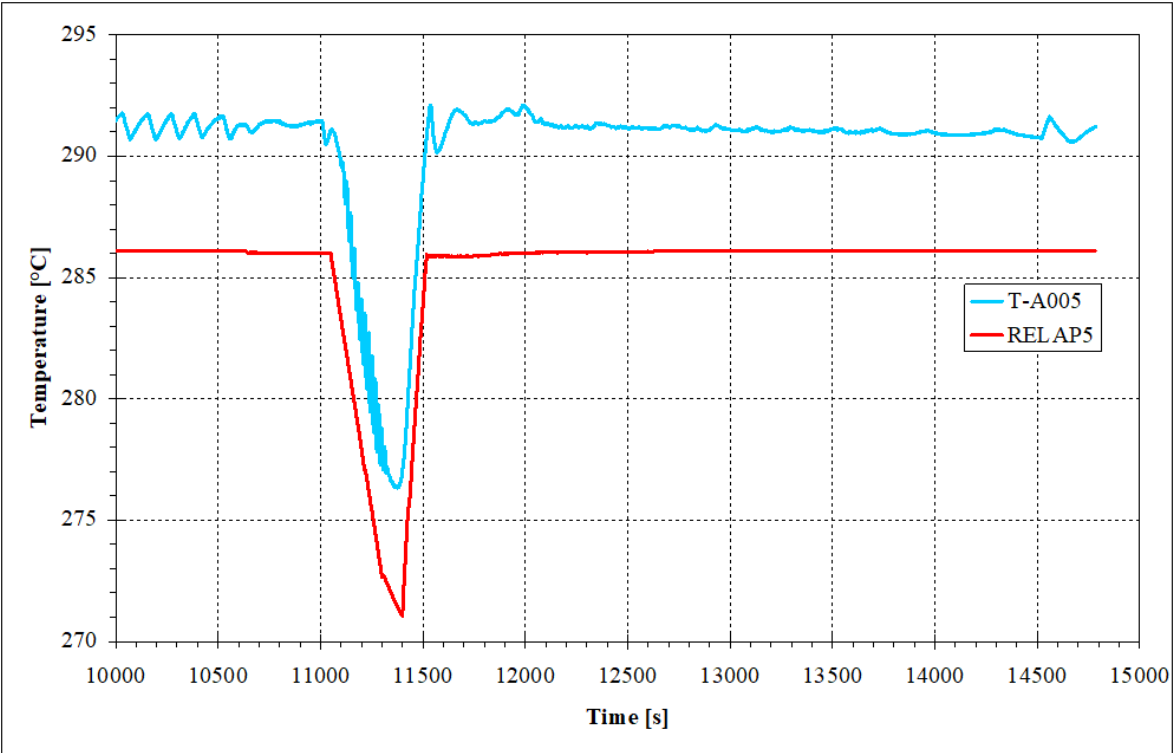


Figure 5.256. Test 7 Part 1 – HX outlet fluid temperature

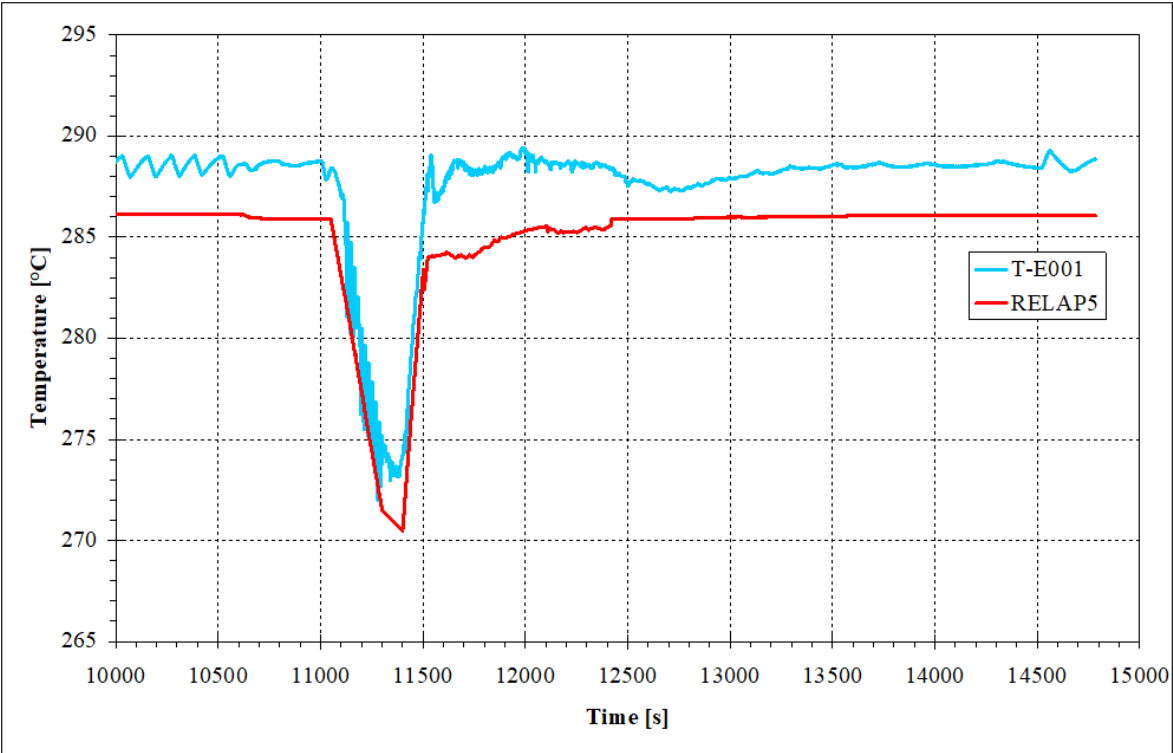


Figure 5.257. Test 7 Part 1 – Level HXP

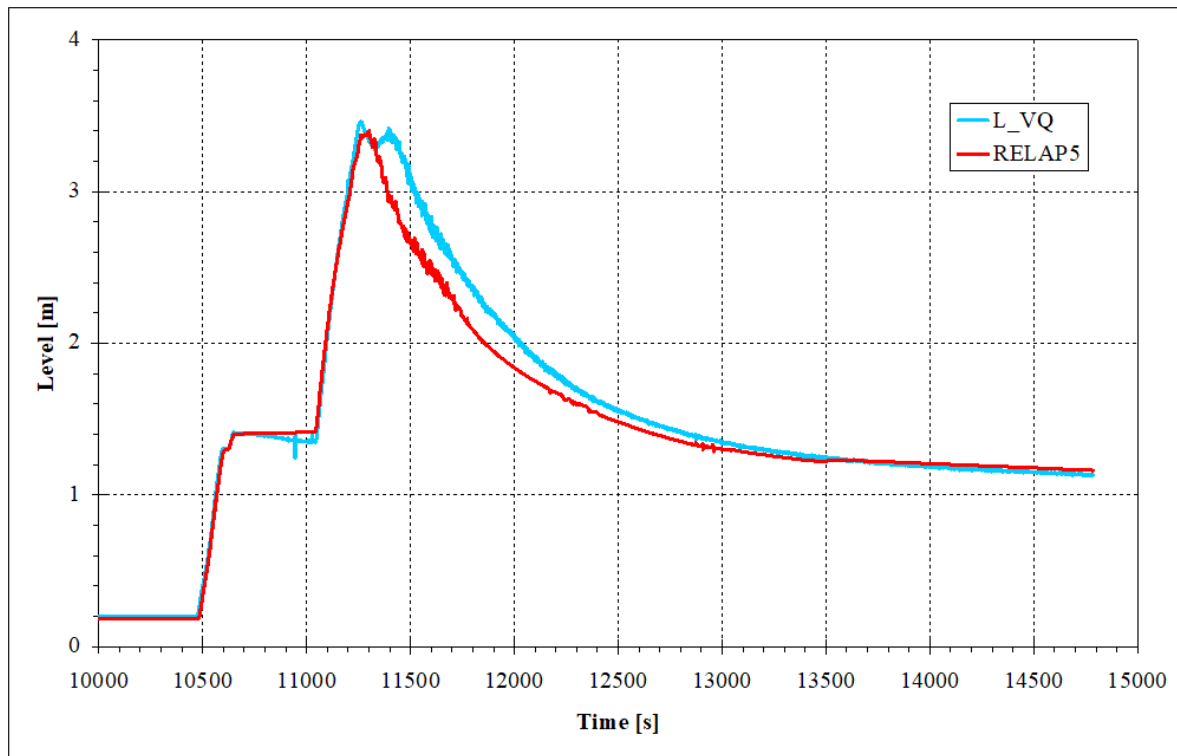


Figure 5.258. Test 7 Part 1 – Level OP

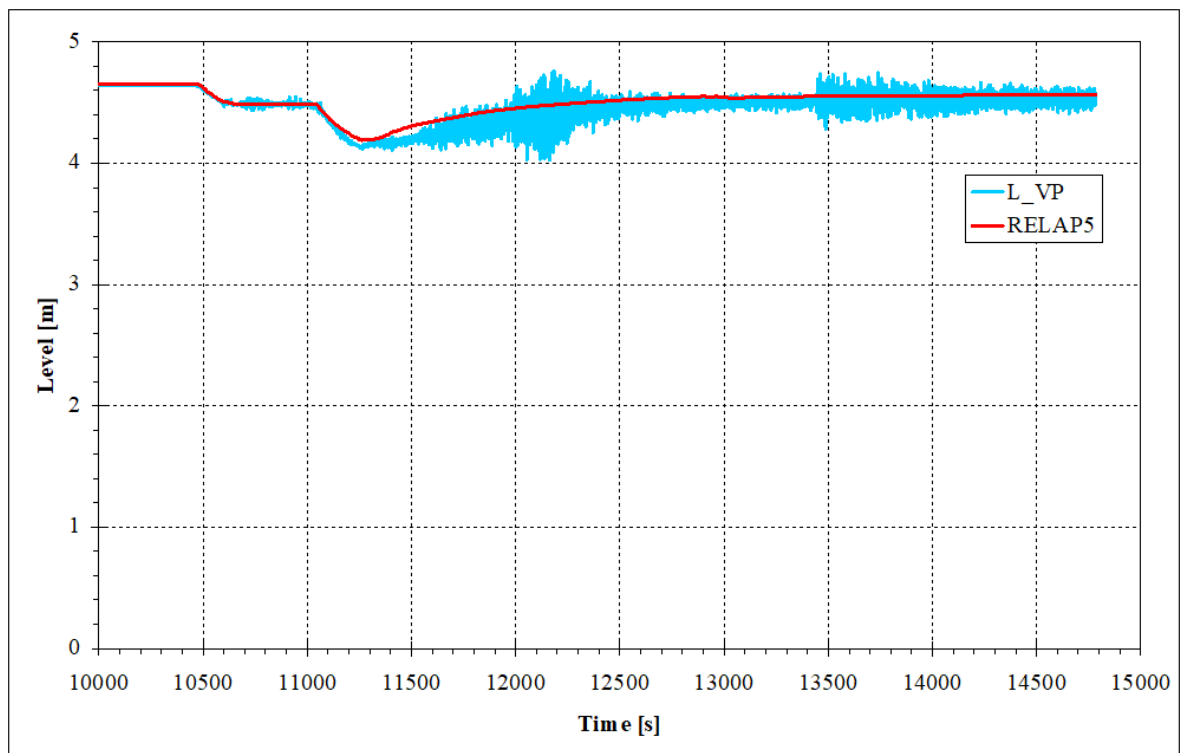


Figure 5.259. Test 7 Part 1 – Fluid temperature HXP (bottom)

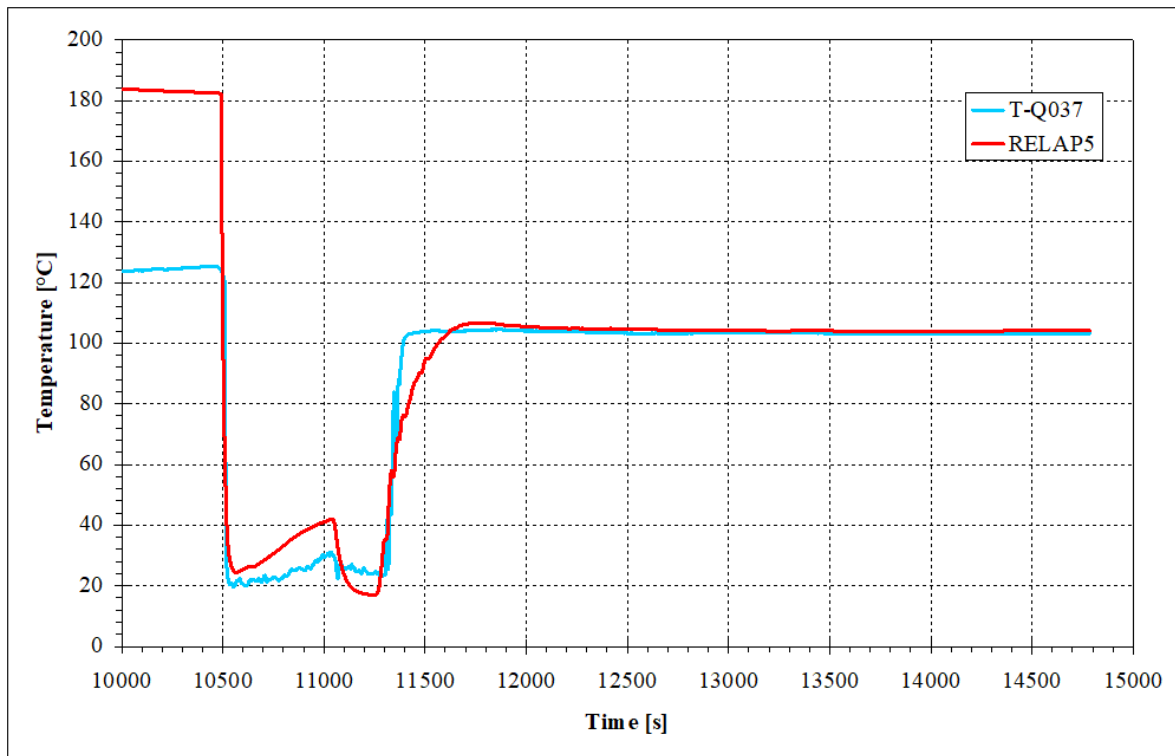


Figure 5.260. Test 7 Part 1 – Fluid temperature HXP (middle)

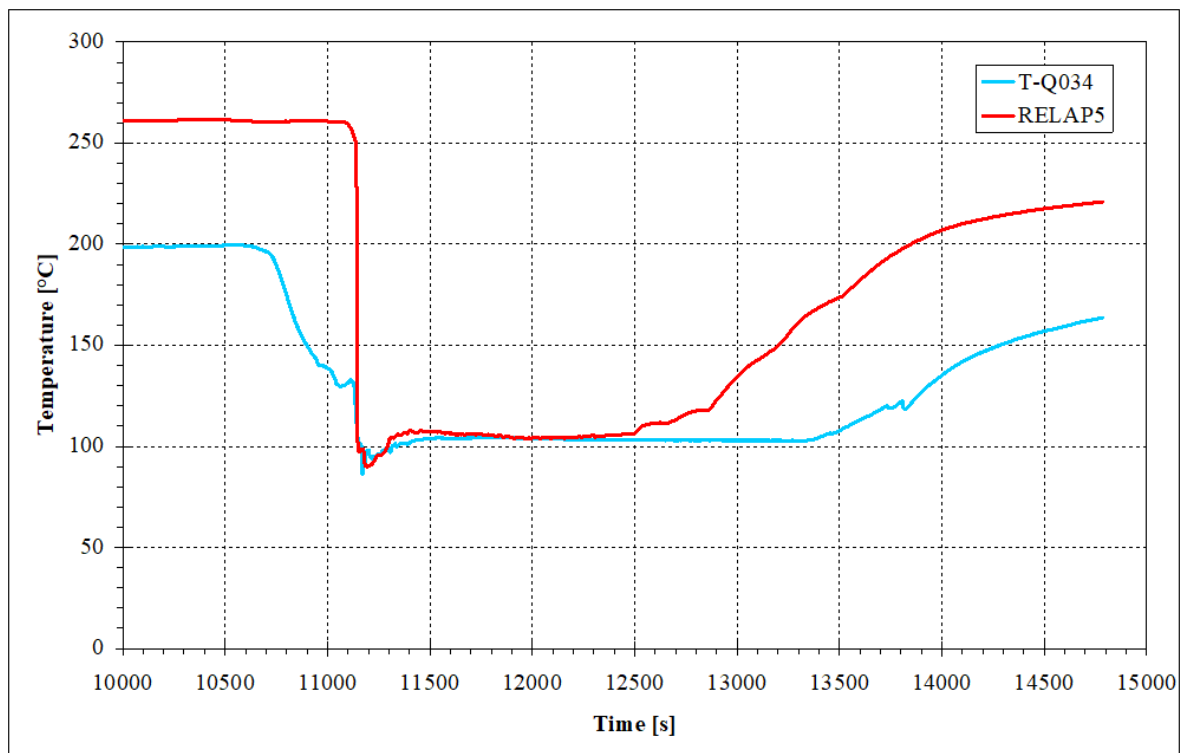


Figure 5.261. Test 7 Part 1 – Fluid temperature HXP (top)

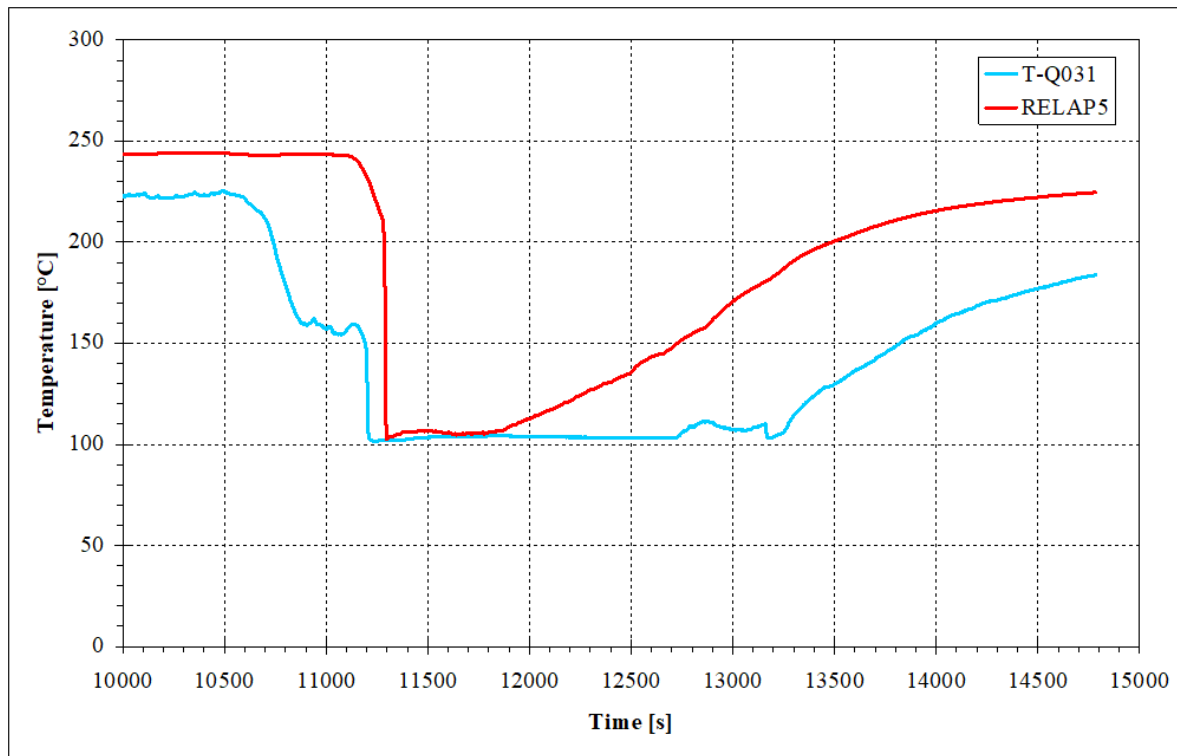


Figure 5.262. Test 7 Part 1 – Relative pressure HXP top

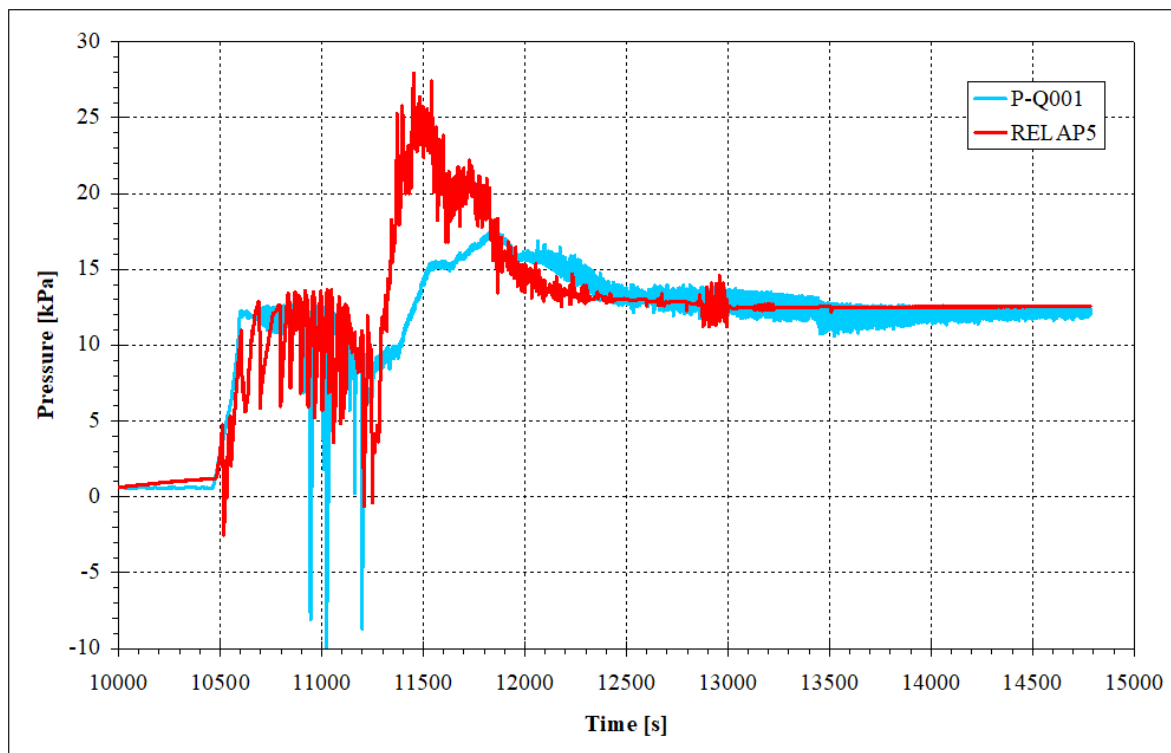


Figure 5.263. Test 7 Part 1 – Fluid temperature OP (bottom)

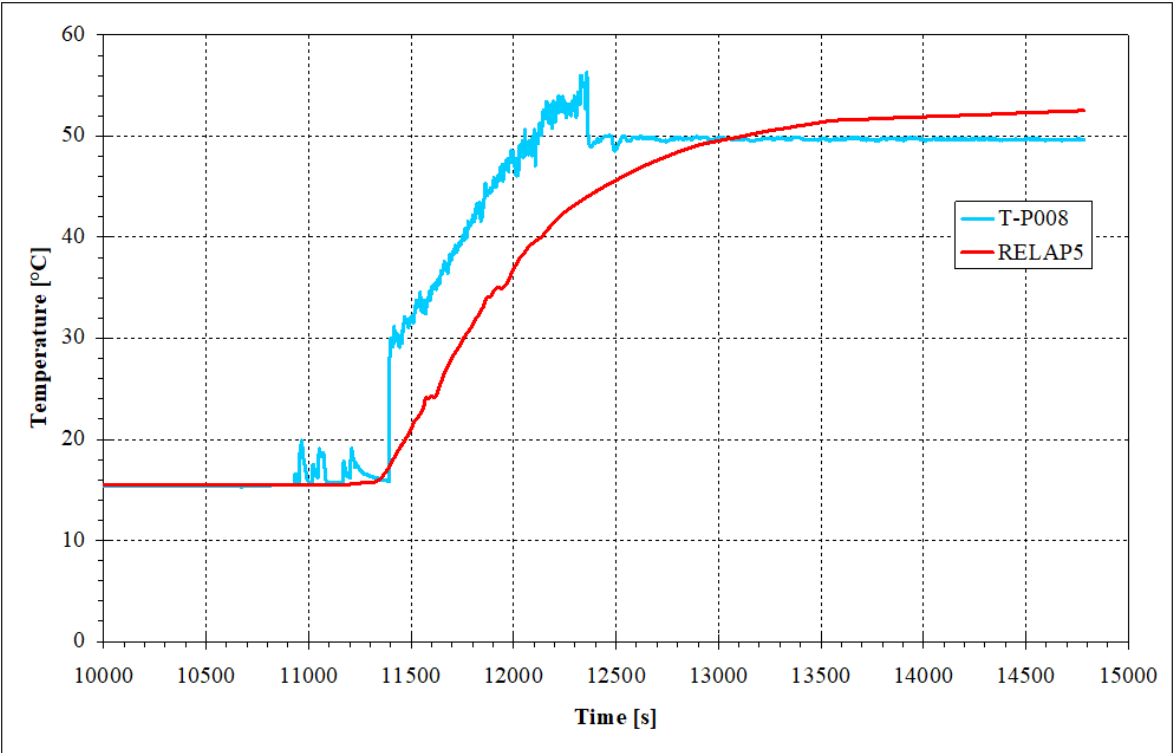


Figure 5.264. Test 7 Part 1 – Fluid temperature OP (top)

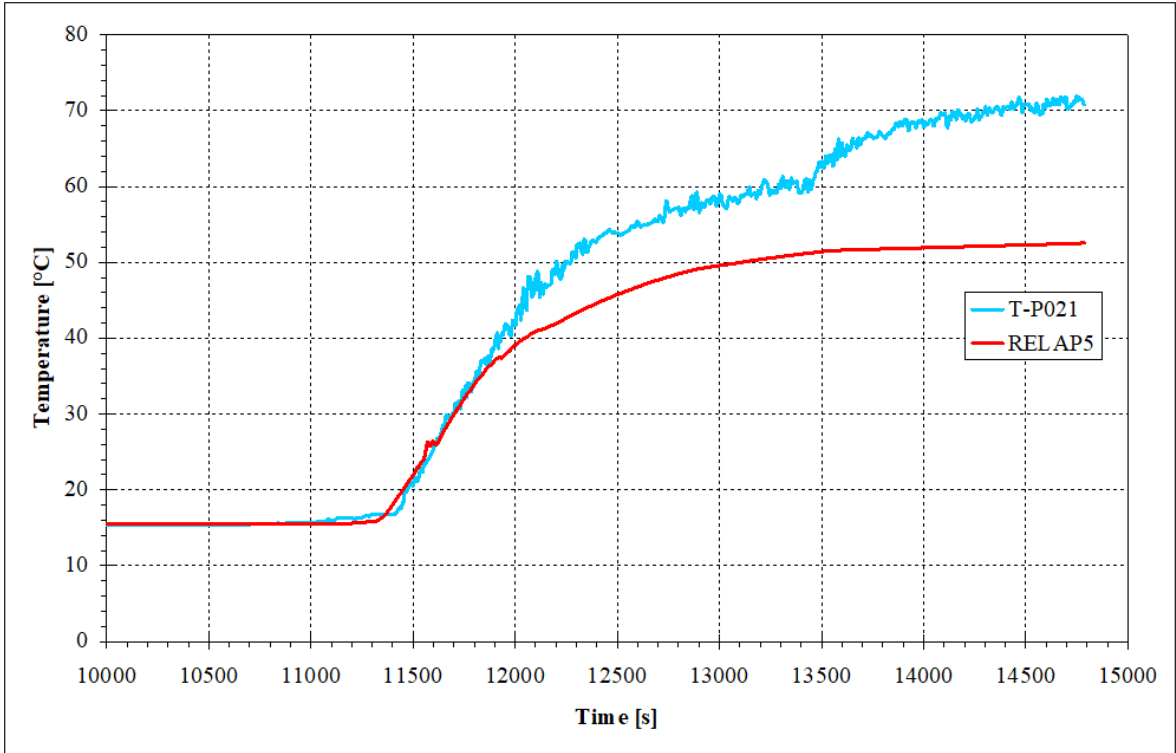


Figure 5.265. Test 7 Part 1 – Differential pressure HX upper-lower header

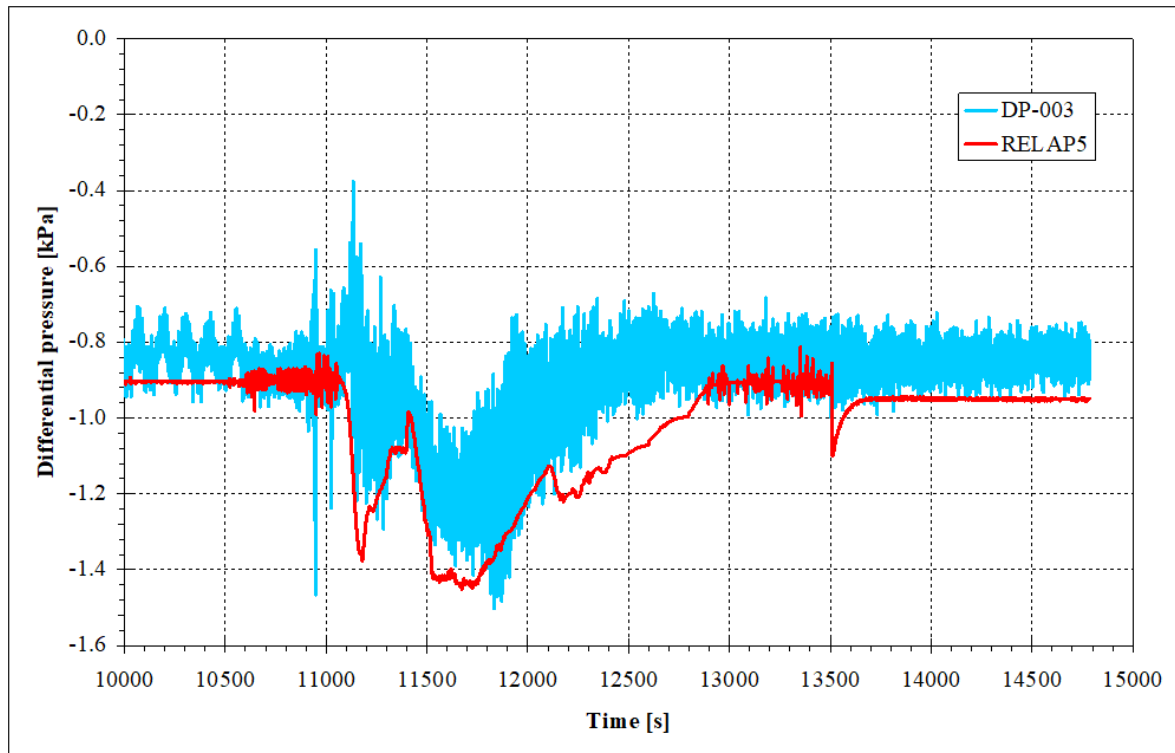


Figure 5.266. Test 7 Part 1 – Differential pressure steam duct injector

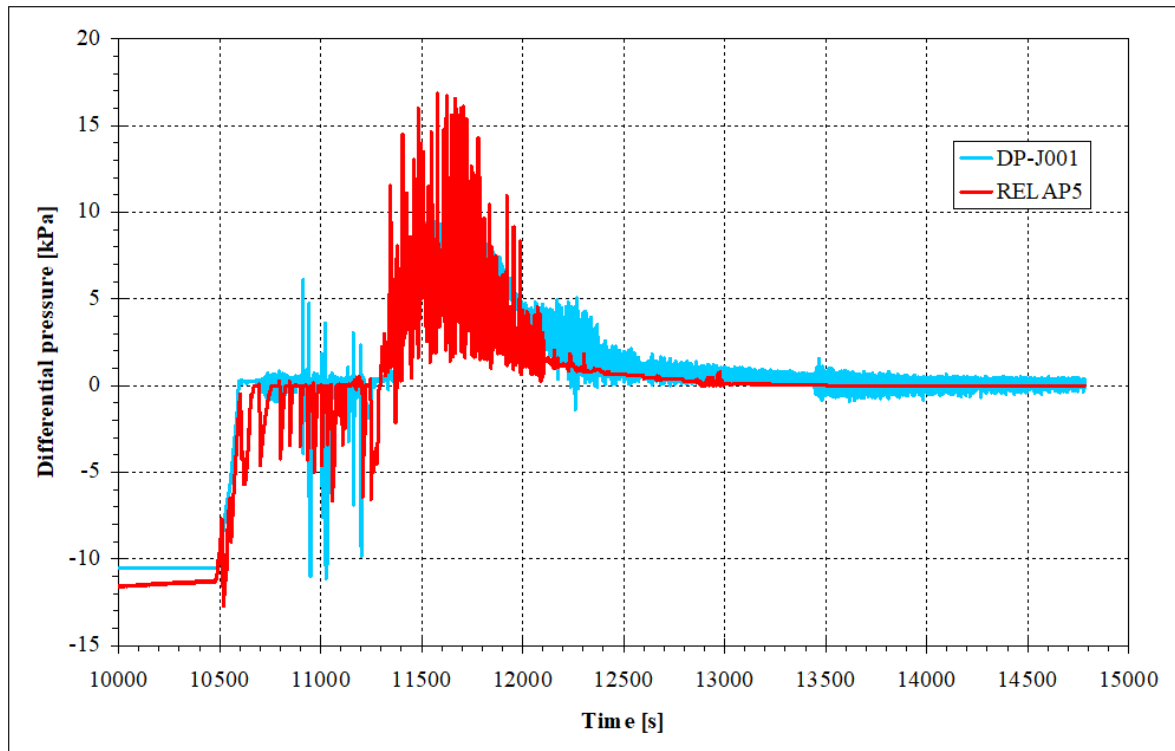


Figure 5.267. Test 7 Part 1 – Wall temperature HX upper header

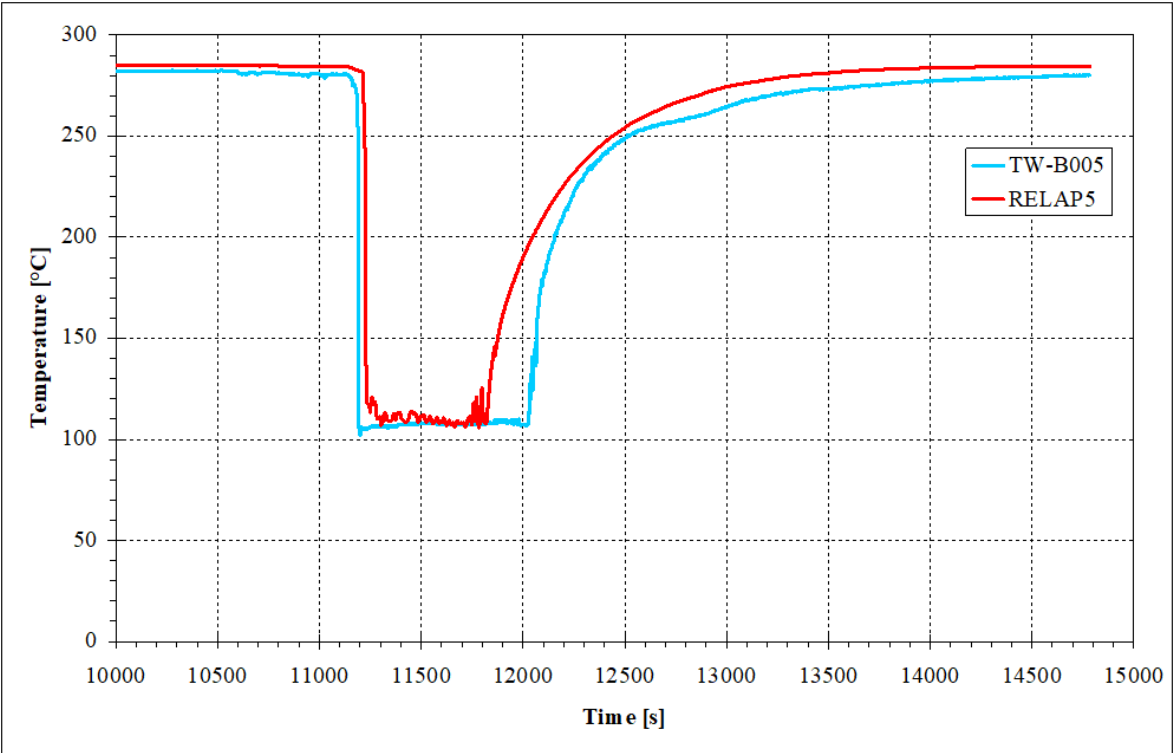


Figure 5.268. Test 7 Part 1 – Wall temperature HX lower header

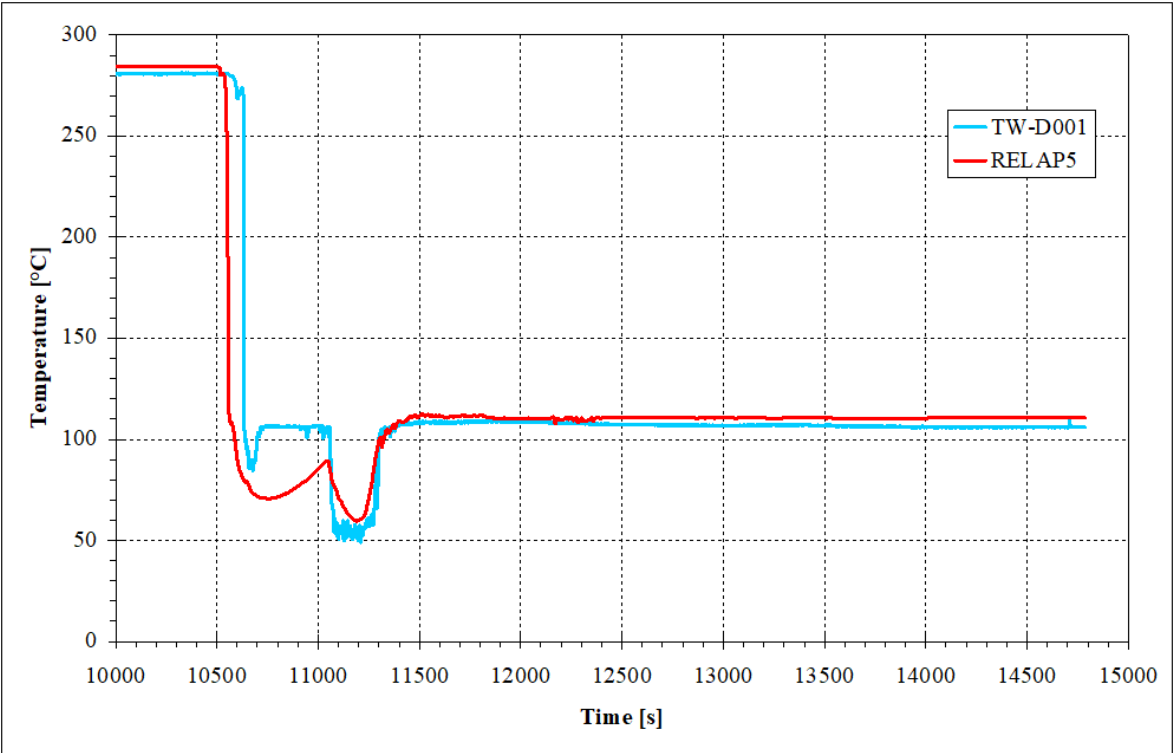
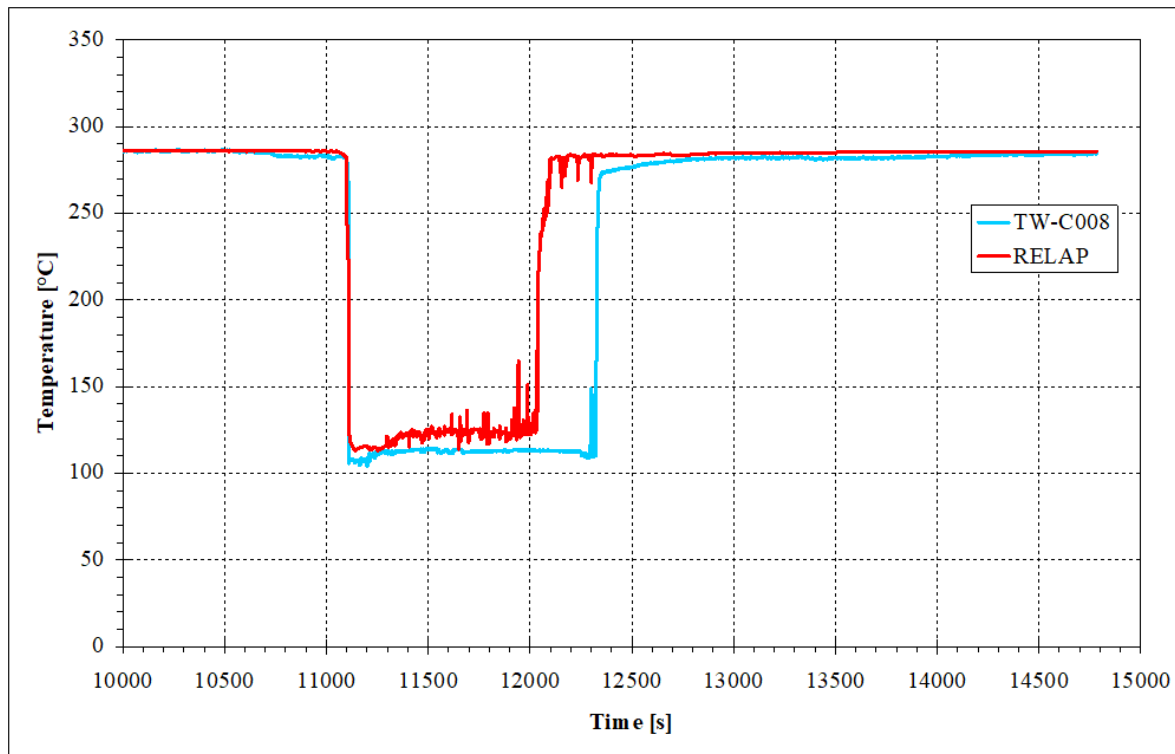


Figure 5.269. Test 7 Part 1 – Wall temperature HX tube (middle)



Test 7 Part 2

Both parts of Test 7 were performed as one calculation. Part 2 starts after Part 1 (at 14 600 s). The significant initial conditions for the Test 7 Part 2 are: saturated fluid in the primary circuit; primary pressure, 7.03 MPa; water level in the pressure vessel, 3.9 m from the bottom (it is kept constant within the whole calculation); HX pool is filled with saturated water and steam (water level 1.17 m); HX pool pressure, 112.5 kPa; steam duct and injector are filled with steam; overall pool water level, 4.56 m; overall pool water temperature, about 52°C; triggering valve is closed.

Note that to achieve reasonable agreement with the measured data (Figure 5.272 and Figure 5.289), heat transfer coefficients were increased by means of a fouling factor value of 2.2 on both sides of HX tubes. Without this modification the maximal exchanged power was about 11 MW.

Natural circulation in the primary circuit (Figure 5.270 and Figure 5.271), levels in both pools (Figure 5.276 and Figure 5.277), the HX pool pressure (Figure 5.281), and the injector differential pressure (Figure 5.285) are in good agreement with the measured data.

At the end of the Test 7 Part 2, condensation in the primary circuit is too low so the pressure decreases slowly (Figure 5.273).

Saturated conditions should be in the primary circuit, but the measured temperatures are “superheated” (Figure 5.274 and Figure 5.275).

Although the wall temperatures correspond to the measured ones (Figure 5.286 and Figure 5.288) the calculated fluid temperatures start rising too early (Figure 5.279 and Figure 5.280; maybe due to higher inner circulation).

Concerning the overall pool temperatures (Figure 5.282 and Figure 283), during the heat-up the thermal stratification is minimum in the calculation. When the injector is uncovered, superheated steam is flowing through the upper part of both channels simulating the overall pool (maybe due to over predicted inner circulation).

The computational time of the Test 7 Part 2 was 1 hour and 13 min. The maximum time step was set to 0.02 s, but it was often reduced by the code.

All important phenomena were clearly predicted by the code, except the HX heat transfer and OP thermal stratification that were predicted partially (Table 5.43).

Table 5.43. Main relevant thermal-hydraulic aspects related to Test 7 Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	326	-
Maximum level in the HXP	462	3.12 m
Maximum exchanged power	435 – 2 220	19.0 MW
OP discharge valve F031 opening	1 150	17.0 kg/s
Triggering valve F045 closure	3 338	-
HX pool level decreasing and loss of mass from the boil-off	1 745 – 4 970	-
Primary side depressurisation beginning for end of test	4 680	-

Table 5.44. PERSEO Test 7 Part 2 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.		Measurement		Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	+
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	+
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
				Diff. pressure HX upper-lower header	DP-003	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure steam duct injector	DP-J001	o
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Power heat exchanger	W IC (der.)	o
				Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (top)	T-Q031	o
				Power heat exchanger	W IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature OP (top)	T-P021	+
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Power heat exchanger	W IC (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Relative pressure HXP top	P-Q001	+
				Level OP	L VP (der.)	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

Figure 5.270. Test 7 Part 2 – Flowrate steam supply line

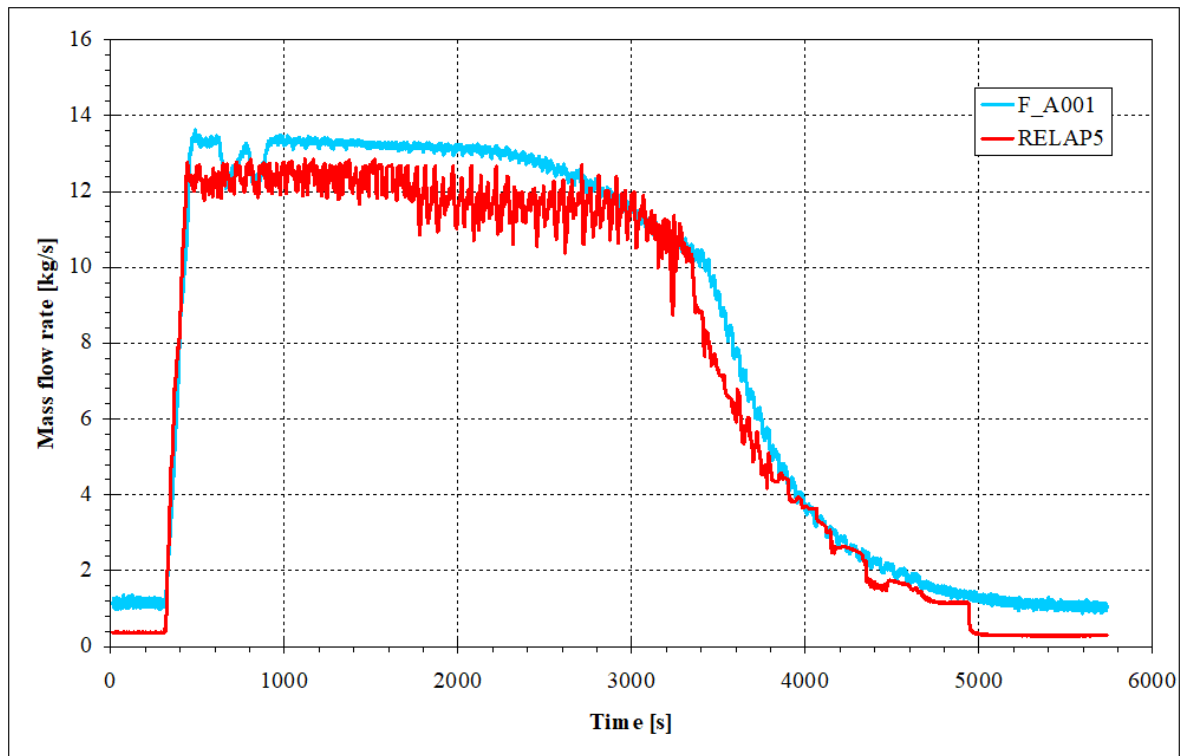


Figure 5.271. Test 7 Part 2 – Flowrate condensate drain line

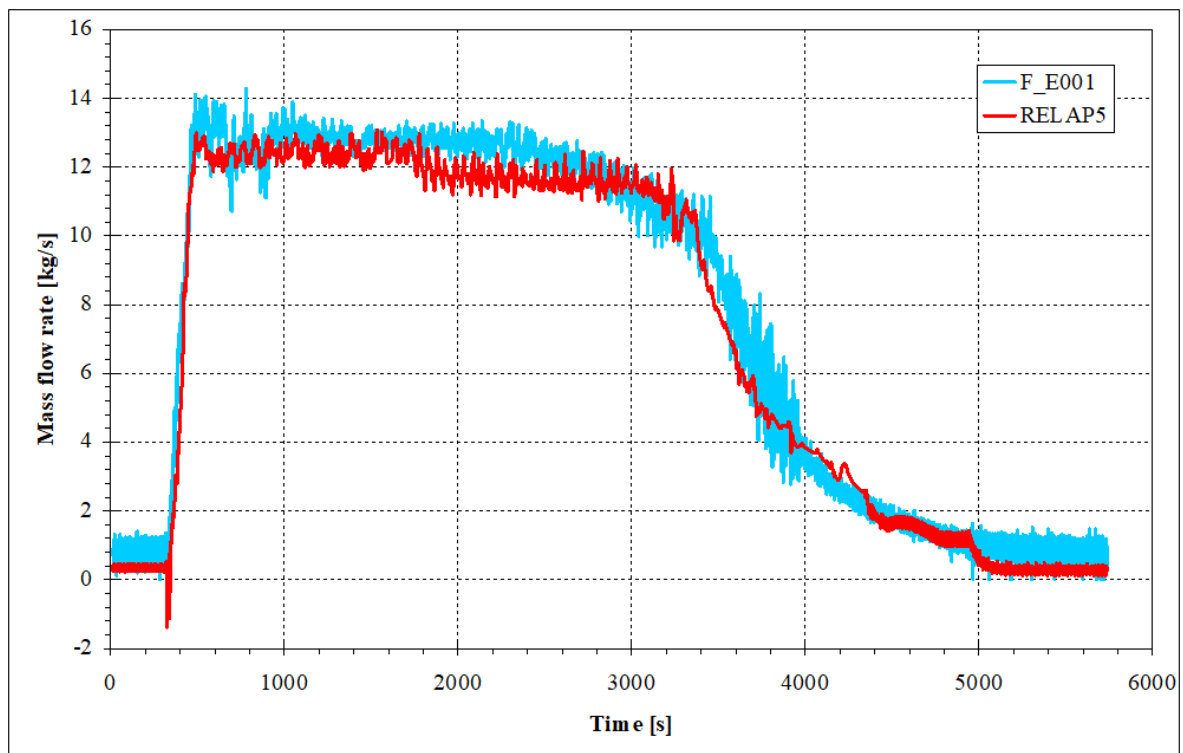


Figure 5.272. Test 7 Part 2 – Power heat exchanger

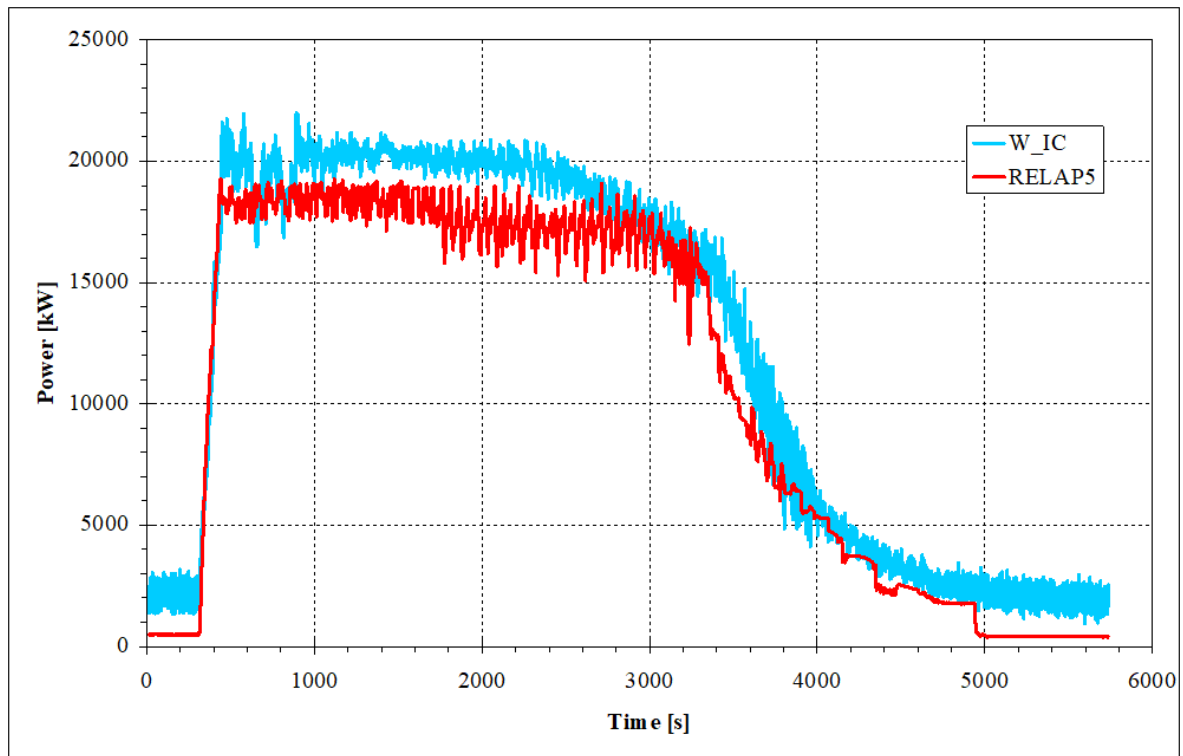


Figure 5.273. Test 7 Part 2 – Absolute pressure vessel

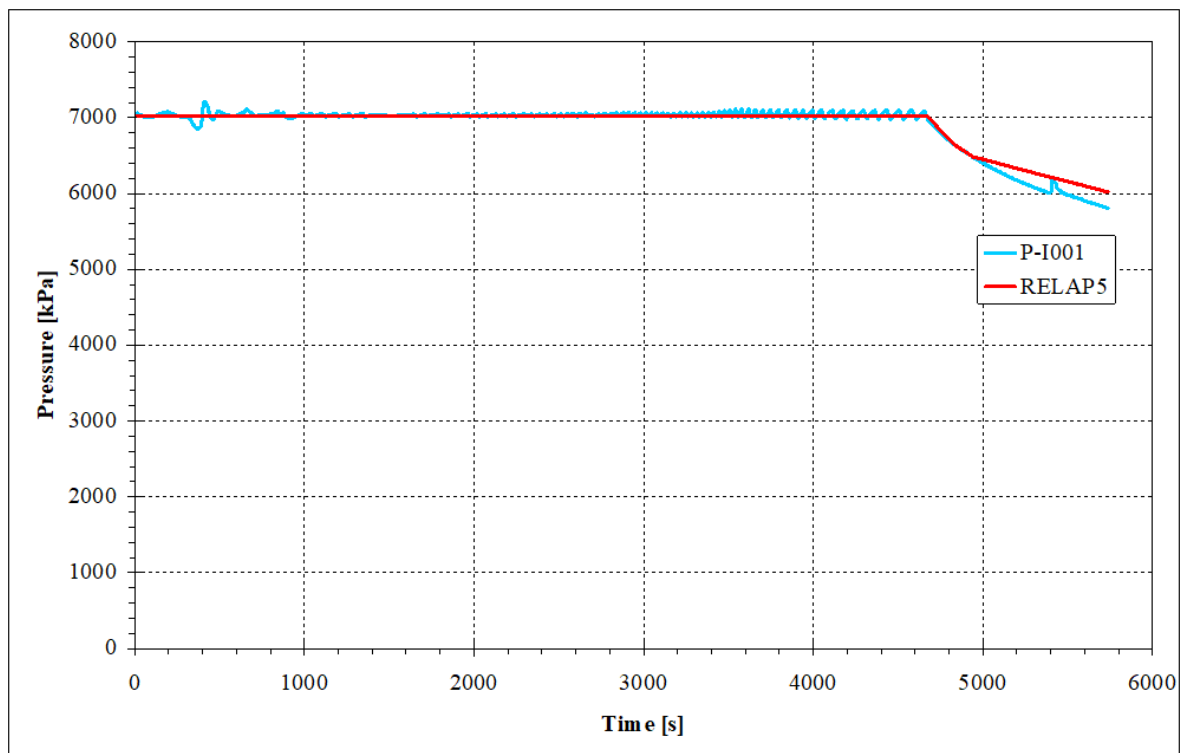


Figure 5.274. Test 7 Part 2 – HX inlet fluid temperature

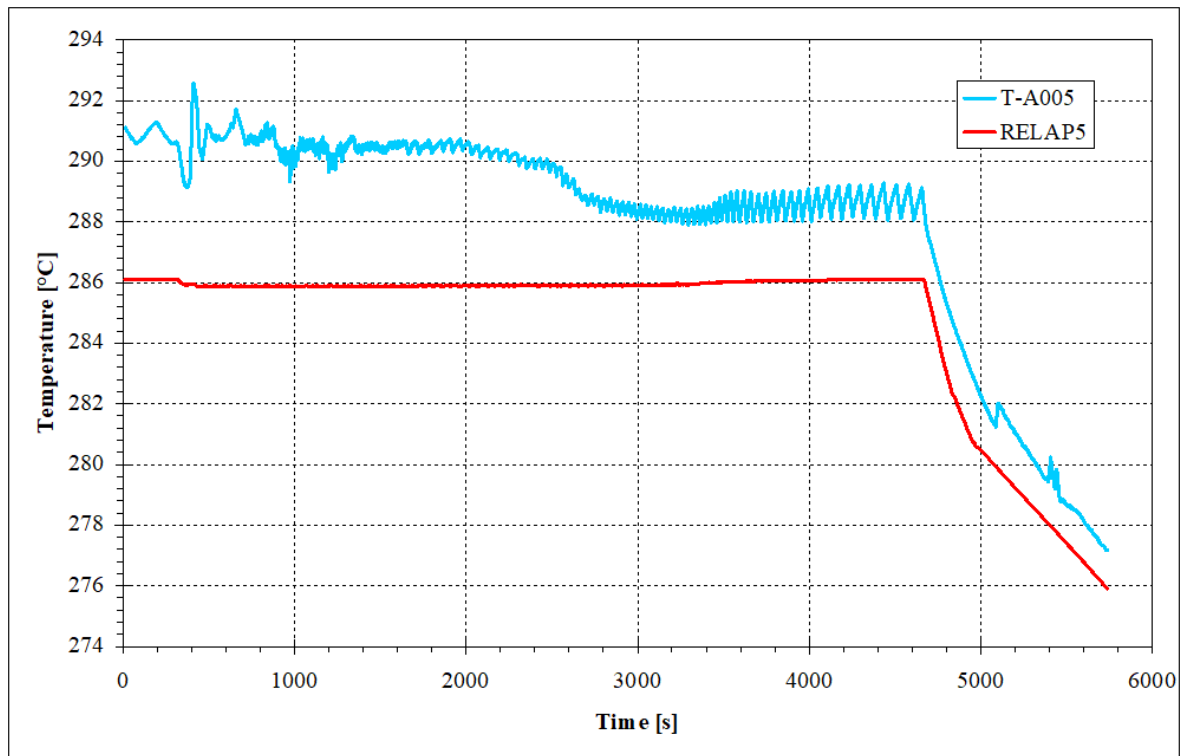


Figure 5.275. Test 7 Part 2 – HX outlet fluid temperature

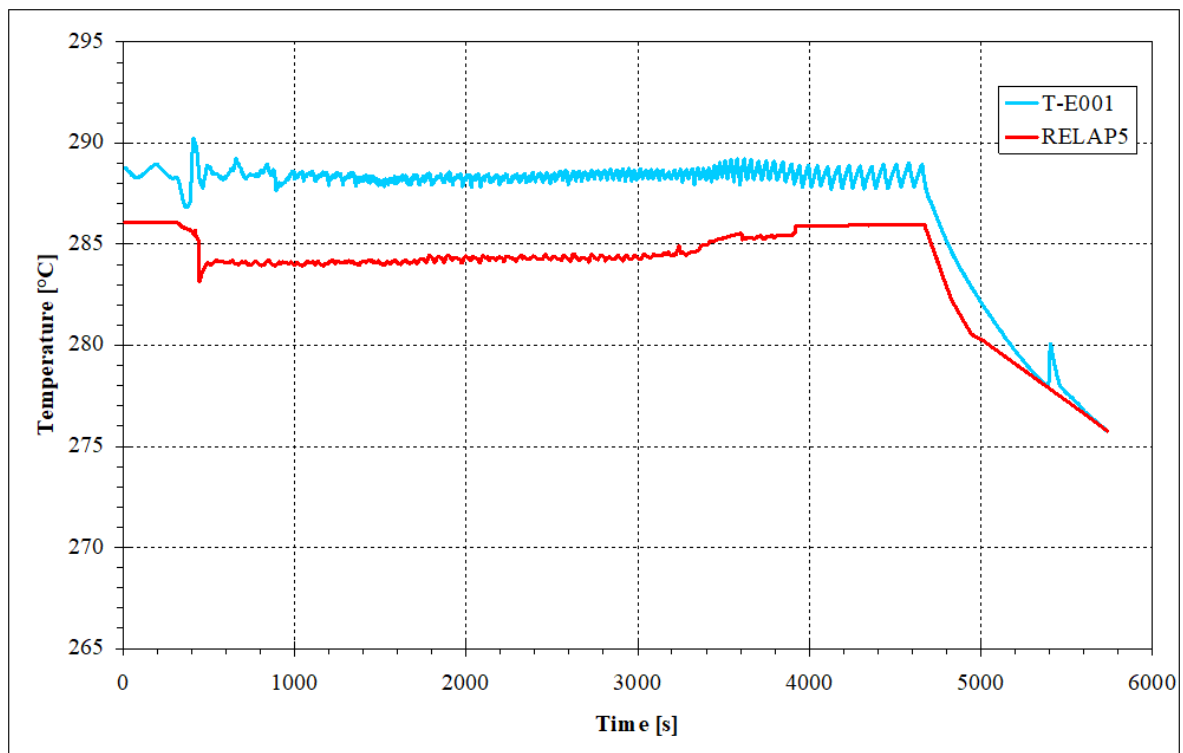


Figure 5.276. Test 7 Part 2 – Level HXP

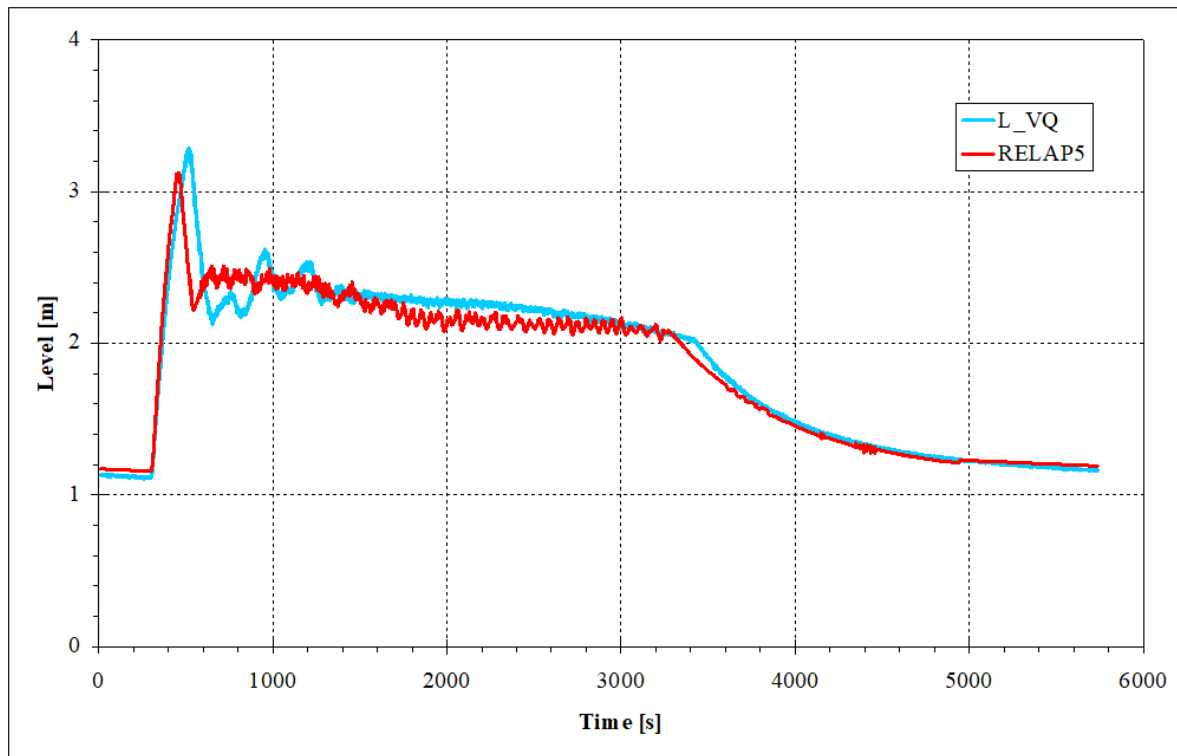


Figure 5.277. Test 7 Part 2 – Level OP

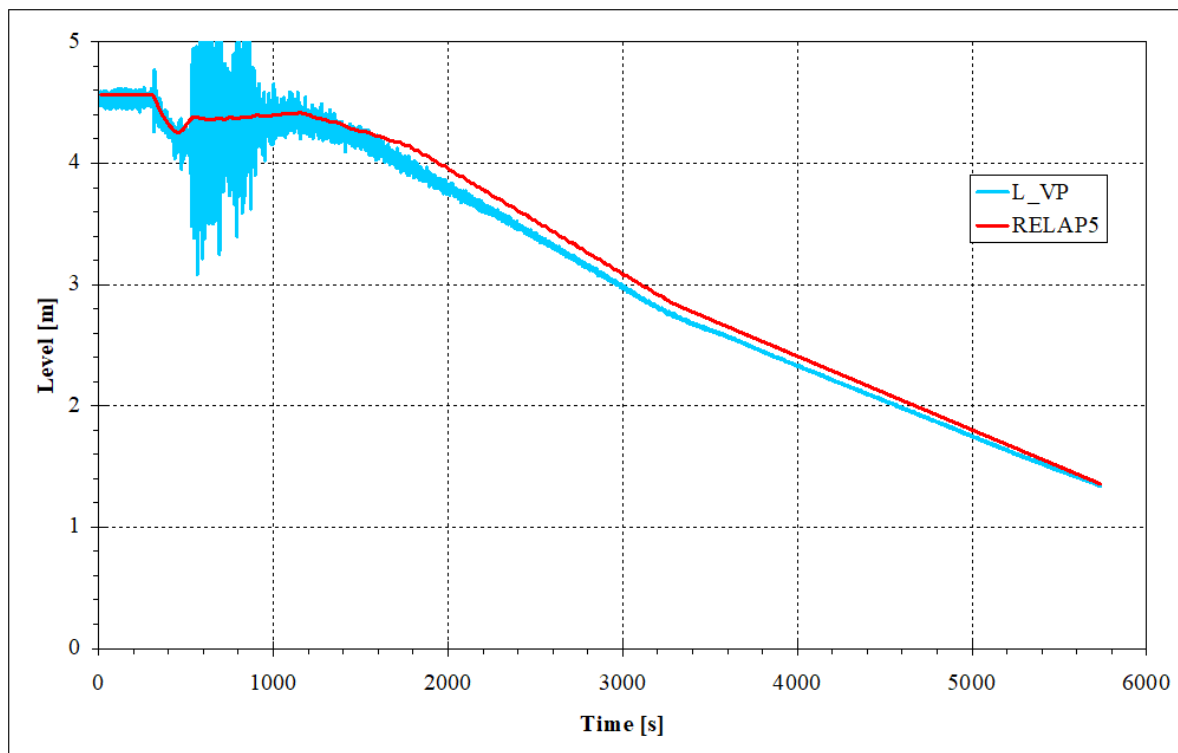


Figure 5.278. Test 7 Part 2 – Fluid temperature HXP (bottom)

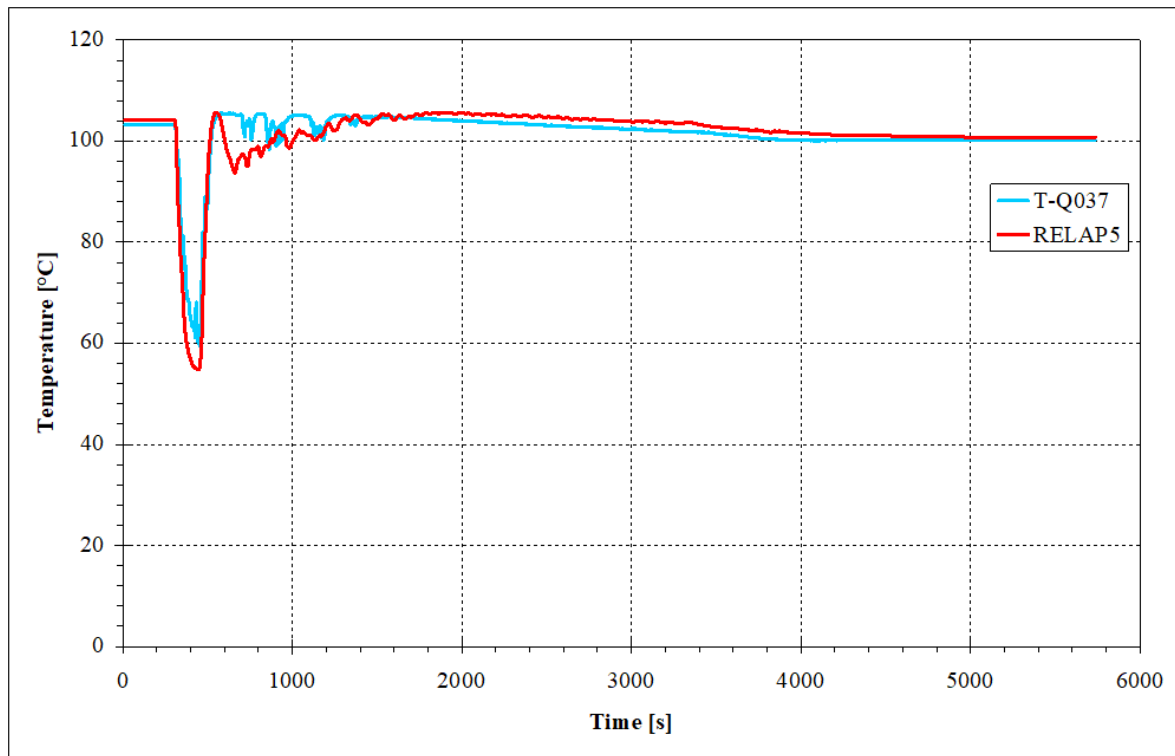


Figure 5.279. Test 7 Part 2 – Fluid temperature HXP (middle)

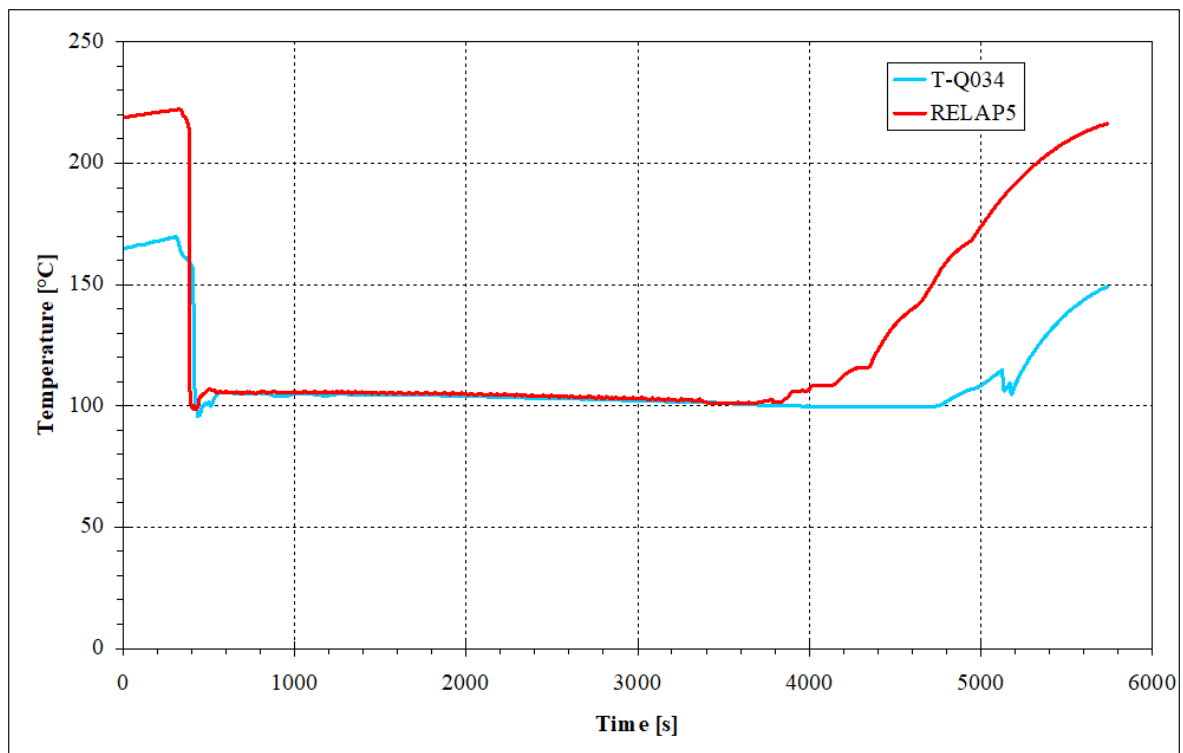


Figure 5.280. Test 7 Part 2 – Fluid temperature HXP (top)

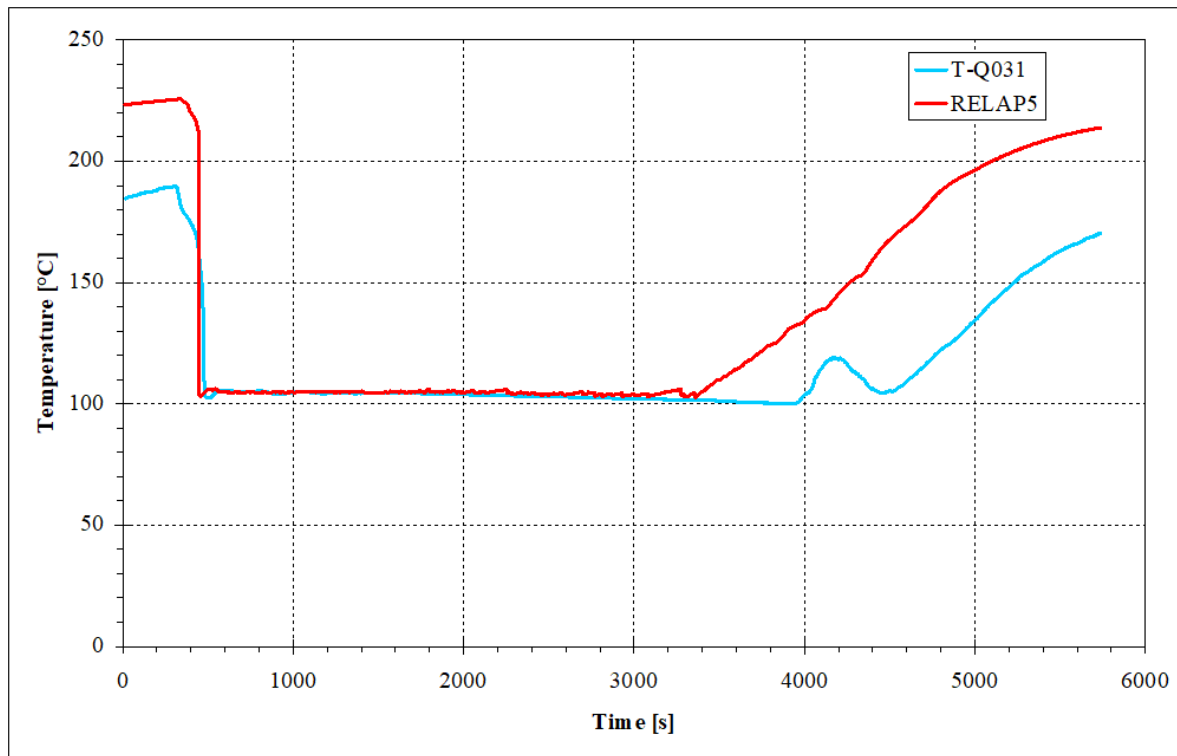


Figure 5.281. Test 7 Part 2 – Relative pressure HXP top

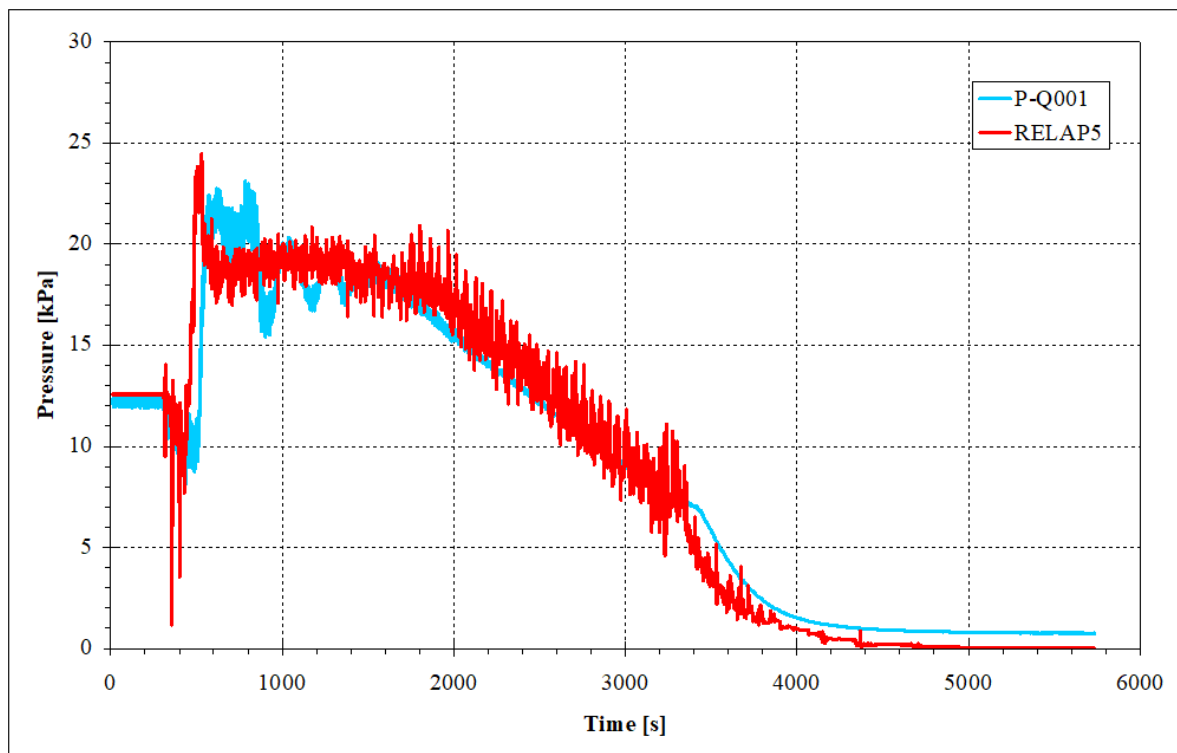


Figure 5.282. Test 7 Part 2 – Fluid temperature OP (bottom)

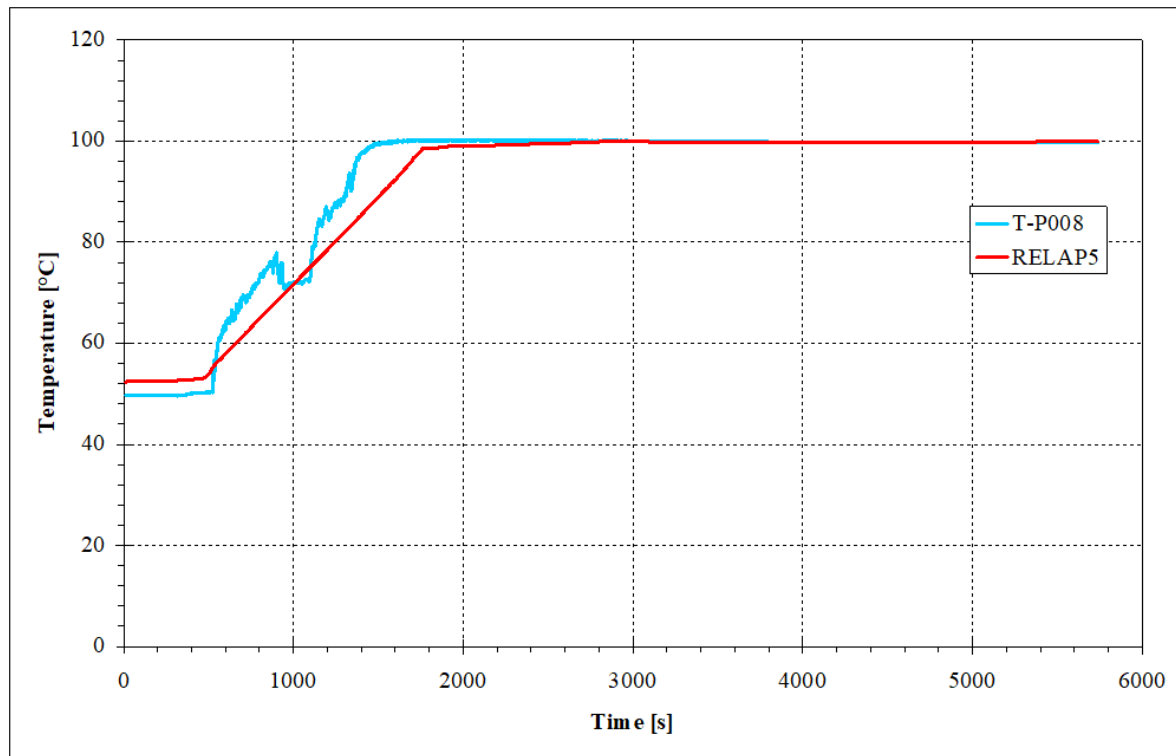


Figure 5.283. Test 7 Part 2 – Fluid temperature OP (top)

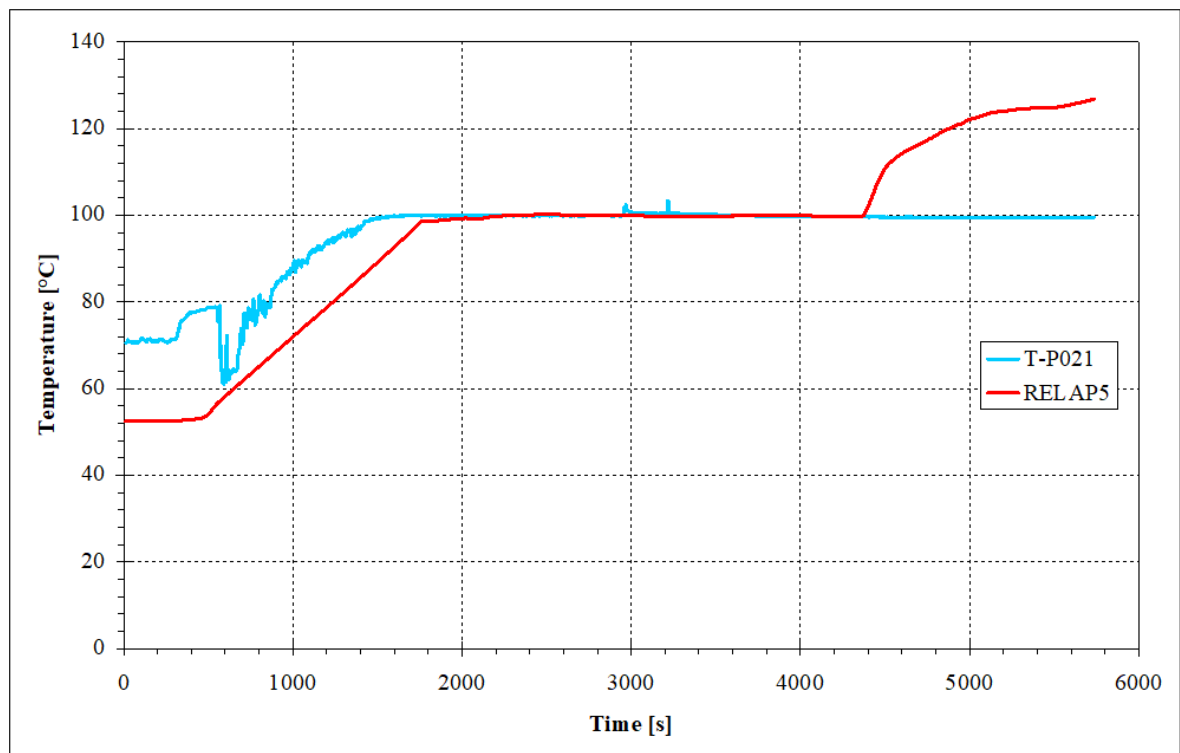


Figure 5.284. Test 7 Part 2 – Differential pressure HX upper-lower header

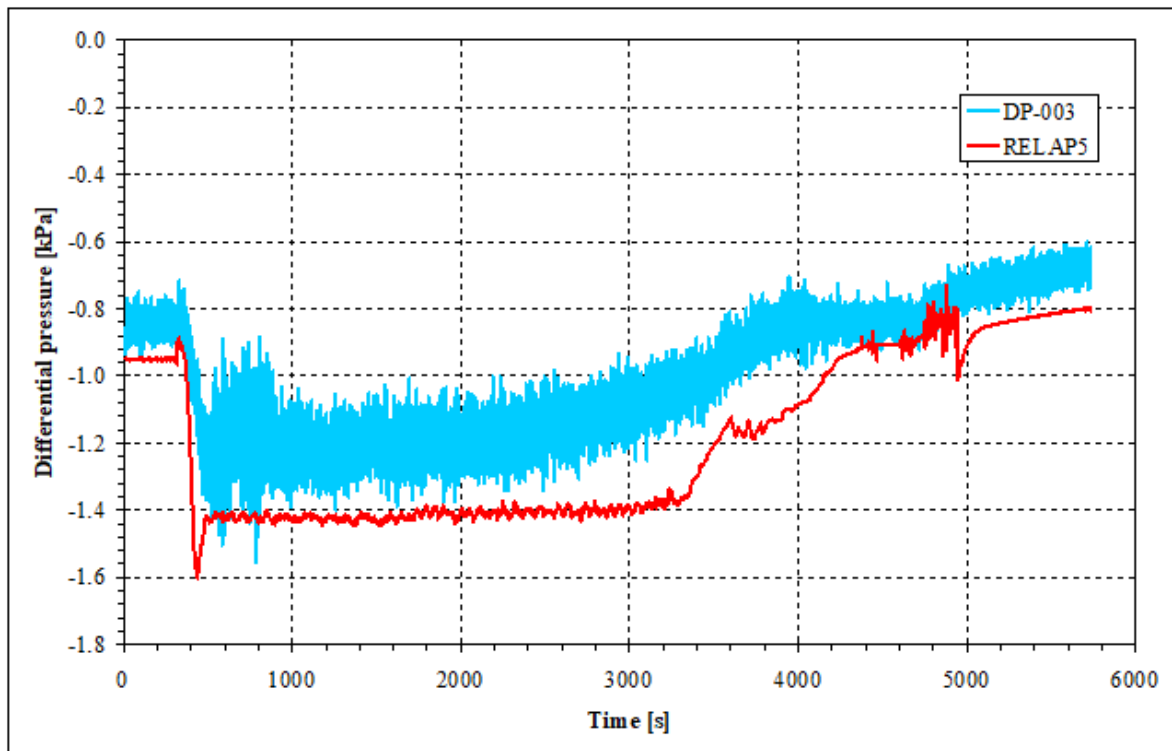


Figure 5.285. Test 7 Part 2 – Differential pressure steam duct injector

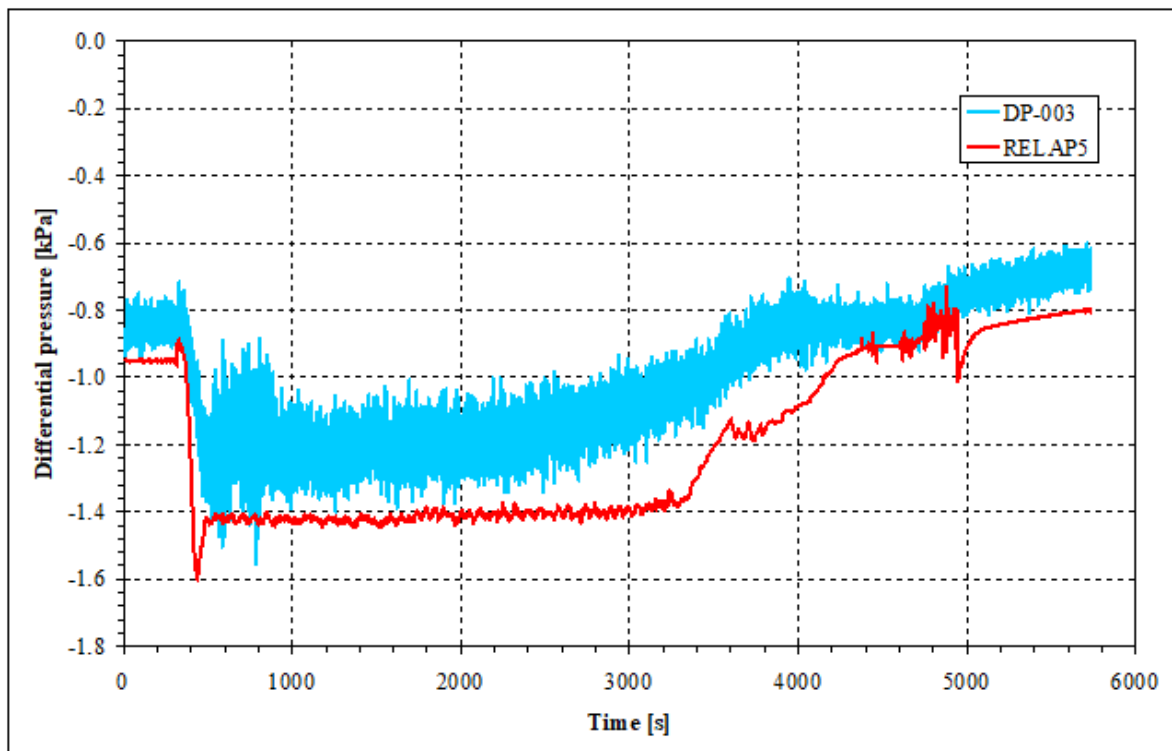


Figure 5.286. Test 7 Part 2 – Wall temperature HX upper header

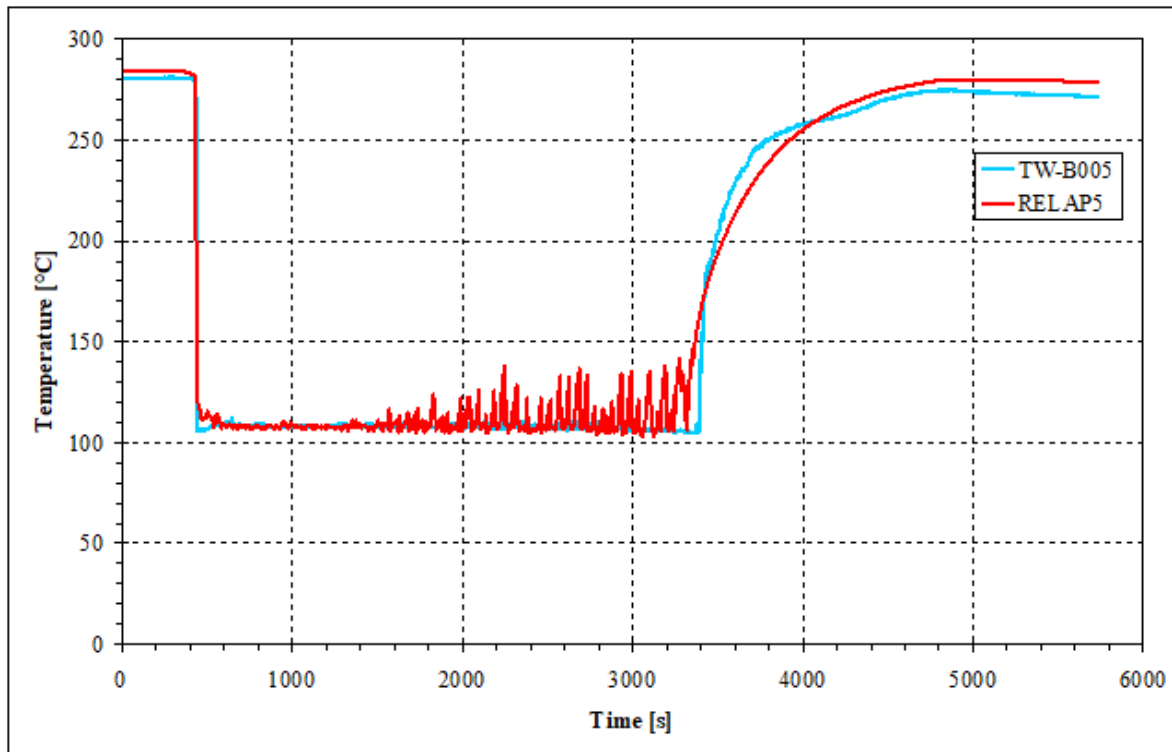


Figure 5.287. Test 7 Part 2 – Wall temperature HX lower header

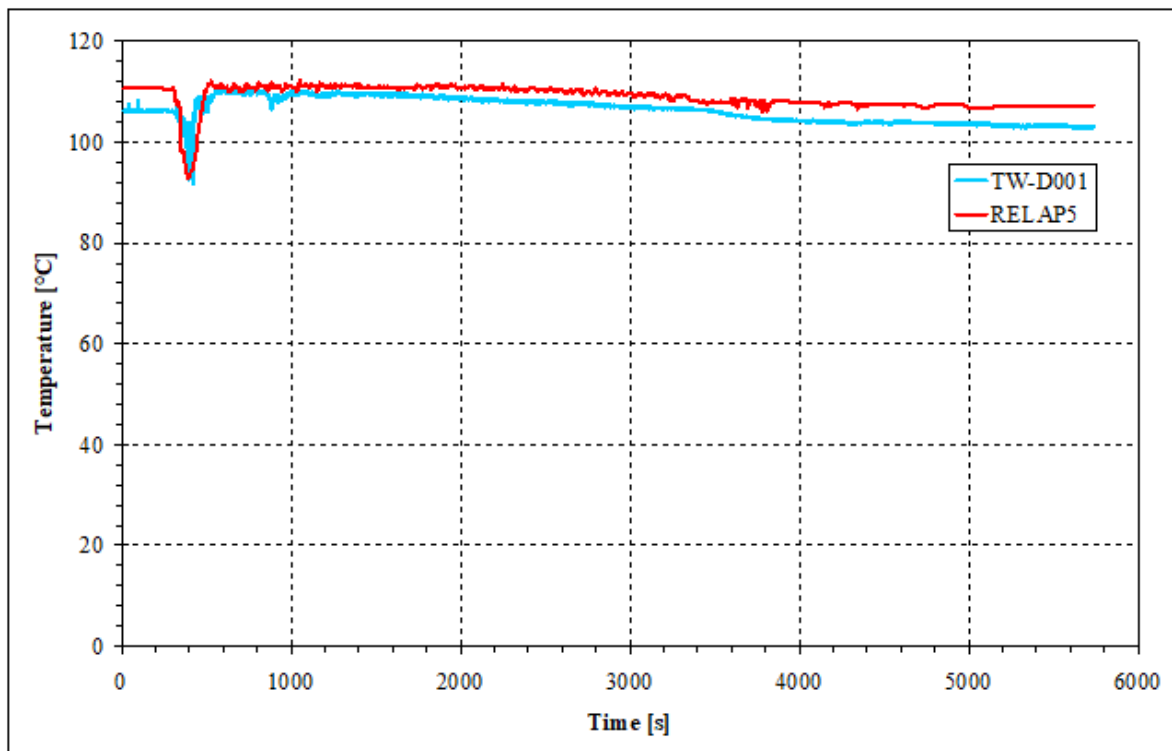


Figure 5.288. Test 7 Part 2 – Wall temperature HX tube (middle)

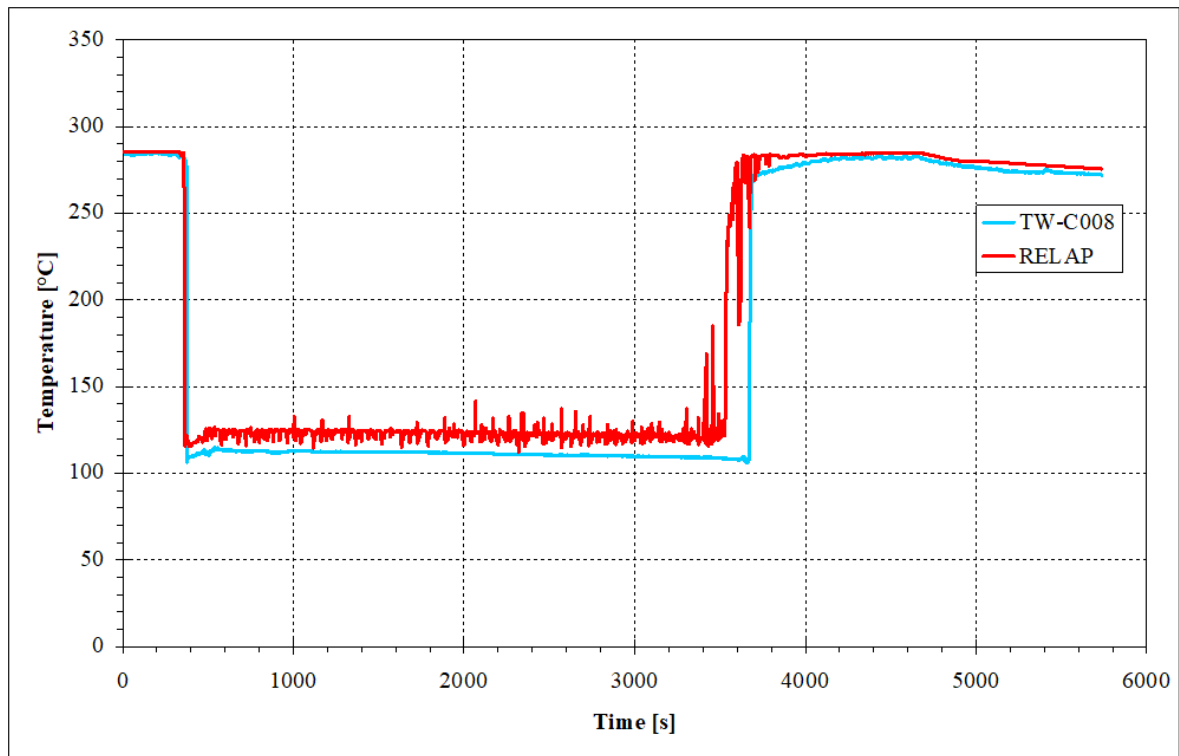
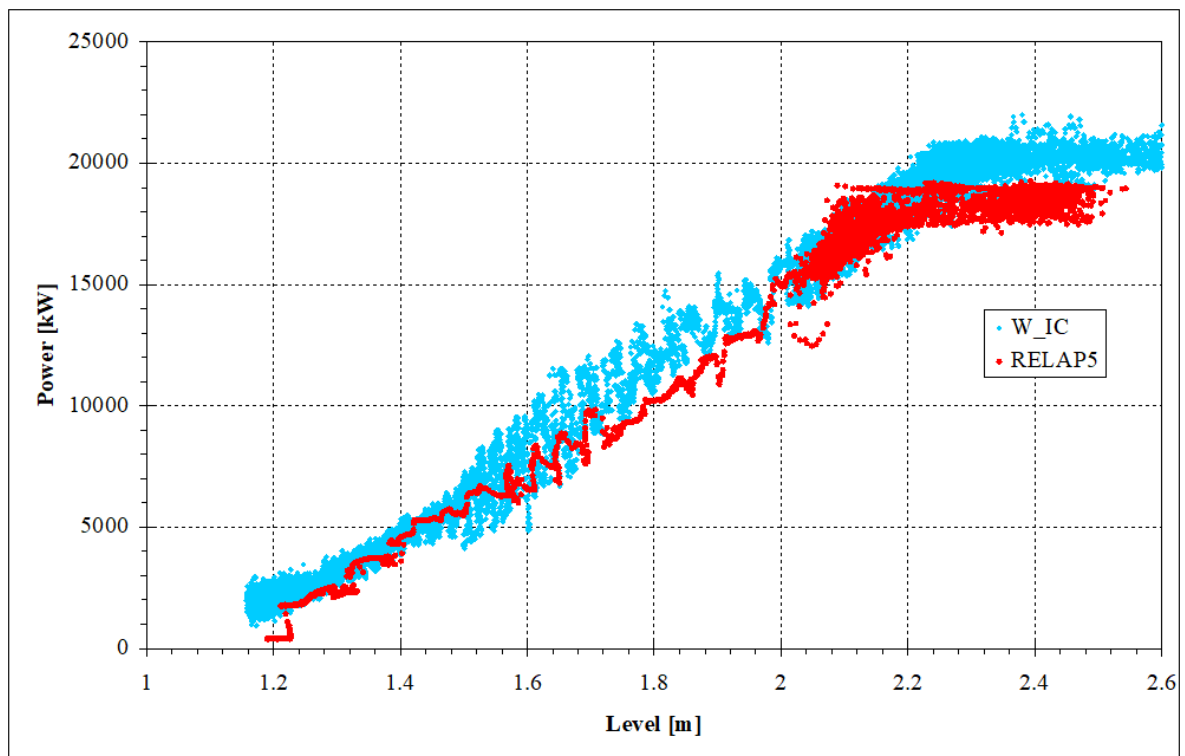


Figure 5.289. Test 7 Part 2 – Power trend as function of the pool collapsed liquid level



SECTION 5: CONCLUSIONS

All the important phenomena were clearly predicted by RELAP5, except the HX heat transfer and overall pool thermal stratification, which were predicted partially. The HX power underestimation was compensated by means of a fouling factor (multiplier for heat transfer coefficients) value of 2.2 applied on the heat transfer coefficients on both sides of the HX tubes.

REFERENCES

[5.2.7 1] *RELAP5/MOD3.3 Code Manual* (2016), NUREG/CR-5535/Rev P5, prepared by ISL for US NRC.

5.2.8. UNIFI

SECTION 1: GENERAL INFORMATION

- Organisation: University of Pisa (Italy)
- Contact persons/authors: A. Bellomo, G. Di Palma, G. Spina, M. Lanfredini* (*contact person), F. D'Auria
- Code: RELAP5/MOD3.3Patch03
- Computing environment:
 - Operative systems: Windows7 Professional
 - RAM: 8 GB
 - CPU characteristics: Intel Core i7 860 @2.80 GHz

SECTION 2: DESCRIPTION OF THE CODE USED

- General description of the code used:

General description of the RELAP5/MOD3.3Patch03 is given in [5.2.8 1]

- Detail also on:
 - Numerical solving scheme:

The PERSEO Test 7 calculations were performed semi-implicit finite-difference technique scheme, see Section 3.1.3 in [1]

- Basic differential equations and approach:

RELAP5 adopt one-dimensional, transient, two-fluid, six-equation model for flow of a two-phase steam-water mixture that can contain non-condensable components in the steam phase and/or a soluble component in the water phase. Additional details are given in [5.2.8 1], Section 3

- Implemented models relevant for PERSEO conditions:
 - Pool side heat transfer, see [5.2.8 2] for further details:
 - Nucleate boiling: Chen-Inayatov.
 - Transition boiling: Chen.
 - Film Boiling: Bromley.
 - Tube side condensation, see [5.2.8 2] for further details:
 - Condensation: Nusselt-Shah-Coburn-Hougen.

SECTION 3: DESCRIPTION OF THE NODALISATION

Figure 5.290 depicts the schematic of the PERSEO nodalisation developed for the purpose of this benchmark. Noticeably, a so-called “sliced approach” is applied throughout the system.

The pressure vessel is modelled with a vertical pipe and branches (overall 39 volumes). Steam is supplied to vessel header by a time-dependent volume (saturated steam; pressure adjusted to set measured pressure at the measurement point).

The heat exchanger (HX) is modelled with pipes components. The headers are modelled as horizontal pipes. One-hundred twenty tubes are lumped into fifteen vertical pipe divided into seventeen volumes. Each equivalent tube represents four HX tubes located on the same radial cross section of HX headers. In general, similar strategies are adopted at UNIFI to attempt capturing possible occurrence of instabilities (flow reversal in SG U-tubes, parallel

Table 5.45. Nodalisation parameters

	Number of hydraulic volumes	Number of junctions	Number of heat structures	Overall volume (m ³)
Vessel	39	39	39	34.7
Steam line	130	129	130	1.95
HX	289	304	293	1.84
Condensate line	69	69	69	0.53
HXP	42	60	0	26.9
Steam duct	16	17	16	12.1
OP	51	75	0	167.5
Heat transfer area HX (m ²)	46.16 m2 (HX pipes, headers and header caps)			
HX heat structure axial nodes number	Each header: 15 (pipe)+2(cap) Each equivalent pipe: 11			
HX heat structure radial nodes number	Header: 12 Pipe: 11			

SECTION 4: RESULTS

TEST 7 Part 1

Test 7 Part 1 starts after 1 500 s of “null transient” calculation performed by keeping the HXP pressure at the experimental initial value by the mean of a time-dependent volume component (time has been properly shifted). The most significant initial conditions for Test 7 Part 1 are:

- Primary pressure: 7 062 kPa;
- Water level in the pressure vessel: 3.63 m (constant value)
- HXP is filled with water up to 0.194 m;
- HXP relative pressure: 0.615 kPa;
- Overall pool water level: 4.65 m;
- Triggering valve is closed.

Additional initial conditions are included in Table 5.47 (end of the section).

Experimental temperature at HX inlet is superheated (Figure 5.295), even if saturated steam is injected in the vessel. This is probably due to measurement errors. The same apply to Test 7 Part 2.

Triggering valve logic was derived by matching HXP experimental level. Adopted values are:

- First opening at 10 475.0 s; opening time: 20.0 s (20% of pipe flow area), close at 10 582 s in 26 s.
- Second opening at 10 621.0 s; opening time: 10.0 s (17% of pipe flow area), close at 10 655 s in 10 s.
- Third opening at 11 039.0 s; opening time: 40.0 s (50% of pipe flow area), close at 11 230 s in 40 s.

Main discrepancies between experimental and calculated results are summarised here after.

Thermal stratification in the OP is significantly underestimated by the code (Figure 5.303, Figure 5.304). This is probably due to overestimation of the recirculation in the OP.

At about time 11 300 s, HXP differential pressure rises faster than experimental value maybe due to overestimation of boiling (Figure 5.302).

HXP temperatures show some spikes at about 10 500 s connected with the opening of the vacuum barker (Figure 5.300 and Figure 5.301). This device is modelled with a very simplified approach in the nodalisation.

HXP fluid temperatures are generally overestimated when gas phase is present (Figure 5.299 to Figure 5.301). This is probably due to higher recirculation predicted by the code. Such error is negligible due to the small impact on the overall energy balance. Wall temperatures of both the headers predicted by the code (external mesh points) are in good agreement with the experimental data, Figure 5.307 and Figure 5.308.

Pressure drop are slightly underestimated during high flow conditions, Figure 5.305 and Figure 5.306.

Main relevant thermal-hydraulic aspects are summarised in Table 5.45.

Qualitative accuracy evaluation of relevant phenomena is given in Table 5.46. It must be stressed that without tuning the HTC to get the correct exchanged power, practically any phenomenon is predicted by the code.

Computational time of the Test 7.1 was 1 hour 56 min; time step was set to 0.003 s.

Table 5.46. Main relevant thermal-hydraulic aspects related to Test 7 Part 1

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	10 475 – 10 608	10 475 s – 10 608 s
Triggering valve (F045) re-opening and re-closure	10 621 – 10 655	10 621 s – 10 655 s
Maximum level in the HX pool for the first filling step	10 655	1.46 m
Small heat removal from the primary side	10 660 – 11 050	2.4 MW – 2.6 MW
Slow water consumption in the HX pool	-	Level is increasing
Instabilities for steam condensation in the injector	10 600 – 11 290	-
Triggering valve (F045) opening and closure	11 039 – 11 260	11 039 s – 11 260 s
Maximum level in the HX pool	11 332	3.45 m
Maximum exchanged power	11 550	18.8 MW
HX pool minimum level	14 784	1.16 m
OP average temperature	13 750	55°C (abt)

Figure 5.291. IC feed line mass flow [Part 1]

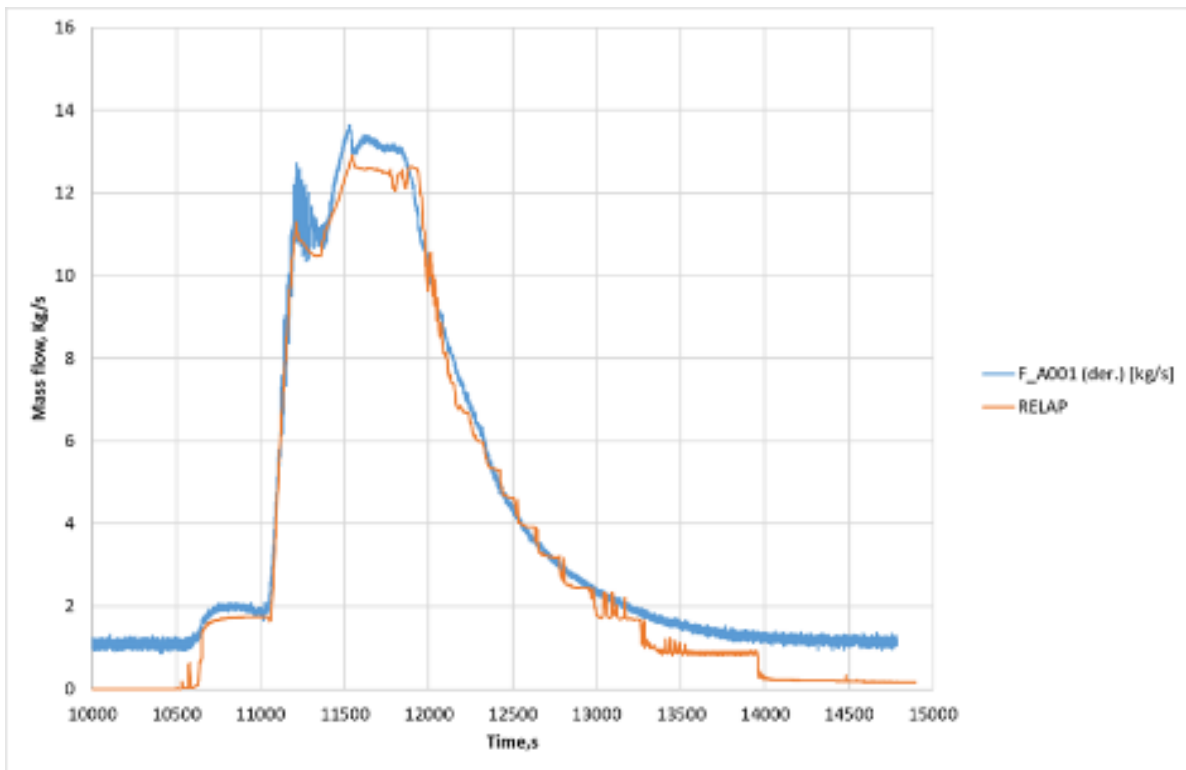


Figure 5.292. IC drain line mass flow [Part 1]

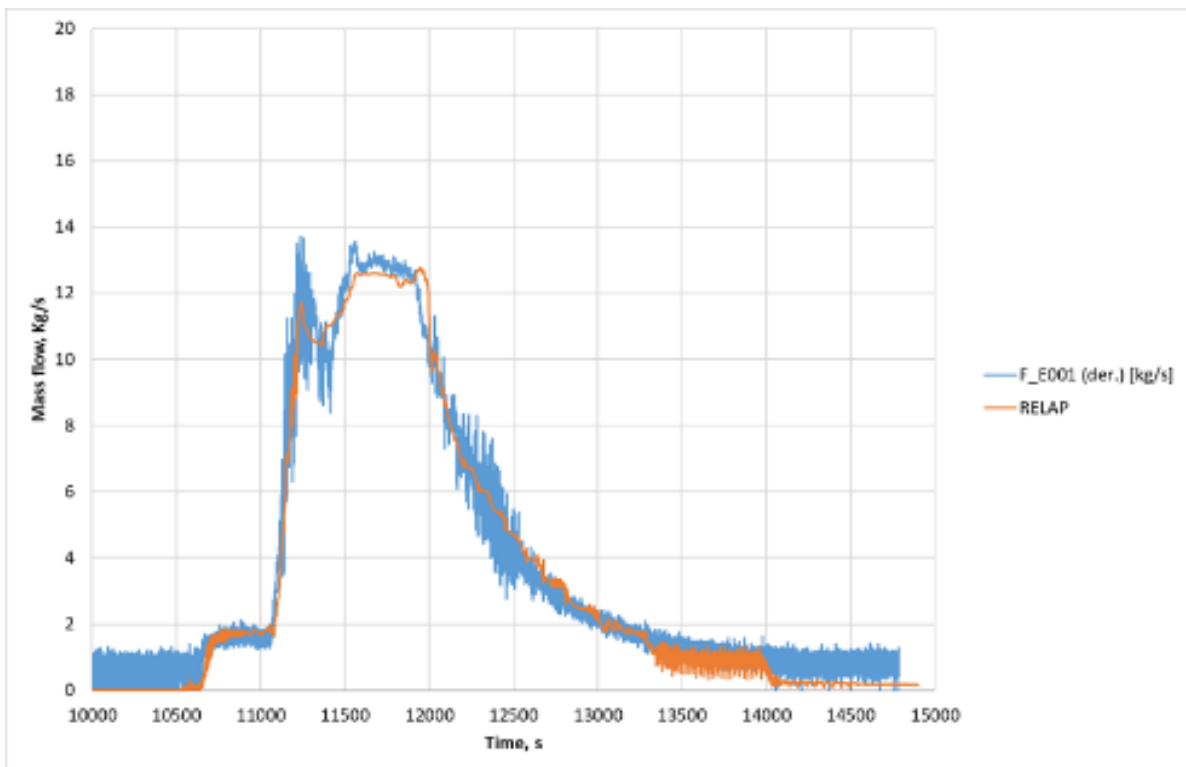


Figure 5.293. IC exchanged power [Part 1]

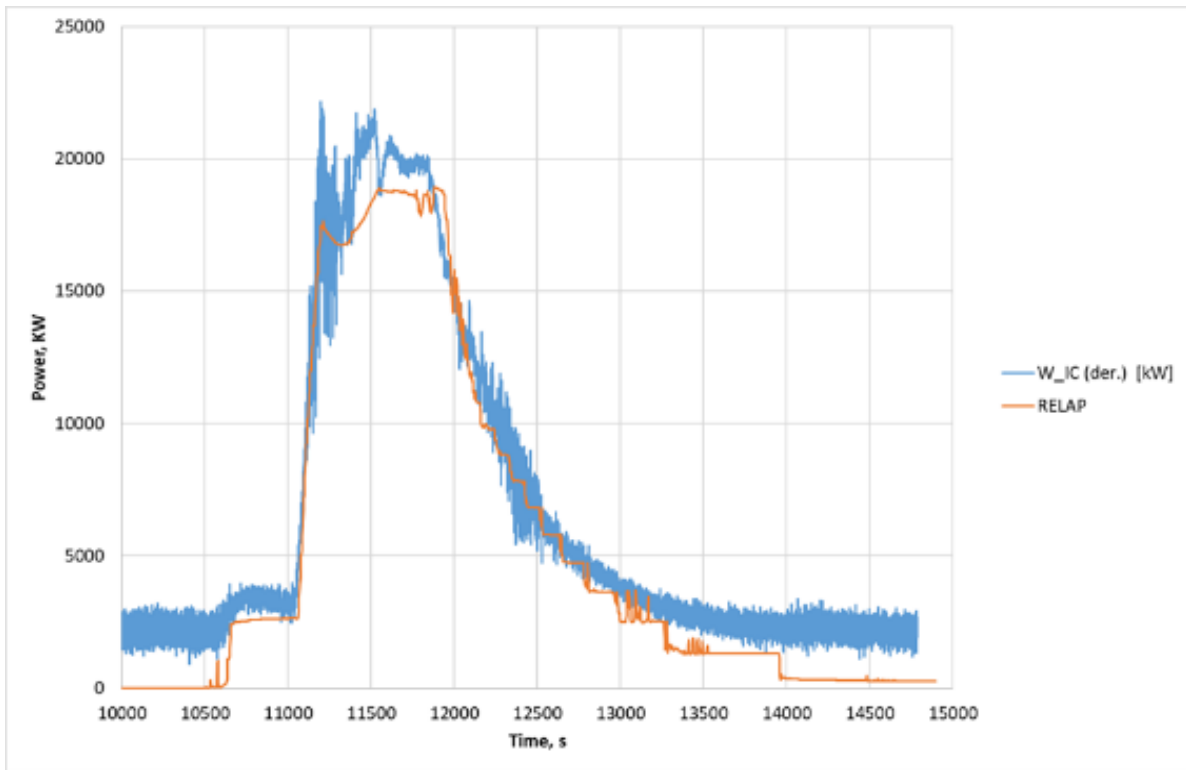


Figure 5.294. Vessel pressure [Part 1]

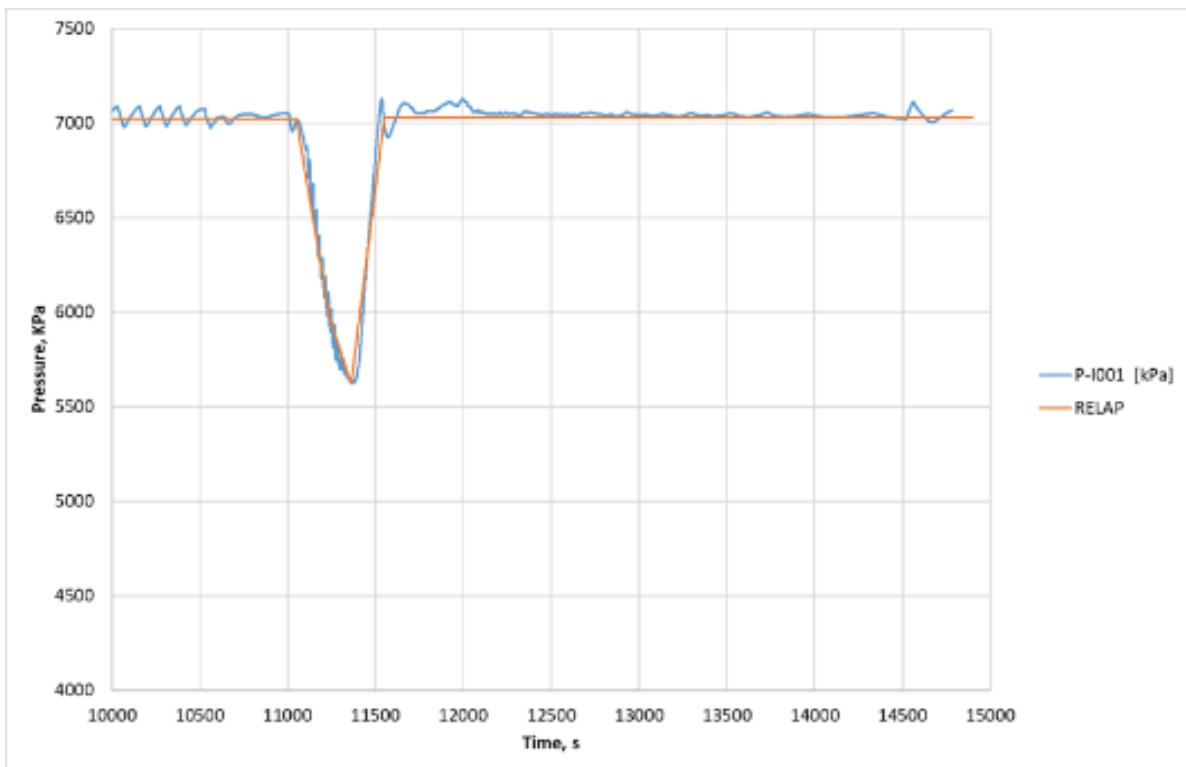


Figure 5.295. IC inlet temperature [Part 1]

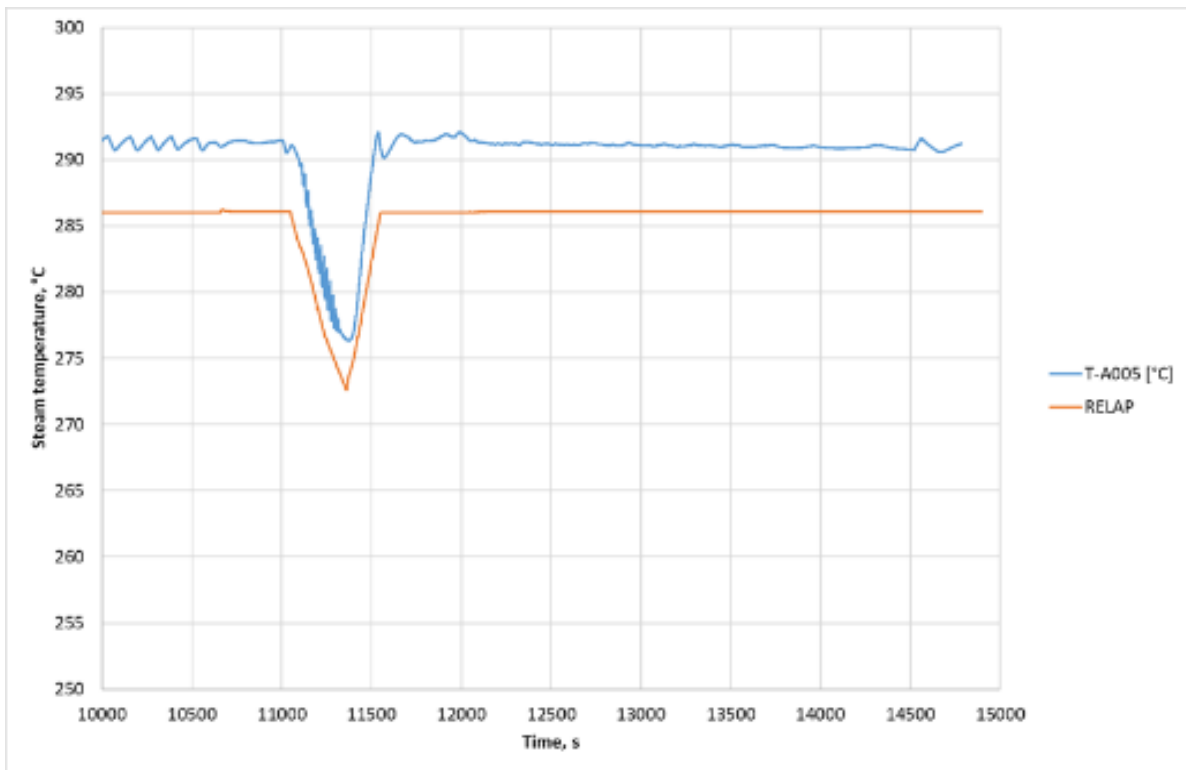


Figure 5.296. IC outlet temperature [Part 1]

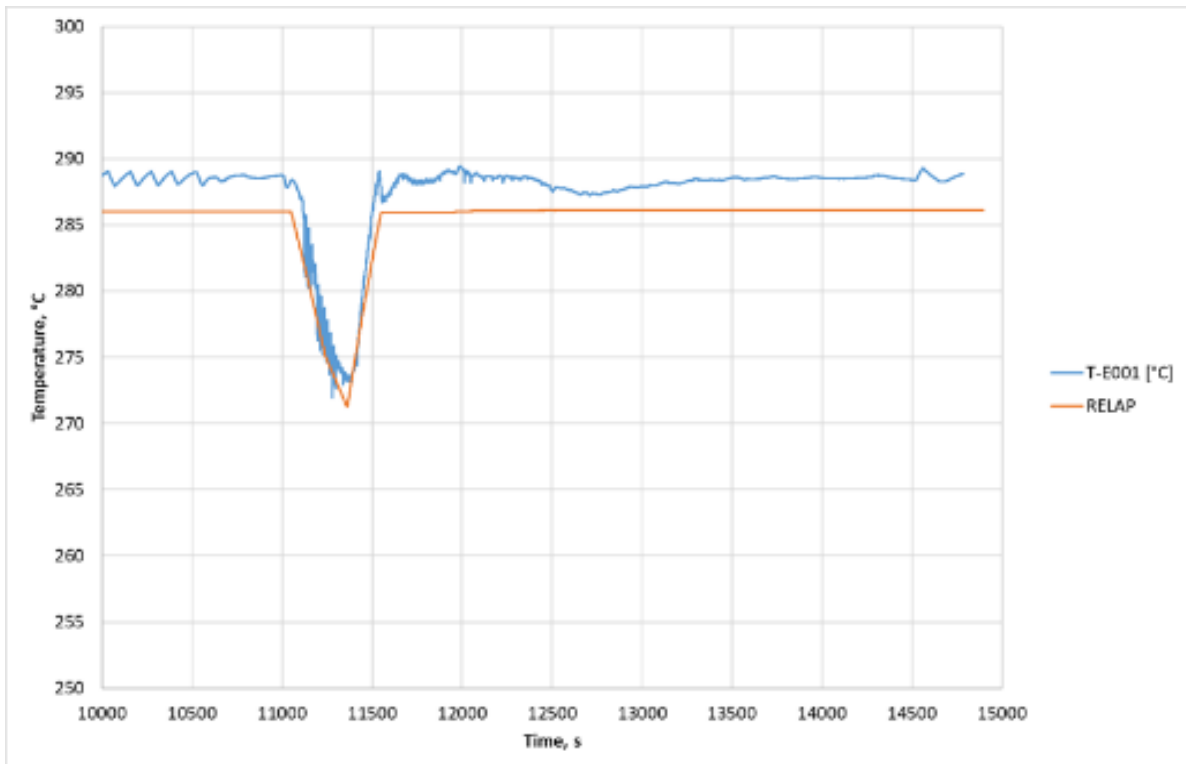


Figure 5.297. HXP collapsed water level [Part 1]

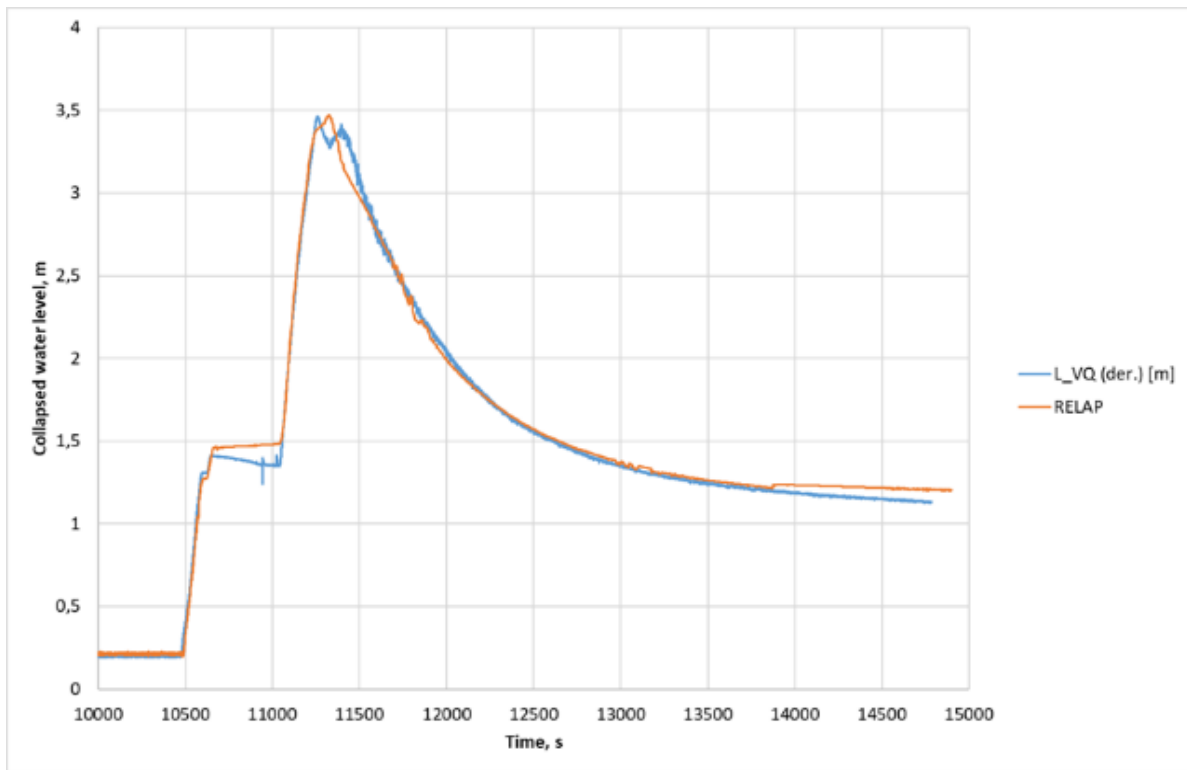


Figure 5.298. OP collapsed water level [Part 1]

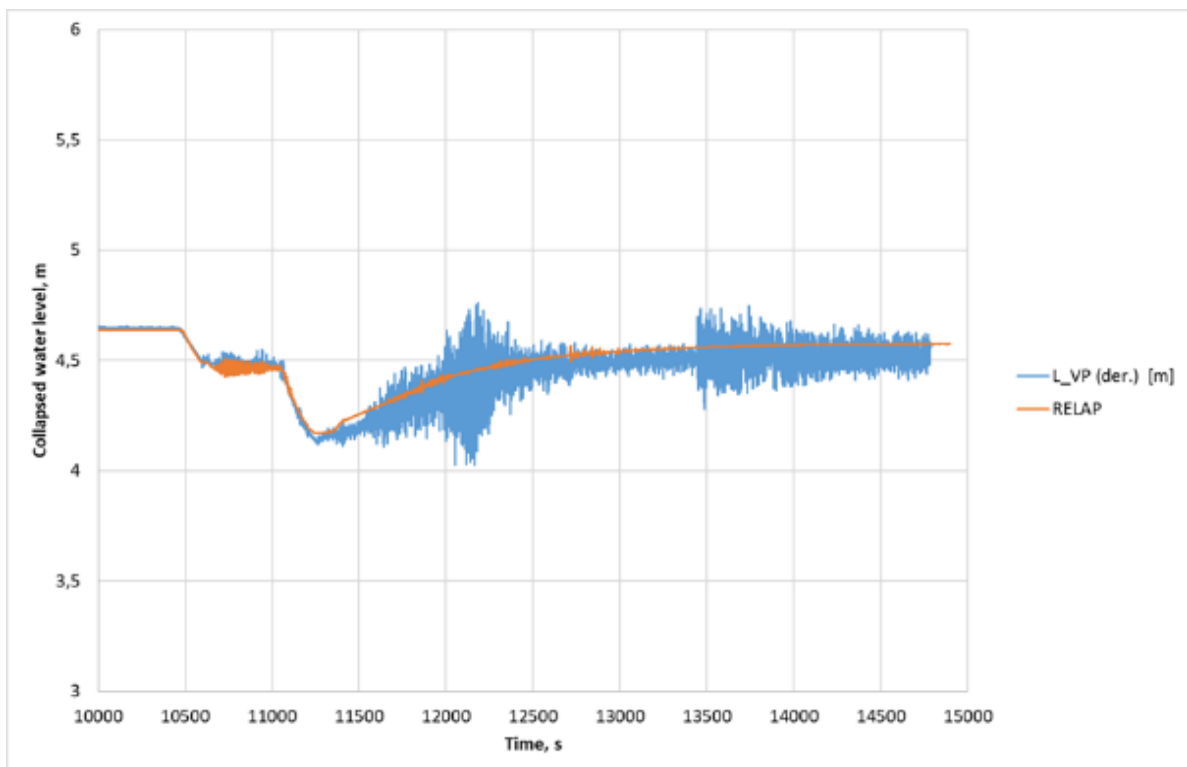


Figure 5.299. HXP fluid temperature -Bottom [Part 1]

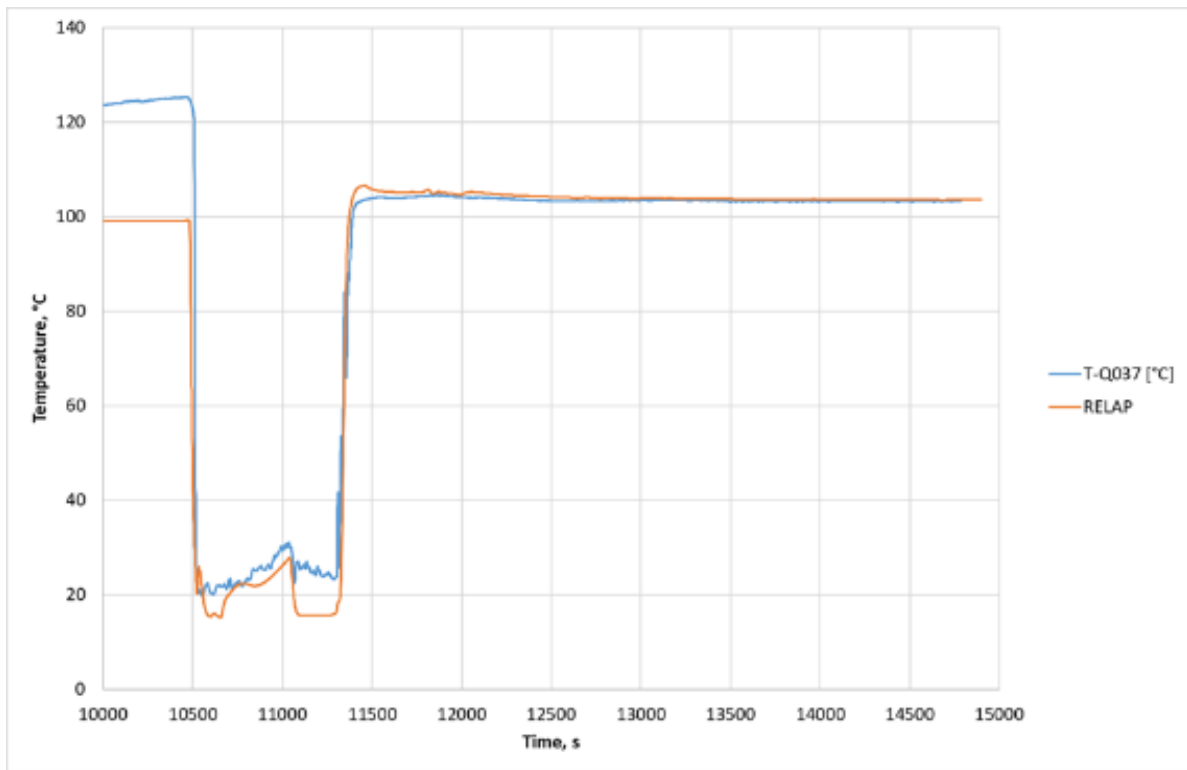


Figure 5.300. HXP fluid temperature - middle [Part 1]



Figure 5.301. HXP fluid temperature -top [Part 1]

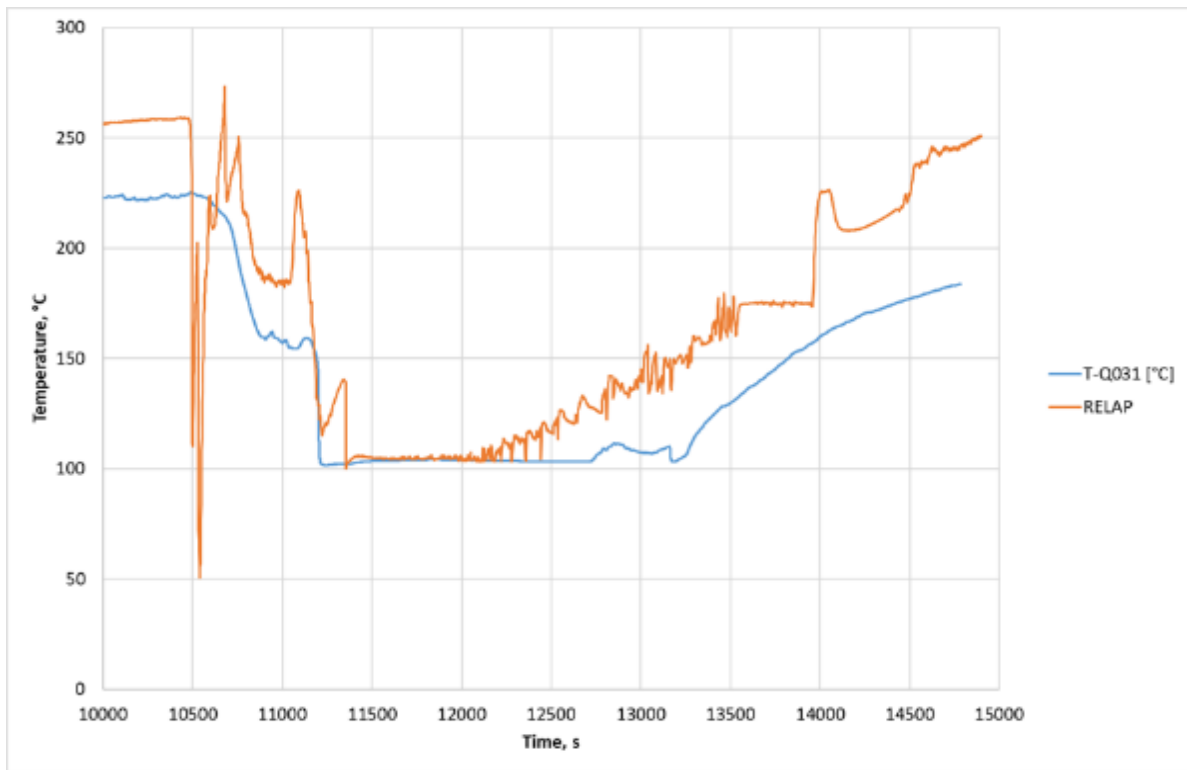


Figure 5.302. HXP relative pressure -top [Part 1]

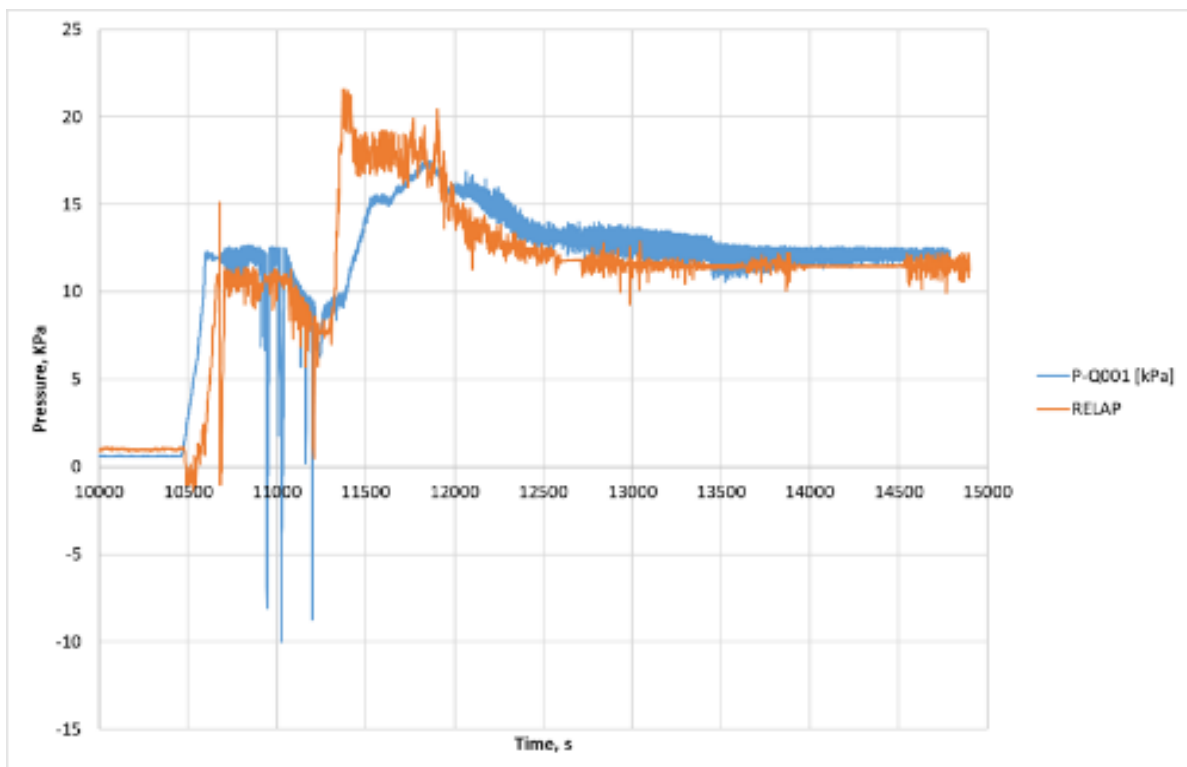


Figure 5.303. OP fluid temperature - bottom [Part 1]

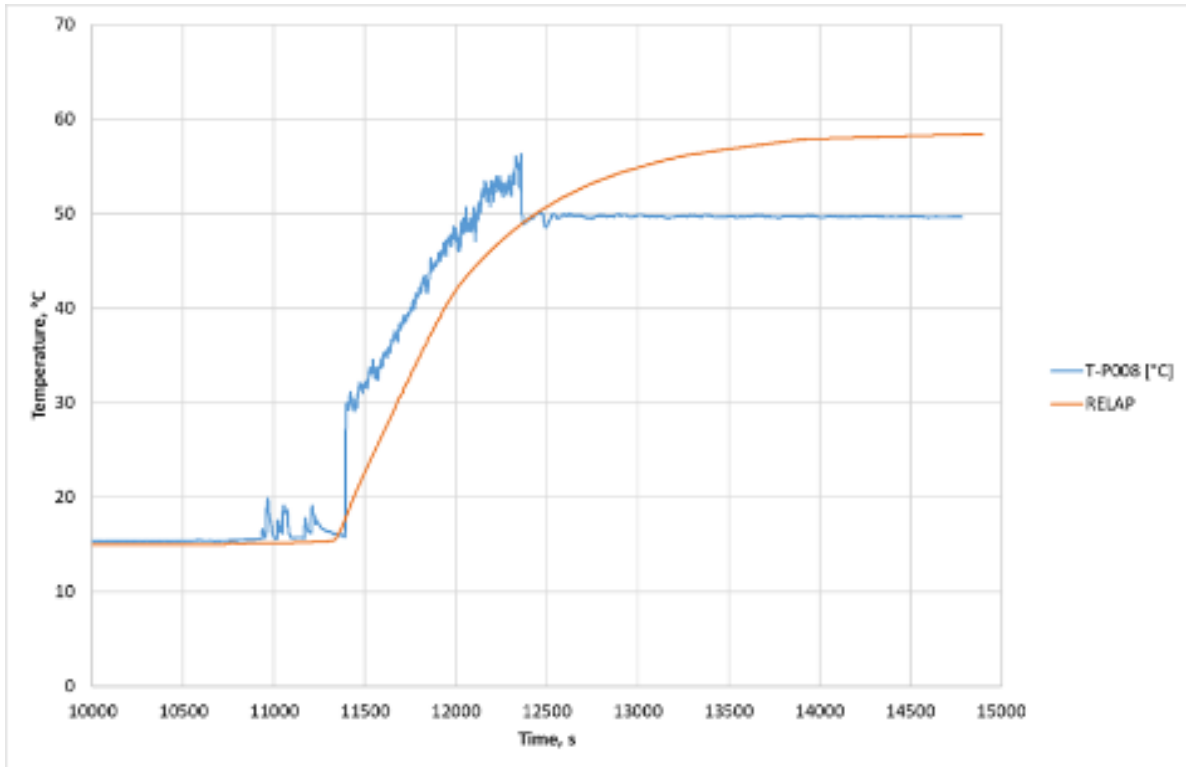


Figure 5.304. OP fluid temperature - middle [Part 1]

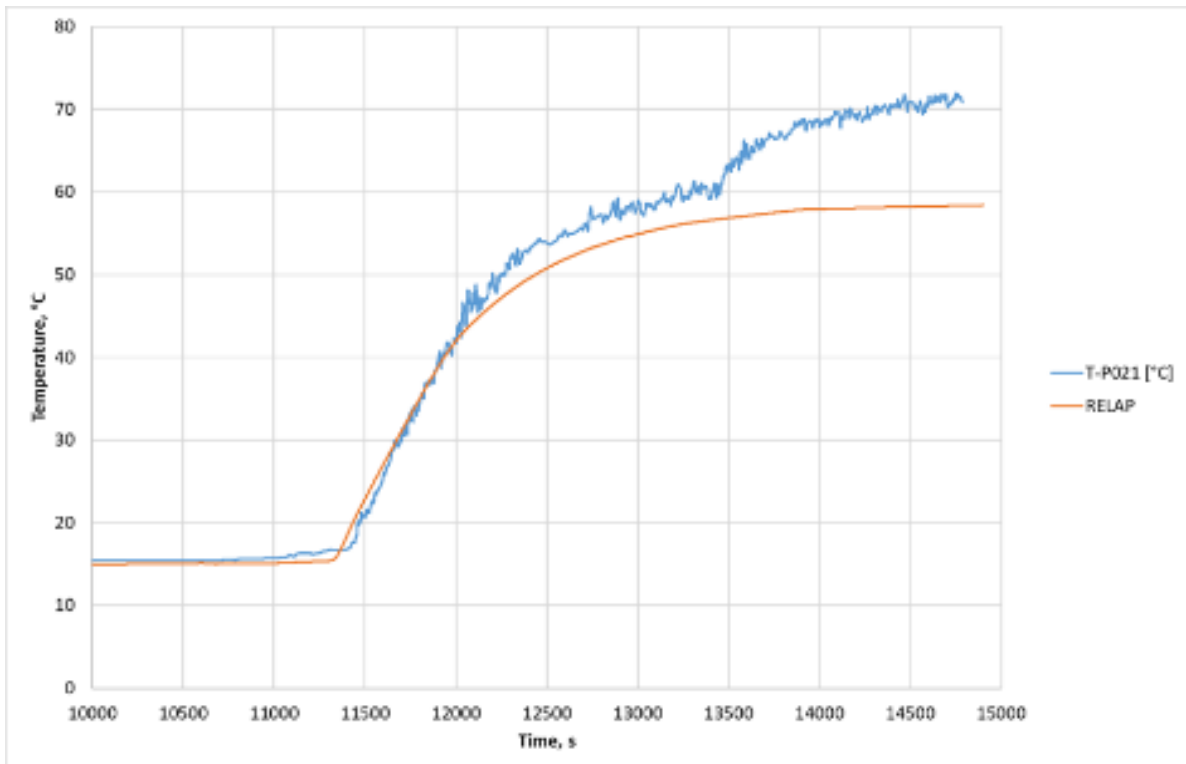


Figure 5.305. Injector differential pressure [Part 1]

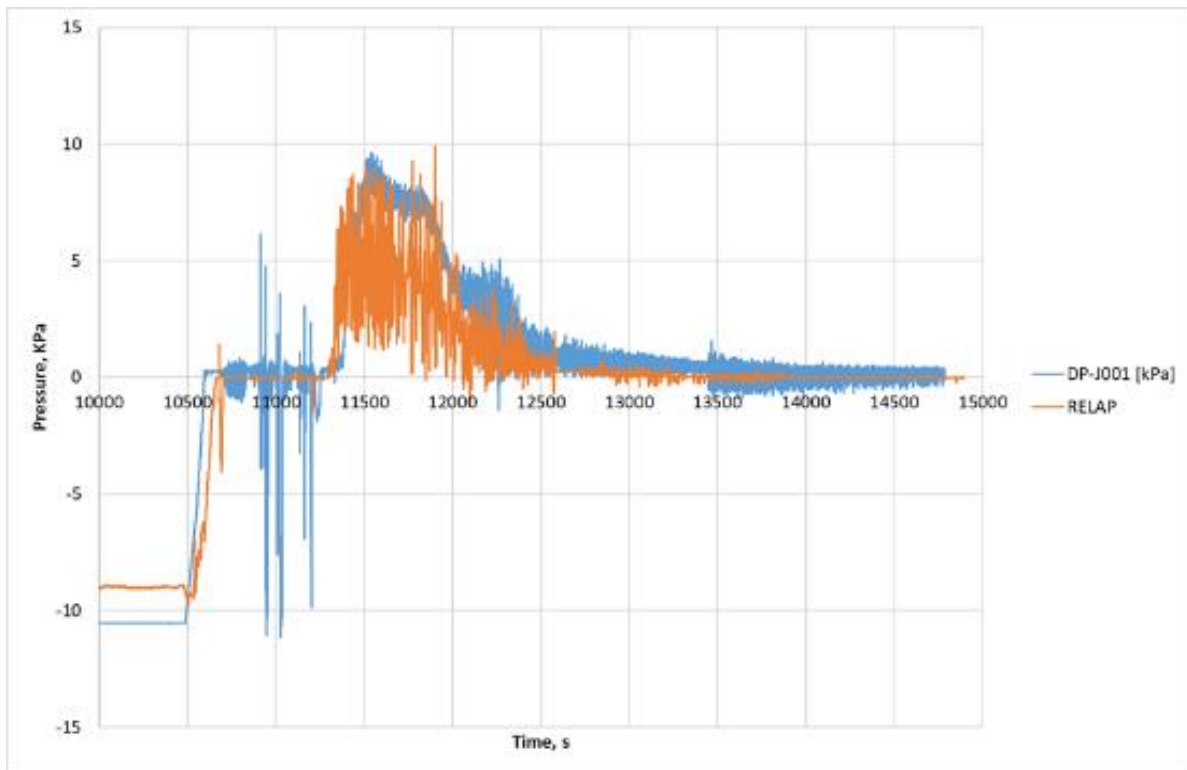


Figure 5.306. Heat exchanger pipe differential pressure [Part 1]

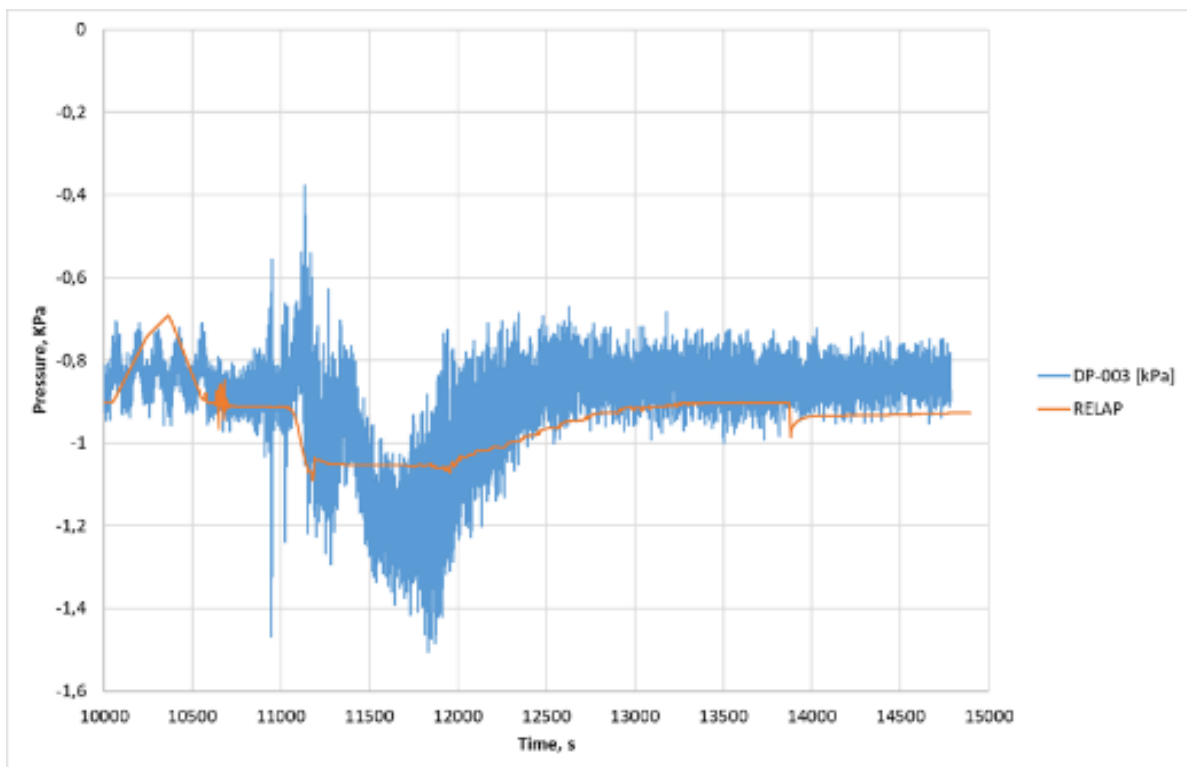


Figure 5.307. Upper header wall temperature [Part 1]

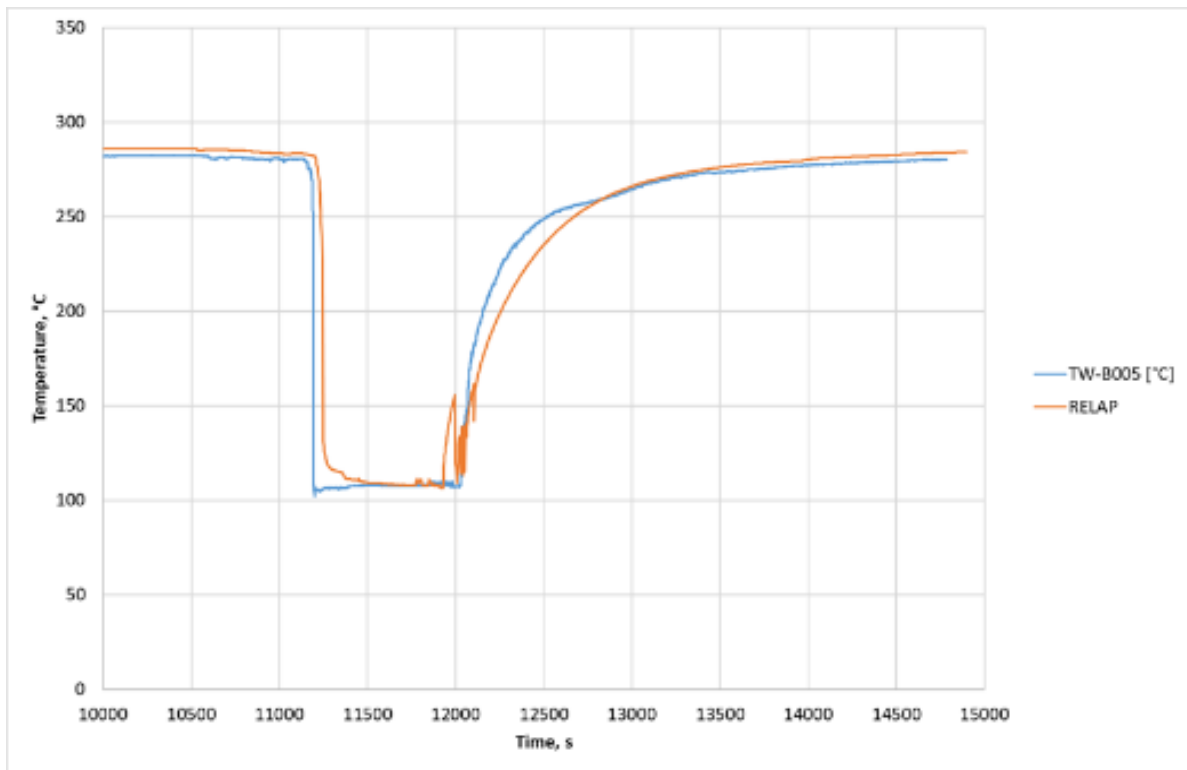


Figure 5.308. Lower header wall temperature [Part 1]

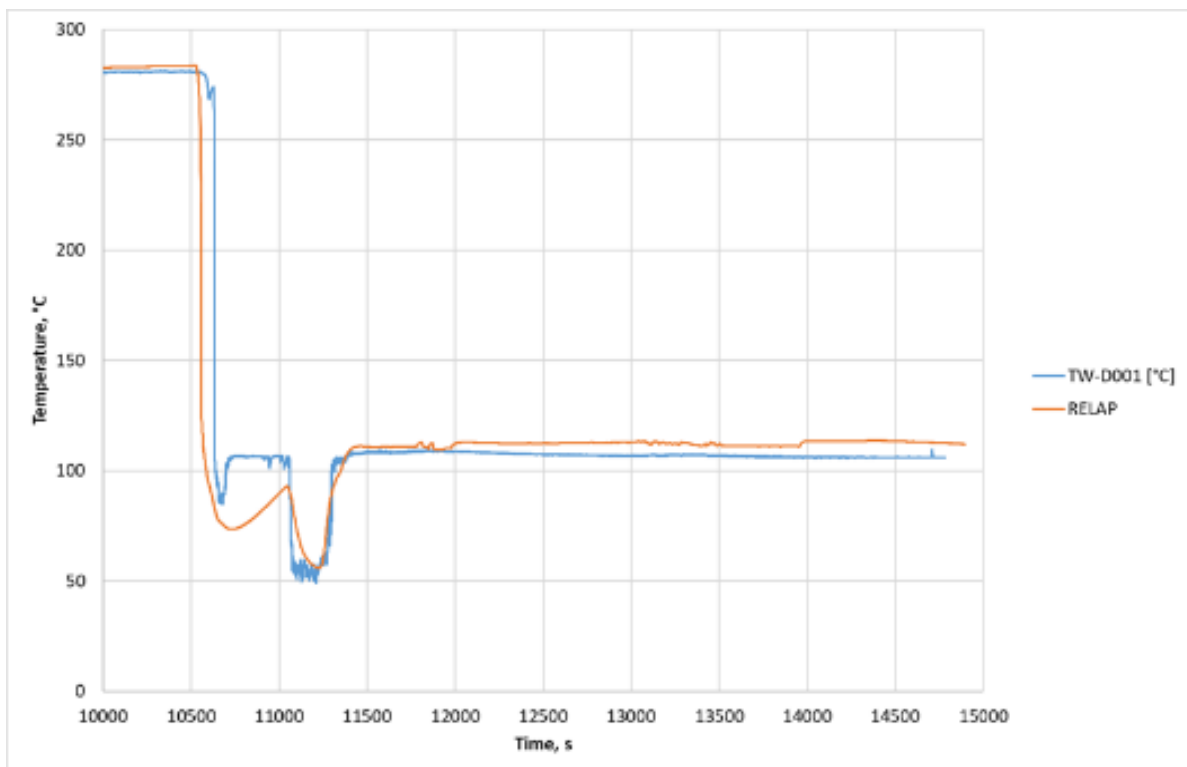


Figure 5.309. Exchanged collapsed water level vs power HXP
[Part 1]



The marks adopted in Table 5.46 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.47. PERSEO Test 7 Part 1 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line Flowrate condensate drain line Power heat exchanger Absolute pressure vessel HX inlet temperature HX outlet temperature	F A001 (der.) F E001 (der.) W IC (der.) P-I001 T-A005 T-E001	+
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger Level HXP Level OP Temperature HXP (bottom) Temperature HXP (middle) Temperature HXP (top) Relative pressure HXP top Temperature OP (bottom) Temperature OP (top)	W IC (der.) L VQ (der.) L VP (der.) T-Q037 T-Q034 T-Q031 P-Q001 T-P008 T-P021	+
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Absolute pressure vessel Flowrate steam supply line Flowrate condensate drain line Power heat exchanger Relative pressure HXP top Diff. pressure HX upper-lower header Diff. pressure steam duct injector	P-I001 F A001 (der.) F E001 (der.) W IC (der.) P-Q001 DP-003 DP-J001	+
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Flowrate steam supply line Flowrate condensate drain line Absolute pressure vessel Diff. pressure HX upper-lower header HX inlet temperature HX outlet temperature Power heat exchanger	F A001 (der.) F E001 (der.) P-I001 DP-003 T-A005 T-E001 W IC (der.)	o
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Level HXP Power heat exchanger Temperature HXP (bottom) Temperature HXP (middle) Temperature HXP (top)	L VQ (der.) W IC (der.) T-Q037 T-Q034 T-Q031	o
F	Behaviour of large pool: Thermal stratification	+	+	Power heat exchanger Diff. pressure steam duct injector Temperature HXP (bottom) Temperature HXP (middle) Temperature HXP (top) Temperature OP (bottom) Temperature OP (top)	W IC (der.) DP-J001 T-Q037 T-Q034 T-Q031 T-P008 T-P021	-
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP Level OP Power heat exchanger Relative pressure HXP top	L VQ (der.) L VP (der.) W IC (der.) P-Q001	+
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP Relative pressure HXP top Diff. pressure steam duct injector	L VP (der.) P-Q001 DP-J001	+
I	Structural Heat	+	+	Wall temperature HX upper header Wall temperature HX lower header	TW-B005 TW-D001	+

Table 5.48. Initial condition simulated by the benchmark participant (Test 7 Part 1)

	PARAMETER	LABEL	EXP	Benchmark Participant value	(%) DISCRPANCIES	NOTE
1	Flowrate steam supply line (kg/s)	F_A001 (der.)	1.1	1.161	5.55	
2	Flowrate condensate drain line (kg/s)	F_E001 (der.)	0.59	0.31	47.46	
3	Power heat exchanger (kW)	W_IC (der.)	2 321.23	2 811.147	21.11	
4	Absolute pressure vessel (kPa)	P-I001	7 056.44	7 062.943	0.09	
5	HX inlet fluid temperature (K)	T-A005	564.59	564.655	0.01	
6	HX outlet fluid temperature (K)	T-E001	561.83	561.888	0.01	
7	Level HXP (m)	L_VQ (der.)	0.19	0.194	2.11	
8	Level OP (m)	L_VP (der.)	4.65	4.652	0.04	
9	Fluid temperature HXP (bottom) (K)	T-Q037	396.75	396.763	0.00	
10	Fluid temperature HXP (middle) (K)	T-Q034	471.4	471.447	0.01	
11	Fluid temperature HXP (top) (K)	T-Q031	495.89	496.252	0.07	
12	Relative pressure HXP top (kPa)	P-Q001	0.61	0.615	0.82	
13	Fluid temperature OP (bottom) (K)	T-P008	288.49	288.492	0.00	
14	Fluid temperature OP (top) (K)	T-P021	288.58	288.578	0.00	
15	Diff. pressure HX upper-lower header (kPa)	DP-003	-0.87	-0.843	3.10	
16	Diff. pressure steam duct injector (kPa)	DP-J001	-10.53	-10.538	0.08	
17	Wall temperature HX upper header (K)	TW-B005	555.01	554.965	0.01	
18	Wall temperature HX lower header (K)	TW-D001	553.48	553.34	0.03	

Test 7 Part 2

Test 7 Part 2 starts after 100 s of “null transient” calculation performed by keeping the HXP pressure at the experimental initial value by the mean of a time-dependent volume component (time has been properly shifted).

The most significant initial conditions for the Test 7 Part 2 are:

- Primary pressure: 7.05 MP;
- Water level in the pressure vessel: 3.63 m from the bottom;
- HXP filled with water up to 1.128 m;
- HXP relative pressure: 12. kPa;
- OP water level: 4.522 m;

- Triggering valve is closed;
- Drain valve (simulator) mass flow rate: 16.2 Kg/s (constant) when valve is opened in the experiment.

Additional initial conditions are included in Table 5.50 (end of the section).

The triggering valve starts to open at 300 s (opening time: 26 s, 100% of the pipe flow area) and closes at 3 338 s.

Maximum exchanged power without the use of fouling factor is about 11 MW.

In general, similar behaviour of Test 7 Part 1 is observed. Main differences deal with the behaviour of the upper header temperature which starts to rise earlier than in the experiment, Figure 5.326. This is due to the underestimation of the HXP level.

Again, thermal stratification in the OP is not predicted by the code and the onset of OP boiling is delayed, Figure 5.322 and Figure 5.323. This is mainly due to the underestimation of exchanged power, more pronounced than in Part 1 because of the underestimation of the HXP level, Figure 5.316.

HXP level (Figure 5.316), HX exchanged power (Figure 5.312) and primary side mass flow (Figure 5.310) show a smooth behaviour after roughly 1 700 s. This is probably connected with the fact that the condensation at the injector outlet becomes very small: the code calculates a condensation rate less than 0.025 kg/m³-s.

Maximum time step adopted are: 1.0e-2 s until triggering valve opening and 4.0e-3 s after triggering valve opening. Maximum mass error is about 100 Kg.

Main relevant thermal-hydraulic aspects are summarised in Table 5.48.

Qualitative accuracy evaluation of relevant phenomena is given in Table 5.49. It must be stressed that without tuning the HTC to get the correct exchanged power, practically any phenomenon is predicted by the code.

Figure 5.310. IC feed line mass flow [Part 2]

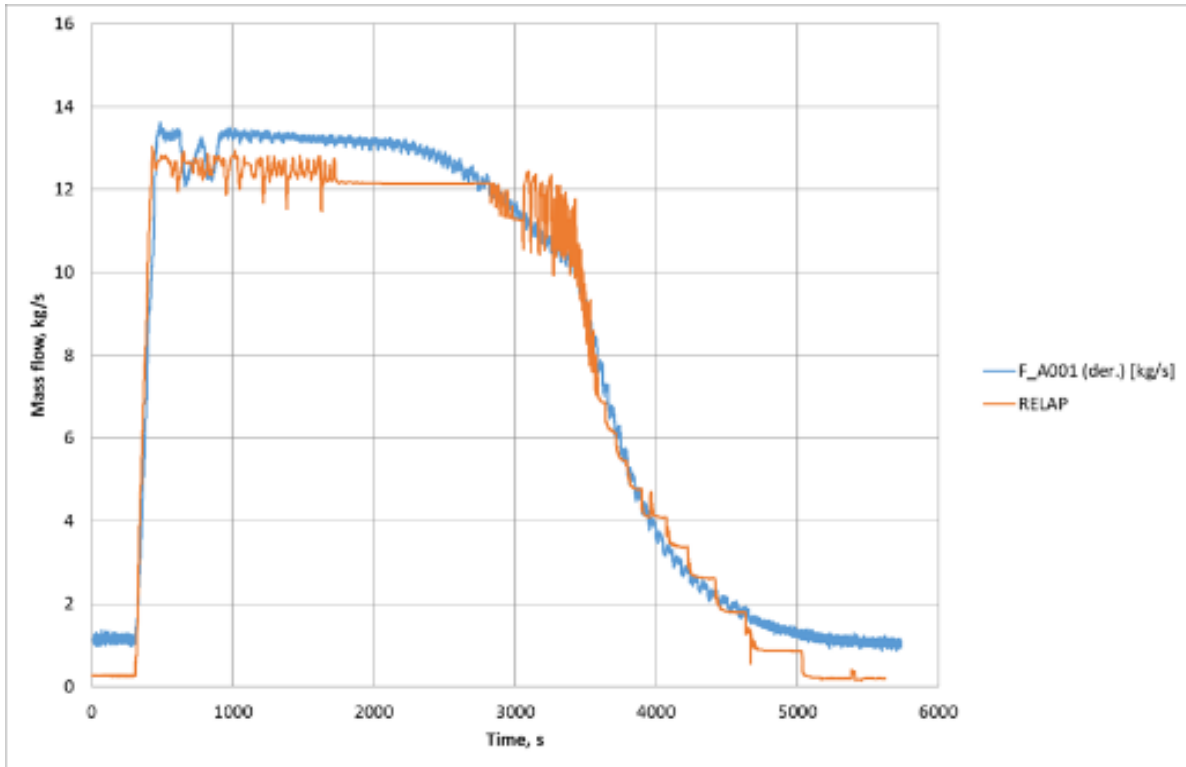


Figure 5.311. IC drain line mass flow [Part 2]

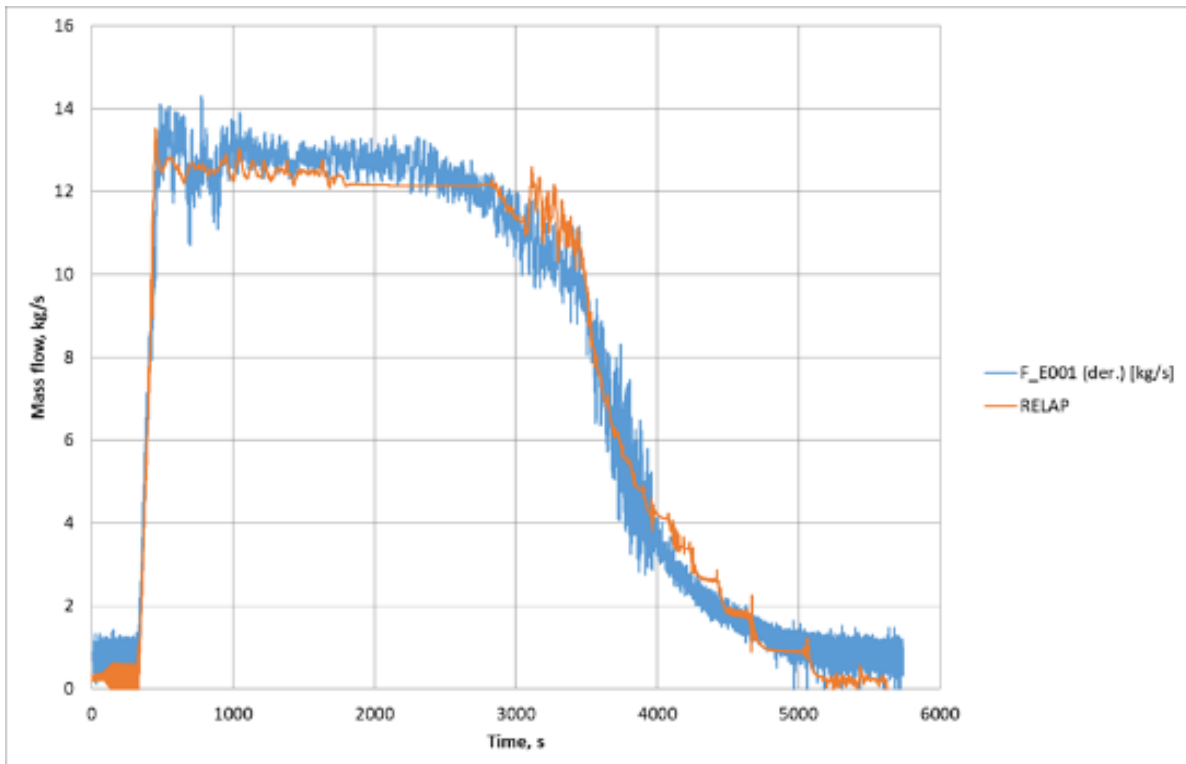


Figure 5.312. IC exchanged power [Part 2]

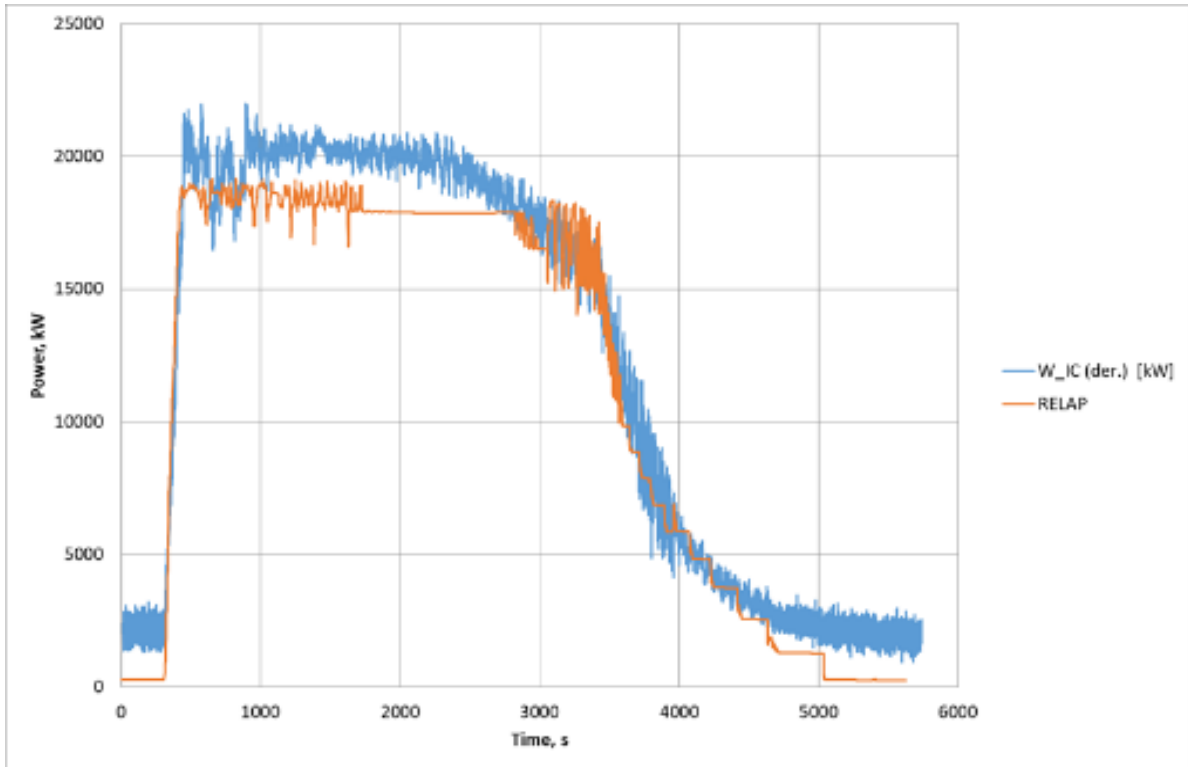


Figure 5.313. Vessel pressure [Part 2]

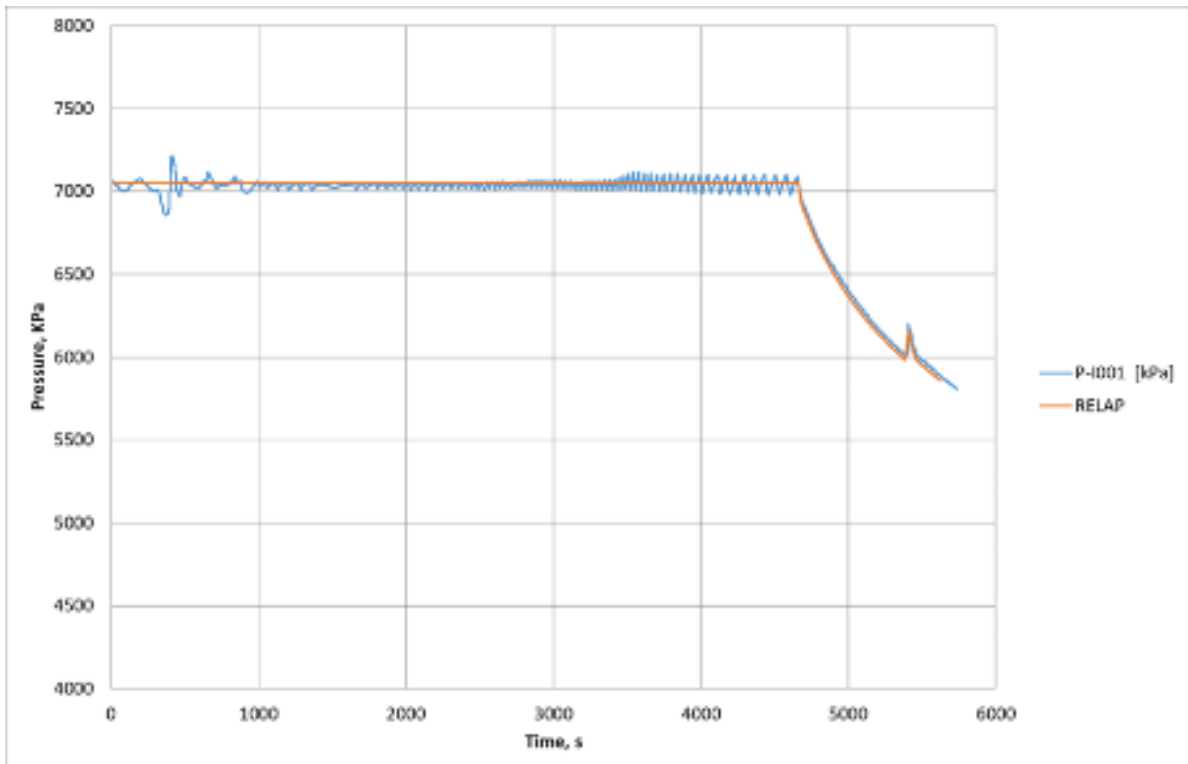


Figure 5.314. IC inlet temperature [Part 2]

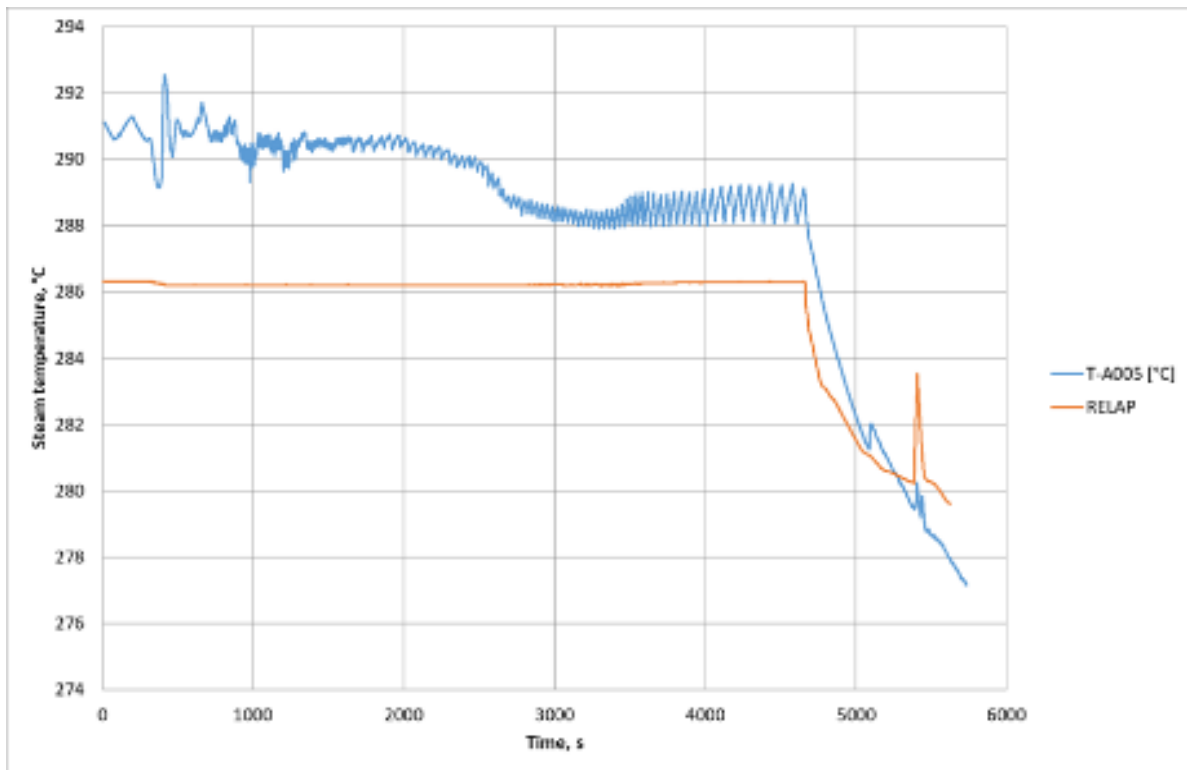


Figure 5.315. IC outlet temperature [Part 2]

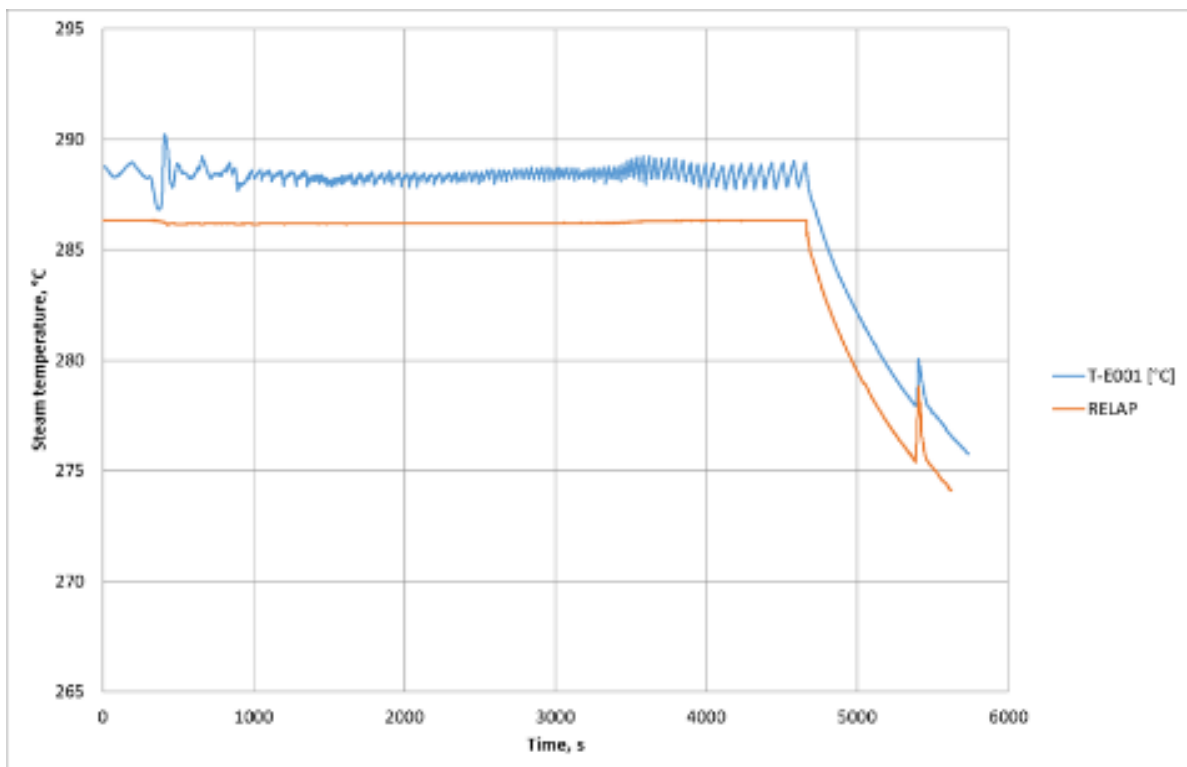


Figure 5.316. HXP collapsed water level [Part 2]

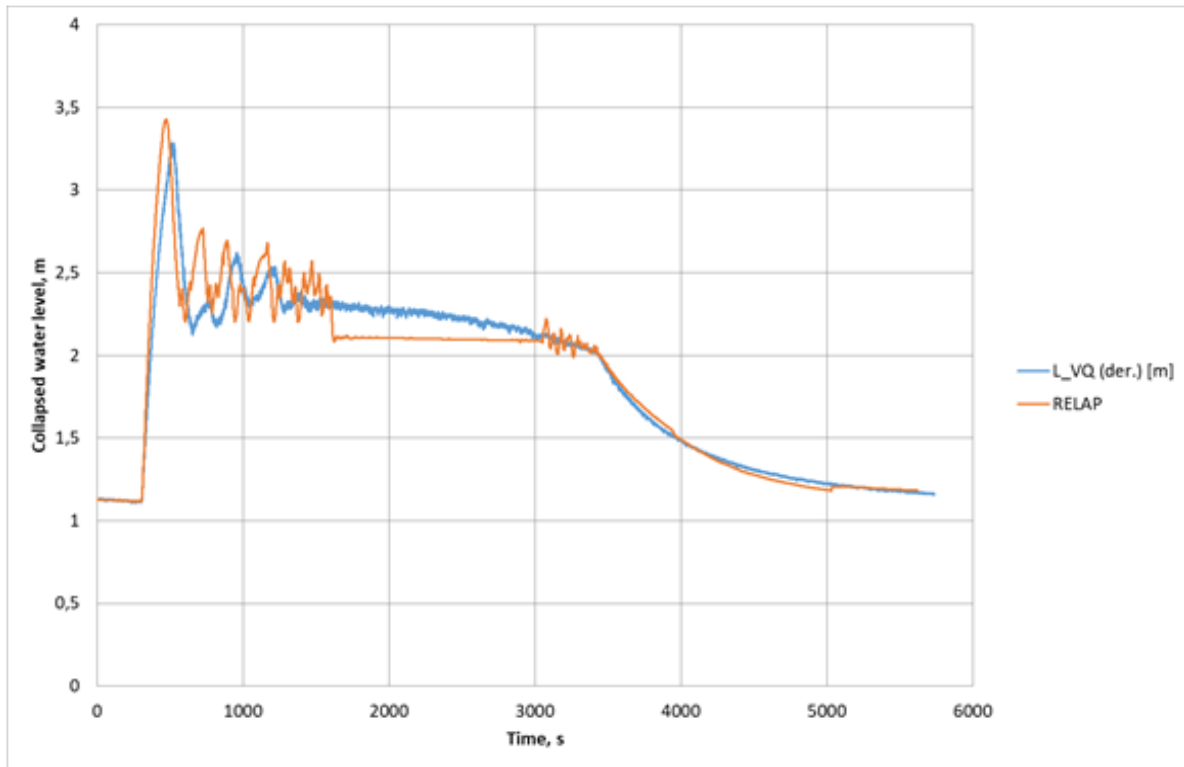


Figure 5.317. OP collapsed water level [Part 2]

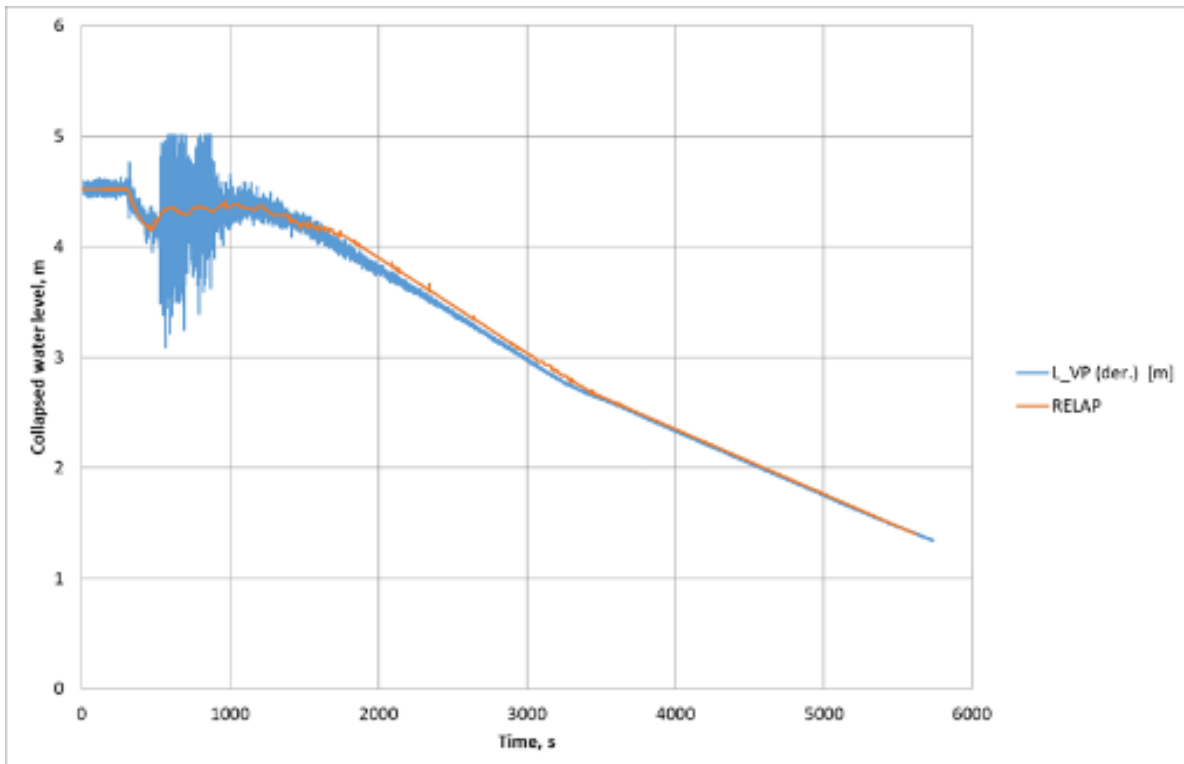


Figure 5.318. HXP fluid temperature -Bottom [Part 2]

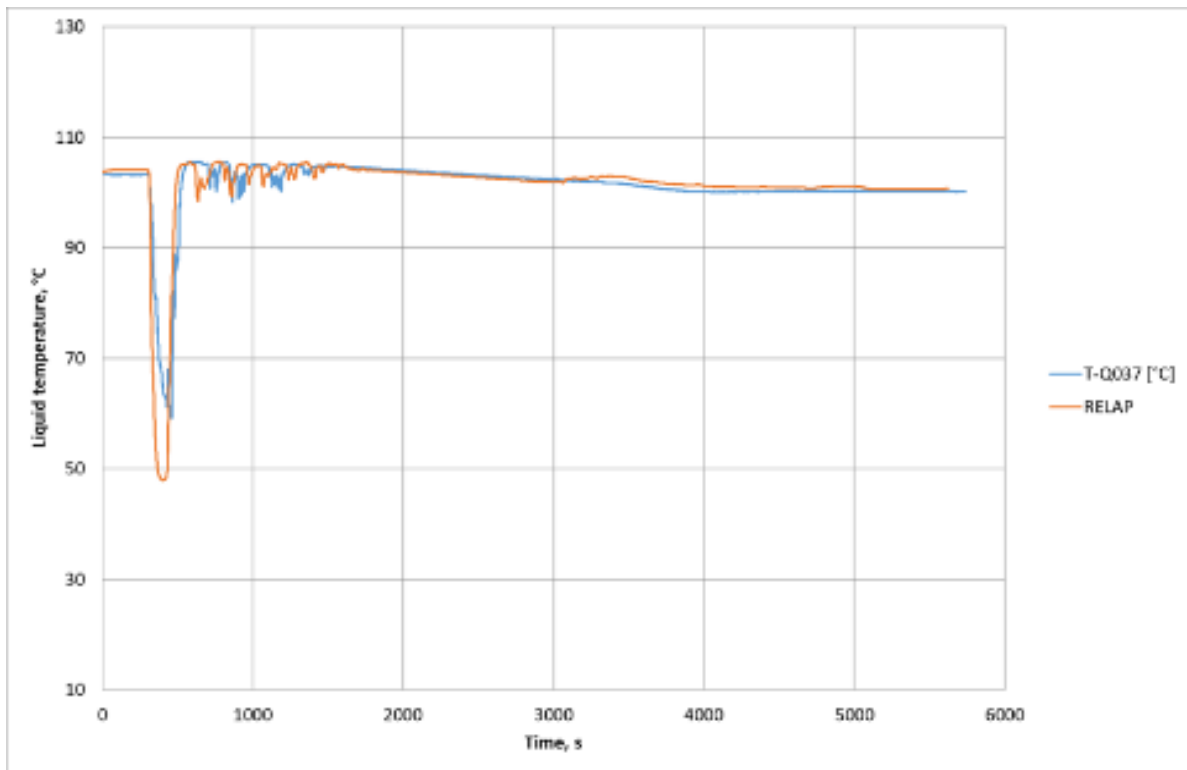


Figure 5.319. HXP fluid temperature - middle [Part 2]

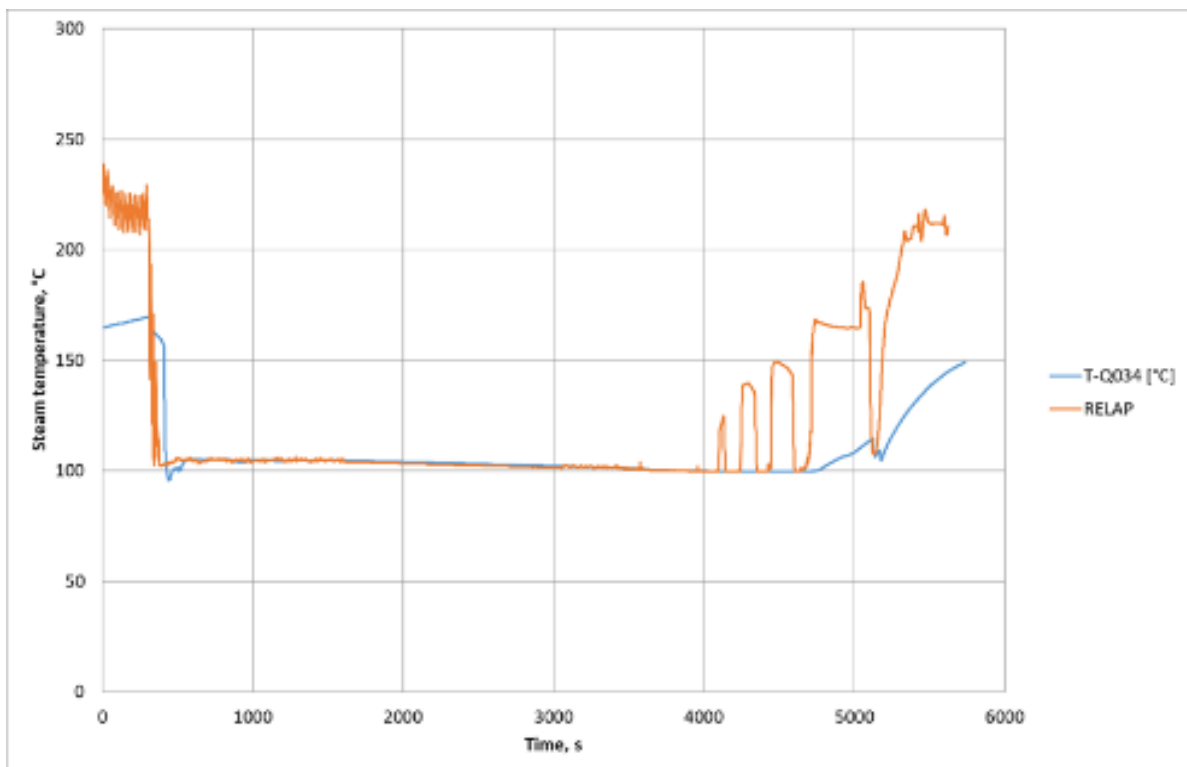


Figure 5.320. HXP fluid temperature -top [Part 2]

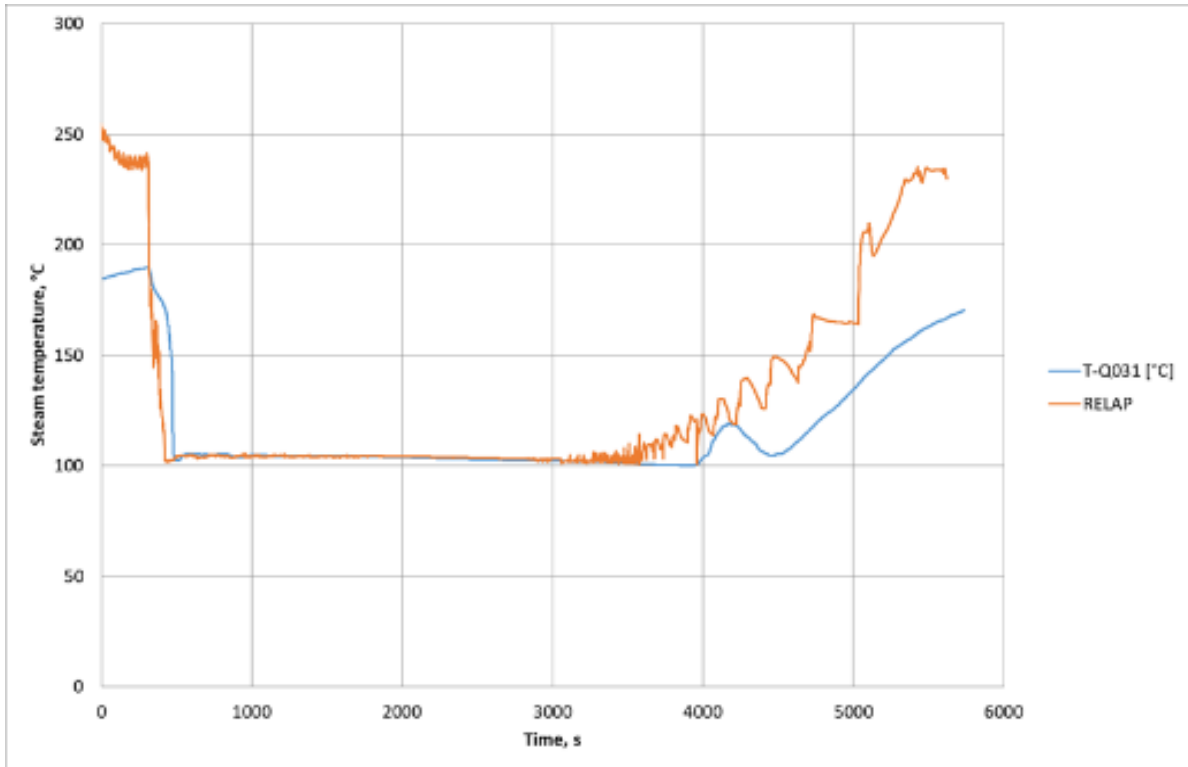


Figure 5.321. HXP relative pressure -top [Part 2]

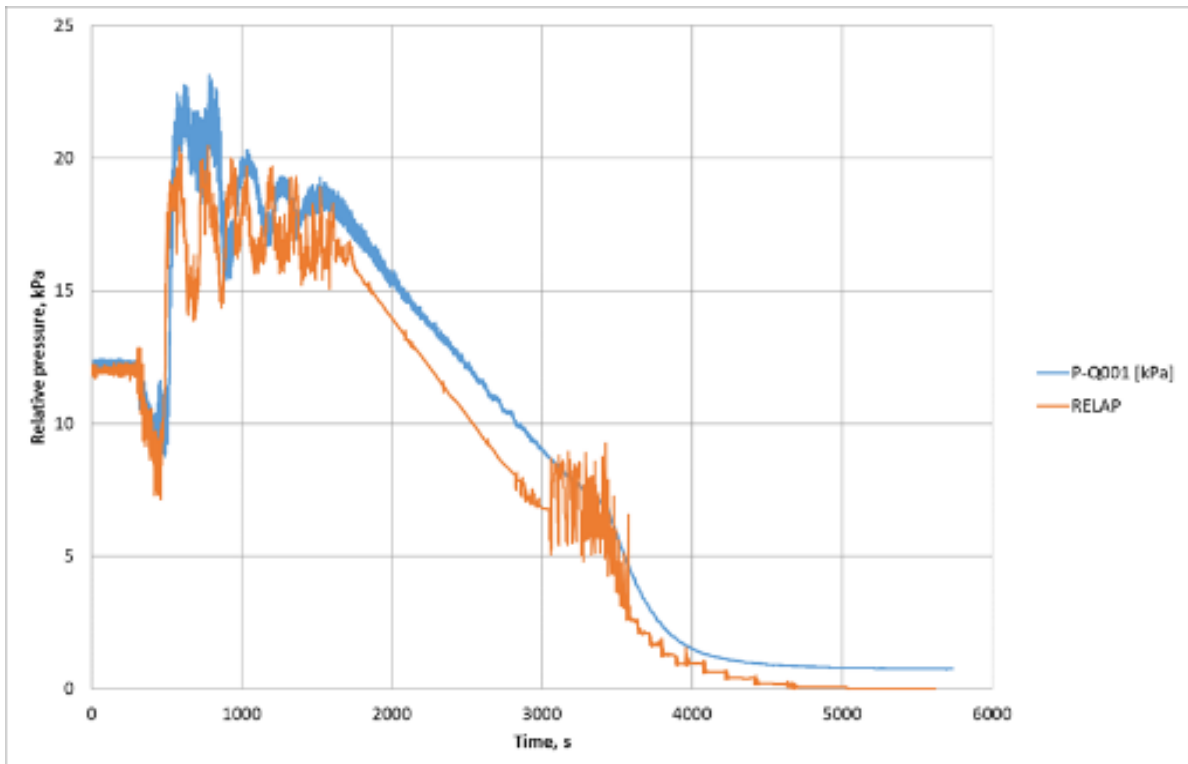


Figure 5.322. OP fluid temperature - bottom [Part 2]

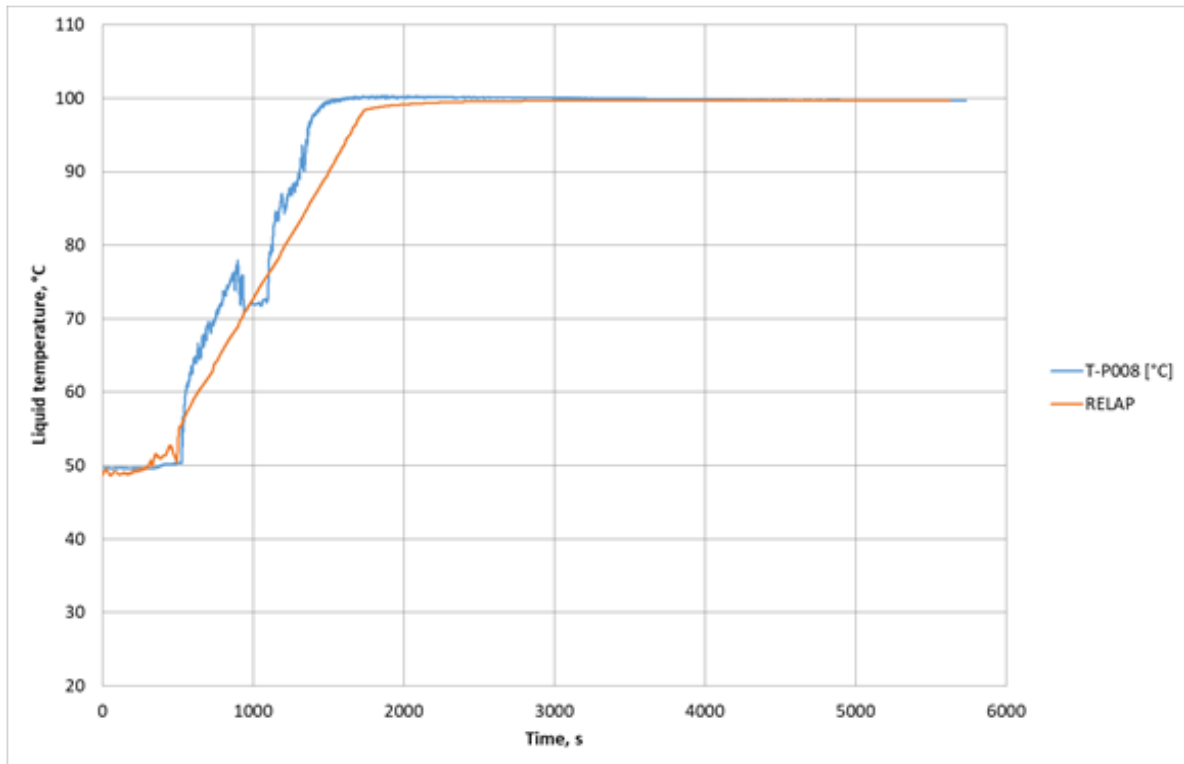


Figure 5.323. OP fluid temperature - middle [Part 2]

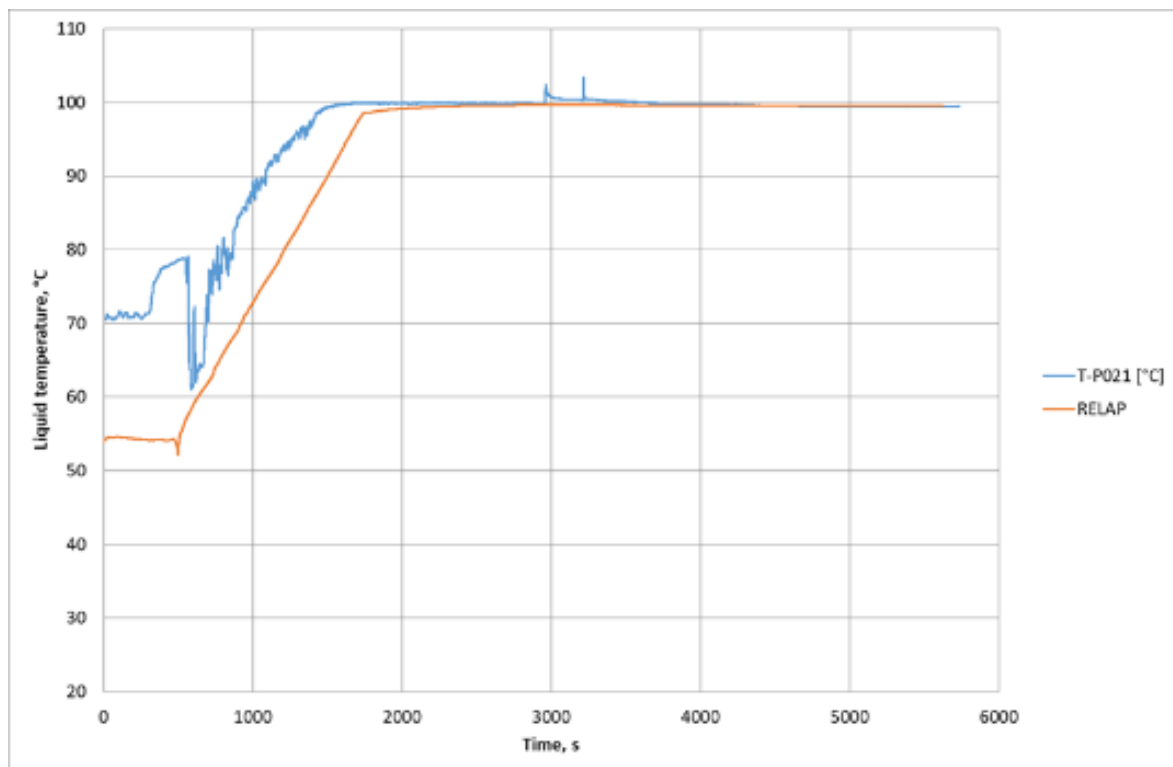


Figure 5.324. Injector differential pressure [Part 2]

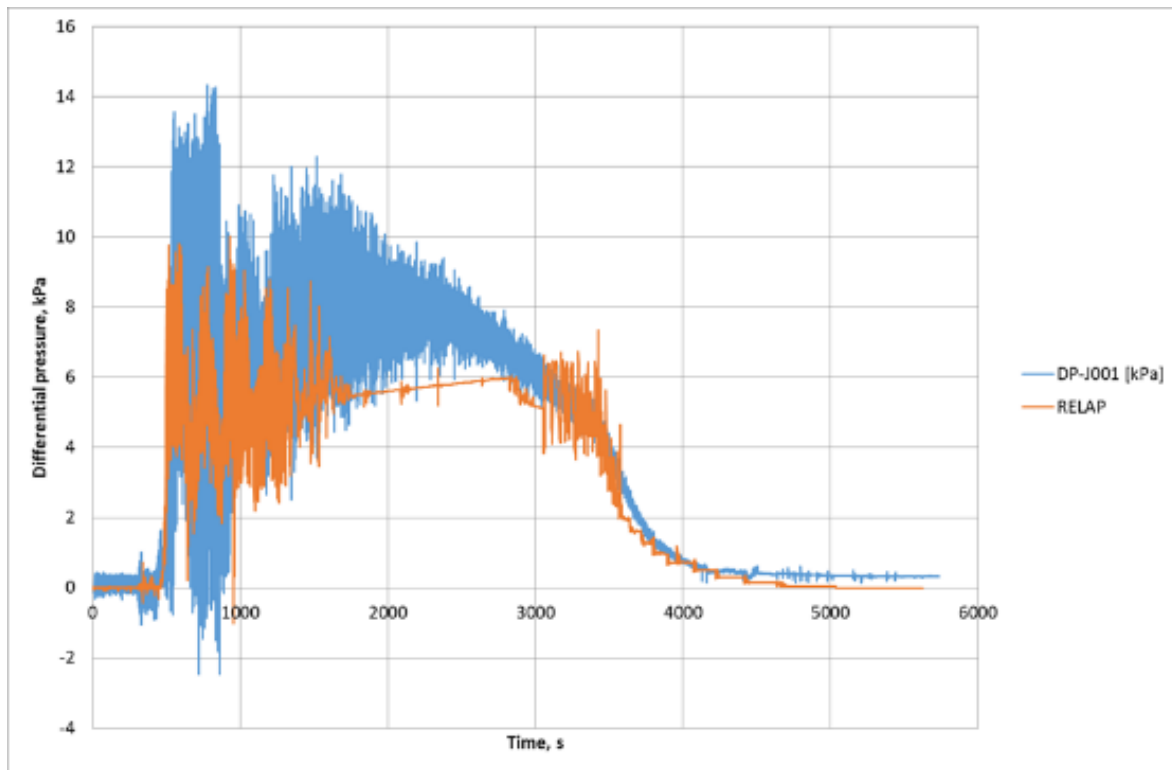


Figure 5.325. Heat exchanger pipe differential pressure [Part 2]

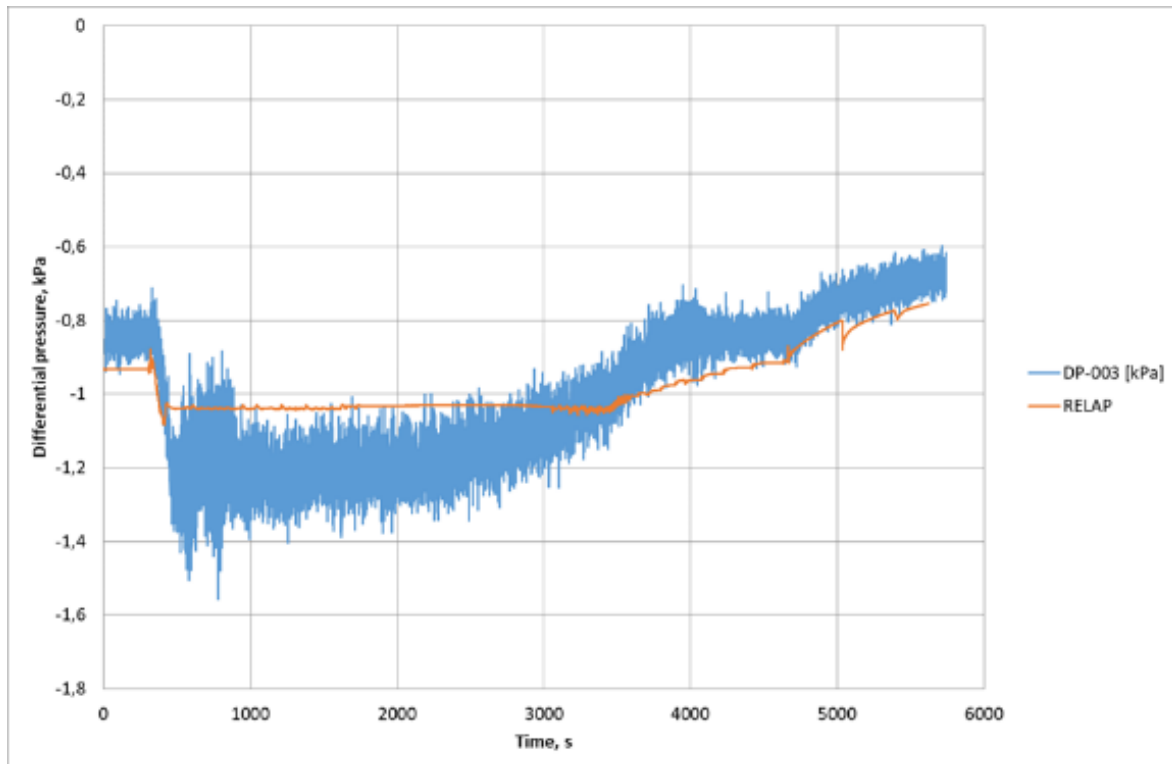


Figure 5.326. Upper header wall temperature [Part 2]

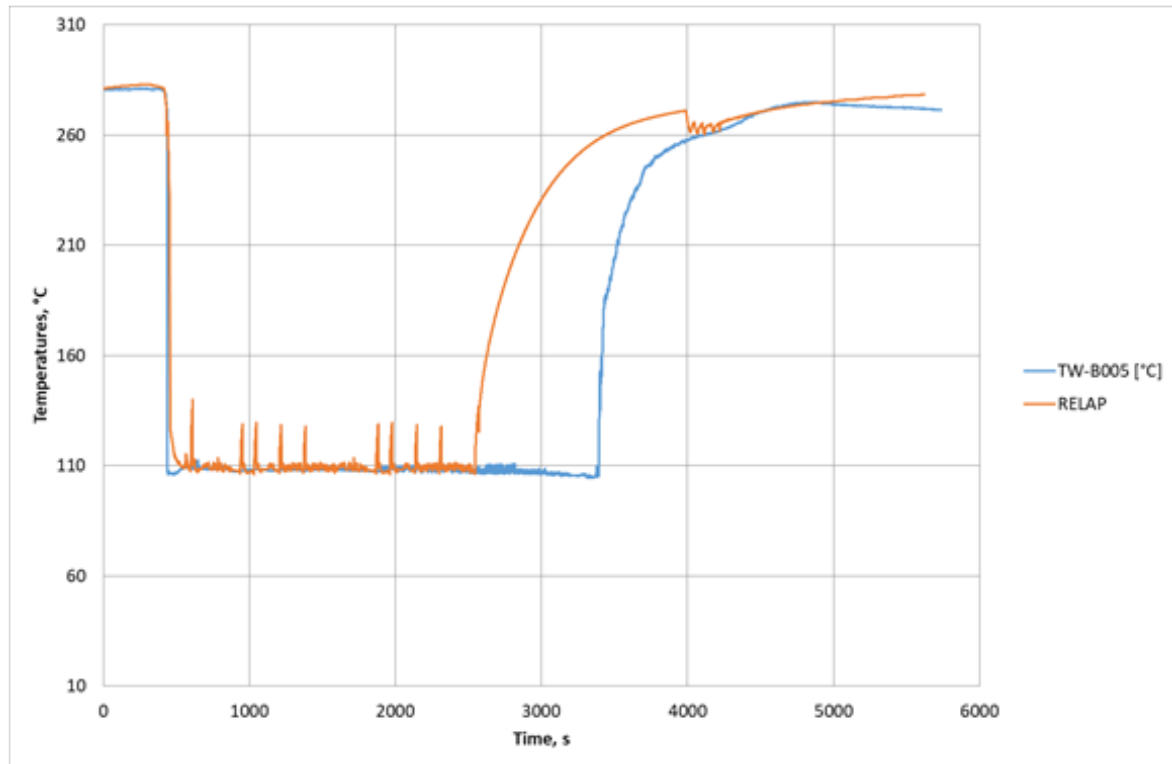


Figure 5.327. Lower header wall temperature [Part 2]

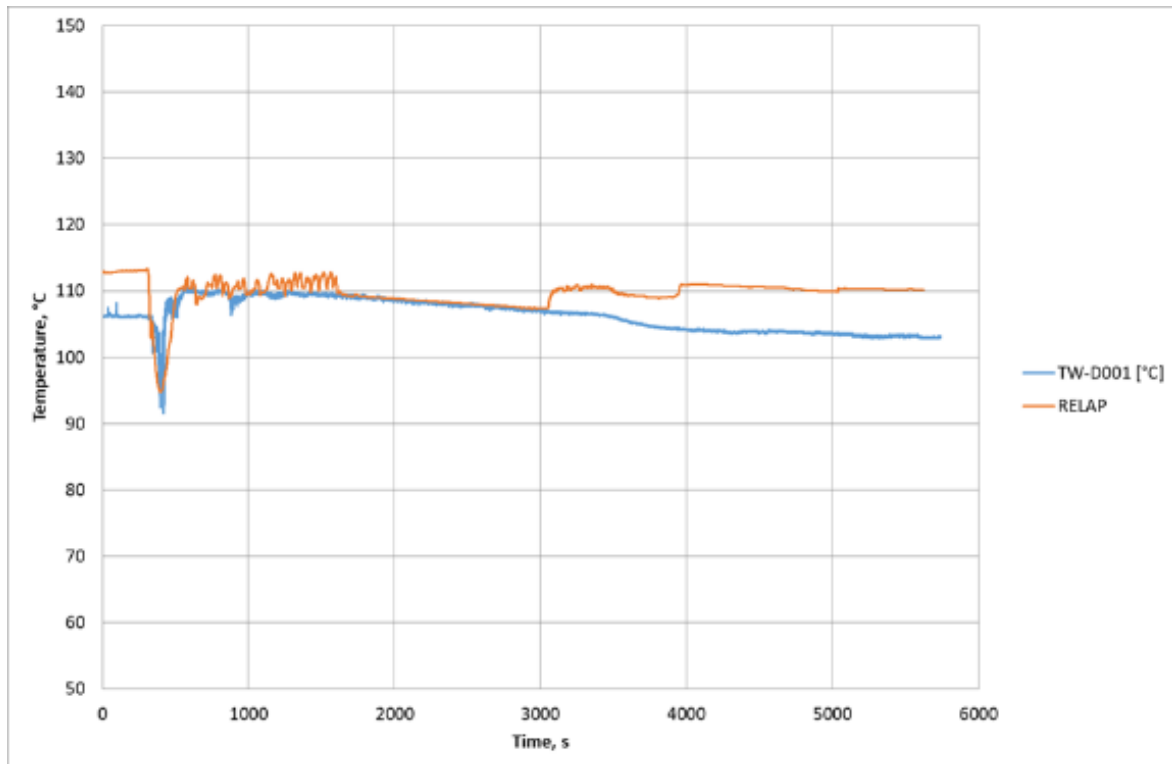


Figure 5.328. Exchanged power vs HXP collapsed water level
[Part 2]

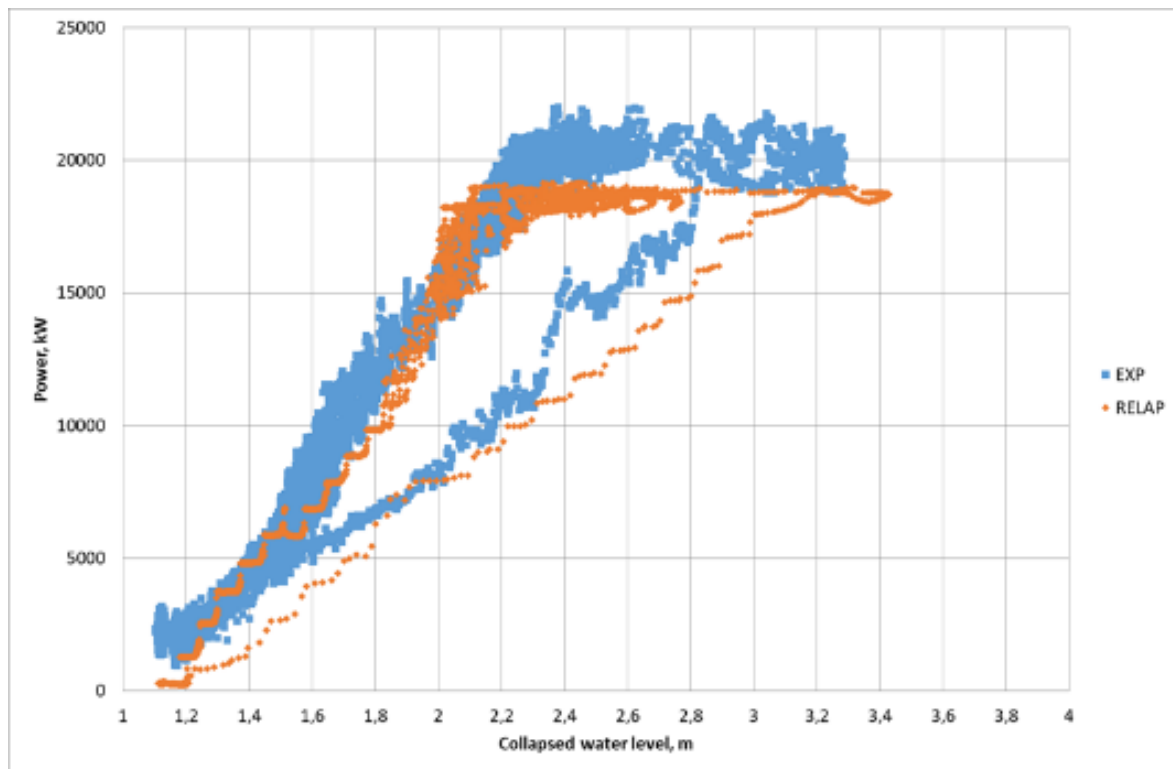


Table 5.49. Main relevant thermal-hydraulic aspects related to Test 7 Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	300 s in 26 s	-
Maximum level in the HXP	471 s	3.43
Maximum exchanged power	424 s-2 821 s	18.5 MW (avg)
OP discharge valve F031 opening	1 150 s	Constant mass flow 16.2 Kg/s (imposed)
Triggering valve F045 closure	3 338 in 26 s	-
HX pool level decreasing and loss of mass from the boil-off	1 690 s	-
Primary side depressurisation beginning for end of test	4 665 s	Primary side pressure imposed

The marks adopted in Table 5.49 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.50. PERSEO Test 7 Part 2 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line Flowrate condensate drain line Power heat exchanger Absolute pressure vessel HX inlet temperature HX outlet temperature	F A001 (der.) F E001 (der.) W IC (der.) P-I001 T-A005 T-E001	+
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger Level HXP Level OP Temperature HXP (bottom) Temperature HXP (middle) Temperature HXP (top) Relative pressure HXP top Temperature OP (bottom) Temperature OP (top)	W IC (der.) L VQ (der.) L VP (der.) T-Q037 T-Q034 T-Q031 P-Q001 T-P008 T-P021	+
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Absolute pressure vessel Flowrate steam supply line Flowrate condensate drain line Power heat exchanger Relative pressure HXP top Diff. pressure HX upper-lower header Diff. pressure steam duct injector	P-I001 F A001 (der.) F E001 (der.) W IC (der.) P-Q001 DP-003 DP-J001	+
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Flowrate steam supply line Flowrate condensate drain line Absolute pressure vessel Diff. pressure HX upper-lower header HX inlet temperature HX outlet temperature Power heat exchanger	F A001 (der.) F E001 (der.) P-I001 DP-003 T-A005 T-E001 W IC (der.)	o
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Level HXP Power heat exchanger Temperature HXP (bottom) Temperature HXP (middle) Temperature HXP (top)	L VQ (der.) W IC (der.) T-Q037 T-Q034 T-Q031	o
F	Behaviour of large pool: Thermal stratification	+	+	Power heat exchanger Diff. pressure steam duct injector Temperature HXP (bottom) Temperature HXP (middle) Temperature HXP (top) Temperature OP (bottom) Temperature OP (top)	W IC (der.) DP-J001 T-Q037 T-Q034 T-Q031 T-P008 T-P021	-
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP Level OP Power heat exchanger Relative pressure HXP top	L VQ (der.) L VP (der.) W IC (der.) P-Q001	+
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP Relative pressure HXP top Diff. pressure steam duct injector	L VP (der.) P-Q001 DP-J001	+
I	Structural Heat	+	+	Wall temperature HX upper header Wall temperature HX lower header	TW-B005 TW-D001	+

Table 5.51. Initial condition simulated by the benchmark participant (Test 7 Part 2)

	PARAMETER	LABEL	EXP	Benchmark Participant value	(%) DISCRPANCIES	NOTE
1	Flowrate steam supply line (kg/s)	F_A001 (der.)	1.13	0.265	76.55	
2	Flowrate condensate drain line (kg/s)	F_E001 (der.)	0.75	0.233	68.93	
3	Power heat exchanger (kW)	W_IC (der.)	2 160.71	267.431	87.62	
4	Absolute pressure vessel (kPa)	P-I001	7 051.89	7 050	0.03	
5	HX inlet fluid temperature (K)	T-A005	564.22	559.15	0.90	
6	HX outlet fluid temperature (K)	T-E001	561.89	559.15	0.49	
7	Level HXP (m)	L_VQ (der.)	1.12	1.128	0.71	
8	Level OP (m)	L_VP (der.)	4.52	4.522	0.04	
9	Fluid temperature HXP (bottom) (K)	T-Q037	376.39	377.15	0.20	
10	Fluid temperature HXP (middle) (K)	T-Q034	438.12	500.15	14.16	
11	Fluid temperature HXP (top) (K)	T-Q031	457.95	526.15	14.89	
12	Relative pressure HXP top (kPa)	P-Q001	12.23	12	1.88	
13	Fluid temperature OP (bottom) (K)	T-P008	322.81	321.75	0.33	
14	Fluid temperature OP (top) (K)	T-P021	343.87	327.15	4.86	
15	Diff. pressure HX upper-lower header (kPa)	DP-003	-0.83	-0.93	12.05	
16	Diff. pressure steam duct injector (kPa)	DP-J001	0.19	0.26	36.84	
17	Wall temperature HX upper header (K)	TW-B005	553.54	554	0.08	
18	Wall temperature HX lower header (K)	TW-D001	379.26	386	1.78	

SECTION 5: CONCLUSIONS

- RELAP5/MOD3.3 does not predict HX exchanged power;
 - Fouling factor adopted (pool side, tube side) which compensate an error of about 50%.
- RELAP5/MOD3.3 does not predict thermal stratification in OP.

REFERENCES

- [5.2.8 1] US NRC (2003), *RELAP5/MOD3.3 Code Manual Volume I: Code Structure, System Models, and Solution Methods*, NUREG/CR-5535/Rev P3-Vol I.
- [5.2.8 2] US NRC (2006), *RELAP3.3 MOD3.3 Code Manual Volume Iv: Models and Correlations*, NUREG/CR-5535/Rev P3-Vol IV.

5.2.9. *UNIROMA1*

SECTION 1: GENERAL INFORMATION

- Organisation: “Sapienza” University of Rome (Italy)
- Contact persons/authors: Vincenzo Narcisi , Fabio Giannetti , Gianfranco Caruso .
- Code: RELAP5-3D v.4.3.4
- Computing environment:
 - Operative systems Windows 10
 - RAM 16 Gb
 - CPU characteristics Intel I7 7 700 K

SECTION 2: DESCRIPTION OF THE CODE USED

RELAP5-3D® (R5-3D) is the latest version of the RELAP5 code series, developed at Idaho National Laboratory (INL). It is a highly generic system code mainly used for the best-estimate transient simulation of light water reactors, but also for simulations concerning a wide variety of thermal-hydraulic transients in non-nuclear systems. R5-3D includes several improvements that can be summarised in the fully integrated multidimensional thermal-hydraulic and kinetic modelling capabilities, and the addition of new working fluids for the simulation of innovative nuclear power plants [5.2.9 1] .

It is a Eulerian code with a finite-difference approach, mainly 1D, with the recent addition of the multidimensional components.

The code adopts a semi-implicit numerical solving scheme and it is based on a non-homogeneous and non-equilibrium model for the two phases; it is based on six equations: the mass, energy and momentum conservation equations for the liquid phase and the same for the vapour [5.2.9 1] .

The closure laws used for the heat transfer are the interphase mass and energy transfer. For the momentum transfer, the interphase drag, wall friction and the eventual source terms (for pumps or turbines) are used. Special models for relevant physical phenomena are also added for Critical Heat Flux (CHF), Choked Flow, countercurrent flow limitation, tracking of non-condensable gases and boron.

Concerning the experimental campaign performed on PERSEO facility, condensation and nucleate boiling are expected respectively in the inner and outer sides of the HX tubes. For the condensation, R5-3D uses the correlations derived by the Nusselt for laminar regime, Chato-Shah for turbulent regime, and Colburn-Hougen for the diffusion of non-condensable gases. For boiling regime, Chen correlation is applied for nucleate and transition boiling, and Bromley is used for film boiling. Regarding the pressure drops, the two-phase friction multiplier approach, according with Lockhart-Martinelli model, is used in two-phase problems.

SECTION 3: DESCRIPTION OF THE NODALISATION

Figure 5.329 shows the nodalisation scheme developed for the simulation activity. The thermal-hydraulic model consists of two main systems: the primary system, including pressure vessel, steam line, heat exchanger (HX) and drain line, and the secondary system, including the two pools and the connections between them.

The pressure vessel is modelled with two vertical pipes (110 and 090 in Figure 5.329), reproducing the steam conduit and the annular volume between the steam conduit and the vessel's walls. Steam inlet conditions are imposed with the time-dependent volume (TDV) 100, connected with the lower part of the steam conduit using a single junction. A BRANCH component (BRANCH 120 in Figure 5.329) connects the two vertical pipes with the steam plenum of the pressure vessel, modelled with a single pipe (130 in Figure 5.329). The steam moves into the HX, flowing through a pipe line (STEAM LINE in Figure 5.329), modelled with three pipes (010, 020 and 030 in Figure 5.329). The heat exchanger is composed of the two headers and the tube bundle. The upper and lower headers are modelled with two pipes (040 and 060 in Figure 5.329), each one composed of six control volumes. The bundle is reproduced with a single equivalent pipe (050 in Figure 5.329), assuming the total flow area, the hydraulic diameter of a single tube and the total heat transfer area. The condensate moves into the pressure vessel, passing through the drain line, which is modelled with two pipes (070 and 080 in Figure 5.329). The lower volume of the component 090 is connected with a TDV, consisting in a condensate drain system.

Regarding the secondary system, a mono-dimensional modelling approach has been selected for the nodalisation of the two pools. Each one is modelled with three vertical pipes, composed of 60 control volumes, connected with several cross junctions in order to reproduce the buoyancy within the large volume. Previous activities were dedicated on the investigation of R5-3D capabilities to reproduce large pools with a mono-dimensional or a multidimensional modelling approach [5.2.9 2], [5.2.9 3]. It was observed that both the approaches provide acceptable results; the multidimensional approach allows a better resolution of the results, even if the computational costs increase. For this reason, the mono-dimensional approach is selected for this exercise. The two pools are connected with the steam duct, modelled with the pipe component 210, including the injector, and the water line, simulated with two pipes (230 and 240 in Figure 5.329) and the triggering valve, modelled with a MOTOR VALVE component.

The upper volumes of the HX pool are connected with two time-dependent volumes:

- TDV 207, connected with the upper volume of component 200; a trip valve component (vacuum breaker valve in Figure 5.329) opens when the pressure within the pool becomes lower than the atmospheric pressure;
- TDV 209, connected with the upper volume of component 201; a trip valve component is set in order to maintain the atmospheric pressure within the HX pool in the first seconds of Test 7 Part 1.

In addition, two time-dependent volumes are connected with the overall pool:

- TDV 227, connected through a single junction with the upper volume of component 220, simulating the atmosphere;
- TDV 229, connected with the lower volume of component 221; a trip valve component is set to reproduce the water discharge in Test 7 Part 2.

The whole nodalisation scheme is developed adopting the sliced modelling approach and the local pressure losses are simulated with constant k-loss coefficient calculated according the geometry data provides to the participants. The heat losses towards the environment are taken into account with several heat structures, imposing the temperature of the environment (15°C) and the heat transfer coefficient on the outside surfaces (6 W/m² K).

Regarding the heat exchanged between primary and secondary systems, 44 heat structures are used for the thermal coupling of the HX and the HX pool. As found in literature [5.2.9 4], [5.2.9 5], a multiplicative factor must be applied to the heat transfer coefficient (HTC) on the tube and pool side. In fact, considering the thermal-hydraulic conditions of Test 7,

the correlations implemented in R5-3D for the HTC evaluation work out of the validity range, underestimating the experimental HTC. For this reason, a multiplicative factor equal to 2.4 has been introduced in both HX sides.

Figure 5.329. Nodalisation scheme

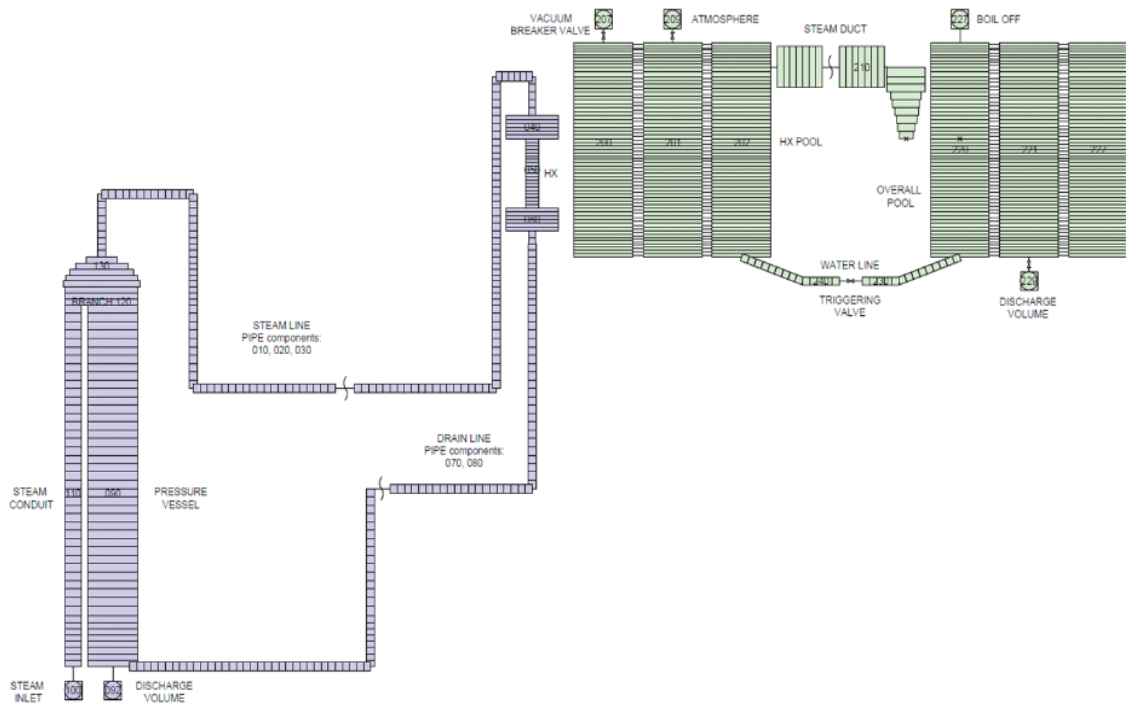


Table 5.52. Summary of the main nodalisation characteristics of the PERSEO model

	Number of hydraulic volumes	Number of junctions	Number of heat structures	Overall volume (m ³)
Vessel	98	96	99	36.92
Steam line	187	186	187	1.71
HX	32	31	44	1.92
Condensate line	158	157	158	0.52
HXP	180	295	186	26.9
Steam duct	66	65	66	12.1
OP	180	295	306	163.66
Heat Transfer Area HX (m ²)	48 m ² (outer surface; HX bundle and headers)			
HX heat structure axial nodes number	20 for tubes, six for lateral surface of each header, six for caps of each header			
HX heat structure radial nodes number	5			

SECTION 4: RESULTS

Test 7 Part 1

The initial conditions for simulation of Test 7 Part 1 are imposed by the user as boundary conditions, following the initial experimental data in a reasonably accurate way. Within the primary system, saturated conditions at 70.3 bar are considered (the initial steam and condensate flow rate is set to 0). On the secondary side, the pressure is set to 1.0 bar. Inside the HXP the water level is initialised at 0.276 m from the bottom of the pool and the rest of the volume is filled with dry air; temperature increases from the bottom to the top of the pool from 78 to 255°C, as specified in the experimental initial conditions. In order to maintain a constant pressure within the HXP in the first minutes of the test, the upper volumes are connected to a time-dependent volume with a trip valve component, which remains open in the first 460 s, ensuring the atmospheric pressure inside the HX pool. The OP is filled with water up to 4 650 mm from the bottom. A uniform temperature of 15°C is considered. The triggering valve is initialised closed.

The first phenomenological window (PhW) (10 000 – 11 260 s) consists in the first activation of the system; the triggering valve opens, water flows from the OP to the HXP, filling the latter up to about 3.5 m in two consecutive openings. R5-3D model provides a satisfactory prediction of the main phenomena occurring in this phase, even if some discrepancies with experiment are observed.

At the beginning of the test, a low value of the water flow rate is measured, probably due to the heat losses towards the environment which promotes a visible natural circulation. The nodalisation scheme includes the modelling of the heat losses, considering a constant value for the external HTC. This is enough to provide a good estimation of the initial natural circulation, when the system is still disabled (see Figure 5.330 and Figure 5.331). In this phase, the experimental value of the power exchanged between the HX and the HXP is about 2 200 kW (average value). As expected, being the HXP filled by dry air, R5-3D does not observe a significant heat exchanged (Figure 5.332). This is not in agreement with the indirect experimental measurement, but the calculation methodology adopted for the evaluation of the experimental value, could introduce a small bias in the zero value.

Regarding the temperature within the primary system, a discrepancy of about 5°C is observed between the simulation and the experiment over the whole test (see Figure 5.334 and Figure 5.335). Before the opening of the triggering valve, the primary system would be in saturation conditions (as in the simulation results), but thermocouples acquire superheated steam. This could be linked to the uncertainties of the instrumentation, explaining the discrepancy with the simulation.

On the secondary side, in the first PhW, a satisfactory prediction is observed within the HXP, even if the code underestimates the thermal stratification (see Figure 5.338, Figure 5.339 and Figure 5.340). Figure 5.341 shows the pressure within the HXP, which is maintained constant in this phase with a time-dependent volume.

At 10 475 s, the first opening of the triggering valve occurs. Regarding Test 7 Part 1, the specifications provided to the participants includes the instant of opening and closure, but not the opening and closure rates of the triggering valve. For this reason, the opening and the closure rates are set by the user in order to reproduce in the most accurate way the HXP filling. This could represent a relevant source of uncertainties in the calculations. The water level inside the HXP is presented in Figure 5.336, where a good agreement is observed between simulation and experiment, even if the code underestimates the maximum level after the first opening of about 0.1 m. The discrepancy could be due to a not perfect reproduction of the first opening rate and it could explain the underprediction of the power

exchanged between 10 475 and 110 450 s (see Figure 5.332) and the absence of the slow water consumption in the simulation results. The underestimation of the power leads to an underprediction of the primary flow rate in this phase (see Figure 5.330 and Figure 5.331). Within the OP, the first level decrease is well reproduced by the code.

After the second opening, the HXP level increases up to the maximum value. Figure 5.336 shows a good agreement of the level increase, even if the maximum level is overestimated by the code of about 0.14 m, probably due to a not perfect opening rate of the valve. The level increase determines a rapid increase of the power exchanged between the HX and the HXP and, therefore, a quick increase of the condensation rate and of the flow rate through the primary system. R5-3D predicts very well the increase rate, even if, the overestimation of the level leads to the slight over prediction of the power and of the primary flow rate (see Figure 5.332, Figure 5.330 and Figure 5.331). Figure 5.344 shows the pressure drop across the HX; the code provides a satisfactory prediction of the minimum value, even if the pressure decrease occurs about 200 s earlier than experimental data. As expected, the absolute value of the pressure drop follows the primary flow rate, reaching the maximum value at the same time of the maximum flow rate. The experimental flow rate reaches two consecutive peaks, determining the two pressure peaks observed in Figure 5.344. The R5- 3D results have a different peaks value on the flow rate, with the first overestimated and the second underestimated; this could explain the discrepancies observed in Figure 5.344.

On the secondary side, at 10 460 s the trip valve connecting the HXP and the atmosphere is closed and, as a consequence of the water boiling, the pressure starts to increase. Figure 5.341 shows an agreement between simulation and experiment, even if the maximum pressure is predicted a bit earlier by the code. This should be related to the over prediction of the power exchanged in the first seconds after the second opening. Regarding the temperatures, after the injection of the cold water, the experimental acquisitions shows the temperature decrease up to the saturated value, as predicted by the code (see Figure 5.338, Figure 5.339 and Figure 5.340). The steam produced within the HXP is driven towards the OP, through the steam duct. Figure 5.345 shows the pressure losses through the steam injector, providing an estimation of the steam flow rate. As presented in the figure, a good agreement is observed in the first PhW between calculation and experiment.

The second PhW consists in the quasi-steady operation at the maximum power (11 260 – 11 845 s). The qualitative quasi-steady state condition is well predicted by the code, even if this condition is predicted shorter than the experimental acquisition. This is clearly shown in Figure 5.330, Figure 5.331 and Figure 5.332. This could be explained by the higher power exchanged and the consequent higher boiling rate within the HXP, demonstrated by the overestimation of the pressure losses across the steam injector observed in the first seconds of the second PhW (see Figure 5.345), highlighting a higher value of the steam flow rate.

The third PhW consists in the level decrease within the HXP and, therefore, the reduction of the power exchanged between the HX and the HXP (11 845 – 14 784 s). The simulation results are globally in good agreement with experimental data. Due to the shorter quasi-steady operation, the decrease of the level within the HXP starts earlier, but the rate is comparable with experimental data. Power reduction shown in Figure 5.332, is caused by the level decrease that highlights a good agreement between experiment and simulation. The decrease rate is well predicted, and the R5-3D power trend assumes typical stepwise change due to the nodalisation scheme. A similar trend is observed in the primary flow rate. The shorter quasi-steady operation causes the discrepancies within the HXP, where the temperature starts to increase earlier than the experimental value (see Figure 5.339, Figure 5.340 and Figure 5.346). The OP level is shown in Figure 5.337; the comparison between

simulation and experiment highlights a good agreement. Some oscillations are observed in the calculation, probably due to the condensation rate of the steam coming from the HXP. Regarding the OP temperature, the code is able to reproduce the temperature increase due to the steam condensation, but the thermal gradient due to the stratification phenomena is underestimated. A multidimensional modelling approach could improve the results, but the increase of the computational cost could be not justified if this aspect is not so relevant.

The maximum time step is set to 0.001 s and the computational time is 12 h 10 min.

Table 5.53. Main relevant thermal-hydraulic aspects related to Test 7 Part 1

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	10 475 – 10 608	-
Triggering valve (F045) re-opening and re-closure	10 621 – 10 655	-
Maximum level in the HX pool for the first filling step	10 647	1.32 m
Small heat removal from the primary side	10 645 – 11 048	600 kW
Slow water consumption in the HX pool	Not observed	
Instabilities for steam condensation in the injector	Not observed	
Triggering valve (F045) opening and closure	11 039 – 11 260	-
Maximum level in the HX pool	11 242	3.65 m
Maximum exchanged power	11 187 – 11 580	20 000 kW
HX pool minimum level	14 784	1.24 m
OP average temperature	13 500	Around 58°C

The marks adopted in Table 5.53 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.54. PERSEO Test 7 Part 1 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.		Measurement		Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F_A001 (der.)	+
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W_IC (der.)	+
				Level HXP	L_VQ (der.)	
				Level OP	L_VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	+
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure HX upper-lower header	DP-003	+
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	HX inlet temperature	T-A005	+
				HX outlet temperature	T-E001	
				Power heat exchanger	W_IC (der.)	
				Level HXP	L_VQ (der.)	
				Power heat exchanger	W_IC (der.)	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (bottom)	T-Q037	o
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
				Diff. pressure steam duct injector	DP-J001	
				Power heat exchanger	W_IC (der.)	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP	L_VQ (der.)	+
				Level OP	L_VP (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L_VP (der.)	+
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

** Ph. = Phenomenon

Figure 5.330. Test 7 Part 1 - Steam flow rate

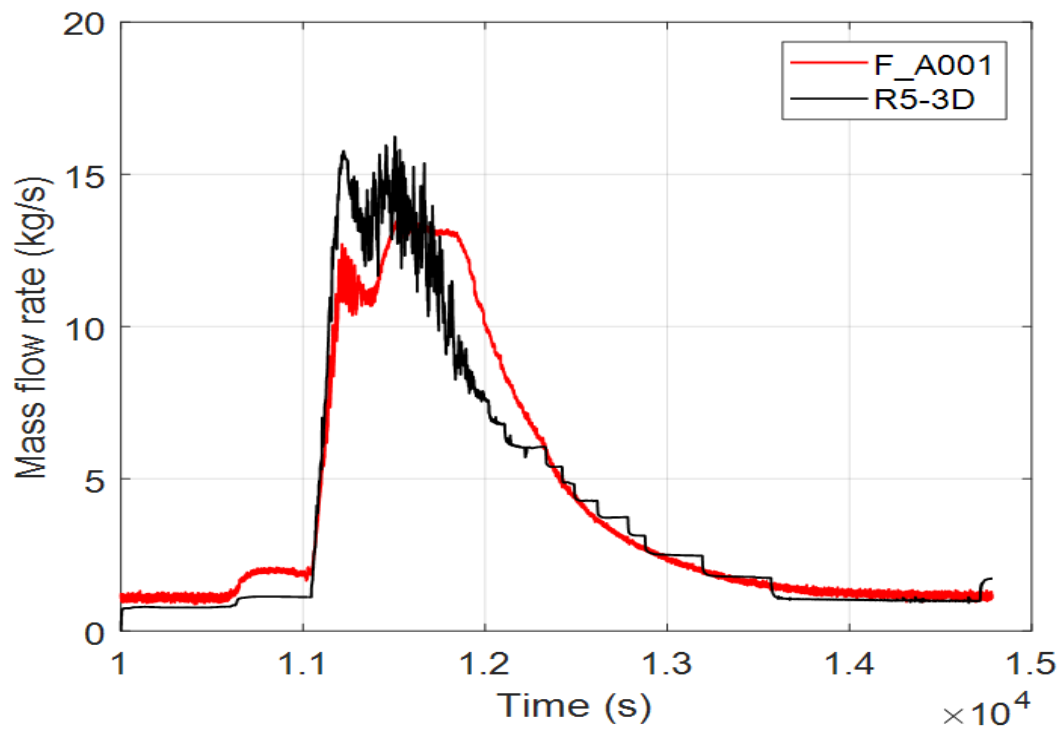


Figure 5.331. Test 7 Part 1 - Condensate flow rate

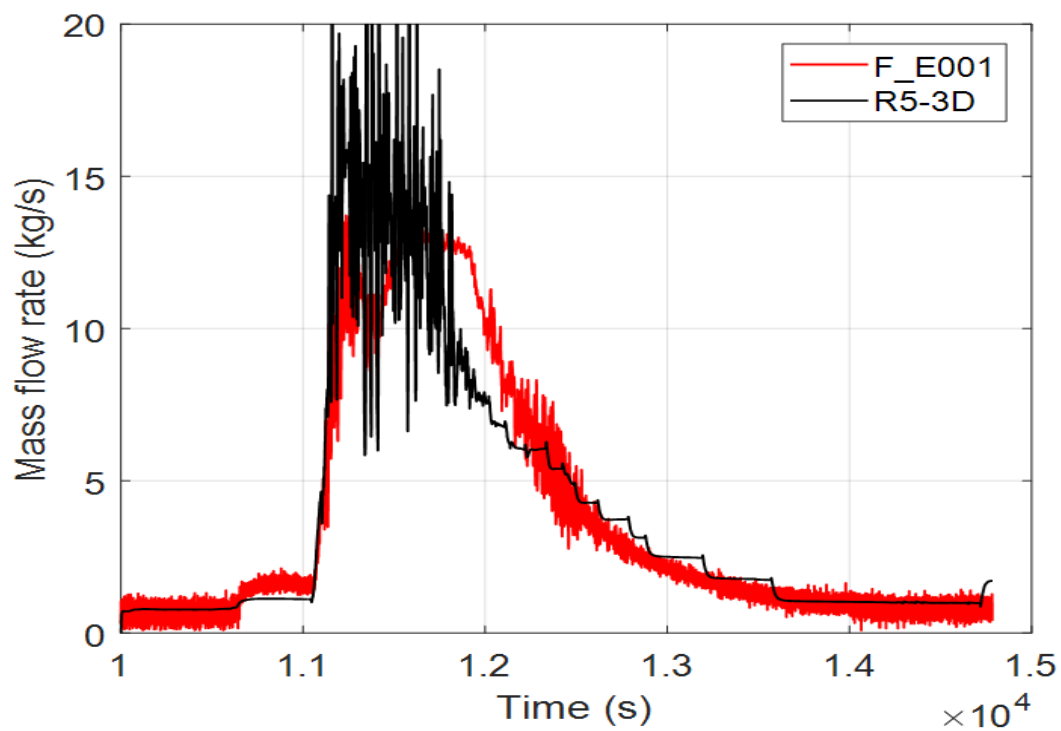


Figure 5.332. Test 7 Part 1 - HX power

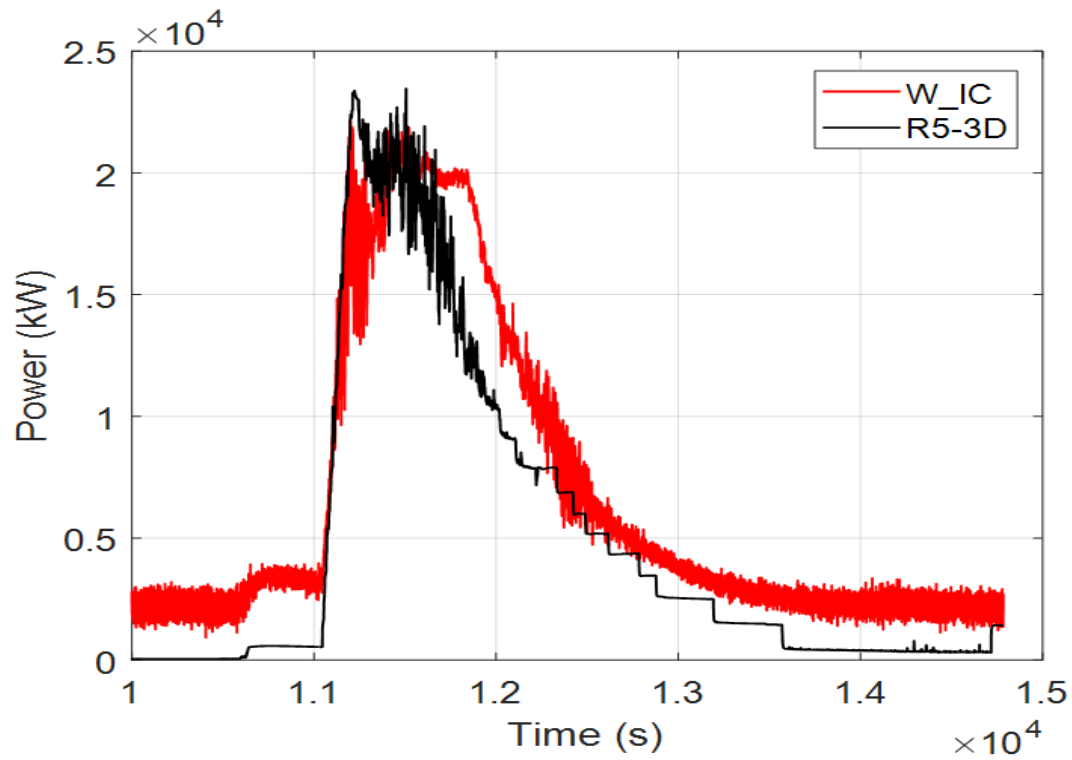


Figure 5.333. Test 7 Part 1 - Primary pressure

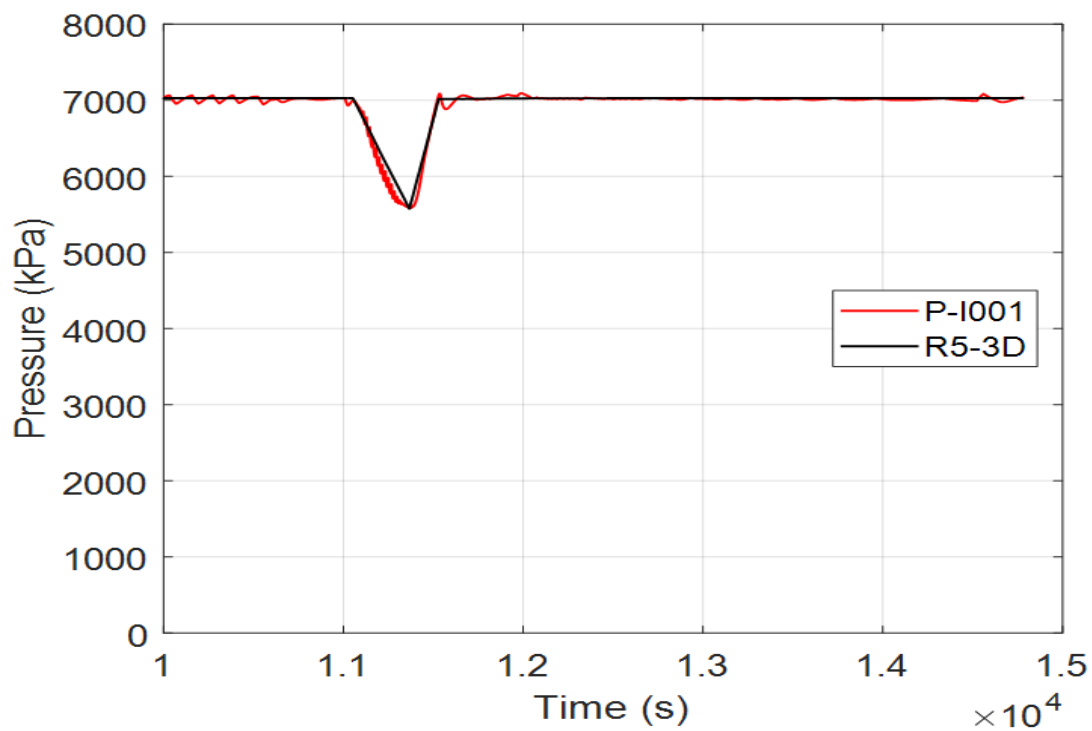


Figure 5.334. Test 7 Part 1 - Steam temperature

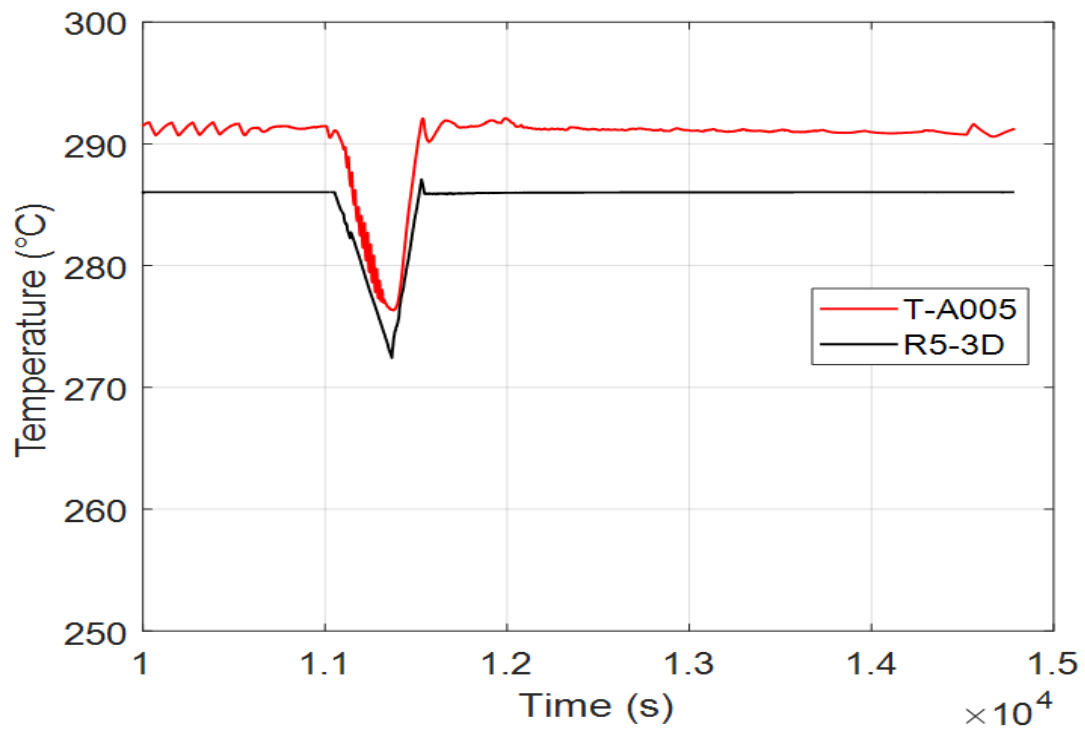


Figure 5.335. Test 7 Part 1 - Condensate temperature

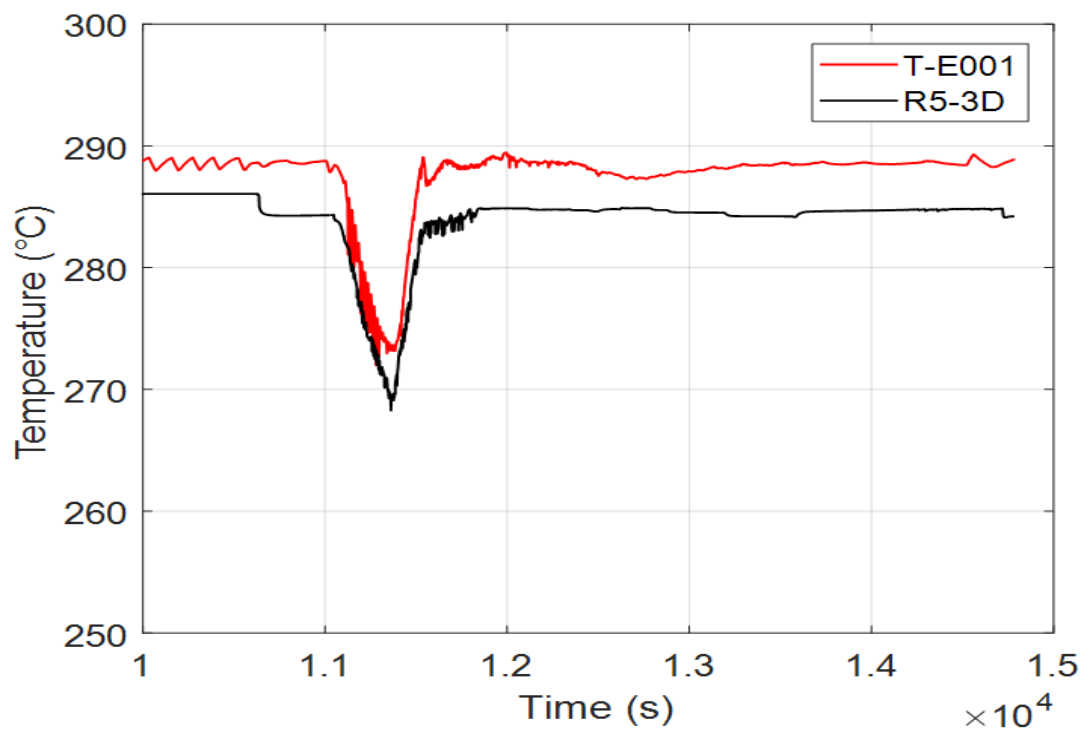


Figure 5.336. Test 7 Part 1 - HXP level

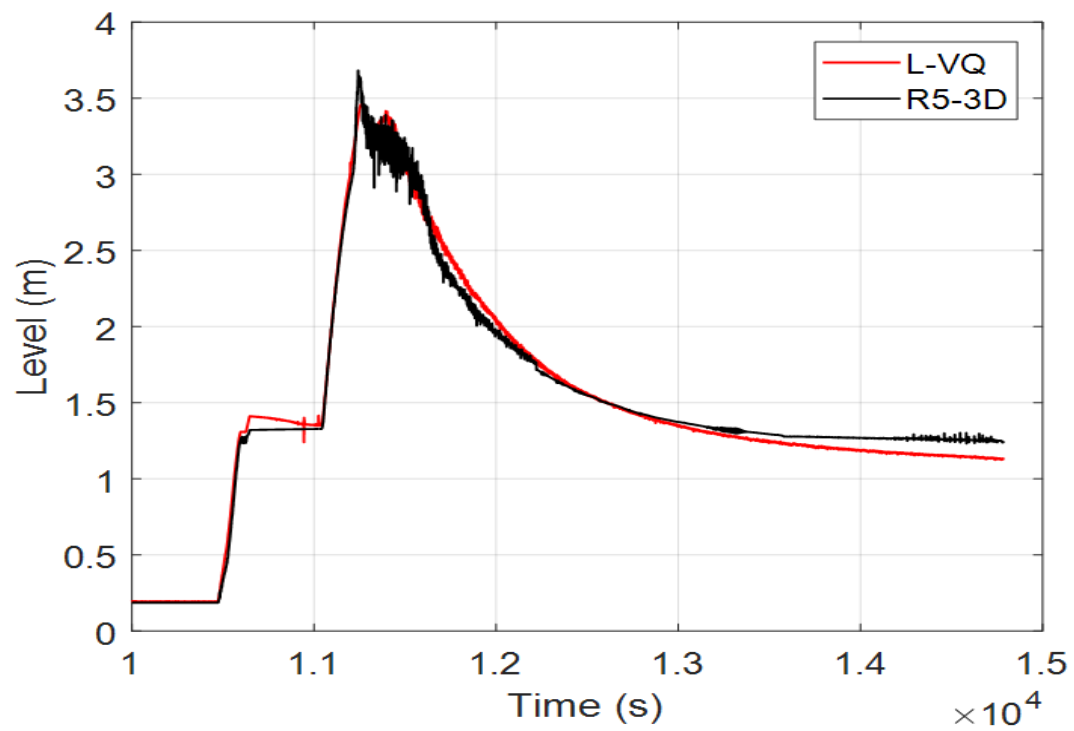


Figure 5.337. Test 7 Part 1 - OP level

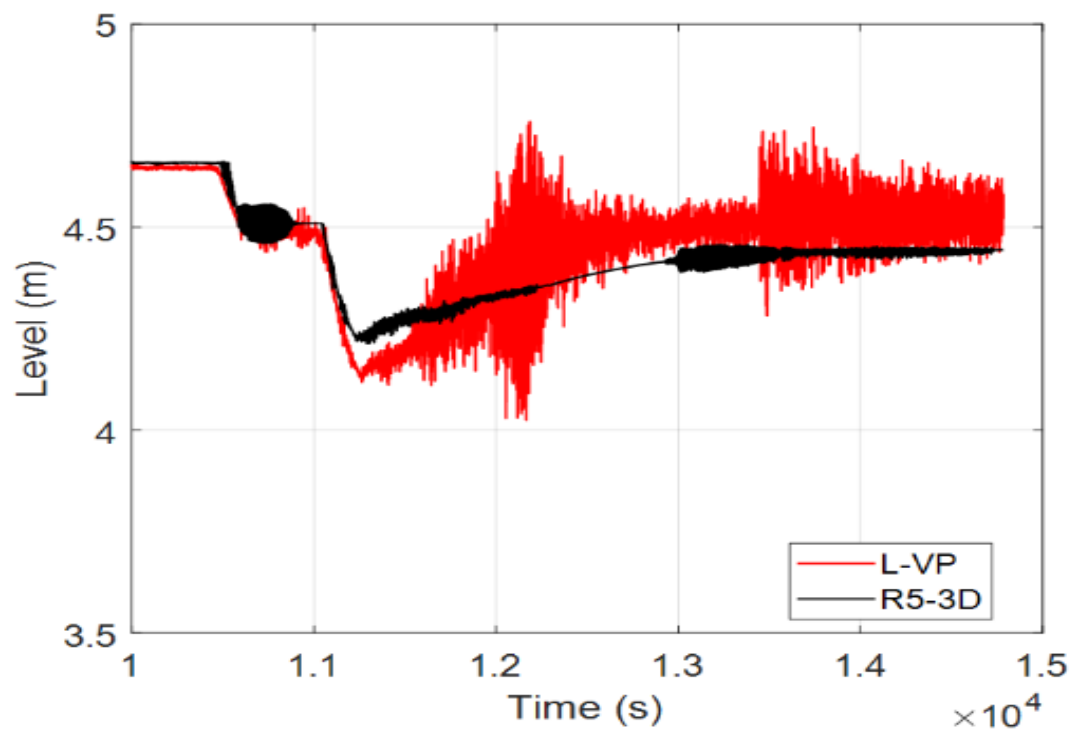


Figure 5.338. Test 7 Part 1 - HXP temperature T-Q037

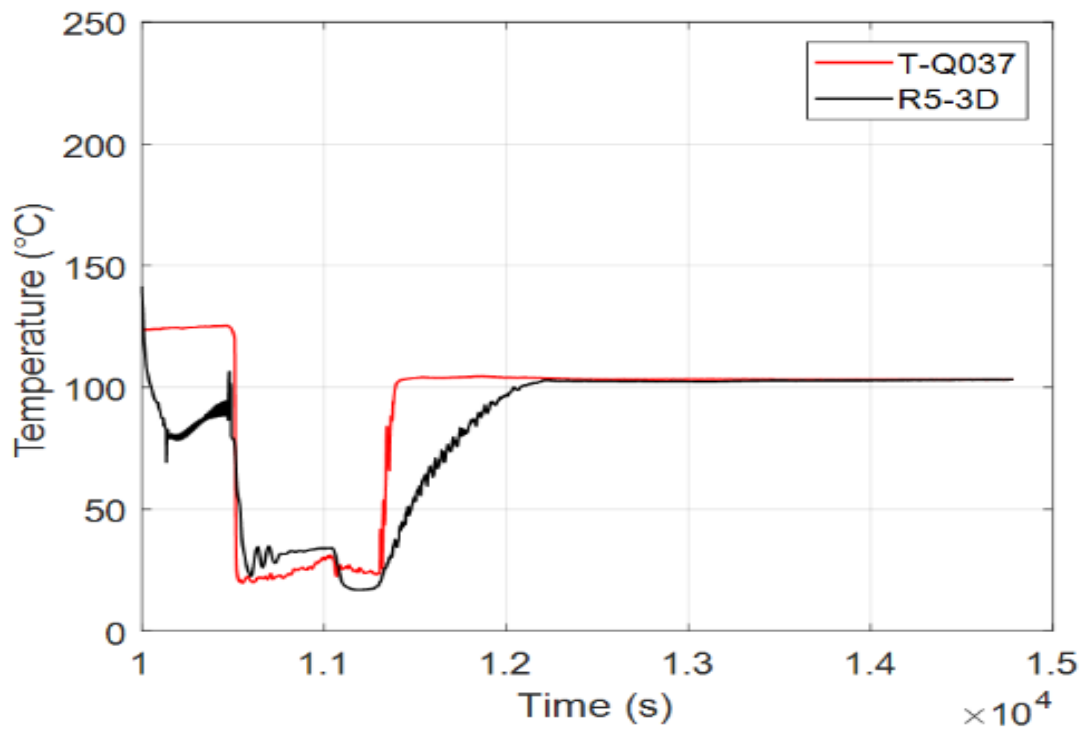


Figure 5.339. Test 7 Part 1 - HXP temperature T-Q034

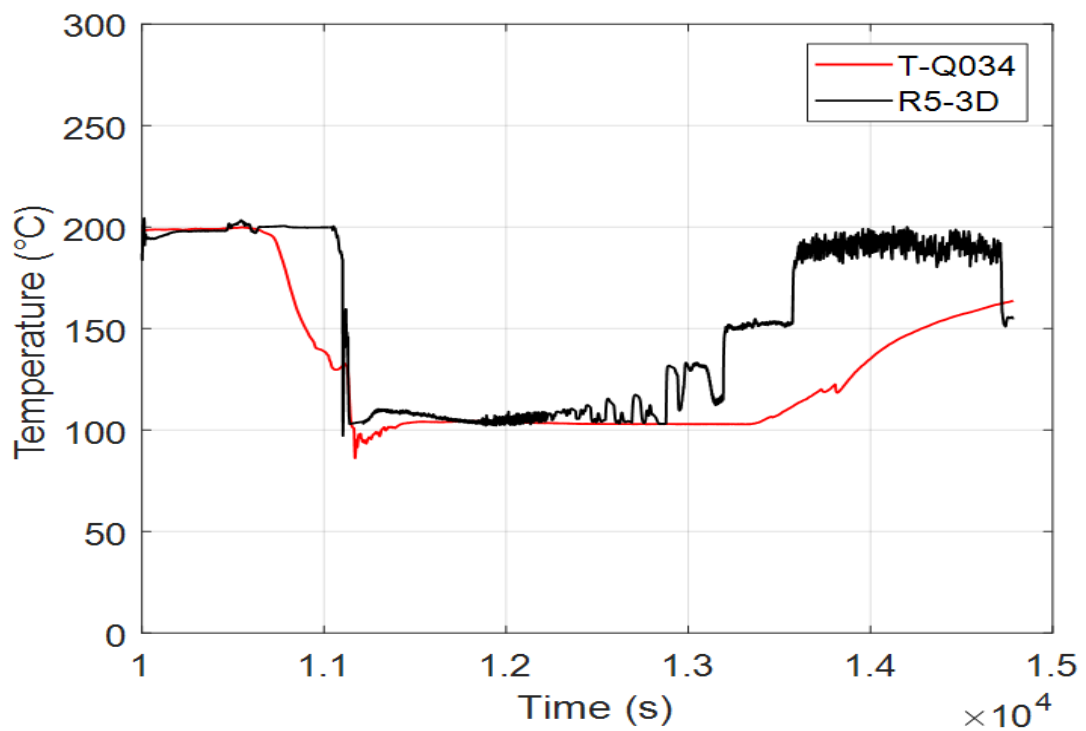


Figure 5.340. Test 7 Part 1 - HXP temperature T-Q031

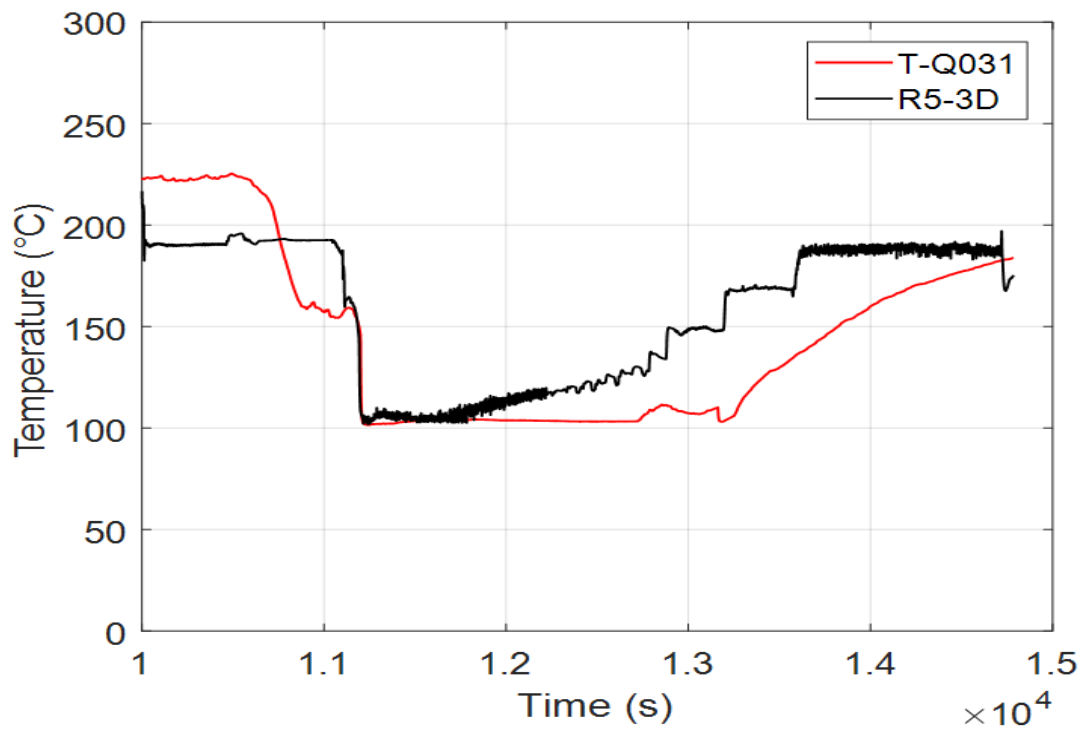


Figure 5.341. Test 7 Part 1 - HXP relative pressure

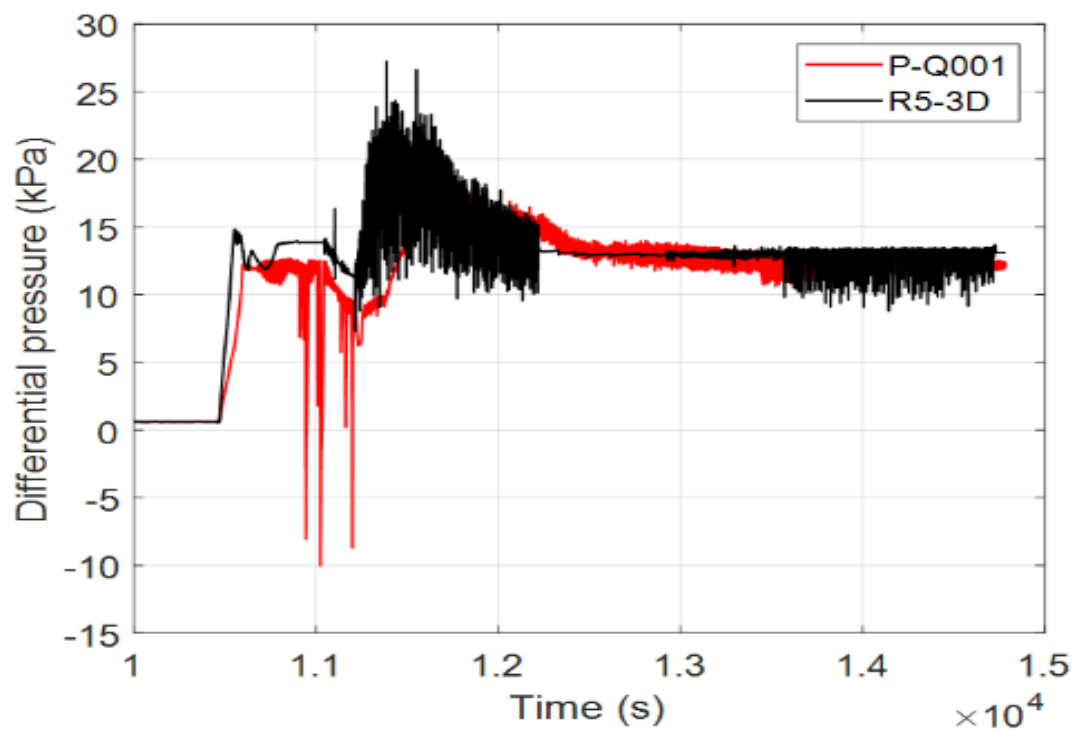


Figure 5.342. Test 7 Part 1 - OP temperature T-P008

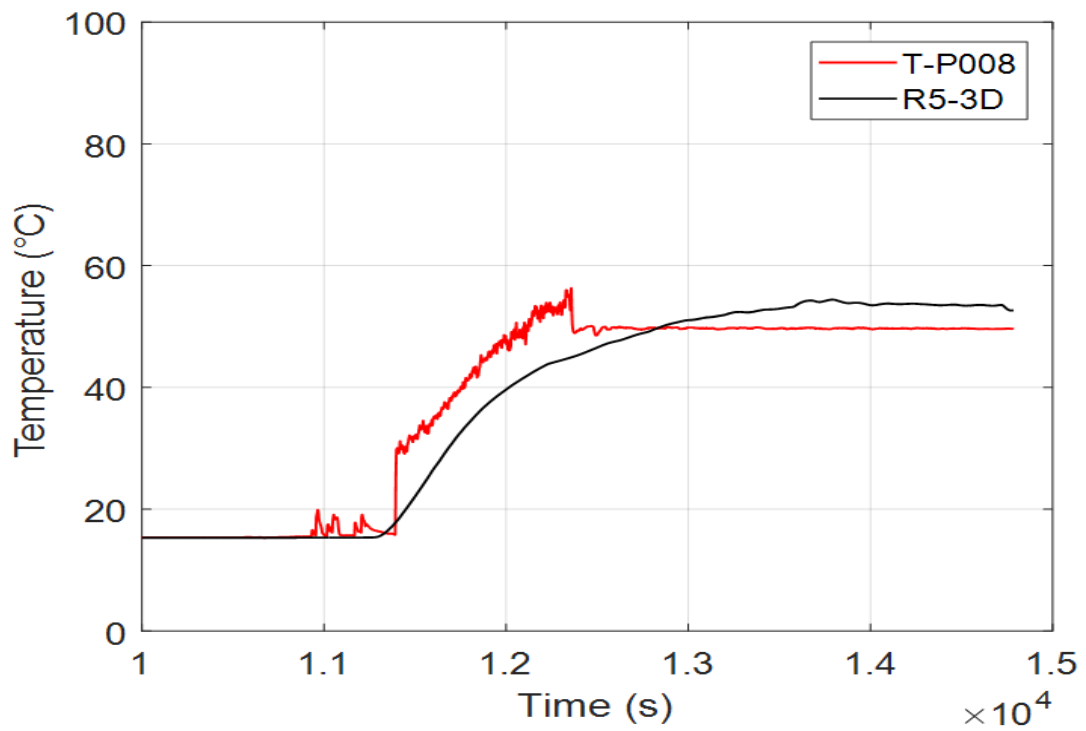


Figure 5.343. Test 7 Part 1 - OP temperature T-P021

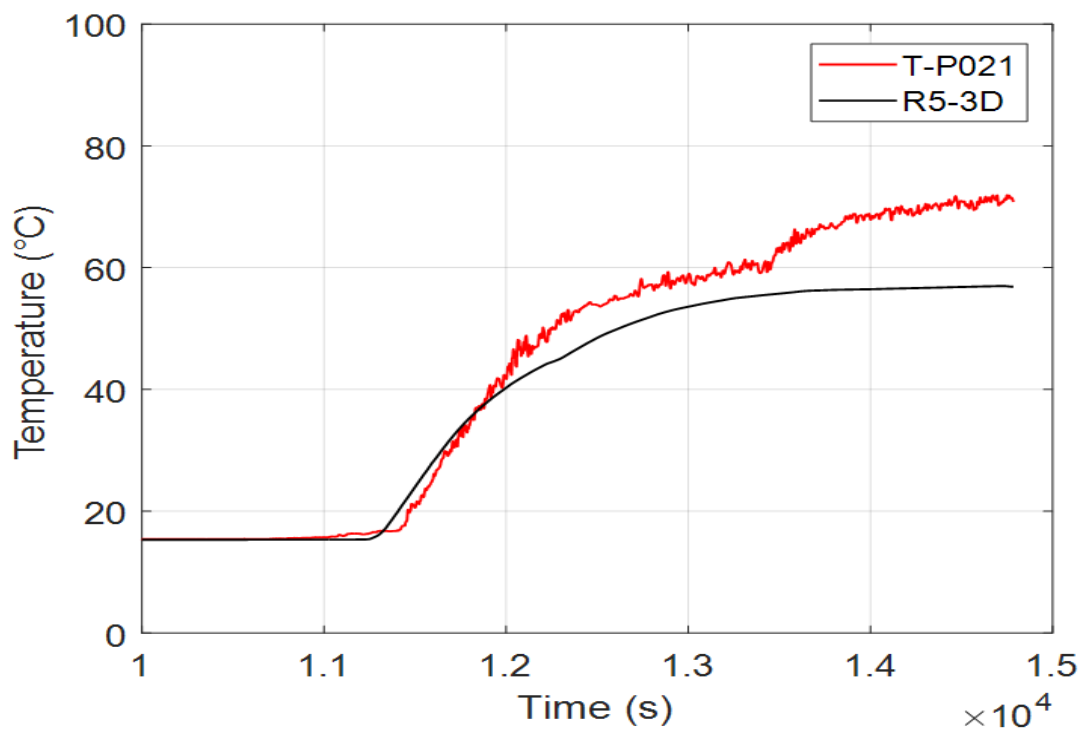


Figure 5.344. Test 7 Part 1 - HX pressure drop

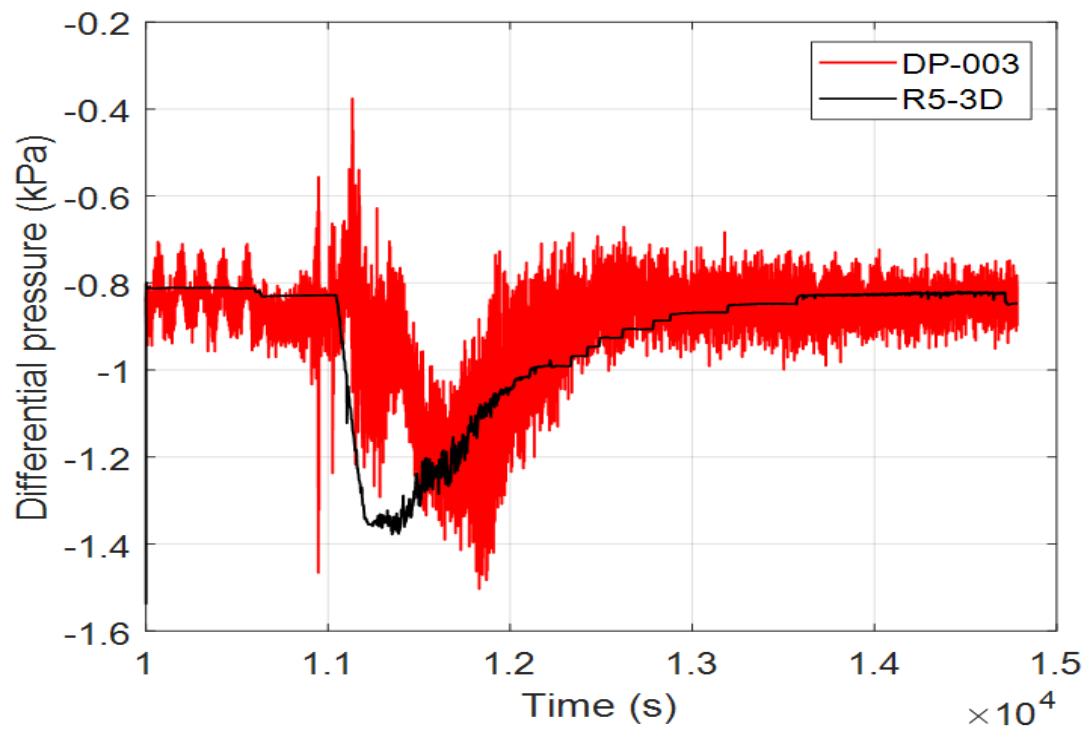


Figure 5.345. Test 7 Part 1 - Injector pressure drop

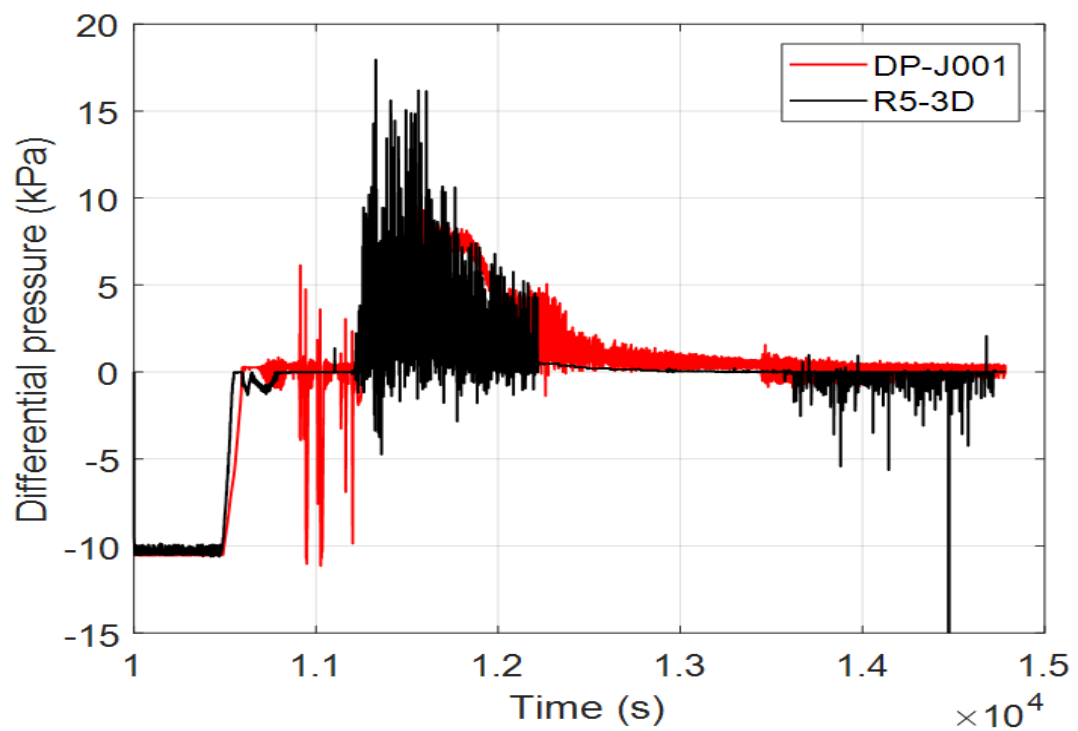


Figure 5.346. Test 7 Part 1 - HX upper header outer wall temperature

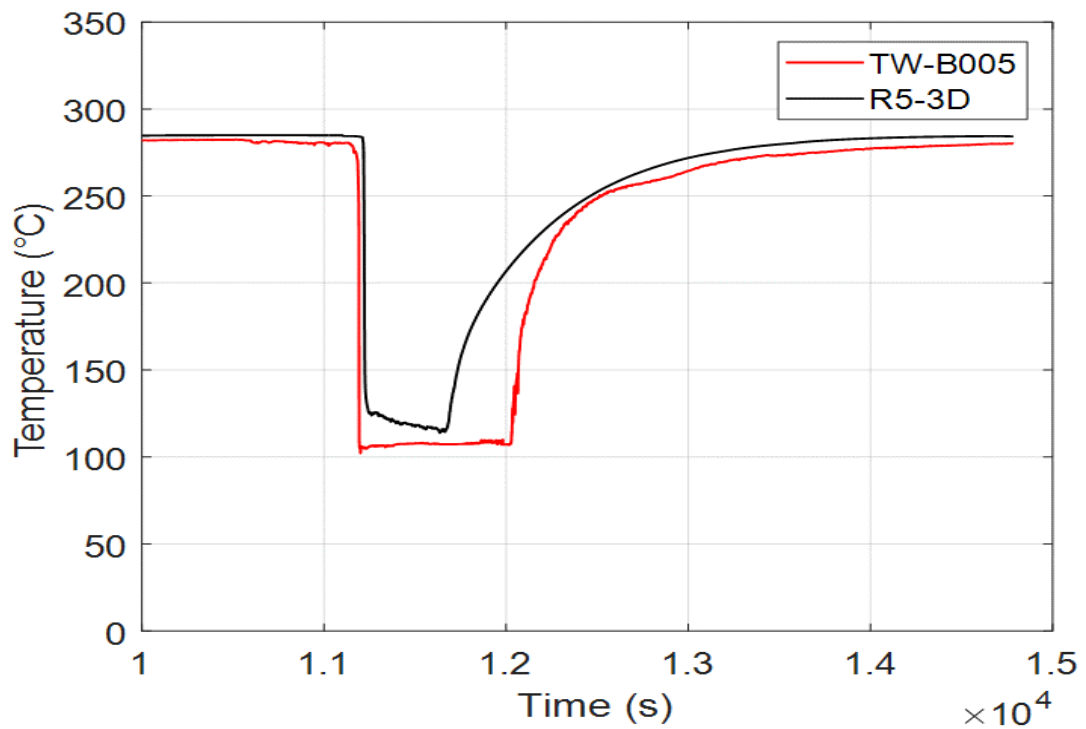
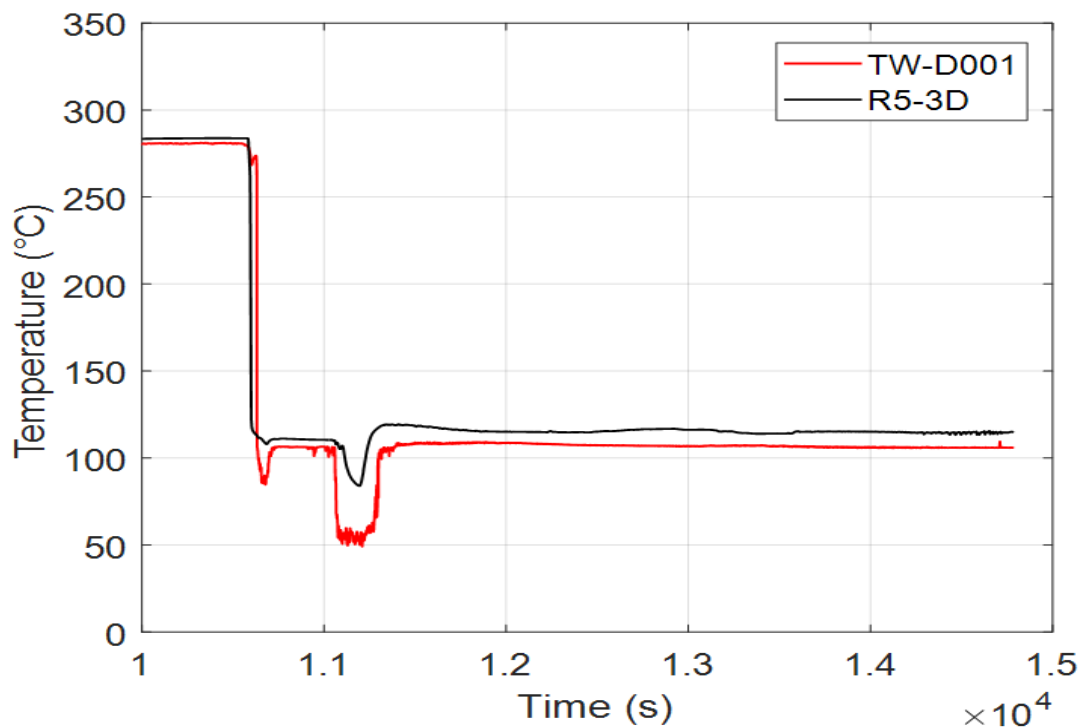


Figure 5.347. Test 7 Part 1 - HX lower header outer wall temperature



Test 7 Part 2

Test 7 Part 2 starts from the final conditions of Part 1. The initial conditions are obtained running the final conditions of the previous simulation for 100 s with constant boundary conditions.

The initial conditions are in good agreement with experimental data. Some discrepancies are observed, as discussed in the previous section: lower power exchanged between HX and HXP, underprediction of the temperature inside the primary system (about five degrees), and underestimation of the thermal stratification phenomenon within the two pools.

The first PhW consists in the activation of the system (0 – 531 s), opening the triggering valve. For this part of Test 7, both the opening and closure instants and rates are provided to the participants.

The opening causes a rapid increase of the level within the HXP, which is well reproduced by the code (see Figure 5.354). The maximum level is well predicted, even if R5-3D predicts the peak about 50 s before the experimental one. On the OP side, the decrease of the level is well reproduced by the code, which is also able to reproduce the oscillations observed in the experimental acquisitions during the first 531 s (Figure 5.355). The HXP level increase causes the rapid power rise. Figure 5.350 shows the comparison between the experimental evaluation of the power and the simulated value, highlighting a good agreement. As a consequence of the condensation within the HX pool, the steam and the condensate start to flow through the primary system. The experimental acquisitions and the simulated values are compared in Figure 5.348 and Figure 5.349. The quick flow rate increase is well reproduced, even if the maximum value is slightly overestimated by R5-3D.

On the HXP side, the injection of the cold water causes the low temperature peak in the bottom part of the pool, as shown in Figure 5.356; this effects is reproduce by the code, even if the minimum temperature is underestimated of about 10°C and it is predicted about 50 s earlier, following the faster level increase inside the HXP. The same discrepancy in the timing is observed in the upper part of the pool, where saturated conditions are rapidly obtained (see Figure 5.357 and Figure 5.358).

The second PhW consists in the quasi-steady state conditions observed between 531 and 2 282 s. After the maximum peak, the level within the HXP maintains a constant value (unless the fluctuations) of about 2.4 m. R5-3D is able to predict this phenomenon, also providing a satisfactory reproduction of the fluctuations. It causes a constant value of the power exchanged and of the primary flow rate. The code provides a good evaluation of the power exchanged between the HX and the HXP, also reproducing the oscillations observed in the experimental acquisitions. The primary flow rate is slightly overestimated. The condensation of the steam within the HX tubes causes the decrease of the total pressure difference across the HX, due to the gravitational contribution (see Figure 5.362), well predicted by the code.

Concerning the secondary side, the water boiling produces a quick pressure increase within the HXP (Figure 5.359), well reproduced by R5-3D, even if the steam flow through the steam duct seems to be under predicted as shown in Figure 5.363 that depicts the pressure losses across the injector. The steam, flowing from the HXP to the OP, causes the temperature increase within the OP, reaching saturation conditions, well predicted by the code.

The third PhW consists in the deactivation of the system (2 282 – 5 735 s). The OP discharge valve is opened, causing the decrease of the water level into the OP and the HXP.

The reduction of the HXP level produces the power decrease and the reduction of the primary flow rate. This sequence is well predicted by the code. At 3 338 s the triggering valve is closed and the HXP level rapidly decreases as shown in Figure 5.354. It causes the rapid decrease of the power and of the primary flow rate, which are well reproduced by R5- 3D, that shows the typical stepwise trend, as observed in Test 7 Part 1. The reduction of the condensation causes the increase of the pressure difference across the HX, due to the reduction of the gravitational term. This phenomenon is well reproduced by the code up to 4660 s, when the depressurisation of the primary system occurs causing the discrepancy between the simulation and the experiment (see Figure 5.362). On the secondary side, the reduction of the boiling rate causes the pressure decrease within the HXP, well predicted by R5-3D (Figure 5.359), and the temperature increase in the upper part of the pool, producing a relevant thermal stratification at the end of the test, which is qualitatively predicted by the code (see Figure 5.356, Figure 5.357 and Figure 5.358).

At the end of the test, the code predicts very well the flow rate across the primary system. The power exchanged between the HX and the HXP presents the same discrepancies observed at the beginning of Test 7 Part 1 and 2, underestimating the experimental value.

The maximum time step is set to 0.01 s and the computational time is 6 h 18 min.

Table 5.55. Main relevant thermal-hydraulic aspects related to Test 7 Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	300 s	-
Maximum level in the HXP	454 s	3.2 m
Maximum exchanged power	430 – 2 000 s	19.5
OP discharge valve F031 opening	1 150 s	-
Triggering valve F045 closure	3 338 s	-
HX pool level decreasing and loss of mass from the boil-off	2 800 s	-
Primary side depressurisation beginning for end of test	4 670 s	-

The marks adopted in Table 5.55 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.56. PERSEO Test 7 Part 2 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.		Measurement		Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F_A001 (der.)	+
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W_IC (der.)	+
				Level HXP	L_VQ (der.)	
				Level OP	L_VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Power heat exchanger	W_IC (der.)	+
				Relative pressure HXP top	P-Q001	
				Diff. pressure HX upper-lower header	DP-003	
				Diff. pressure steam duct injector	DP-J001	
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Power heat exchanger	W_IC (der.)	+
				Diff. pressure HX upper-lower header	DP-003	
				Absolute pressure vessel	P-I001	
				Flowrate condensate drain line	F_E001 (der.)	
				Flowrate steam supply line	F_A001 (der.)	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Level HXP	L_VQ (der.)	o
				Power heat exchanger	W_IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
F	Behaviour of large pool: Thermal stratification	+	+	Power heat exchanger	W_IC (der.)	o
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP	L_VQ (der.)	+
				Level OP	L_VP (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L_VP (der.)	O
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

Figure 5.348. Test 7 Part 2 - Steam flow rate

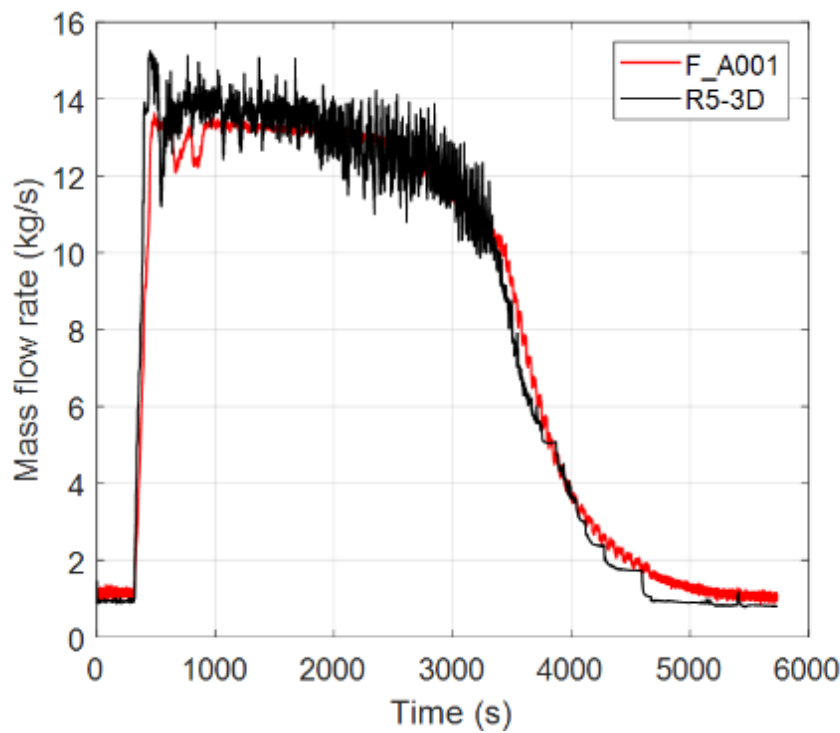


Figure 5.349. Test 7 Part 2 - Condensate flow rate

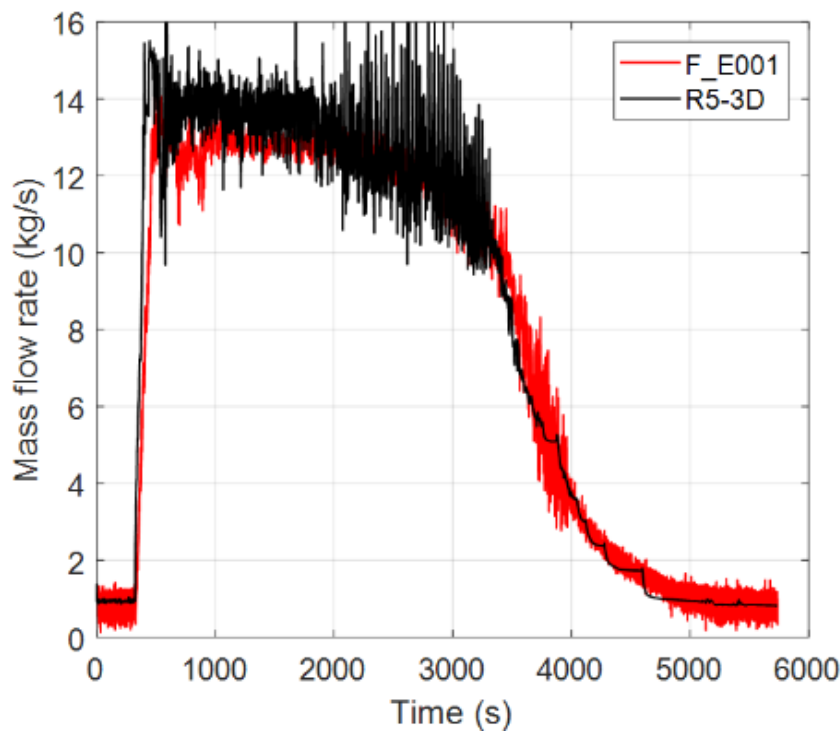


Figure 5.350. Test 7 Part 2 - HX power

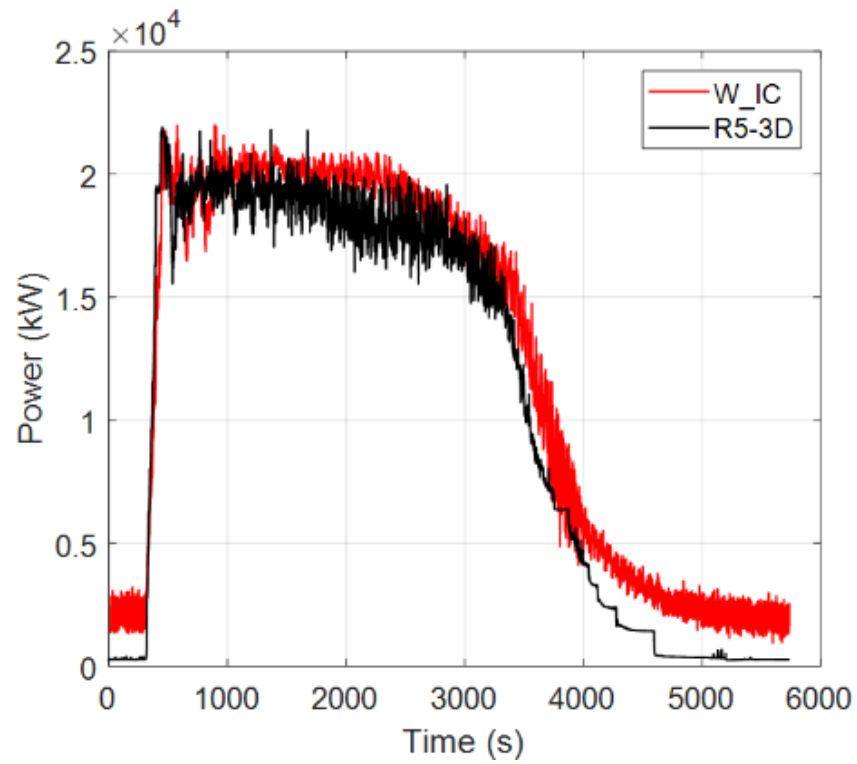


Figure 5.351. Test 7 Part 2 - Primary pressure

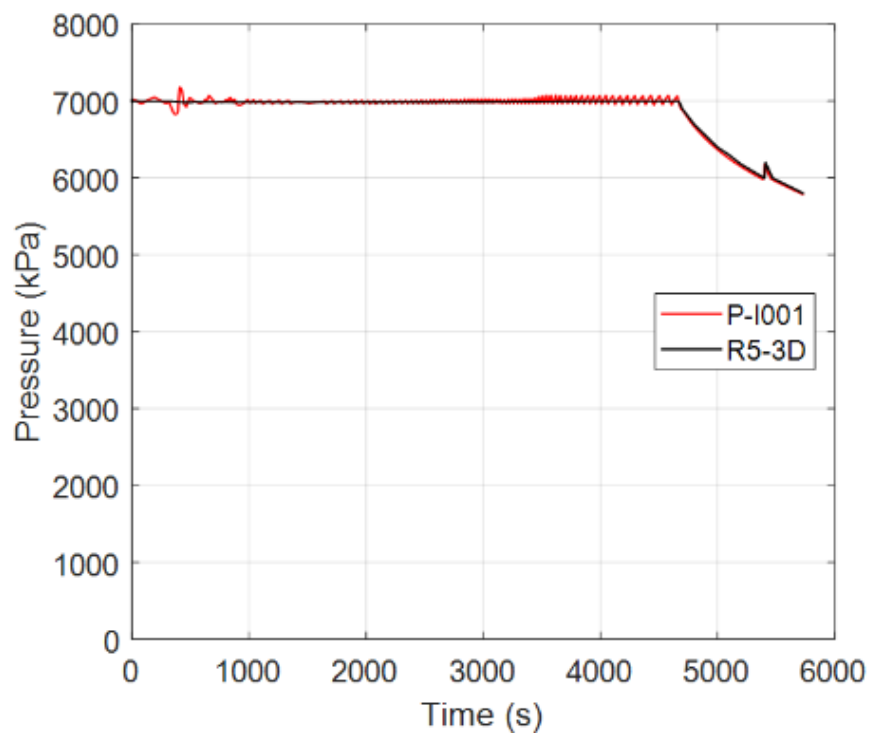


Figure 5.352. Test 7 Part 2 - Steam temperature

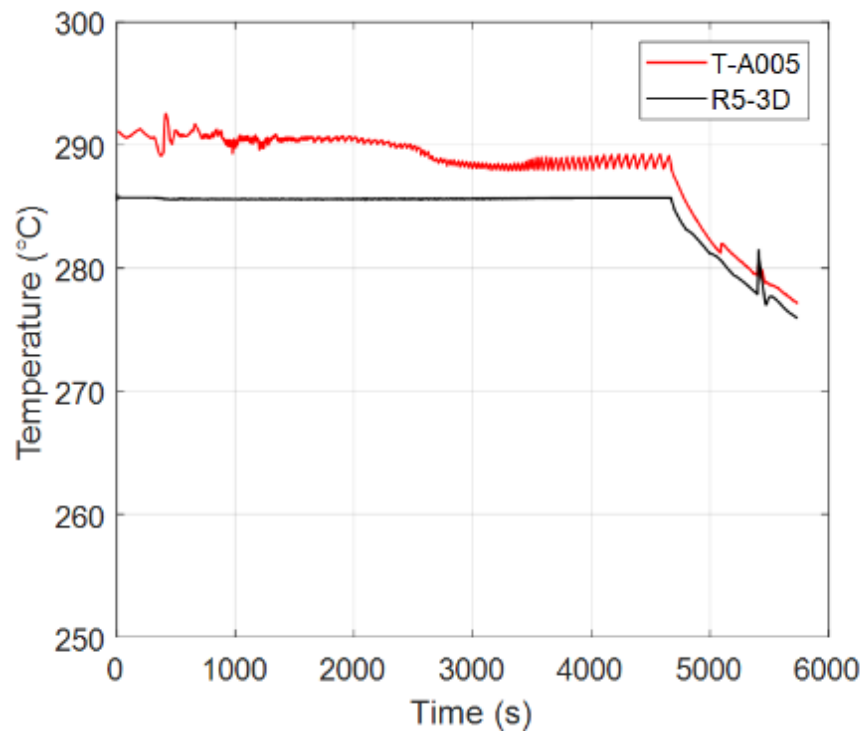


Figure 5.353. Test 7 Part 2 - Condensate temperature

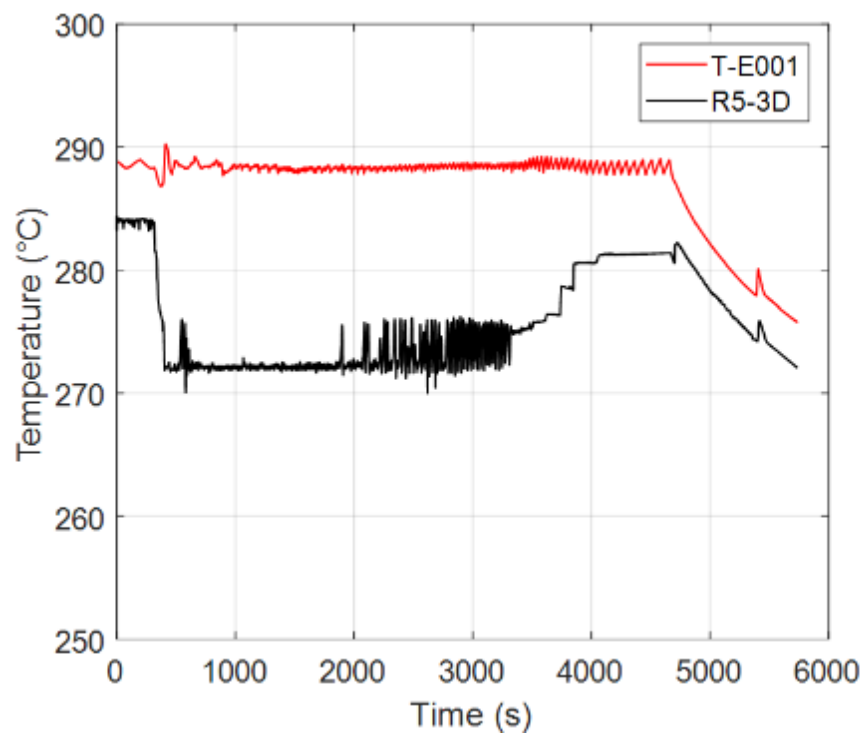


Figure 5.354. Test 7 Part 2 - HXP level

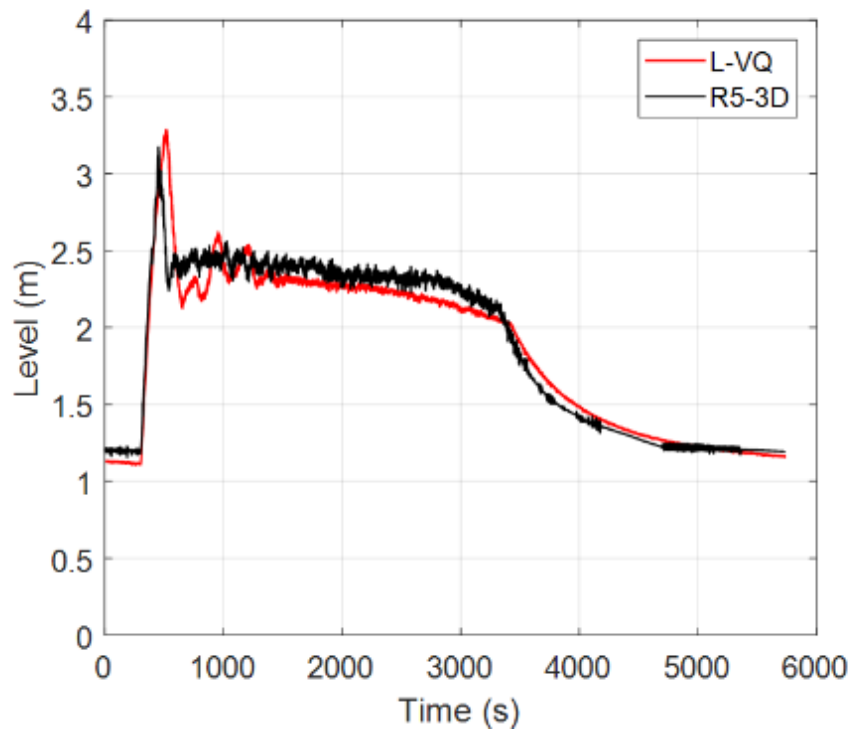


Figure 5.355. Test 7 Part 2 - OP level

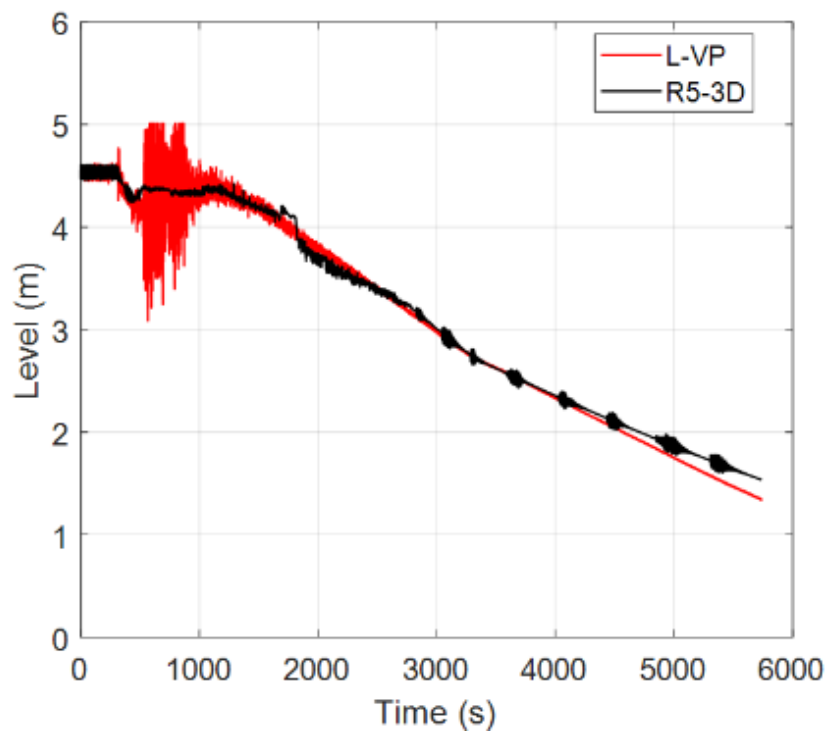


Figure 5.356. Test 7 Part 2 - HXP temperature T-Q037

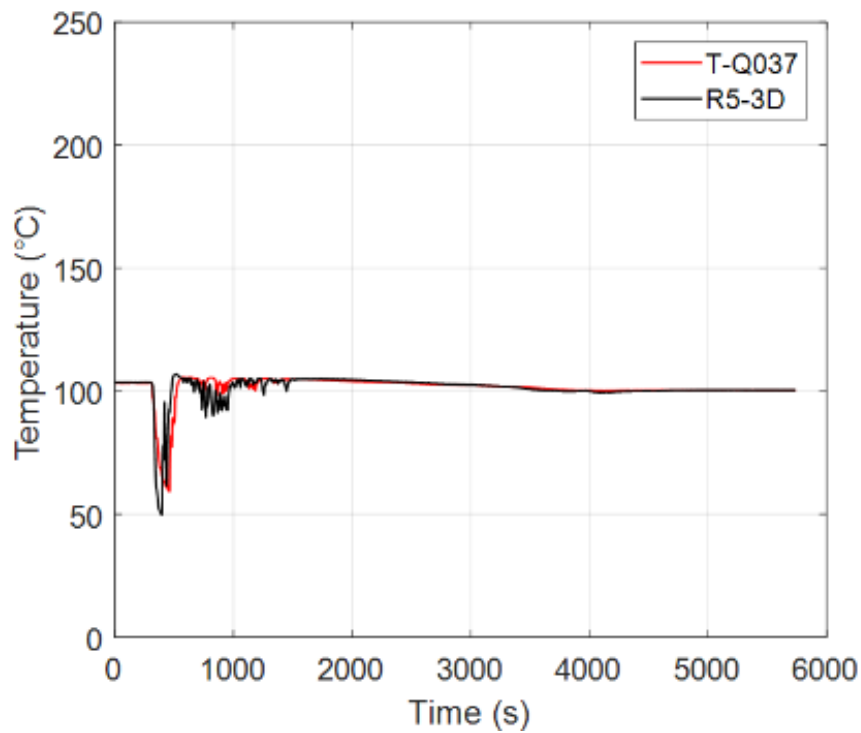


Figure 5.357. Test 7 Part 2 - HXP temperature T-Q034

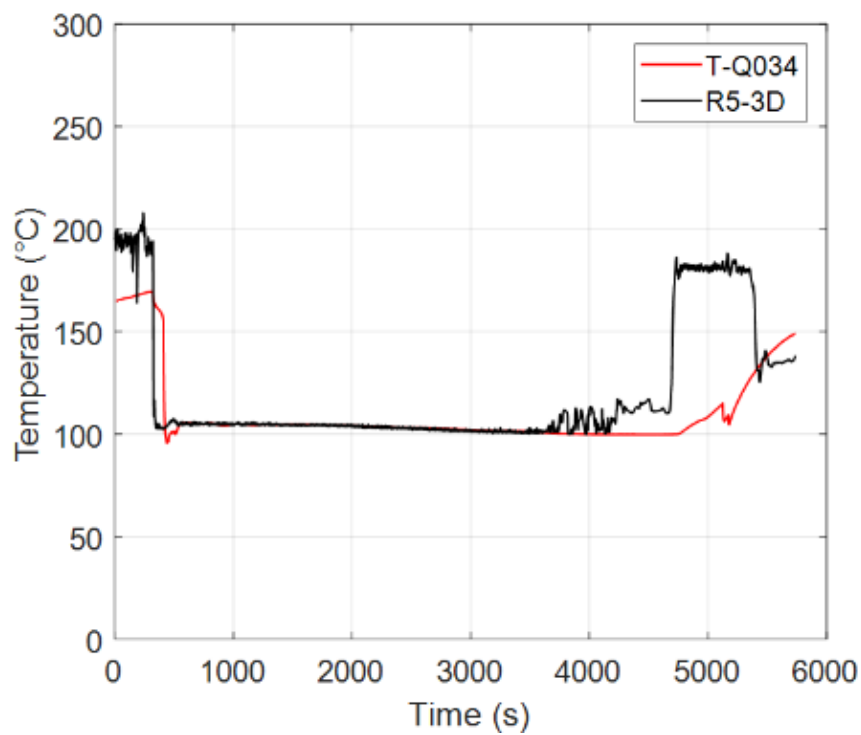


Figure 5.358. Test 7 Part 2 - HXP temperature T-Q031

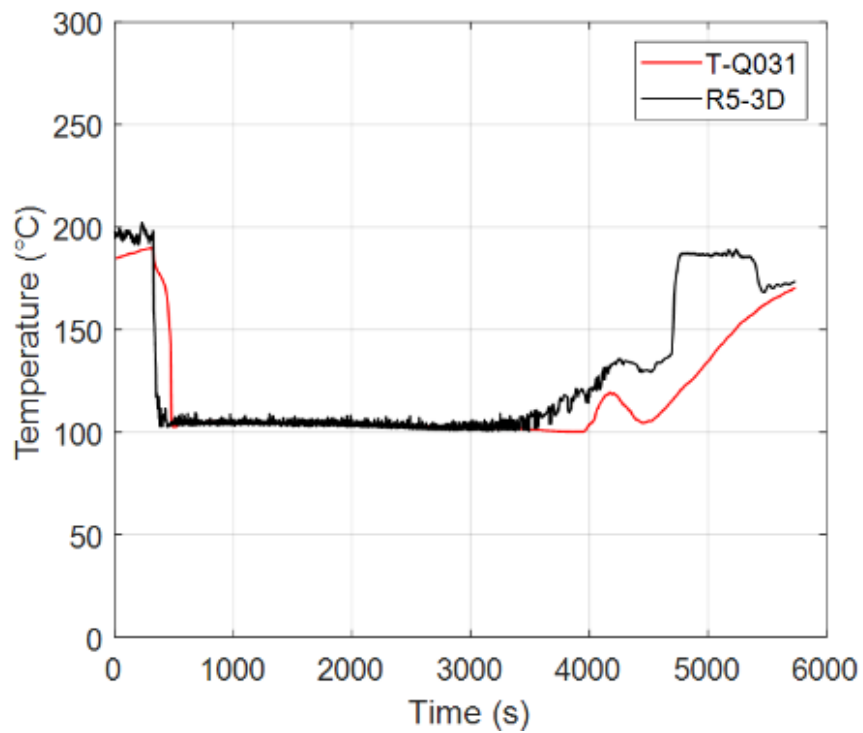


Figure 5.359. Test 7 Part 2 - Relative pressure HXP

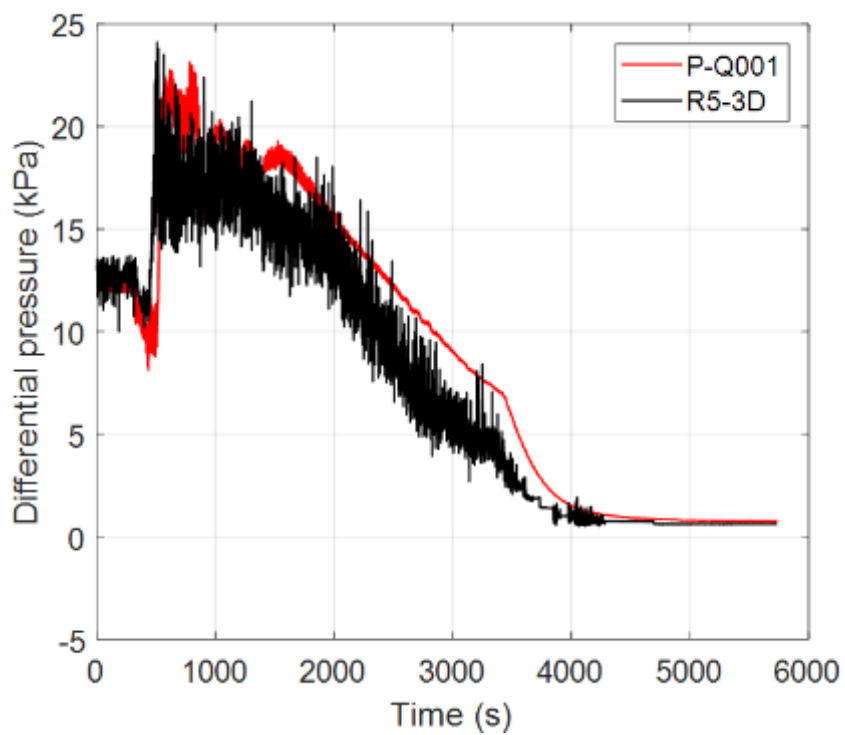


Figure 5.360. Test 7 Part 2 - OP temperature T-P008

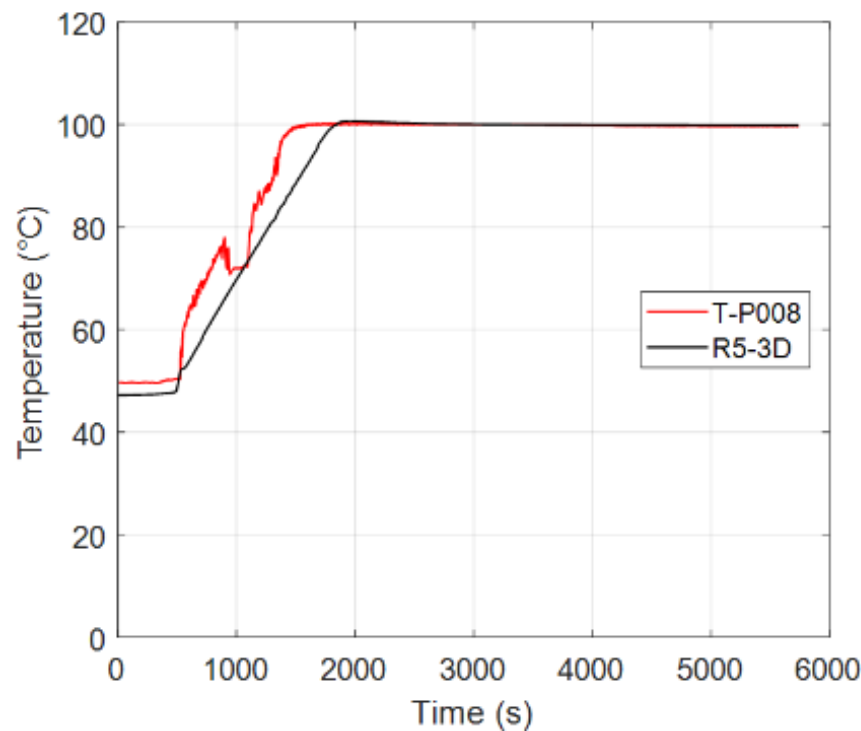


Figure 5.361. Test 7 Part 2 - OP temperature T-P021

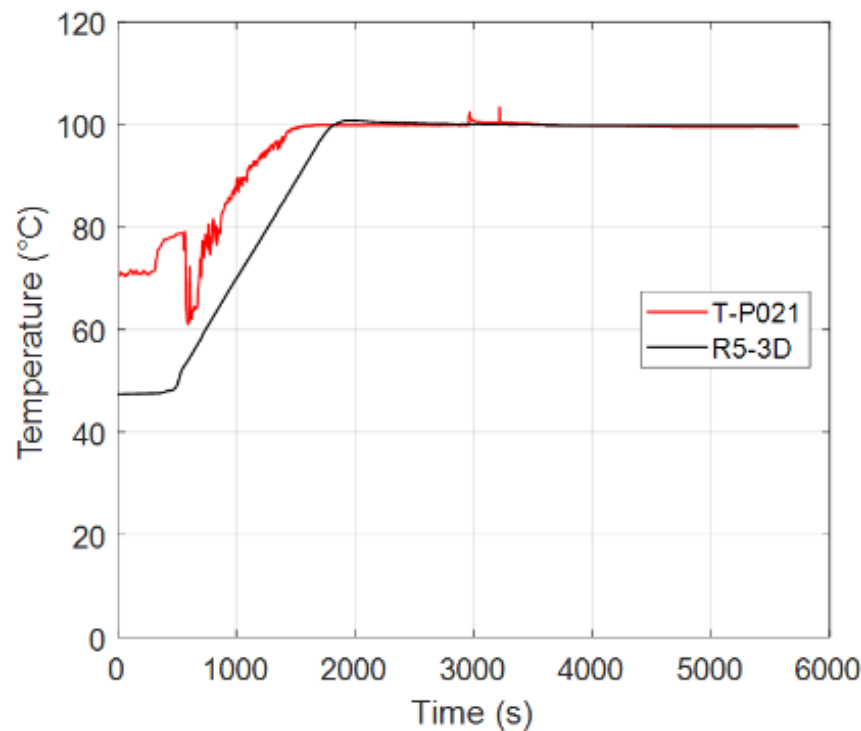


Figure 5.362. Test 7 Part 2 - HX differential pressure

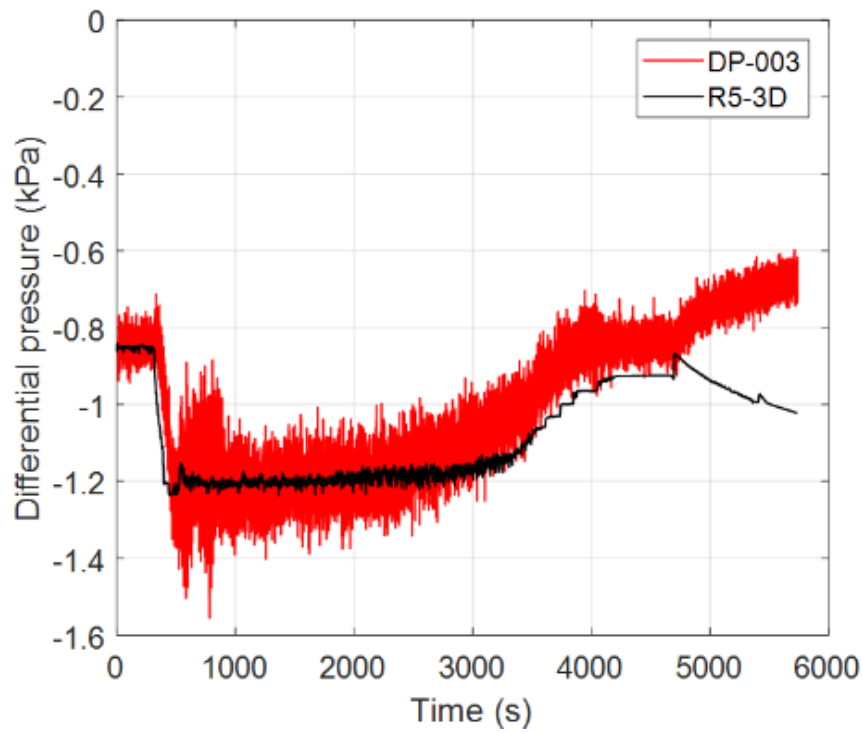


Figure 5.363. Test 7 Part 2 - Injector differential pressure

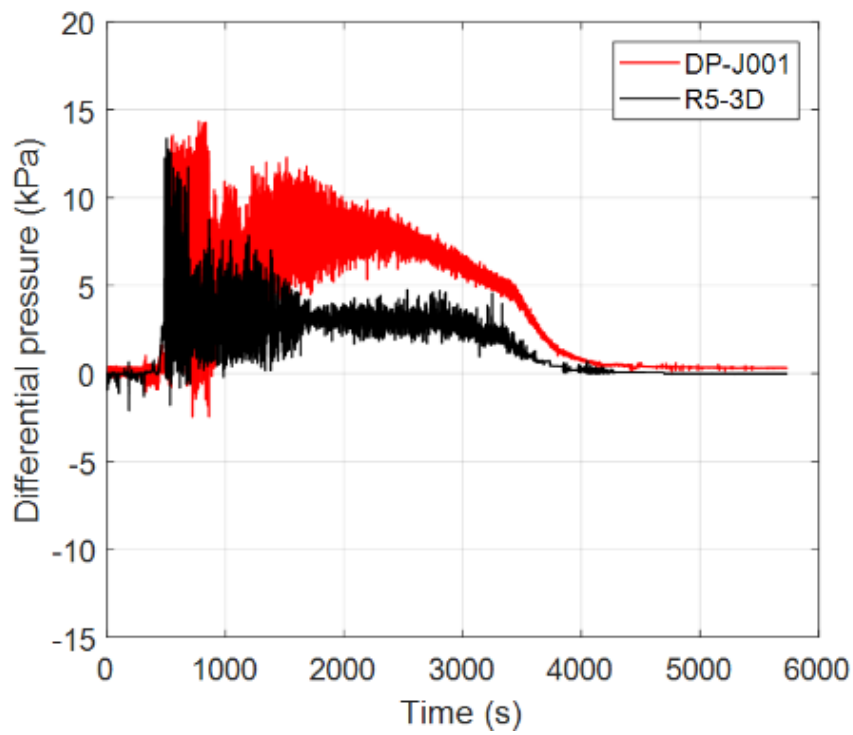


Figure 5.364. Test 7 Part 2 - HX upper header outer wall temperature

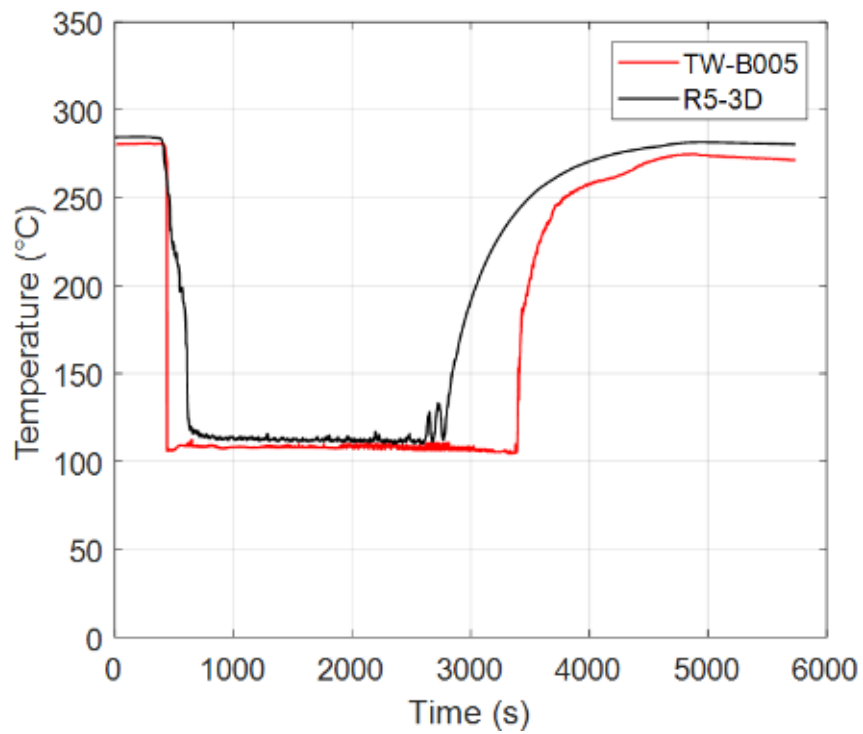
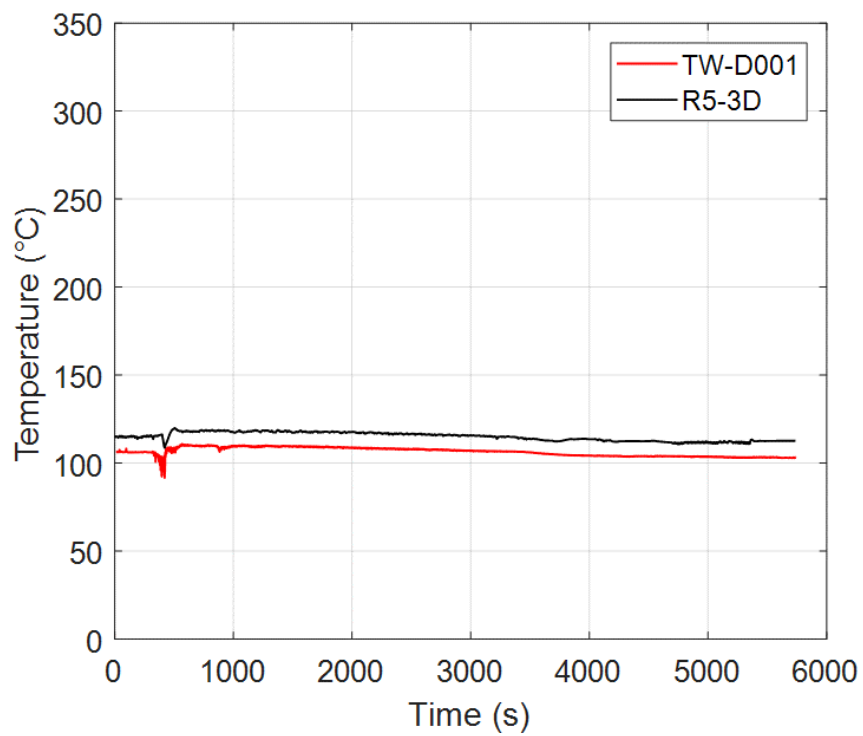


Figure 5.365. Test 7 Part 2 - HX lower header outer wall temperature



SECTION 5: CONCLUSIONS

The comparison between experiment and calculations highlighted the good capabilities of R5-3D to reproduce the main phenomena occurring in the PERSEO facility during Test 7.

Two key points are highlighted:

- The need to improve the heat exchanged between the HX and the HXP, using a calibrated HTC multiplicative factor (fouling factor equal to 2.4);
- The difficulty of reproducing thermal stratification adopting a mono-dimensional modelling approach for the pools.

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- [5.2.9 2] Narcisi, V., F. Giannetti, M. Tarantino, D. Martelli, G. Caruso (2017) “Pool temperature stratification analysis in CIRCE-ICE facility with RELAP5-3D© model and comparison with experimental tests”, *J. Phys. Conf. Ser.*, 923 (012006).
- [5.2.9 3] Narcisi, V., F. Giannetti, G. Caruso (2019), “Investigation on RELAP5-3D© capability to predict thermal stratification in liquid metal pool-type system and comparison with experimental data”, *Nucl. Eng. Des.*, Vol. 352, 110152.
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- [5.2.9 5] Bianchi, F., P. Meloni, R. Ferri, A. Achilli (2004), “Assessment of RELAP5 mod3.3 and CATHARE 2 v1.5A against a full scale test of PERSEO device”, *Proceedings of ICONE12: 12th International Conference on Nuclear Engineering*, 25-29 April 2004 Arlington, Virginia, United States.

5.2.10. UofU

SECTION 1: GENERAL INFORMATION

- Organisation: University of Utah (United States) (graduate student), Sandia National Laboratories (United States) (graduate intern)
- Contact persons/authors: Primary: Lucas Albright, Nathan Andrews, Randall Gauntt, Dr Tatjana Jevremovic
- Code: MELCOR v2.2.11 620
- Computing environment:
 - Operative systems: Microsoft Windows 10 Enterprise
 - RAM: 64 GB
 - CPU characteristics: Processor Intel(R) Xeon(R) CPU E5-1 620 v2 @ 3.70 GHz, 3 701 Mhz, 4 Core(s), 8 Logical Processor(s)

SECTION 2: DESCRIPTION OF THE CODE USED

MELCOR is a fully integrated, engineering-level computer code with the primary purpose of modelling the progression of accidents in light water reactor nuclear power plants. A broad spectrum of severe accident phenomena in both boiling and pressurised water reactors is treated in MELCOR in a unified framework. MELCOR is developed by Sandia National Laboratories under contract to the USNRC.

Thermal-hydraulic processes interact with and are coupled to all aspects of accident phenomenology. In the MELCOR code, thermal-hydraulic data calculated by the control volume hydrodynamics (CVH) and flow path (FL) packages provide boundary conditions to other phenomenological packages such as burn (BUR), cavity (CAV), core (COR), fuel dispersal interactions (FDI), and heat structures (HS). These packages, in turn, calculate sources and sinks of mass and energy for CVH. COR and HS also calculate changes to the volumes available to hydrodynamic materials. In some cases, CVH results are used directly by another package. The RadioNuclide (RN) package uses CVH results for advection to transport aerosols and vapours from one calculational volume to another; RN also uses CVH results for the liquid water content of the atmosphere (fog) as the water content of aerosols, rather than integrating a separate equation for condensation and evaporation. Therefore, even though the primary interest in accident research is *not* solely thermal hydraulics, the thermal-hydraulic modelling in CVH and FL forms the backbone of the MELCOR code.

The choice of modelling in CVH and FL was influenced by a number of often conflicting requirements. The packages were desired to be computationally fast but also reliable and accurate. They should not produce minor non-physical variations in behaviour that would adversely affect the performance of other packages and should not be unduly sensitive to such variations in the conditions calculated by other packages. They should permit great flexibility in nodalisation to simplify sensitivity studies and should extract the maximum amount of information from coarse nodalisations while allowing more detailed ones for comparison to more specialised codes. In addition, they should be user friendly with respect to input.

The calculational method chosen uses a control volume/flow path approach similar to RELAP4, HECTR, and CONTAIN. The same models and solution algorithms are used for all volumes (i.e. the primary, secondary, and containment volumes are modelled

consistently, and the resulting equations are solved simultaneously). Within the basic control volume formulation, the treatment is quite general; no specific nodalisation is built in. No component models are explicitly included; pipes, vessels, pressurisers, steam generators, for example, are built through user input from control volumes, flow paths, and elements of other packages such as heat structures. Control logic used to simulate active or passive systems is introduced using control functions. (There are separate models for a few special safety systems including fan coolers and containment sprays.) It is anticipated that, as experience with MELCOR grows, a set of “standard” nodalisations are developed, validated, and employed for most calculations. However, the freedom exists to investigate sensitivities to variations in nodalisation (and to develop representations of systems) entirely from code input, without modification to MELCOR itself.

A semi-implicit (linearised) formulation of the governing equations is used to permit time steps greater than the acoustic Courant limit. The numerical-solution technique is similar to that in RELAP4, with two major differences: (1) MELCOR uses a full two-fluid treatment rather than the drift-flux formulation of RELAP4 and (2) the resulting equations are iterated when necessary so that the result is fully implicit with respect to pressures used in the momentum equation. A significant feature of this method is that the resulting equations are exactly conservative (to within machine round off) with respect to masses and to thermal energy.

More information on the flow equations and solution strategy used in MELCOR can be found in the MELCOR reference manual [5.2.10 1].

Pool convection heat transfer

By default, MELCOR calculates the convective heat transfer in a pool according to the type of convection assumed by MELCOR, shown in Table 5.56.

Table 5.57. MELCOR convection regime

Convection Regime	Criteria
Natural Convection	$Re^2 < 1.0 \text{ Gr}$
Forced Convection	$Re^2 > 10.0 \text{ Gr}$
Mixed Convection	$1.0 \text{ Gr} \leq Re^2 \leq 10.0 \text{ Gr}$

Table 5.58. MELCOR flow regime logic

Flow Regime	Geometry	Criteria
Laminar natural convection	Rectangular	$Ra^2 < 10^9$
	Cylindrical/Spherical	
Turbulent natural convection	Rectangular	$Ra^2 > 10^{10}$
	Cylindrical/Spherical	
Transition between laminar and turbulent natural convection	Rectangular	$10^9 \leq Ra^2 \leq 10^{10}$
	Cylindrical/Spherical	
Laminar forced convection	Rectangular	$Re^2 < 3 \times 10^5$
	Cylindrical/Spherical	$Re^2 < 2 \times 10^3$
Turbulent forced convection	Rectangular	$Re^2 > 6 \times 10^5$
	Cylindrical/Spherical	$Re^2 > 1 \times 10^4$
Transition between laminar and turbulent forced convection	Rectangular	$3 \times 10^5 \leq Re^2 \leq 6 \times 10^5$
	Cylindrical/Spherical	$2 \times 10^3 \leq Re^2 \leq 1 \times 10^4$

where

Ra : Rayleigh number

1. Natural Convection

$$Nu = CRa^m + D$$

where

Nu : Nusselt number

C, m, D : flow condition and geometry dependent constants

2. Forced Convection

$$Nu = CRe^m Pr^n + D$$

where

Pr : Prandtl number

n : flow condition and geometry dependent constant

3. Mixed Convection

$$Nu_{\text{mixed}} = \left[\frac{\frac{Re^2}{Gr} - 1}{9} \right] [Nu_{\text{forced}} - Nu_{\text{natural}}] + Nu_{\text{natural}}$$

Table 5.59. MELCOR convection heat transfer parameters

Convection Regime	Flow Type	Flow Regime	Geometry	C	m	D	n
Natural Convection	Internal	Laminar	Rectangular	0.046	1/3	0	-
			Cylindrical	0.046	1/3	0	-
			Spherical	0.028	0.226	0	-
		Turbulent	Rectangular	0.046	1/3	0	-
			Cylindrical	0.046	1/3	0	-
			Spherical	0.028	0.226	0	-
	External	Laminar	Rectangular	0.59	0.25	0	-
			Cylindrical	0.59	0.25	0	-
			Spherical	0.43	0.25	2.0	-
		Turbulent	Rectangular	0.10	1/3	0	-
			Cylindrical	0.10	1/3	0	-
			Spherical	0.43	0.25	2.0	-
Forced convection	Internal	Laminar	Rectangular	8.235	0	0	0
			Cylindrical	48/11	0	0	0
			Spherical	48/11	0	0	0
		Turbulent	Rectangular	0.023	0.8	1/3	0
			Cylindrical	0.023	0.8	1/3	0
			Spherical	0.023	0.8	1/3	0
	External	Laminar	Rectangular	0.664	0.5	1/3	0
			Cylindrical	0.664	0.5	1/3	0
			Spherical	0.60	0.5	1/3	2.0
		Turbulent	Rectangular	0.037	0.8	1/3	0
			Cylindrical	0.037	0.8	1/3	0
			Spherical	0.60	0.5	1/3	2.0

Pool boiling heat transfer

When a heat structure is submerged in a pool and its surface temperature is greater than the saturation temperature of the control volume, pool boiling occurs according to the following logic:

- Nucleate boiling if $q''_{nb} < q''_{chf}$

- Film boiling if $q''_{film} < q''_{mfilm}$
- Transition boiling if neither of the above conditions are met

1. Nucleate Boiling: Rohsenow Correlation

$$\left[\frac{c_{pl}(T_{surf} - T_{sat})}{h_{fg}} \right] = C_{sf} \left[\frac{q''_{nb}}{\mu h_{fg}} \left(\frac{\sigma}{g(\rho_l - \rho_v)} \right)^{\frac{1}{2}} \right]^n Pr^m$$

$$T_{avg} = \frac{T_{surf} + T_{sat}}{2}$$

where

c_{pl} : heat capacity of liquid at T_{sat} [J/Kg·K]

T_{surf} : Temperature of heat structure surface [K]

T_{sat} : Saturation temperature of boundary volume pool [K]

h_{fg} : latent heat in boundary volume [J/Kg]

C_{sf} : Empirically derived constant [unitless]

q''_{nb} : nucleate boiling heat flux [W/m²]

T_{avg} : average temperature [K]

μ : dynamic viscosity of liquid at T_{avg} [kg/m·s]

σ : surface tension at T_{avg} [N/m]

g : gravitational acceleration [m/s²]

ρ_l : density of liquid at T_{sat} [kg/m³]

ρ_v : density of vapour at T_{sat} [kg/m³]

n : constant (default=0.33)

Pr : Prandtl number of liquid in boundary volume

m : constant (default = 1.0)

2. Critical Heat flux: Zuber Correlation

$$q''_{CHF} = 0.18 \rho_v h_{fg} \left[\frac{\sigma(\rho_l - \rho_v)g}{\rho_v^2} \right]^{\frac{1}{4}} \left[\frac{\rho_l}{\rho_l + \rho_v} \right]^{\frac{1}{2}}$$

where

q''_{CHF} : critical heat flux [W/m²]

3. Minimum Film Boiling Heat Flux: Zuber Correlation

$$q''_{mfilm} = 0.09 \rho_v h_{fg} \left[\frac{\sigma(\rho_l - \rho_v)g}{\rho_l^2} \right]^{\frac{1}{4}} \left[\frac{\rho_l}{\rho_l + \rho_v} \right]^{\frac{1}{2}}$$

where

q''_{mfilm} : minimum film boiling heat flux [W/m²]

4. Stable Film Boiling: Bromley Correlation

$$q''_{film} = 0.943 \left[\frac{\rho_v(\rho_l - \rho_v)gk_v^3 \left(h_{fg} + \frac{c_{pv}\Delta T_{surf}}{2} \right)}{\mu_v L_c} \right]^{\frac{1}{4}} \Delta T^{0.75}$$

$$\Delta T_{surf} = T_{surf} - T_{sat}$$

where

q''_{film} : film boiling heat flux [W/m²]

k_v : thermal conductivity of vapour at T_{avg} [W/m·K]

c_{pv} : heat capacity of vapour at T_{sat} [J/kg·K]

μ_v : dynamic viscosity of vapour at T_{avg} [kg/m·s]

L_c : characteristic length of the heat structure surface [m]

5. Radiation during boiling:

During transition and film boiling radiation heat transfer is calculated by:

$$q''_{rad} = C\sigma(T_{surf}^4 - T_{pool}^4)$$

where

q''_{rad} : radiation to pool heat flux [W/m²]

C : Sensitivity coefficient allowing user modification of radiation heat transfer [unitless]

σ : Stefan-Boltzmann constant; 5.669×10^{-8} [W/m²·K⁴]

T_{pool} : Temperature of boundary volume pool [K]

6. Transition boiling:

$$T_c = T_{sat} + \left(\frac{q''_{chf} \Delta T_{surf}^3}{q''_{nb}} \right)^{\frac{1}{3}}$$

$$T_{mfilm} = T_{sat} + \left[\frac{q''_{mfilm} \Delta T_{surf}^{0.75}}{q''_{film} + q''_{rad}} \right]^{\frac{4}{3}}$$

$$q''_{tran} = \exp \left(\frac{[\ln(q''_{chf}) (\ln \Delta T_{surf} - \ln \Delta T_{mfilm}) + \ln(q''_{mfilm}) (\ln \Delta T_c - \ln \Delta T_{surf})]}{[\ln \Delta T_c - \ln \Delta T_{mfilm}]} \right) + q''_{rad}$$

$$\Delta T_{mfilm} = T_{mfilm} - T_{sat}$$

$$\Delta T_c = T_c - T_{sat}$$

where

q''_{tran} : transition boiling heat flux [W/m²]

T_c : critical temperature [K]

More information on the heat transfer and other thermal-hydraulic models available in MELCOR can be found in the MELCOR reference manual [5.2.10 1].

SECTION 3: DESCRIPTION OF THE NODALISATION

For this analysis a simplified nodalisation, shown in Figure 5.366, is implemented. The model includes a single control volume (CV) for the overall pool (OP), three axial CVs for the heat exchanger pool (HXP), three CVs for the steam duct, and a single CV for the nozzle. Each CV in the pool circuit is connected to neighbouring CVs through a single flow path. The flow path connecting the nozzle to the OP is one-directional. A single CV is used to represent the “environment” (25°C, 298.0 K). A unidirectional flow path representing the vacuum breaker connects the environment to the steam duct. The OP has two extra flow paths representing the boil-off and OP drain line at the top and bottom of the OP, respectively. The primary side nodalisation is simplified and does not include a reactor pressure vessel (RPV). A single, time-dependent CV is used to represent the steam source. Steam is delivered from the source to the upper header of the heat exchanger (HX) through six CVs representing the steam supply line. The upper and lower HX headers are each represented by a single CV, while the HX tubes connecting the two headers are represented by 18 axial CVs. Finally, the condensate line connects the lower HX header to the mass sink through a series of six CVs. As with the pool circuit, a single flow path connects each CV in the primary side to its neighbouring CVs.

To model heat transfer in both HX headers two heat structures are used; a single cylindrical shell heat structure to represent the header body, and spherical heat structure to represent hemispherical end caps of the header. To better model the pool/atmosphere interface and heat structure response, each HX tube was subdivided into 18 axial heat structures (with a multiplier to correct for the number of tubes at each axial level). Four cylindrical shell heat structures of decreasing radii are used to represent heat transfer from the conical nozzle to the OP.

Heat losses from the primary side are assumed to be negligible and are not modelled. Heat losses from the secondary side are also assumed to be negligible in the OP, liquid line, and steam duct. Heat losses from the HXP are modelled with a stainless-steel heat structure with a constant external temperature of 25°C (298.0 K).

Nodalisation strategy:

The primary side nodalisation strategy employed was selected to minimise the user effect in primary side modelling assumptions. Namely, assumptions in the steam supply line and RPV drain line operation.

- Three axial control volumes are used to model the HXP.
- The steam duct was modelled using three control volumes to accurately capture the large volumetric capacity and associated energy within the duct.
- A single control volume with four non-uniform altitude/volume table entries was used to model the nozzle’s volumetric capacity as accurately as possible.
- A single control volume was used to model the OP to avoid inadvertently defining artificial, non-physical natural circulation loops.
- A single flow path was used to model the liquid line, connecting the OP and HXP; no CVs are associated with the liquid line due to its small volumetric capacity.

Table 5.60. PERSEO model nodalisation summary

	Number of hydraulic volumes	Number of flow paths	Number of heat structures	Overall volume (m ³)
Vessel	Not modelled			
Steam supply line	1	1	0	0.32
Steam line	6	6	0	1.4331
HX	20	20	22	1.83984
Condensate line	6	6	0	0.4947
HXP	3	3	3	26.55564
Steam duct	3	3	0	12.22198
Nozzle	1	1	4	0.41
OP	1	3	0	172.91
Internal heat transfer area HX (m ²)	12.571 (total) 6.155 (upper header) 0.0261 (single 1.8 m long HX tube) 6.155 (lower header)			
External heat transfer area HX (m ²)	15.507 (total) 7.610 (upper header) 0.0287 (single 1.8 m long HX tube) 7.610 (lower header)			
HX heat structures modelled	1 spherical, 1 cylindrical (upper header) 18 cylindrical (per HX tube) 1 spherical, 1 cylindrical (upper header)			
HX heat structure radial nodes number	4			

Figure 5.366. PERSEO facility nodalisation, heat structures are shown in red

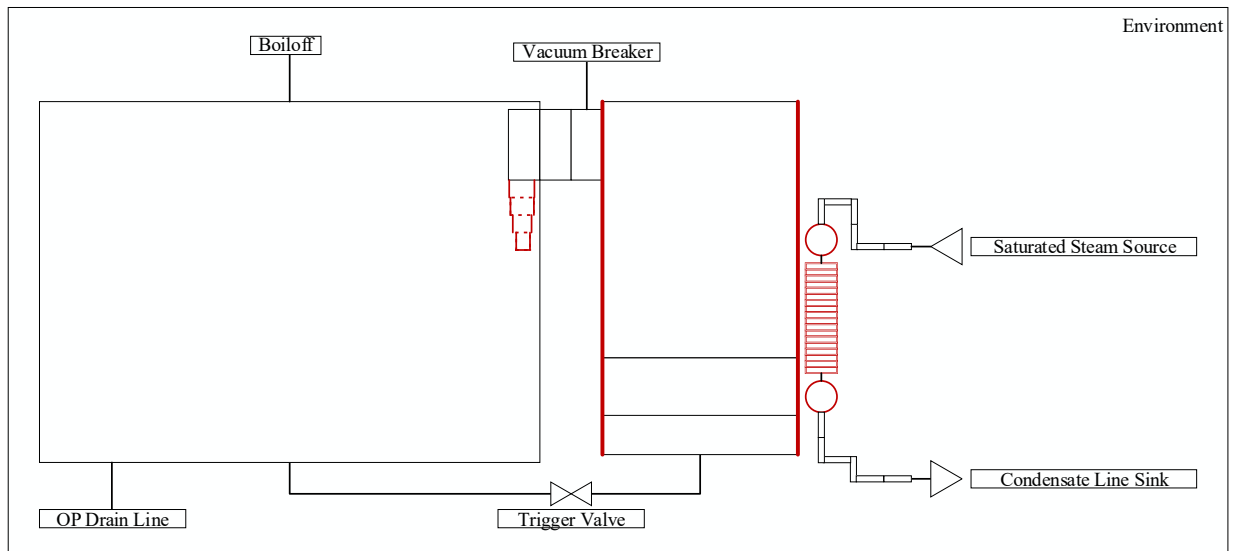


Table 5.61. List of parameters selected for the benchmark

	PARAMETER	LABEL	Comment
1	Flowrate steam supply line	F_A001 (der.)	
2	Flowrate condensate drain line	F_E001 (der.)	
3	Power HX	W_IC (der.)	
4	Absolute pressure vessel	P-I001	Steam supply line pressure
5	HX inlet fluid temperature	T-A005	Taken from the CV just before HX upper header: TVAP
6	HX outlet fluid temperature	T-E001	Taken from the CV just after HX lower header: TLIQ
7	Level HXP	L_VQ (der.)	Collapsed liquid level
8	Level OP	L_VP (der.)	Collapsed liquid level
9	Fluid temperature HXP (bottom)	T-Q037	T_{liquid} or T_{vapour} of CV based on water level and sensor elevation
10	Fluid temperature HXP (middle)	T-Q034	T_{liquid} or T_{vapour} of CV based on water level and sensor elevation
11	Fluid temperature HXP (top)	T-Q031	T_{liquid} or T_{vapour} of CV based on water level and sensor elevation
12	Relative pressure HXP top	P-Q001	
13	Fluid temperature OP (bottom)	T-P008	Single control volume represents OP
14	Fluid temperature OP (top)	T-P021	Same as OP (bottom)
15	Diff. pressure HX upper-lower header	DP-003	
16	Diff. pressure steam duct injector	DP-J001	
17	Wall temperature HX upper header	TW-B005	External node temperature, cylindrical section
18	Wall temperature HX lower header	TW-D001	External node temperature, cylindrical section

Test 7 Part 1

Initial and boundary conditions for the MELCOR model of Test 7 Part 1 are shown in Table 5.61 and Table 5.62, respectively.

Code results are able to reproduce the experimental results of Test 7 Part 1.

Table 5.62. MELCOR model initial conditions for Test 7 Part 1

Parameter	Initial Condition
Primary	
Control volume pressure	Approximated based on the available PERSEO data
Control volume state	All primary side CVs filled with saturated steam
Flow between control volumes	Assumed no flow
Secondary	
Control volume temperature and pressure	Approximated based on the available PERSEO data
Control volume state	All secondary side CVs filled with dry air
Control volume pool levels	Approximated based on the available PERSEO data
Flow between control volumes	Assumed no flow
HX wall temperatures	Approximated based on the available PERSEO data
HXP wall temperatures	Assumed to be near 'Environment' CV temperature (25°C)
Nozzle wall temperatures	Assumed to be near OP water temperature

Table 5.63. MELCOR model boundary conditions for Test 7 Part 1

Parameter	Boundary Condition
Primary	
Steam supply	A time-specified control volume was used to represent primary side steam supply. Control volume pressure was defined by a control function to match measured primary pressures (P-I001). The control volume was filled with saturated steam.
Condensate line sink	The condensate line sink was defined by a separate control volume with a time-specified pressure defined to account for the change in water level in the RPV.
Secondary	
Environment	Time-independent control volume (10 000 m ³) filled with dry air; P = 100 kPa, T = 25°C
OP drain line	Closed for the duration of Test 7 Part 1
Vacuum breaker	One-way valve that opens when pressure in steam duct drops below atmospheric pressure in the environment
Triggering valve operation	Due to the unavailability of data for the operation of the triggering valve, a control function was used to define triggering valve operation. The control function used approximate flow rates (FPOOL) and valve opening times to simulate valve operation. The control function was also tuned to match the maximum HXP height reported during each period of triggering valve operation.

Table 5.63 summarises the main relevant thermal-hydraulic aspects of Test 7 Part 1.

Table 5.64. Main relevant thermal-hydraulic aspects related to Test 7 Part 1

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	10 471 – 10 601 s	-
Triggering valve (F045) re-opening and re-closure	10 622 – 10 649 s	-
Maximum level in the HXP for the first filling step	10 649 s	1.41 m
Small heat removal from the primary side	10 630 – 11 056 s	~ 1.9 MW
Slow water consumption in the HXP	Not observed	Not observed
Instabilities for steam condensation in the injector	Not observed	Not observed
Triggering valve (F045) opening and closure	11 039 – 11 264 s	-
Maximum level in the HXP	11 260 s	3.4 m
Maximum exchanged power	11 263 s	21 MW
HXP minimum level	14 784 s	1.13 m
OP average temperature	13 000 s	59 C

Flow through the primary circuit, shown in Figure 5.367 and Figure 5.368, show good agreement between the MELCOR model and experiment. During the third period of triggering valve operation the flow rates increase rapidly as observed during the experiment. During the later phase of Test 7 Part 1, while flow rates are observed to decrease, MELCOR predicts larger primary flow rates than those measured during the experiment.

Figure 5.367. PERSEO Test 7 Part 1 simulation vs experiment
steam supply line flowrate (F_A001)

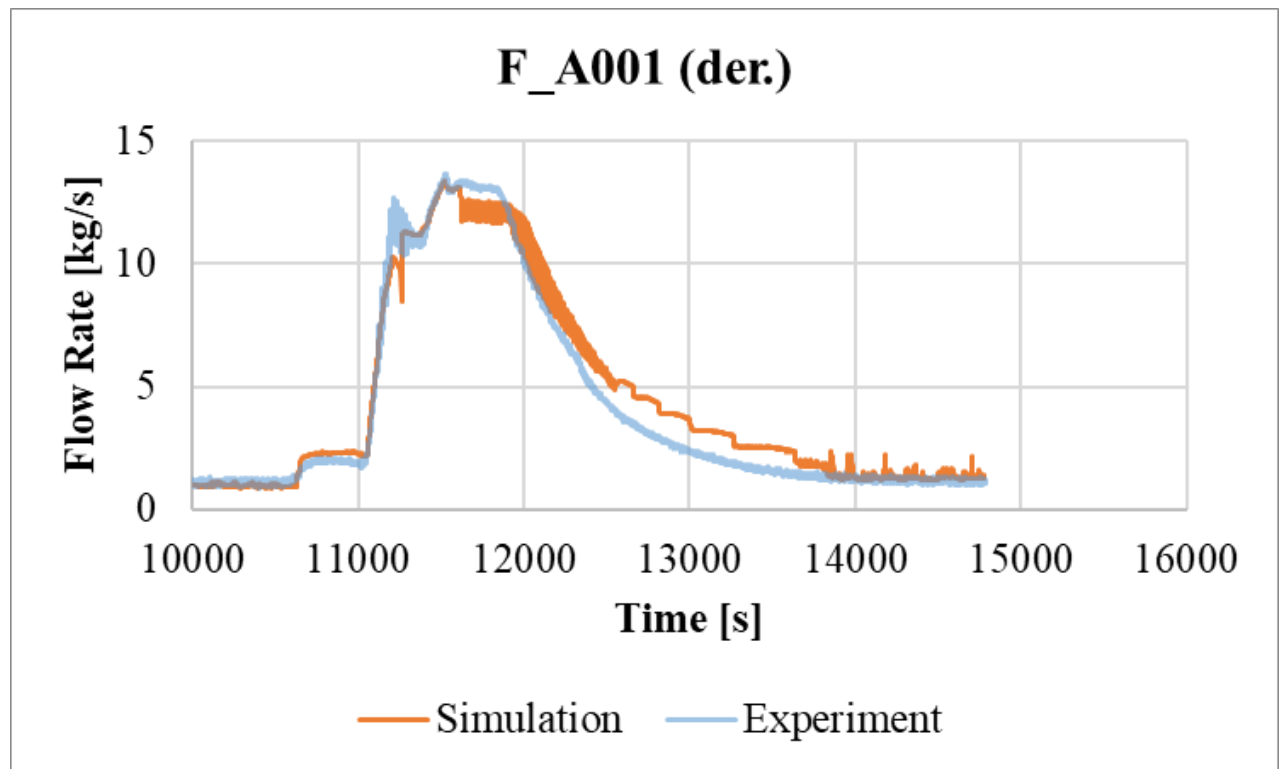


Figure 5.368. PERSEO Test 7 Part 1 simulation vs experiment
condensate drain line flowrate (F_E001)

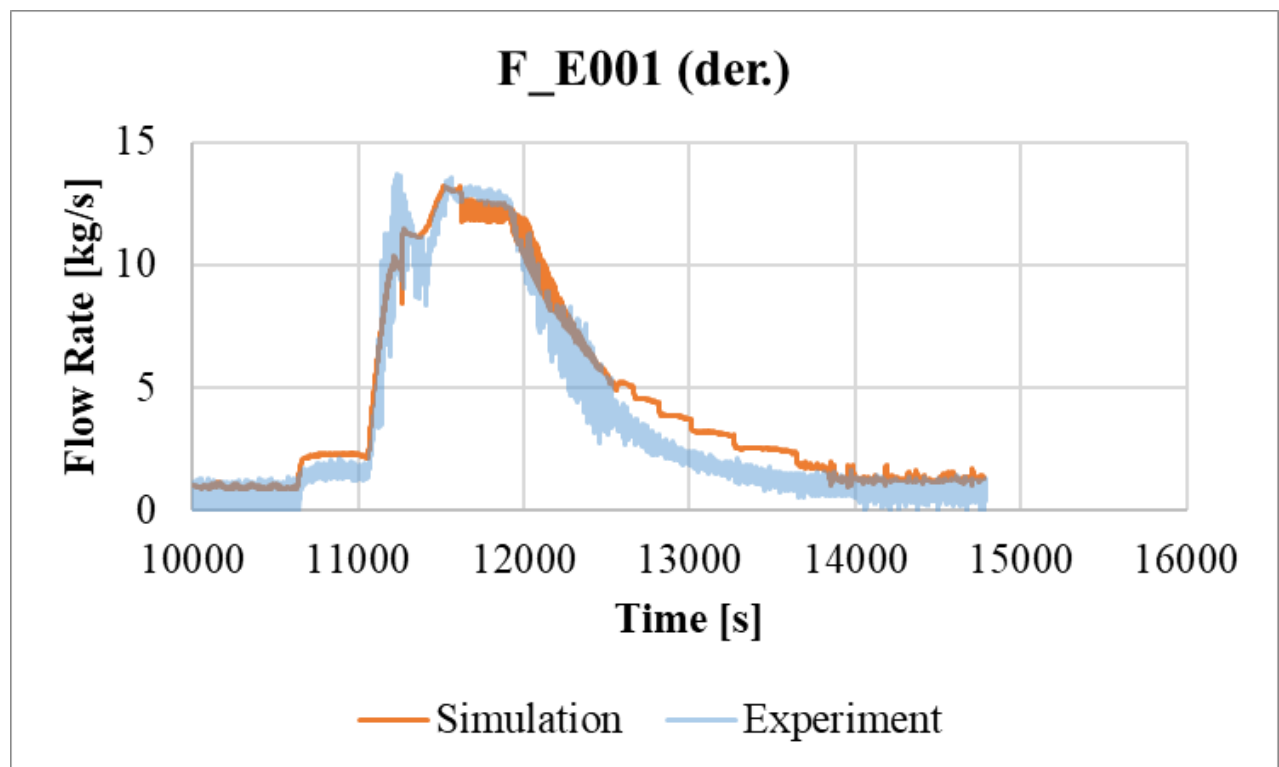
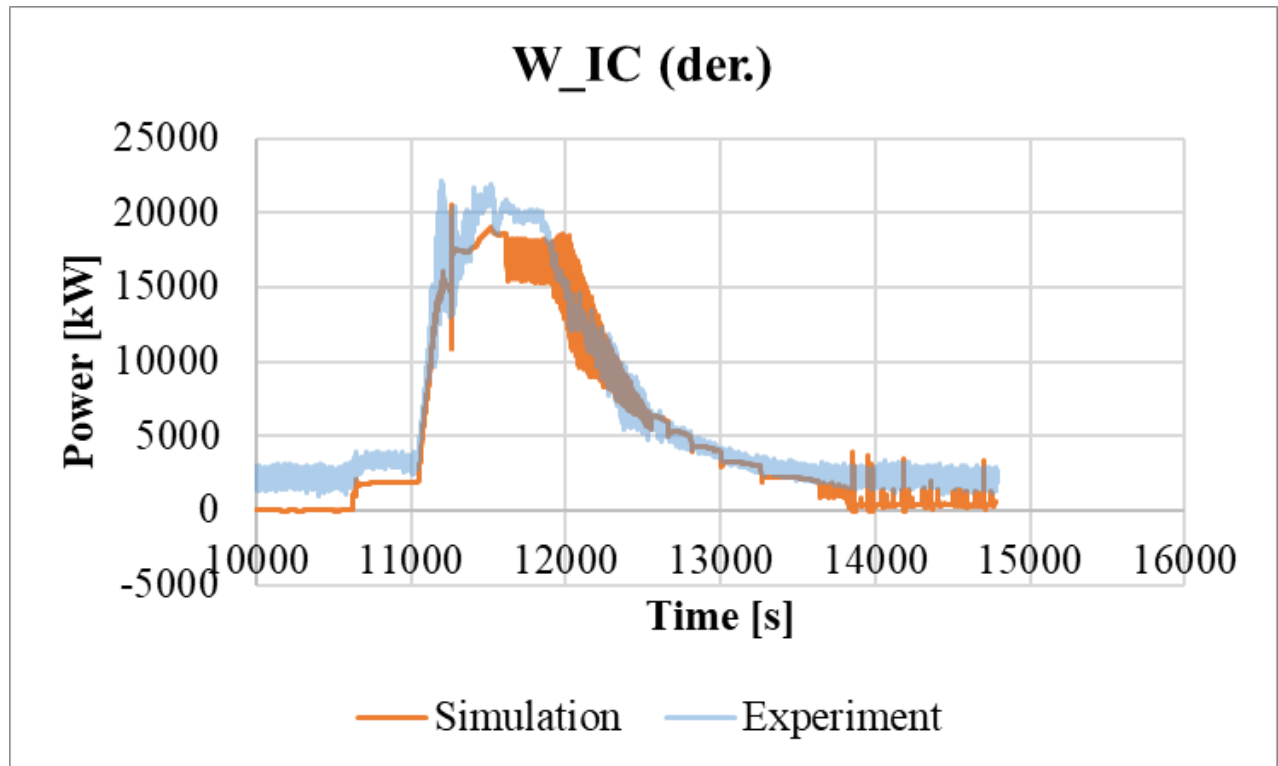


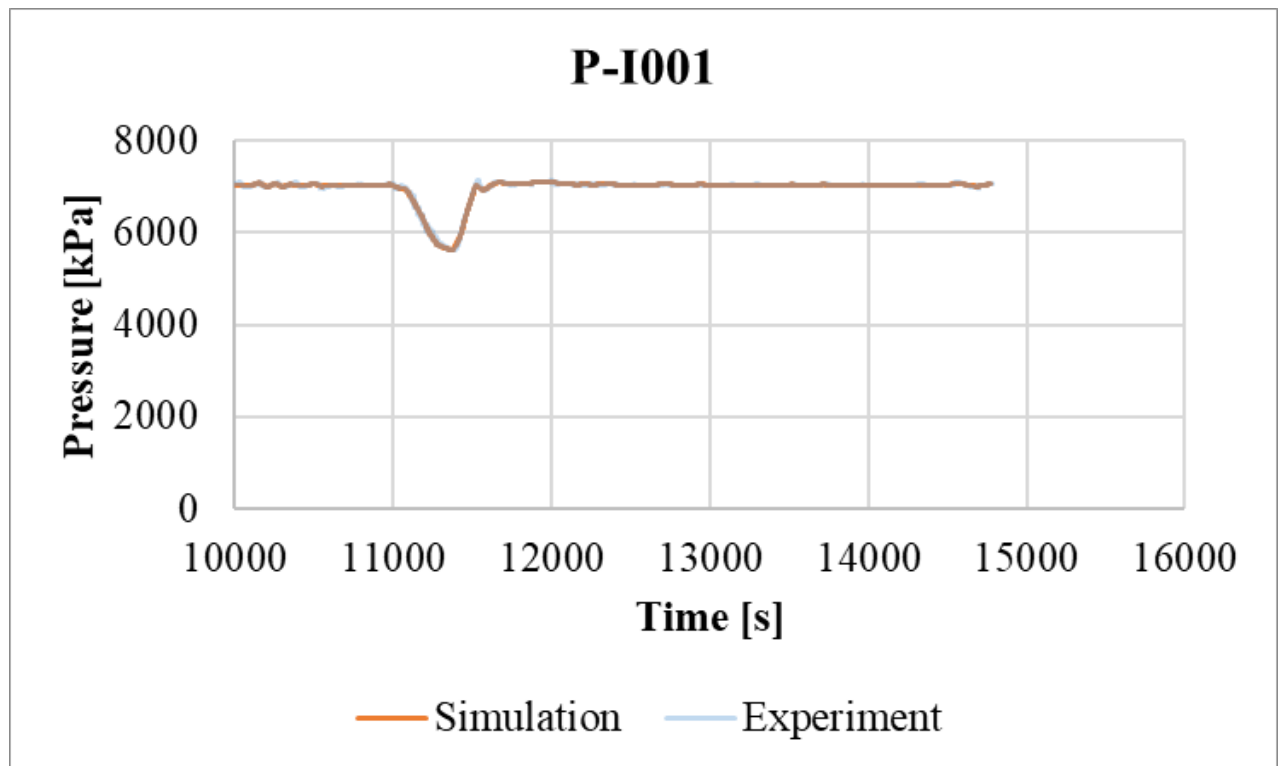
Figure 5.369 shows the power extracted by the HX during Test 7 Part 1. The MELCOR model shows good qualitative agreement with experimental results.

**Figure 5.369. PERSEO Test 7 Part 1 simulation vs experiment
power extracted (W_IC)**



Primary pressure is shown in Figure 5.370. As stated above, experimental measurements of primary pressure are defined as a control function used as a boundary condition in the MELCOR model.

Figure 5.370. PERSEO Test 7 Part 1 simulation vs experiment
primary pressure (P-I001)



HX inlet and outlet temperatures are shown in Figure 5.371 and Figure 5.372, respectively. Moderate differences are observed throughout the test.

Figure 5.371. PERSEO Test 7 Part 1 simulation vs experiment HX inlet fluid temperature (T-A005)

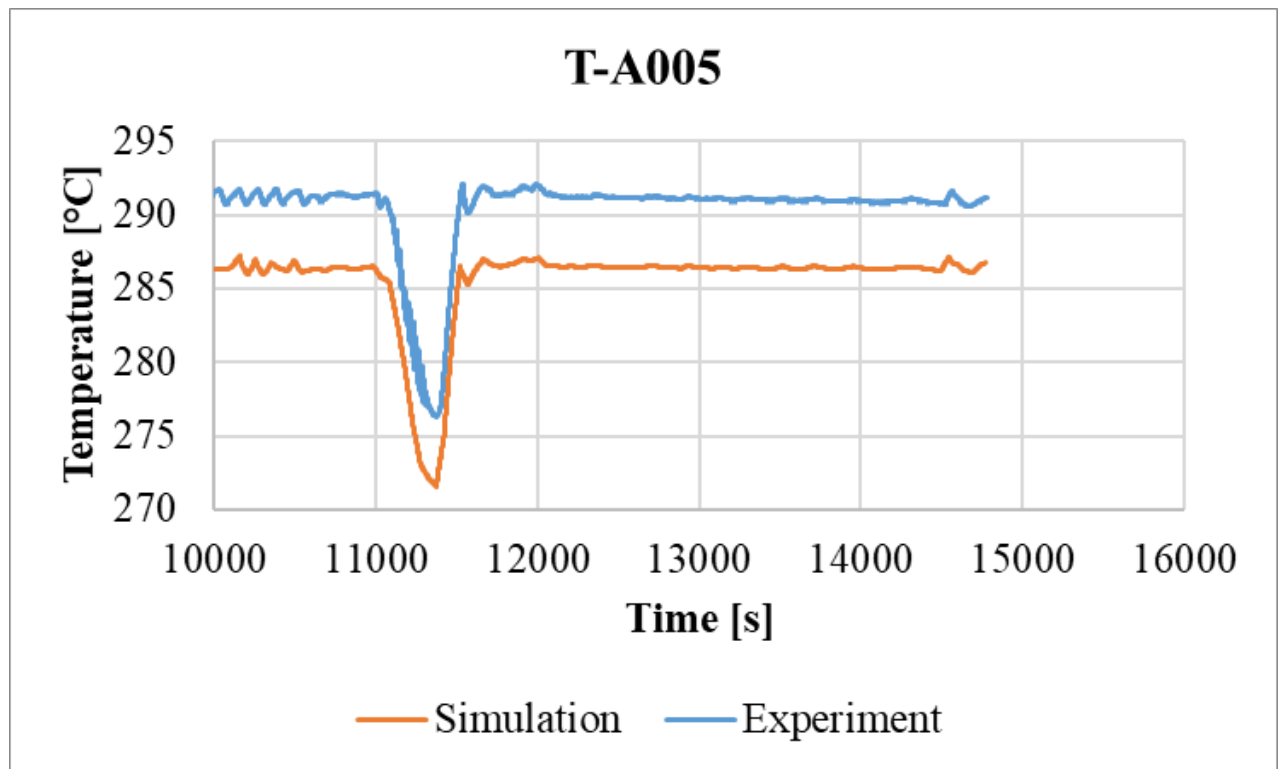
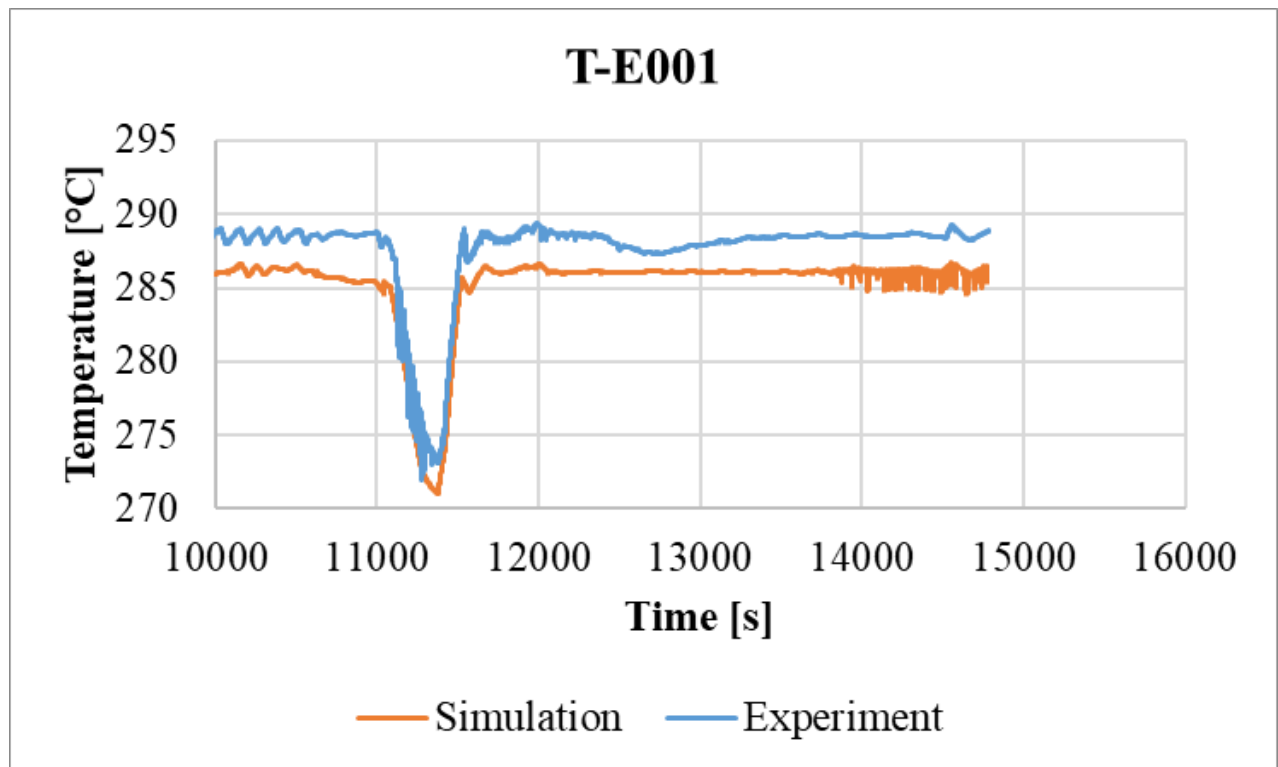


Figure 5.372. PERSEO Test 7 Part 1 simulation vs experiment HX outlet fluid temperature (T-E001)



Collapsed water levels in the OP and HXP are shown in Figure 5.373 and Figure 5.374. Both collapsed water levels agree well with experimental results. Between the second and third triggering valve operation periods, slow water consumption in the HXP was observed along with a decrease in water level. No decrease in HXP water level was observed in the MELCOR model during this period. The collapsed water level in the OP predicted by MELCOR agrees well with the experimental data.

Figure 5.373. PERSEO Test 7 Part 1 simulation vs experiment HXP collapsed water level (L_VQ)

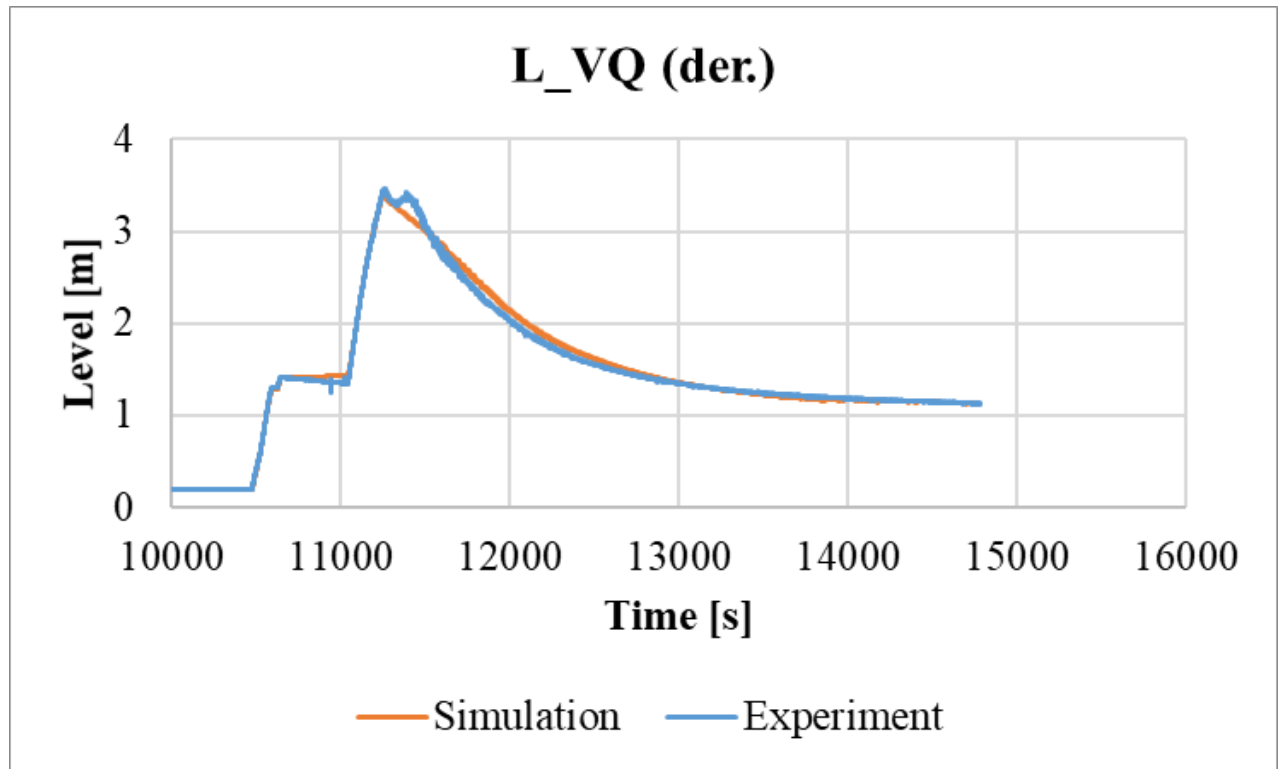


Figure 5.374. PERSEO Test 7 Part 1 simulation vs experiment OP
collapsed water level (L_VP)

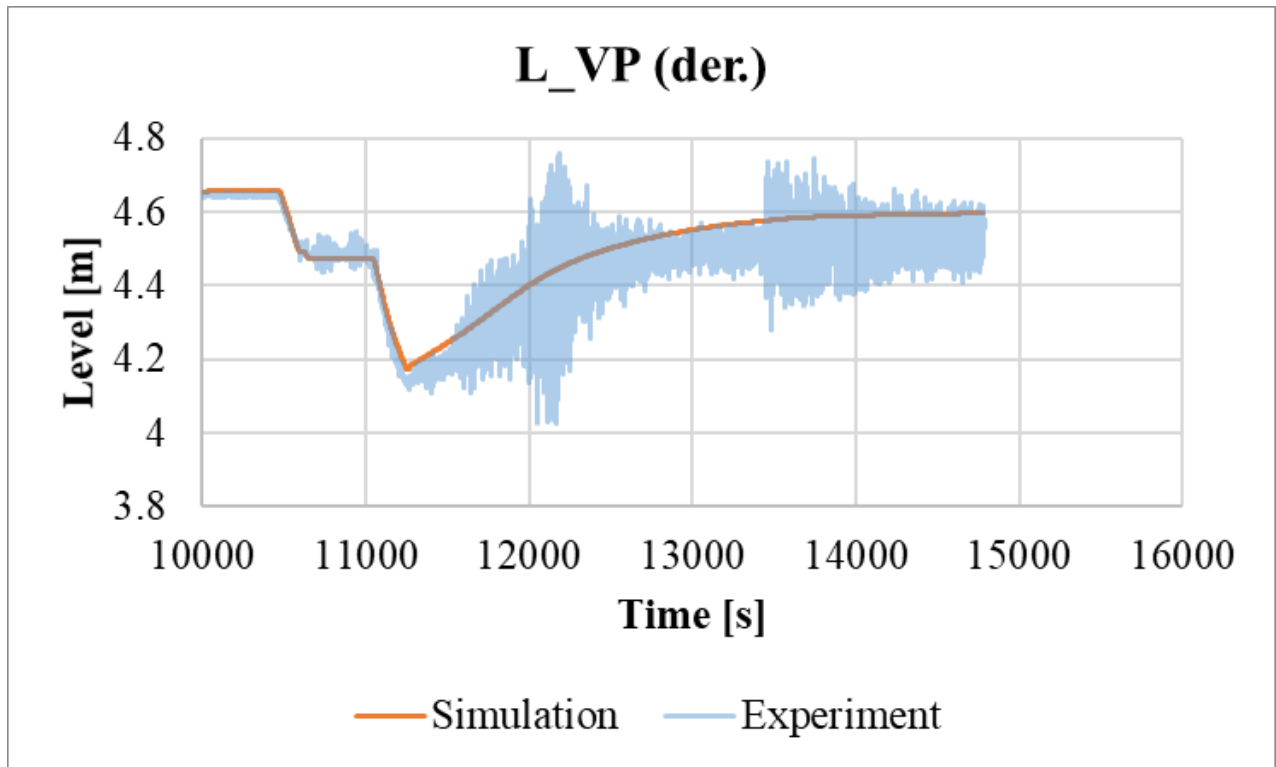


Figure 5.375, Figure 5.376 and Figure 5.377 show HXP temperatures. Experimental temperatures collected by thermocouples provide local axial atmosphere and/or pool conditions. Given the modelling methodology applied, each control volume spans regions that correspond to multiple thermocouples. Furthermore, given the lumped parameter modelling approach, a **single** temperature is reported for comparison in each volume (vapour or liquid temperature depending on the collapsed liquid level in the HXP).

Figure 5.375. PERSEO Test 7 Part 1 simulation vs experiment HXP
(bottom) fluid temperature (T-Q037)

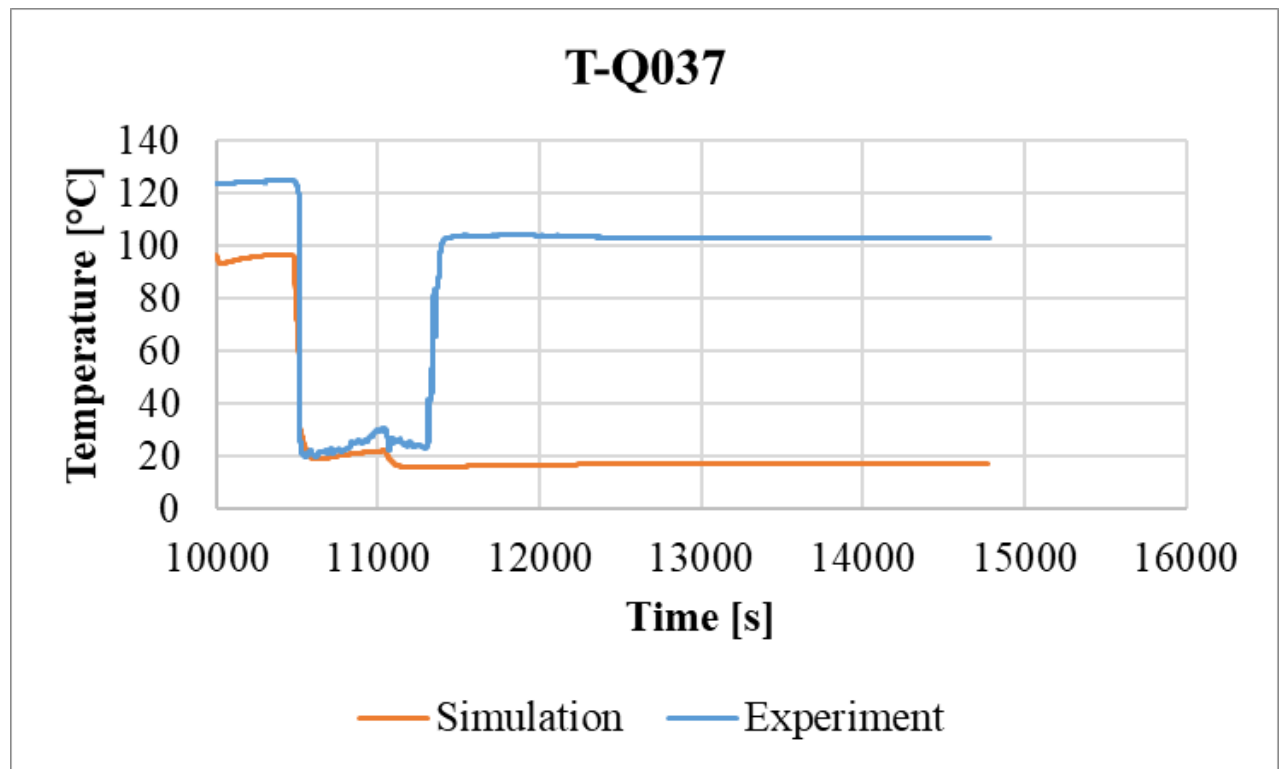
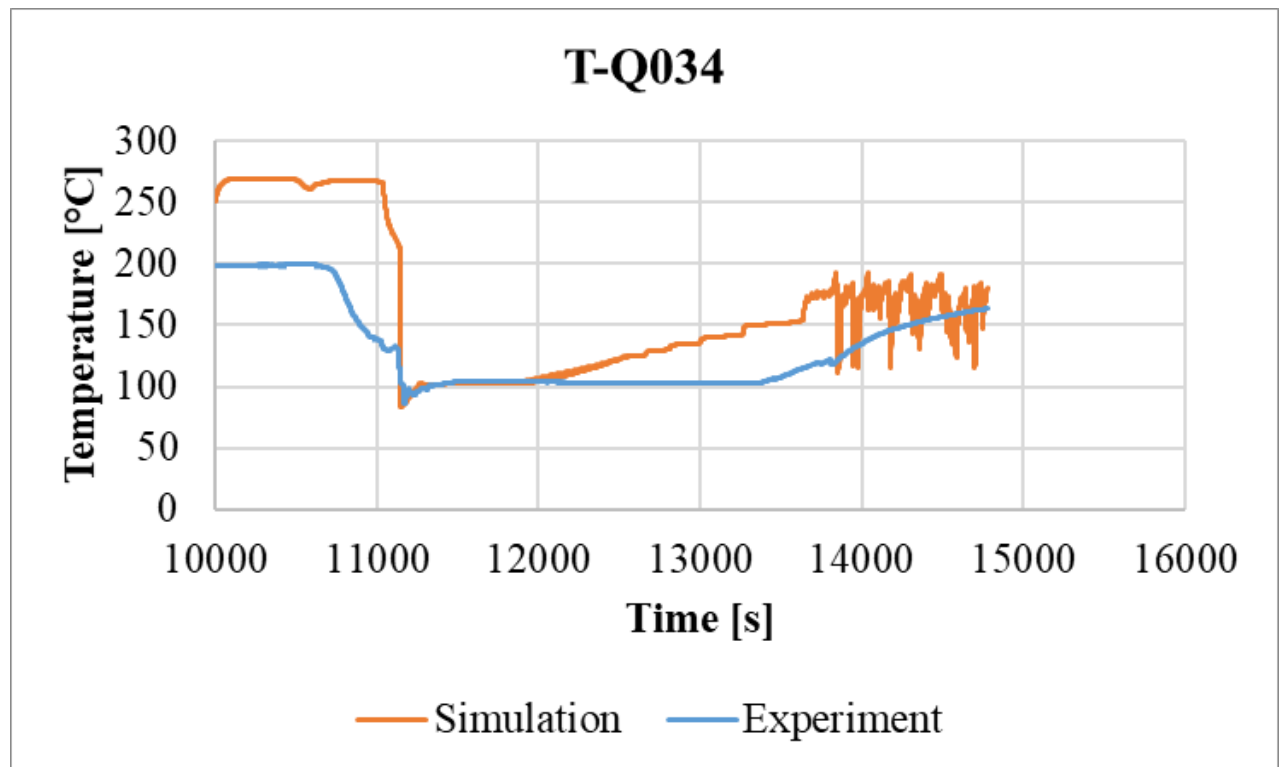
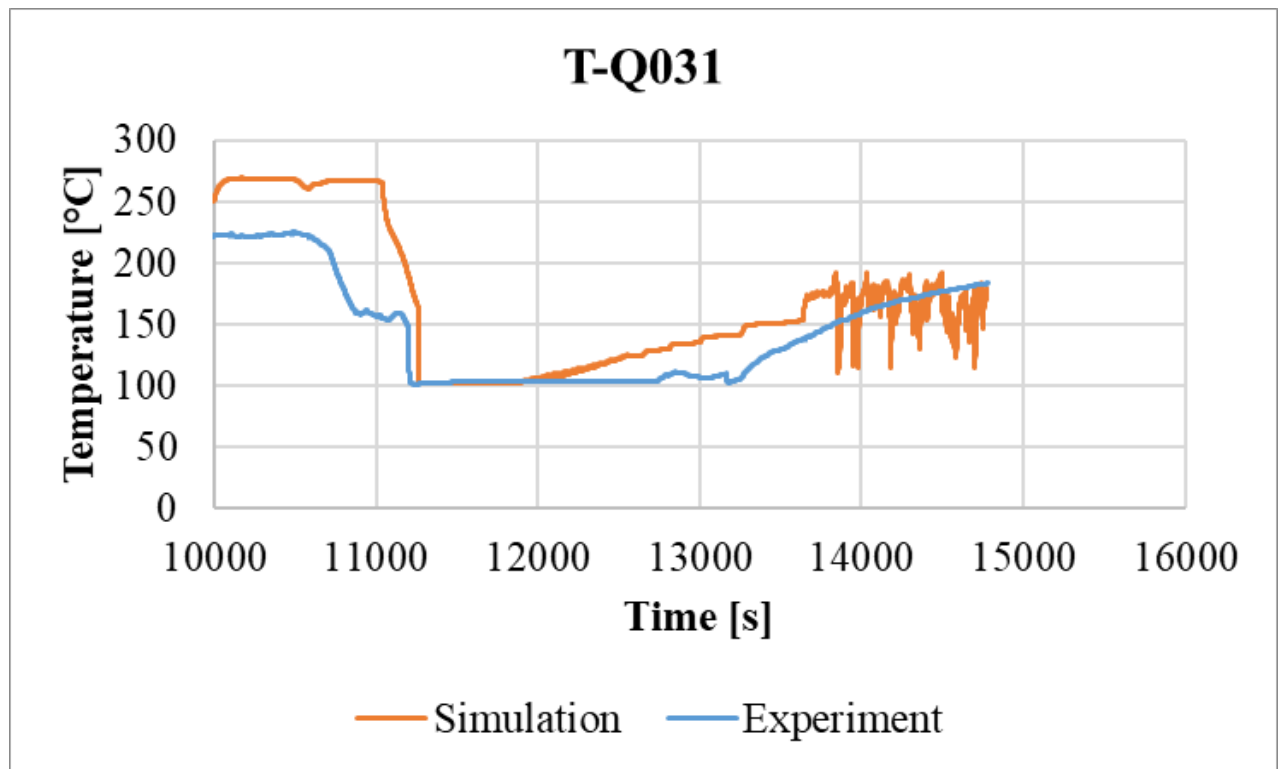


Figure 5.376. PERSEO Test 7 Part 1 simulation vs experiment HXP
(middle) fluid temperature (T-Q034)

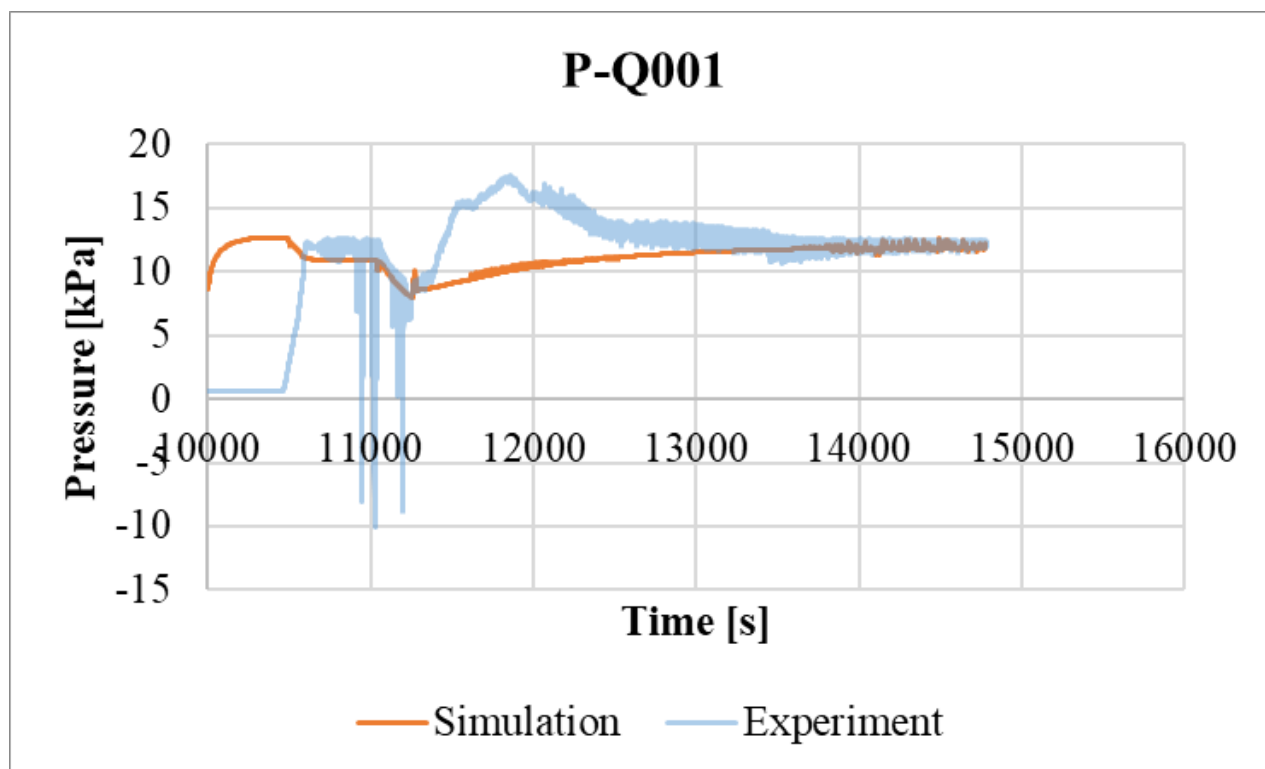


**Figure 5.377. PERSEO Test 7 Part 1 simulation vs experiment HXP
(top) fluid temperature (T-Q031)**



Relative pressure in the HXP is shown in Figure 5.378. The MELCOR model provides a reasonable estimation of these small pressure differences in the HX with good agreement.

**Figure 5.378. PERSEO Test 7 Part 1 simulation vs experiment HXP
(top) relative pressure (P-Q001)**



The OP temperature data are shown in Figure 5.379 and Figure 5.380. The bulk liquid temperature in the OP predicted by the MELCOR model agrees well with local experimental temperatures.

Figure 5.379. PERSEO Test 7 Part 1 simulation vs experiment OP
(bottom) fluid temperature (T-P008)

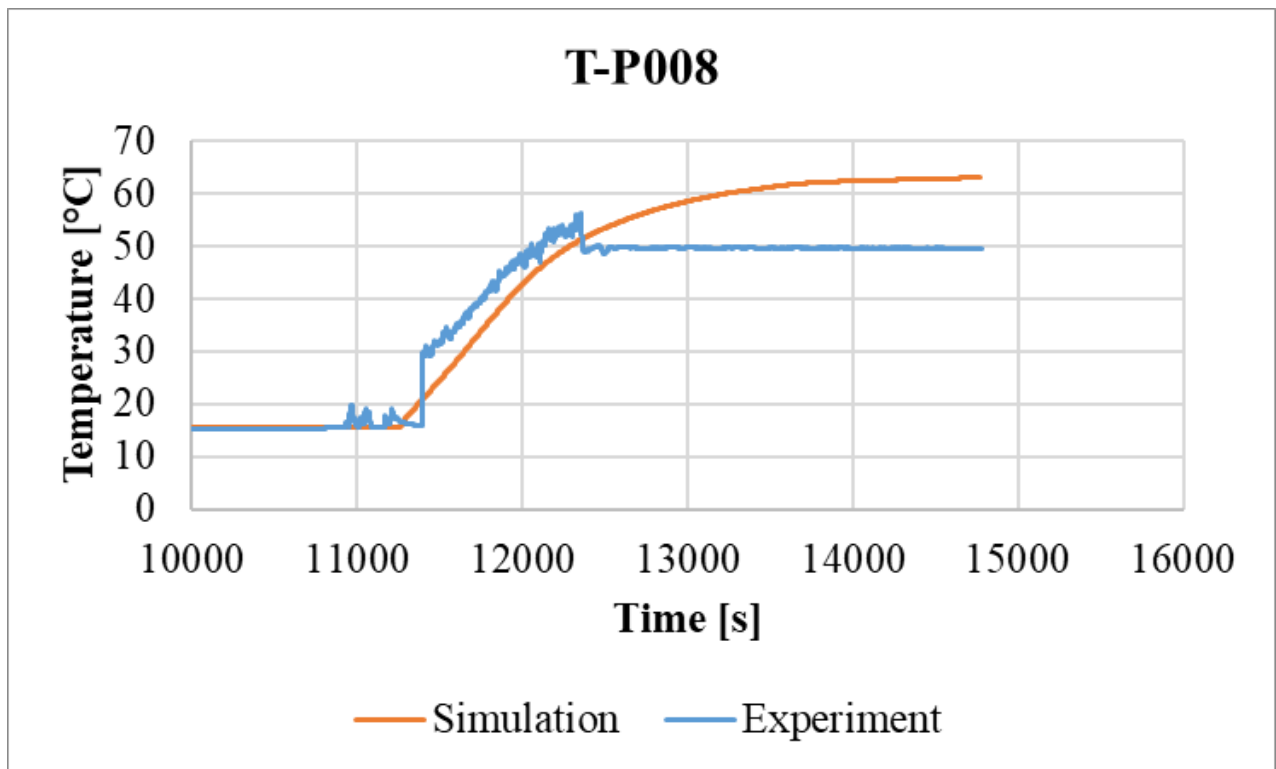
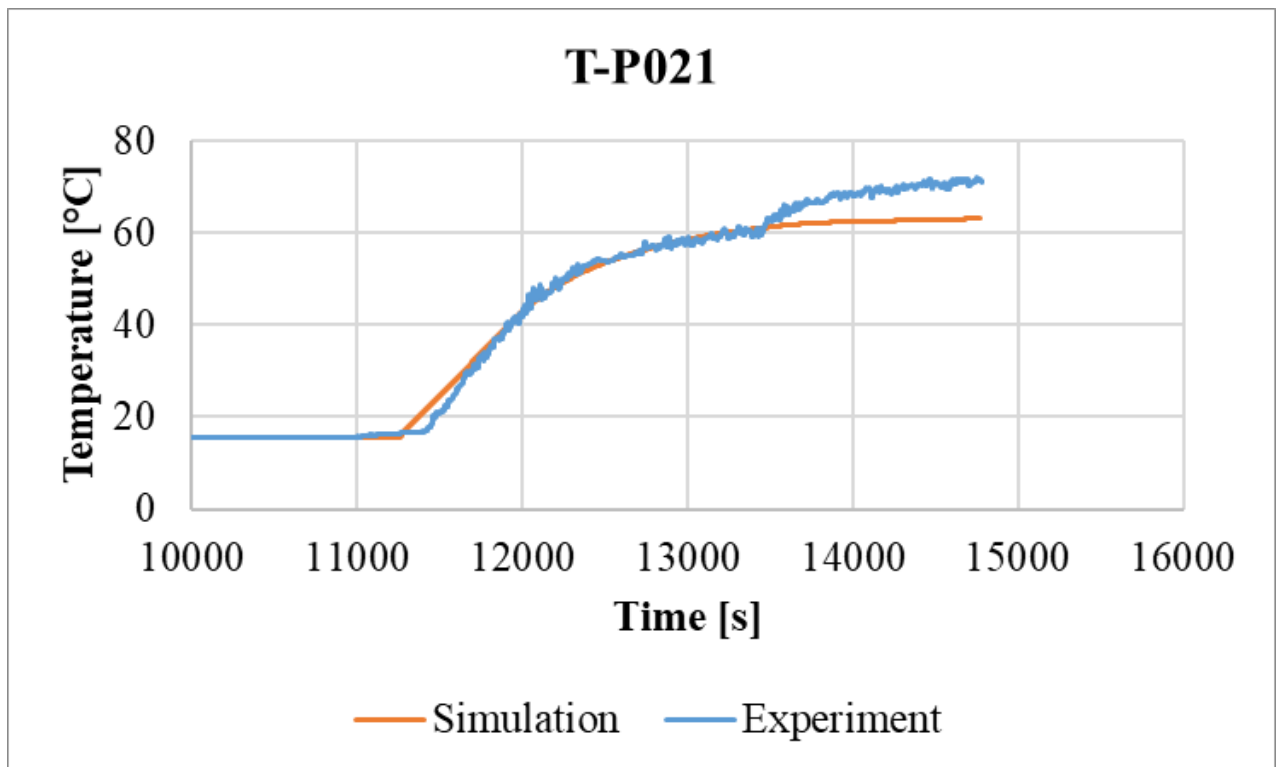


Figure 5.380. PERSEO Test 7 Part 1 simulation vs experiment OP
(top) fluid temperature (T-P021)



Differential pressure in the HX upper and lower headers is shown in Figure 5.381. MELCOR was able to reasonably predict the differential pressure in the HX upper and lower headers.

Figure 5.381. PERSEO Test 7 Part 1 simulation vs experiment differential pressure between the HX upper and lower headers (DP- 003)

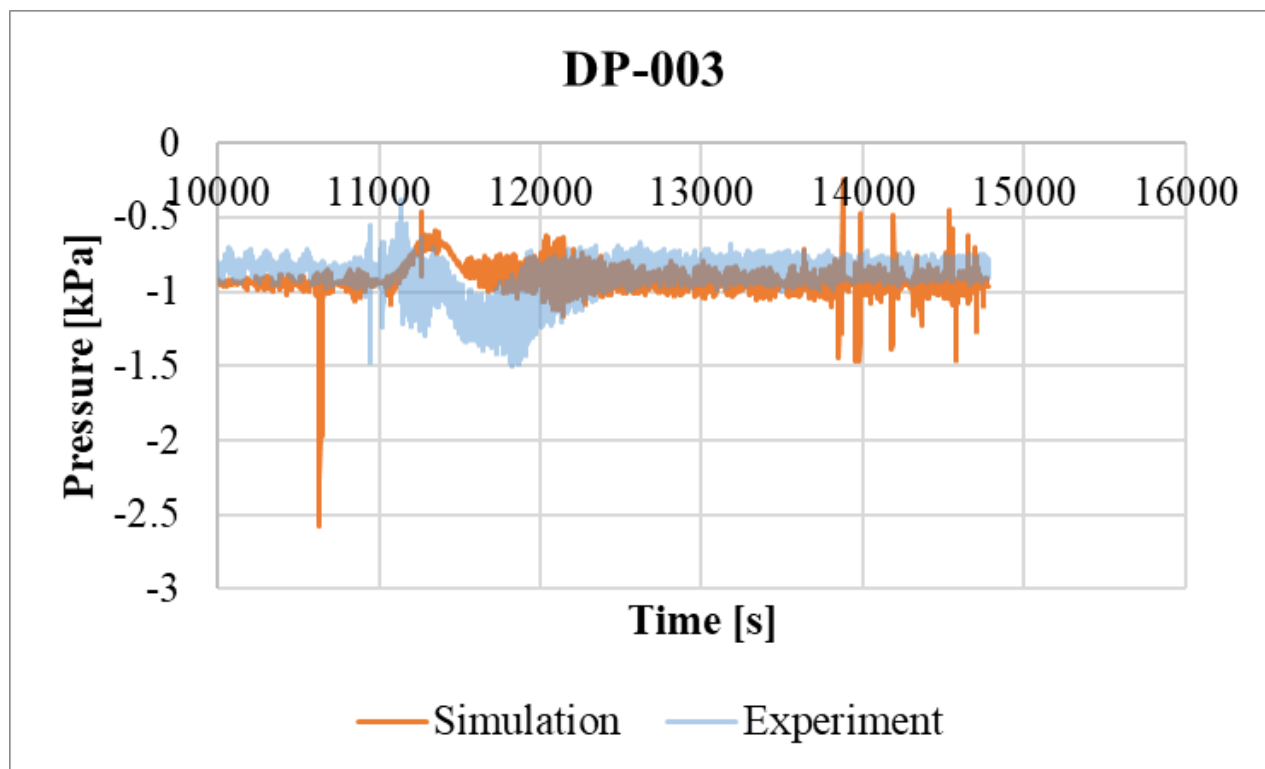


Figure 5.382 shows the differential pressure in the steam duct injector. MELCOR provides a reasonable estimation of the small pressure differences pressure in the steam duct injector.

Figure 5.382. PERSEO Test 7 Part 1 simulation vs experiment differential pressure in the steam duct injector (DP-J001)

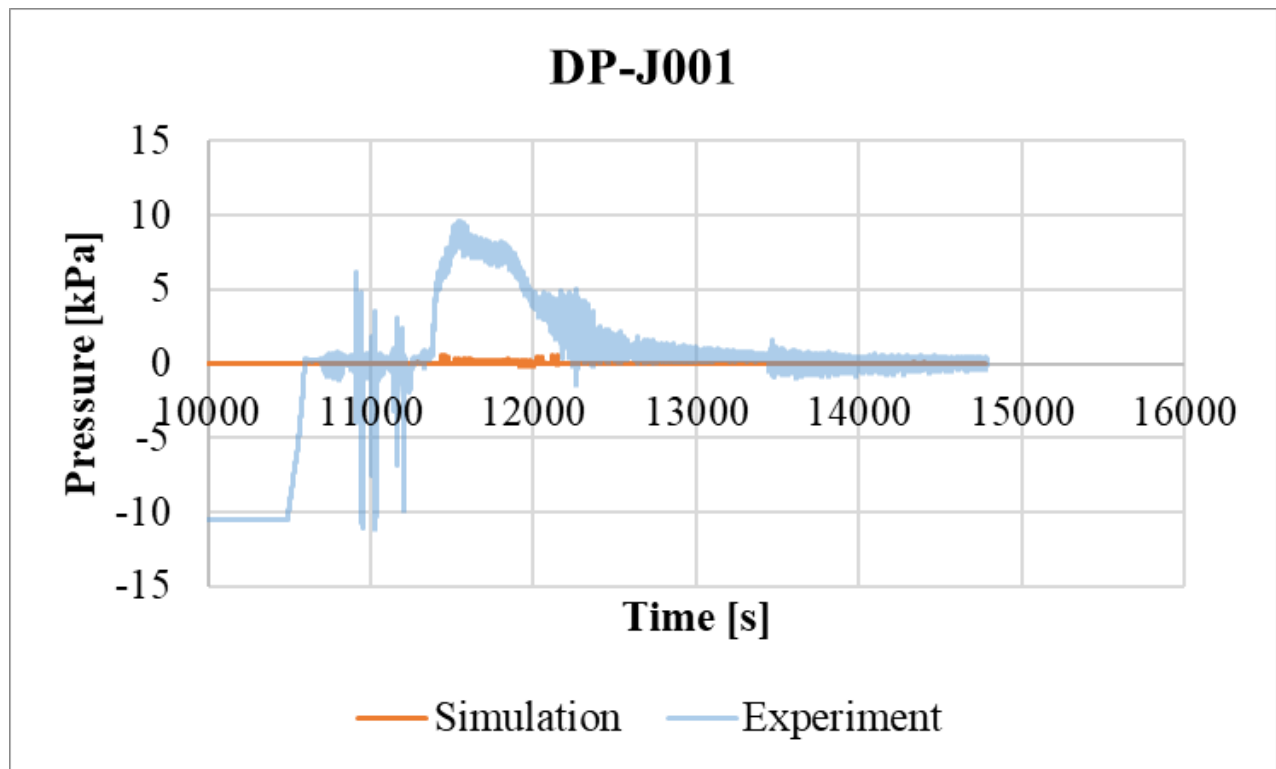


Figure 5.383 and Figure 5.384 show the wall temperatures of the HX upper and lower headers respectively. The wall temperatures predicted by the MELCOR model agree well with the local experimental temperatures. The MELCOR model predicts delayed HX upper header wall temperature decrease during the rise in HXP water level, as well as premature increase in temperature during HXP boil-off.

Figure 5.383. PERSEO Test 7 Part 1 simulation vs experiment upper header wall temperatures (TW-B005)

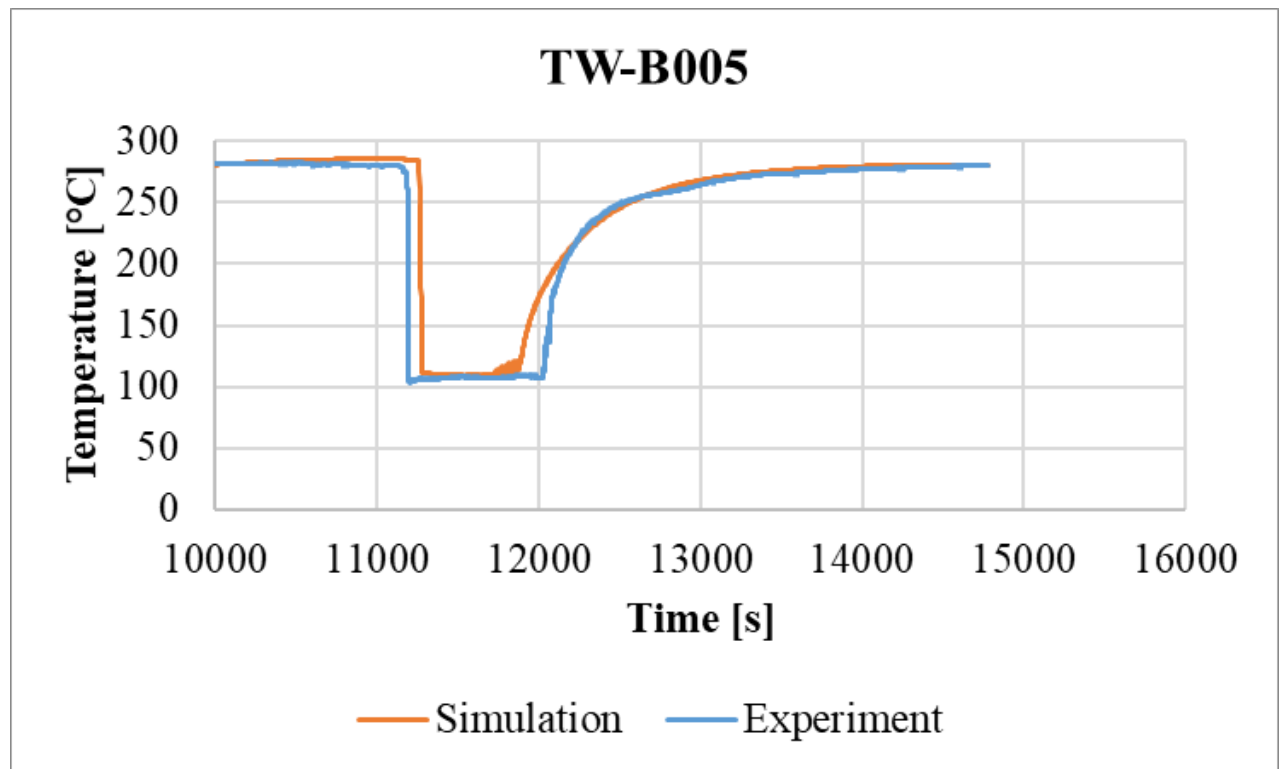
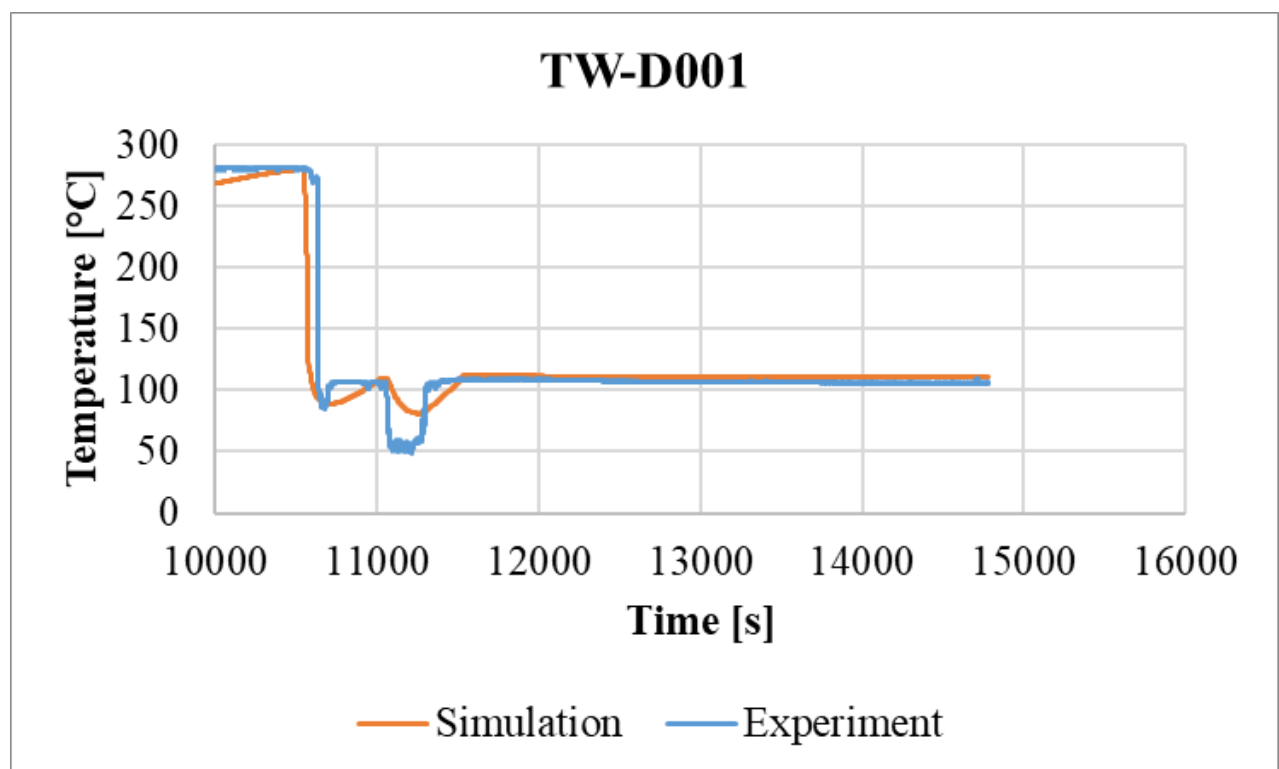


Figure 5.384. PERSEO Test 7 Part 1 simulation vs experiment lower header wall temperatures (TW-D001)



The marks adopted in Table 5.64 for the qualitative accuracy evaluation are reported in Table 4.2.

**Table 5.65. PERSEO Test 7 Part 1 Versus Phenomena, Code
Prediction Versus Phenomena**

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power HX	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power HX	W IC (der.)	+
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	+
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power HX	W IC (der.)	
				Relative pressure HXP top	P-Q001	
D	Behaviour of emergency HXs and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure HX upper-lower header	DP-003	+
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
E	Behaviour of emergency HXs and isolation condensers: Pool side convection heat transfer	+	+	Power HX	W IC (der.)	+
				Level HXP	L VQ (der.)	
				Power HX	W IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (top)	T-Q031	+
				Power HX	W IC (der.)	
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature OP (top)	T-P021	+
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Power HX	W IC (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Relative pressure HXP top	P-Q001	+
				Level OP	L VP (der.)	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

** Ph. = Phenomenon

Test 7 Part 2

Initial and boundary conditions for the MELCOR model of Test 7 Part 2 are shown in Table 5.65 and Table 5.66, respectively.

Table 5.66. MELCOR model initial conditions for Test 7 Part 2

Parameter	Initial Condition
Primary	
Control volume pressure	As captured at the end of Test 7 Part 1 through a restart file
Control volume state	As captured at the end of Test 7 Part 1 through a restart file
Flow between control volumes	As captured at the end of Test 7 Part 1 through a restart file
Secondary	
Control volume temperature and pressure	As captured at the end of Test 7 Part 1 through a restart file
Control volume state	As captured at the end of Test 7 Part 1 through a restart file
Control volume pool levels	As captured at the end of Test 7 Part 1 through a restart file
Flow between control volumes	As captured at the end of Test 7 Part 1 through a restart file
HX wall temperatures	As captured at the end of Test 7 Part 1 through a restart file
HXP wall temperatures	As captured at the end of Test 7 Part 1 through a restart file
Nozzle wall temperatures	As captured at the end of Test 7 Part 1 through a restart file

Table 5.67. MELCOR model boundary conditions for Test 7 Part 2

Parameter	Boundary Condition
Primary	
Steam supply	A time-specified control volume was used to represent primary side steam supply. Control volume pressure was defined by a control function to match measured primary pressures (P-I001). The control volume was filled with saturated steam.
Condensate line sink	The condensate line sink was defined by a separate control volume with a time-specified pressure defined to account for the change in water level in the RPV.
Secondary	
Environment	Time-independent control volume (10 000 m ³) filled with dry air; P = 100 kPa, T = 298.0 K
OP drain line	Partially open from 5 972 s – end of scenario
Vacuum breaker	One-way valve that opens when pressure in steam duct drops below atmospheric pressure in the environment
Triggering valve operation	Fully open from 300 s – 3 461 s

Code results are able to reproduce the experimental results with good agreement. Table 5.67 summarises the main relevant thermal-hydraulic aspects of Test 7 Part 2.

Table 5.68. Main relevant thermal-hydraulic aspects related to Test 7 Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	Begins at 300 s, fully open at 326 s	-
Maximum level in the HXP	442 s	3.5 m
Maximum exchanged power	444 s – 2 500 s	17 – 19 MW
OP discharge valve F031 opening	1 150 s	-
Triggering valve F045 closure	3 461 s	-
HXP level decreasing and loss of mass from the boil-off	442 s – 5 736 s	-
Primary side depressurisation beginning for end of test	4 685 s	-

Flow through the primary circuit, shown in Figure 5.385 and Figure 5.386, show good agreement between the MELCOR model and experiment.

**Figure 5.385. PERSEO Test 7 Part 2 simulation vs experiment
steam supply line flowrate (F_A001)**

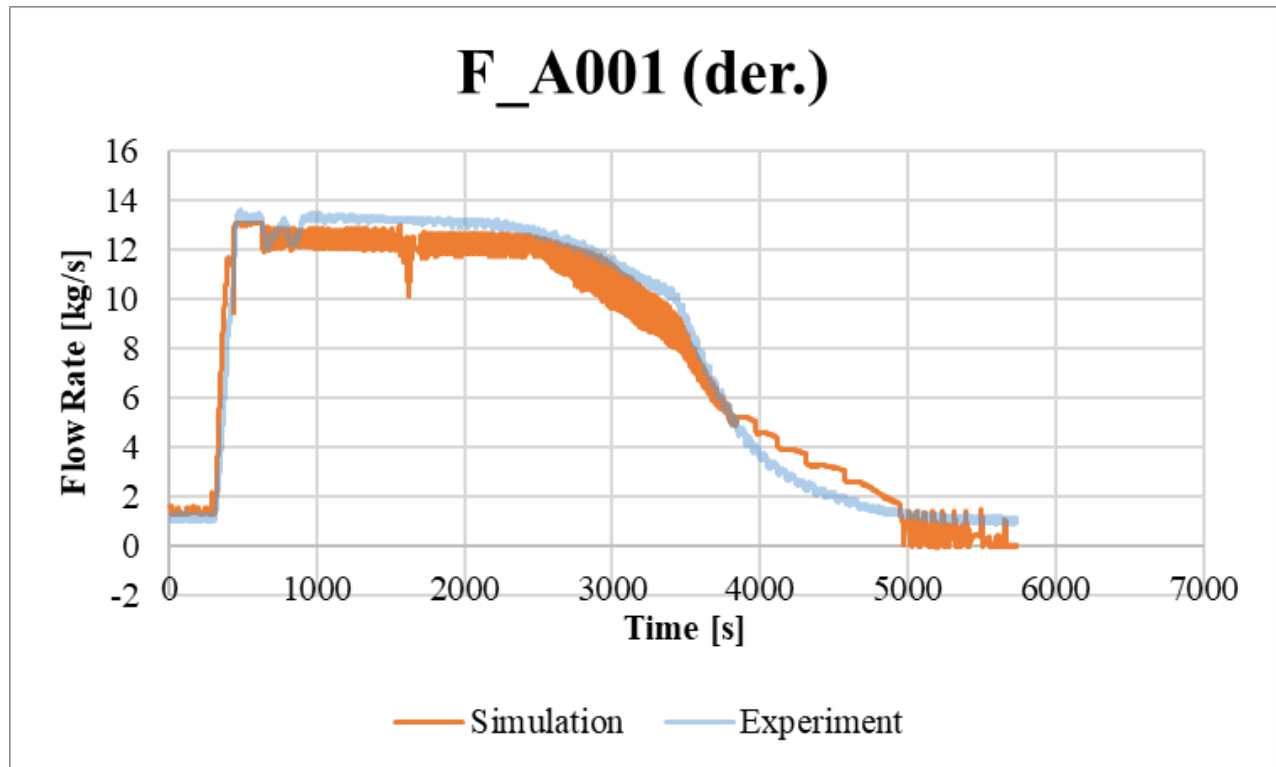


Figure 5.386. PERSEO Test 7 Part 2 simulation vs experiment
condensate drain line flowrate (F_E001)

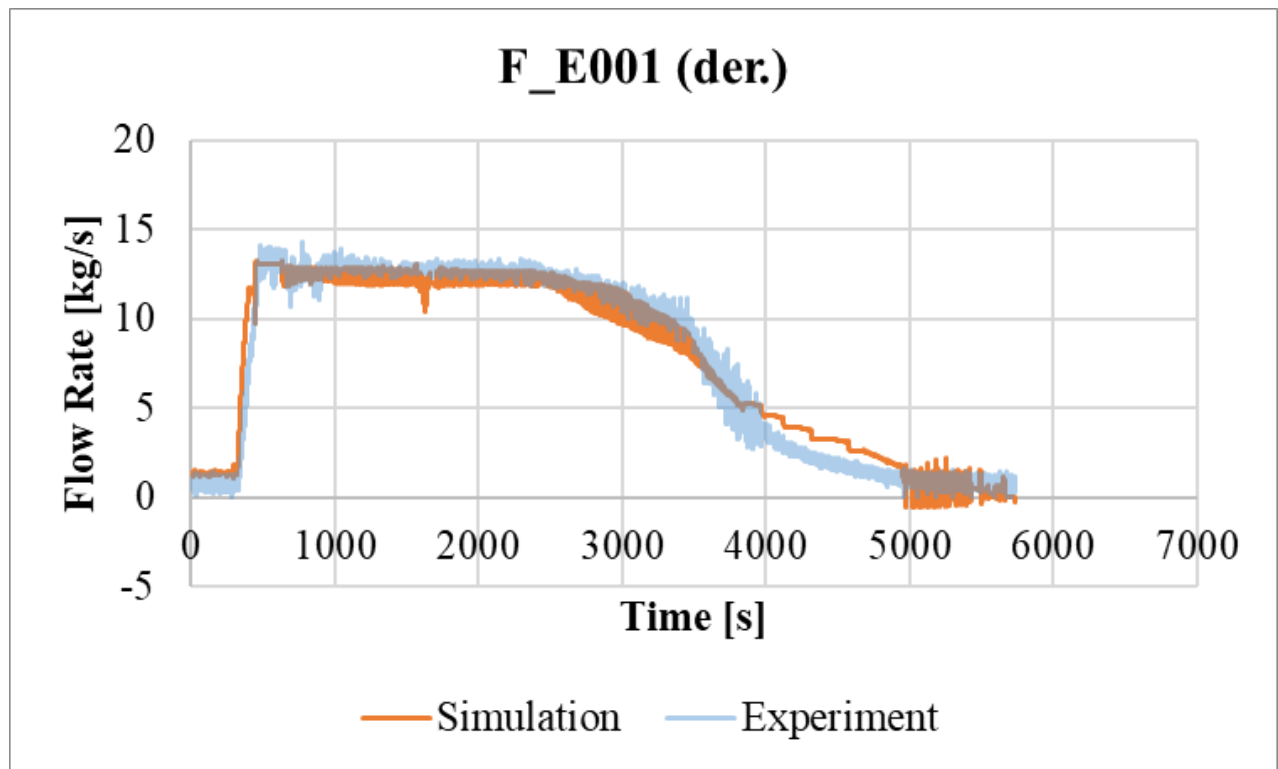
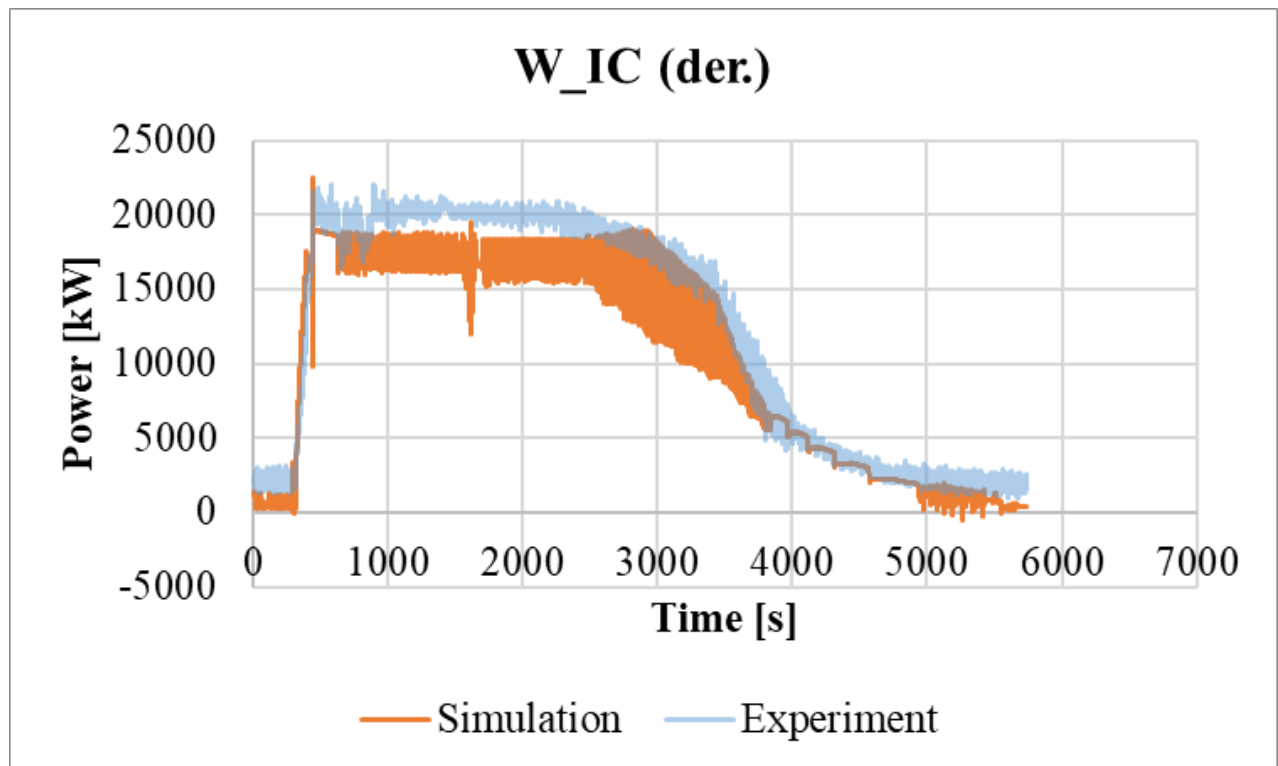


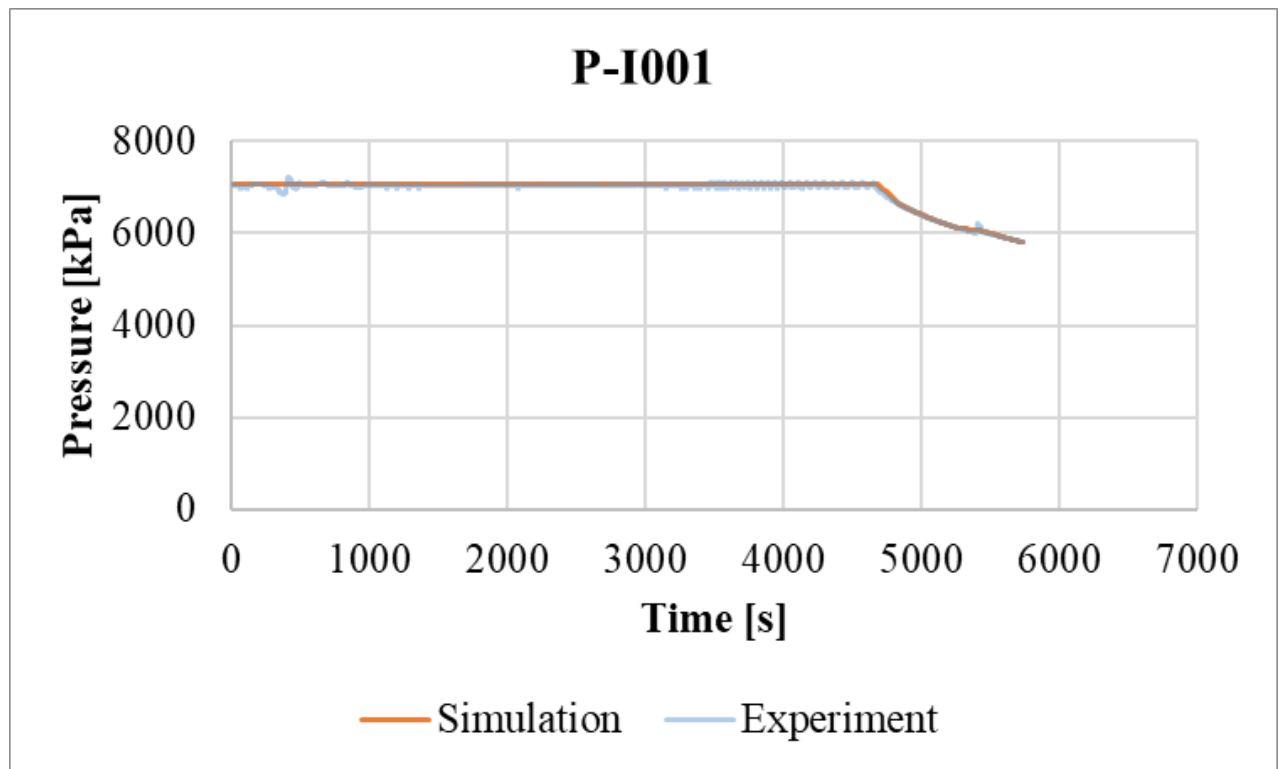
Figure 5.387 shows the power extracted by the HX during Test 7 Part 2. The power extracted shows good agreement with the experiment.

**Figure 5.387. PERSEO Test 7 Part 2 simulation vs experiment
power extracted (W_IC)**



Primary pressure is shown in Figure 5.388. As stated above, experimental measurements of primary pressure are defined as a control function used as a boundary condition in the MELCOR model.

Figure 5.388. PERSEO Test 7 Part 2 simulation vs experiment
primary pressure (P-I001)



HX inlet and outlet temperatures are shown in Figure 5.389 and Figure 5.390, respectively. MELCOR provides a reasonable estimation of these temperatures.

Figure 5.389. PERSEO Test 7 Part 2 simulation vs experiment HX inlet fluid temperature (T-A001)

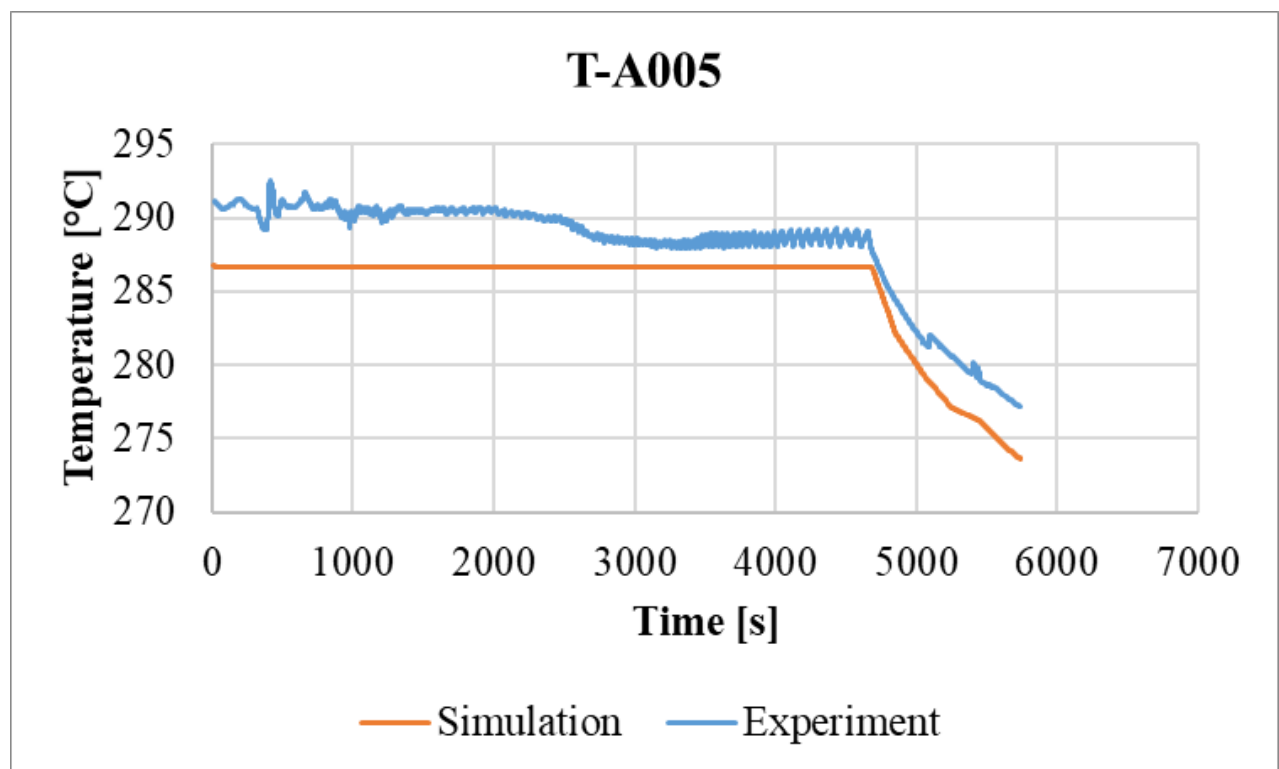
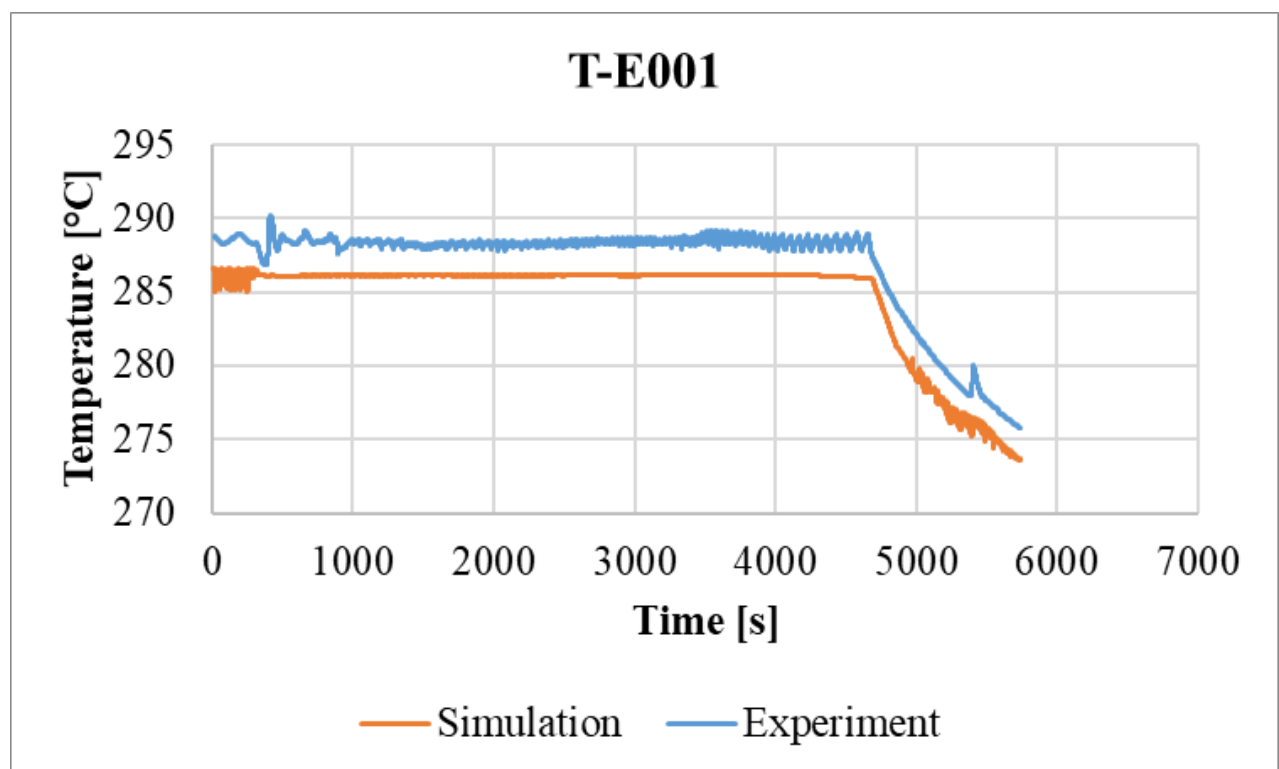


Figure 5.390. PERSEO Test 7 Part 2 simulation vs experiment HX outlet fluid temperature (T-E001)



Collapsed water levels in the HXP and OP are shown in Figure 5.391 and Figure 5.392. The MELCOR model predicts the water levels in the HXP and OP.

Figure 5.391. PERSEO Test 7 Part 2 simulation vs experiment HXP collapsed water level (L_VQ)

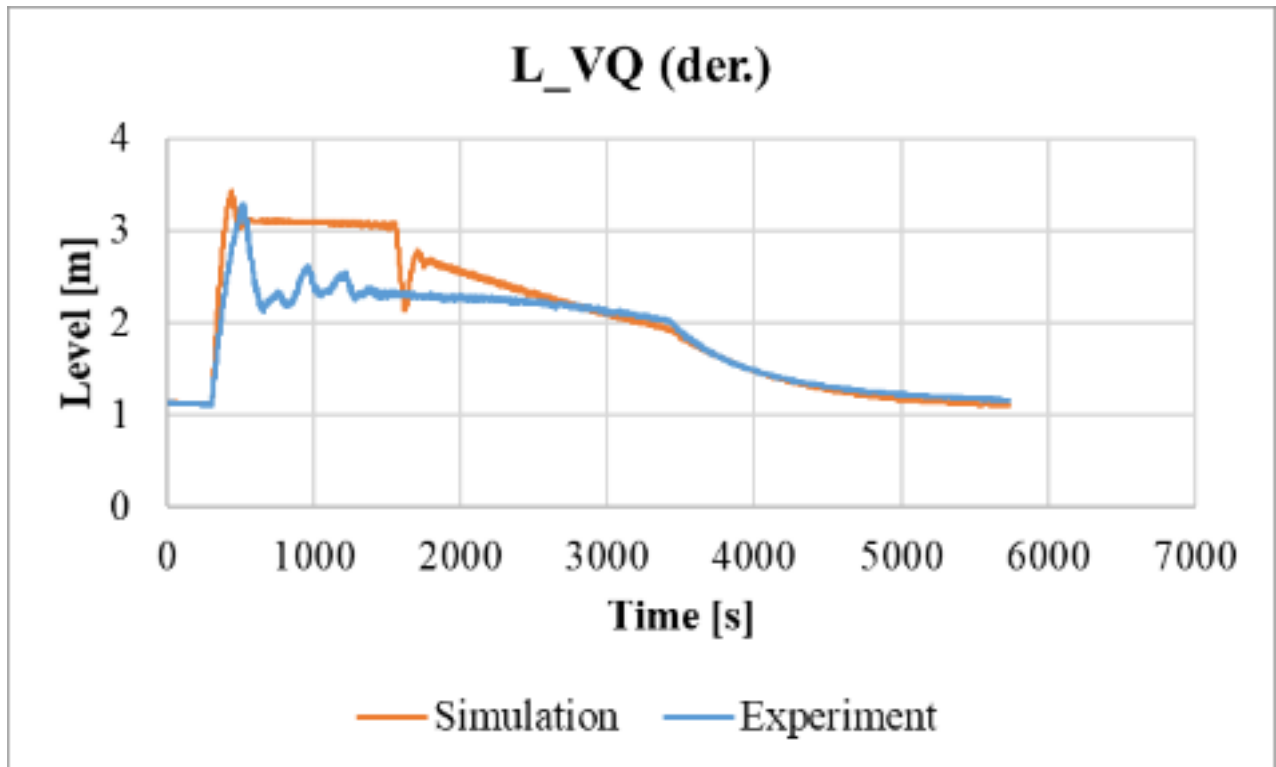


Figure 5.392. PERSEO Test 7 Part 2 simulation vs experiment OP collapsed water level (L_VP)

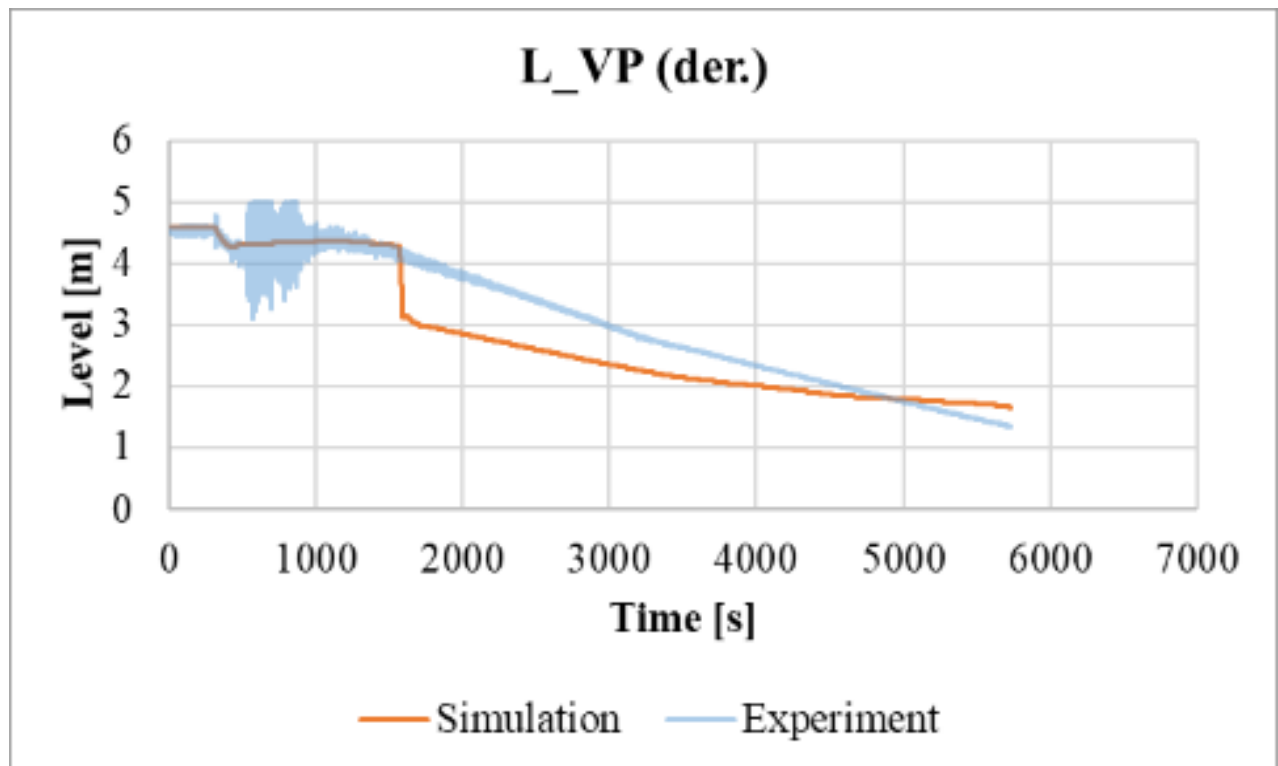


Figure 5.393, Figure 5.394 and Figure 5.395 show HXP temperatures. The MELCOR model reproduces the HXP temperatures with good agreement. As with the results reported for Test 7 Part 1, the reported temperatures correspond to the calculated bulk vapour or liquid temperatures in a control volume depending on the collapsed liquid level in the HXP.

Figure 5.393. PERSEO Test 7 Part 2 simulation vs experiment HXP
(bottom) fluid temperature (T-Q037)

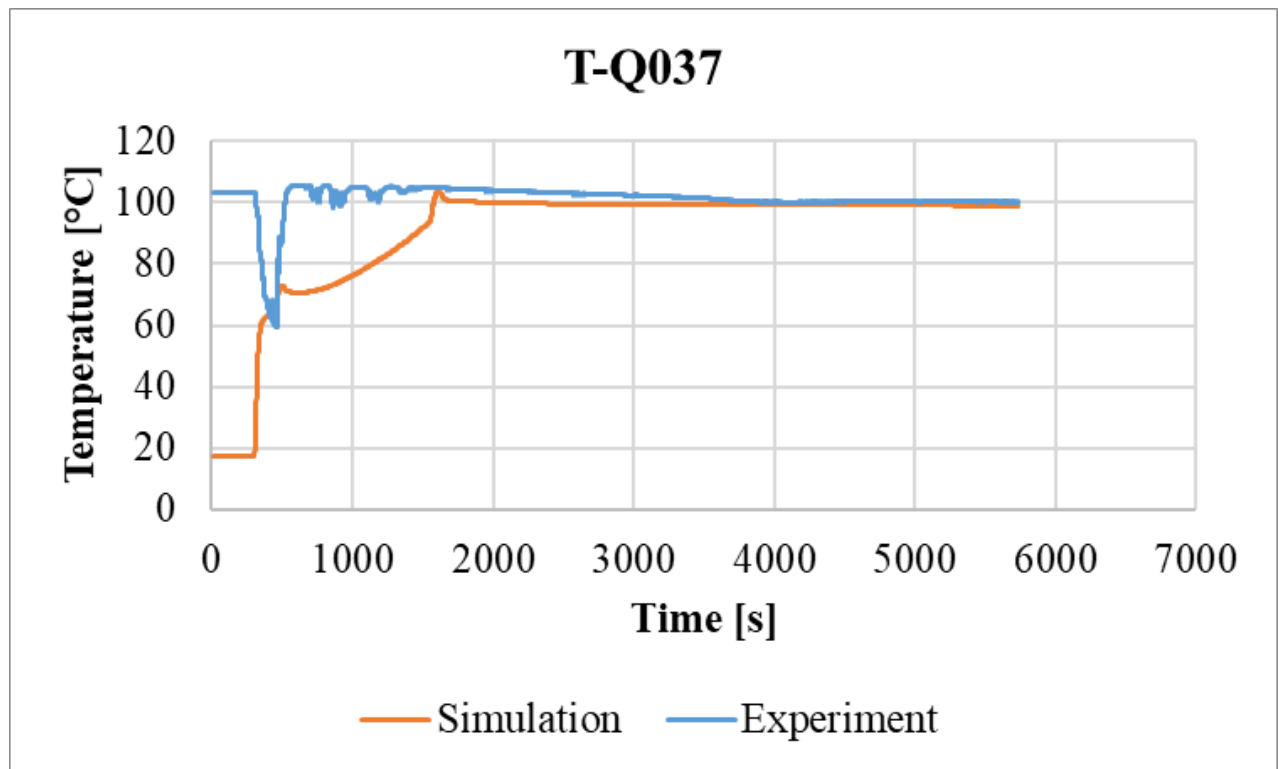


Figure 5.394. PERSEO Test 7 Part 2 simulation vs experiment HXP
(middle) fluid temperature (T-Q034)

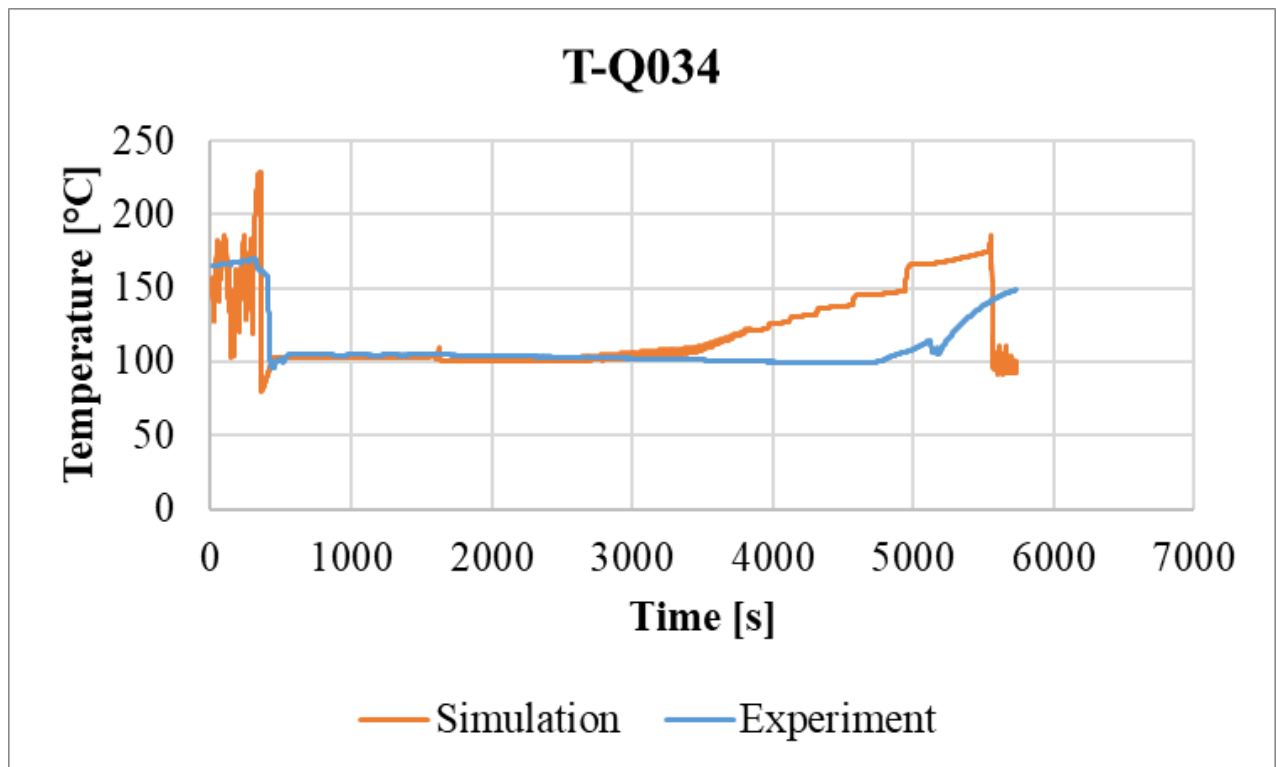
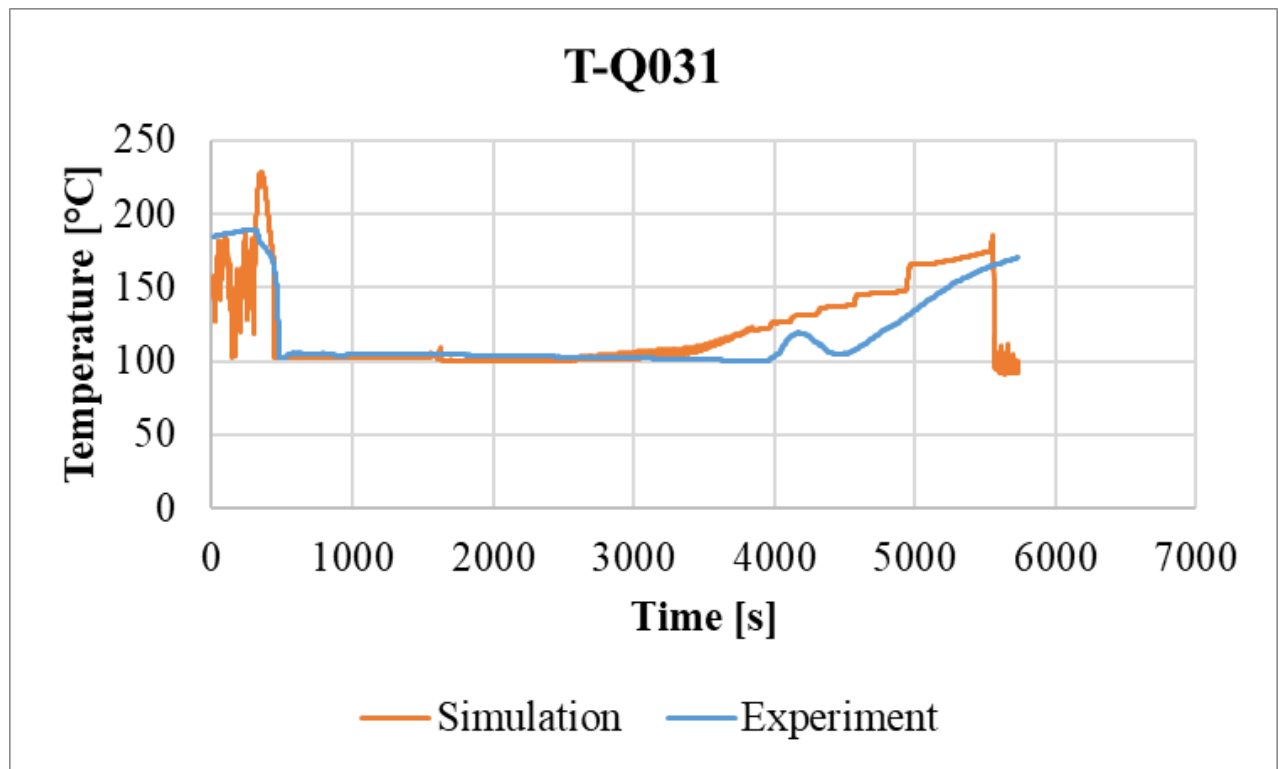
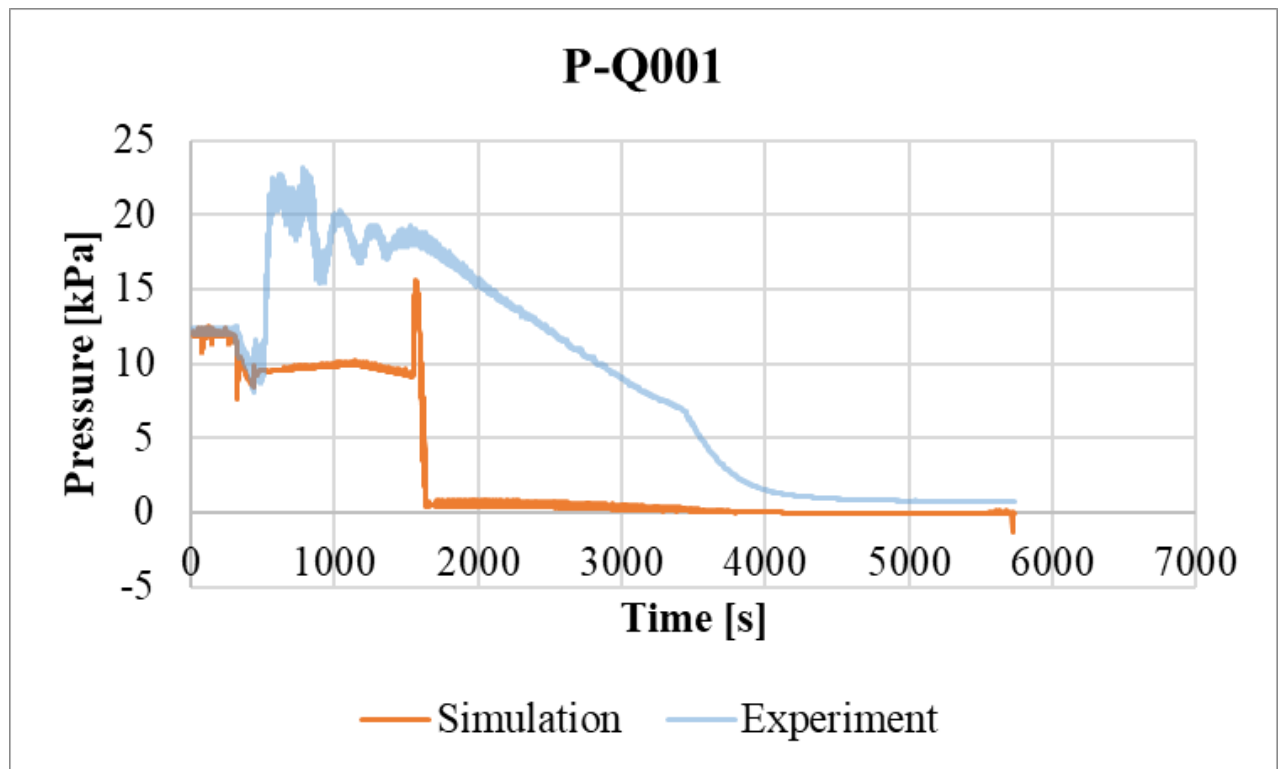


Figure 5.395. PERSEO Test 7 Part 2 simulation vs experiment HXP (top) fluid temperature (T-Q031)



Relative pressure in the HXP is shown in Figure 5.396. The MELCOR model provides a reasonable estimation of the very small pressure differences in the HX.

**Figure 5.396. PERSEO Test 7 Part 2 simulation vs experiment HXP
(top) relative pressure (P-Q001)**



OP temperatures are shown in Figure 5.397 and Figure 5.398. The OP temperatures predicted by the MELCOR model agree well with the experimental data.

Figure 5.397. PERSEO Test 7 Part 2 simulation vs experiment OP
(bottom) fluid temperature (T-P008)

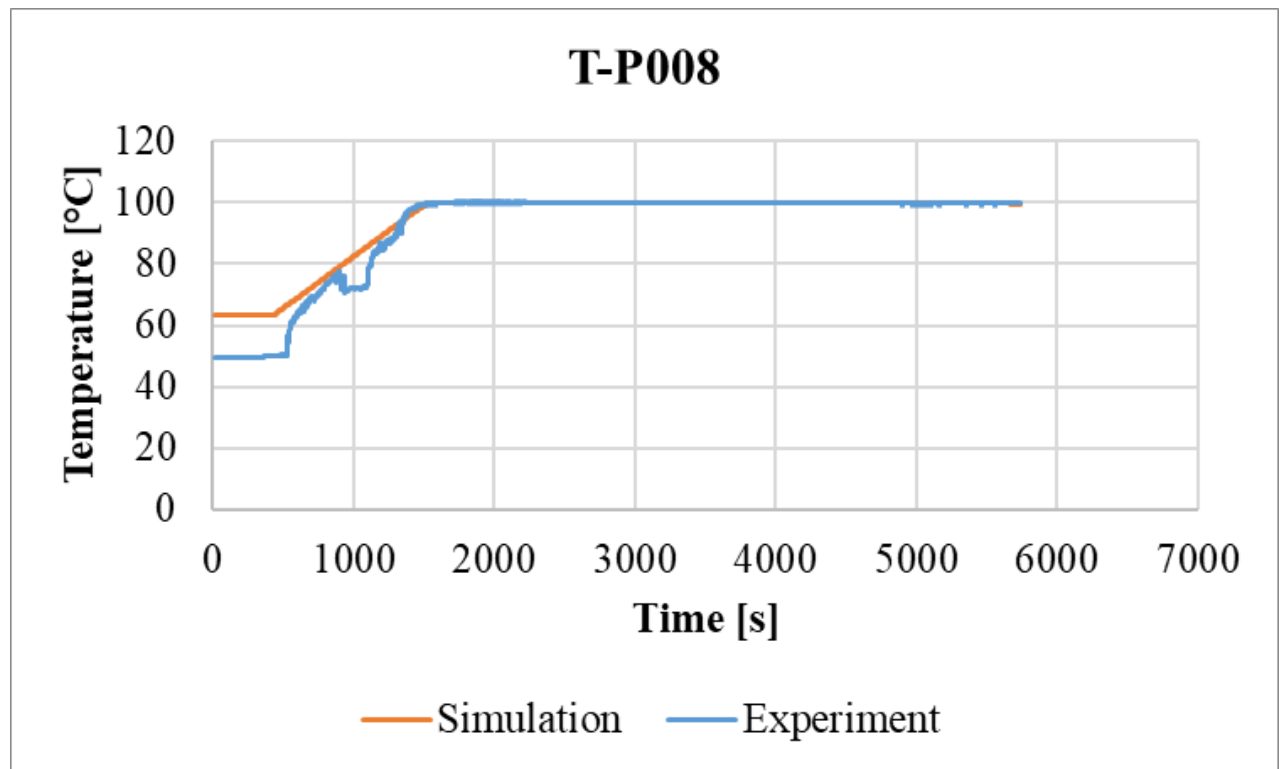
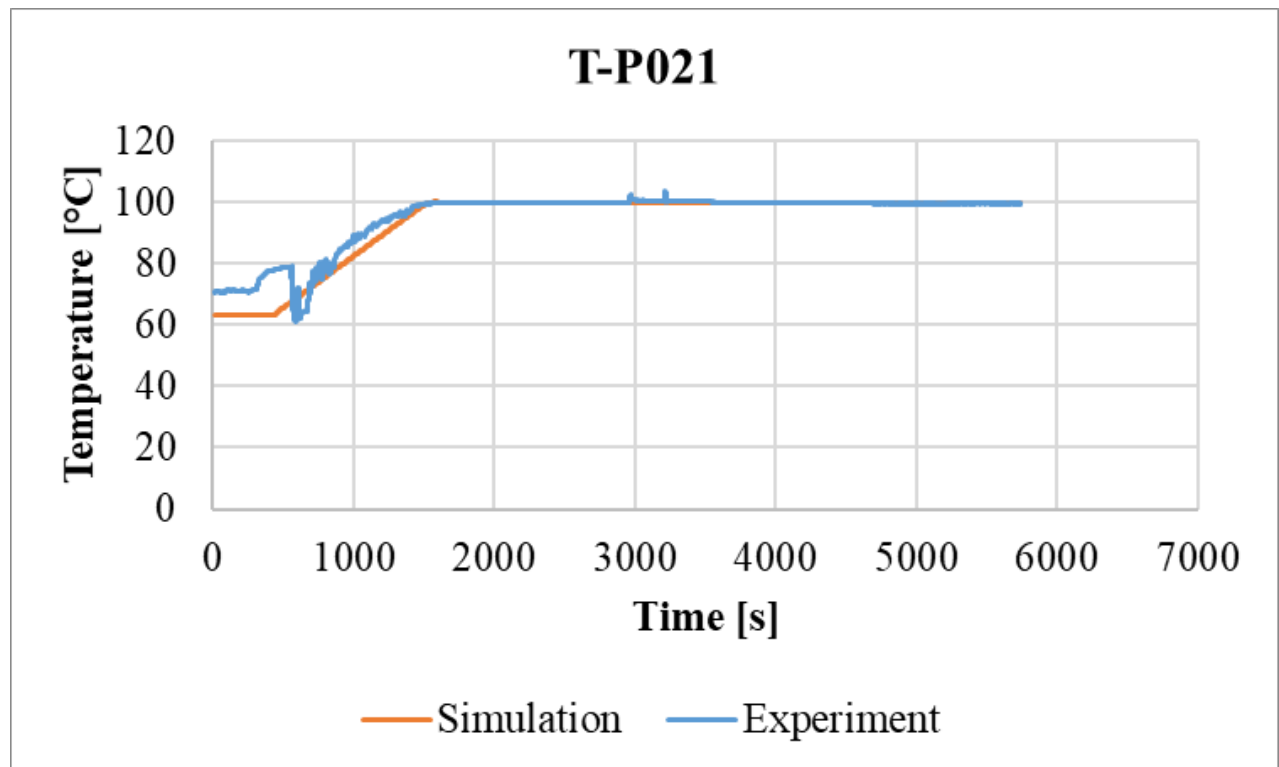


Figure 5.398. PERSEO Test 7 Part 2 simulation vs experiment OP
(top) fluid temperature (T-P021)



Differential pressure in the HX upper and lower headers is shown in Figure 5.399. The MELCOR model provides a reasonable estimation of the very small pressure differences in the HX upper and lower headers.

Figure 5.399. PERSEO Test 7 Part 2 simulation vs experiment differential pressure between the HX upper and lower headers (DP-003)

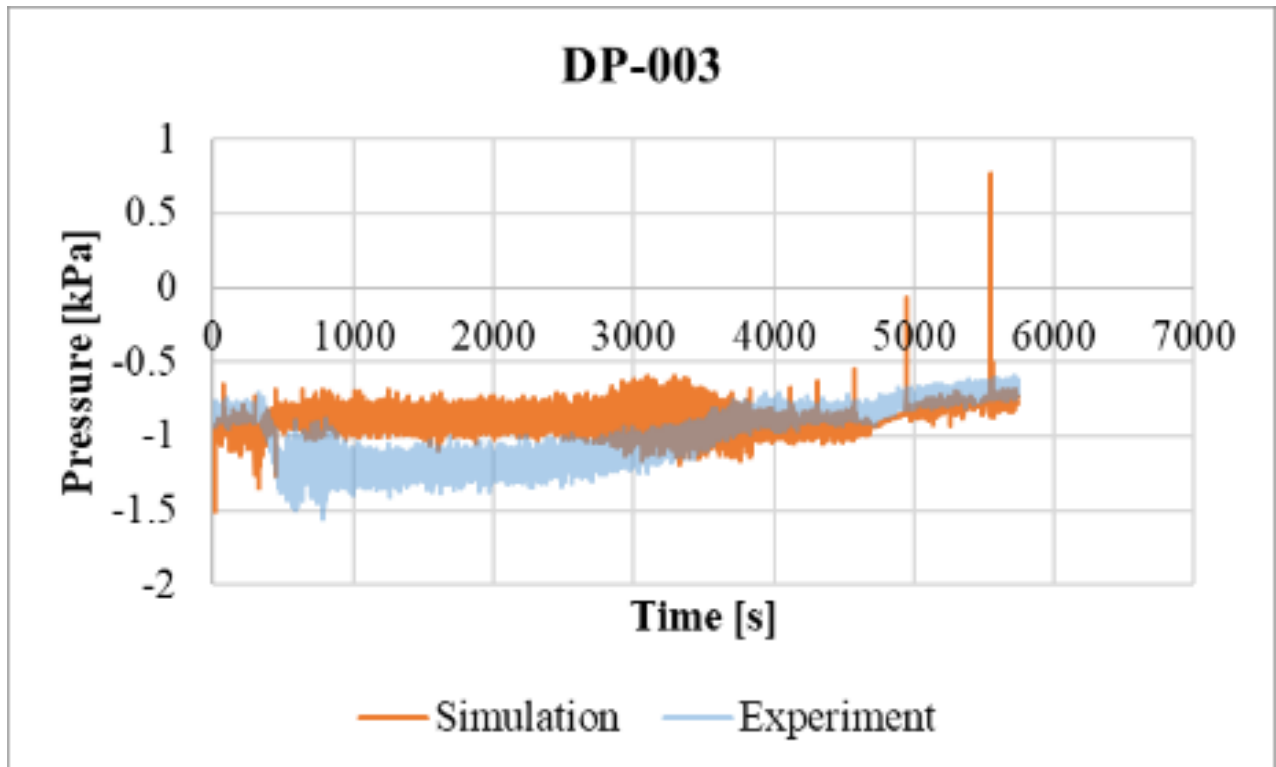


Figure 5.400 shows the differential pressure in the steam duct injector.

Figure 5.400. PERSEO Test 7 Part 2 simulation vs experiment differential pressure in the steam duct injector (DP-J001)

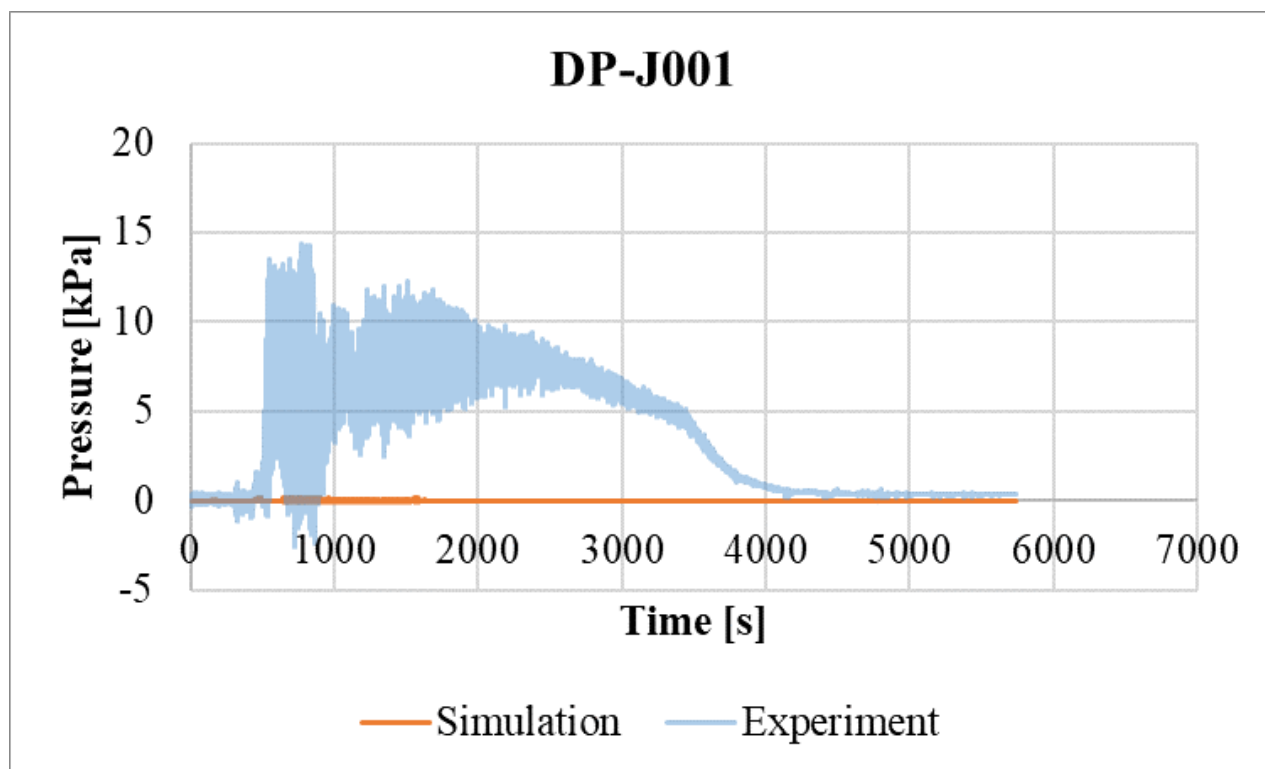


Figure 5.401 and Figure 5.402 show the wall temperatures of the HX upper and lower headers respectively. The wall temperatures predicted by the MELCOR model agree well with the local experimental temperatures. The MELCOR model predicts early HX upper header heat-up compared to experimental data.

Figure 5.401. PERSEO Test 7 Part 2 simulation vs experiment
upper header wall temperatures (TW-B005)

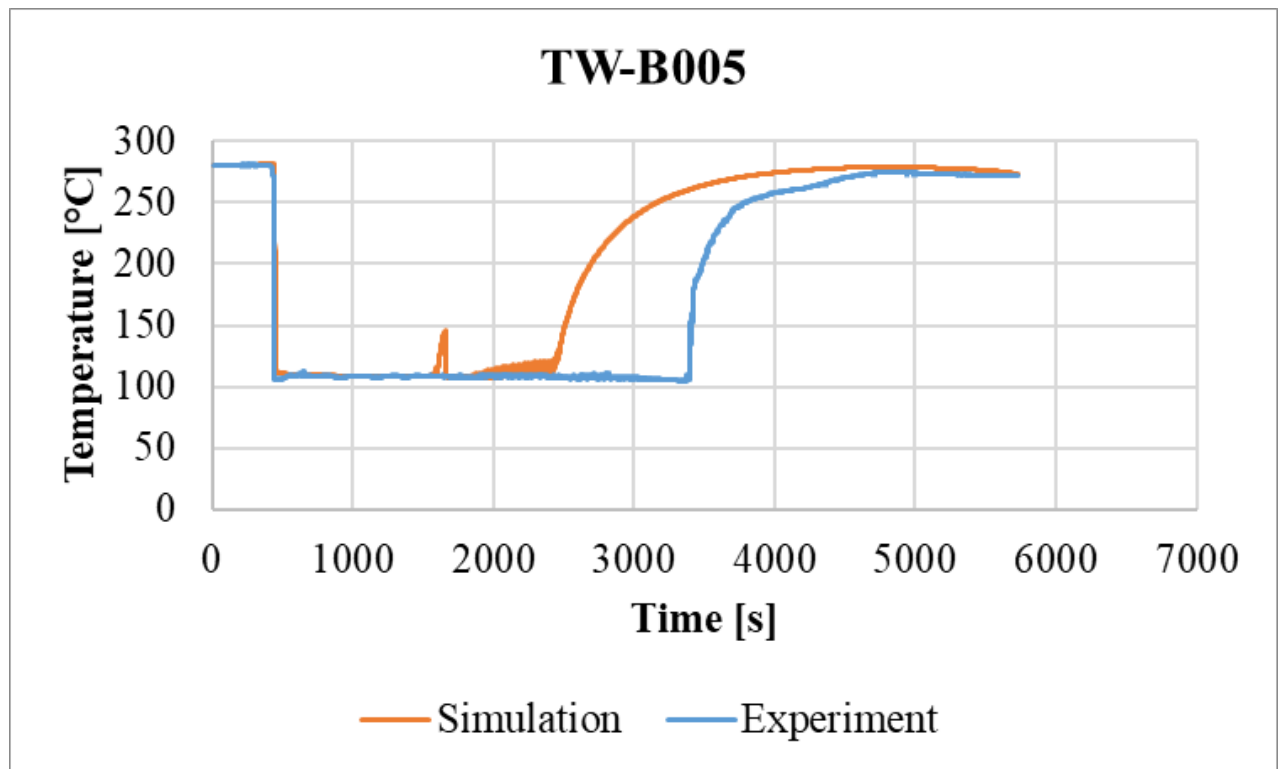
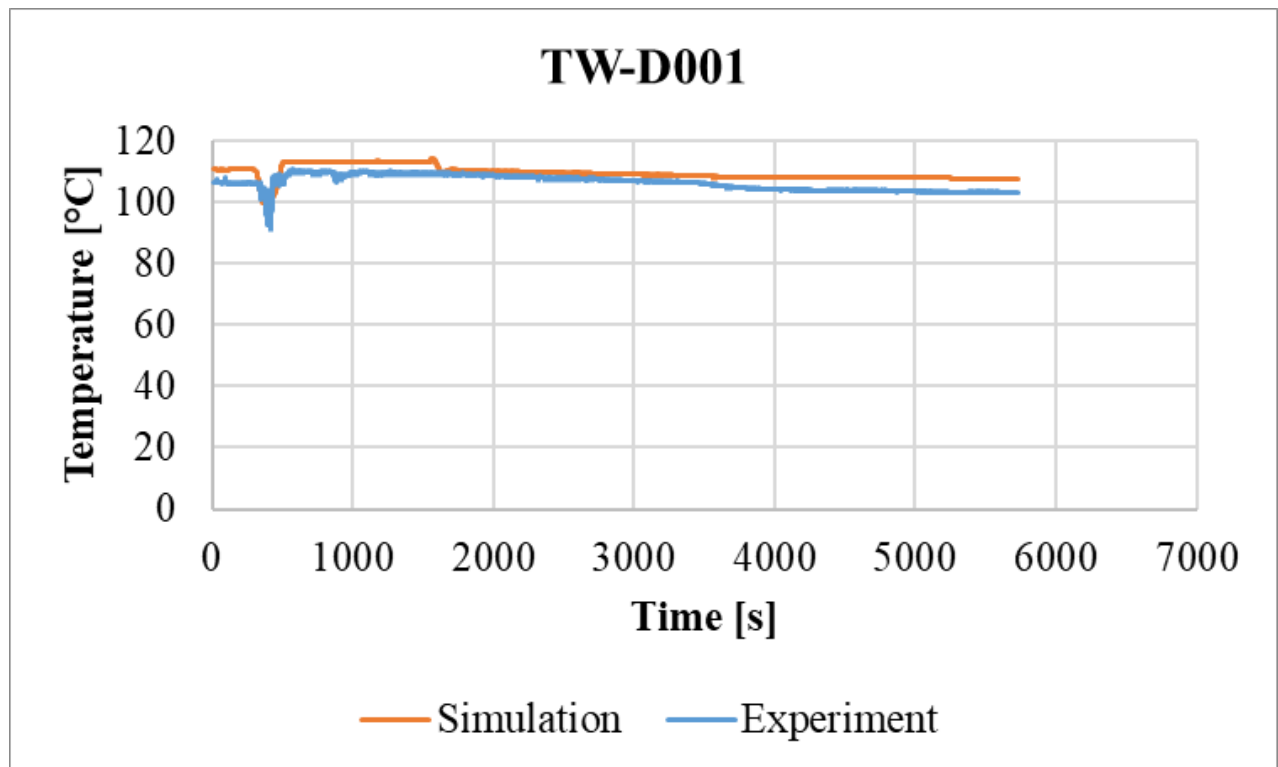
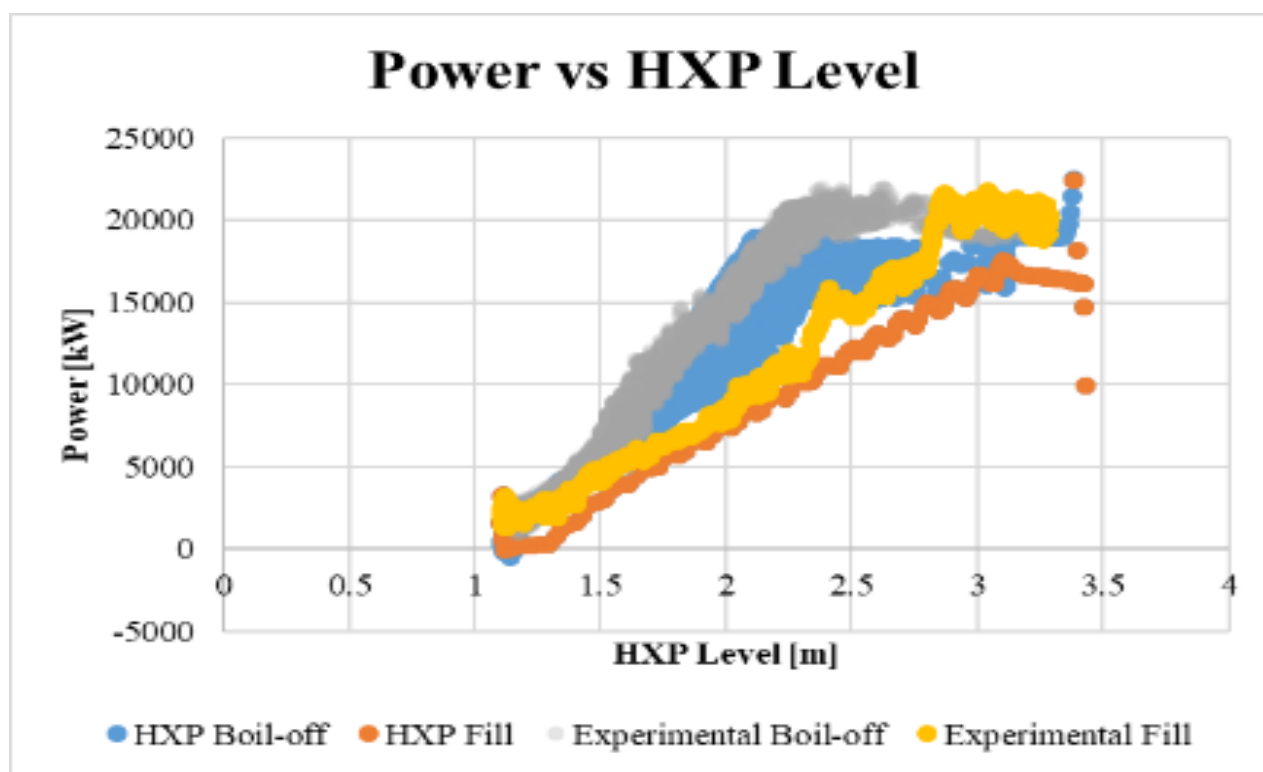


Figure 5.402. PERSEO Test 7 Part 2 simulation vs experiment lower
header wall temperatures (TW-D001)



The power trend as a function of the HXP water level is shown in Figure 5.403. The MELCOR model shows good agreement with the experimental data until the water level reaches approximately halfway up the HX tube bundle.

Figure 5.403. PERSEO Test 7 Part 2 simulation vs experiment power trend as a function of the HXP water level



The marks adopted in Table 5.68 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.69. PERSEO Test 7 Part 2 versus Phenomena, Code Prediction Versus Phenomena

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power HX	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power HX	W IC (der.)	+
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	

**Table 5.68. PERSEO Test 7 Part 2 versus Phenomena, Code
Prediction Versus Phenomena (Continued)**

Phenomenon		Experiment				TH code
		Ph.	Measurement			Ph.
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Absolute pressure vessel	P-I001	+
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power HX	W IC (der.)	
				Relative pressure HXP top	P-Q001	
				Diff. pressure HX upper-lower header	DP-003	
				Diff. pressure steam duct injector	DP-J001	
D	Behaviour of emergency HXs and isolation condensers: Tube side convection heat transfer	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
				Power HX	W IC (der.)	
E	Behaviour of emergency HXs and isolation condensers: Pool side convection heat transfer	+	+	Level HXP	L VQ (der.)	+
				Power HX	W IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
F	Behaviour of large pool: Thermal stratification	+	+	Power HX	W IC (der.)	+
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP	L VQ (der.)	+
				Level OP	L VP (der.)	
				Power HX	W IC (der.)	
				Relative pressure HXP top	P-Q001	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L VP (der.)	+
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

Section 5: Conclusions

The MELCOR model of the PERSEO facility was able to reproduce key experimental results with good agreement.

Acknowledgements

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References

[5.2.10 1] Humphries, L.L., B.A. Beeny, F. Gelbard, D. L. Louie and J. Phillips (2017), *MELCOR Computer Code Manuals Vol. 2: Reference Manual*, US Nuclear Regulatory Commission, Washington, D.C.

5.2.11. USNRC

SECTION 1: GENERAL INFORMATION

- Organisation: Office of Nuclear Regulatory Research of US Nuclear Regulatory Commission (NRC) (United States)
- Contact person: Peter. H. Lien, Ph.D., Senior Reactor Systems Engineer
- Code: In this benchmark, a TRACE model was created for PERSEO experiment. The version of TRACE is V5.1 175 and SNAP version 2.6.9 is used for model creation and execution
- Computing environment:
 - Core i7 CPU
 - 12 GB RAM

SECTION 2: DESCRIPTION OF THE CODE USED

In order to analyse the thermal-hydraulic behaviour of LWR reactors, the USNRC has maintained four codes, the RAMONA, the RELAP5, the TRAC-B and the TRAC-P. In recent years the NRC has been developing an advanced best-estimate thermal-hydraulic system code, by merging, among other things, the capability of the previous codes into a single code. This new code is called TRAC/RELAP advanced computational engine or TRACE, and is a component-oriented code designed to perform best-estimate analyses for LWR. In particular, this code is developed to simulate operational transient, LOCA, other transient typical of the LWR and to model the thermal-hydraulic phenomena taking place in the experimental facilities used to study the steady state and transient behaviour of reactor systems. TRACE is a finite volume, two fluids, code with 3D capability which gives user the possibility to model heat structures and control systems that interact with the component models. It can be run coupled with the 3D reactor kinetics code PARCS as well. TRACE can be used together with a user friendly front end, symbolic nuclear analysis package (SNAP), able to support the user in the development and visualisation of the model, to show a direct visualisation of selected calculated data using the animation model capability and accepts existing RELAP5 and TRAC-P input. The computational complexity of a generic TRACE model is only limited by the availability of the computer memory. The code is based on two fluids, two-phase field equations. This set of equations consists of the conservation laws of mass, momentum and energy for liquid and gas fields. The resulting equation set is coupled to additional equations for non-condensable gas, dissolved boron, control systems and reactor power. Relations for wall drag, interfacial drag, wall heat transfer, interfacial heat transfer, equation of state and static flow regime maps are used for the closure of the field equations. The interaction between the steam-liquid phases and the heat flow from solid structures is also considered. These interactions are in general dependent on flow topology and for this purpose a special flow regime dependent constitutive-equation package has been incorporated into the code. TRACE uses a pre-CHF flow regime, a stratified flow regime and a post-CHF flow regime. In order to study the thermal history of the structures the heat conduction equation is applied to different geometry. A 2D(r and z) treatment of conduction heat transfer is taken into account as well. A finite volume numerical method is used to solve the partial differential equations governing the two-phase flow and heat transfer. By default, a multi-step time-differencing procedure that allows the material Courant limit condition to be exceeded is used to solve the fluid-dynamics equations. TRACE version 5.0 Patch 5 was used in analysing the benchmark problems. The graphical user interface tool used is SNAP version

2.6.9. Field equations and choked flow models are standard TRACE models and the helical coils were modelled with standard PIPE components. These models are explained in the TRACE user's manual in detail.

Model for PERSEO Test 7 Part 1 and Part 2:

One-dimensional straight PIPE components are used throughout the entire system. Default heat transfer models on both sides of the heat exchanger tubes are invoked for the model. On the tube side, superheated or saturated steam from reactor pressure vessel (RPV) was condensed on the inside surface as the tube is cooled by the cold water coming from overall pool (OP) into heat transfer pool (HXP). After quasi-steady heat transfer is established on both sides, energy is transmitted via primary side steam condensation. The energy heats up the tube itself and then heats up the coolant in the HXP coming from OP via valve F045. If the initial condition of HXP is near saturation (as in Part 2 of Test 7), the coolant is heated up quickly to boiling state and the saturated steam goes through the steam duct/injector and mixes with the colder water in OP. The OP can be warmed up to near saturation condition depending on the amount of heat transmitted, e.g. Part 2 experiment.

TRACE models implemented regarding tube side and pool side heat transfer are included in the table below.

Table 5.70. TRACE models implemented regarding tube side and pool side heat transfer

Code version	Pool side heat transfer	Tube side heat transfer
TRACE V5.1175	Single phase: Pipe: Laminar forced convection – Nusselt analytical formula Turbulent forced convection – Gnielinski Natural convection - traditional model with function of Raleigh number Rod bundle – El-Genk Boiling Nucleate boiling (Chen formulation with Gorenflo correlation for pool boiling component) Transition boiling - Interpolation between CHF and Minimum Film Boiling (MFB) Film boiling (Inverted annular – Cachard; Dispersed flow: radiative flux to both phase plus convective flux to superheated steam)	Kuhn-Schrock-Peterson (K-S-P) for laminar film condensation, Modified Gnielinski Correlation for turbulent film condensation. Noncondensable effect -Coburn-Hougen

SECTION 3: DESCRIPTION OF THE NODALISATION

The PERSEO system is composed of a primary loop and a secondary heat sink loop. The TRACE PIPE component is used throughout both loops. Heat structures are built externally linked to or embedded in the PIPE components. BREAKs are used to provide boundary conditions for the secondary heat transfer pool (HXP) and overall pool (OP). The steam source is modelled by BREAK component as reactor pressure vessel boundary and the pressure was input according to data. level. Primary side reactor pressure vessel level is controlled by a separate PI controller to maintain the RPV normal water level by removing excess liquid through drain line.

Reactor pressure vessel (RPV) is modelled by a few PIPE components – a steam inlet node is used to connect pressure boundary BREAK component. After the steam inlet node, a 4-node PIPE component is used to model the riser. Then the riser component is connected to

the separator component. The outlet of the separator is connected to the dryer component above it. The liquid fall-back junction of the separator is linked to the lower downcomer pipe of RPV. The separator node has three axial-node main tubes and one-node side tube. Above the separator a one-node PIPE is used to model the dryer region. The dryer outlet is connected to the vessel dome. Parallel to the dryer connection, the vessel dome node is connected to the upper downcomer (one node). The upper downcomer then connects to the 3-node middle downcomer and then to the 4-node lower downcomer where the liquid fallback junction of separator side tube connects. The drain line from the heat exchanger connects to the lowest volume of lower downcomer through a side junction connection. The steam line is modelled by an 8-node pipe connected to the top of pressure vessel. Then the steam line is split into two horizontal smaller lines before connecting vertically to the top header of the heat exchanger. The two smaller steam lines are connected to the larger steam line via a TEE component. The heat exchanger top header is modelled as a horizontal cylinder. The cylinder is represented by 3-node horizontal PIPE component. The heat exchanger tubes, 120 of them, are divided into three PIPE components with eight vertical nodes, which represent 30, 60 and 30 heat exchanger tubes respectively. The lower heat exchanger header is similar to the top header with 3 horizontal nodes. The heat exchanger tubes are connected through the header's side junctions vertically. After the lower heat exchanger header, the drain pipe is modelled by 15 nodes based on the P&ID. The drain line connects to the reactor pressure vessel lowest downcomer node.

The secondary heat sink system includes the heat transfer pool (HXP) and overall pool (OP). They are connected by a horizontal pipe with a triggering valve. HXP is modelled with slice approach to approximate 2-D phenomena using three vertical pipes with horizontal junctions connecting them, each has 14 volumes, one node is for the bottom and one node for the top for connection purpose. The “right” region connected with the steam duct/injector, and the “left” region is on the other side of the middle heat exchanger region. Dividing the HXP into three components is mainly due to the instrumentation locations. Three pipes of 14 volumes are connected horizontally through side junctions in order to simulate any cross-flow between regions resulting from natural circulation. Please see the nodalisation diagram below. The top volume of the right region of HXP is connected to steam duct and also the vacuum breaker. The steam duct is a horizontal pipe with five volumes. It connects to the 4-node steam injector. The steam injector is embedded inside OP. A vacuum breaker is modelled with a check valve connected to the atmosphere. The valve will pop open when HXP pressure drops below atmospheric pressure by 50 Pa. In Part 1 test of Test 7, multi-step opening of valve F045 caused HXP level increase in two steps. Since the level is half the length of the heat exchanger tube, TRACE level tracking option is needed to better model the heat transfer from heat exchanger tubes.

OP is modelled with a slice approach using three regions like HXP with horizontal junctions connecting them. The “right” region is the region where the steam injector is installed. The left region is connected with a drain line which is turned on to reduce level in the second part of Test 7. All three regions have 12 vertical volumes, which are arranged according to the instrumentation consideration. The fluid under the steam injector is modelled separately with a pipe to capture the local steam condensation phenomenon. The pipe diameter is the same as the injector outlet diameter. This is to prevent the localised condensation from being “diluted” in the big volume of OP. Details on the modelling of the steam injector downstream region is described in Section 5. Between OP and HXP, a horizontal pipe is connected. Triggering valve (F045) is in the middle of the pipe. The pipe is connected to the lowest volume of both tanks.

Since no PI controller information is available, assumptions are made for reactor level control: DeltaT of PI controller (time to remove error) is assumed as 500 s and lag time Tau (first-order lag function) is assumed as 1 s. The valve opening history is according to

the test report. The valve stroke time is assumed as 0.1 s^{-1} . For reactor pressure, experimental data is input as boundary condition justifiably since reactor pressure vessel is only served as boundary condition for thermal-hydraulic phenomena in HXP and OP. BREAK components of atmosphere are used for both HXP and OP for initial instability control until shortly after triggering valve opens.

Heat structures for heat loss are modelled through pipe wall options with two radial nodes for most connecting pipes. Constant ambient temperature of 300 K and heat transfer coefficients of 10.0 W/mK are assumed throughout both primary and secondary systems. Separate heat structures are modelled for heat exchanger tubes and headers with Inconel 600 tubes. Five radial intervals are arranged for heat conduction.

Boundary conditions are assumed as in the following table:

Table 5.71. Boundary conditions

PARAMETER	USNRC
Heat losses (% of the Max PERSEO POWER)	HTC assumed: 10 w/mK ambient temperature = 27 C Heat losses: RPV ~ 260 kw, HXP ~ 35 KW, OP ~ 20 KW, steam duct ~ 6 kw. Assume no heat losses in steam line and drain line.
Saturated steam at the HX inlet	Experimental temperature data of steam entering RPV used as table input, ~ 291°C. Steam enters HX inlet is calculated.
Condensate water to the vessel	Flow and temperature are calculated based on upstream in the lower heat exchanger header
P_Vessel	Experimental data of steam boundary connected to RPV is used as table input around 7 055 KPa.
Water drain from OVP	Connected to ambient, flow and temperature are calculated based on upstream
P_OP	Connected to ambient
P_Vacuum breaker	Connected to ambient, modelled as check valve

Note: Ambient pressure is set at $1.0061\text{e}5 \text{ Pa}$ (100.61 kPa)

Figure 5.404. Nodalisation diagram

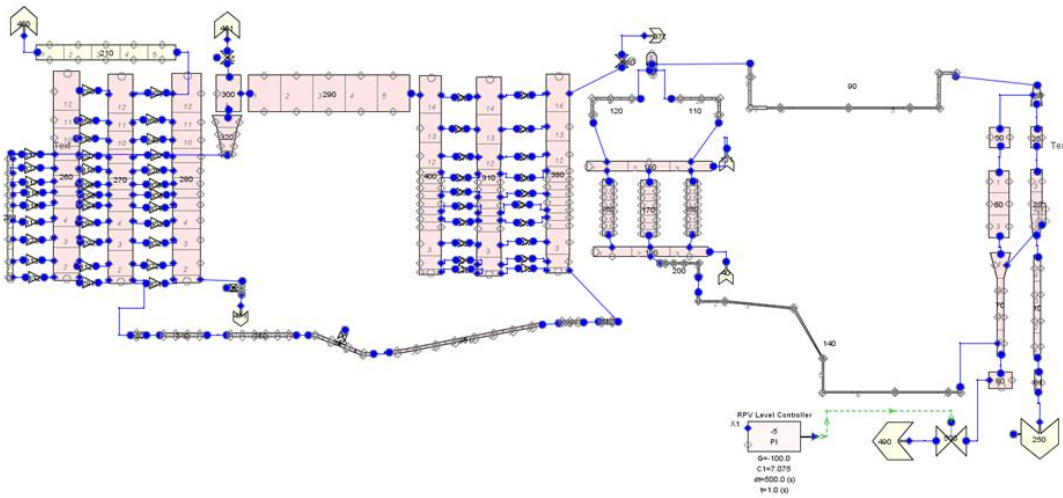


Table 5.72. Summary of the main nodalisation characteristics of the PERSEO model

	Number of hydraulic volumes	Number of junctions	Number of heat structures	Overall volume (m ³)
Vessel	18	10	1	32.1
Steam line	18	24	4	1.84
HX	30	36	5	1.91
Condensate line	16	17	1	0.61
HXP	42	73	3	27.4
Steam duct	10 (include jet)	12	2	11.57
OP	45	69	3	166.4
Heat transfer area HX (m ²)	34.47			
HX heat structure axial nodes number	8			
HX heat structure radial nodes number	4			

SECTION 4: RESULTS

TEST 7 Part 1

The initial condition is prescribed as close as possible according to Table 5.72 for each volume of each component. Before triggering valve is open, the model will go through some initialisation transient and will reach to a quasi-steady condition before F045 opens. Ambient BREAK nodes (460 and 461) were connected to top volume of HXP and OP. The approach of adding boundary volume is to speed up the initialisation process before triggering valve opening and to reduce the instabilities. The following table describes the initial condition:

Table 5.73. Initial condition simulated by the benchmark participant (Test 7 Part 1)

	PARAMETER	LABEL	EXP	Benchmark Participant value	(%) DISCRPANCIES	NOTE
1	Flowrate steam supply line (kg/s)	F_A001 (der.)	1.10	0.156	85.81818182	1
2	Flowrate condensate drain line (kg/s)	F_E001 (der.)	0.59	0.153	74.06779661	1
3	Power heat exchanger (kW)	W_IC (der.)	2 321.23	305.3	86.84749034	1
4	Absolute pressure vessel (kPa)	P-I001	7 056.44	7 054	0.034578343	
5	HX inlet fluid temperature (°C)	T-A005	291.44	286.3	1.763656327	
6	HX outlet fluid temperature (°C)	T-E001	288.68	286.3	0.824442289	
7	Level HXP (m)	L_VQ (der.)	0.19	0.19	0	
8	Level OP (m)	L_VP (der.)	4.65	4.64	0.215053763	

Table 5.72. Initial condition simulated by the benchmark participant (Test 7 Part 1) (Continued)

	PARAMETER	LABEL	EXP	Benchmark Participant value	(%) DISCRPANCIES	NOTE
9	Fluid temperature HXP (bottom) (°C)	T-Q037	123.60	100.0	19.09385113	2
10	Fluid temperature HXP (middle) (°C)	T-Q034	198.25	160.0	19.29382093	2
11	Fluid temperature HXP (top) (°C)	T-Q031	222.74	168.0	24.57573853	2
12	Relative pressure HXP top (kPa)	P-Q001	0.61	0.76	24.59016393	3
13	Fluid temperature OP (bottom) (°C)	T-P008	15.34	14.8	3.520208605	
14	Fluid temperature OP (top) (°C)	T-P021	15.43	15.18	1.62022035	
15	Diff. pressure HX upper-lower header (kPa)	DP-003	-0.87	-0.88	1.149425287	4
16	Diff. pressure steam duct injector (kPa)	DP-J001	-10.53	-8.2	22.12725546	3.4
17	Wall temperature HX upper header (°C)	TW-B005	282.01	286.6	1.627601858	
18	Wall temperature HX lower header (°C)	TW-D001	280.48	279.8	0.242441529	

Note:

- 1: Experiment has minimum steam flow. TRACE initialises as zero flow.
- 2: TRACE steady state (~300 sec) is not long enough to heat up the structures.
- 3: Denominator (experimental data) is smaller. Deviation is magnified.
- 4: No calibration was intended. Only nominal losses were added.

After triggering valve opens for about 10 s, the boundary node of HXP is removed, but boundary node attached to boil-off valve for OP stays for entire transient.

- Code calculated results considering the phenomenological window identified in the PERSEO Test 7 report (Section 4.1).

1. 10 000 s – 11 260 s (maximum level in the HXP): Increase of level in two steps due to valve opening in the HXP with a consequent increase of the exchanged power removed. Relevant thermal-hydraulic aspects are:

- HXP level increase: Based on L_VQ, HXP level increase was clearly seen in two steps.
- OP level decrease: Based on L_VP, OP level decrease was seen accordingly.
- Mass flow increase in-tube side: Mass flow increase inside heat exchanger tube was clearly seen due to condensation, which decrease RPV pressure and calls for more steam supply to maintain RPV pressure.
- Power removed increase: Yes. In two-step pattern.
- Progressive covering of the HX in the pool side: Yes in two steps. The first step only covers partial length of the tube length.

- System instability with cold water – steam interface at the injector (strong condensation shocks): The phenomenon was clearly seen in the DP_j001 plot.
2. 11 260 s – 11 845 s (HX power around 20 MW, the ending time of the PhW is when the HX power decreases under 20 MW): Quasi-steady-operation starting from the HXP level of 3.4 m. Relevant thermal-hydraulic aspects are:
- Quasi-steady power removed: Quasi-steady power of 21.5 MW in average was seen between 11 260 to 12 011 s.
 - Quasi-steady flow rate in-tube side: Flow rate of 13.4 kg/s in average was seen, slightly higher than 13.3 kg/s in experiment.
 - Initial boil-off in the HXP: Yes, it was seen in the top part of HXP.
 - Mixing of the OP water due to the acceleration of the steam in the injector: Based on DP_j001 plot, positive dp indicated flow enters OP through the injector.
3. 11 845 s – 14 784 s: Boil-off in the HXP with a consequent level reduction. Therefore, reduction of power removed (no accelerated level decrease by opening of the pool discharge valve). Relevant thermal-hydraulic aspects are:
- Boil-off in the HXP: Yes, top part of HXP reaches boiling point and start boils.
 - Reduction of HXP level: Yes, reduction of HXP level is seen.
 - Increase of OP level due to steam condensation: Yes. OP was recovered due to steam injected to OP.
 - Reduction of removed power: Power reduction was seen in W-IC plot.
 - Reduction of flow rate in-tube side: Reduction of flow rate is seen in F_A001 and F_E001 plot.
 - Progressive uncovering of the HX in the pool side: HXP level was dropping but not totally uncovered.
 - Thermal stratification in the OP due to the reduction of mixing for the decrease of steam accelerated in the injector: The stratification reduces as the injector flow reduces according to the temperature plots of OP. This is due to the limitation of one-dimensional approach. The injector is connected to the upper part of the tank. As injector flow increases, the upper part liquid is getting warmer but not propagating to the lower nodes. So, the stratification increases. In this period, as injector flow reduces, stratification reduces.

Based on the TRACE plots, TRACE did reproduce most phenomena well. However, HXP temperature predictions have deviations, in particular in the later part of the transient as boiling became significant. There is minor disagreement in the timing for the events. They were mainly due to valve opening size and timing since no precise data is available. Level in HXP shows significant oscillation in the later part due to boiling in HXP and steam condensation via steam injector.

The maximum time step used throughout the transient is 0.01 s and total CPU time is about 9.68E03 s for 6 736 s of problem time.

Table 5.74. Main relevant thermal-hydraulic aspects related to Test 7 Part 1

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	10 475-10 608	-
Triggering valve (F045) re-opening and re-closure	10 621-10 655	-
Maximum level in the HX pool for the first filling step	10 655	1.41 m
Small heat removal from the primary side	10 632-11 048	3 698 kw
Slow water consumption in the HX pool	10 651-11 090	1.41 to 1.36 m
Instabilities for steam condensation in the injector	10 500-10 670, 11 040-11 270	Yes, seen in DP-jool plot and P-Q001 plot
Triggering valve (F045) opening and closure	11 056 – 11 298	-
Maximum level in the HX pool	11 284 s	3.52 m
Maximum exchanged power	11 437-11 620	21 400 kw
HX pool minimum level	4 768	1.15 m
OP average temperature	3 000	60 C (T-P021)

The marks adopted in Table 5.74 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.75. PERSEO Test 7 Part 1 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W IC (der.)	o
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (top)	T-P021	+
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Diff. pressure HX upper-lower header	DP-003	+
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
				Power heat exchanger	W IC (der.)	

Table 5.74. PERSEO Test 7 Part 1 versus phenomena, code prediction versus phenomena (Continued)

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Level HXP	L_VQ (der.)	+
				Power heat exchanger	W_IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
F	Behaviour of large pool: Thermal stratification	+	+	Power heat exchanger	W_IC (der.)	o
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Temperature OP (top)	T-P021	o
				Level HXP	L_VQ (der.)	
				Level OP	L_VP (der.)	
				Power heat exchanger	W_IC (der.)	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Relative pressure HXP top	P-Q001	+
				Level OP	L_VP (der.)	
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

** Ph. = Phenomenon

The judgement is based on evaluating the deviation for each parameter under the phenomena, according to the marks proposed in Table 4.2. Some phenomena are rated as “O” because of the following identified code deviations. TRACE has less agreement with data if liquid temperature is used as prediction for T-E001. TRACE uses saturate temperature instead for this indication since a two-phase mixture is in the location. P-I001 is basically determined by the boundary condition input in the model. For HXP temperatures has larger deviation in the later part of the transient when temperature rises as level reduces. TRACE predicts slower rise since larger nodes are allocated for the sensor location, mixture temperature is more prominent than steam temperature. As for T-P021 and T-P008, disagreement may be due to instrumentation location and nodalisation. TRACE uses a separate pipe (PIPE 261) to model the fluid under the steam injector. Therefore, the uncertainty plays a significant part in this comparison. For TW-B005, the disagreement is the timing when the upper header gets uncovered and heated up in the later part of the transient. The thermocouple is located at the lower part of the cylinder according to the P&ID. It is sensitive to the level reduction at this stage. As the level is reduced to the top of the tubes, the temperature rises immediately. At this stage, TRACE predicts earlier uncover of the location.

Test 7 Part 2

The initial condition is prescribed as close as possible according to Table 5.75 for each volume of each component. Before triggering valve is open, the model will go through some initialisation transient and will reach to a quasi-steady condition before F045 opens. Ambient BREAK nodes (460 and 461) were connected to top volume of HXP and OP. The approach of adding boundary volume is to speed up the process of initialisation before triggering valve opening and to reduce the instabilities. Shortly after triggering valve opens, about 325 s, the boundary node of HXP is removed to avoid initial transition, but boundary node for OP, attached to the boil-off pipe, stays for entire transient to represent boil-off valve. The following table describes the initial condition:

Table 5.76. Initial condition simulated by the benchmark participant (Test 7 Part 2)

	PARAMETER	LABEL	EXP	Benchmark Participant value	(%) DISCRPANCIES	NOTE
1	Flowrate steam supply line (kg/s)	F_A001 (der.)	1.13	0.196	82.65486726	1
2	Flowrate condensate drain line (kg/s)	F_E001 (der.)	0.75	0.193	74.26666667	1
3	Power heat exchanger (kW)	W_IC (der.)	2 160.71	315.2	85.41220247	1
4	Absolute pressure vessel (kPa)	P-I001	7 051.89	7 055.0	0.044101652	
5	HX inlet fluid temperature (°C)	T-A005	291.07	288.6	0.848593122	
6	HX outlet fluid temperature (°C)	T-E001	288.74	286.3	0.845050911	
7	Level HXP (m)	L_VQ (der.)	1.12	1.125	0.446428571	
8	Level OP (m)	L_VP (der.)	4.52	4.56	0.884955752	
9	Fluid temperature HXP (bottom) (°C)	T-Q037	103.24	103.6	0.348702053	
10	Fluid temperature HXP (middle) (°C)	T-Q034	164.97	202.2	22.56773959	2
11	Fluid temperature HXP (top) (°C)	T-Q031	184.80	211.95	14.69155844	2
12	Relative pressure HXP top (kPa)	P-Q001	12.23	11.36	7.113654947	
13	Fluid temperature OP (bottom) (°C)	T-P008	49.66	54.95	10.65243657	4
14	Fluid temperature OP (top) (°C)	T-P021	70.72	54.95	22.29920814	4
15	Diff. pressure HX upper-lower header (kPa)	DP-003	-0.83	-0.87	4.819277108	3.5
16	Diff. pressure steam duct injector (kPa)	DP-J001	0.19	0.082	56.84210526	3.5
17	Wall temperature HX upper header (°C)	TW-B005	280.54	286.55	2.142296999	
18	Wall temperature HX lower header (°C)	TW-D001	106.26	106.8	0.508187465	

Note:

- 1: Experiment has minimum steam flow. TRACE initialises as zero flow.
- 2: TRACE steady state (~1 000 sec) is not long enough to heat up the structures.
- 3: Denominator (experimental data) is smaller. Deviation is magnified.
- 4: OP temperatures stratification was not specified enough in Part 2.
- 5: No calibration was intended. Only nominal losses were added.

The code calculated results considering the phenomenological window identified in the PERSEO Test 7 report (Section 4.2). Specify also:

1. 0 s – 531 s (maximum level in the HXP): Increase of level in one step in the HXP with a consequent increase of the exchanged power removed. Relevant thermal-hydraulic aspects are:

- HXP level increase: HXP level L-VQ increases as expected.
- OP level decrease: OP level L_VP decreases as expected.
- Mass flow increase in-tube side: Mass flow F_A001 inside tube increases due to condensation. More steam flow from steam supply is seen to make up the depressurisation in RPV.
- Power removed increase: Transfer power increases as more water covers the HX tubes.
- Progressive covering of the HX in the pool side: Based on L-VQ, covering is seen.

2. 531 s – 2 282 s (HX power around 20 MW, the ending time of the PhW is when the HX power decreases under 20 MW): Quasi-steady state operation starting from the HXP level of 3.3 m. Relevant thermal-hydraulic aspects are:

- Quasi-steady state power removed: phenomenon is clearly seen.
- Quasi-steady state flow rate in-tube side: quasi-steady state is clearly seen for a period of time. Flow rate is close to experimental data, i.e. 12.5 (TRACE) vs. 13.2 kg/s.
- Initial boil-off in the HXP: boil-off in HXP was clearly seen.
- Instabilities in the OP water level: instability was not clearly seen. It is due to the instrumentation location. In TRACE, the level is based on the larger OP pipe (PIPE 260) which excludes the instability occurring in the smaller area where pipe (PIPE 261) is to model the liquid under the steam injector.

3. 2 282 s – 5 735 s: boil-off in the HXP with a consequent level reduction. Therefore, reduction of power removed (accelerated level decrease by opening of the pool discharge valve). Relevant thermal-hydraulic aspects are:

- Boil-off in the HXP: boil-off was seen in HXP.
- Reduction of HXP level and OP level due to the accelerated water draining from the drain valve: phenomenon was clearly seen as soon as the drain line opens.
- Reduction of removed power: reduction of power is clearly seen due to level dropping in HXP.
- Reduction of flow rate in-tube side: flow reduction in the heat exchanger tubes is clearly seen.
- Progressive uncovering of the HX in the pool side: HXP level uncovering is clearly seen.

Based on the TRACE plots, TRACE did reproduce most phenomena; however, the HXP level response has deviation from experimental data in terms of the number of up and down period. TRACE has more peaks compared to data. The deviation is due to the flow resistance in manometer oscillation path. TRACE did not add artificial resistance to match data since no flow resistance data is available.

Maximum time step used throughout the transient is 0.01 s and total CPU time is about 6.86E03 s of CPU time for 6 736 s problem time (including 1 000 s steady state run).

Power trend as function of the HXP water level

The following plot is a comparison of transferred power at various water levels for TRACE and experimental results. A reasonable match of code-data comparison is shown. Test data show clear hysteresis, which indicates different heat transfer modes co-exist in a quasi-steady state. TRACE did not show the hysteresis clearly. Further exploration is needed.

Figure 5.405. Power trend as function of the HXP water level

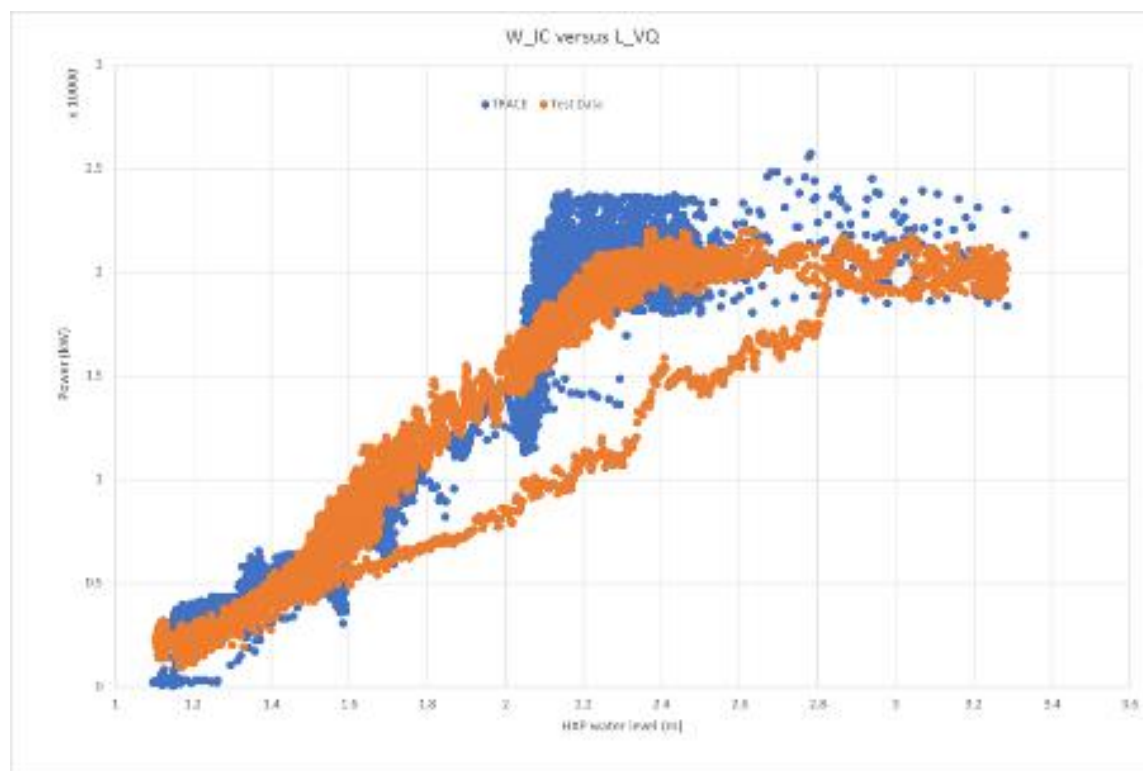


Table 5.77. Main relevant thermal-hydraulic aspects related to Test 7 Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	300 (open in 26 s until 326 s)	-
Maximum level in the HXP	470	3.34 m
Maximum exchanged power	408 – 2 765	21.1 MW
OP discharge valve F031 opening	1 150	-
Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve F045 closure	3 338 (closed in 123 s at 3 461 s)	-
HX pool level decreasing and loss of mass from the boil-off	2 827 – 5 735	-
Primary side depressurisation beginning for end of test	4 524	-

The marks adopted in Table 5.77 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.78. PERSEO Test 7 Part 2 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F A001 (der.)	+
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
B	Natural circulation in HXP and OP coupled circuit	+	+	HX outlet temperature	T-E001	o
				Power heat exchanger	W IC (der.)	
				Level HXP	L VQ (der.)	
				Level OP	L VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Temperature OP (bottom)	T-P008	+
				Temperature OP (top)	T-P021	
				Absolute pressure vessel	P-I001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Power heat exchanger	W IC (der.)	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Relative pressure HXP top	P-Q001	+
				Diff. pressure HX upper-lower header	DP-003	
				Diff. pressure steam duct injector	DP-J001	
				Flowrate steam supply line	F A001 (der.)	
				Flowrate condensate drain line	F E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	HX inlet temperature	T-A005	+
				HX outlet temperature	T-E001	
				Power heat exchanger	W IC (der.)	
				Level HXP	L VQ (der.)	
				Power heat exchanger	W IC (der.)	
F	Behaviour of large pool: Thermal stratification	+	+	Temperature HXP (bottom)	T-Q037	o
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
				Diff. pressure steam duct injector	DP-J001	
				Power heat exchanger	W IC (der.)	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP	L VQ (der.)	o
				Level OP	L VP (der.)	
				Power heat exchanger	W IC (der.)	
				Relative pressure HXP top	P-Q001	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L VP (der.)	+
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

The judgement is based on evaluating the deviation for each parameter under the phenomena. Some phenomena are rated as “O” because of the following identified code deviations. TRACE has less agreement with data if liquid temperature is used as prediction for T-E001. TRACE uses saturate temperature instead for this indication since a two-phase mixture is in the location. P-I001 is basically determined by the boundary condition input in the model. For HXP temperatures has larger deviation in the later part of the transient

when temperature rises as level reduces. TRACE predicts slower rise since larger nodes are allocated for the sensor location, mixture temperature is more prominent than steam temperature. As for T-P021 and T-P008, disagreement may be due to instrumentation location and nodalisation. TRACE uses a separate pipe (PIPE 261) to model the fluid under the steam injector. Therefore, the uncertainty plays a significant part in this comparison. For TW-B005, the disagreement is the timing when the upper header gets uncovered and heated up in the later part of the transient. The thermocouple is located at the lower part of the cylinder according to the P&ID. It is sensitive to the level reduction at this stage. As the level is reduced to the top of the tubes, the temperature rises immediately. At this stage, TRACE predicts earlier uncover of the location.

SECTION 5: STEAM INJECTOR DOWNSTREAM REGION MODELLING

Introduction

In the NEA/WGAMA passive system reliability workgroup initiative, a code benchmark exercise was proposed to explore important phenomena in a passive system. The PERSEO experiment was selected as the vehicle to conduct this exercise. The operation of its primary loop is to simulate a BWR vessel or a PWR steam generator. A triggering valve concept was introduced between the heat exchanger pool (HXP) and the overall pool (OP) to initiate the condensing operation. Both the HXP and OP are operated in a range of atmospheric conditions and OP serves as the ultimate heat sink of the primary system.

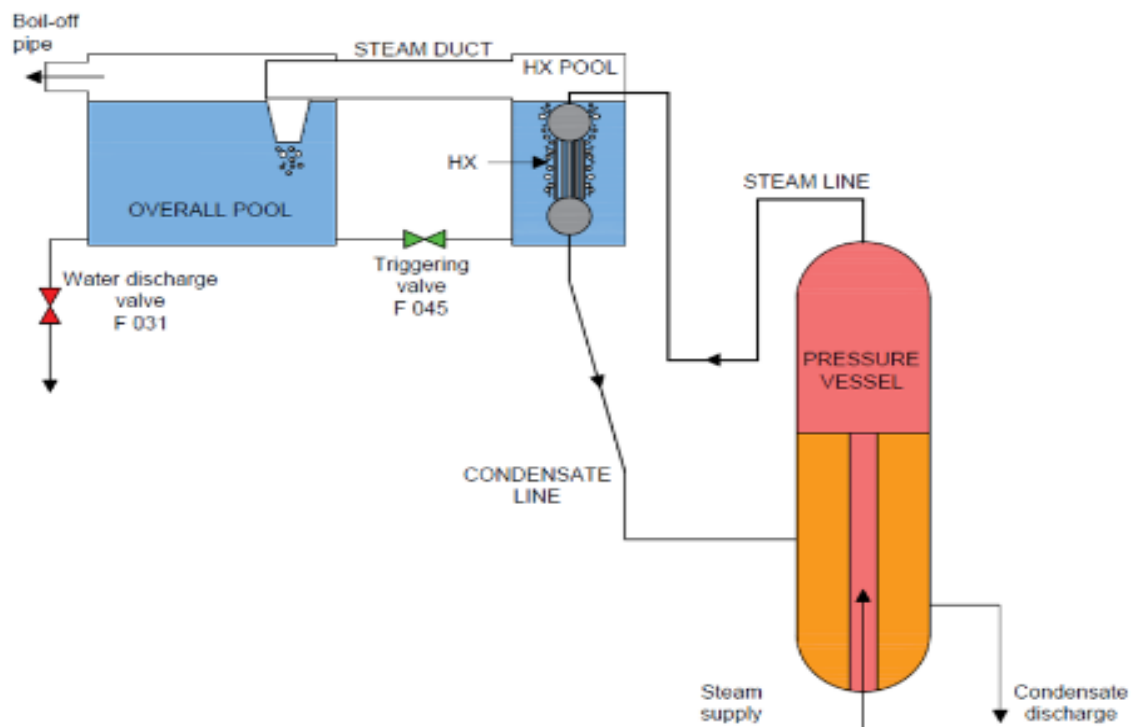
To illustrate the concept of operation, Test 7 Part 2 operation was chosen for its simplicity. Before the triggering valve operated, the primary loop was filled with high pressure steam; it is 7 MPa in this test case. Minimum steam and condensate flow were in the loop to overcome heat losses. The pressure and level in the reactor vessel were controlled in a steady state. Cold water in OP was warmed up to 50 C in earlier tests. HXP was filled with superheated steam with minimum water in the bottom. As the operation started, triggering valve (F045) opened and cold water entered the HXP to cover the heat exchanger tubes. Triggering valve stayed open for about 2 600 seconds. Water in HXP was heated up and reached boiling condition after valve opened for a while. The steam in the HXP was pushed into the OP through the steam duct and steam injector [5.2.11 1],[5.2.11 2]. The high pressure steam inside heat exchanger tubes was condensed by the cold tube wall and the condensate returned to the vessel. Figure 5.406 illustrates the operational concept.

In this quasi-steady state operation, important thermal-hydraulic phenomena involve tube wall condensation inside the heat exchanger tubes, subcooled and saturate boiling in HXP, direct steam condensation inside HXP, and direct steam condensation near the steam injector nozzle in the overall pool. In this benchmark exercise, the experimental data provides valuable information for these phenomena. Participants can verify the system code performance on high pressure tube wall condensation, which is extremely important to determine the heat transfer capability from primary side to secondary side. The measured pressure, temperature and level response in HXP also verify the model performance as cold water enters a superheated single-phase steam environment, e.g. direct contact condensation and boiling. The injector nozzle is another key component process. It relieves pressure build-up due to the heat transfer from primary side. And the pressure drop between two inter-connecting pools (HXP and OP) determines the HXP level. These phenomena interact closely with one another in a transient process because these components form a closed natural circulation path.

Most participants in this benchmark predict reasonable to good results against experimental data. However, one key parameter deviates from data greatly, i.e. the heat transfer power

from primary side to secondary side. Most codes need fouling factor up to 2.4 in order to have major parameters matched to data except SOCRAT and TRACE code [5.2.11 3],[5.2.11 4]. In TRACE model, TRACE was able to transfer power around 20 MW during the early part of transient as the HXP level is higher than the top of heat exchanger tubes, i.e. 2.15 m. However, in the first submittal, TRACE HXP was not able to maintain level above the top of heat exchanger tubes for the entire period. TRACE HXP level reduced in the early period of the transient and power transfer reduced accordingly. After extensive modelling investigation, a key modelling change resolves this discrepancy. The modelling change also reveals an important modelling practice in this configuration – i.e. the modelling of steam injector downstream region.

Figure 5.406. PERSEO experimental facility



Source: Mascari, F., A. Bersano, R. Ferri, C. Lombardo and L. Burgazzi (2019), [5.2.11 1].

Modelling experiment

In the process of searching for reasons of TRACE HXP level discrepancy, a few modelling experiments were conducted to eliminate possibilities. The original default nodalisation uses TRACE PIPE component to represent HXP, OP and all connecting pipes. Because of the internal structures layout and instrumentation locations, three 1-D pipes were used to represent HXP and OP respectively. Side junctions were used to connect the three pipe components. Side junction is also used to connect the steam injector (PIPE 320) and one pipe (PIPE 260) representing the corresponding region in the OP. Nodalisation diagram is shown below in Figure 5.407 and is named as PIPE nodalisation in this report [5.2.11 5]. Connection between steam injector and OP is highlighted in Figure 5.407, Figure 5.408, Figure 5.409 and Figure 5.412. The initial condition of HXP is established by adding a fixed pressure boundary (BREAK 461) in the steam duct to maintain the initial HXP pressure. This pressure boundary is removed at 326 s (valve opens at 300 s for 26 s).

A potential error was suspected using 1-D pipes with side junction connecting each other to represent 2-D phenomena. The flow from side junction from steam injector enters the 1-D pipe has to overcome the gravity from fluid above the connecting cell, which may resist the steam from getting into OP pipe component. A 2-D VESSEL component may be advantageous in providing radial cell to facilitate flow from steam injector. Therefore 2-D Cartesian-co-ordinate VESSEL components were implemented to model HXP and OP respectively (Figure 5.408). The nodalisation is named as VESSEL nodalisation in this report. Before VESSEL component was used for both HXP and OP, it was used for OP alone to observe the performance.

To isolate the influence of pressure in the receiving end of steam injector, another nodalisation is tested by connecting the steam injector directly to ambient (Figure 5.409). The nodalisation is named as ambient nodalisation in the report. This is not an accurate representation of the flow path but it provides valuable model response.

Figure 5.407. PIPE nodalisation (default)

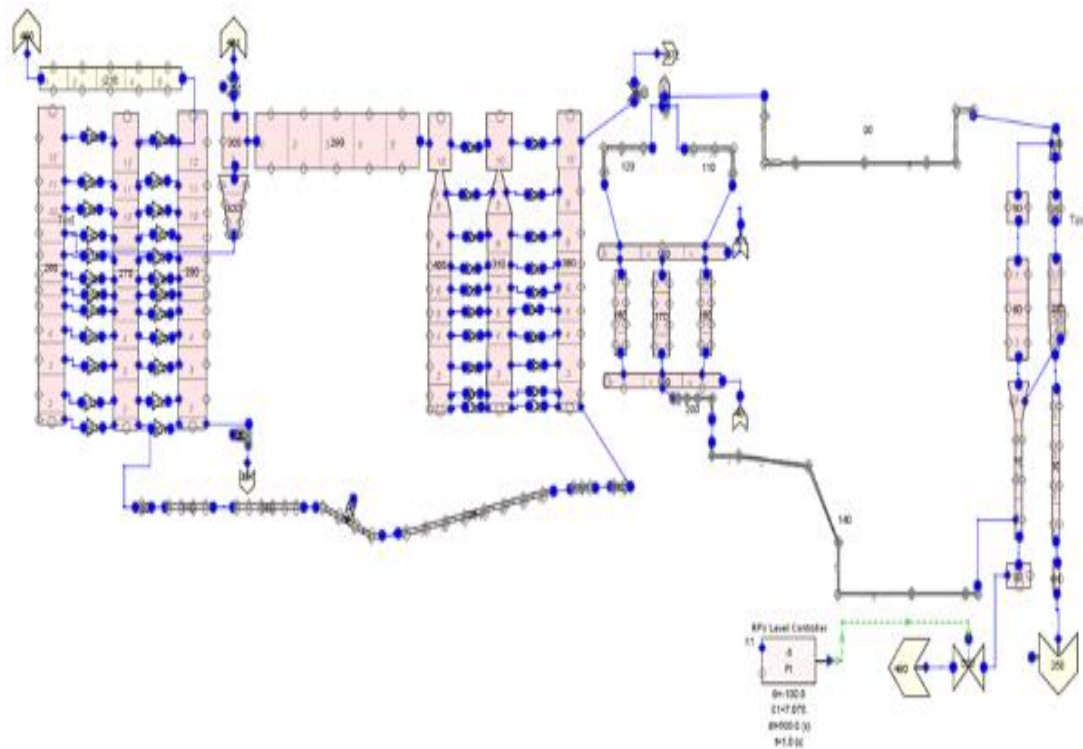


Figure 5.408. VESSEL nodalisation

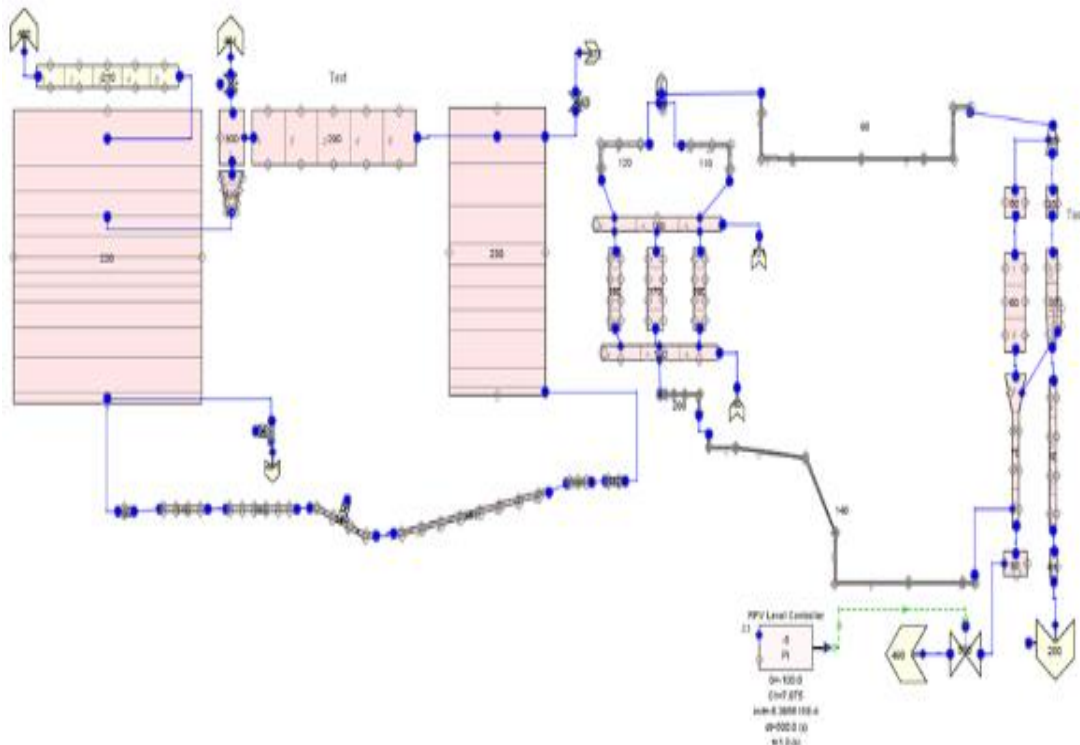
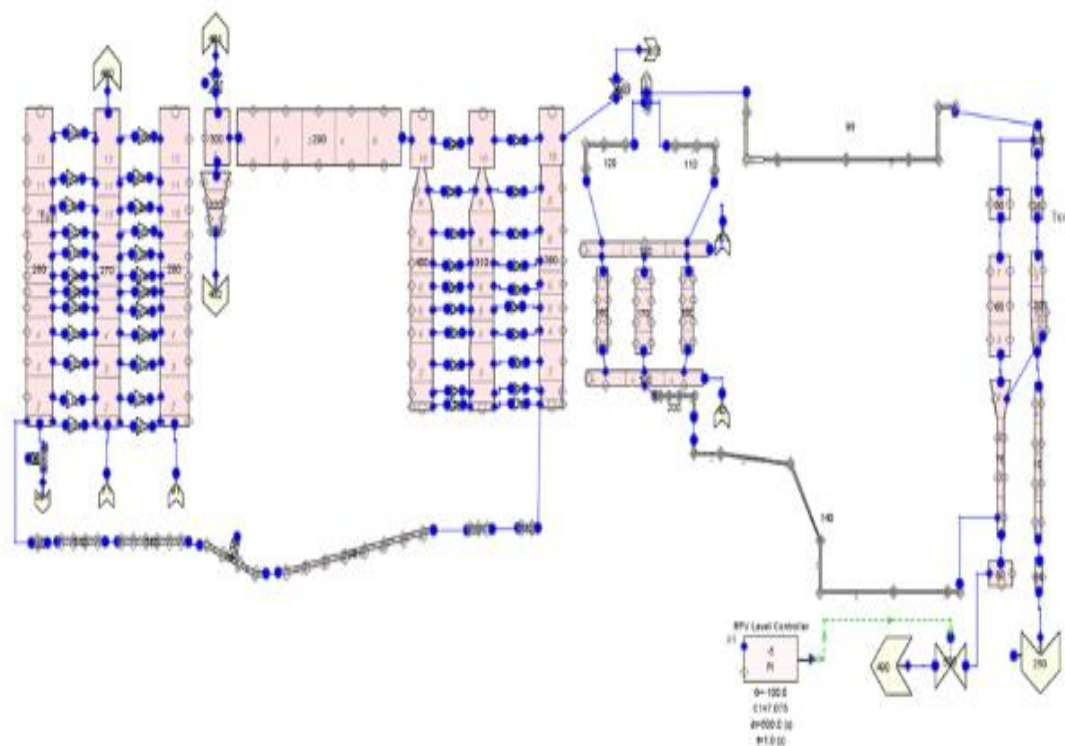


Figure 5.409. Ambient nodalisation



The flow path in the secondary side is a closed loop when the triggering valve is open. It starts from HXP and goes through the steam duct, steam injector, overall pool, and triggering valve and finally returns to the lower end of HXP. Major parameters of interests in the flow path (Test 7 Part 2) are HXP pressure (P-Q001), HXP level (L_VQ), steam injector pressure drop (DP-j001), heat transfer power (W-IC). During the transient, these major parameters are interacting together. As triggering valve opens, water in OP goes through valve FO45 and enters HXP bottom due to the gravity force. The water from OP floods the HXP and heat exchanger tubes. As the water goes up and gets heated in HXP, pressure builds up in the loop and the steam gets pushed through the steam duct and injector. The hot steam enters OP and mixes with the cold water in OP where direct contact condensation occurs. The amount of the condensation determines the local pressure near the two-phase plume region, which determines the pressure drop in the steam injector nozzle and the pressure in HXP. HXP pressure also affect the flow thru the triggering valve because the driving force is based on pressure difference between two pools. In addition, the pressure rise in HXP is affected by the heat transfer power from the heat exchanger tubes. Any deviation of these parameters from data causes deviations in other major parameters.

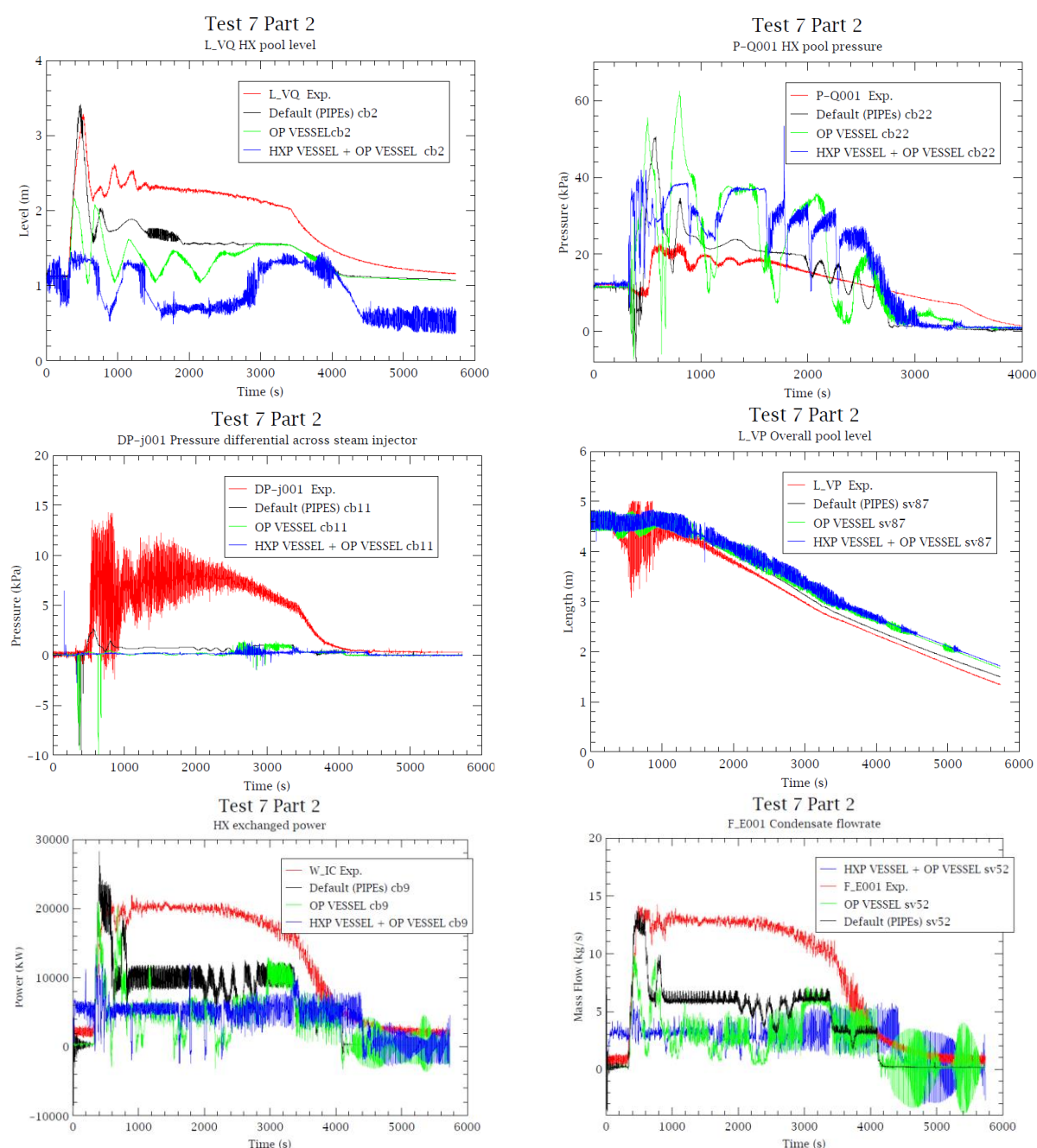
Comparison of PIPE nodalisation with VESSEL nodalisation

In Figure 5.410 the major parameters are plotted; the red curves represent experimental data. In the HXP level plot (L-VQ), the PIPE model predicts the initial rise well. However, the level reduces to below 2 m around 600 s and stays below 2 m. The VESSEL model (OP only) has much lower initial level rise and the level is below 2 m in most of the transient. With both pools modelled with VESSEL components, level performance deviates from data further. In the HXP pressure plot (P-Q001), TRACE results are significantly higher than data. VESSEL model has even higher HXP pressure than PIPE model. In the pressure drop across steam injector, all these TRACE nodalisations predict much smaller value than data. It means much smaller steam flow goes through the steam injector. VESSEL model has even lower DP than PIPE model. In examining the OP level, the VESSEL model has higher level than the PIPE model and the PIPE model level is higher than the data. It means less flow can enter the HXP in these models. These four parameters all point to one common problem – the condensation in the injector nozzle is far underpredicted, which pressurises HXP and prevents the OP flow from entering.

PIPE model HXP level reaches 3.4 m as a maximum and it remains above 2.15 m (top of the heat exchanger tubes) for about 300 seconds and the heat transfer (W_IC) across the heat exchanger in this period is around 21 MW, close to data. After the level reduces below 2.15 m, the heat transfer drops accordingly since the tubes are uncovered. Consistent with HXP level and W_IC, the condensate flow is reduced as the level drops below 2.15 m. Condensate flow rate matches data well in the first 300 seconds.

According to these plots, the VESSEL models did not improve the issue and the suspected reason of early level reduction is not valid. However, one conclusion that can be drawn is the underprediction of the steam injector pressure drop. The lower the injector pressure drop is, the higher the HXP pressure is. And it results in a lower HXP level. The heat transfer power from the primary side predicted by TRACE is matching the data well as long as the heat exchanger tubes are covered.

Figure 5.410. Comparison between PIPE nodalisation and VESSEL nodalisation



Comparison of PIPE nodalisation with ambient nodalisation

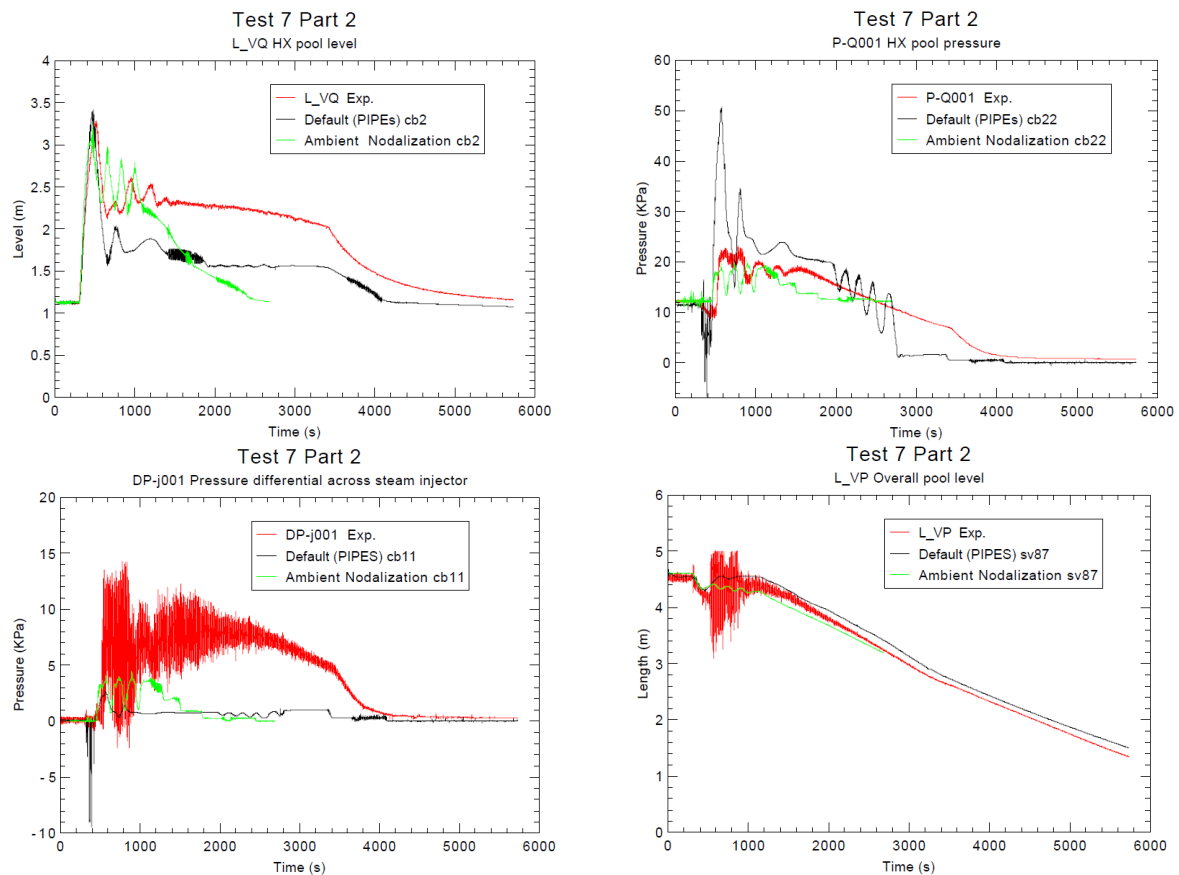
Based on the conclusion from comparison between PIPE nodalisation and VESSEL nodalisation, lowering the HXP pressure in the transient is critical to prevent HXP levels from reduction early. Therefore, another nodalisation test is designed to verify this concept by connecting steam injector directly to an ambient boundary. Ambient nodalisation is named for this nodalisation. By this arrangement, the steam generated in HXP leaves the system directly and HXP will not be overly pressurised. The purpose is to verify the HXP pressure, HXP level and injector DP relationship. However, since the steam leaves the system, the transient last only for 2 000 seconds and execution failed. No attempt was made

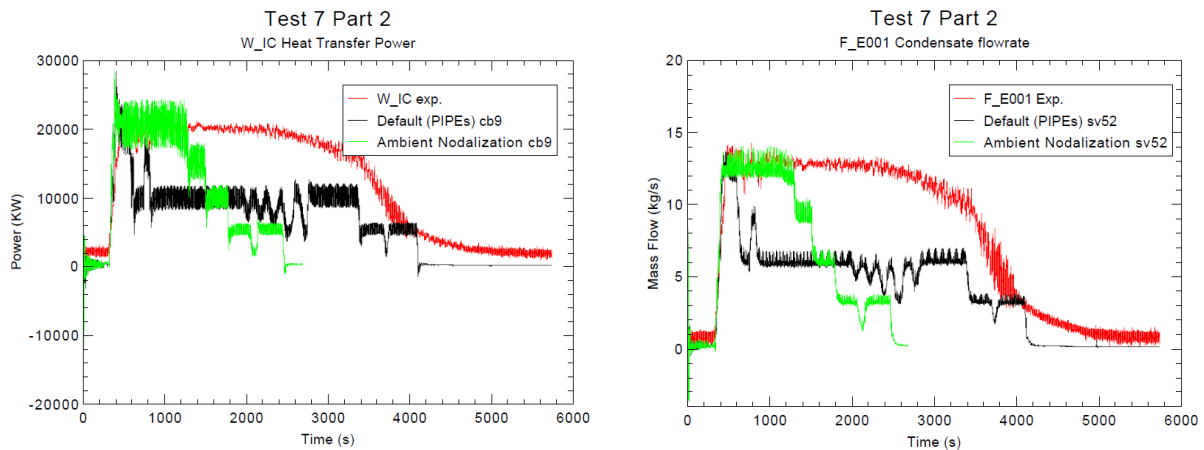
to extend the execution since the configuration is not the same as experiment and the results are enough to confirm the conjecture.

Figure 5.411 shows major parameter plots. Green curves represent ambient model results. In the HXP level plot, the ambient model level stays above 2.15 m much longer, until 1 200 s. After 1 200 s, level starts to reduce because OP starts to drain through the drain pipe and loses driving head. HXP pressure is much lower than the prediction by PIPE model. The pressure drop across the steam injector shows better agreement to data. More steam goes through the injector in the ambient model, which relieves the pressure buildup in HXP.

Ambient model OP level is lower than the PIPE model, which is expected since the water enters HXP more easily and steam from HXP does not return to OP. The heat transfer power (W-IC) and condensate flow (F_E001) in ambient model again confirm that they match data well if the HXP level is higher than top of the heat exchanger tubes. In this case, the HXP level holds up longer due to reasonable HXP pressure.

Figure 5.411. Comparison between PIPE nodalisation and ambient nodalisation





Based on the above nodalisation experiments, the main reason for an early reduction in the HXP level is the pressure buildup in HXP with heat transfer power of 20 MW. And the pressure buildup lies in insufficient pressure drop in the steam path. Another observation is the injector pressure drop (DP-j001) appears relatively smooth; no apparent instability occurs when steam contacts water in OP.

New modelling for the plume

In order to investigate the steam injector downstream nodalisation, all connections to the steam injector were closely examined. Focus was centred on the downward connection to OP through side junction because it affects the steam condensation directly. In the PERSEO facility, the steam injector is installed inside the overall pool and the injector nozzle exit is (at the height of 3.7 m) immersed in the OP tank water. According to the initial condition of DP-j001, the liquid interface is either inside the injector (Part 1 test) or outside (Part 2 test). Therefore, as HXP pressure rises, the steam gets pushed and condensed in OP. The interfacial area depends on the driving force created by the pressure difference between HXP and the local pressure near the interface.

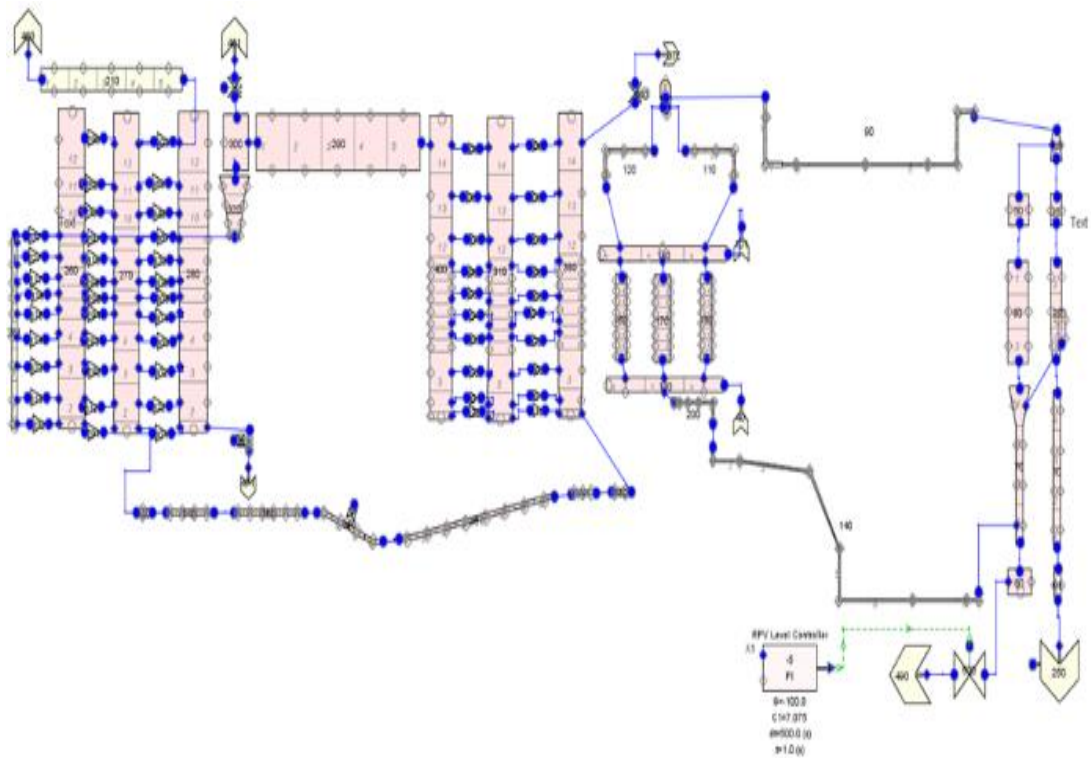
After checking the injector nozzle exit area, one significant issue was discovered, which is that the injector area was much smaller than the axial cross section area of the connecting pipe (PIPE 260), i.e. 0.0985 m^2 versus 9.7752 m^2 . The huge area difference is easily overlooked in 2-D nodalisation representation. This difference creates a significant problem from system code perspective. As the steam flow enters the connecting pipe cell, the steam mass and energy are homogenised in the much larger connecting cell. The steam mass and energy are insignificant to those of the connecting cell, i.e. Cell 9 of PIPE 260 in PIPE nodalisation. This implies that the steam from injector would not affect local fluid properties much at downstream of the steam injector. Besides, depending on the momentum force in the injector, the depth of steam penetration into OP determines the size of interfacial area. In the PIPE nodalisation, the benign instability response indicates there is benign condensation.

To remedy the deficiency, a separate PIPE component (PIPE 261) with small axial flow area is introduced and it is connected to the steam injector axially. This pipe represents the water region downstream the steam injector, named as “plume pipe” hereafter in this report. Since no measurement was available to inform the two-phase plume geometry, the injector nozzle exit area is assumed as the axial flow area and the nodal lengths are kept the same as the connecting pipe (PIPE 260). Cell 1-9 volume and flow area of PIPE 261 are deducted from PIPE 260 to preserve system mass and energy. Side junctions are used to connect PIPE 260 and PIPE 261 horizontally to preserve elevation. Cylindrical surface area of PIPE

261 at each cell is used as side junction flow area. This nodalisation is named Plume nodalisation in this study.

The SNAP representation is shown in Figure 5.412 below. Compared to PIPE nodalisation, the additional pipe (PIPE 261) is the only difference in this study. No other changes (elevation, area, volume, initial and boundary conditions) were made.

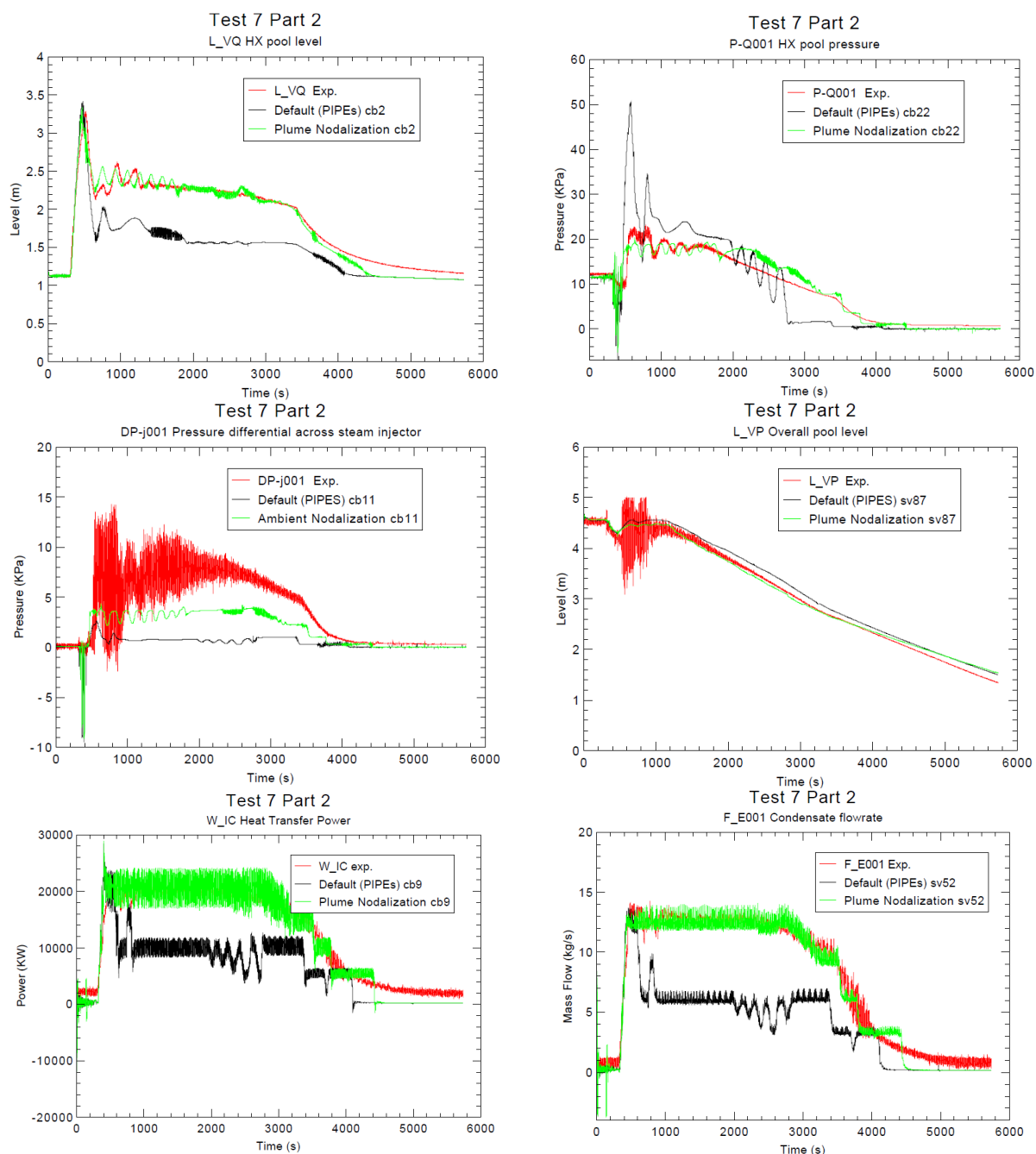
Figure 5.412. Plume nodalisation



Results

Like the trend observed in ambient nodalisation, the nodalisation change immediately affects the pressure prediction in HXP. Instead of pressure buildup, HXP pressure (P-Q001) matches data well, as shown in Figure 5.413. Once pressure buildup is corrected, the HXP level (L_VQ) is corrected as well to the right level and heat exchanger tubes are covered long enough as in the data. The pressure drop across the nozzle (DP-j001) is much improved compared to the PIPE nodalisation, and yet deviation still exists. Another encouraging finding is the instability observed in the Plume nodalisation in the early part of the transient (300 to 500 seconds). The observed instabilities in the Plume model are larger in frequency because TRACE graphic output frequency is set at 1 s instead of 0.25 s in data. OP level also improved since more water is able to enter HXP due to less pressure build up. The heat transfer across heat exchanger tubes has excellent agreement with data in terms of magnitude and timing. Same agreement is reached for the condensate flow rate in the primary loop.

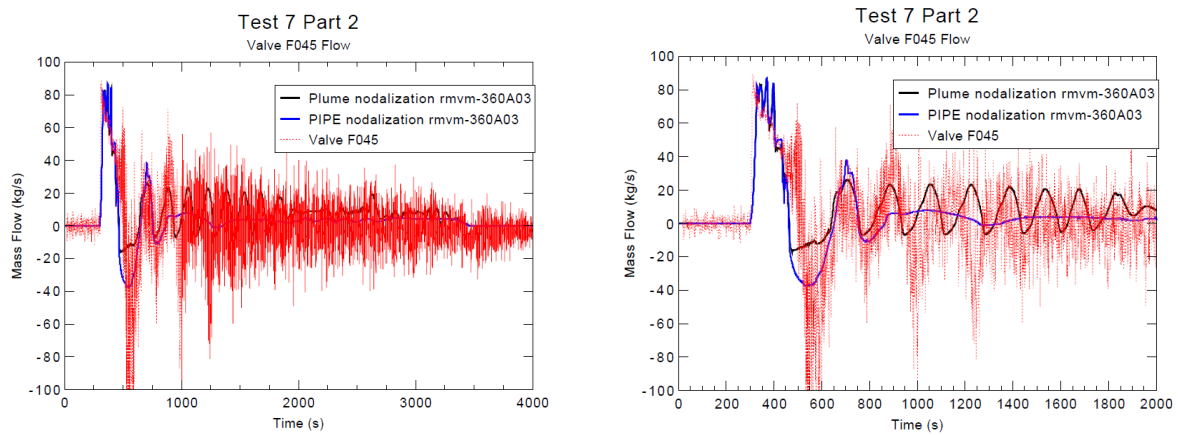
Figure 5.413. Comparison between Plume nodalisation and PIPE nodalisation



The pool connecting the pipe with valve F045 is an important boundary condition in this experiment. And yet no precise opening history is available for comparison. In this exercise, a valve opened to 80% in 26 s was prescribed to match the initial peak flow rate but no attempt was intended to match data for the rest of the transient. In this comparison, the valve opening position is kept the same as 80% for all nodalisations throughout the transient. Figure 5.414 shows the flow in both configurations. A separate zoom-in plot is attached for better comparison. In the PIPE nodalisation, the manometer oscillation between two pools was not apparent, and yet the first reverse flow was stronger due to stronger initial pressure buildup. In the Plume nodalisation, the manometer oscillation

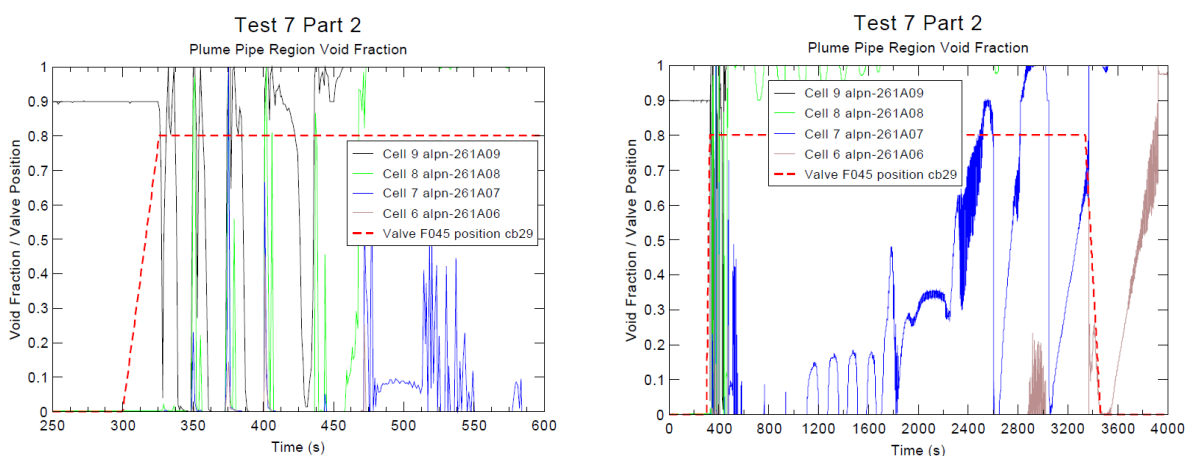
phenomenon becomes more apparent. Experimental data is noisier because output frequency is 0.25 s.

Figure 5.414. Connecting pipe (Valve F045) flow



In the earlier part of the transient (300 s to 600 s), the plume pipe component (PIPE 261) shows the steam jet effects and condensation. The void fractions of the cells in the upper part of the pipe are shown in Figure 5.415, with zoom-in plot for better comparison. Before the valve opens (until 326 s), top cell (Cell 9) void fraction is stabilised at 0.9 and void fractions of cells below (Cell 8,7,6) are 0.0. As the valve opens after 326 s, void fractions of cell 9 and 8 become oscillatory indicating strong condensation takes place as hot steam enters the pipe. Void fraction of cell 9 and 8 becomes 1.0 around 475 seconds. Void fraction of cell 7 starts to increase afterwards. The progression of void fraction shows the liquid interface is moving downward by the jet effect force. Void fraction at cell 6 starts to increase around 3 000 seconds.

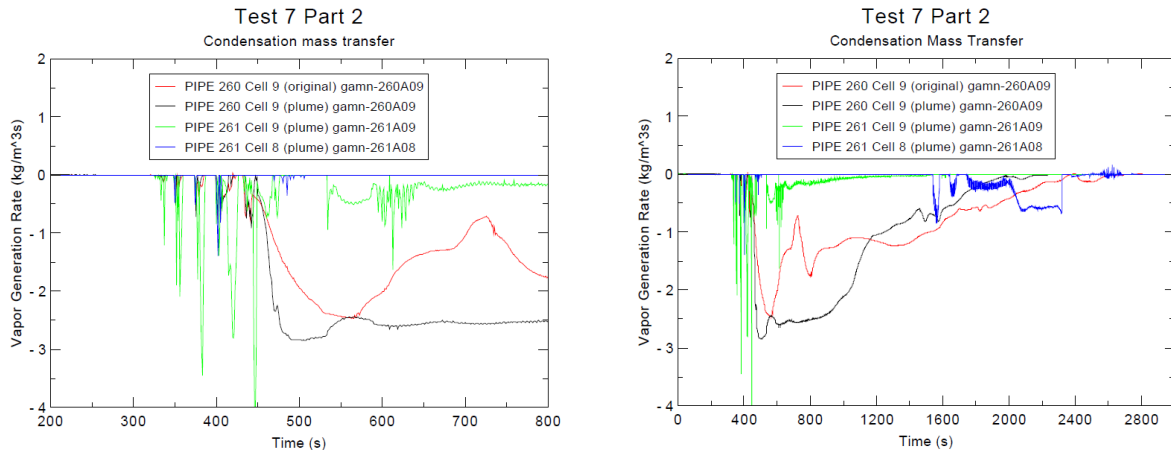
Figure 5.415. Plume pipe void fraction



As the liquid interface moves downward, more steam enters the liquid space. Not only in an axial direction: steam also travels to the large connecting cell (PIPE260) in a radial direction via the side junctions. Figure 5.416 shows the steam condensation rate (per unit volume) in the region downstream the steam injector. In the Plume nodalisation, condensation occurs not only in the plume pipe (PIPE 261), it occurs in PIPE 260 as well and is stronger than PIPE nodalisation. With combination of PIPE 260 and PIPE 261, more

condensation occurs in the Plume nodalisation. A zoom-in plot is attached as well for evaluation.

Figure 5.416. Condensation heat transfer comparison



Conclusion

The steam injector in the PERSEO experiment is an important component in the natural circulation path. It determines the steam flow rate from heat exchanger pool to overall pool as the superheated steam is driven by the HXP liquid interface during the valve opening transient. The original PIPE nodalisation with steam injector connected to the overall pool pipe with side junction results in insufficient condensation in the downstream region of the steam injector. It causes pressure to build up in the heat exchanger pool, and in turn prevents the liquid level from staying above the top of the heat exchanger tubes.

Several nodalisation experiments were tested to identify the cause of this model deficiency. The first intent was to use VESSEL components to eliminate the gravity force issue of using 1-D pipes with side junctions. The results did not improve the result. A second intent was to improve the downstream pressure of the steam injector by connecting the injector to an ambient boundary. It significantly improved the level response for a short period. However, the configuration makes the natural circulation path interrupted and makes the configuration different than in the test facility. However, it confirms that the issue lies in the nodalisation of the fluid region downstream of the steam injector.

By adding an additional pipe component to represent the plume region under the steam injector, the PIPE nodalisation deficiency is improved significantly. The new plume pipe connects to the steam injector axially and connects to the overall pool with side junctions. The arrangement increases steam condensation downstream of the steam injector and relieves the heat exchanger pressure build-up, which results in excellent level response and heat transfer power prediction. All major parameters in the loop agree with the data excellently. As seen in the data, the instabilities predicted by the model are observed more clearly in the early period as hot steam contacts the cold liquid surface. Compared to the PIPE nodalisation, the Plume nodalisation shows much better performance in capturing direct steam condensation phenomena.

SECTION 6: CONCLUSIONS

According to the simulation results, TRACE is doing an excellent job in steam condensation on the heat exchanger tube inner wall. The level and pressure response of the heat exchanger pool and overall pool agree excellently with data in terms of magnitude and

timing. Regarding heat transfer capability, as the heat exchanger pool level is maintained above 2.15 m, where heat exchanger tubes were fully covered, TRACE predicts averagely 21 MW heat transfer for both the Part 1 and Part 2 tests. In the partial filling scenario of the Part 1 test, TRACE shows excellent heat transfer agreement with data as well.

TRACE has lesser performance on the direct steam condensation. It shows on the deviation of the heat exchanger pool relative pressure and steam injector pressure drop. However, the instability of direct steam condensation was captured well through a smaller separate pipe component to model the fluid directly under the steam injector. The steam condensation below the steam injector creates a low pressure point to relieve the pressure buildup in the heat exchanger pool. It is important to determine the level response in the heat exchanger pool.

The steam inlet and condensate outlet temperature prediction were reasonable. The outlet condensate temperature has much lesser agreement with data if liquid temperature is used since the thermal couple location is filled with two-phase mixture. A mixture temperature is used in TRACE instead and it shows much more reasonable agreement with data.

Relative to level and pressure response, heat exchanger pool fluid temperature has less agreement with the data, in particular the later part of the transient when the level drops. It might be contributed by a larger nodalisation. However, the physical trends are in the right direction.

In the overall pool, the temperature predictions match reasonably well with data in terms of the heat-up rate. The discrepancy in the later part has to do with a separate pipe used in the TRACE modelling. The TRACE signal is extracted from the larger pipe portion of the overall pool. The temperature mixing effect between the larger pipe and the smaller pipe may cause significant uncertainty. Thus, the temperature discrepancy is expected.

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5.2.12. VTT

SECTION 1: GENERAL INFORMATION

- Organisation: VTT (Finland)
- Contact person/author: Ismo Karppinen
- Code: Apros 6.09
- Computing environment:
 - Operative systems Windows 7
 - RAM 16 GB
 - CPU characteristics Intel Core i7-4 900MQ

SECTION 2: DESCRIPTION OF THE CODE USED

The Apros® thermal hydraulics model library contains three different thermal-hydraulic models for one-dimensional water/steam/gas flow (homogenous, 5-equation and 6-equation), one for single-phase flow, one for the containment and one for the steady state flow with tank dynamics. Thermal hydraulics is described using the conservation equations for mass, momentum and energy and correlations for friction and heat transfer [5.2.12 1].

All except the steady state model employ the staggered-grid discretisation scheme. In this scheme the state variables such as pressure and enthalpy are calculated in the middle of the mesh, i.e. in a node. The flow related variables are calculated at the border of two nodes, i.e. in a branch. The water and steam properties are obtained as a function of pressure and enthalpy by using a fast look-up table. All models include the effects of pumps and valves as well as the calculation of boron concentration. A unified model for non-condensable gases and transport of chemicals and radioactive species is used in all the two-phase flow models.

All the thermal-hydraulic models include several correlation sets, which can be changed according to the plant modelling needs. The heat conduction solution can be connected to all the thermal-hydraulic models by defining model specific heat transfer modules. The heat flows between solid heat structures and fluid are calculated from empirical correlations. The heat transfer regimes are defined on the basis of wall, fluid and saturation temperatures. Separate parts of a simulated system can be described with different thermal-hydraulic models. The different models can be interconnected by using special connection modules.

The numerical solution of the PDEs is based on the implicit or semi-implicit time integration (implicit Euler). The control volume approach is used in the space discretisation and staggered grids are adopted, i.e. control volumes of the momentum equation are displaced with respect to the control volumes of the pressure and enthalpy equations. Upwind scheme is used in convective terms. The implicit time integration results in solving a set of algebraic equations for each time step. The algebraic equations are linearised and then solved iteratively (for 3-and 6-equation models). The thermal-hydraulic solution algorithm is an adaptation of the SIMPLER method.

The performance of the Apros code has been validated extensively (more than 70 cases) by modelling different test facilities and comparing calculation results to a large set of measurements from selected transients. The thermal-hydraulic models have been validated against a set of separate effect tests and integral tests (integral tests mean e.g. test facility experiments, such as ISPs - International Standard Problems). The thermal-hydraulic and

reactor models together with the automation system have been thoroughly tested by comparing calculation results with real plant data.

SECTION 3: DESCRIPTION OF THE NODALISATION

The heat exchanger, heat exchanger pool (HX pool), steam duct (injector) and the overall pool (OP) are modelled in detail. The steam vessel and feed and condensate lines serve mainly as boundary conditions and are modelled more approximately. The HX pool is modelled taking in account stratification and mixing with convective flows. Although the Apros code is one-dimensional, a 2D modelling approach is applied. This kind of approach is justified, since the driving force for flows in the pool are mainly density differences and velocities and flow momentums are small.

The heat exchanger tubes are modelled with a heat exchanger process component of Apros to allow easy refining of nodalisation, if needed. The heat exchanger tube bundle is divided in 20 axial nodes. The tube material is set to Inconel 600 (heat conductivity and capacity of Apros material library are used). The pool, on the elevation of the heat exchanger is modelled with a pipe component to create similar axial nodalisation than in the heat exchanger. The cross-flow branches between the tube bundle and the open pool are created with a SCL script to be able to easily regenerate the branches if the nodalisation is refined. Condensation heat transfer inside the heat exchanger tubes was modelled with Chen interfacial heat transfer correlation (in Apros the user can choose between Shah and Chen correlations or Nusselt interfacial heat transfer models). Boiling heat transfer coefficient on the tubes surface is calculated with Thom correlation.

The walls of the HX pool are defined to take in account heat losses to the environment. The heat structure components in the lowermost and topmost nodes (HXP_WALL0 and HXP_WALL5) include also the floor and the ceiling of the pool. Information of the pool walls was not available, but the walls were modelled as 5 mm stainless steel.

The overall pool of PERSEO facility is modelled with a tank process component of Apros. The steam duct is connected on elevation 3.300 m, from bottom of the tank. The tank is divided axially in to 15 equal nodes, with height of 0.3867 m, each. This division of the overall pool in to nodes results with connecting the steam duct into the 9th node of the tank component. The boil of line of the overall pool was connected to an external with saturated steam and air in 20°C temperature and 0.1 MPa pressure.

Mixing in the overall pool is modelled with diffusion coefficients of the branches. Turbulent or eddy diffusion caused by the momentum of the steam flow from the steam duct is propositional to the steam velocity and fades away by the distance of the duct. In the case of an ejector, which directs the flow mainly in one direction the diffusion coefficient can be estimated with equation:

$$D = \frac{u}{l} c$$

Where:

D = diffusion coefficient

u = steam velocity in the duct

l = distance from the duct

c = coefficient depending on the geometry, etc.

The diffusion coefficients are calculated with user functions of the Apros codes (i.e. boundary condition modules). In this case the scaling coefficient $c = 0.001$ gave reasonable mixing of the pool. The mixing model with diffusion coefficients was originally implemented in the Apros code to model mixing between parallel channels, e.g. in reactor pressure vessel, but could be also used to model mixing between vertical nodes.

According measurements, steam in the feed line was slightly overheated and both steam pressure and temperature fluctuated throughout the test. Therefore, in the final model, the steam source was not connected to the steam Vessel but, directly to the feed line. The measured steam pressure and temperature were set as boundary conditions, with 10 s filtration to reduce oscillations.

The vacuum breaker in the steam duct was modelled with a one-directional valve setting upstream pressure to 0.1 MPa, i.e. pressure in the steam duct and in the HX pool could not drop below 0.1 MPa. An additional vent valve was set parallel to the vacuum break to ease setting initial conditions and to prevent pressure build up during initialisation. Both the vacuum breaker and the vent valves were connected to an external point with saturated steam and air in 20°C temperature and 0.1 MPa pressure.

The most important measurements of the PERSEO facility were modelled either with measurement components of the Apros or with so-called boundary condition modules (i.e. user functions) to account for e.g. differences in elevations of the measurements and the centre elevation of the corresponding node in the Apros model.

Table 5.79. Summary of the main nodalisation characteristics of the PERSEO model

	Number of hydraulic volumes	Number of junctions	Number of heat structures	Overall volume (m ³)
Vessel	1	-	-	14.1
Steam line (Feed line)	9	10	-	1.24
HX	22	21	22	1.826
Condensate line	7	8	6	0.27
HXP	49	74	49	26.98
Steam duct	8	9	-	10.45
OP	15	14	-	173.07
Heat transfer area HX (m ²)	tubes: inside 31.35 m ² , outside 34.47 m ² , collectors: inside 9.82 m ² , outside 11.69 m ² total: inside 41.17 m ² , outside 46.16 m ²			
HX heat structure axial nodes number	20 + 2 in collectors			
HX heat structure radial nodes number	tubes: 2 collectors: 5			

Figure 5.417. Sketch of the nodalisation of the main components

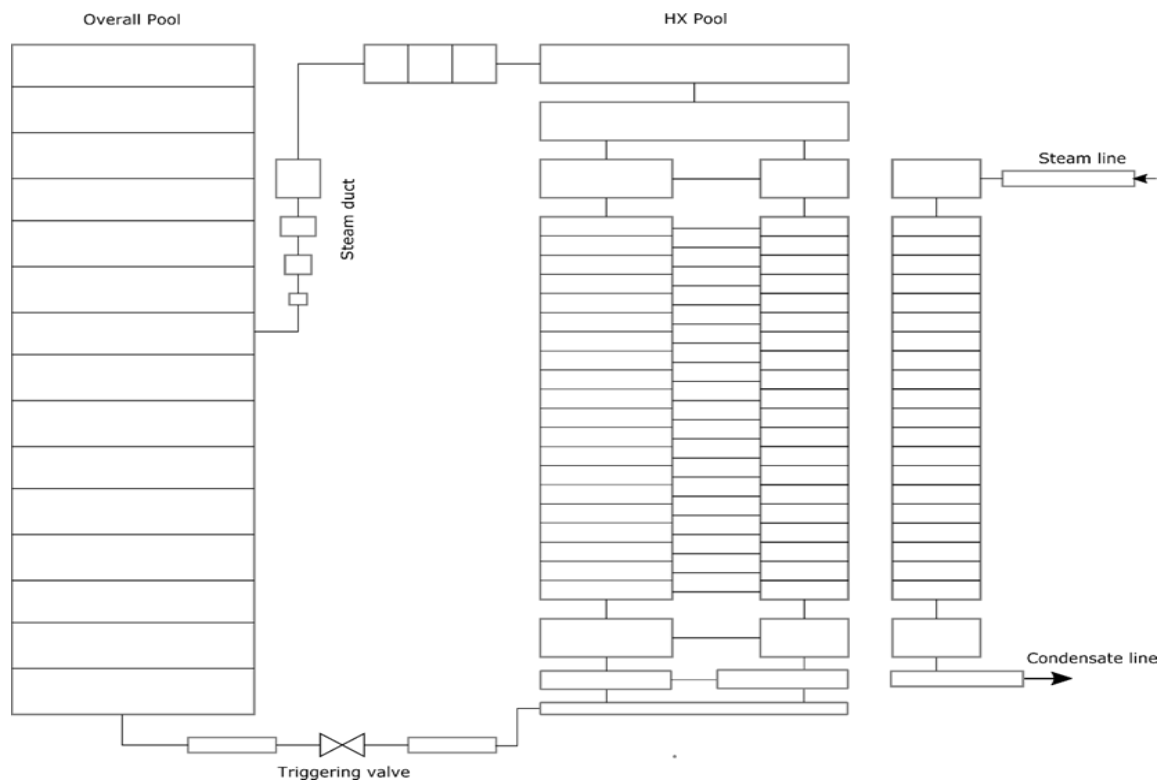
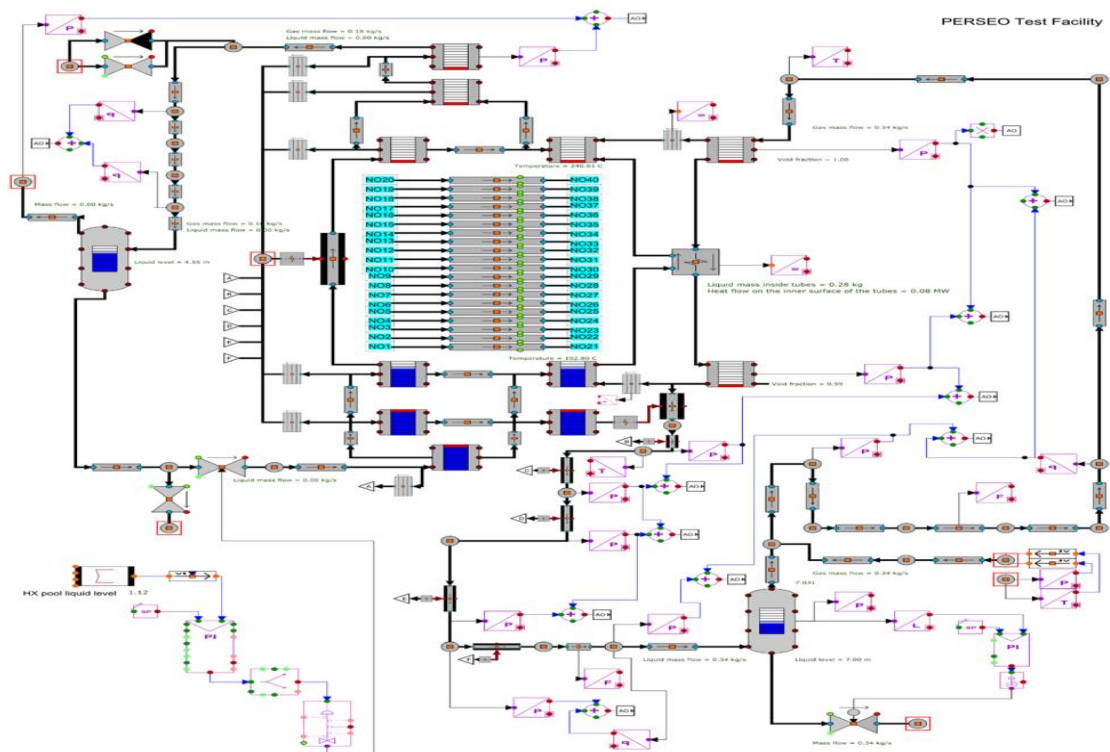


Figure 5.418. Flow diagram of the complete Aprós model (in initial state for Test 7 Part 2)



SECTION 4: RESULTS

TEST 7 Part 1

VTT joined in the benchmark in a very late phase and it might have missed some information on the initial and boundary conditions of the tests. The initial conditions were set according to the best understanding of the tests, but there are still some uncertainties and possible lack of information of the tests. Especially the initial quite high steam flow to the condenser and consequent initial heat exchanger power of about 2 MW remained inexplicable. Heat losses could probably not explain this high power before startup of the system.

In the initial state the HX pool was filled with mixture of steam and air. Air mass fraction was set to 80%. Measured temperatures of the heat exchanger headers were 280°C, but measured gas temperatures in the top, middle and bottom sections of the pool were 220, 200 and 120°C, respectively. Moreover, temperature close to the pool wall was about 100°C lower than in centre part, closer to the steam line (T-Q008 and T-Q032 at elevation 3.42 and T-Q006 and T-Q030 on elevation 5.14 m). It seemed obvious that heat losses or heat capacity of the pool walls effect initial temperatures. Therefore, the pool walls with heat transfer to the environment were modelled. However, it was not possible to set and maintain in the steady state run, the actual initial temperature distribution in the model. The temperature differences tend to even out during the initial “steady state” phase of the test. However, the initial temperatures were tried to set close to the measured ones. Initial gas temperature in HX pool bottom (T-Q037) and middle sections (T-Q034) were higher than measured, due to heat transfer from the hot heat exchanger. Heat losses from the HX pool in the initial conditions were about 150 kW. Liquid level was set on elevation 0.2 m, i.e. 0.1 m above the bottom of the HX pool. Heat transfer from the hot primary side heat exchanger resulted with gas expansion and water evaporation from the pool bottom. To prevent pressure, build up the vent valve, connected to the steam duct, was kept open until the triggering valve was opened.

The overall pool was filled with 15.5°C water (collapsed level 4.65 m). Boundary condition at the outlet of the overall pool boil-off line was set to 0.1 MPa pressure and 20°C temperature using gas atmosphere.

In the initial state of the test the heat exchanger power was about 2 MW, which is equal of condensing 1.3 kg/s of steam (Latent heat of steam in 7 MPa pressure is 1 505 kJ/kg). Reason for this initial steam condensation was not available and the initial steam flow was not tried to reproduce.

The feed line pressure and temperature was read from the measured data and set as boundary conditions. Even though the data was filtered with 10 s filtering time, pressure fluctuated quite a lot and caused fluctuations of pressure difference between the HX upper and lower headers (DP-003). Especially during the first 500 s the pressure difference went up and down periodically.

After the initial “steady” phase, at time 10 475 s., the HX pool vent valve is closed and the triggering valve (F-045) is set to fully open, with opening time of 10 s. The triggering valve is controlled by a PI controller to close the valve when HX pool water level reaches 1.3 m. Due to fully opening the valve, the water level in the HX pool increases faster than in the experiment and the triggering valve is soon closed. It would have been better to open the valve only partly, but no information of the valve opening nor the flow through the valve was available. At time 10 621 s the triggering valve is again set to open by increasing the

set point of the valve control logic. The valve opens only slightly before it is set to close at time 10 655 s. During the closure of the triggering valve, 10 655 – 11 039 s, the Apros model do not reproduce the slow boil-off of the HX pool. Steam flow through the injector and condenses, but not sufficiently. The HX pool water level stays constant during that time period. Steam flow and velocity in the steam injector is quite high (see Figure 5.439 of gas velocity in the injector), but the Apros model did not reproduced sufficiently the strong condensation shocks and pressure oscillations caused by contact of subcooled water and steam. After opening again, the triggering valve at time 11 039 s, the HX pool water level increases to its maximum, about 3.5 m at 11 260 s. The triggering valve is set to close at time 11 260 s. The Apros model somewhat over predicts the maximum condensation power of the heat exchanger.

The overall pool water level decrease until 11 000 s is quite well reproduced, except the fact that the level decreases faster than in the experiment (due to fully opened valve). Overall, the calculated pool water levels, both in the overall pool and in the HX pool (L-VQ and L-VP), are in good agreement with the measured data. Heat transfer in the heat exchanger (W-IC) reduces stepwise as the water level drops in the HX pool. This behaviour could be improved by dividing the heat exchanger and the pool in smaller nodes.

Overall pool temperature distribution was well simulated. The diffusion coefficients (Figure 5.440) increased with increasing steam flow in the injector and resulted with mixing the pool close to measured data (Figure 5.441). The maximum temperature difference between the steam injection point (node nine in the pool) and the pool bottom is about 20°C at 12 000 s, reducing to about 15°C, when steam injection ceases in the end of the test (Figure 5.442).

The heat exchanger power as a function of the HX pool water level is plotted in Figure 5.443. When the triggering valve is opened at time 11 039 s and the pool water level increases, both the calculated and the measured, HX power follows the lower curve. Until about 2.5 m water level and corresponding 15 MW power the Apros simulation is in good agreement with the experiment. When the water level increases further, the Apros model overpredicts HX power. The first peak of condenser power is reached at 3.1 m water level. When the water level decreases from 3.5 m to 2.25 m the measured power stays quite constant, but the power calculated by the Apros code slightly increases, reaching its maximum, about 24 MW at a water level of 2.25 m (the upper and left curves both for the experiment and the simulation).

Figure 5.419. Test 7 Part 1 - Steam flow rate

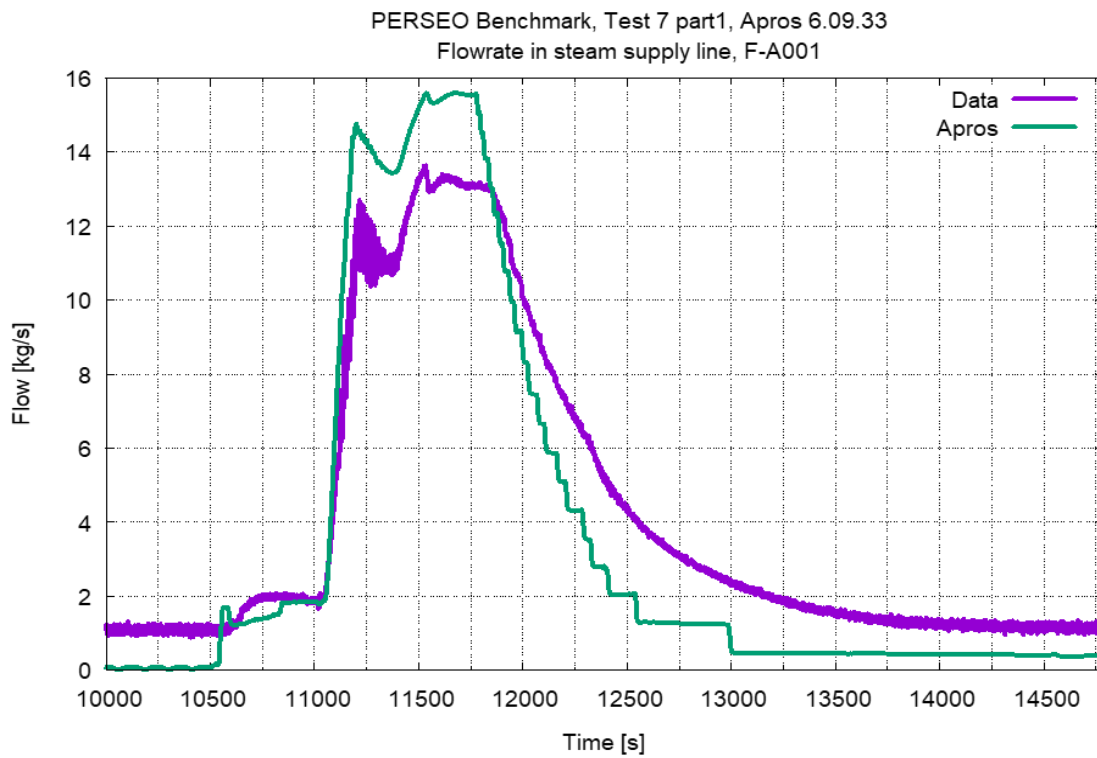


Figure 5.420. Test 7 Part 1 - Condensate flow rate

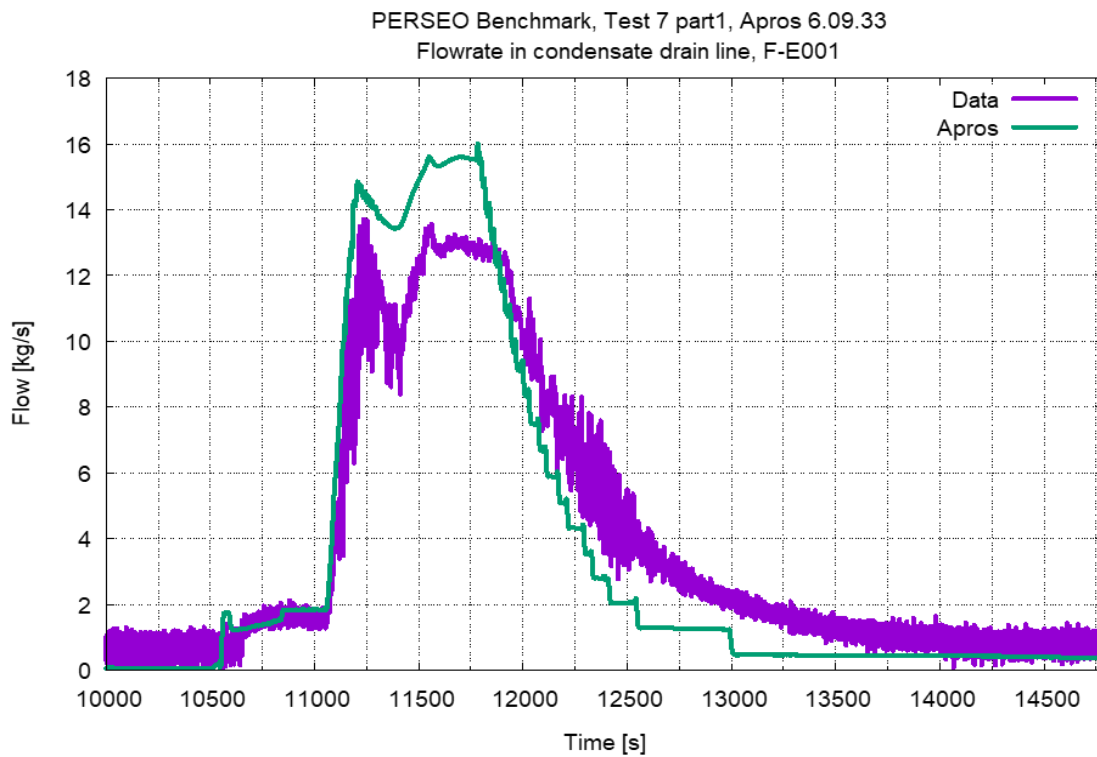


Figure 5.421. Test 7 Part 1 - HX power

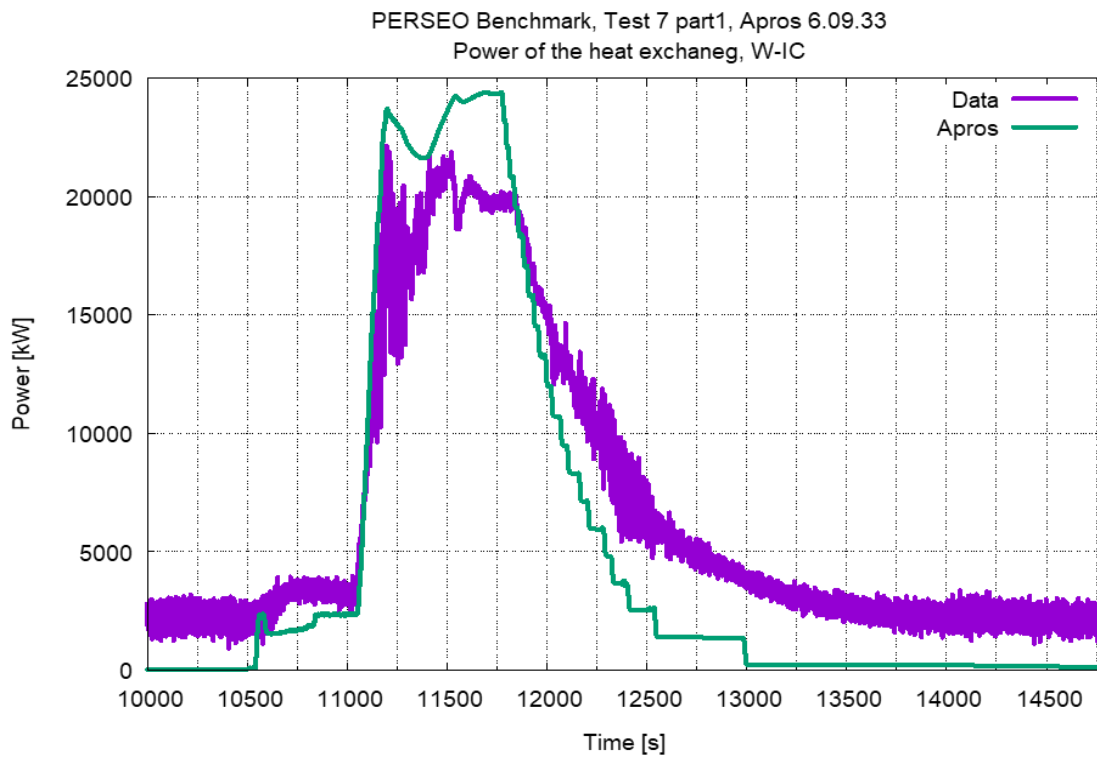


Figure 5.422. Test 7 Part 1 - Primary pressure

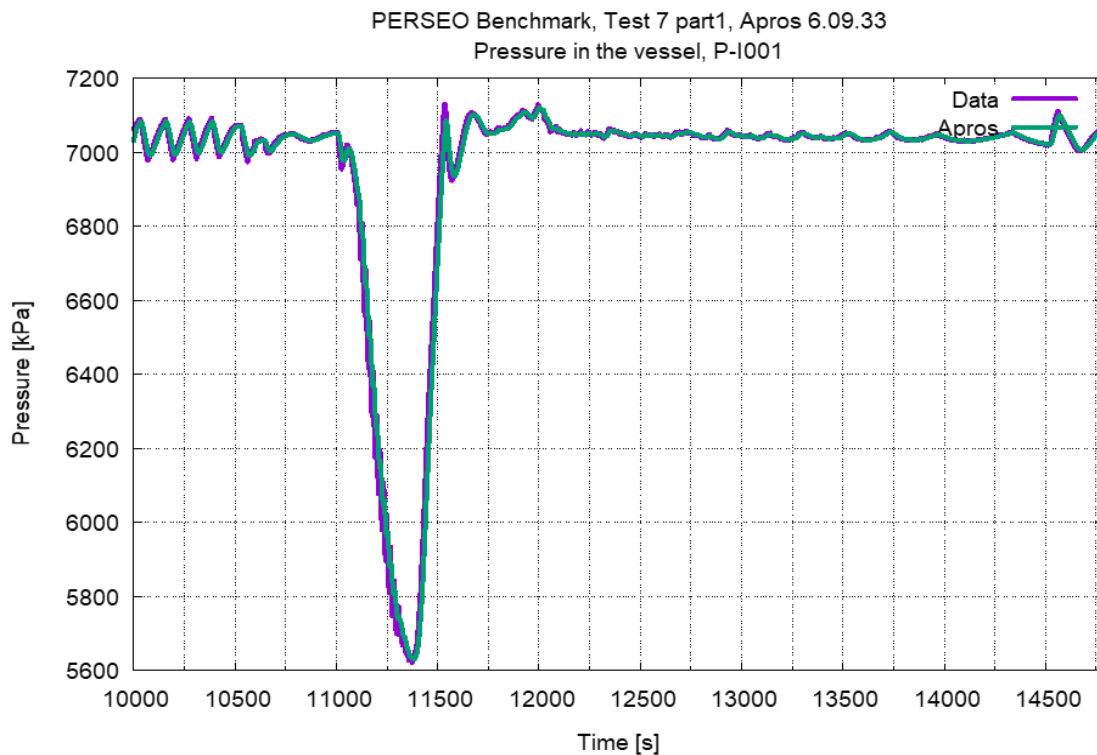


Figure 5.423. Test 7 Part 1 - HX inlet fluid temperature

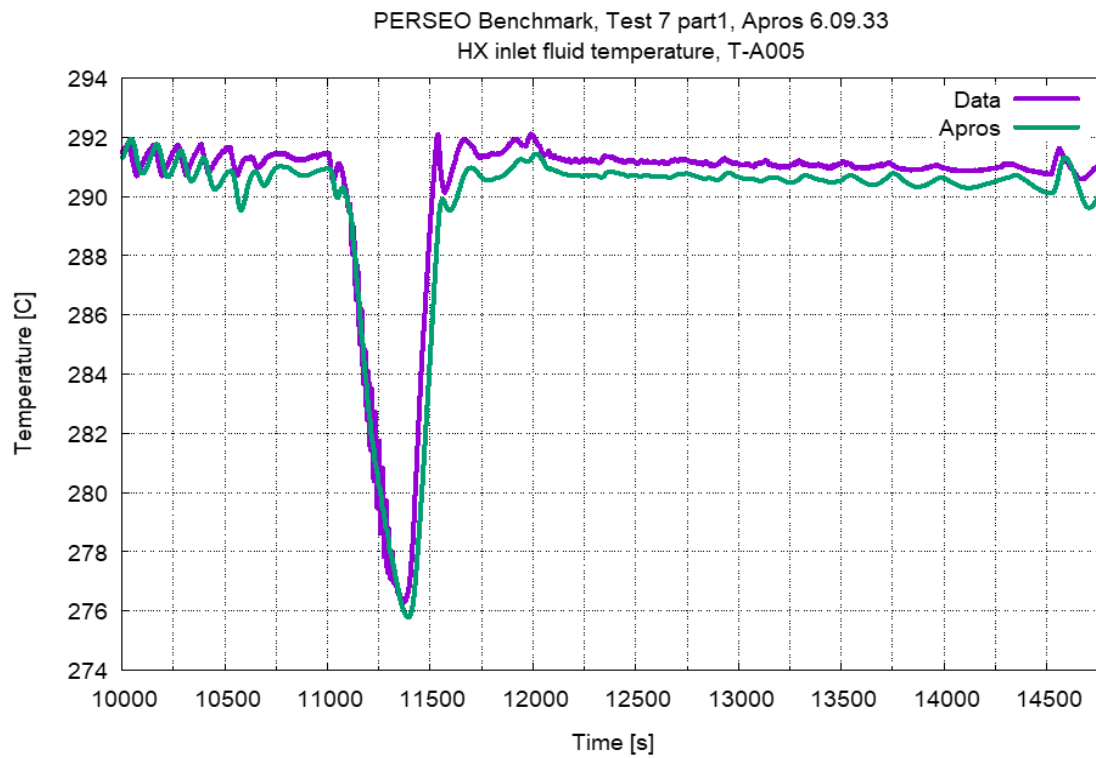


Figure 5.424. Test 7 Part 1 - HX outlet fluid temperature

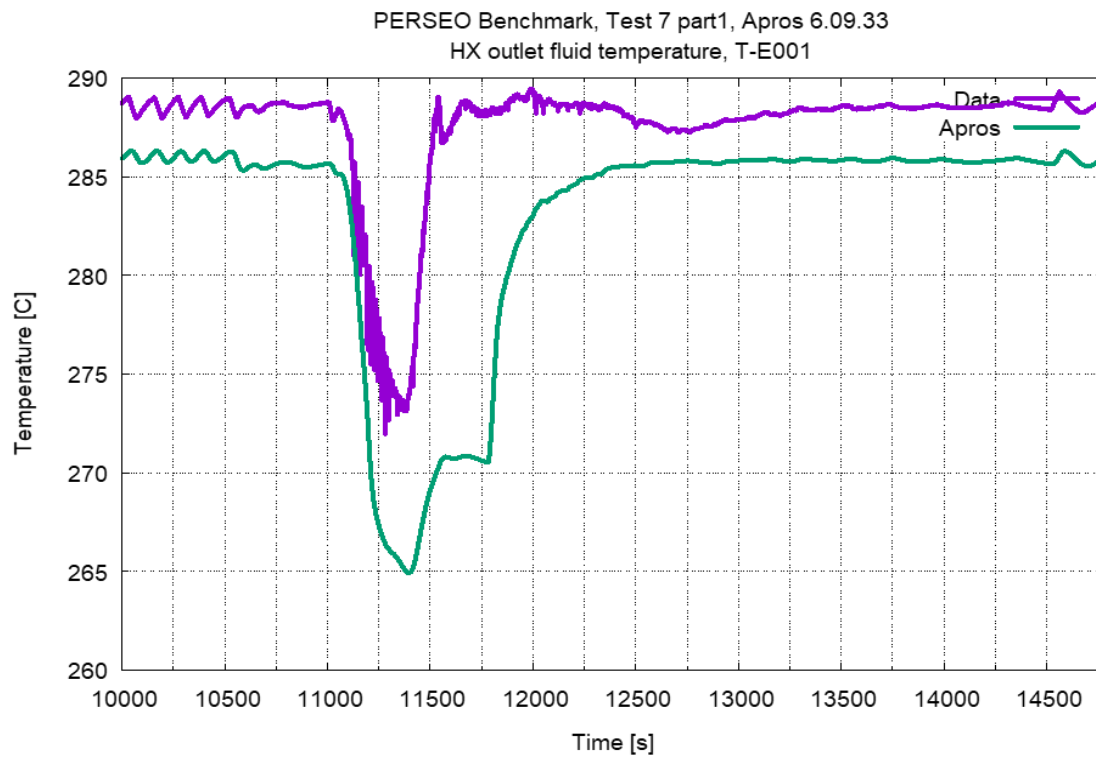


Figure 5.425. Test 7 Part 1 - HXP level

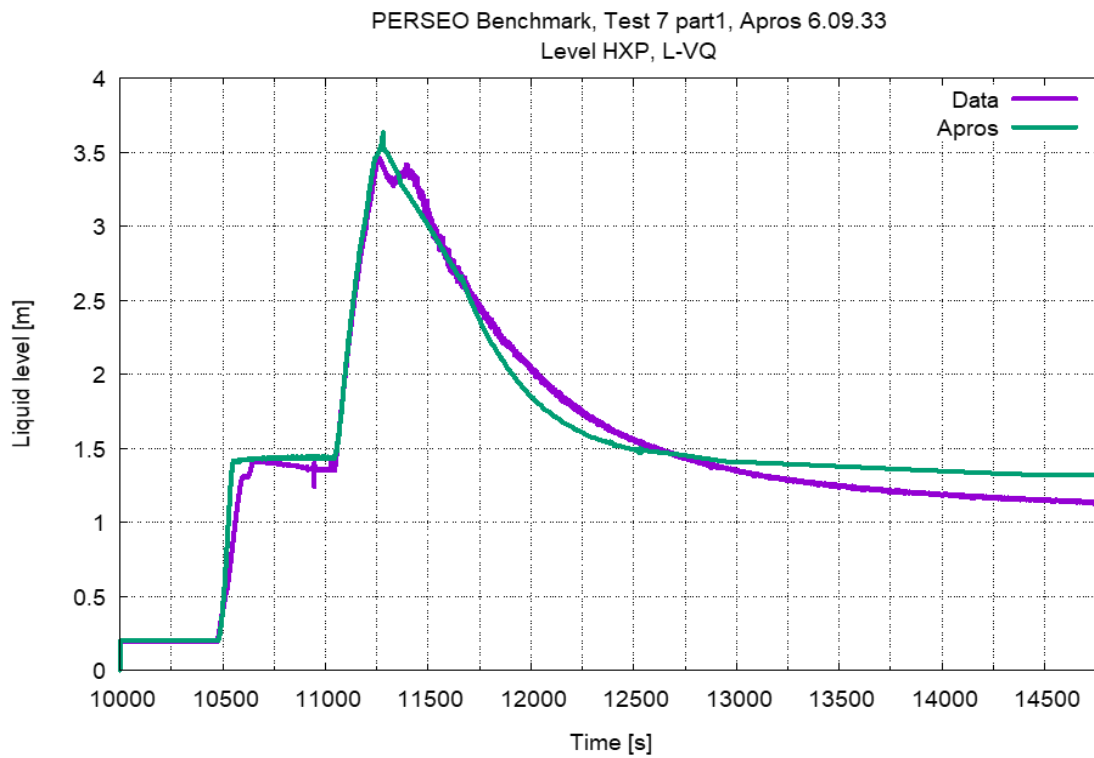


Figure 5.426. Test 7 Part 1 - OP level

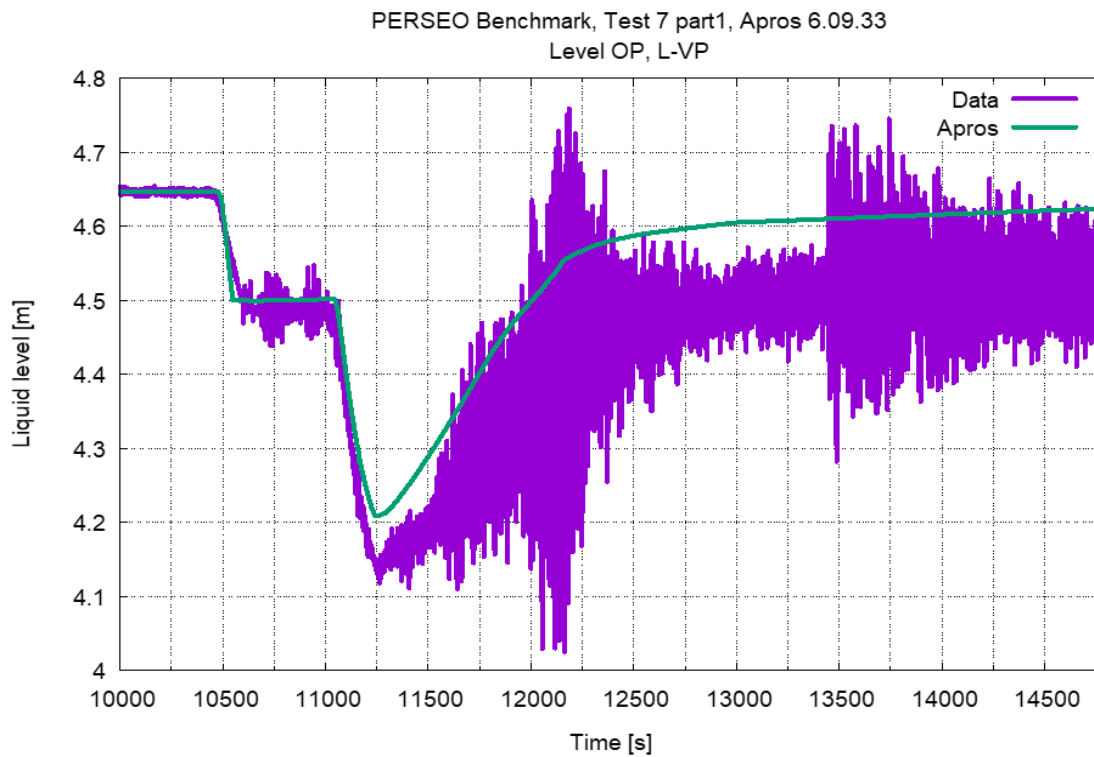


Figure 5.427. Test 7 Part 1 - Fluid temperature HXP bottom

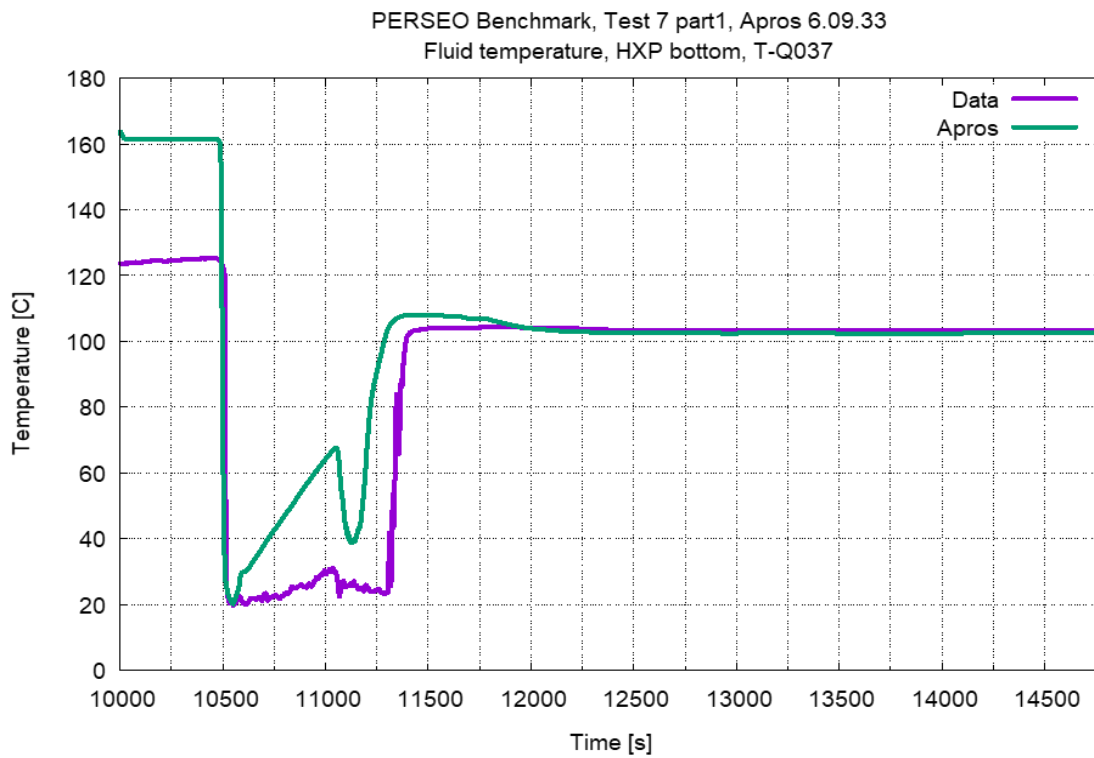


Figure 5.428. Test 7 Part 1 - Fluid temperature HXP middle

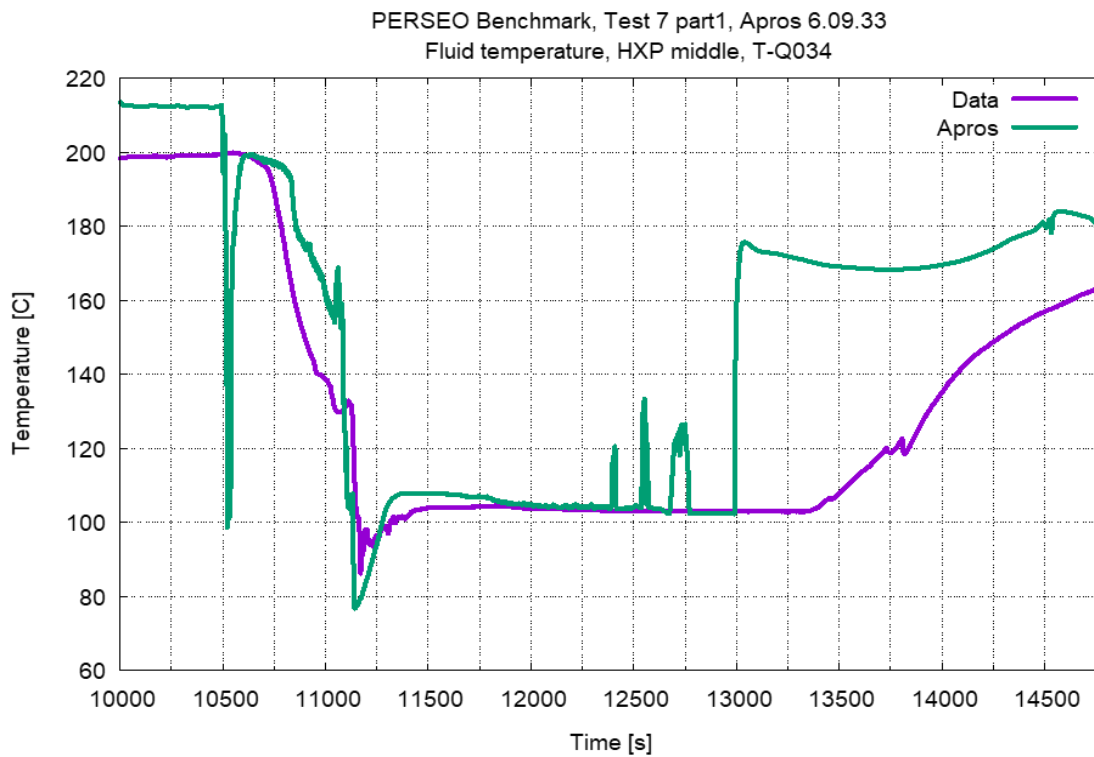


Figure 5.429. Test 7 Part 1 - Fluid temperature HXP top

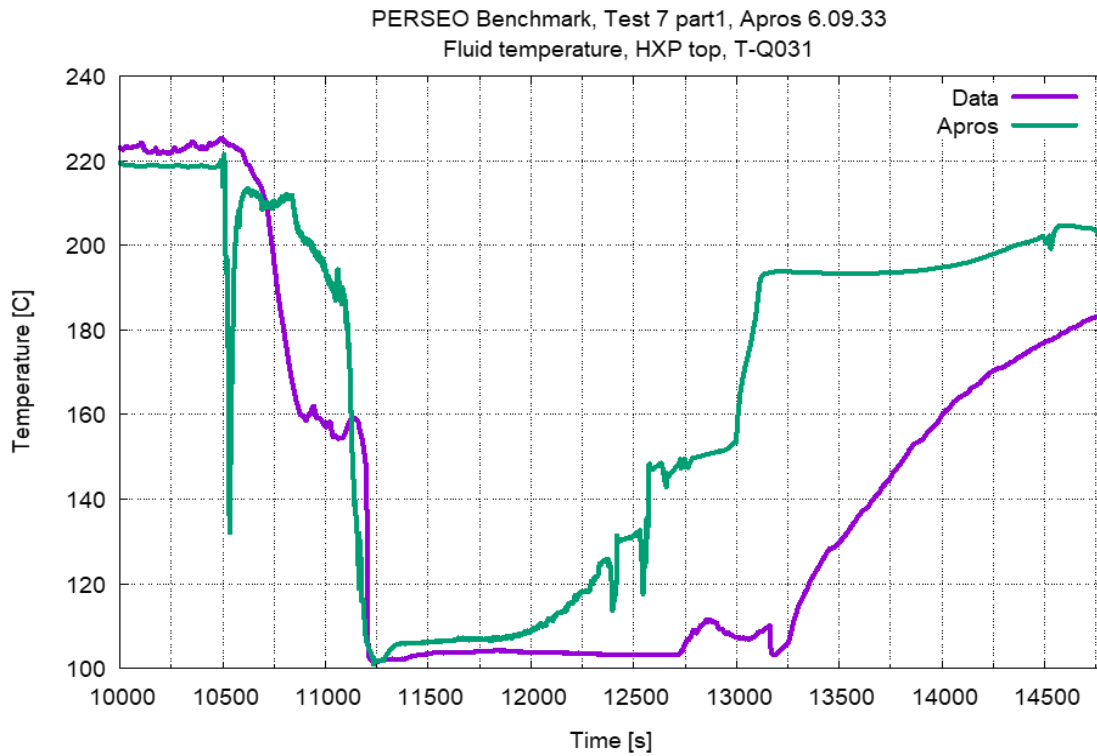


Figure 5.430. Test 7 Part 1 - Relative pressure HXP top

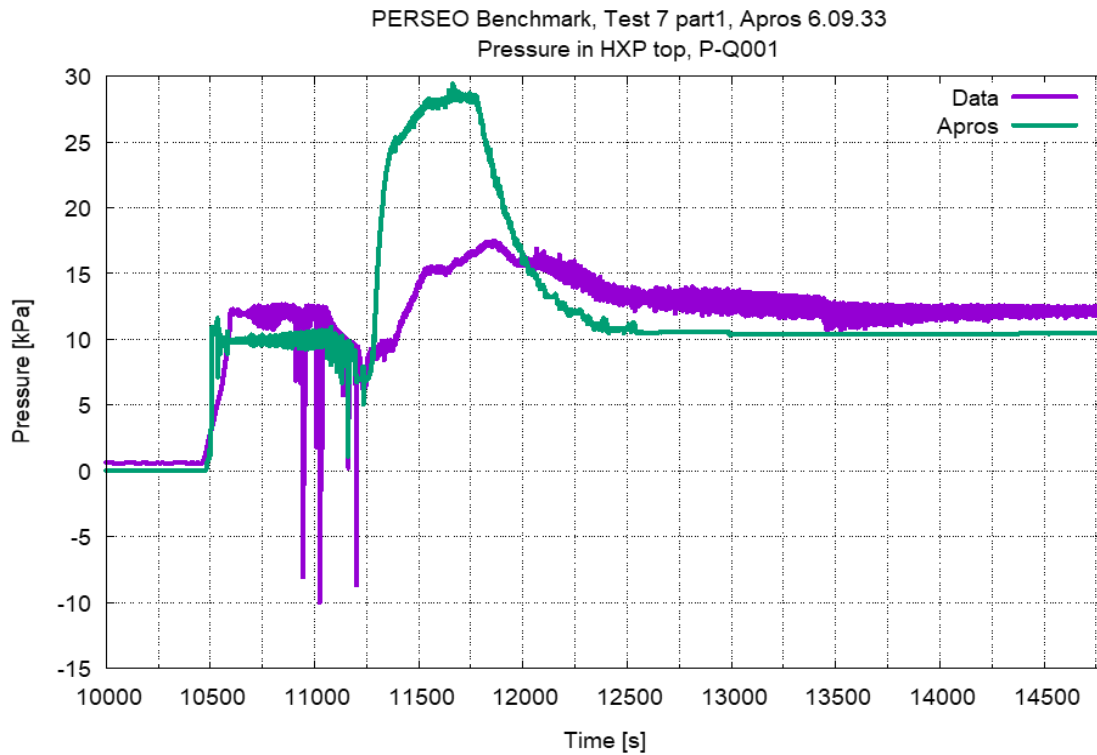


Figure 5.431. Test 7 Part 1 - Fluid temperature OP bottom

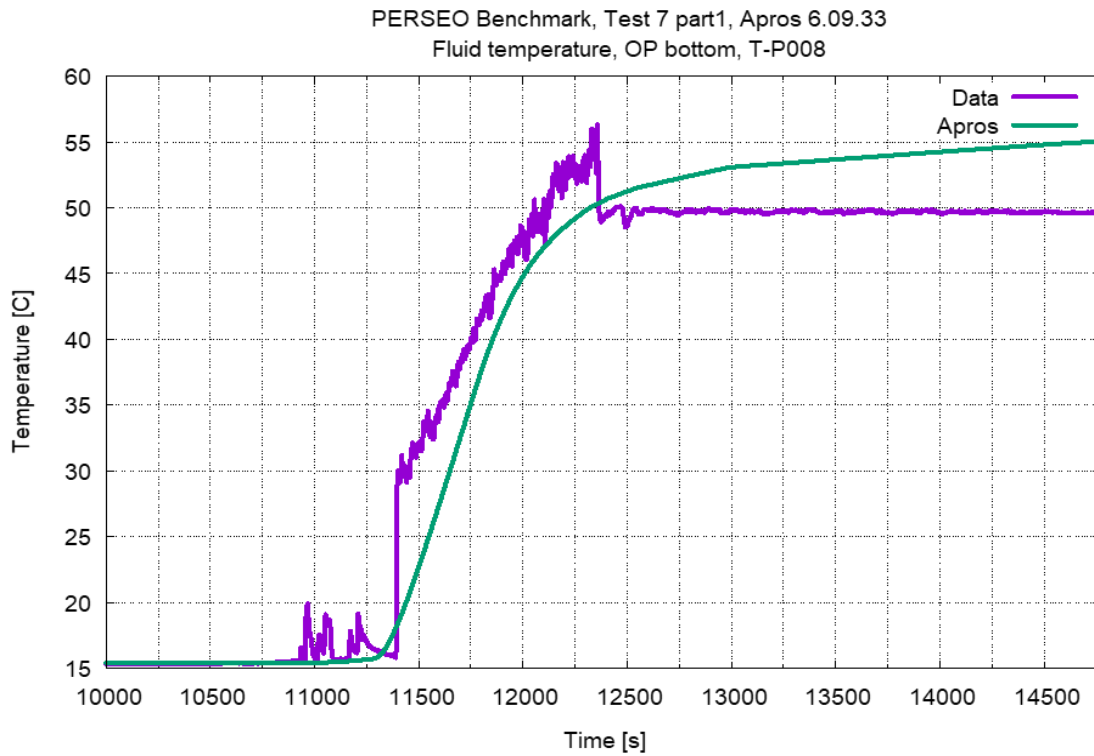


Figure 5.432. Test 7 Part 1 - Fluid temperature OP top

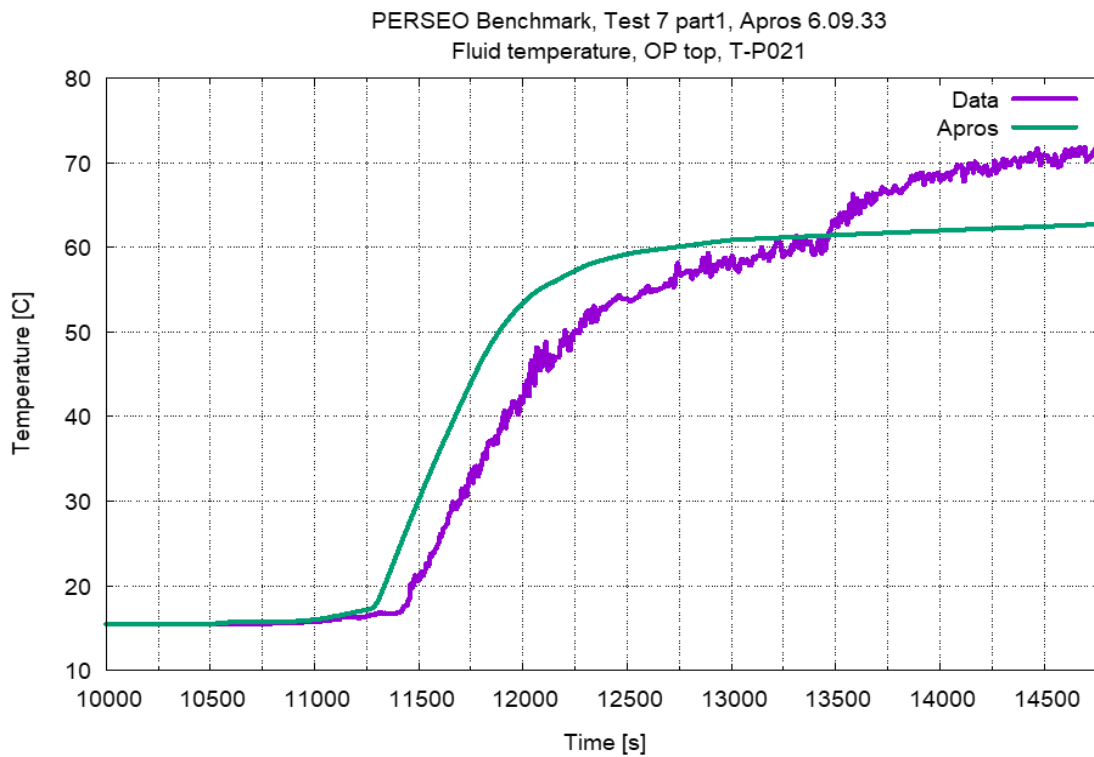


Figure 5.433. Test 7 Part 1 - Differential pressure HX upper - lower header

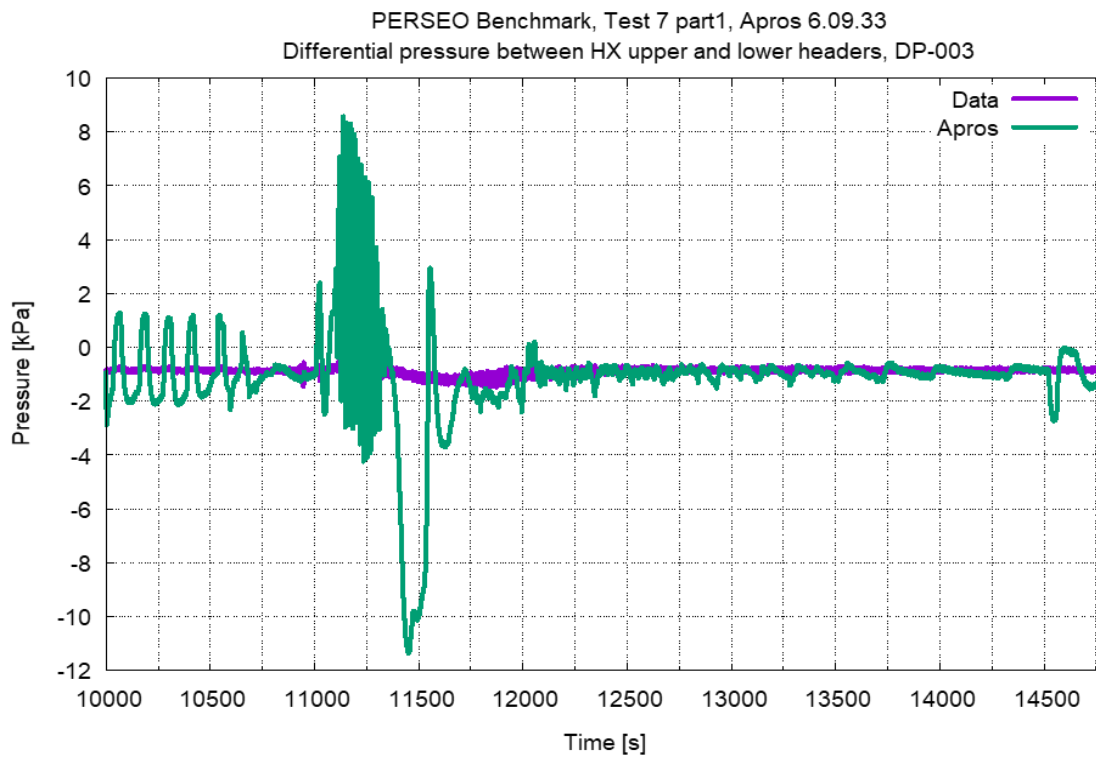


Figure 5.434. Test 7 Part 1 - Differential pressure -steam duct injector

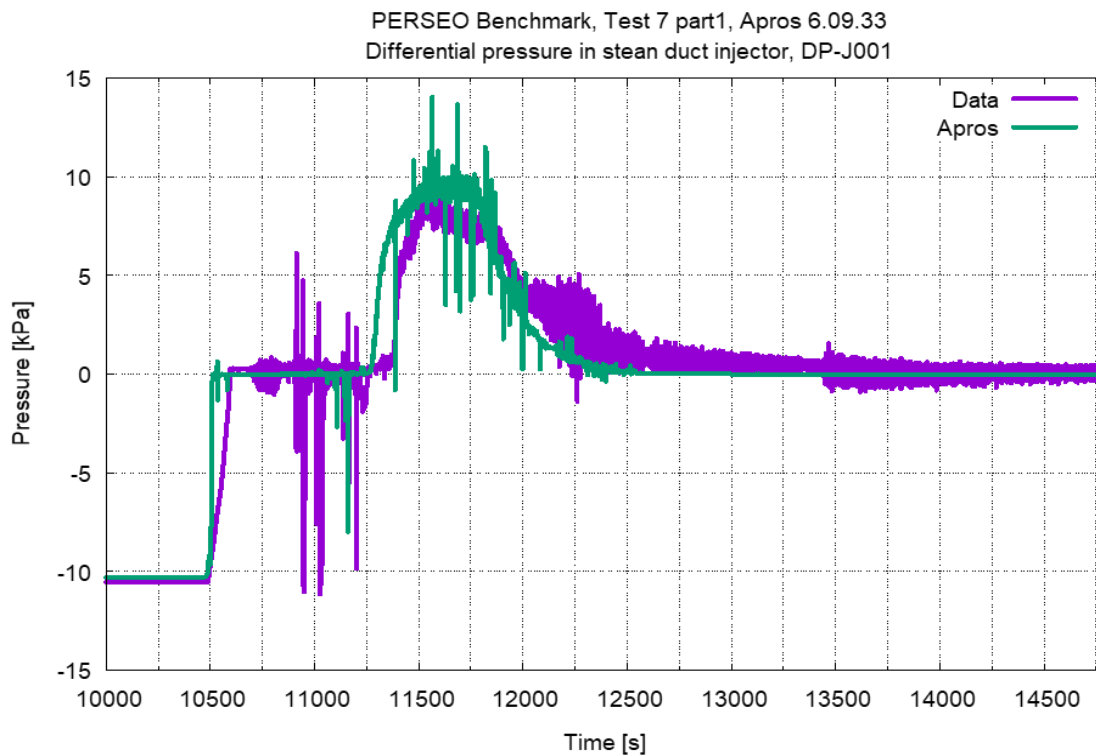


Figure 5.435. Test 7 Part 1 - Wall temperature HX upper header

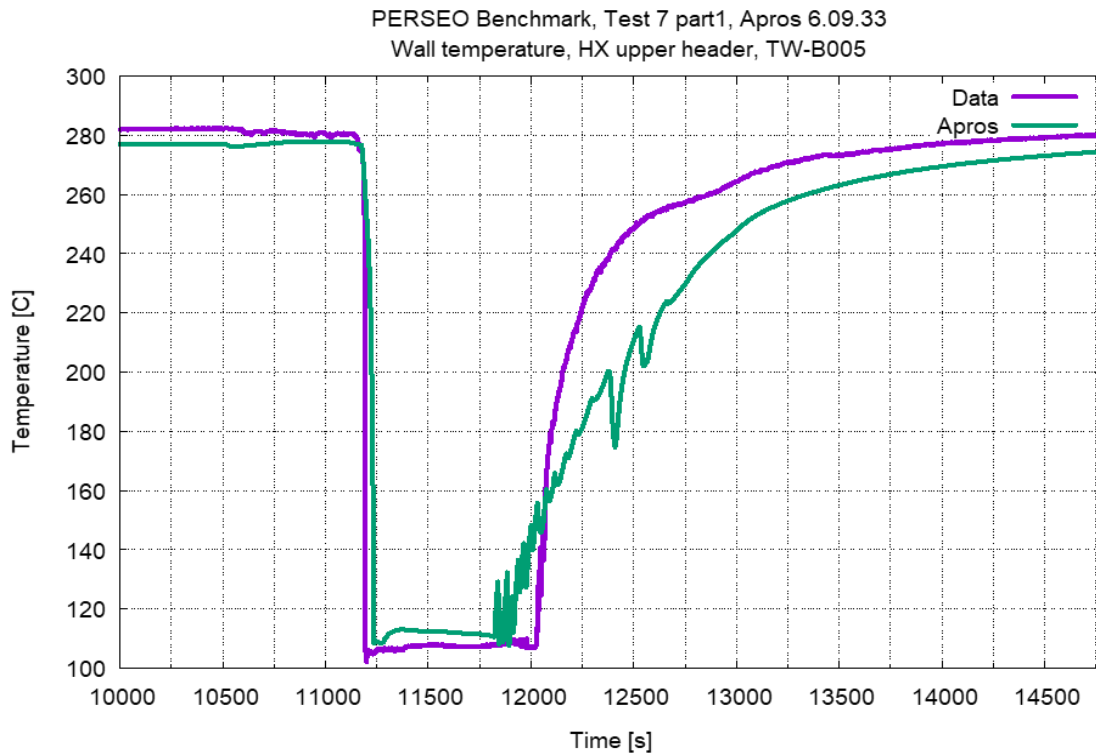


Figure 5.436. Test 7 Part 1 - Wall temperature HX lower header

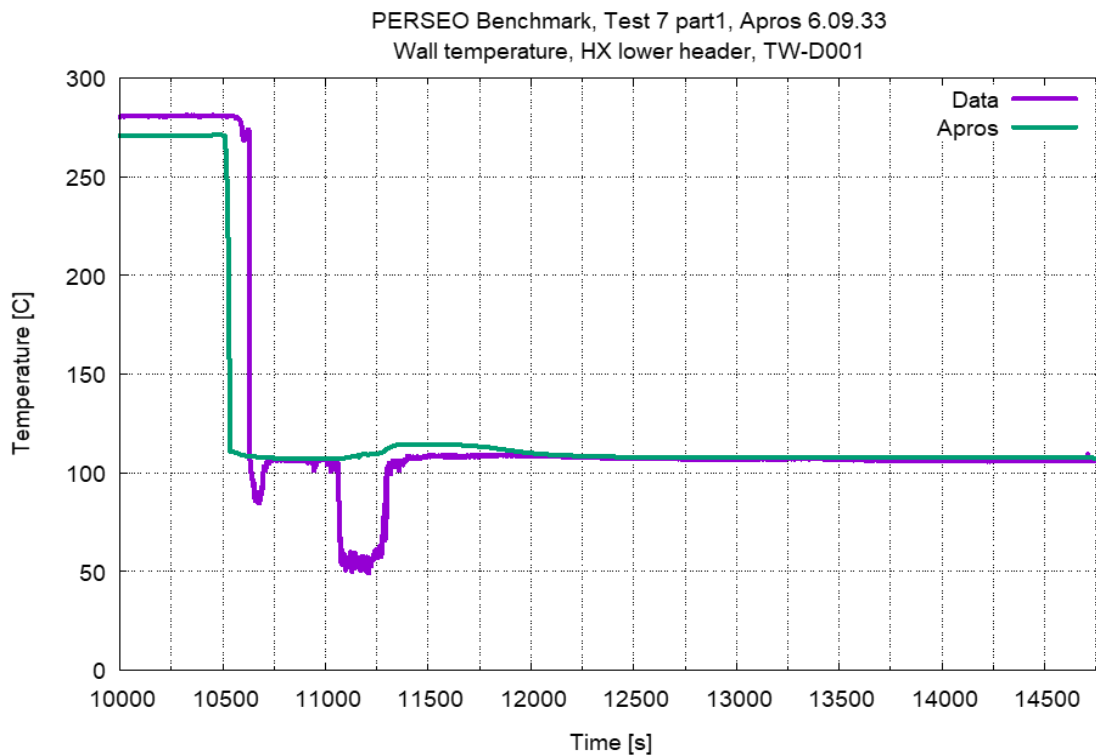


Figure 5.437. Test 7 Part 1 - Position of the triggering valve

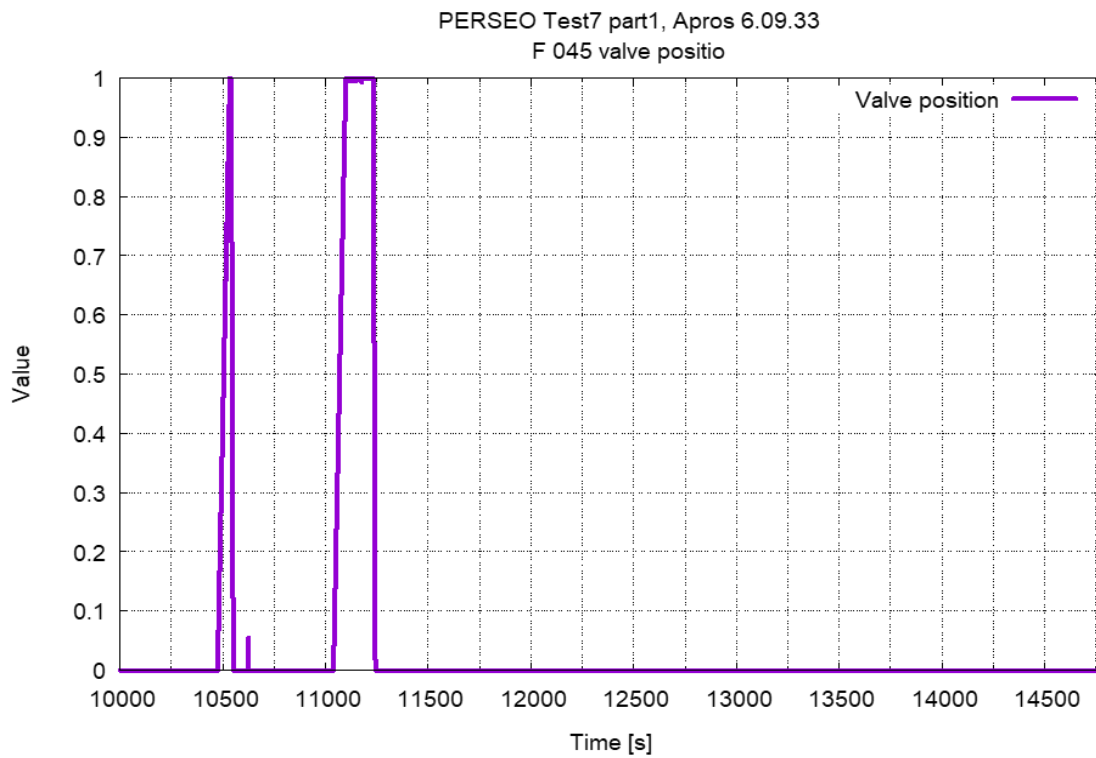


Figure 5.438. Test 7 Part 1 - Flow through the triggering valve

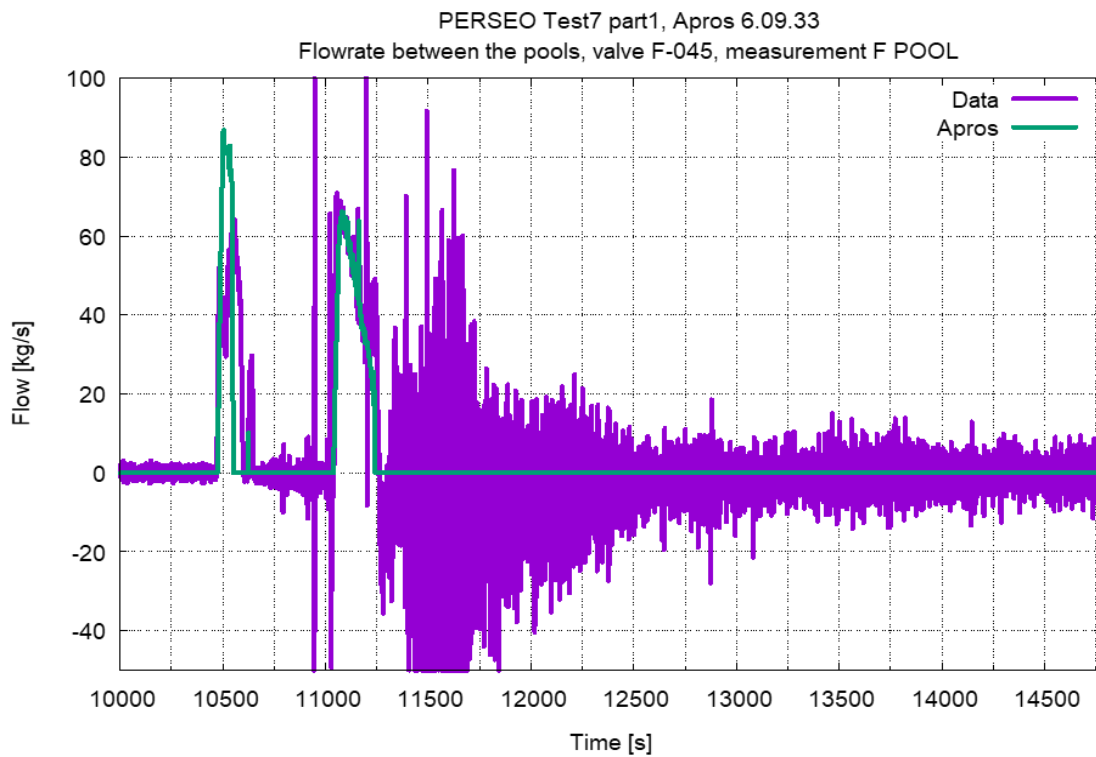


Figure 5.439. Test 7 Part 1 - Gas velocity in the injector

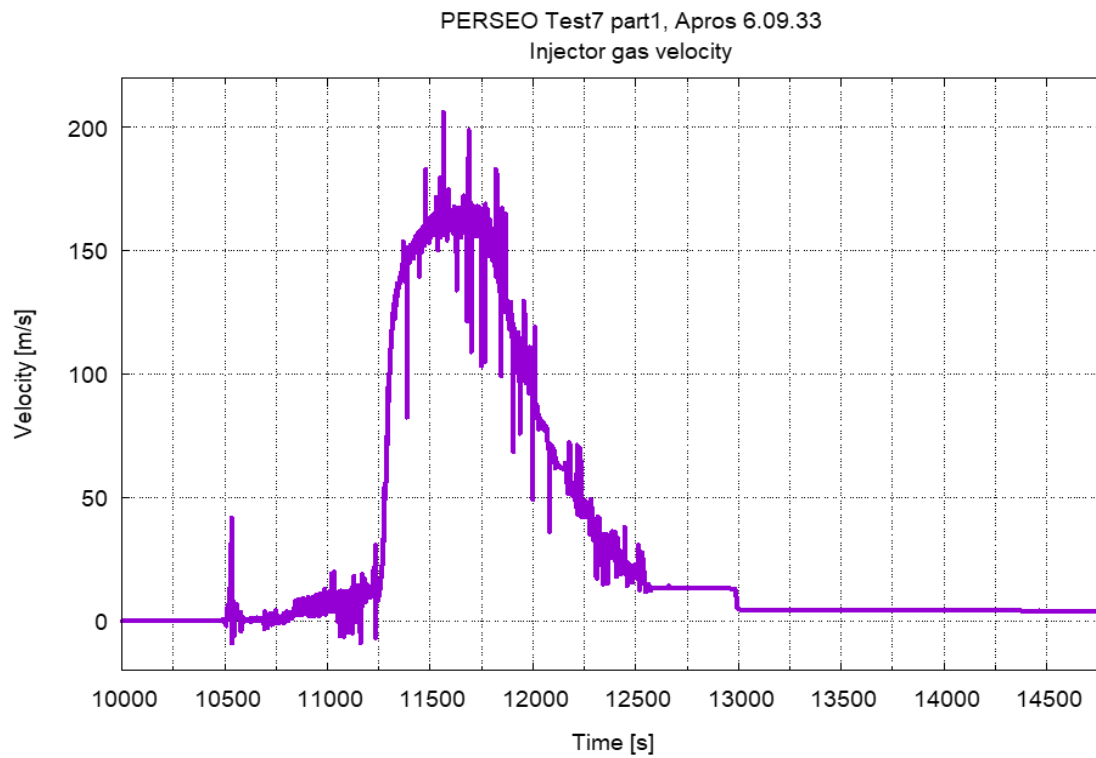


Figure 5.440. Test 7 Part 1 - Diffusion coefficients in the overall pool

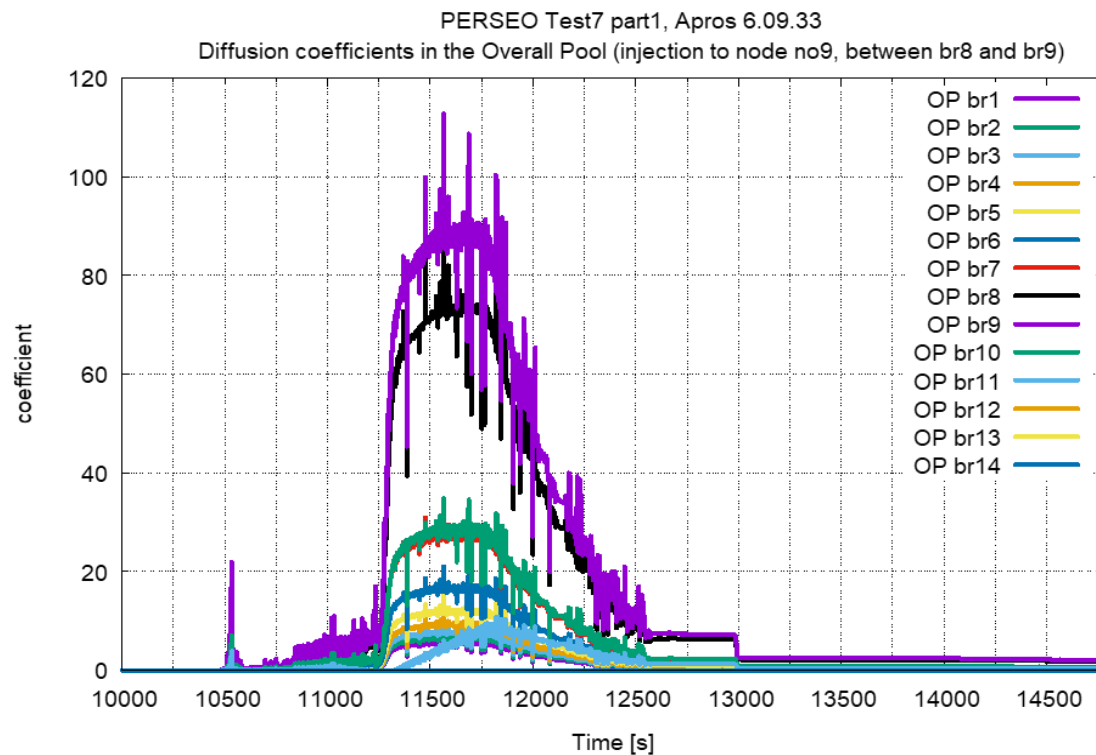


Figure 5.441. Test 7 Part 1 - Fluid temperature in overall pool bottom and top

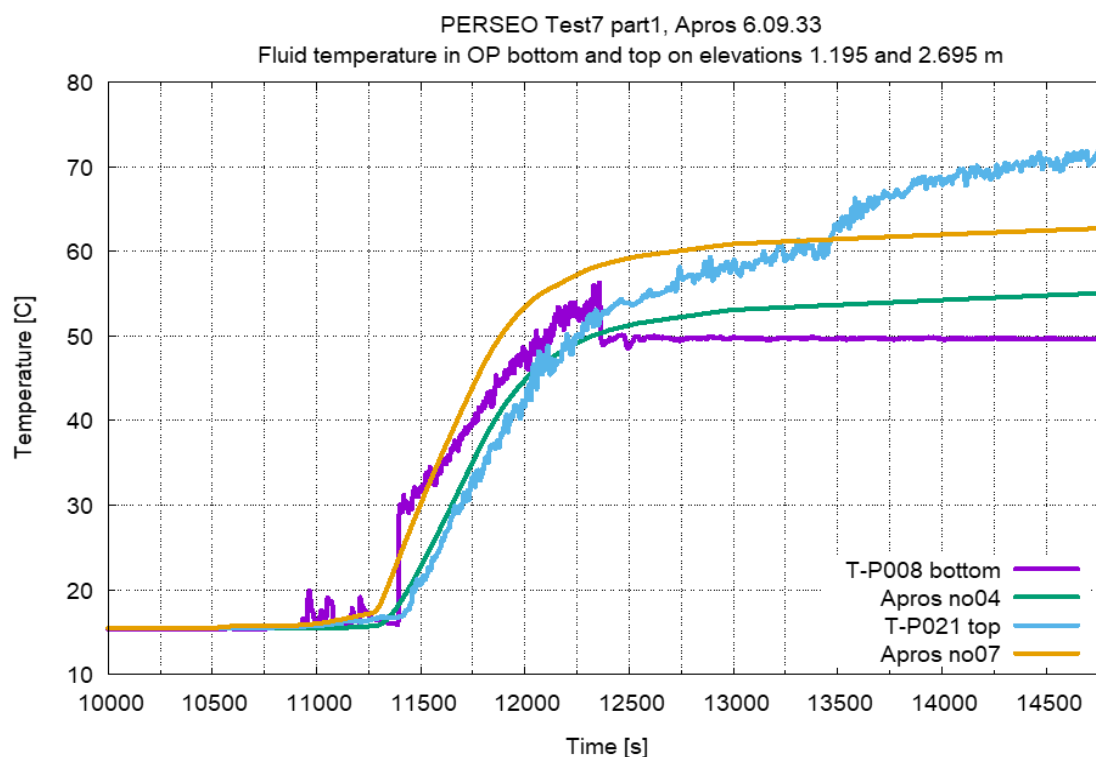


Figure 5.442. Test 7 Part 1 - Fluid temperature in overall pool

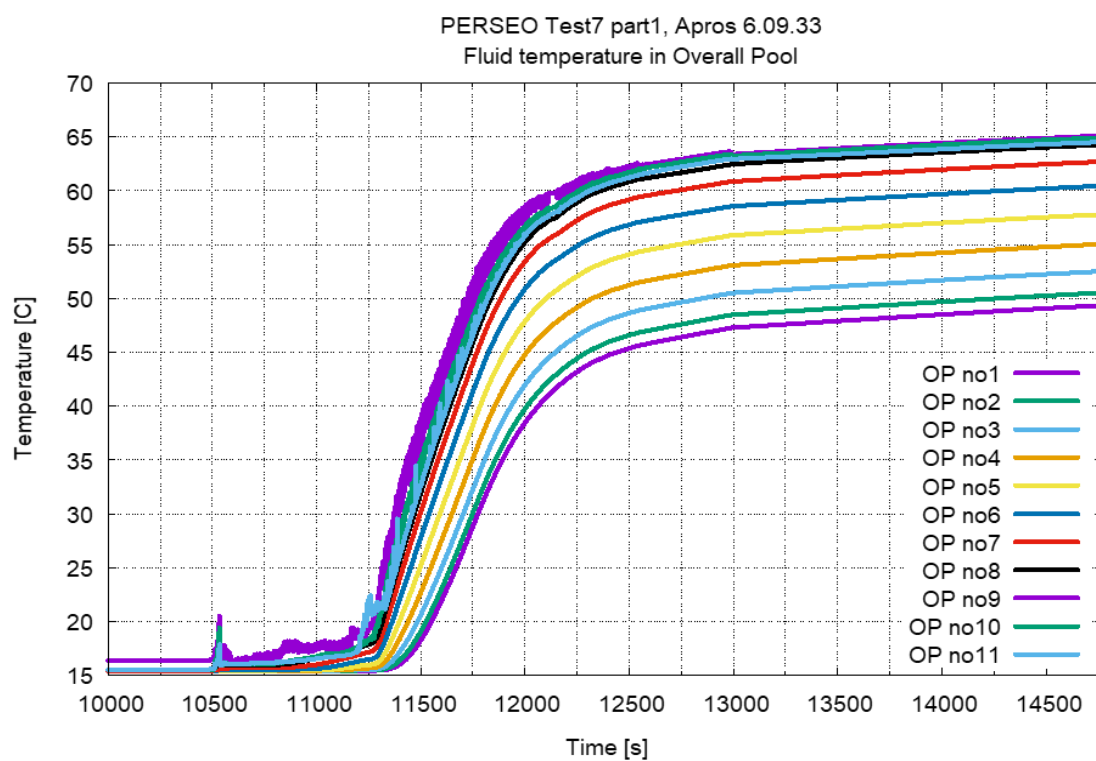


Figure 5.443. Test 7 Part 1 - HX power as function of pool water level

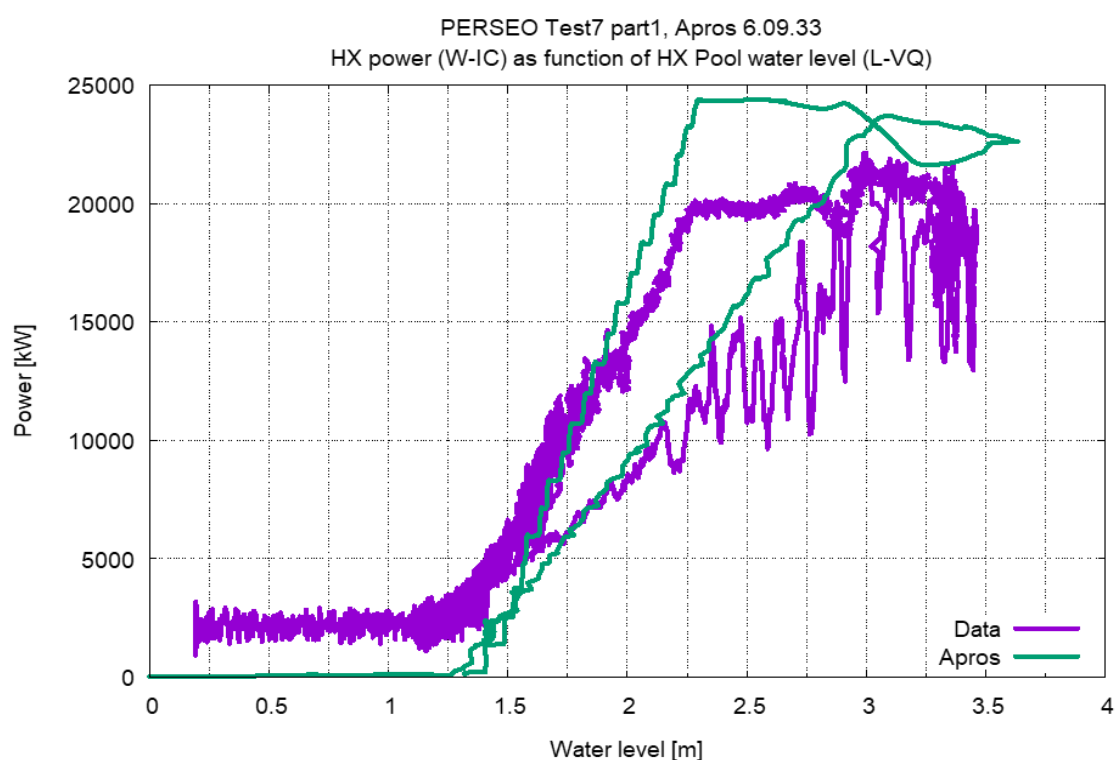


Table 5.80. Main Relevant thermal-hydraulic aspects related to Test 7 Part 1

Relevant thermal-hydraulic aspects	Time(s)	Quantity
Triggering valve (F045) opening and closure	10 475 – 10 608	-
Triggering valve (F045) re-opening and re-closure		-
Maximum level in the HX pool for the first filling step	10 600 – 11 000	1.43 m
Small heat removal from the primary side	10 600 – 11 000	1520 – 24 100 kW
Slow water consumption in the HX pool		-
Instabilities for steam condensation in the injector	11 100 – 11 170	-8 kPa
Triggering valve (F045) opening and closure		-
Maximum level in the HX pool	11 260	3.6 m
Maximum exchanged power	~11 750	24 300 kW
HX pool minimum level	14 784	1.32 m
OP average temperature	14 784	59°C

The marks adopted in Table 5.80 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.81. PERSEO Test 7 Part 1 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F_A001 (der.)	+
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W_IC (der.)	+
				Level HXP	L_VQ (der.)	
				Level OP	L_VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Absolute pressure vessel	P-I001	+
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
				Diff. pressure HX upper-lower header	DP-003	
				Diff. pressure steam duct injector	DP-J001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Flowrate steam supply line	F_A001 (der.)	+
				Flowrate condensate drain line	F_E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
				Power heat exchanger	W_IC (der.)	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Level HXP	L_VQ (der.)	+
				Power heat exchanger	W_IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	

Table 5.80. PERSEO Test 7 Part 1 versus phenomena, code prediction versus phenomena (Continued)

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
F	Behaviour of large pool: Thermal stratification	+	+	Power heat exchanger	W_IC (der.)	+
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP	L_VQ (der.)	+
				Level OP	L_VP (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L_VP (der.)	o
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

* (der.) = derived quantity

** Ph. = Phenomenon

Test 7 Part 2

The initial conditions of the model were set as close to the measured data as reasonably possible, by defining the water level and temperature profile both in the overall pool and in the HX pool according to measured values. However, the same heat losses that gave a quite good HX pool gas temperature distribution in Part 1 seemed to be too high for Part 2. Consequently, the calculated gas temperatures in the middle and top sections of the HX pool decrease during the initial 300 s period, when the triggering valve is closed. In this case the added vent valve in the steam line was closed, i.e. HX pool pressure was calculated by the code already in the initialisation phase.

Similarly, then in Part 1, the feed line pressure and temperature was read from the measured data and set as boundary conditions. Even though the data was filtered with 10 s filtering time, pressure fluctuated quite a lot and caused fluctuations of pressure difference between the HX upper and lower headers (DP-003).

The triggering valve starts to open at time 300 s. The opening time is set according to the test data to 26 s. When the valve is opening, water starts to flow from the overall pool to the HX pool (Figure 5.463). After the initial flow peak the flow first reverses and then starts to fluctuate between the pools. The overall behaviour is replicated by the model, but the strong flow oscillations measured in the test are not reproduced by the Apros model. The calculated OP level (L-VP) is in quite good agreement with the measurement, but the HX pool level (L-VQ) (Figure 5.450) increases first close to the measured maximum level, about to 3.1 m, but remained until 3 500 s on higher level than in the experiment. However, the calculated pressure difference from elevation 0.2 m to elevation 4.4 m (DP-Q005) is close to the measured data during that period (Figure 5.451). In the Apros model the collapsed liquid level is calculated by summing up the liquid level in the peripheral nodes

of the HX pool model, while in the experiment the liquid level is calculated from the pressure difference and taking in account the liquid density in measured temperature. These different calculation procedures may partly explain the difference in the HX pool liquid level.

When water flows to the HX pool and wets the heat exchanger tubes, steam condensation inside the tubes increases rapidly. Steam flow to the condenser increases and exceeds the measured data in the beginning, but falls soon below the measured value. Consequently, the condenser power is also under estimated.

The HX pool fluid temperatures, T-Q037, T-Q034 and T-Q031 are quite well reproduced in the simulation. However, the temperature drop in the pool bottom temperature is not as deep as measured in the experiment. Nodalisation in the bottom of the pool was probably not dense enough to catch the local temperature and mixing in pool bottom was over estimated.

The overall pool temperatures, T-P008 and T-P021, were in quite good agreement with measurements (Figure 5.466). In the experiment the pool seems to mix up after 500 s and then stratify again just before 1 000 s. This behaviour is probably due to strong condensation induced flow oscillations in the steam duct. The Apros model does not produce sufficiently the condensation inside the steam duct, but calculates more stable condensation. The steam condenses on the pool side, but water is not sucked inside the duct. The chugging phenomena, which probably took place in the experiment, was not reproduced by the code. The calculated steam velocity in the injector oscillated around 100 m/s (Figure 5.464). The resulting diffusion coefficients to simulate pool mixing are plotted in Figure 5.465. Please note that the diffusion coefficient is reduced to zero when corresponding node dries out (diffusion is calculated only for the liquid phase). The overall pool heats up and is completely mixed at 2 500 s. (Figure 5.467).

After sending the benchmark calculations results, it was noted that the upper part of the HX tubes were dried out on the pool side. The extremely high heat flux in the beginning of the heat exchanger power operation around 500 s resulted in the pool side drying out in the simulation. The pool side heat transfer coefficient on the upper part of the HX tubes is very small (Figure 5.469) due to the drying out. Resulting temperature profiles show very high tube outer surface temperatures in the upper 1/3 of the tubes. The drying out of the tubes explains the lower heat transfer capacity in Part 2 of the test compared to Part 1. This deficiency was noted so late, after delivering the results, that it could not be corrected.

Table 5.82. Main relevant thermal-hydraulic aspects related to Test 7 Part 2

Relevant thermal-hydraulic aspects	Time (s)	Quantity
Triggering valve (F045) opening	300	-
Maximum level in the HXP	476	3.11 m
Maximum exchanged power	442	25.0 MW
OP discharge valve F031 opening	1 150	-
Triggering valve F045 closure	3 338 (closing time 123 s)	-
HX pool level decreasing and loss of mass from the boil-off	-	-
Primary side depressurisation beginning for end of test	4 660	-

Figure 5.444. Test 7 Part 2 - Steam flow rate

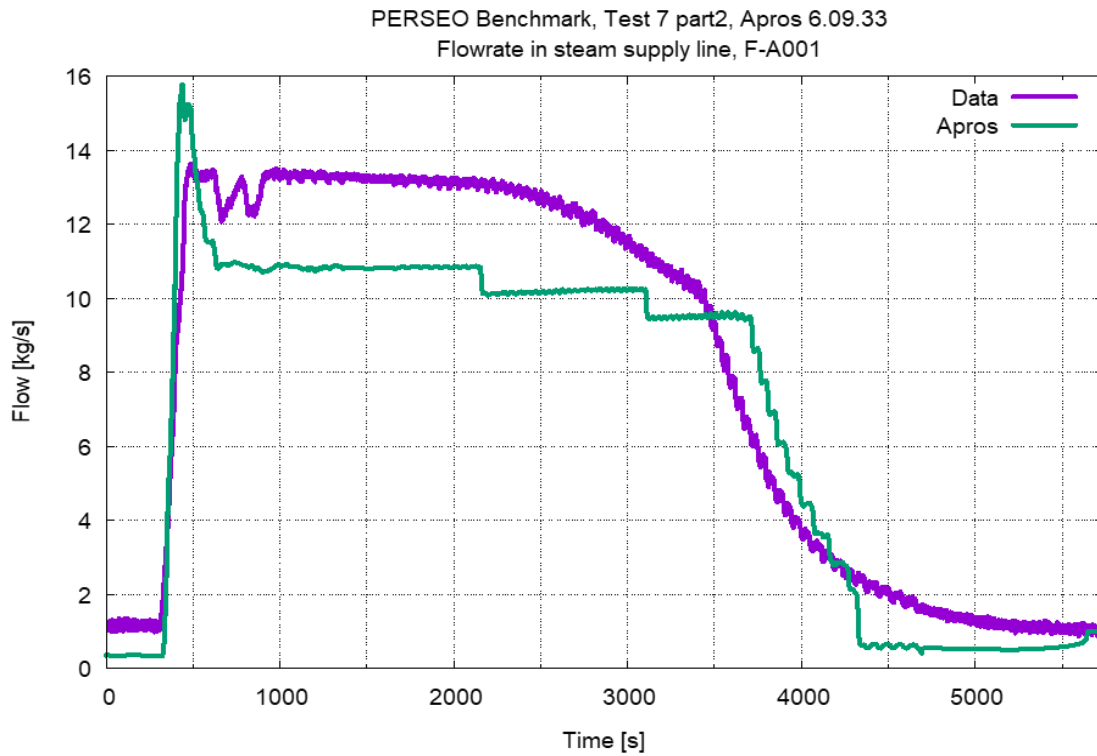


Figure 5.445. Test 7 Part 2 - Condensate flow rate

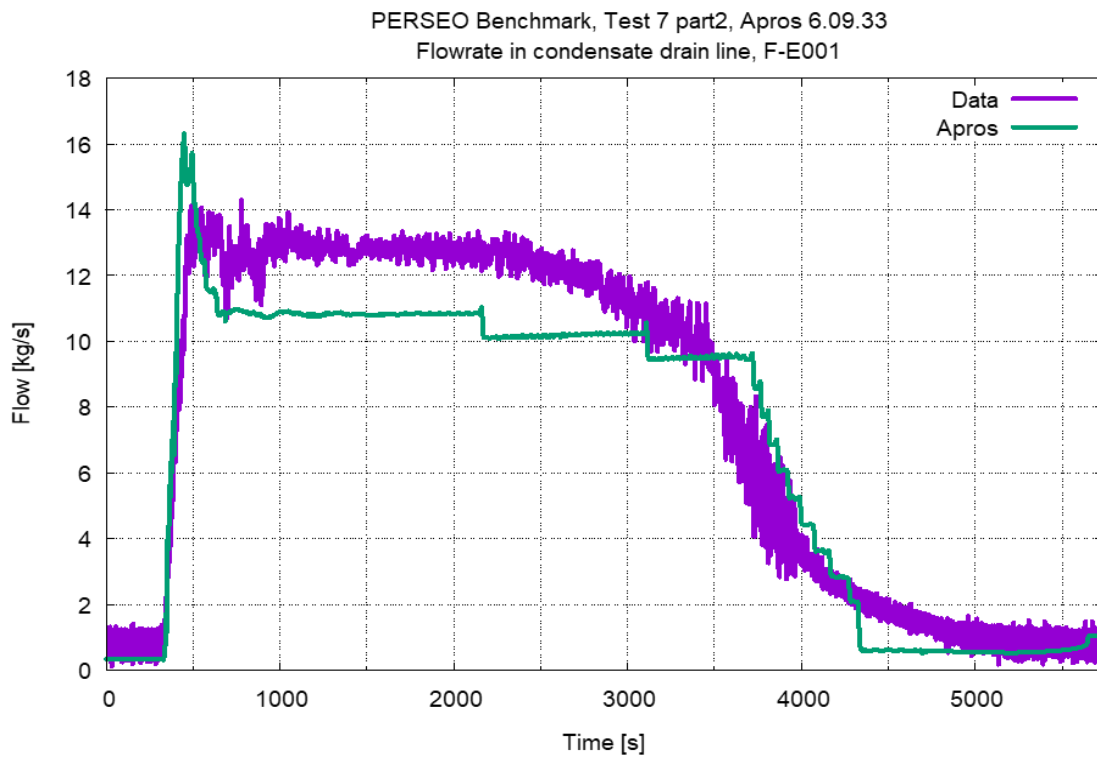


Figure 5.446. Test 7 Part 2 - HX power

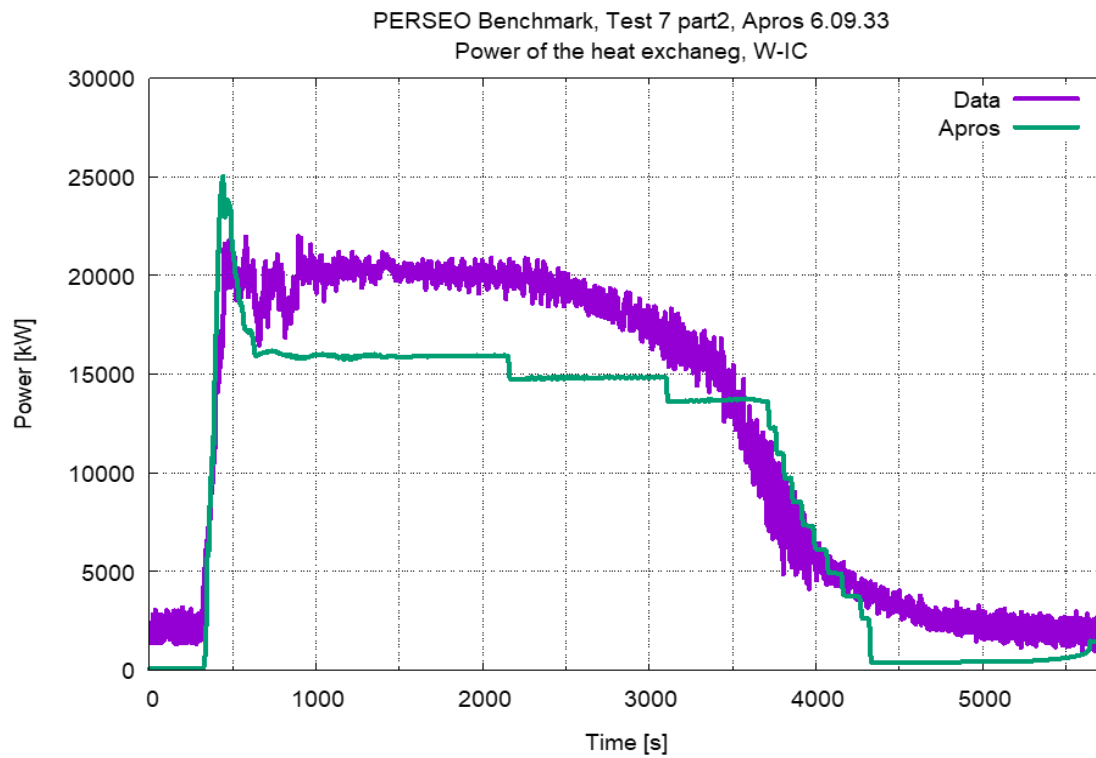


Figure 5.447. Test 7 Part 2 - Primary pressure

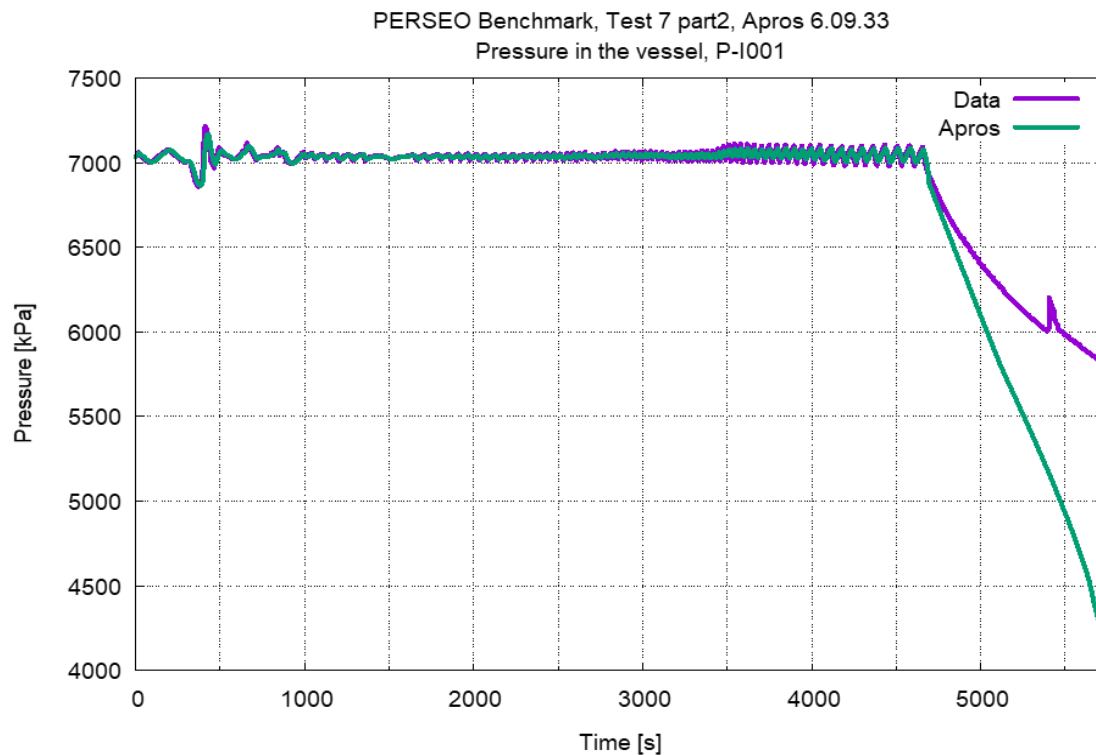


Figure 5.448. Test 7 Part 2 - HX inlet fluid temperature

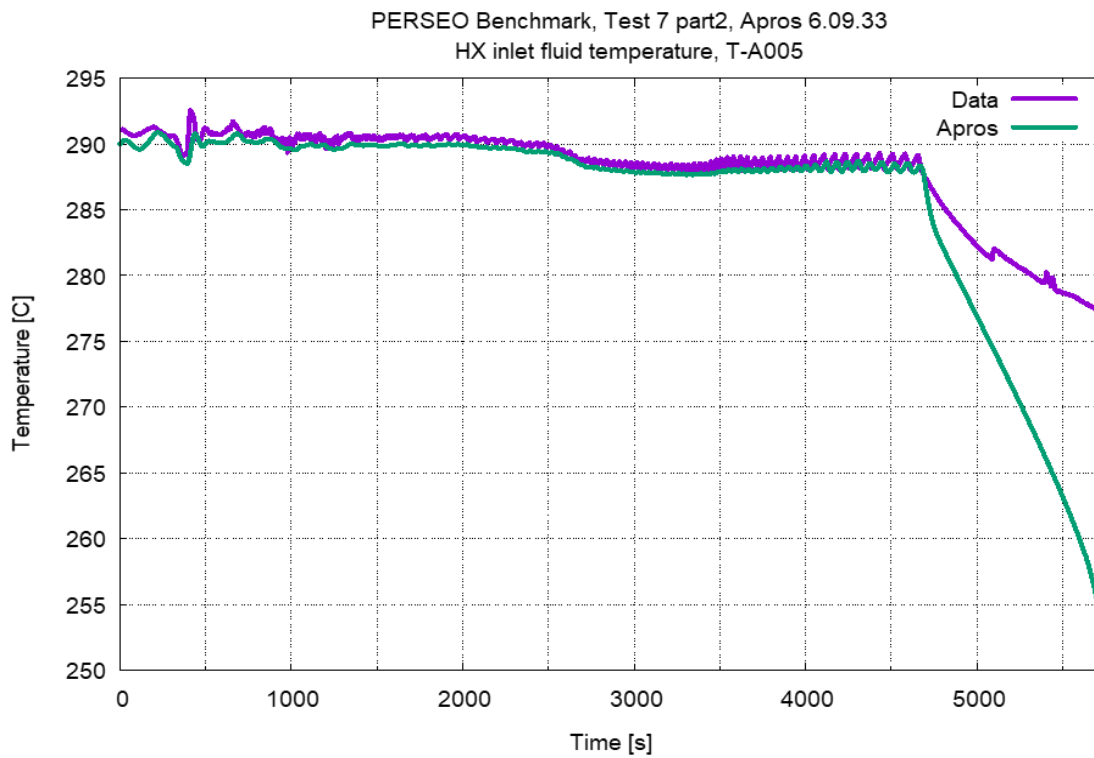


Figure 5.449. Test 7 Part 2 - HX outlet fluid temperature

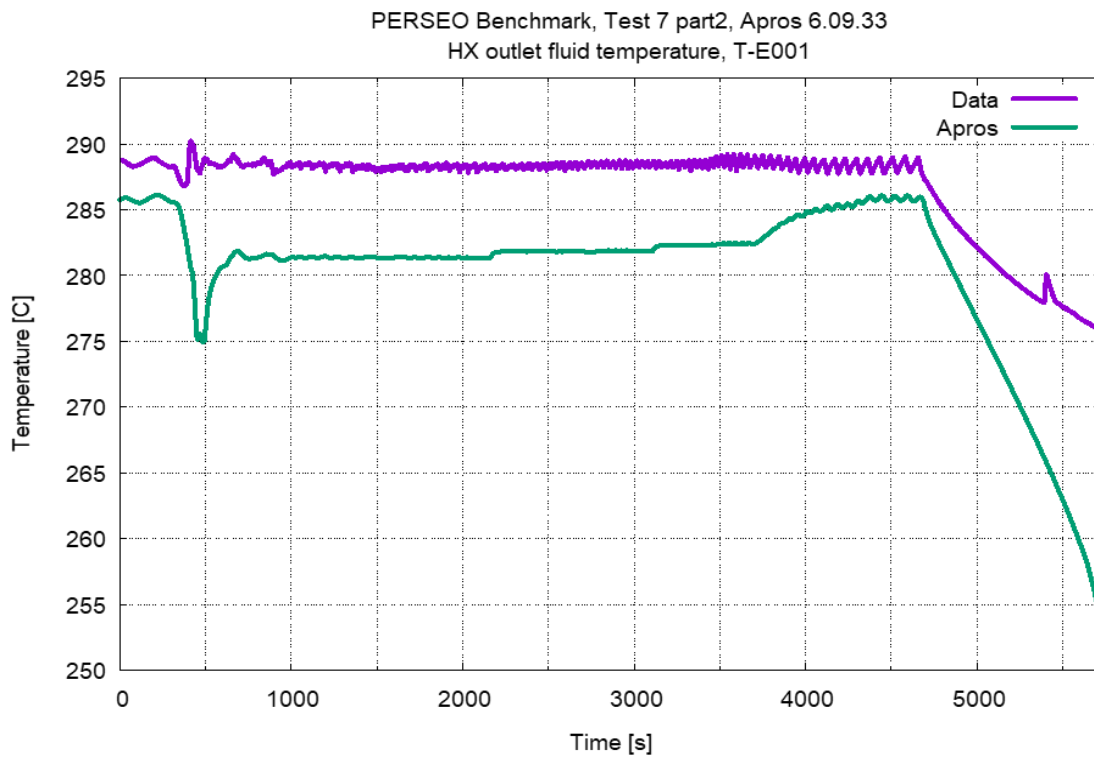


Figure 5.450. Test 7 Part 2 - HXP level

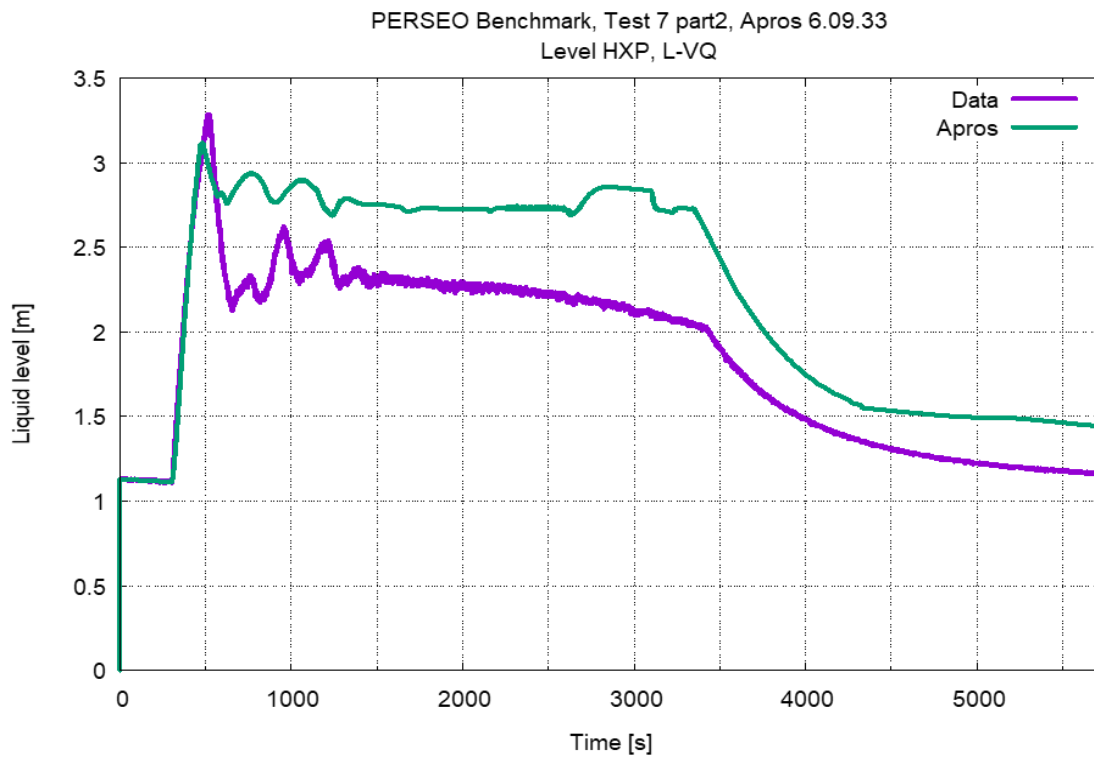


Figure 5.451. Test 7 Part 2 - HXP pressure difference from elevation 0.2 to 4.4 m

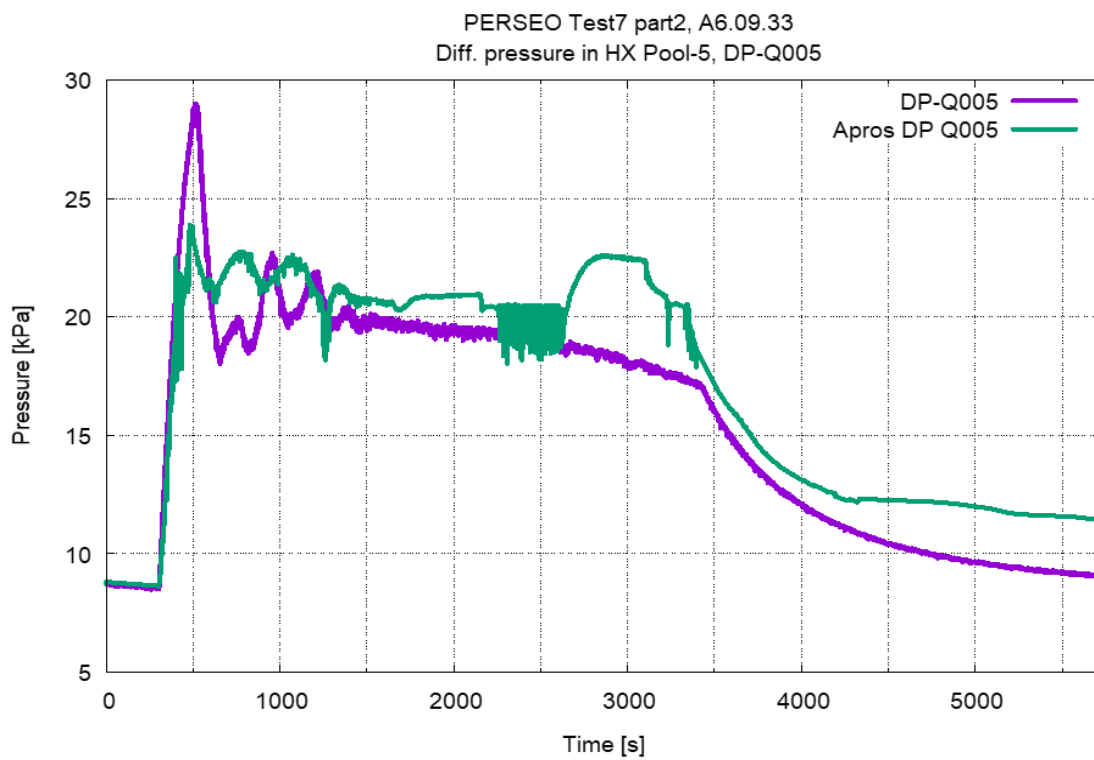


Figure 5.452. Test 7 Part 2 - OP level

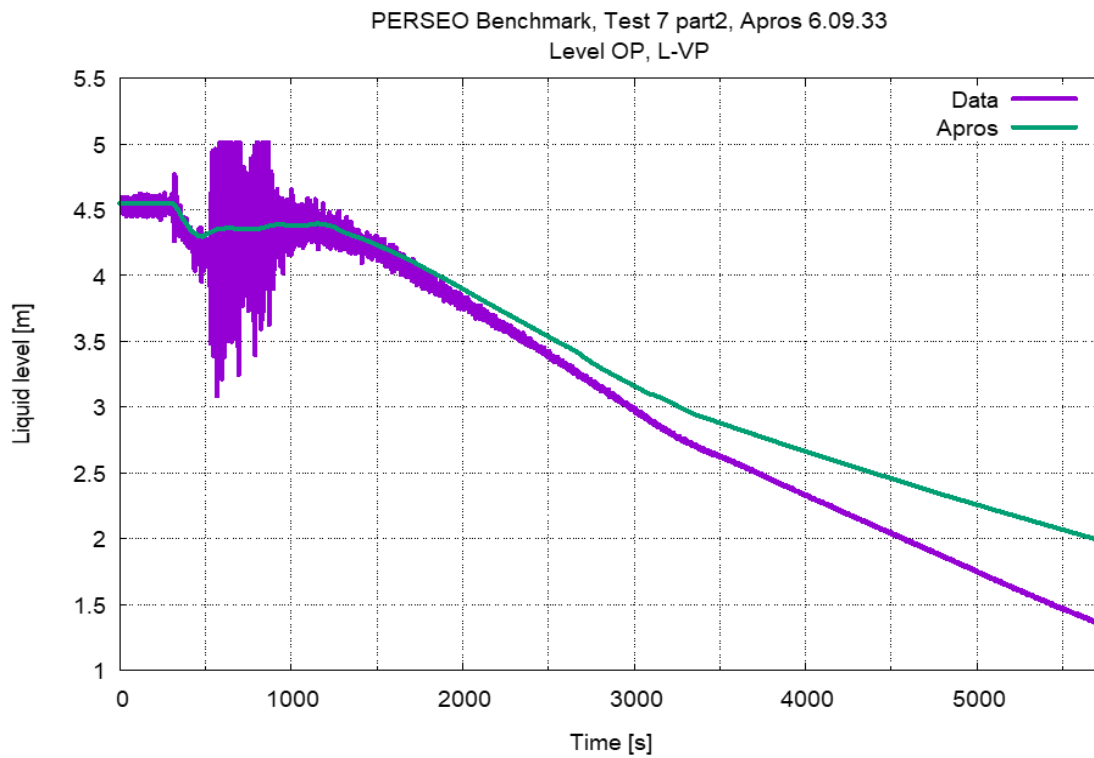


Figure 5.453. Test 7 Part 2 - Fluid temperature HXP bottom

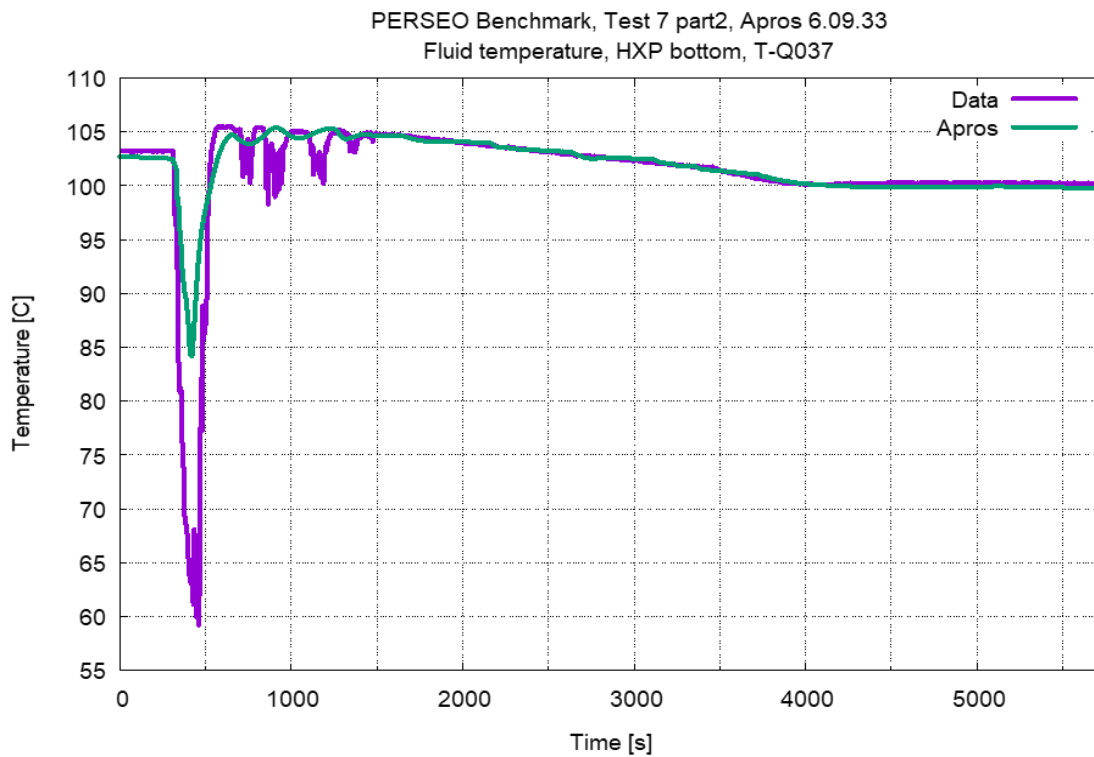


Figure 5.454. Test 7 Part 2 - Fluid temperature HXP middle

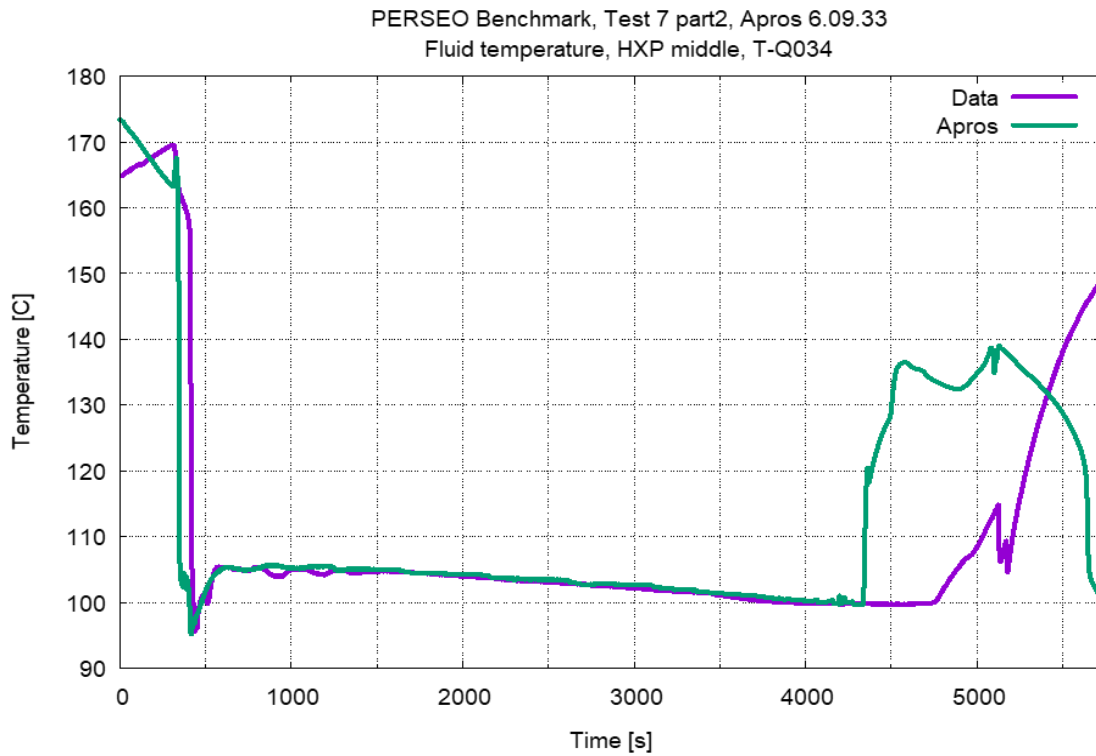


Figure 5.455. Test 7 Part 2 - Fluid temperature HXP top

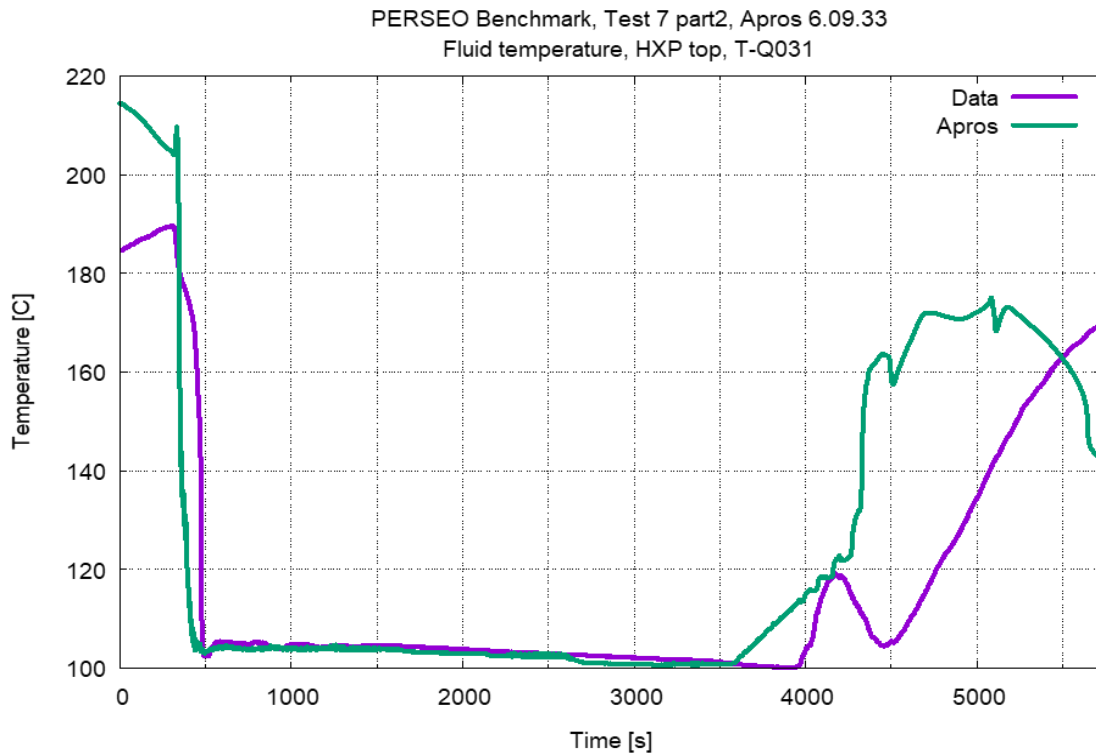


Figure 5.456. Test 7 Part 2 - Relative pressure HXP top

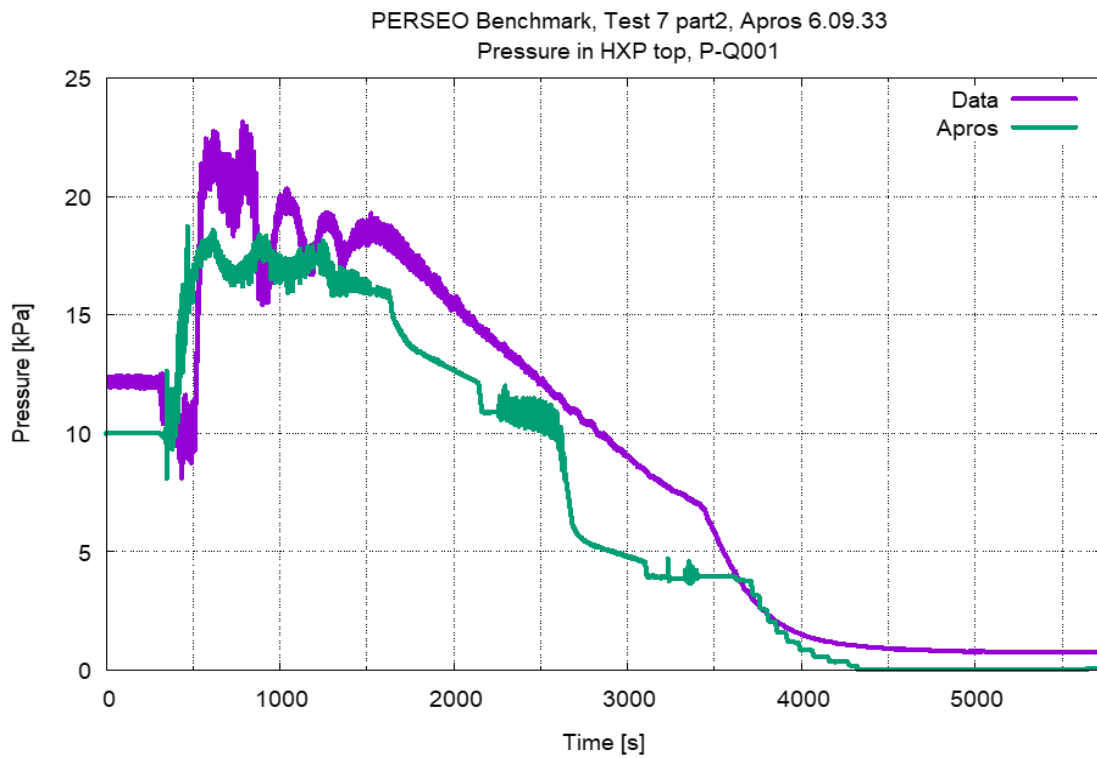


Figure 5.457. Test 7 Part 2 - Fluid temperature OP bottom

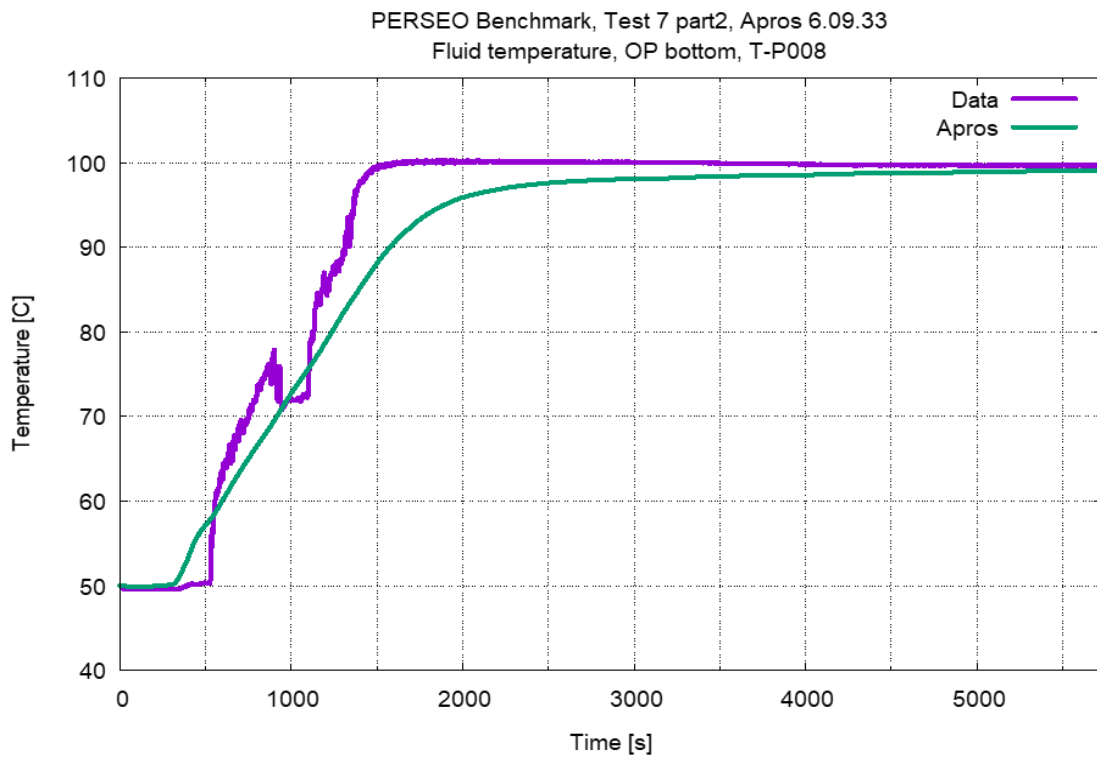


Figure 5.458. Test 7 Part 2 - Fluid temperature OP top

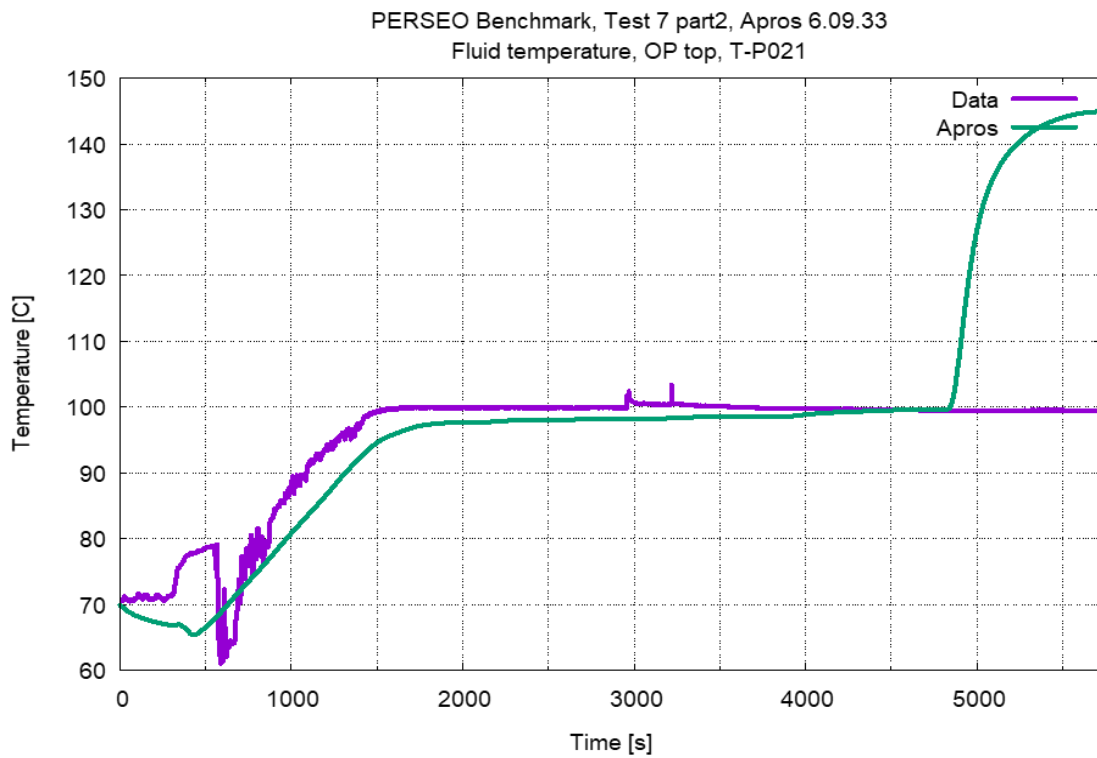


Figure 5.459. Test 7 Part 2 - Differential pressure HX upper - lower header

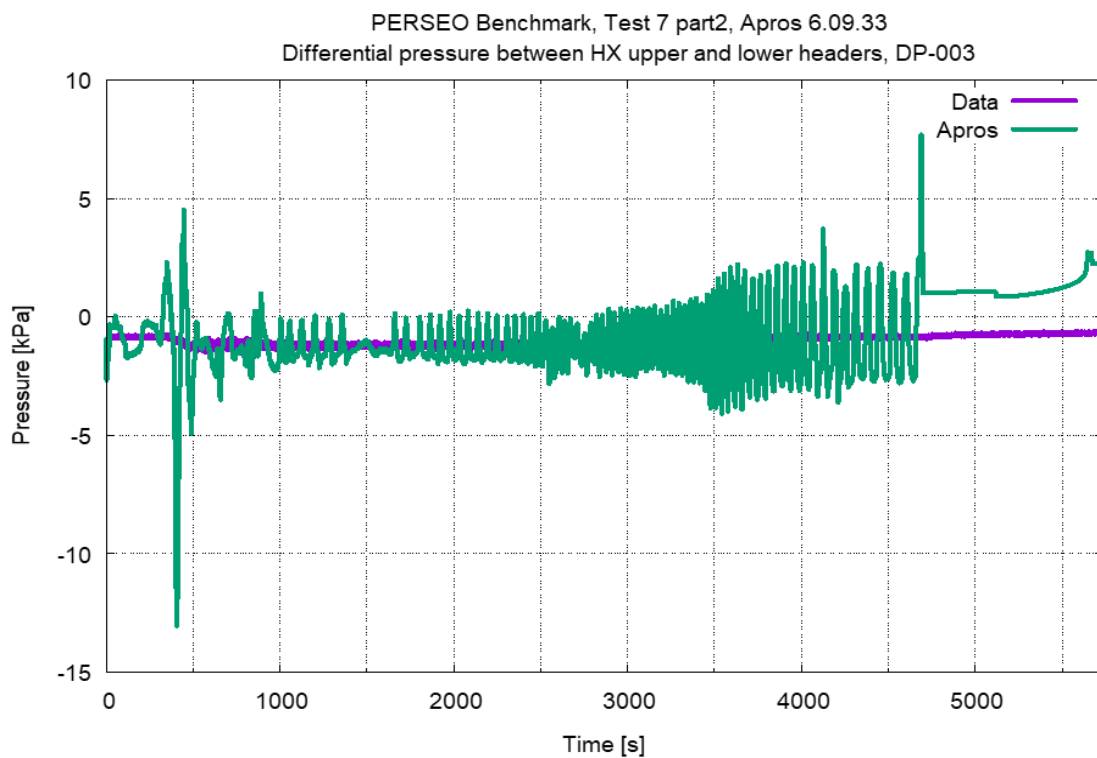


Figure 5.460. Test 7 Part 2 - Differential pressure -steam duct injector

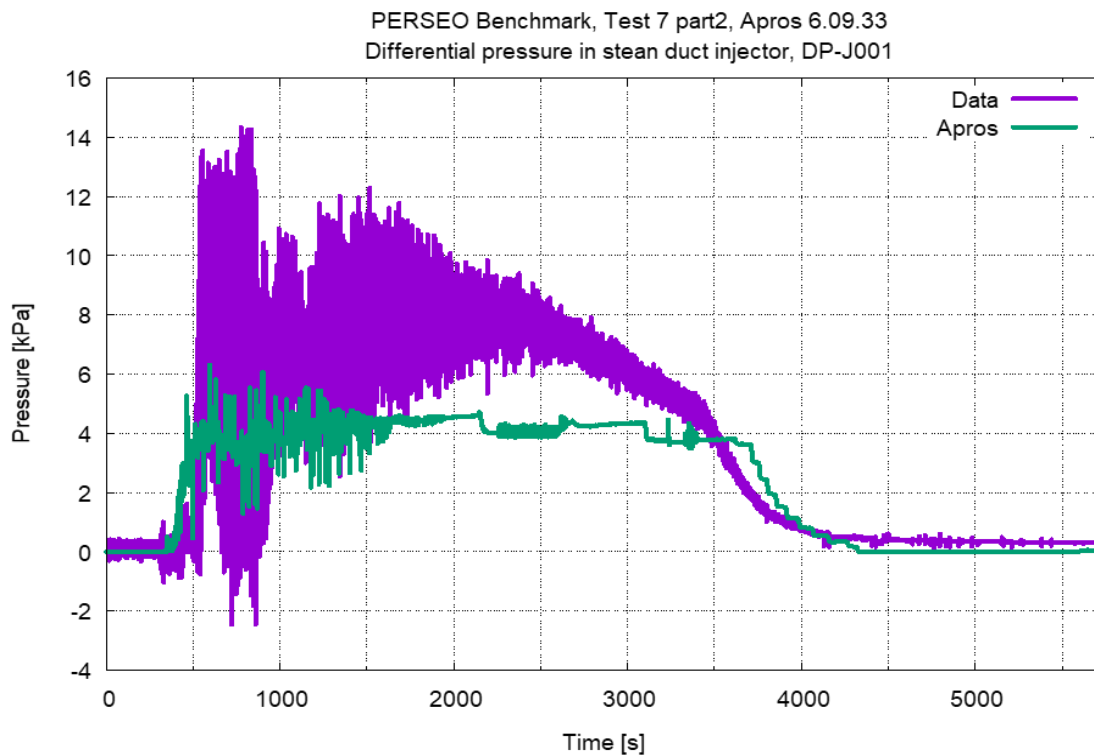


Figure 5.461. Test 7 Part 2 - Wall temperature HX upper header

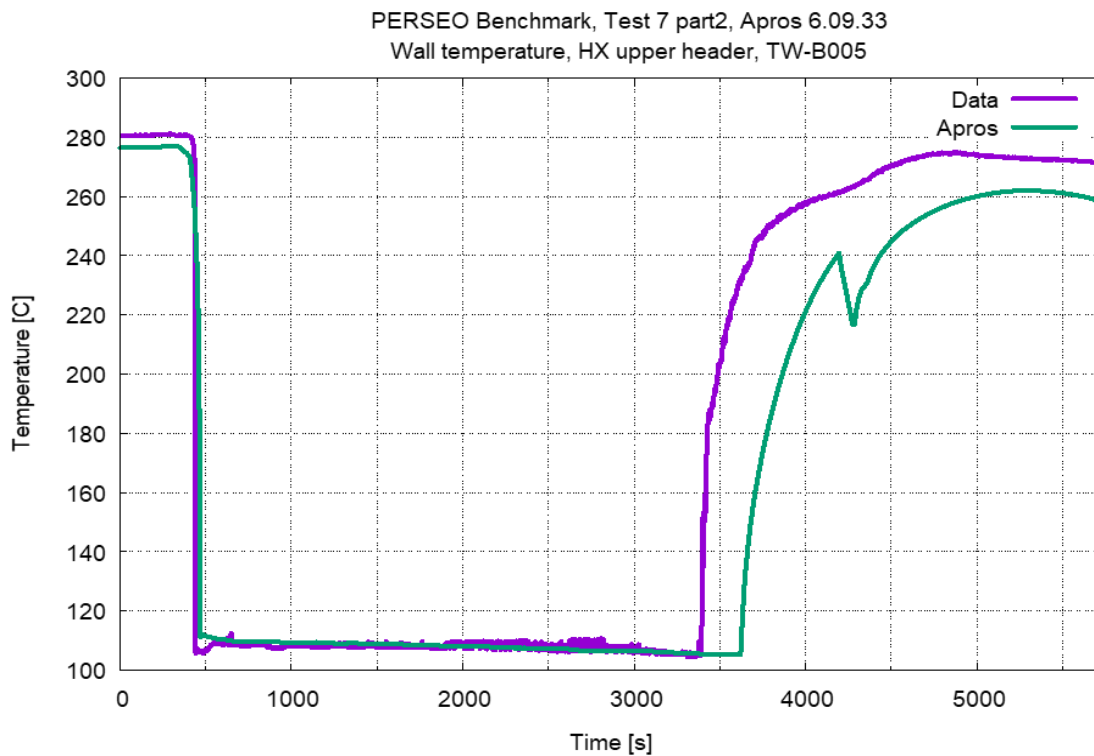


Figure 5.462. Test 7 Part 2 - Wall temperature HX lower header

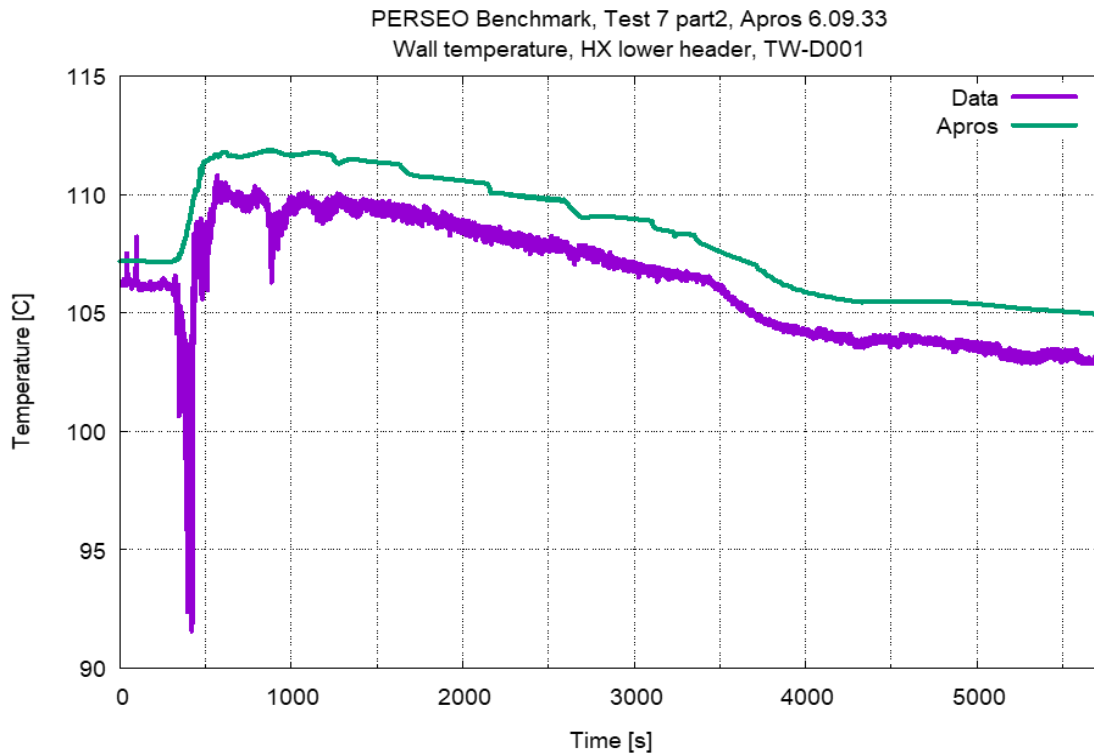


Figure 5.463. Test 7 Part 2 - Flow through the triggering valve

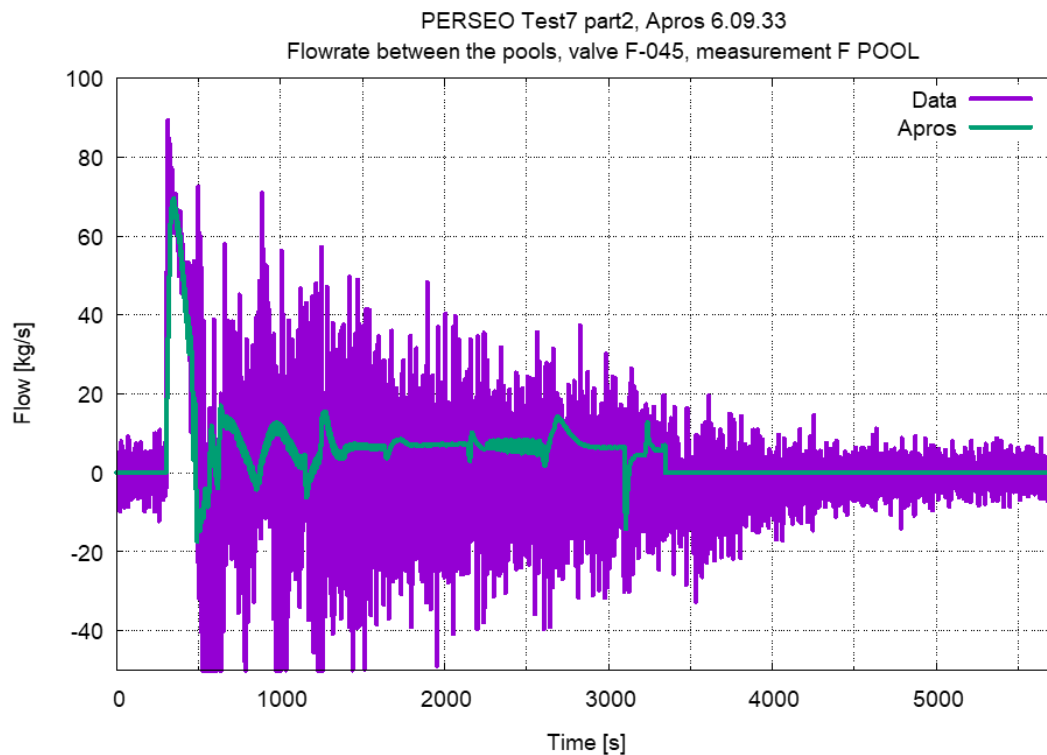


Figure 5.464. Test 7 Part 2 - Gas velocity in the injector

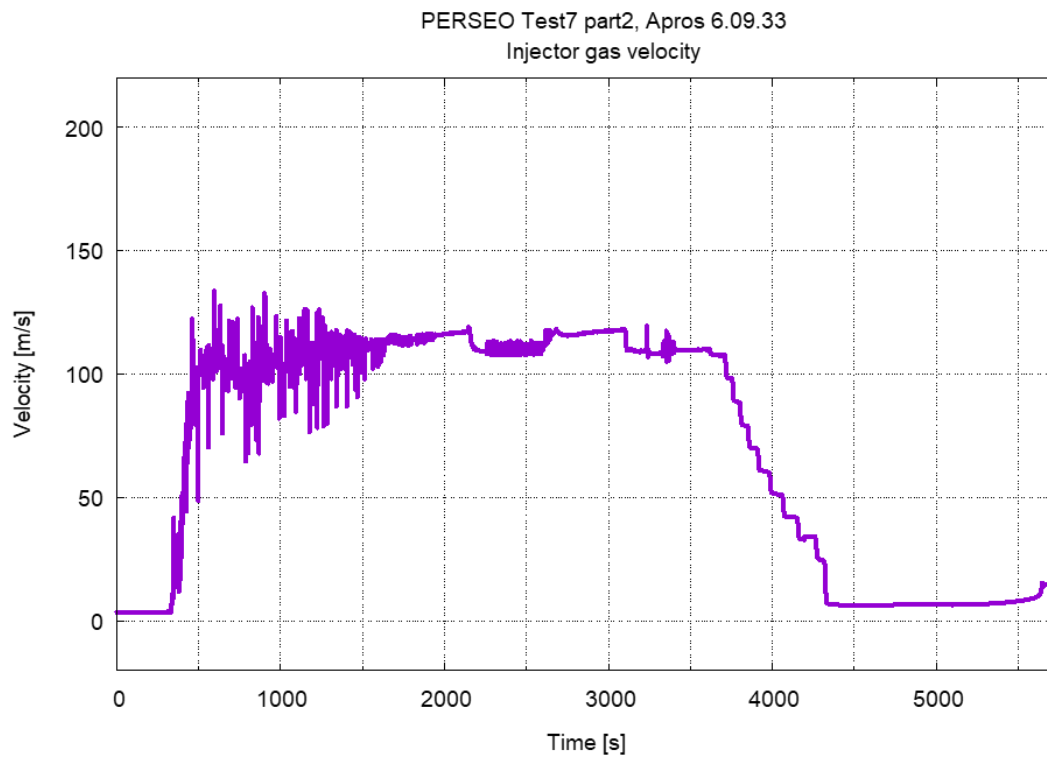


Figure 5.465. Test 7 Part 2 - Diffusion coefficients in the overall pool

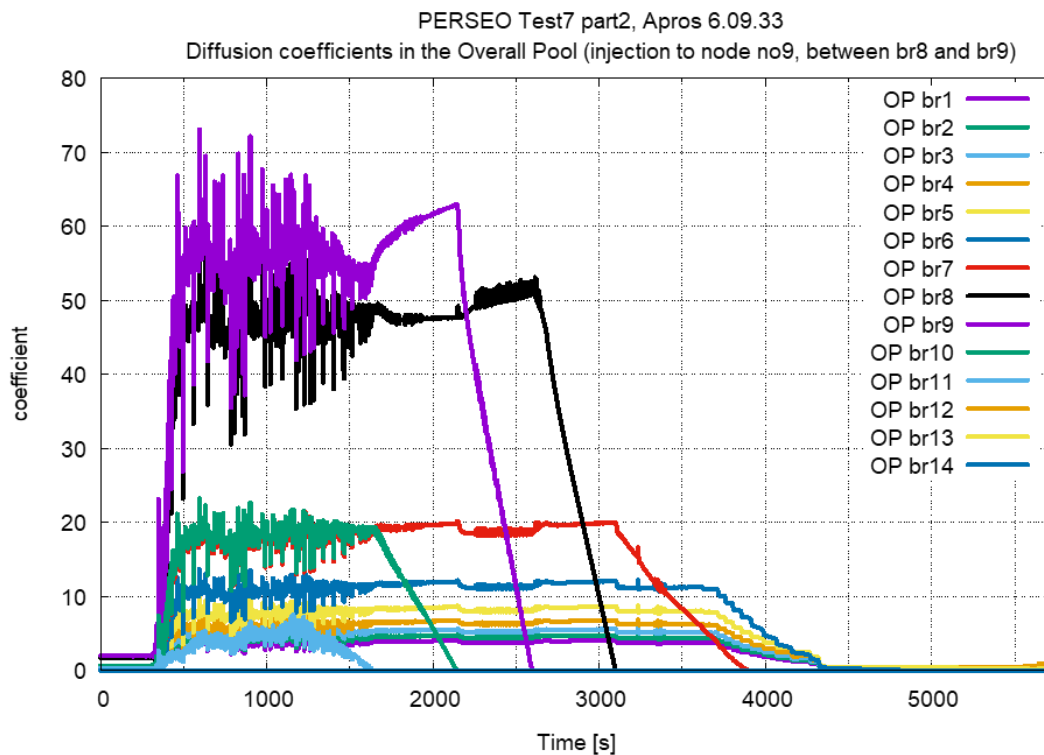


Figure 5.466. Test 7 Part 2 - Fluid temperature in overall pool bottom and top

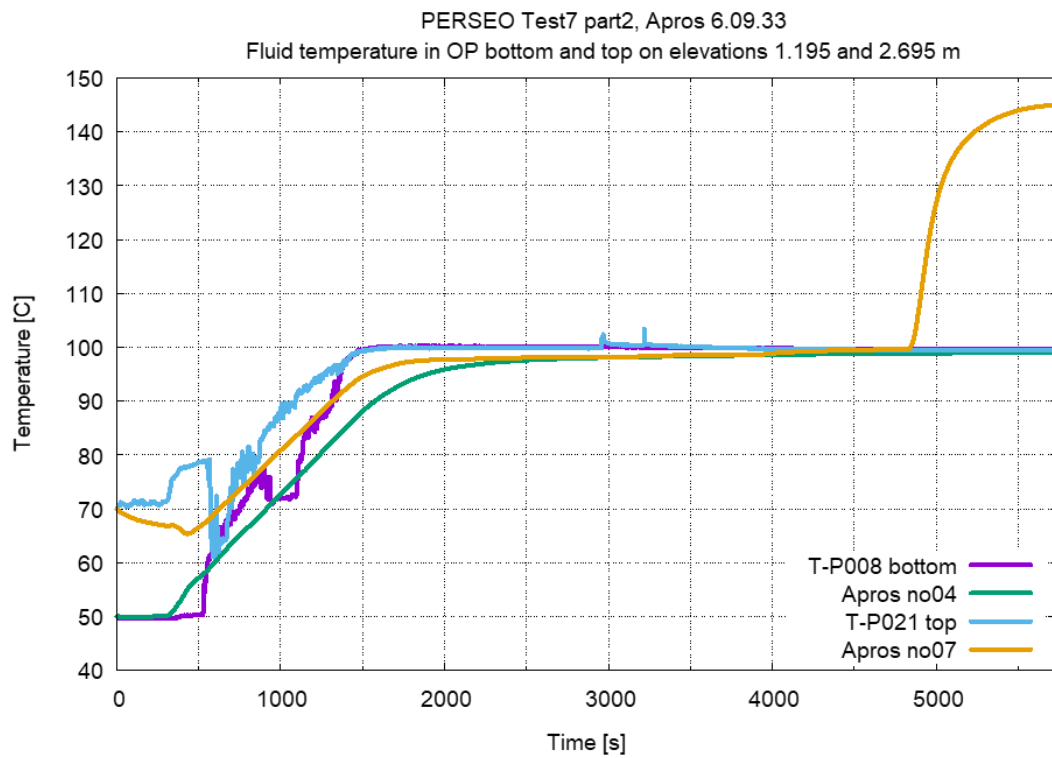


Figure 5.467. Test 7 Part 2 - Fluid temperature in overall pool

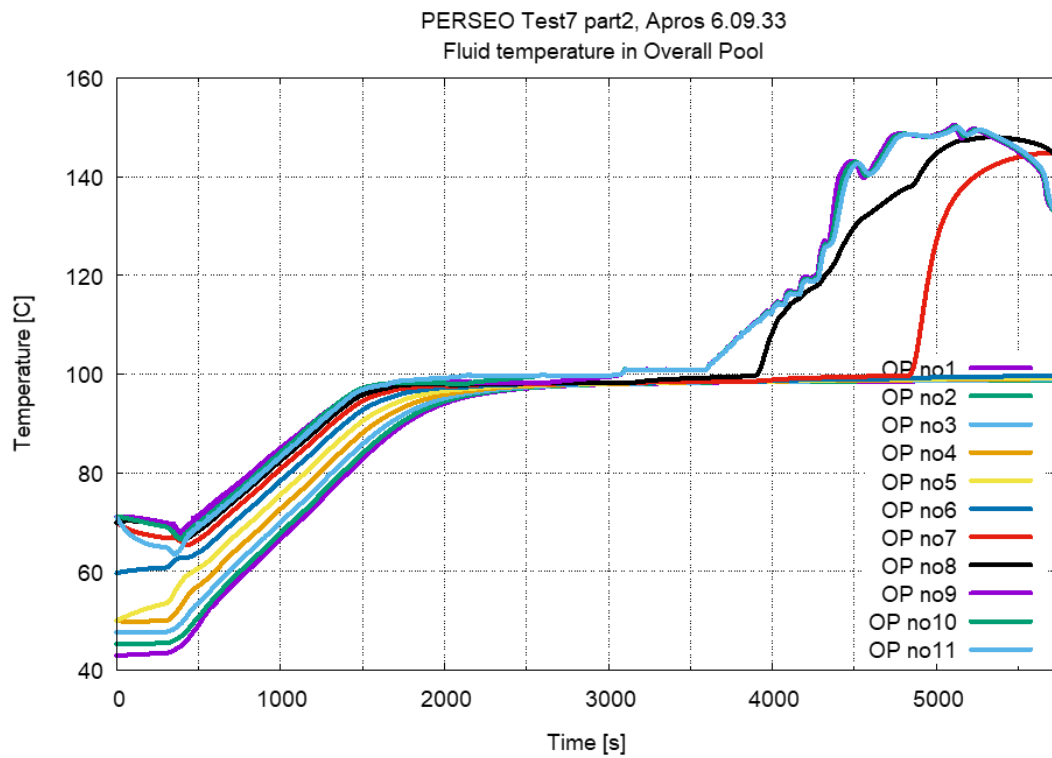


Figure 5.468. Test 7 Part 2 - HX power as function of pool water level

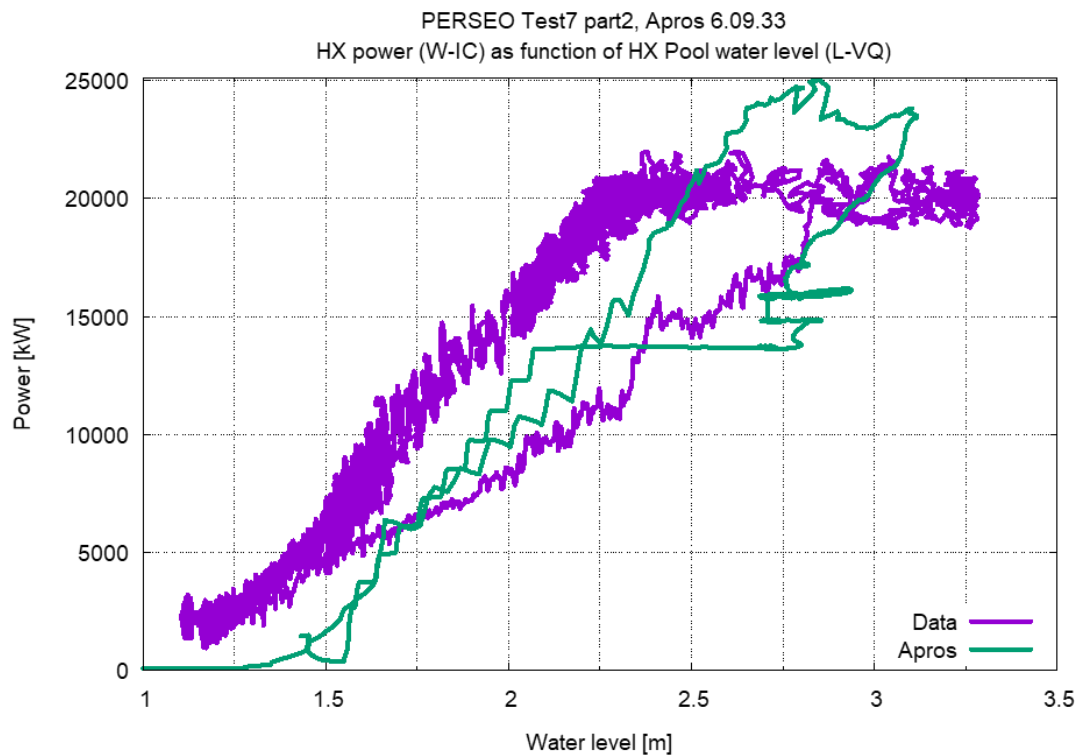


Figure 5.469. Test 7 Part 2 - Heat transfer coefficient in the heat exchanger collectors and tubes (plotted at 1 600 s)

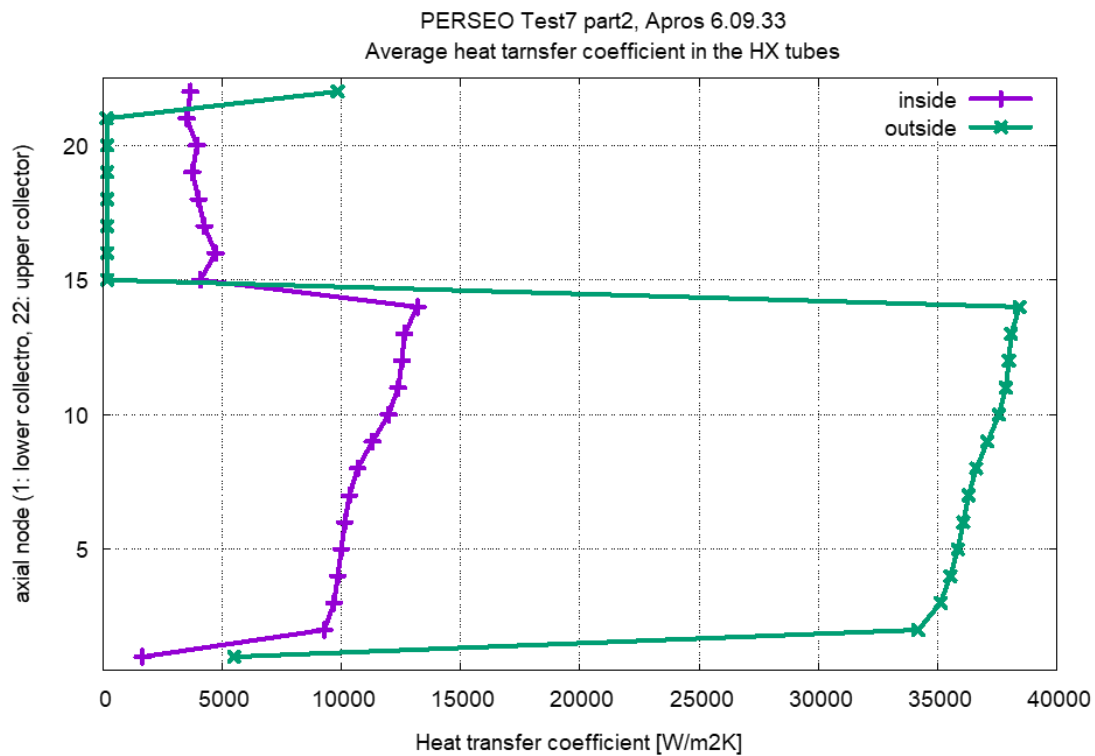
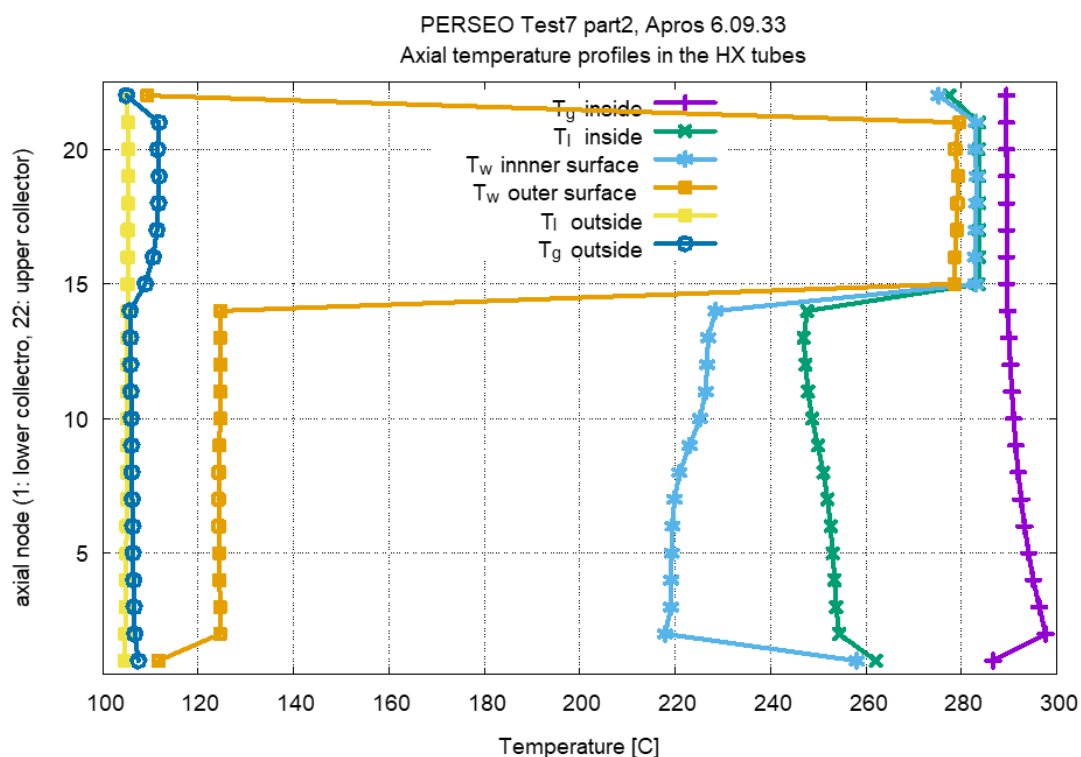


Figure 5.470. Test 7 Part 2 - Axial temperature profiles in the heat exchanger (plotted at 1 600 s)



The marks adopted in Table 5.82 for the qualitative accuracy evaluation are reported in Table 4.2.

Table 5.83. PERSEO Test 7 Part 2 versus phenomena, code prediction versus phenomena

	Phenomenon	Experiment				TH code
		Ph.	Measurement			Ph.
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	Flowrate steam supply line	F_A001 (der.)	+
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Absolute pressure vessel	P-I001	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
B	Natural circulation in HXP and OP coupled circuit	+	+	Power heat exchanger	W_IC (der.)	+
				Level HXP	L_VQ (der.)	
				Level OP	L_VP (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Relative pressure HXP top	P-Q001	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	

Table 5.82. PERSEO Test 7 Part 2 versus phenomena, code prediction versus phenomena (Continued)

	Phenomenon	Experiment				TH code
		Ph.		Measurement		Ph.
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+	+	Absolute pressure vessel	P-I001	+/o
				Flowrate steam supply line	F_A001 (der.)	
				Flowrate condensate drain line	F_E001 (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
				Diff. pressure HX upper-lower header	DP-003	
				Diff. pressure steam duct injector	DP-J001	
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	Flowrate steam supply line	F_A001 (der.)	+/o
				Flowrate condensate drain line	F_E001 (der.)	
				Absolute pressure vessel	P-I001	
				Diff. pressure HX upper-lower header	DP-003	
				HX inlet temperature	T-A005	
				HX outlet temperature	T-E001	
				Power heat exchanger	W_IC (der.)	
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	Level HXP	L_VQ (der.)	+/o
				Power heat exchanger	W_IC (der.)	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
F	Behaviour of large pool: Thermal stratification	+	+	Power heat exchanger	W_IC (der.)	+/o
				Diff. pressure steam duct injector	DP-J001	
				Temperature HXP (bottom)	T-Q037	
				Temperature HXP (middle)	T-Q034	
				Temperature HXP (top)	T-Q031	
				Temperature OP (bottom)	T-P008	
				Temperature OP (top)	T-P021	
G	Behaviour of large pool: Natural convection (within a single pool)	+	o	Level HXP	L_VQ (der.)	+/o
				Level OP	L_VP (der.)	
				Power heat exchanger	W_IC (der.)	
				Relative pressure HXP top	P-Q001	
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+	o	Level OP	L_VP (der.)	+/o
				Relative pressure HXP top	P-Q001	
				Diff. pressure steam duct injector	DP-J001	
I	Structural Heat	+	+	Wall temperature HX upper header	TW-B005	+
				Wall temperature HX lower header	TW-D001	

Test 7 Part 2 run B

After sending the results of the benchmark simulations it was noted that in the Apros simulation the upper part of the heat exchanger was in heat transfer crisis (dry out). This explains the difference in the heat exchanger power in the Part 1 and Part 2 simulations. A reason for the difference is additional friction added in the peripheral part of the HX pool for the Part 2 run. To better adjust the initial temperature distribution for Part 2, friction (form loss coefficients) was added in the pipe component in the HX pool, parallel to the heat exchanger. The component describes the open pool area on the elevation of the heat exchanger. Unexpectedly, the added friction had a quite large effect on internal circulation in the pool and consequently on void fraction distribution and calculated critical heat flux. In this case Apros calculated critical heat flux using Zuber-Griffith and Biasi correlations. Zuber-Griffith correlation is used for low fluid flow and Biasi for higher flow. The flow conditions in the heat exchanger were just in the transition zone between the correlations. During the Part 2 quasi-steady condenser operation phase, between 1 500 and 2 000 s, the water level was close to the upper end of the HX tubes and predicted void fraction, and

the coolant flow and critical heat flux in the upper part of the HX tube bundle (pool side) were sensitive to the form loss coefficients set in the model. The form loss coefficient was reduced and the results of this calculation are presented in the following figures. Unfortunately, the calculation was made so late that the results could not be updated in the benchmark comparison but are presented here as additional sensitivity run. In the new calculation run the upper part was still in dry-out condition, but the area was shorter (Figure 5.497) and the heat exchanger power was higher (Figure 5.473). Please note that the axial temperature profiles are plotted as a function of elevation for clarity. The water level in the HX pool (Figure 5.477) agreed better with measured data. Also, the pressure differences between elevations 1.6 and 3.0 m (DP-Q002, Figure 5.499) were close to the experimental data. However, the water swell level did not reach above an elevation of 3.0 m during the quasi-steady operation phase between 1 500 and 2 000 s (see DP-Q003, Figure 5.500). In the experiment the upper header was cooled with water splashes, but in the calculation cooling was not sufficient and consequently the upper header and the upper part of the heat exchanger tubes were in dry-out condition, see calculated heat transfer coefficients (Figure 5.496) and temperature profiles (Figure 5.497). In the new calculation the heat transfer is better in line with the experiment and consequently mixing in the overall pool is simulated better (Figure 5.493). The HX power as function of pool water level is plotted in Figure 5.495. The lower curves, both for the experiment and the calculation, represent the early part of the test, when the water level is increasing. When the water level is decreasing the power of the condenser is higher, both in the experiment and in the calculation. The Apros model over predicts the condenser power with high water levels.

This sensitivity calculation shows a limitation of the quasi-2D modelling approach with a 1D code. Attempts to improve some aspects of modelling, i.e. initial temperature distribution, may have drawbacks in overall behaviour of the model. User effects may be strong with this kind of quasi-2D modelling approach.

Figure 5.471. Test 7 Part 2 run B - Steam flow rate

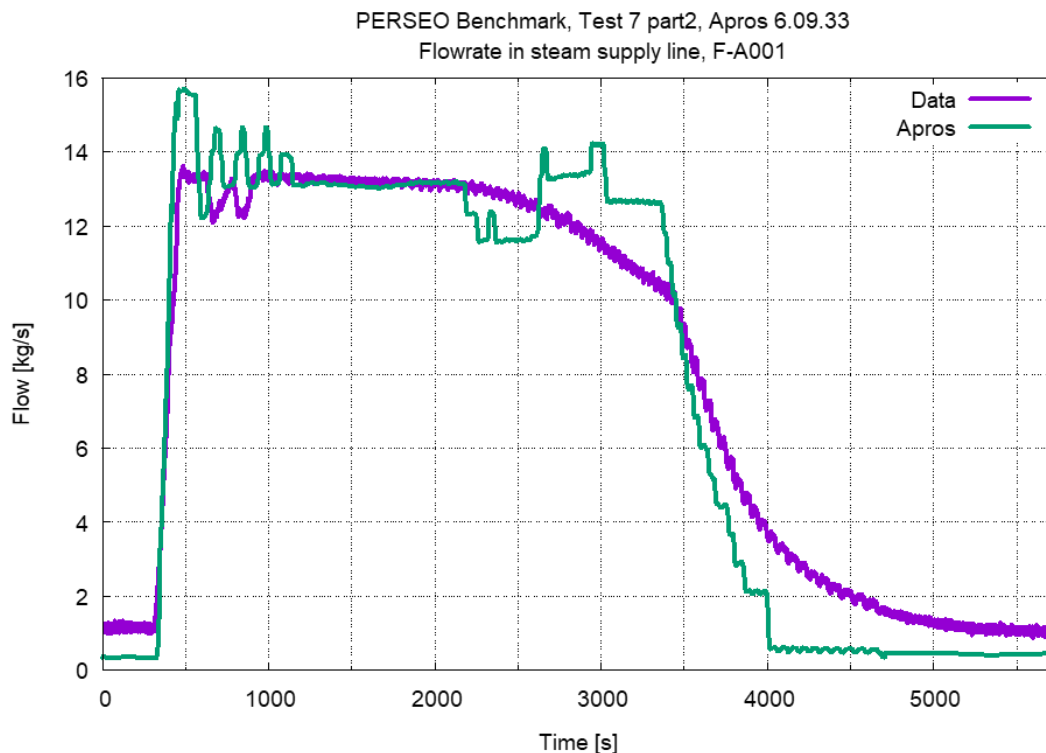


Figure 5.472. Test 7 Part 2 run B - Condensate flow rate

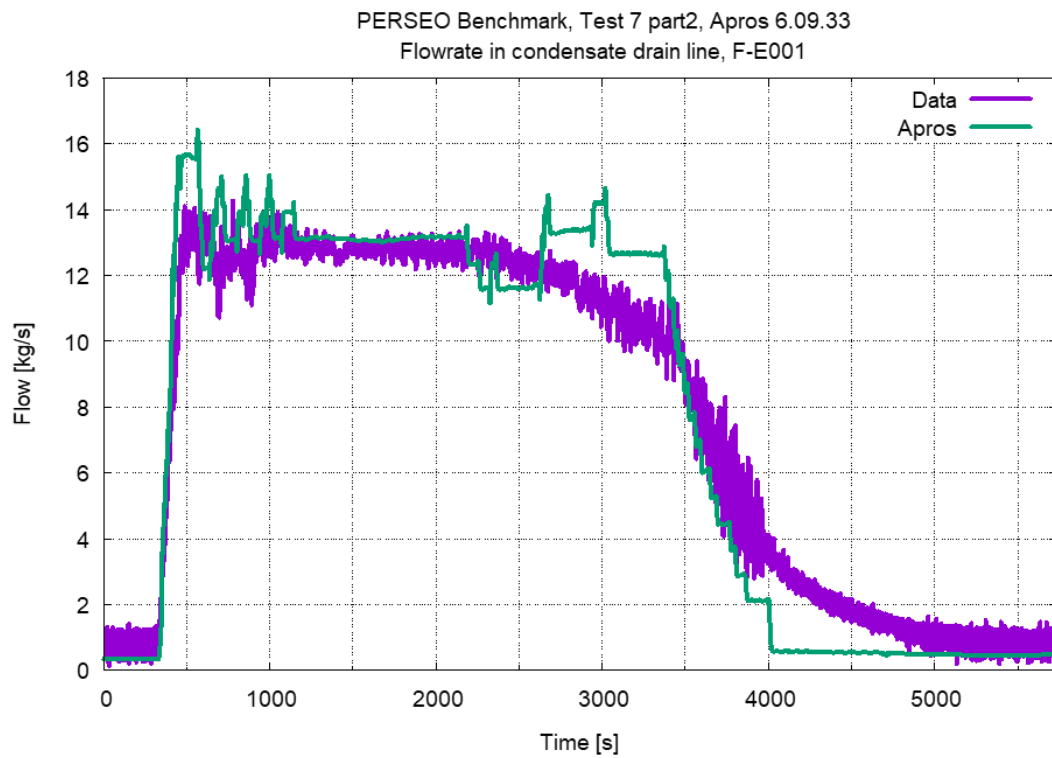


Figure 5.473. Test 7 Part 2 run B - HX power

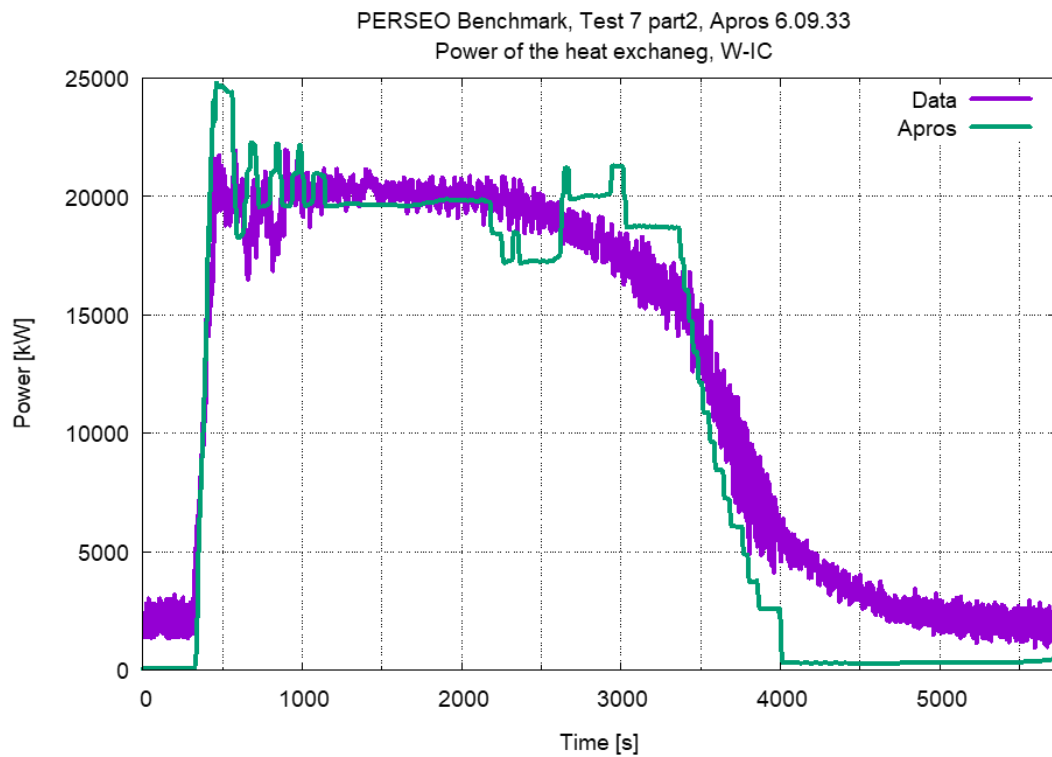


Figure 5.474. Test 7 Part 2 run B - Primary pressure

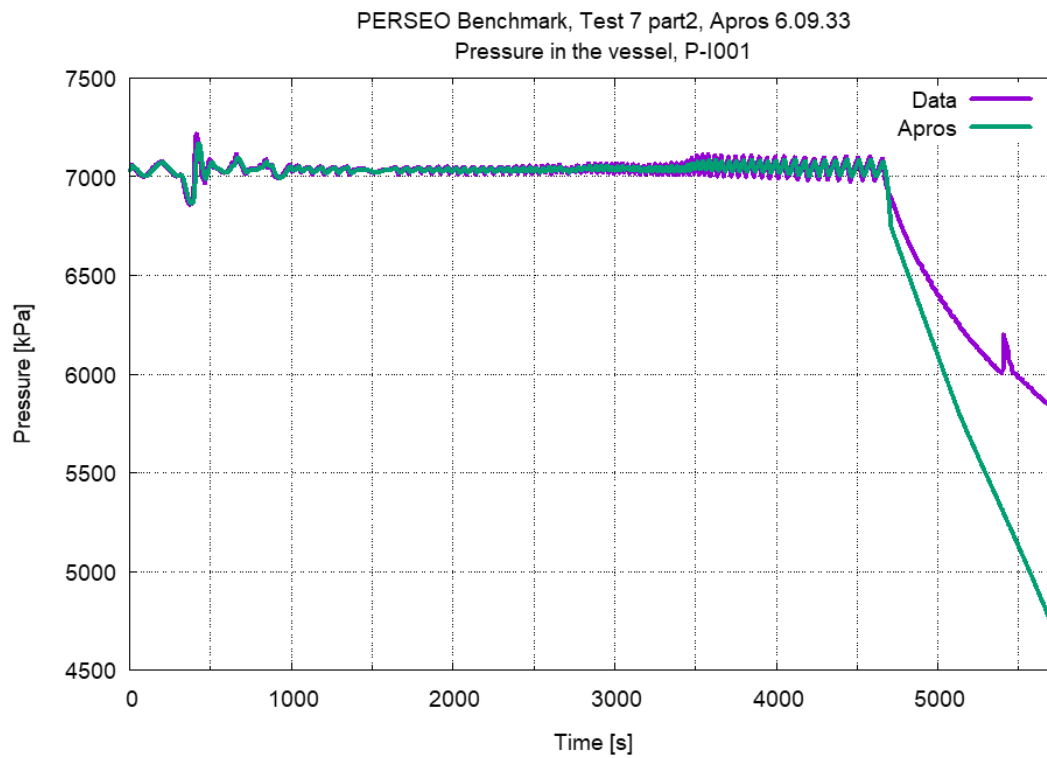


Figure 5.475. Test 7 Part 2 run B - HX inlet fluid temperature

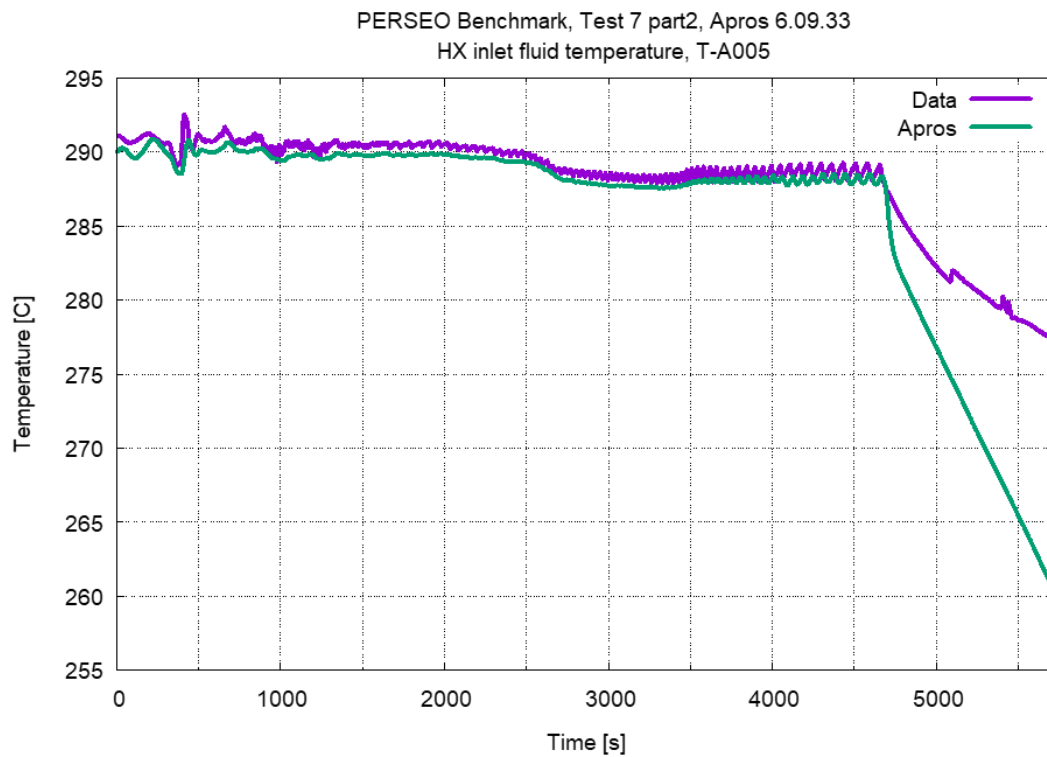


Figure 5.476. Test 7 Part 2 run B - HX outlet fluid temperature

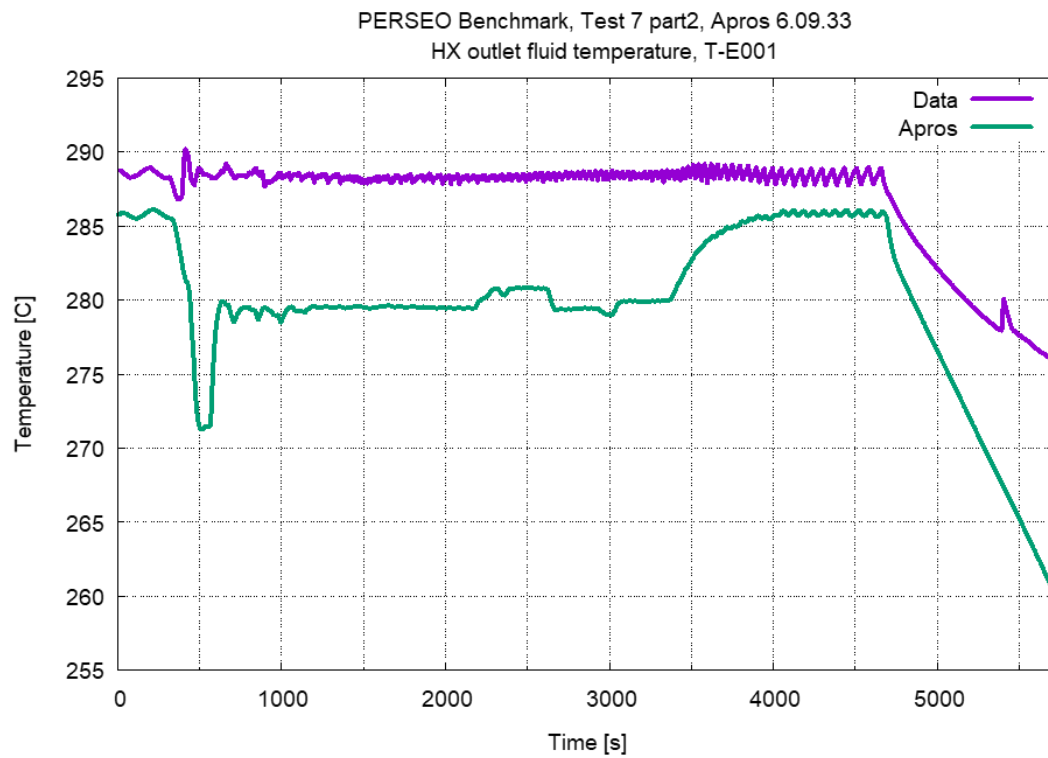


Figure 5.477. Test 7 Part 2 run B - HXP level

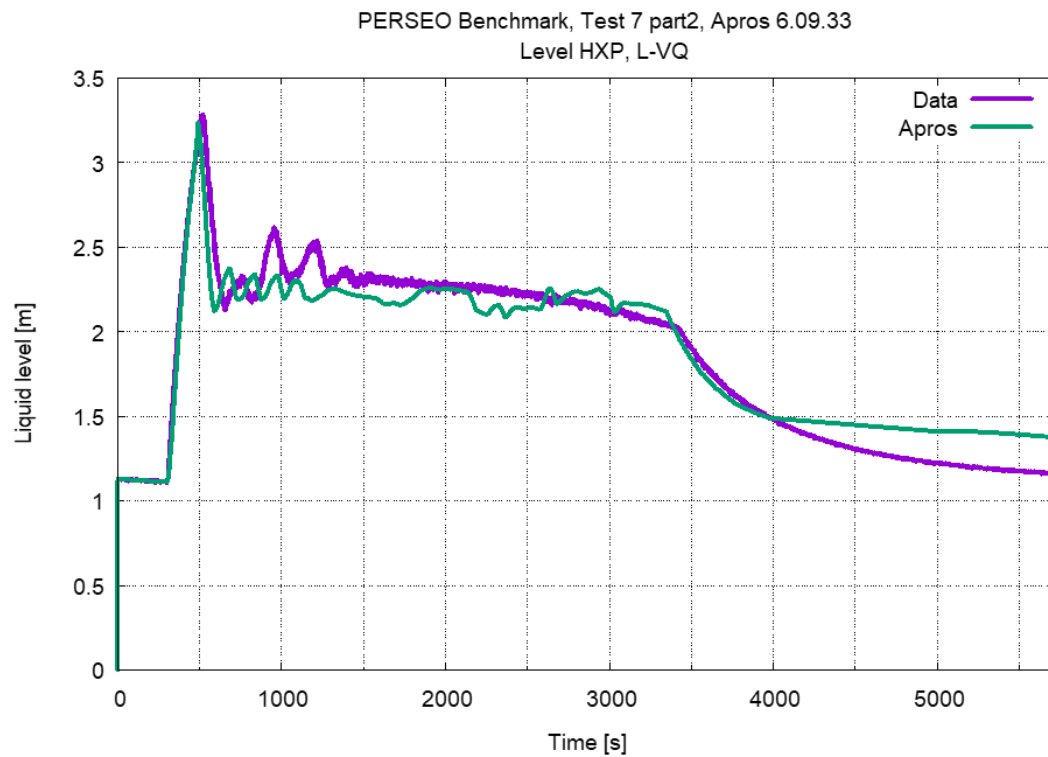


Figure 5.478. Test 7 Part 2 run B - HXP pressure difference from elevation 0.2 to 4.4 m

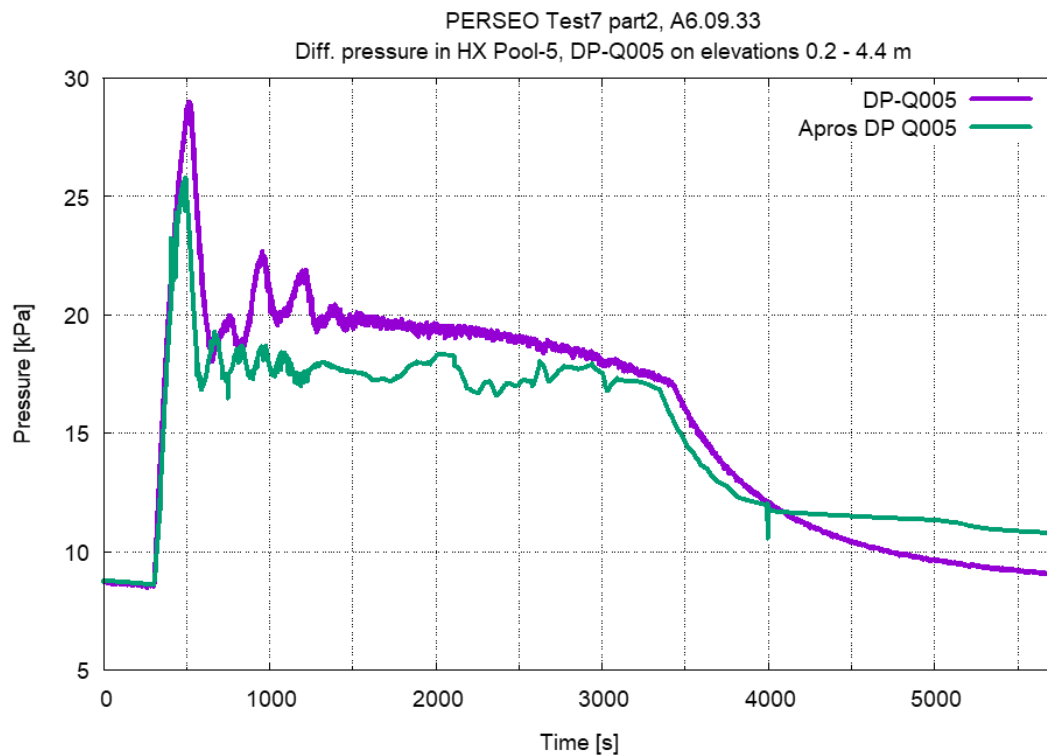


Figure 5.479. Test 7 Part 2 run B - OP level

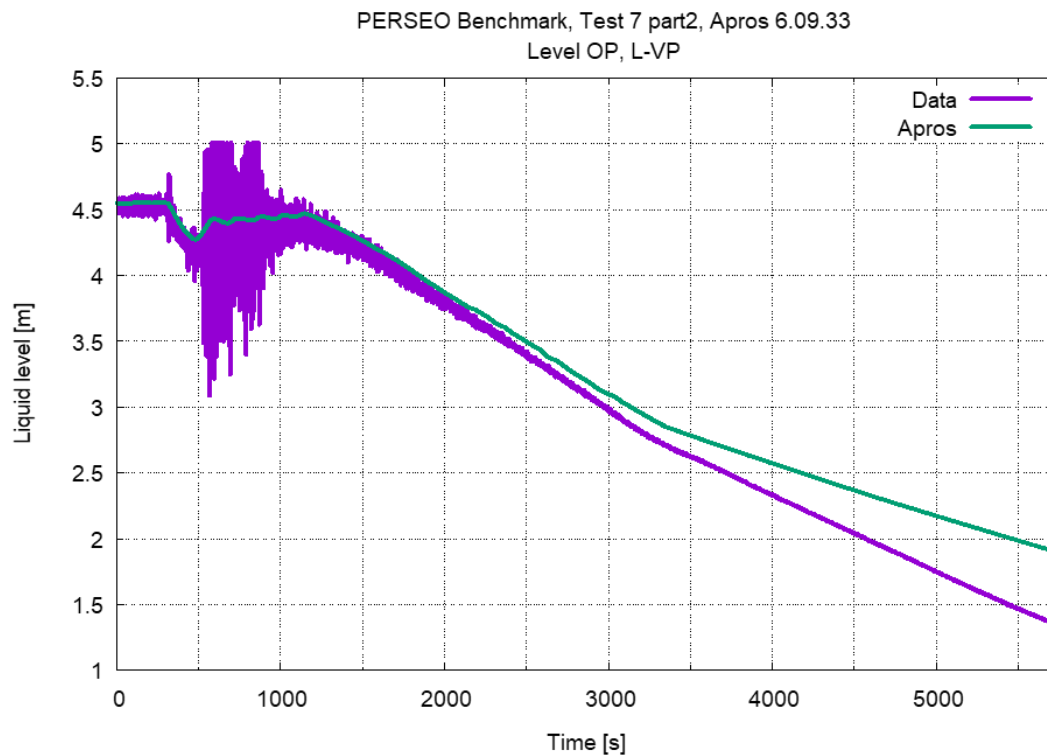


Figure 5.480. Test 7 Part 2 run B - Fluid temperature HXP bottom

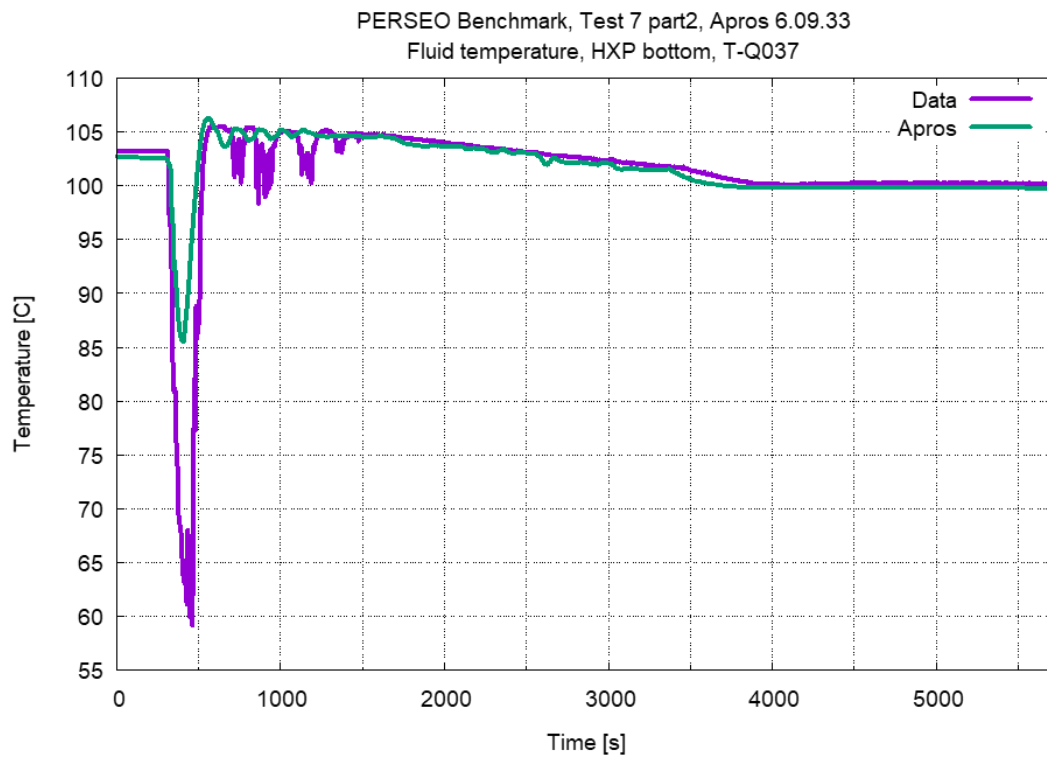


Figure 5.481. Test 7 Part 2 run B - Fluid temperature HXP middle

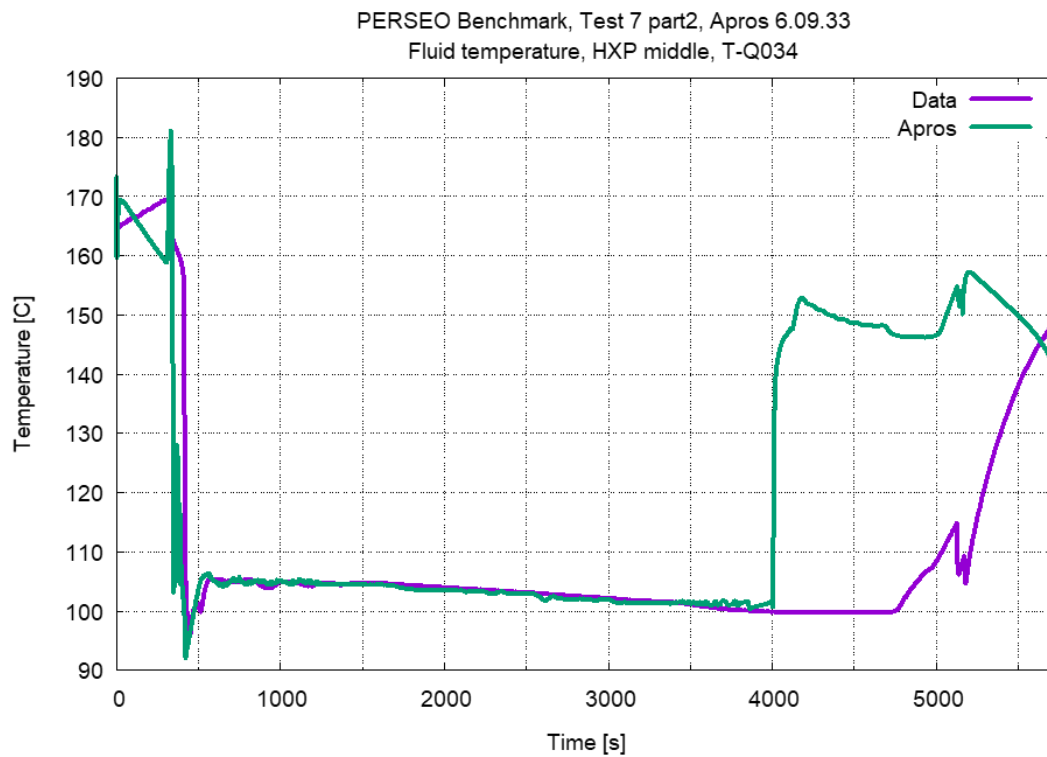


Figure 5.482. Test 7 Part 2 run B - Fluid temperature HXP top

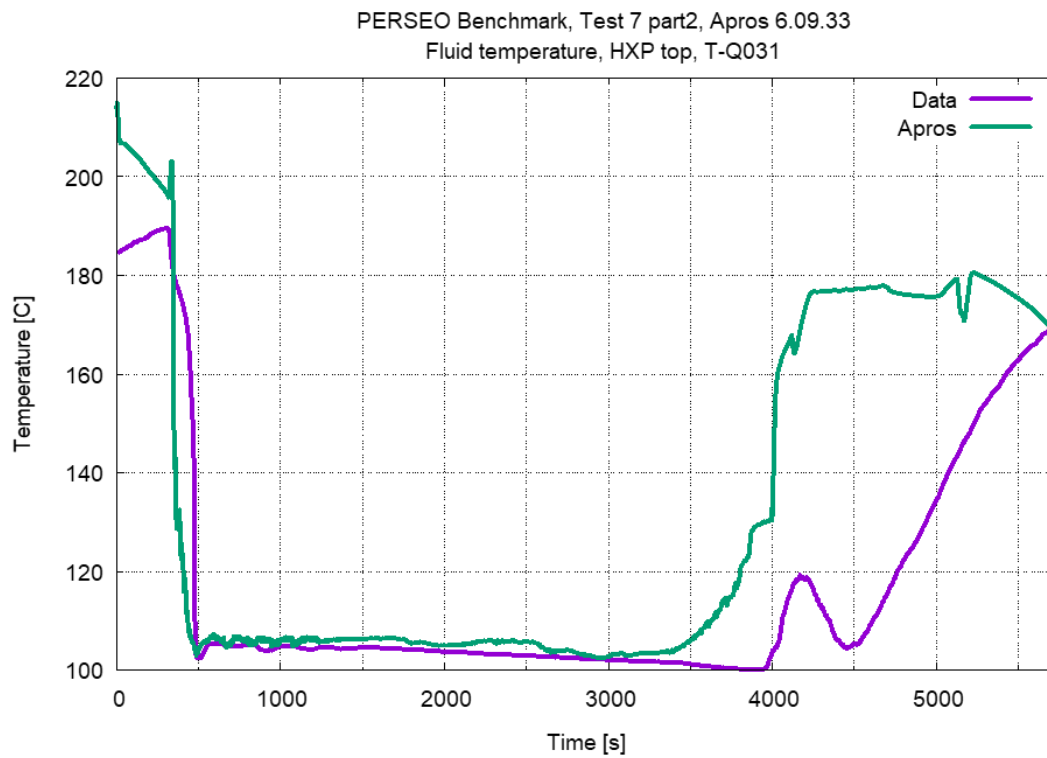


Figure 5.483. Test 7 Part 2 run B - Relative pressure HXP top

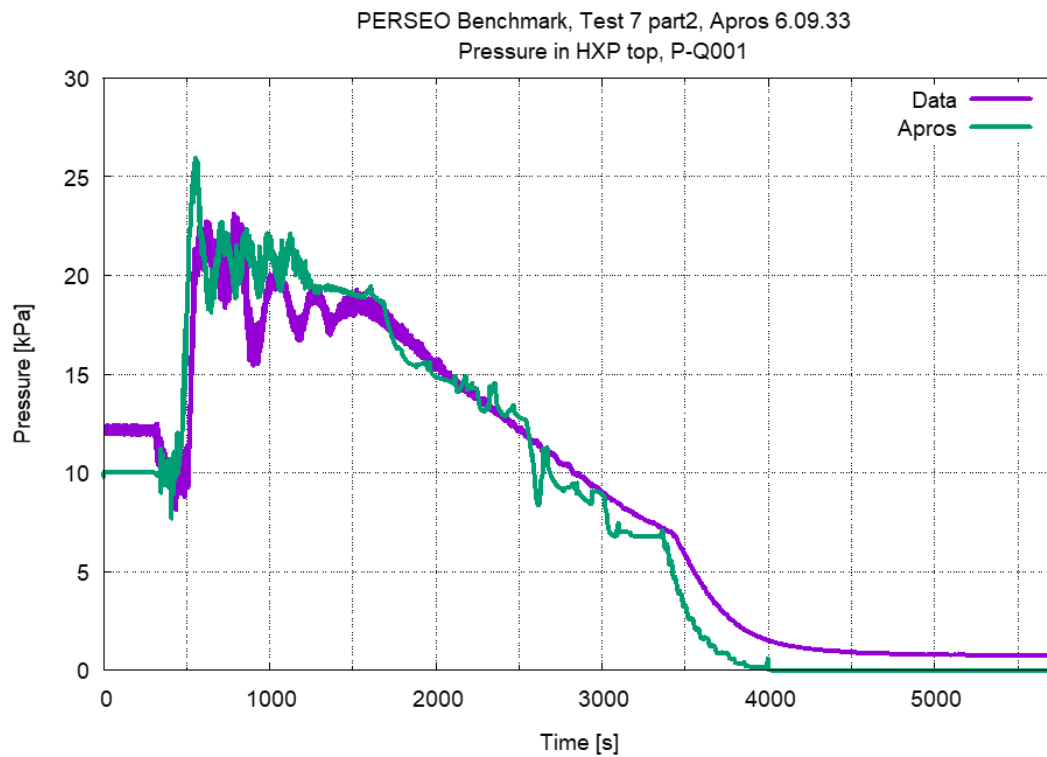


Figure 5.484. Test 7 Part 2 run B - Fluid temperature OP bottom

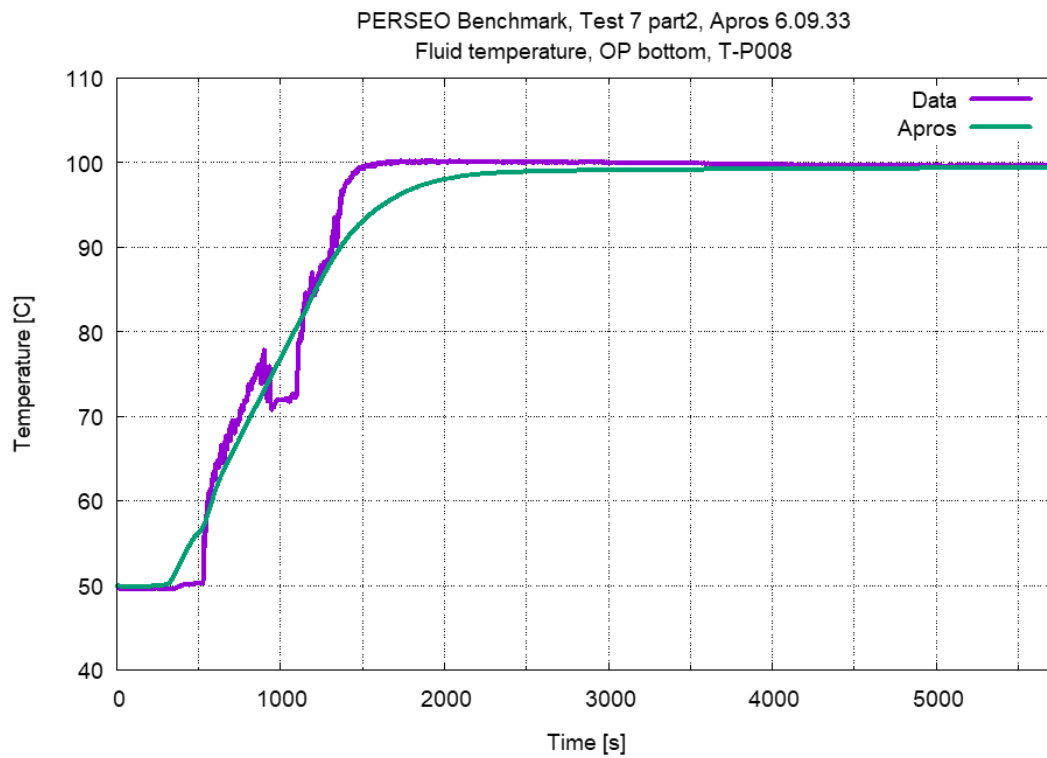


Figure 5.485. Test 7 Part 2 run B - Fluid temperature OP top

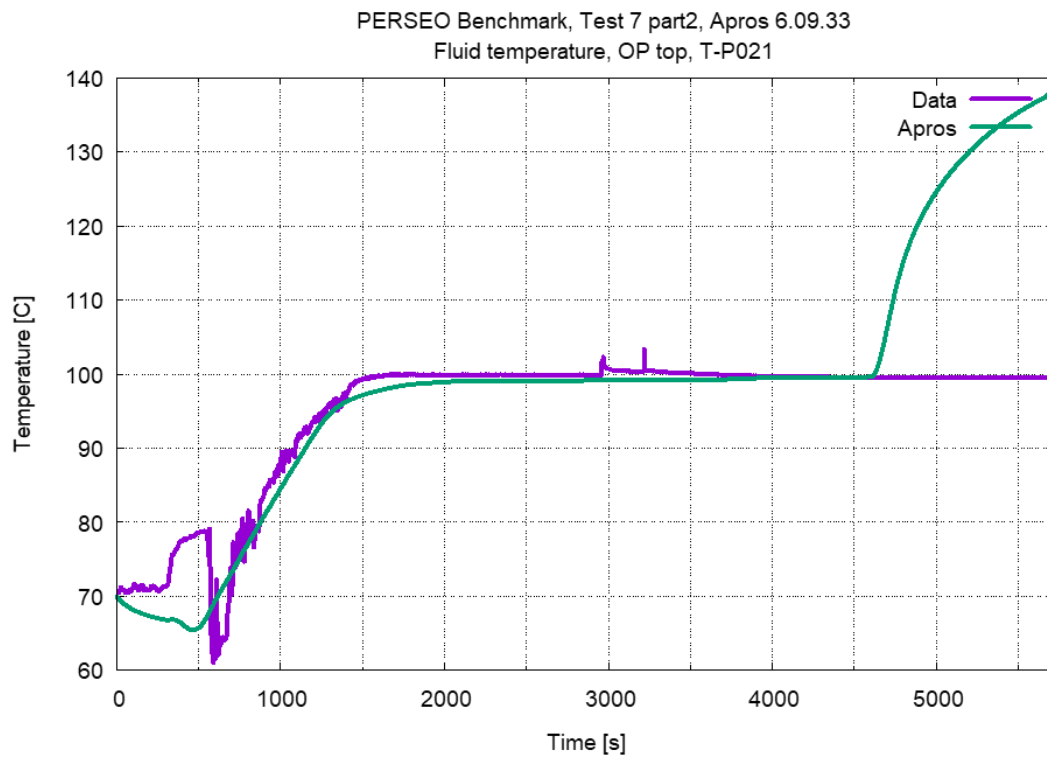


Figure 5.486. Test 7 Part 2 run B - Differential pressure HX upper - lower header

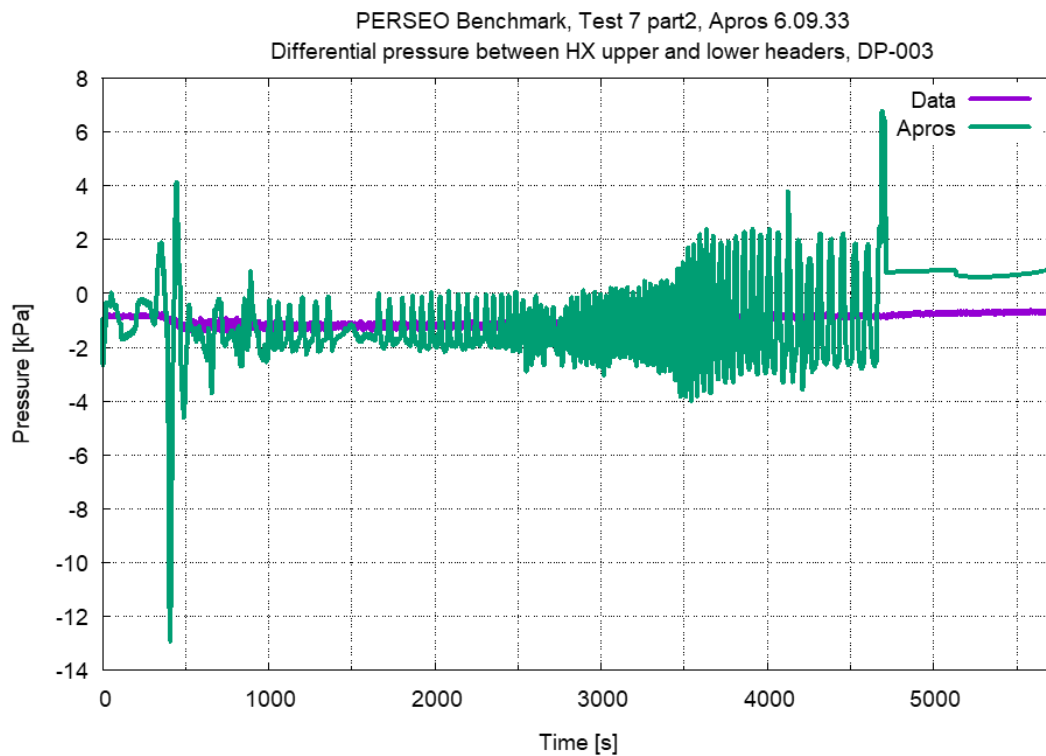


Figure 5.487. Test 7 Part 2 run B - Differential pressure -steam duct injector

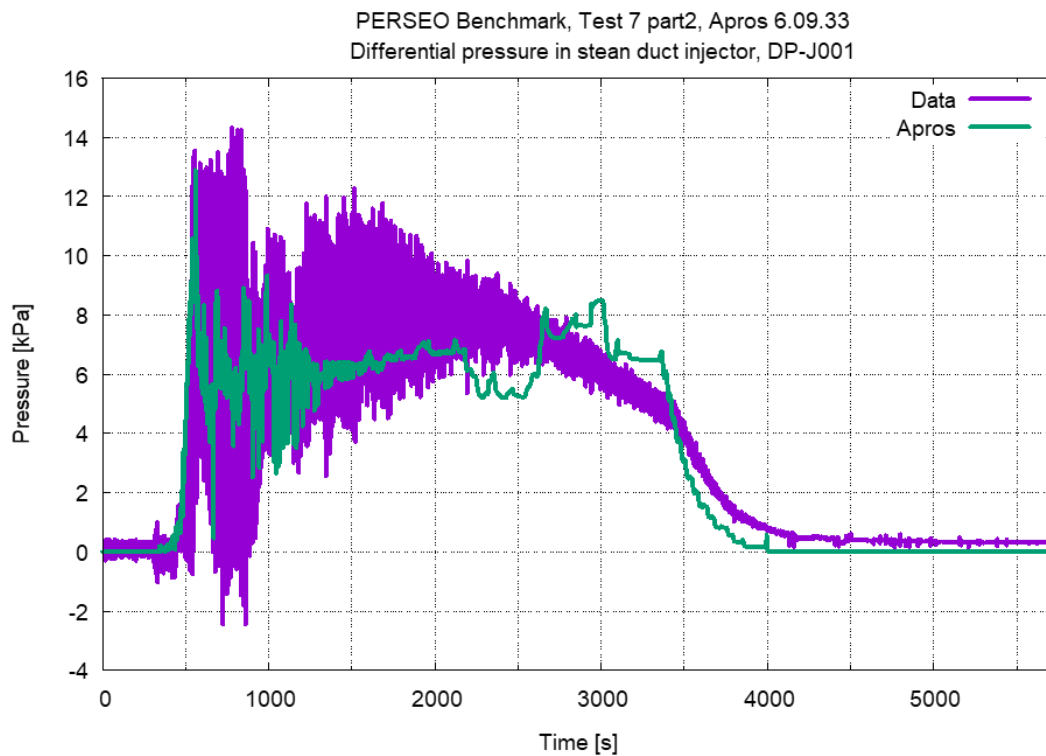


Figure 5.488. Test 7 Part 2 run B - Wall temperature HX upper header

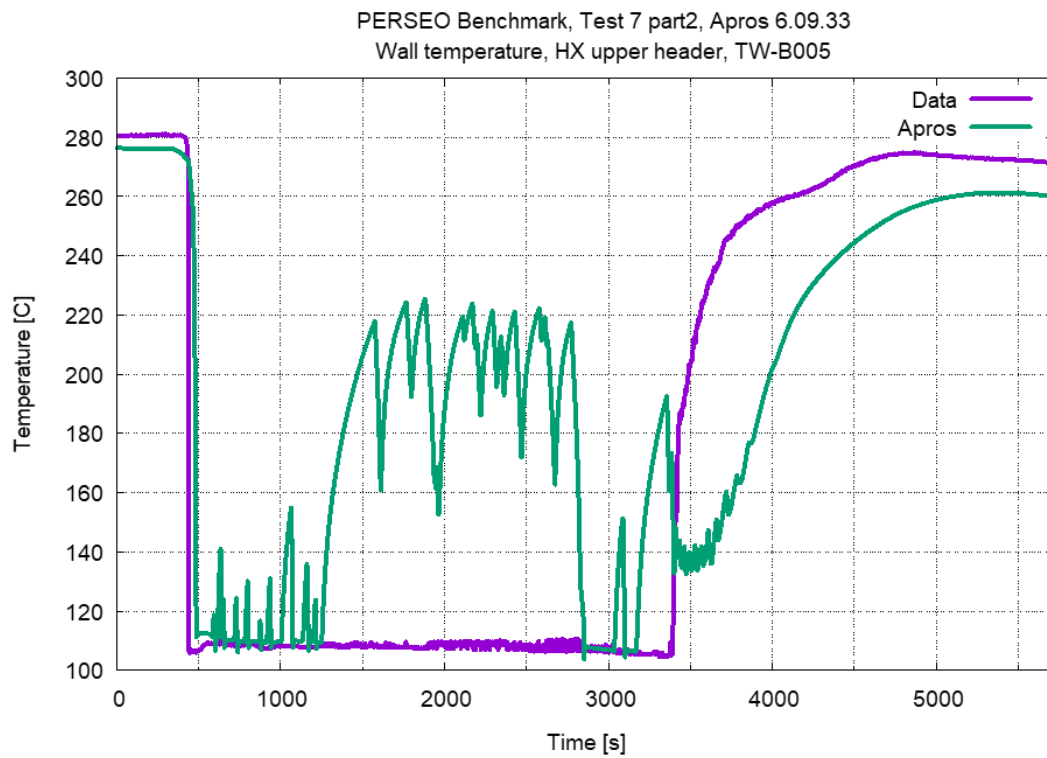


Figure 5.489. Test 7 Part 2 run B - Wall temperature HX lower header

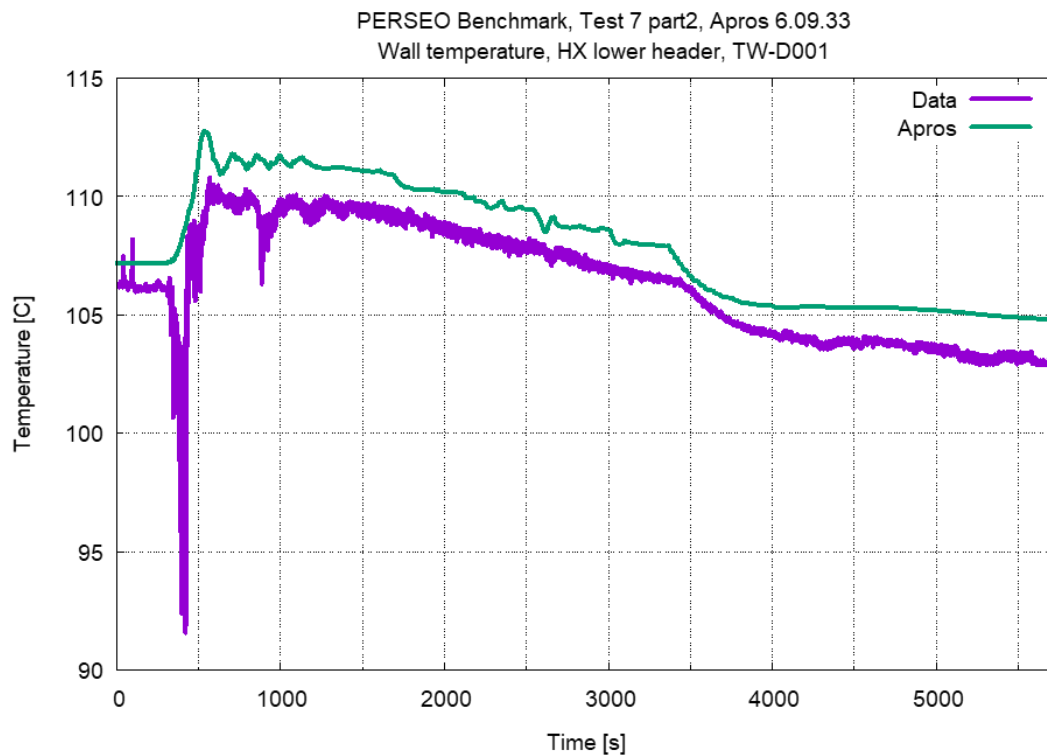


Figure 5.490. Test 7 Part 2 run B - Flow through the triggering valve

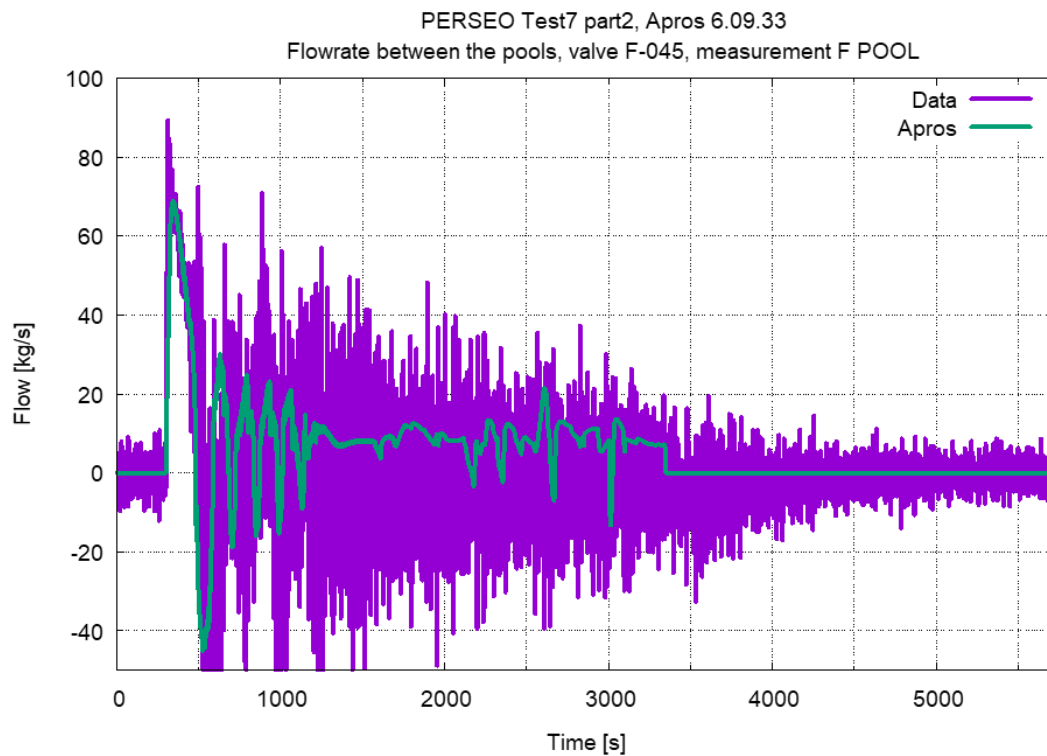


Figure 5.491. Test 7 Part 2 run B - Gas velocity in the injector

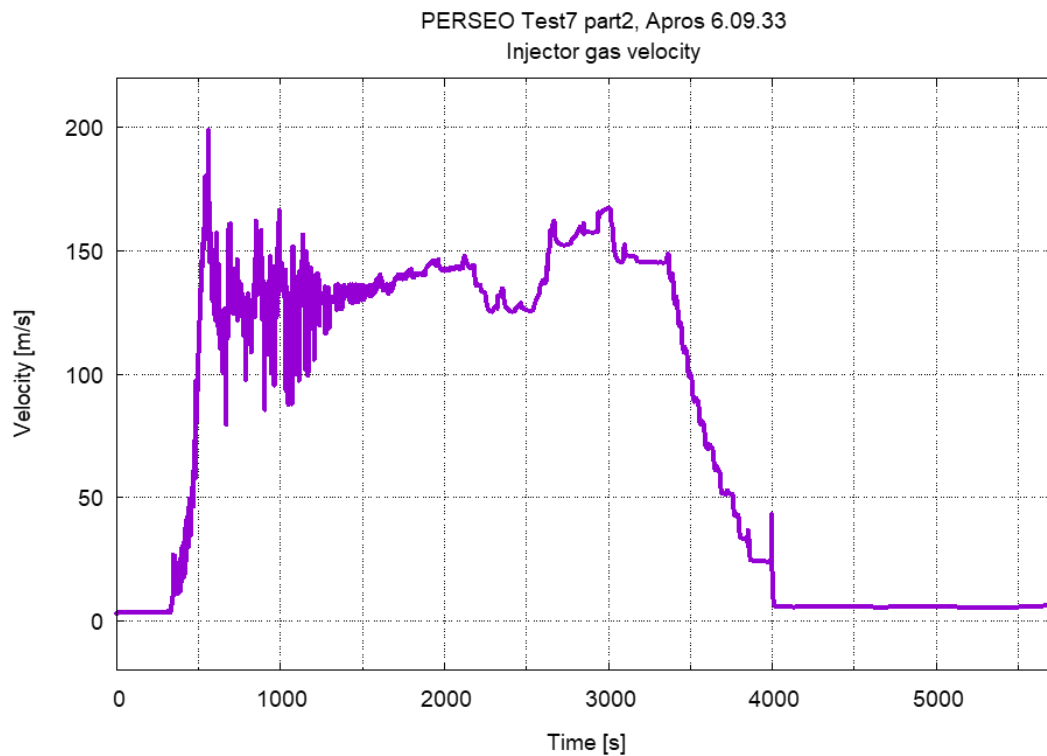


Figure 5.492. Test 7 Part 2 run B - Diffusion coefficients in the overall pool

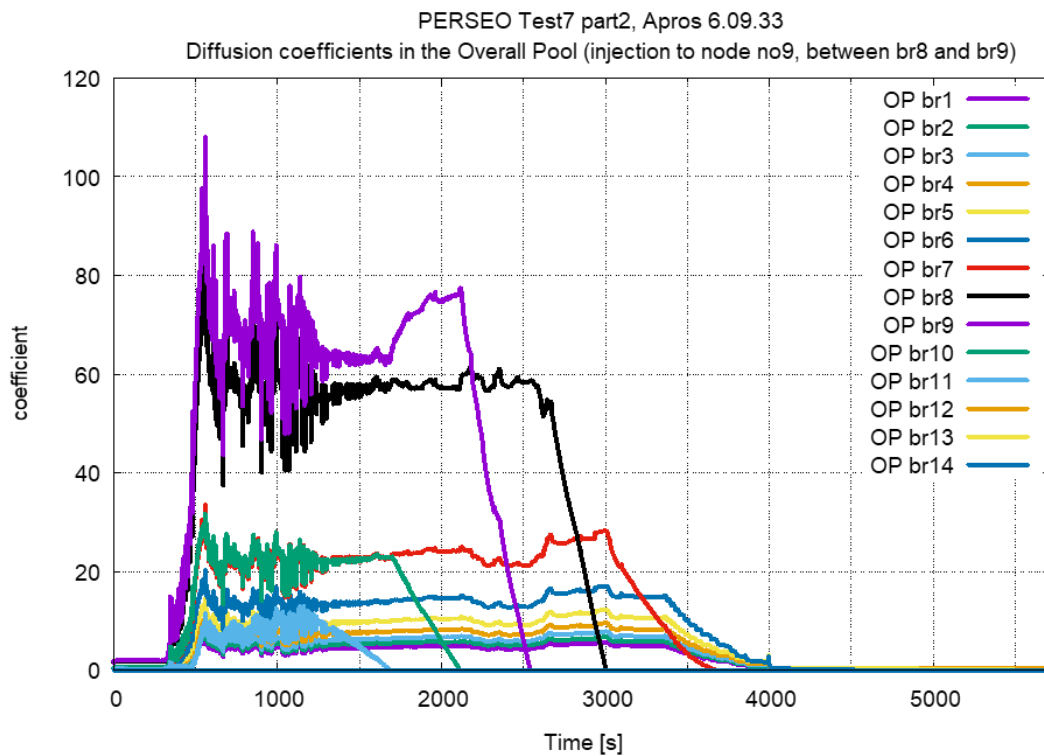


Figure 5.493. Test 7 Part 2 run B - Fluid temperature in overall pool bottom and top

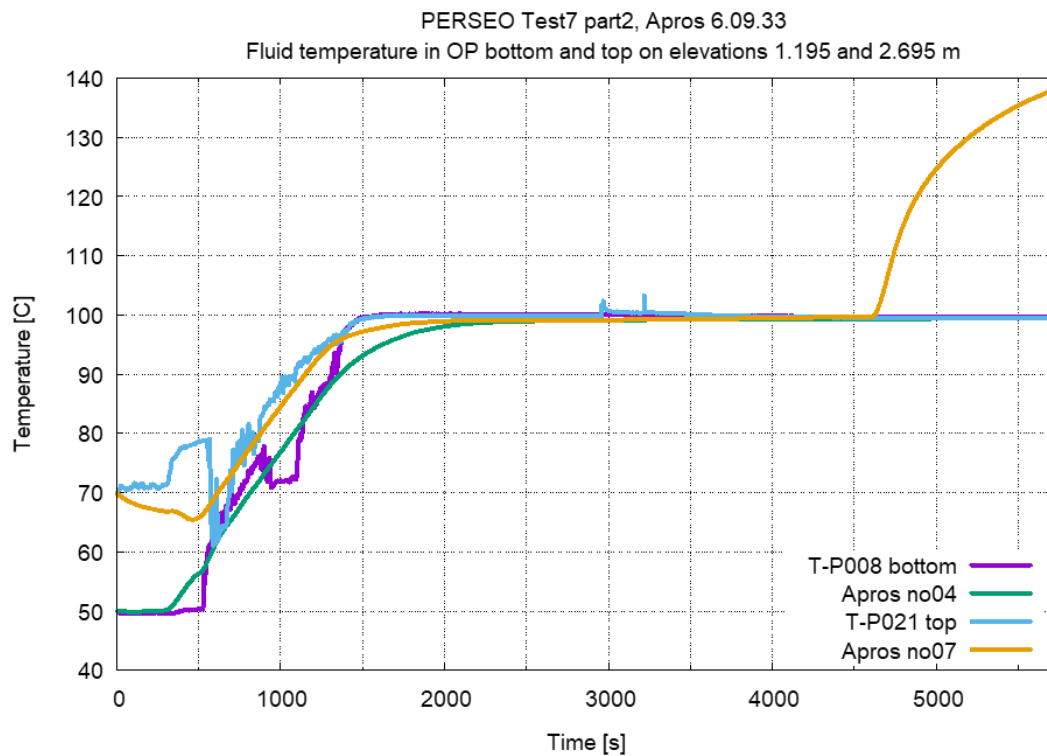


Figure 5.494. Test 7 Part 2 run B - Fluid temperature in overall pool

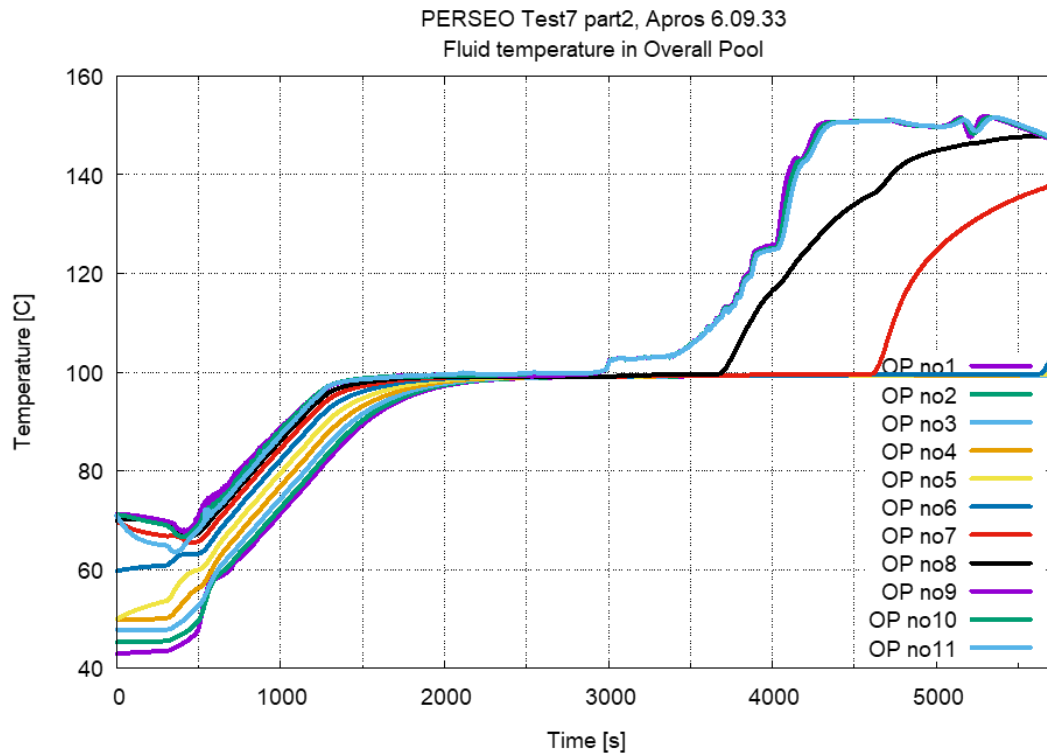


Figure 5.495. Test 7 Part 2 run B - HX power as function of pool water level

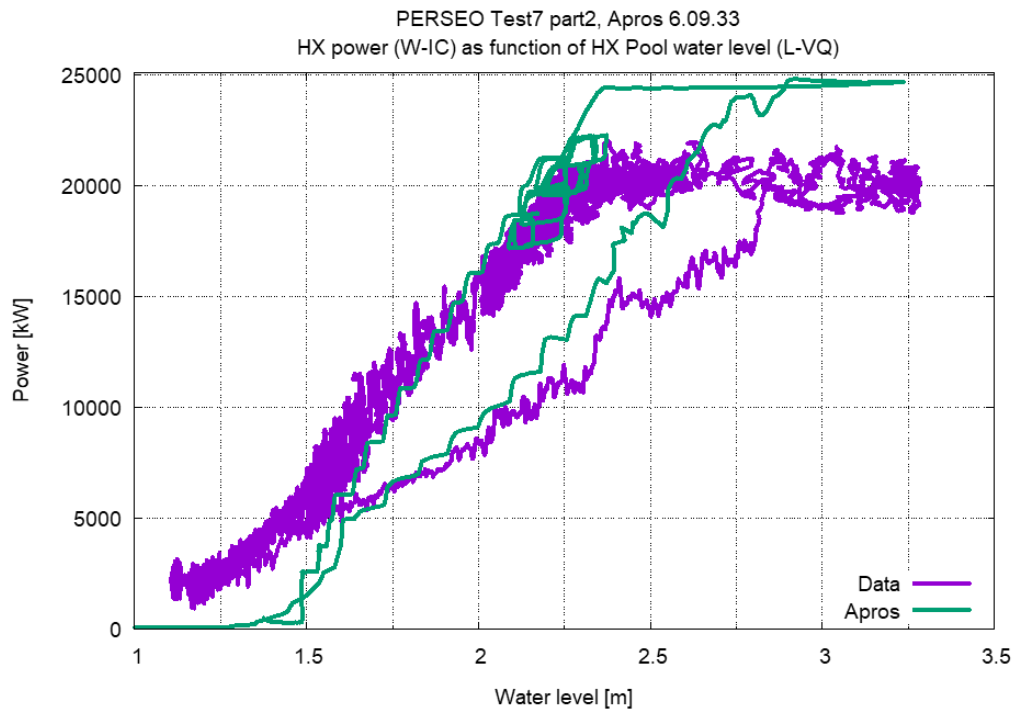


Figure 5.496. Test 7 Part 2 run B - Heat transfer coefficient in the heat exchanger collectors and tubes (plotted at 1 500 s)

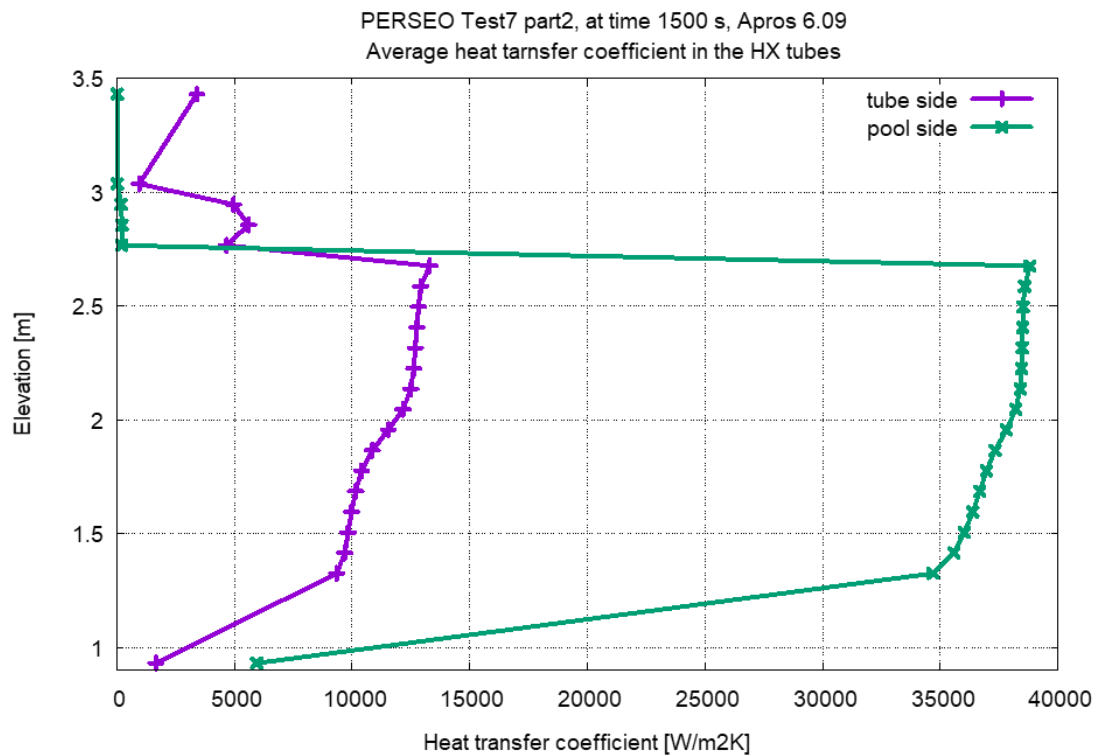


Figure 5.497. Test 7 Part 2 run B - Axial temperature profiles in the heat exchanger (plotted at 1 500 s)

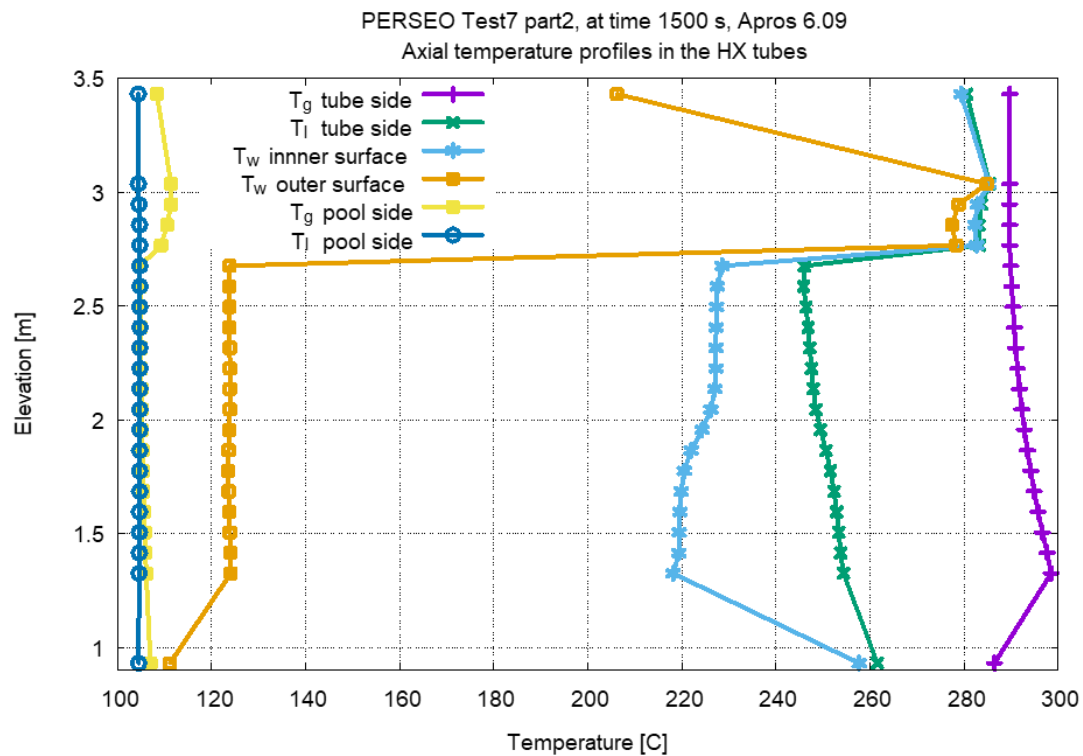


Figure 5.498. Test 7 Part 2 run B - Differential pressure in the bottom of the HX pool

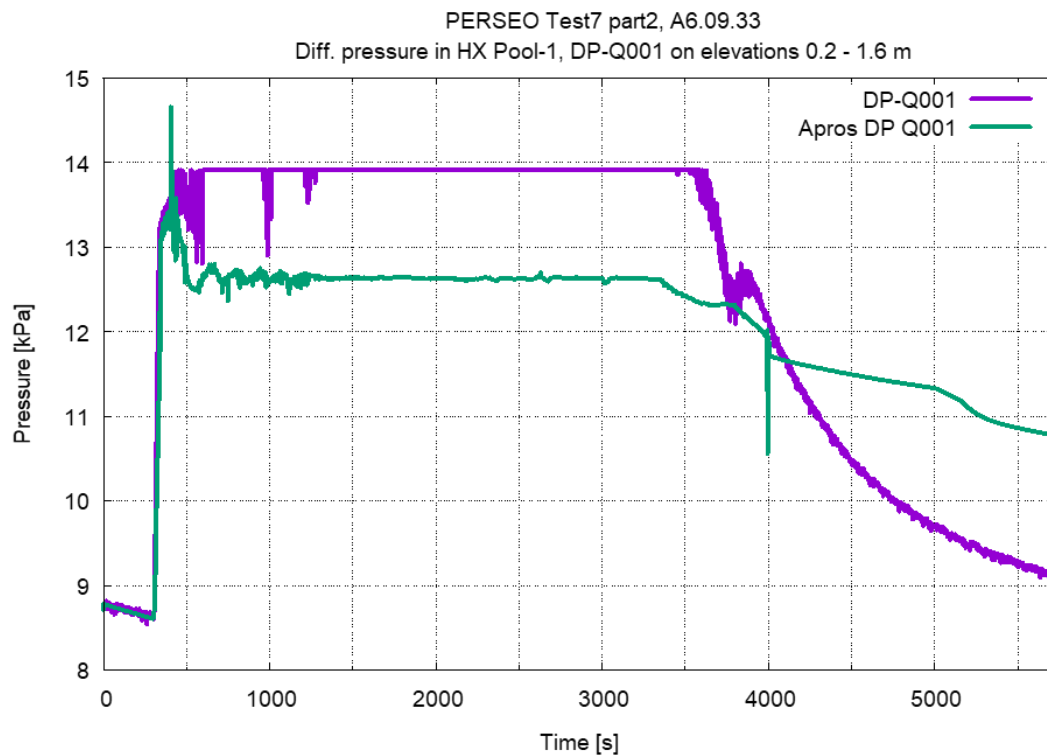


Figure 5.499. Test 7 Part 2 run B - Differential pressure between elevations 1.6 and 3.0 m in the HX pool

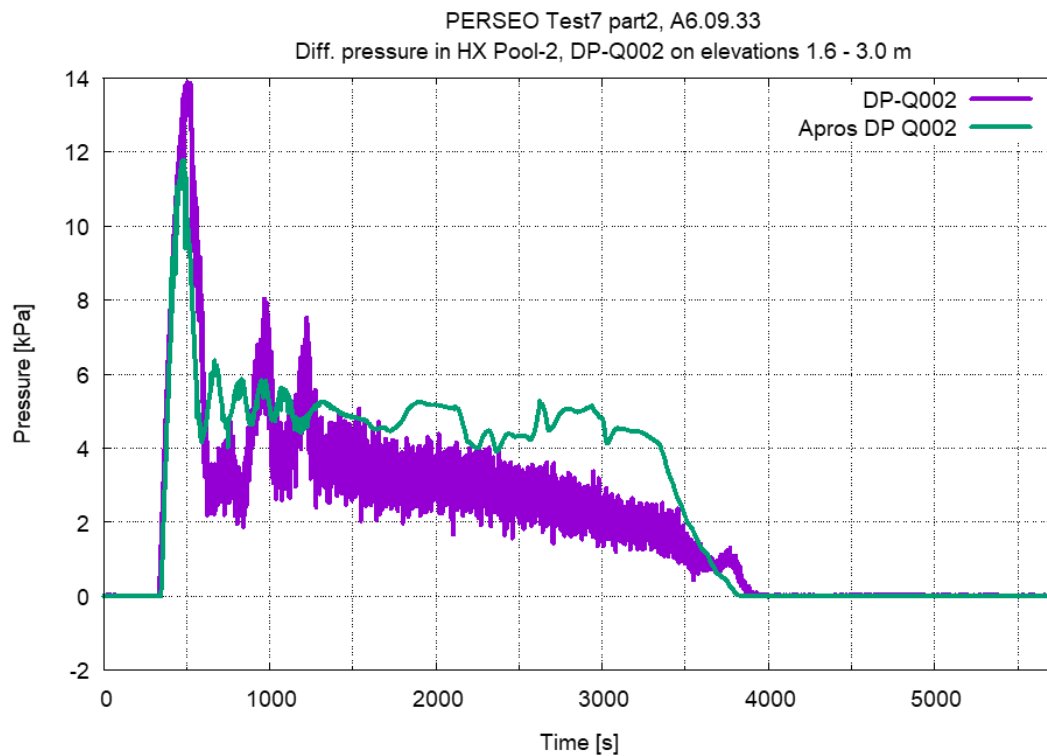
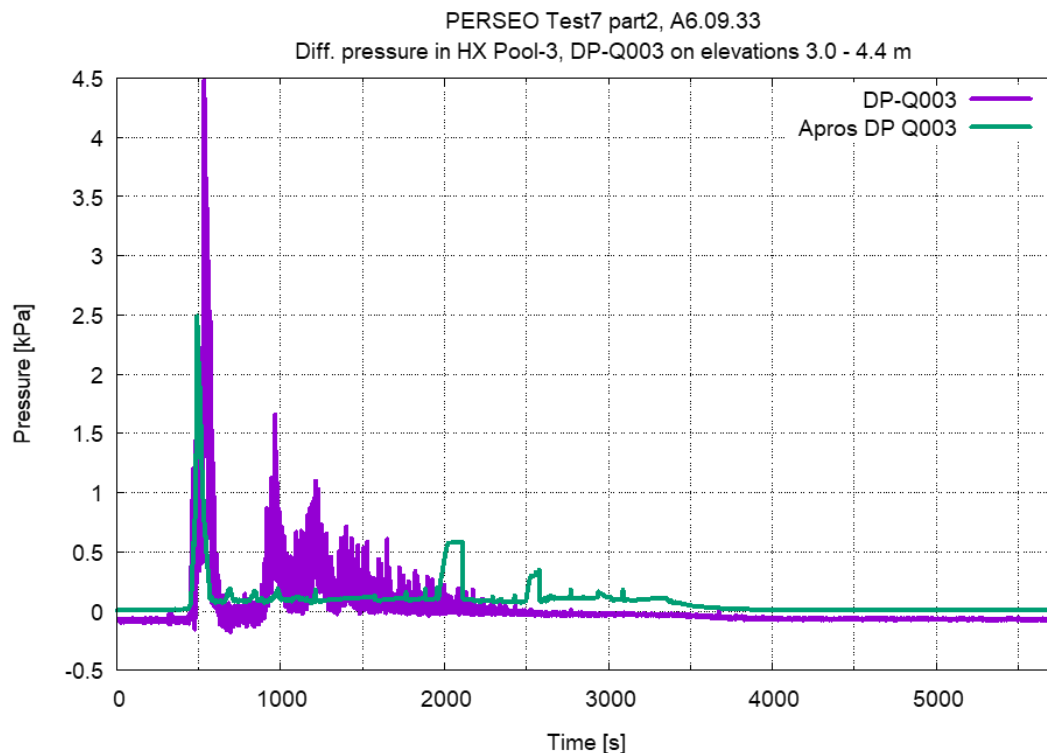


Figure 5.500. Test 7 Part 2 run B - Differential pressure between elevations 3.0 and 4.4 m in the HX pool



SECTION 5: CONCLUSIONS

The PERSEO Test 7 Part 1 and Part 2 were modelled with Apros. The model was capable of simulating the main phenomena of the experiments. The approach of modelling overall pool mixing with 1D components and a diffusion coefficient calculated from steam injection velocity was successful. However, the strong condensation inducing oscillations in the steam duct (chugging) was not reproduced in the calculation. More detailed modelling of the heat losses and boundary conditions might improve predictions of initial temperature distribution. The sensitivity calculation of Test 7 Part 2, with modified form loss coefficients in the open pool area of the HX pool, shows limitations of a quasi-2D modelling approach with a 1D code. Attempts to improve some aspects of modelling, i.e. initial temperature distribution, may have drawbacks in overall behaviour of the model. The user effects in modelling this kind of phenomena, which is beyond the original application area of a thermal-hydraulic system code, i.e. the 2D modelling approach with a 1D code, may be strong.

REFERENCES

[5.2.12 1] <http://www.apros.fi/en>

6. Comparison of codes and modelling approaches

6.1. Summary of the models implemented in the codes for the heat exchanger heat transfer

The heat transfer from the HX to the HXP is one of the main phenomena investigated in the PERSEO facility. The correct prediction of the pool side and tube side heat transfer is fundamental to reproducing the transient behaviour. The models implemented in the codes adopted by the benchmark participants are summarised in Table 6.1. As a reference it is possible to consider the individual benchmark partners' reports.

Table 6.1. Models implemented in the codes for the HX heat transfer

CODE (Participant Institution)	Pool side heat transfer	Tube side heat transfer
Apros 6.09 (VTT)	Convection: Dittus-Boelter Boiling: Thom correlation	Chen (with Vierow-Schrock correction for non-condensable gases)
ATHLET 3.2 (GRS)	Modified model of Chen (for subcooled and saturated nucleate boiling) and the model of McAdams (natural convection)	The Models of Chen (macroscopic part only, forced convection), Nusselt (laminar condensation) and Carpenter and Colburn (turbulent condensation) have been replaced by models of Nusselt (laminar condensation), Kutateladze (laminar wavy condensation) and Chen (turbulent condensation)
MARS-KS v1.4 (KAERI)	Chen model	Maximum value of Shah and Nusselt models
MELCOR v2.2.11620 (UoFU)	Convection, Nucleate boiling (Chen), CHF (Zuber), minimum film boiling heat flux (Zuber), film boiling (Bromley)	MELCOR calculates a diffusion mass transfer coefficient using the Sherwood number correlation to model condensation. Condensed materials are then computed by MELCORs liquid film model
RELAP5-3D v4.3.4. (POLITO, UNIROMA1)	Nucleate boiling (Chen), transition boiling (Chen), and film boiling (Bromley), natural convection (Churchill-Chu or McAdams)	Laminar condensation (Nusselt), turbulent condensation (Shah), presence of non-condensable gases (Coburn-Hougen)
RELAP5/MOD3.3Patch05 (UJV)	Nucleate (Chen-Inayatov), transition (Chen), and film (Bromley) modes are dominant	Nusselt-Shah-Coburn-Hougen
RELAP5/MOD3.3Patch03 (UNIP1)	Nucleate (Chen-Inayatov), transition (Chen), and film (Bromley) modes are dominant	Nusselt-Shah-Coburn-Hougen
SOCRAT V1 (IBRAE)	Chen (for boiling) Dittus (convection)	Combined correlations from Dittus, Bromley & Rohsenow and $\text{coeff} * \text{Ra}^m * \text{Pr}^n$
SPACE v3.2 (KAERI)	Chen model	Maximum value of Shah and Nusselt models

Table 6.1. Models implemented in the codes for the HX heat transfer (Continued)

CODE (Participant Institution)	Pool side heat transfer	Tube side heat transfer
SPECTRA v3.61 (NRG)	Chen (nucleate boiling), McAdams (natural convection)	Nusselt correlation for laminar flow in vertical tubes
TRACE V5.1175 (USNRC)	Single phase: Pipe: Laminar forced convection – Nusselt analytical formula Turbulent forced convection – Gnielinski Natural convection - traditional model with function of Raleigh number Rod bundle – El-Genk Boiling Nucleate boiling (Chen formulation with Gorenflo correlation for pool boiling component) Transition boiling - Interpolation between CHF and Minimum Film Boiling (MFB) Film boiling (Inverted annular – Cachard; Dispersed flow: radiative flux to both phase plus convective flux to superheated steam)	Kuhn-Schrock-Peterson (K-S-P) for laminar film condensation, Modified Gnielinski Correlation for turbulent film condensation. Noncondensable effect -Coburn-Hougen

6.2. Summary of the nodalisation modelling approaches

6.2.1. Nodalisation approach comparison

Table 6.2 summarises the main nodalisation choices adopted by the benchmark participants. The majority of the participants decided to adopt a single equivalent vertical hydraulic region to model the HX, with the exception of KAERI_a and USNRC (which used three pipes) and UNIPI (which used 15 pipes).

Most of the participants modelled the HXP and the OP by mono-dimensional components connected through lateral junctions. IBRAE in the lateral junctions included an additional two equations for the momentum. KAERI_a adopted a 3D model for the OP only. UofU used one control volume for the OP and three control volumes for the HXP.

The “slice nodalisation” technique was adopted by UNIPI for all the nodalisations, by POLITO, UJV, UNIROMA1 and USNRC for the pools, and was not adopted by the other participants. The “slice nodalisation” technique is adopted to improve the capability of the code to reproduce natural circulation phenomena. This technique consists in realising the mesh cells of different nodalisation zones, at the same elevation, with the same cell length. This avoids the error due to the position/elevation of the cell nodalisation centre, which can influence the results of the calculated data when natural circulation regime is present. If the “slice nodalisation” technique is not used, this error has to be taken into account and its effect increases if larger nodalisation cells are used. In this case it can be reduced by using a “fine nodalisation”. In general, its effect on the results is less important when forced

circulation regimes are simulated. However, the “slice nodalisation” technique could require nodes of small length increasing the numerical error and the computational time. The “code user” must take into account these disadvantages during the nodalisation development [20].

Heat losses have been considered by eight participants for the entire system or for the HXP. Pressure drops have been calibrated against experimental data by six participants.

Table 6.2. Comparison of nodalisation approaches

Participant	Nodalisation approach	HX tube side equivalent vertical hydraulic regions	HX pool side equivalent vertical hydraulic regions	OP equivalent vertical hydraulic regions	Heat losses modelling	Pressure drops calibration
GRS	No slice	1	2 + lateral junctions	2 + lateral junctions	Yes	No
IBRAE	No slice	1	2 + lateral junctions that include additional two equations for the momentum	2 hydraulic regions with lateral junctions	Yes (not in the steam duct)	Yes
KAERI_a	No slice	3	2 + lateral junctions	3D model 3x2x9	No	Yes
KAERI_b	No slice	1	2 + lateral junctions	2 + lateral junctions	No	No
NRG	No slice	1	2 + lateral junctions	2 + lateral junctions	No	No
POLITO	Partial slice (pool)	1	2 + lateral junctions	2 + lateral junctions	Yes	Yes
UJV	Partial slice (pool)	1	2 + lateral junctions	2 + lateral junctions	Yes	Yes (injector)
UNIP	Slice	15	2 + lateral junctions	2 + lateral junctions	No	Yes
UNIROMA1	Partial slice (pool)	1	3 + lateral junctions	3 + lateral junctions	Yes	Yes
UofU	No slice	1	3 volumes	1 volume	Yes (only HXP)	No
USNRC	Partial slice (pool)	3	3 + lateral junctions	3 + lateral junctions	Yes	No
VTT	Partially slice (HX pool)	1	2 + lateral junctions	1	Yes (only HXP)	No (steam duct losses adjusted)

6.2.2. Nodalisation approach for the simulation of the HX heat transfer

The accurate prediction of the heat transfer between the HX and the HXP is fundamental for the simulation of the test behaviour. To do that, IBRAE, USNRC and VTT did not implement any additional correlations or performed any user tuning, GRS implemented an additional set of correlations for the tube side condensation [21] and all the other participants tuned their model to improve their predictions.

Table 6.3 summarises the main modification and user tuning adopted by the benchmark participants.

Table 6.3. User approach for the correct simulation of the heat transfer in the heat exchanger

Participant	Code	Note
GRS	ATHLET 3.2	MODIFIED VERSION OF ATHLET 3.2 For the tube side, the models of Chen (macroscopic part only, forced convection), Nusselt (laminar condensation) and Carpenter and Colburn (turbulent condensation) has been replaced by the models of Nusselt (laminar condensation), Kutateladze (laminar wavy condensation) and Chen (turbulent condensation) [21]
IBRAE	SOCRAT V1	NO USER TUNING OR NEW CORRELATIONS IMPLEMENTED
KAERI_a	MARS-KS v1.4	USER TUNING Heat transfer coefficient in the HX was multiplied by 2.4
KAERI_b	SPACE v3.2	USER TUNING Heat transfer coefficients for the nucleate boiling and condensation was multiplied by 3.0.
NRG	SPECTRA v3.61	USER TUNING In order to improve the prediction of the power removal, the value of the characteristic length for the film condensation adopted is 5 cm, corresponding to a multiplier of 2.44 for the HTC. Additionally, the opening fraction of the triggering valve was tuned in order to obtain the expected mass flow rate.
POLITO	RELAP5-3D v4.3.4.	USER TUNING To correctly reproduce the HX power a multiplication factor for the heat transfer coefficients has been applied on the inner and outer side of the HX heat structure. This multiplication factor, called fouling factor in RELAP5-3D, has been set equal to 2.4
UJV	RELAP5/MOD3.3 Patch05	USER TUNING The HX power underestimation was compensated by means of a fouling factor (multiplier for heat transfer coefficients) value of 2.2 applied on the heat transfer coefficients on both sides of HX tubes.
UNIPI	RELAP5/MOD3.3 Patch03	USER TUNING Tuning is the application of a multiplication factor for the heat transfer coefficients on the inner and outer side of the HX heat structure. This multiplication factor, called fouling factor in RELAP5 has been set equal to 2.4
UNIROMA1	RELAP5-3D v4.3.4.	USER TUNING A multiplicative factor equal to 2.4 has been introduced in both HX sides.

Table 6.3. User approach for the correct simulation of the heat transfer in the heat exchanger (Continued)

Participant	Code	Note
UofU	MELCOR v2.2.11620	USER TUNING Several sensitivity coefficients in the heat structure package are modified Initial versions of the MELCOR model of the PERSEO facility used a multiplier of 120 to match the PERSEO facility description supplied, however, this value was increased to 180 in the final version of the model.
USNRC	TRACE V5.1175	NO USER TUNING OR NEW CORRELATIONS IMPLEMENTED
VTT	Apros 6.09	NO USER TUNING FOR THE HEAT TRANSFER

6.3. Boundary conditions

In Table 6.4 the main boundary conditions set by the participants for the calculation are summarised.

Table 6.4. Boundary condition postulated by the different benchmark participants

PARAMETER	GRS	IBRAE	KAERI_a	KAERI_b	NRG	POLITO
Heat losses (% of the maximum HX power)	< 2.5%	< 1%	Neglected	Neglected	Neglected	Around 2%
Saturated steam at the HX inlet	Yes	No	Yes	Yes	No, superheated steam according to experimental data	Saturated steam supplied to the upper volume of the vessel
Condensate water to the vessel	Water in the vessel is drained. The drain mass flow rate is calculated by a PIDT1 controller to keep a constant water level within the RPV.	Condensate drain flowrate is set to match L_101 experimental data	Water in the vessel is drained to maintain the RPV water level.	Water level in the vessel is kept constant (3.9 m from the bottom)	No vessel in the model	Water is drained from the vessel to maintain an almost constant level
PV pressure	Constant, approximately 70.5 bar	Set as BC	Calculated (Steam injection rate set as BC)	Set as BC	Pressure imposed at the HX outlet	Imposed according to experimental data
Water drain from OP in Test 7 Part 2	18 kg/s in (tuned to experimental data)	Drain line (D= 50 mm) is open at ~16 160 s	16.2 kg/s	Tuned to experimental data (When the drain valve is opened: 12 kg/s, When the triggering valve is closed: 16 kg/s)	Valve	Valve opening area set to get the correct OP level decrease (flow rate around 17.5 kg/s)
OP pressure	100 kPa	100 kPa	100 kPa	100 kPa	100 kPa	101.3 kPa
Vacuum breaker pressure	112 kPa	95 kPa	100 kPa	100 kPa	No vacuum breaker in the model	101.3 kPa

Table 6.4. Boundary condition postulated by the different benchmark participants (Continued)

PARAMETER	UJV	UNIP1	UNIROMA1	UofU	USNRC	VTT
Heat losses (% of the maximum HX power)	Around 1.5%	Neglected	0.2%		Around 1.5 %	Around 0.5 %
Saturated steam at the HX inlet	Saturated steam is supplied to the upper volume of the vessel	Yes	Yes	Yes	Experimental temperature data of steam entering RPV used as table input, ~ 291°C. Steam enters HX inlet is calculated	Measured temperature set as boundary condition for steam entering PV
Condensate water to the vessel	Water level in the vessel is kept constant (3.9 m from the bottom)	Water level in the vessel is kept constant (3.9 m from the bottom)	Water drained to keep almost constant level within the vessel	No vessel in the model	Flow and temperature are calculated based on upstream in the lower heat exchanger header	Condensate is returned to the vessel. Vessel level is controlled with a drain valve.
PV pressure	According to measured pressure	Imposed according to exp. data	Set as BC	Pressure imposed at the HX inlet	Experimental data of steam boundary connected to RPV is used as table input around 7 055 KPa	Measured pressure set as boundary condition.
Water drain from OP in Test 7 Part 2	17.0 kg/s	12.6 kg/s (constant)	Valve	OP drain valve opening fraction set to 0.1	Connected to ambient, flow and temperature are calculated based on upstream	Valve area and loss coefficient set to get roughly the correct flow
OP pressure	100 kPa	100 kPa	100.61 kPa	100 kPa	100.61 kPa	100 kPa
Vacuum breaker pressure	100 kPa	100 kPa	100 kPa	100 kPa	100.61 kPa	100 kPa

6.4. Initial conditions

6.4.1. Initial conditions Test 7 Part 1

The comparison of the initial conditions of the requested parameters for Test 7 Part 1 of the various participants is reported in Table 6.5 and the relative error in Table 6.6 (for the temperatures the relative error has been computed using the absolute temperature).

Considering the steam flow rate (F_A001), the experimental value is imposed by the participants that do not simulate the PV (NRG and UofU). All the other participants obtained a value lower than the experimental one. The condensate flow rate (F_E001) is in general not well reproduced by the participants. The initial HX power (W_IC) is negligible for all the participants, with the exception of NRG and USNRC; USNRC shows a major discrepancy. This discrepancy on the steam and condensate flow rates and on the HX power can be due to the measurement uncertainty at low values. Therefore, it does not affect the general accuracy of the code prediction.

The primary pressure (P-I001) is imposed by all the participants as a boundary condition; the steam temperature (T-A005) is close to the saturation value for all the participants, with the exception of NRG and VTT, which imposed a higher temperature than the experimental one. Considering the condensate temperature (T-E001) all participants obtained a temperature close to the saturation one even if the experimental measurement is superheated. The discrepancies are probably due to the uncertainty on the experimental data.

The initial HXP level (L_VQ) is set by the various participants with a maximum discrepancy of 3 cm (corresponding to a relative error of 16%) with respect to the experimental one. Only GRS and NRG begin with the empty HXP (corresponding to a higher relative error); this initial error can be considered negligible with respect to the complete flooding of the HXP. The initial OP level (L_VP) is correctly set by all participants with a maximum discrepancy of 3 cm with respect to the experimental value.

The initial temperatures of the HXP (T-Q037, T-Q034 and T-Q031), which is initially filled with air in Test 7 Part 1, are the most critical initial conditions to be set according to the participant results. In fact, almost all participants obtained temperatures higher than the experimental ones and the initial thermal stratification is in general not predicted (GRS, UNIROMA1 and USNRC qualitatively predict the thermal stratification in the three thermocouples). However, it should be noted that the initial discrepancies on the HXP temperatures values do not significantly affect the remaining part of the transient since the energy stored in the fluid (air) is negligible and the HXP is subsequently flooded with water.

Considering the HXP relative pressure (P-Q001) some participants imposed a value close to the experimental one (0.61 kPa), while others considered the pool initially at ambient pressure since the difference is negligible. Two participants (GRS and UofU) have a relatively high initial HXP pressure. In the case of GRS, the initial pressure has been set higher in the simulation for the steady state case, since otherwise water from the overall pool would have flowed backwards through the steam duct into the heat exchanger pool during the steady state phase.

The temperatures in the OP (T-P008 and T-P021), which is initially filled with water, are set by the various participants in reasonable agreement with the experimental data.

The initial HX differential pressure (DP-003) is computed by all the participant with a reasonable agreement, with the exception of VTT, which predicts a lower initial value.

VTT used the measured PV pressure as a boundary condition for the steam inlet in the PV, resulting in fluctuating gas flow and pressure differences in the initial state.

The initial injector differential pressure (DP-J001) is set by most of the participants with some agreement to the experimental data (with a maximum relative error of 29.3%); GRS and UofU show sensible discrepancies.

Finally, the HX upper and lower header wall temperatures (TW-B005 and TW-D001) have a reasonable agreement for almost all the participants.

Table 6.5. Comparison of initial conditions Test 7 Part 1

PARAMETER	Unit	EXP	GRS	IBRAE	KAERI_a	KAERI_b	NRG	POLITO	UJV	UNIPI	UNIROMA1	UofU	USNRC	VTT
F_A001	kg/s	1.10	0.09	0.11	0.00	0.00	1.07	0.15	0.05	0.01	0.75	1.00	5.89	0.08
F_E001	kg/s	0.59	0.07	0.09	0.05	-0.05	0.04	0.11	0.02	0.00	0.72	1.02	3.36	0.05
W_IC	kW	2 321	160	26	-43	1	738	5	28	8	65	42	12 407	44
P-I001	kPa	7 056	7 057	7 037	6 948	7 022	7 038	7 000	7 031	7 022	7 031	7 017	7 051	7 034
T-A005	°C	291.4	286.4	286.1	286.3	286.0	292.1	287.1	286.1	286.0	286.1	286.3	286.6	291.3
T-E001	°C	288.7	286.4	286.2	285.3	286.0	286.9	285.8	286.1	286.0	286.1	286.0	286.3	285.9
L_VQ	m	0.19	0.10	0.20	0.19	0.21	0.00	0.22	0.18	0.22	0.19	0.19	0.19	0.20
L_VP	m	4.65	4.66	4.64	4.65	4.66	4.68	4.65	4.65	4.64	4.66	4.65	4.65	4.65
T-Q037	°C	123.6	166.8	137.6	100.2	244.8	34.7	167.8	183.8	99.0	141.6	96.5	99.8	163.4
T-Q034	°C	198.3	196.5	202.8	283.6	277.4	34.7	262.3	261.0	284.7	186.8	251.4	185.8	213.5
T-Q031	°C	222.7	201.4	202.7	224.2	277.1	33.4	265.4	243.6	256.3	216.7	251.4	208.3	219.5
P-Q001	kPa	0.61	12.60	0.01	1.94	0.50	2.15	0.00	0.63	0.61	0.61	8.59	2.08	0.00
T-P008	°C	15.3	15.4	15.4	15.1	15.0	15.4	15.4	15.4	15.0	15.3	15.6	14.9	15.4
T-P021	°C	15.4	15.4	15.5	15.1	15.0	15.4	15.4	15.4	15.0	15.3	15.6	14.9	15.4
DP-003	kPa	-0.87	-0.91	-0.91	-0.86	-0.90	-0.83	-0.89	-0.90	-0.90	-0.81	-0.92	-0.83	-2.09
DP-J001	kPa	-10.53	-0.95	-10.16	-7.44	-10.02	-11.63	-11.36	-11.58	-9.08	-10.29	0.01	-7.51	-10.28
TW-B005	°C	282.0	283.6	286.0	285.1	285.8	283.5	288.3	284.8	285.7	284.6	280.9	287.8	276.9
TW-D001	°C	280.5	281.8	284.6	284.6	285.0	279.1	288.1	284.1	282.7	283.4	268.9	279.8	270.9

Table 6.6. Initial conditions relative error Test 7 Part 1

PARAMETER	GRS	IBRAE	KAERI_a	KAERI_b	NRG	POLITO	UJV	UNIPI	UNIROMA1	UofU	USNRC	VTT
F_A001	91.9%	90.0%	99.6%	100.0%	3.1%	86.4%	95.2%	99.5%	31.8%	9.0%	>100%	92.3%
F_E001	88.1%	84.5%	92.4%	>100%	93.2%	81.4%	96.5%	99.8%	22.0%	72.5%	>100%	91.6%
W_IC	93.1%	98.9%	>100%	100.0%	68.2%	99.8%	98.8%	99.6%	97.2%	98.2%	>100%	98.1%
P-I001	0.0%	0.3%	1.5%	0.5%	0.3%	0.8%	0.4%	0.5%	0.4%	0.6%	0.1%	0.3%
T-A005	0.9%	0.9%	0.9%	1.0%	0.1%	0.8%	0.9%	1.0%	0.9%	0.9%	0.9%	0.0%
T-E001	0.4%	0.4%	0.6%	0.5%	0.3%	0.5%	0.5%	0.5%	0.5%	0.5%	0.4%	0.5%
L_VQ	47.4%	5.2%	2.6%	12.1%	99.9%	15.8%	4.2%	16.2%	2.1%	0.0%	0.2%	5.0%
L_VP	0.2%	0.1%	0.0%	0.1%	0.6%	0.0%	0.0%	0.3%	0.2%	0.1%	0.1%	0.1%
T-Q037	10.9%	3.5%	5.9%	30.6%	22.4%	11.1%	15.2%	6.2%	4.5%	6.8%	6.0%	10.0%
T-Q034	0.4%	1.0%	18.1%	16.8%	34.7%	13.6%	13.3%	18.3%	2.4%	11.3%	2.7%	3.2%
T-Q031	4.3%	4.0%	0.3%	11.0%	38.2%	8.6%	4.2%	6.8%	1.2%	5.8%	2.9%	0.7%
P-Q001	>100%	98.9%	>100%	17.7%	>100%	100.0%	3.4%	0.3%	0.0%	>100%	>100%	>100%
T-P008	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.1%	0.2%	0.0%
T-P021	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.1%	0.2%	0.0%
DP-003	5.0%	5.1%	0.7%	3.6%	4.8%	2.3%	4.0%	3.5%	6.7%	6.1%	4.6%	>100%
DP-J001	91.0%	3.5%	29.3%	4.8%	10.4%	7.9%	10.0%	13.7%	2.3%	>100%	28.7%	2.4%
TW-B005	0.3%	0.7%	0.6%	0.7%	0.3%	1.1%	0.5%	0.7%	0.5%	0.2%	1.0%	0.9%
TW-D001	0.2%	0.7%	0.7%	0.8%	0.3%	1.4%	0.7%	0.4%	0.5%	2.1%	0.1%	1.7%

6.4.2. Initial conditions Test 7 Part 2

The comparison of the initial conditions for Test 7 Part 2 of the various participants is reported in Table 6.7 and the relative error in Table 6.8 (for the temperatures the relative error has been computed using the absolute temperature).

Considering the steam flow rate (F_A001), the experimental value is imposed by the participants that do not simulate the PV (NRG and, with a higher discrepancy, by UofU). All the other participants obtained a value lower than the experimental one. The condensate flow rate (F_E001) is in general not well reproduced by the participants. The calculated initial HX power (W_IC) by all the participants shows discrepancy with the experimental data, with GRS showing a negative value. This discrepancy on the steam and condensate flow rates and on the HX power can be due to the measurement uncertainty at low values. Therefore, it does not affect the general accuracy of the code prediction.

The primary pressure (P-I001) is imposed by all the participants as a boundary condition; the steam temperature (T-A005) is close to saturation value for all the participants with the exception of NRG and VTT that imposed a higher temperature closer to the experimental value. Considering the condensate temperature (T-E001) all participants obtained a temperature close to the saturation one, even if the experimental measurement is superheated. The discrepancies are probably due to the uncertainty on the experimental data.

The initial HXP level (L_VQ) is set in reasonable agreement with the experimental data by the various participants. The higher discrepancy (15 cm) is present in IBRAE calculation, which was performed in a single run for both parts together. The initial OP level (L_VP) is reasonably set by all participant with a maximum discrepancy of 8 cm by UofU.

The initial temperature in the bottom part of the HXP (T-Q037) is in general well predicted by all the participants, since saturated liquid is present, with the exception of UofU; NRG shows a small discrepancy. In the middle and top parts of the HXP (T-Q034 and T-Q031), which are initially filled with steam in Test 7 Part 2, sensible discrepancies are present in almost all the calculated results. In fact, almost all participants obtained temperatures higher than the experimental ones and the initial thermal stratification is not predicted. Only KAERI_b and VTT obtained reasonable results from a qualitative and quantitative point of view. However, it should be noted that the initial discrepancies on the HXP temperatures values do not significantly affect the remaining part of the transient since the energy stored in the fluid (superheated steam) is negligible and the HXP is subsequently flooded with water.

Considering the HXP relative pressure (P-Q001) all participants obtained or imposed a value close to the experimental one, though some quantitative discrepancies are present.

The OP temperatures (T-P008 and T-P021) are in general different from the experimental data (49.7°C and 70.7°C respectively). All the participants show similar temperatures for the two thermocouples (no thermal stratification) with the exception of GRS, IBRAE, KAERI_b, NRG and VTT (qualitative prediction of thermal stratification).

The initial HX differential pressure (DP-003) is computed by all the participants close to the experimental data; VTT shows a higher relative error. VTT used the measured PV pressure as boundary condition for the steam inlet in the PV, resulting in fluctuating gas flow and pressure difference in the initial state.

The initial injector differential pressure (DP-J001) shows discrepancies with the experimental data for all the participants. At the beginning of the transient the flow in the injector is negligible, therefore the differential pressure is only due to the pressure

difference between the two pools; but it can be noted that a discrepancy on the initial condition on this parameter does not preclude the correct prediction of the remaining part of the transient.

Finally, the HX upper and lower headers wall temperatures (TW-B005 and TW-D001) are reasonably set or computed by all the participants. The only exception is the lower header wall temperature for the NRG results which is comparable to the upper header temperature. This is due to the fact that the heat structure (HS) where the temperature is measured lays at the top of the lower header and is not flooded initially (HS-164 of Figure 5.165). The lower structures are at around 110°C and no axial conduction in the HS is implemented.

Table 6.7. Comparison of initial conditions Test 7 Part 2

PARAMETER	Unit	EXP	GRS	IBRAE	KAERI_a	KAERI_b	NRG	POLITO	UJV	UNIPI	UNIROMA1	UofU	USNRC	VTT
F_A001	kg/s	1.13	0.49	0.27	0.19	0.17	1.11	0.23	0.38	0.27	0.88	1.60	0.20	0.36
F_E001	kg/s	0.75	2.20	0.25	0.16	0.17	0.04	0.20	0.41	0.30	0.88	1.20	0.20	0.35
W_IC	kW	2 161	-1424	273	324	37	755	145	494	273	275	1 401	315	85
P-I001	kPa	7 052	7 052	7 037	6 927	7 053	7 075	7 030	7 031	7 052	6 996	7 068	7 056	7 053
T-A005	°C	291.1	286.3	286.3	285.5	286.3	292.6	287.3	286.1	286.3	285.8	286.7	288.7	290.1
T-E001	°C	288.7	286.1	286.2	285.1	286.3	286.9	286.0	286.1	286.3	284.0	286.6	286.4	285.8
L_VQ	m	1.12	1.12	1.27	1.02	1.10	1.11	1.11	1.17	1.13	1.21	1.13	1.13	1.13
L_VP	m	4.52	4.53	4.58	4.50	4.58	4.76	4.49	4.56	4.52	4.47	4.60	4.56	4.55
T-Q037	°C	103.2	103.4	103.8	103.0	103.4	97.9	103.1	104.1	103.8	103.4	17.4	103.7	102.7
T-Q034	°C	165.0	188.3	175.9	224.6	178.9	164.1	232.7	219.0	230.4	190.5	149.8	201.4	173.2
T-Q031	°C	184.8	193.0	175.9	245.9	204.5	164.0	245.2	223.3	249.8	196.7	149.8	199.4	214.3
P-Q001	kPa	12.23	11.49	12.50	13.80	12.00	10.02	12.00	12.58	12.24	12.59	11.86	11.44	10.01
T-P008	°C	49.7	46.8	47.1	55.2	47.0	49.8	58.4	52.4	49.2	47.2	63.1	55.2	50.0
T-P021	°C	70.7	65.4	73.2	56.1	70.5	70.5	58.6	52.4	54.3	47.4	63.1	55.2	69.6
DP-003	kPa	-0.83	-0.92	-0.93	-0.88	-0.90	-0.85	-0.88	-0.95	-0.93	-0.85	-1.06	-0.88	-1.64
DP-J001	kPa	0.19	-0.59	0.04	0.00	-0.01	-4.00	1.65	-0.01	0.01	0.00	0.01	0.08	0.00
TW-B005	°C	280.5	282.7	284.5	284.5	284.8	283.5	287.9	284.4	281.1	284.5	280.7	286.2	276.5
TW-D001	°C	106.3	110.8	107.2	111.1	116.3	279.1	115.2	110.6	112.9	115.2	110.6	106.8	107.2

Table 6.8. Initial conditions relative error Test 7 Part 2

PARAMETER	GRS	IBRAE	KAERI_a	KAERI_b	NRG	POLITO	UJV	UNIPi	UNIROMA1	UofU	USNRC	VTT
F_A001	56.5%	76.1%	83.4%	85.1%	1.7%	79.6%	66.8%	75.9%	22.1%	41.7%	81.9%	68.4%
F_E001	>100%	67.2%	79.3%	76.8%	95.1%	73.3%	44.8%	60.4%	17.3%	60.6%	72.8%	53.9%
W_IC	>100%	87.3%	85.0%	98.3%	65.0%	93.3%	77.2%	87.4%	87.3%	35.1%	85.4%	96.1%
P-I001	0.0%	0.2%	1.8%	0.0%	0.3%	0.3%	0.3%	0.0%	0.8%	0.2%	0.1%	0.0%
T-A005	0.8%	0.8%	1.0%	0.8%	0.3%	0.7%	0.9%	0.8%	0.9%	0.8%	0.4%	0.2%
T-E001	0.5%	0.5%	0.7%	0.4%	0.3%	0.5%	0.5%	0.4%	0.8%	0.4%	0.4%	0.5%
L_VQ	0.3%	13.7%	9.0%	2.1%	0.8%	0.9%	4.6%	0.7%	8.0%	1.1%	0.5%	0.8%
L_VP	0.2%	1.4%	0.4%	1.4%	5.3%	0.7%	1.0%	0.0%	1.1%	1.7%	0.9%	0.7%
T-Q037	0.0%	0.1%	0.1%	0.0%	1.4%	0.0%	0.2%	0.2%	0.0%	22.8%	0.1%	0.1%
T-Q034	5.3%	2.5%	13.6%	3.2%	0.2%	15.5%	12.3%	14.9%	5.8%	3.5%	8.3%	1.9%
T-Q031	1.8%	1.9%	13.3%	4.3%	4.5%	13.2%	8.4%	14.2%	2.6%	7.7%	3.2%	6.5%
P-Q001	6.0%	2.2%	12.8%	1.9%	18.1%	1.9%	2.9%	0.1%	2.9%	3.0%	6.4%	18.1%
T-P008	0.9%	0.8%	1.7%	0.8%	0.0%	2.7%	0.8%	0.1%	0.8%	4.2%	1.7%	0.1%
T-P021	1.6%	0.7%	4.2%	0.1%	0.1%	3.5%	5.3%	4.8%	6.8%	2.2%	4.5%	0.3%
DP-003	10.4%	11.6%	6.1%	8.6%	2.4%	6.0%	14.3%	12.3%	2.4%	27.3%	5.4%	97.4%
DP-J001	>100%	81.2%	>100%	>100%	>100%	>100%	>100%	95.7%	100.0%	96.1%	55.8%	>100%
TW-B005	0.4%	0.7%	0.7%	0.8%	0.5%	1.3%	0.7%	0.1%	0.7%	0.0%	1.0%	0.7%
TW-D001	1.2%	0.2%	1.3%	2.6%	45.6%	2.4%	1.1%	1.8%	2.4%	1.2%	0.1%	0.2%

7. Comparison of the results and accuracy evaluation

In this chapter, the benchmark results are collected and commented on. To explain the behaviour of the calculated data and the agreement/discrepancy with respect to the experimental ones, the comments given by the various participants in their individual reports (Section 5.2) are considered, as well as the differences in code models (Section 6.1), nodalisation approaches (Section 6.2) and initial and boundary conditions (Section 6.3 and 6.4). Finally, the accuracy evaluation procedure described in Chapter 4 is applied.

7.1. Comparison of the results

7.1.1. Test 7 Part 1

Analysis of the first phenomenological window (10 000 s – 11 260 s)

After the start of the transient, at time 10 475 s, valve F045 begins to be opened slowly and then it is completely closed at 10 608 s. At time 10 621 s a further opening is actuated, and the valve is completely closed at 10 655 s. This sequence of F045 valve opening and closure represents the first phase of water injection. The second phase of water injection occurs between 11 039 s and 11 260 s when F045 valve is opened and then completely closed.

The first phenomenological window is characterised by the opening of the triggering valve with the increase of the HXP level. Therefore, the HX tubes are flooded with a consequent beginning of the heat transfer between the HX and the HXP and the increase of the in-tube side mass flow rate. All the participants followed the experimental test logic.

The analysis of the HXP level (Figure 7.1) shows that all codes reproduce the experimental triggering valve logic. Due to the first valve opening (at 10 475 s, first phase of water injection), a first level increase is observed, and most of the calculation results agree with the experimental data. Due to the second valve opening (at 10 621 s, still in the first phase of water injection) an additional HXP filling occurs and all the codes mostly predict the second HXP level plateau. It should be underlined that the experimental data show a slight level decrease, probably due to the boiling of the water in the HXP. This phenomenon seems not to be predicted by the various participants in this time interval. Due to the final valve opening (second phase of water injection), the HXP level increases up to the maximum experimental value of 3.4 m. All codes qualitatively predict the level increase. From a quantitative point of view, it can be noted that the maximum HXP experimental level is not predicted by most of the codes. In particular, some codes overpredict it and other underpredict the maximum value. In addition, some participants show a delay in the prediction of the HXP maximum, which is predicted at the beginning of PhW2. Moreover, the slope of the level increase is in general well predicted. KAERI_a calculation correctly predicts the first part of the level increase but at around 11 800 s the slope is higher than the experimental one, with a consequent higher level. Though GRS and NRG show a higher discrepancy on the initial condition for this parameter (see Section 6.4.1), this does not preclude its prediction along the first phase of water injection.

The opening of the triggering valve, which causes the HXP level increase, determines the OP level decrease (Figure 7.2). The three steps are well predicted by all codes and also the minimum OP level. It should be underlined that the codes that overpredict the maximum HXP level now underpredict the OP minimum level and vice versa. In this case, the level error is smaller compared to the HXP one due to the different flow area of the two pools.

The level increase in the HXP due to the first phase of water injection, determines the inception of the power exchanged from the primary to the pool side. As a result, steam and condensate flow rates increase (Figure 7.3 and Figure 7.4). A first flow rate plateau is predicted by the codes, even if with some quantitative discrepancies against the experimental data. In particular, GRS, IBRAE, UJV, UNIPi and UNIROMA1 slightly underestimate the steam flow rate, while KAERI_a overestimates it. It must be underlined that these discrepancies are present even if the HXP level is reasonably predicted by all codes. The increase of the flow rate due to the final triggering valve opening is correctly predicted by almost all codes together with its maximum value. UNIROMA1 and VTT show a higher maximum flow rate value than the experimental one. In the case of VTT this is due to an overestimation of the HX power. Similar considerations can be drawn for the condensate flow rate where additional oscillations can be observed in the code results. The general initial conditions discrepancies against experimental data (Section 6.4.1), due to the measurement uncertainty, do not sensibly affect the code predictions in the remaining part of the transient.

Considering the HX power (Figure 7.5), a similar behaviour is observed. From a qualitative point of view all codes reproduce the first increment. However, it should be underlined that there are some quantitative discrepancies. For example, GRS, IBRAE, NRG, UJV, UoF and VTT slightly underestimate the first power increment. UNIROMA1 shows a larger quantitative discrepancy with respect to the experimental results. Noticeable oscillations are present in KAERI_a results. The second and more significant power increment is correctly qualitatively and quantitatively predicted by all the participants. IBRAE results show a temporary peak of power around 33 MW. The reason is water back flow from the steam duct to the HX at 11 194 s. It interacts with the HX upper header and the peak power is 16 MW. It may be a nodalisation problem, the diaphragm does not prevent the interaction of this water with the top part of the heat exchanger. The general initial conditions discrepancies against experimental data (see Section 6.4.1), due to the measurement uncertainty, do not sensibly affect the code predictions in the remaining part of the transient.

In relation to the primary pressure (Figure 7.6), it has been imposed as a boundary condition by most of the participants and as expected no particular discrepancy in the initial condition has been observed (see Section 6.4.1). However, in the case of KAERI_a, some discrepancies are present in the second part of PhW1 since a time-dependent steam flowrate was imposed instead of a time-dependent pressure.

The steam and condensate temperatures (Figure 7.7 and Figure 7.8) are superheated in the experiment. This can be due to an experimental measurement uncertainty since the fluid is expected to be at saturation temperature. All participants HX inlet temperatures are at saturation conditions with the exception of NRG, which imposed the experimental value at the HX inlet, VTT, which imposed the temperature in the steam line downstream PV, and KAERI_a, which in the second part of PhW1 shows a decrease of the steam temperature following the reduction of the primary pressure, as previously underlined. Considering the HX outlet temperatures, the main discrepancies are found by POLITO, which considered a mixture temperature of the fluid which is not in equilibrium between the gas and liquid phase, KAERI_a and VTT, which shows a sensible temperature decrease. In the case of VTT the mixture temperature is shown at the actual location of the T-E001 measurement,

i.e at elevation -1.727 m, about 4.3 m downstream the lower header and the model includes also heat transfer from the condensate line to the pool. No sensible relative error is present in the initial conditions (see Section 6.4.1).

Considering the temperatures in the HXP (Figure 7.9, Figure 7.10 and Figure 7.11) in general the benchmark participants are not able to capture the thermal stratification of the air initially present in the pool (with the exception of GRS, UNIROMA1 and USNRC, which qualitatively predict the thermal stratification considering the three thermocouples). However, it should be noted that the initial discrepancies on the HXP temperatures values do not significantly affect the remaining part of the transient since the energy stored in the fluid is negligible and the HXP is subsequently flooded with water. At the first triggering valve opening the temperature in the lower part (T-Q037, Figure 7.9) drops to around 20°C. The temperature drop is correctly predicted by all codes; NRG, since the initial temperature is lower than the experimental one, predicts a first temperature increase and then the drop, in agreement with the experimental data. The first temperature increase is due to the choice of the initial condition for the transient. Note that the NRG simulation starts at 10 400 s (the preceding values are just a copy of the value at 10 400, they are not coming from an actual calculation). The thermocouples in the middle and upper part of the HXP are not flooded by the first phase of water injection; their measurements gradually decrease due to the steam produced in the lower part of the pool. IBRAE and NRG results better reproduce the qualitative behaviour of T-Q034 and T-Q031 in this phase. At the final water injection all the considered thermocouples are flooded. T-Q034 and T-Q031 measure the saturation temperature and their behaviour is correctly predicted by all the participants. T-Q037 initially measures a subcooled temperature due to the income of colder water from the OP (then in PhW2 it reaches the saturation value). When the temperature T-Q037 is subcooled, before the final triggering valve opening, all the participant predict a higher temperature with respect to the experimental data, with the exception of NRG, UNIPI and UofU, which show a better agreement with the experiment.

The HXP relative pressure (Figure 7.12) is almost constant and close to the atmospheric one before the first water injection; only GRS and UofU results show significant discrepancies with respect to the experimental results due to initial conditions differences. After the flooding of the HXP the pressure increases due to the boiling in the pool. The pressure increment is qualitatively reproduced by all the participants, which show a consistent initial condition; the main discrepancies are shown by NRG, which anticipates the pressure increase, KAERI_a, which shows a delay, and USNRC, which shows an oscillation not observed in the experimental results. During the final water injection, negative pressure peaks are observed in the experimental data; the income of colder water from the OP causes the condensation of the steam in the HXP with a consequent strong pressure reduction and also the opening of the vacuum breaker. KAERI_a, POLITO, UJV, UNIPI and USNRC qualitatively capture the phenomenon but discrepancies are present in the magnitude and the timing. Though the sensible initial conditions discrepancy (see Section 6.4.1), GRS and UofU correctly predict the plateau after the pressure increment; therefore, the missing prediction of the initial pressure does not preclude the simulation of the remaining part of the transient.

The OP is initially at ambient temperature around 15.4°C (Figure 7.13 and Figure 7.14). In the first PhW a very little amount of steam is produced in the HXP and directed in the OP by the steam duct and the injector. Therefore, the OP temperatures are almost constant with some small oscillations shown by T-P008 (which is coaxial to the injector). These oscillations are not predicted by any participants.

The HX differential pressure (Figure 7.15) has some oscillations around an almost constant average value in the first PhW. The experimental data are reasonably predicted by almost

all the participants with the exception of GRS, which predicts a reduction in the end of the PhW, and UofU that shows a strong oscillation at around 10 630 s. Significant oscillations are also present in the VTT results, since the experimental pressure that presents oscillations is imposed. At the end of PhW1, KAERI_a and NRG predict an increase of the HX differential pressure, while in the experimental data a decrease occurs. For NRG, it may be due to a non-optimal choice of loss factors on the primary side. Also UofU shows a similar behaviour but with a minor increase. No particular discrepancies are present in the initial conditions (see Section 6.4.1).

Considering the injector differential pressure (Figure 7.16) the initial experimental value is close to -10.5 kPa. It is due to the gravitational contribution of the water that initially fills the injector, and, in fact, it is consistent with the difference of elevation between the pressure taps (1.06 m). Almost all the participants agree with the experimental data before the water injection. GRS and UofU results show significant discrepancies with respect to the experimental results due to initial conditions differences regarding the HXP pressure. After the first phase of water injection, the production of steam in the HXP causes the clearance of the liquid water in the injector, therefore the differential pressure becomes close to 0. Almost all participants are able to qualitatively predict the injector differential pressure behaviour, with the exception of GRS and UofU (which remained close to zero), due to the initial condition. NRG anticipates the pressure increase with respect to the experimental data. KAERI_a shows a delay in the rise of the differential pressure and USNRC shows oscillations not observed in the experimental data. During the second phase of water injection, oscillations are present caused by the opening of the vacuum breaker. Only POLITO, UJV, USNR and VTT predicts some oscillations, in the phase when also the experimental data shows oscillations, even if the magnitude and the timing is not in agreement with the experimental data.

The HX lower header wall temperature (Figure 7.17) is almost constant until the first phase of water injection when the lower header is flooded. This behaviour is predicted by almost all the codes; UofU starts from a lower initial condition, as VTT, and it shows a temperature increase instead of a plateau. Then, the experimental temperature drops and the behaviour is qualitatively predicted by all codes. The initial minimum is quantitatively predicted by UofU while small discrepancies are present in the other results. Between the first and the second phase of water injection the temperature is almost constant at around 104°C and NRG, KAERI_b, UNIROMA1 and VTT show the closest prediction. All the other participants underestimate the temperature value in this phase. During the second phase of water injection the temperature decreases up to around 50°C due to the income of colder water from the OP. IBRAE, KAERI_a, POLITO, UNIPI and UJV quantitatively predict this temperature reduction while the other participants overestimate the temperature value in this phase. VTT does not predict the temperature reduction in the final part of the PhW.

The HX upper header wall temperature (Figure 7.18) is almost constant in the first PhW until the level in the HXP reaches its maximum, flooding the upper header. Then, the upper header temperature drops to around 102°C. The behaviour is reasonably predicted by all codes even if they all overestimate the minimum temperature. UofU predicts the temperature decrease with some delay in PhW2 instead of at the end of PhW1.

Analysis of the second phenomenological window (11 260 s – 11 845 s)

The second PhW represents the phase with the maximum exchanged power between the HX and the HXP. Even if the HXP level decreases in this phase, it is sufficiently high to exchange the maximum power (around 20 MW).

In PhW2 the triggering valve is closed; therefore, the water evaporated in the HXP is not reintegrated by the OP. For this reason, the HXP level (Figure 7.1) shows a gradual

decrease due to the boiling of the water in the pool. The HXP level decrease is qualitatively predicted by all the participants but quantitative differences are present. In particular, NRG predicts an earlier level decrease caused by the higher HXP pressurisation in the SPECTRA simulation between 11 250 s and 11 750 s. This phenomenon is probably due to the lack of HXP water mixing and therefore the slight depressurisation observed in the experiment, likely caused by steam condensation on the water surface front, is not experienced in the SPECTRA simulation. KAERI_a, KAERI_b and UJV underestimate the HXP level in this phase. Regarding UJV results the underestimation is probably caused by more intensive boiling in the calculation with respect to the experiment. Conversely, POLITO, UNIPI and UofU slightly overpredict the HXP level in this phase, probably due to an underprediction of the water evaporation. UNIROMA1, USNRC and VTT slightly overestimate the maximum level and show oscillations close to the experimental data. It can be noted that an overestimation of the maximum HXP level does not directly bring to an overestimation of the level in the remaining part of the transient (e.g. KAERI_a overestimate the maximum level but it underestimates the level in the PhW2).

The OP level (Figure 7.2) gradually increases in this phase since the water evaporated in the HXP is directed to the OP by the steam duct and the injector. The behaviour is qualitatively predicted by all the participants. NRG slightly overpredicts the OP level at the beginning of the PhW consistently with the underprediction of the HXP one.

The steam and condensate mass flow rate behaviours (Figure 7.3 and Figure 7.4) follow the HX power. When power is exchanged, the steam is condensed inside the HX tubes and new steam is sucked from the PV. The two flow rates have analogous trends and they are slightly underestimated by almost all the participants, following the slight underestimation of the HX power. UNIROMA1 and VTT overestimate the primary side flow rate following the slight overestimation of the HX power. In addition, in UNIROMA1 results significant oscillations are present, in particular for the condensate flow rate. Also USNRC shows oscillations in the two flow rates but with a lower amplitude. In NRG results even if the steam flow rate is imposed according to the experimental data, the condensate flow rate is underestimated. This is due to the fact that the HX power is lower compared to experimental measurements and part of the steam is not condensed.

As previously mentioned, in this phase the maximum HX power is exchanged (Figure 7.5). The power is around 20 MW with a reduction at the beginning of the PhW that follows the reduction of the primary pressure (a lower pressure determines a lower saturation temperature, so a reduced temperature difference between the primary and the pool side). This temporary HX power reduction is not predicted by GRS due to the choice of imposing a constant primary pressure, as previously mentioned. In general, all the participants are able to qualitatively predict the HX power behaviour, even if they all slightly underestimate it with the exception of VTT, which overestimates the power. The larger discrepancy with respect to the experimental results are shown by NRG, probably due to the underestimation of the HXP level, KAERI_b, UJV and UNIROMA1, which also underestimate the power at the end of the PhW. At the beginning of the PhW2, UNIROMA1 slightly overestimates the power (following the slight over prediction of the HXP level); this can explain the shorter quasi-steady state operation, comparing with the experiment. Indeed, higher power leads to a higher boiling rate and it causes a slightly faster level decrease within the HXP, leading to the underestimation of the power at the end of PhW2. UNIROMA1, UofU and USNRC show several oscillations.

When the HXP is completely flooded and significant power is exchanged between the HX and the HXP, the high amount of steam sucked by the HX from the PV causes a reduction of the primary pressure (Figure 7.6) that is then manually restored to around 7 MPa. All the participants, which imposed the primary pressure as a boundary condition, replicates

this pressure decrease and increase. The only exception is GRS, which decided to keep a constant pressure throughout the entire transient. KAERI_a obtained different results with respect to the experimental ones since a time-dependent steam flowrate was imposed instead of a time-dependent pressure.

As regards the steam temperature (Figure 7.7), it follows the reduction of the primary pressure even if the measurement is superheated instead of saturated, as previously mentioned. With the exception of NRG and VTT, which imposed the steam temperature, and USNRC, the temperature predicted by all the other participants follows the pressure behaviour and the fluid is saturated. For IBRAE the temperature increases over the saturation value after the initial reduction. For KAERI_a the temperature follows the behaviour of the calculated primary pressure. For GRS the temperature is constant since a constant primary pressure is imposed. Considering the condensate temperature (Figure 7.8) a similar behaviour is present with the exception of POLITO (since the liquid and gas phase are not at equilibrium, a mixture temperature has been computed at the HX outlet and the resulting temperature is lower than the saturation one) and VTT. In the case of VTT, as previously mentioned, the simulations show the mixture temperature at the actual location of the T-E001 measurement, including also heat transfer from the condensate line to the pool. UJV and UNIROMA1 present a slight underestimation in the second phase of the PhW and reaches the saturation in PhW3. NRG, though having imposed the steam temperature behaviour versus time according to the experimental one, obtained an almost constant condensate temperature.

In the present PhW, the HXP temperature in the lower part of the pool (T-Q037 in Figure 7.9) rises up to the saturation temperature. The behaviour is correctly predicted by almost all the participants. UJV and more significantly NRG and UNIROMA1 predict a delay in the temperature increment. UofU does not predict the lower temperature increment. T-Q034 and T-Q031 (Figure 7.10 and Figure 7.11) are close to the saturation value. This is correctly predicted by all the participants.

The HXP relative pressure (Figure 7.12) increases during this phase up to around 17 kPa to the pressurisation of the HXP caused by the production of steam. The pressurisation is qualitatively predicted by all the participants. UofU shows slight pressure increment and no pressure peak is predicted. From a quantitative point of view, GRS, KAERI_a, KAERI_b, UNIPI, UNIROMA1, UJV, USNRC and VTT overpredict and anticipate the HXP pressure peak.

The steam produced in the HXP is directed to the OP causing the increase of the OP temperatures (Figure 7.13 and Figure 7.14). In the present PhW the temperature measured at the lower elevation (T-P008) is higher than T-P021 since T-P008 thermocouple is placed correspondingly to the injector. Almost all the participants, in the present PhW, underestimate T-P008 and overestimate T-P021 probably due to the higher mixing present in the calculations with respect to the experiment. Moreover, no participant is able to capture the sharp increase of T-P008. GRS and NRG do not predict the increase of the lower OP temperature (T-P008). In the case of GRS this is probably due to a low mixing in the OP. In the case of NRG, the condensation of the steam occurs in the vicinity of the injector and is not propagated downwards, therefore the lower OP temperature is almost unmodified as there is no mixing. USNRC shows an evident non-monotonic increase of T-P008.

The HX differential pressure (Figure 7.15) reduces in this PhW due to the gravitational contribution of a condensate level which is formed in the HX tubes. Most of the participants are able to qualitatively predict the HX differential pressure behaviour. NRG, KAERI_a and UofU, starting from a higher value at the end of PhW1, show a reduction of the HX differential pressure but the minimum is overpredicted in comparison with the experimental

data. GRS underpredicts the HX differential pressure, maintaining a constant value along the PhW. Large oscillations are present in the VTT results due to the presence of oscillations in the primary pressure imposed as boundary condition.

The injector differential pressure (Figure 7.16) increases in this phase up to around 9 kPa. This is due to the flowing of the steam produced in the HXP that becomes relevant. The experimental behaviour is better qualitatively and quantitatively predicted by IBRAE and VTT; GRS and NRG qualitatively predicts the general trend but underestimate the quantitative value. For GRS calculation, one reason may be the higher temperature at the top of the overall pool leading to a less high counterpressure above the injector, leading to a lower differential pressure. KAERI_b, POLITO, UJV and UNIPi predict the qualitative trend but with strong oscillations, which are also present in UNIROMA1 results. UofU does not predict any variation of the injector differential pressure during the entire test. In the case of UofU this could be due to the fact that MELCOR does not have dedicated models to capture the behaviour of the injector component.

The HX lower header remains completely flooded after the triggering valve opening. Therefore, the wall temperature (Figure 7.17) is almost constant. All the codes predict a constant temperature even if slightly overestimated with respect to the experimental data, with the higher discrepancy found in KAERI_b, NRG and UNIROMA1 results. This can be due to a general underprediction of the pool side heat transfer coefficient and/or to the experimental uncertainty in the measurement of the wall temperature, which is usually more challenging than the measurement of the fluid temperature.

Also the HX upper header wall temperature (Figure 7.18) is almost constant in the present PhW. NRG results show a significant anticipation of the upper header temperature rise, which occurs in PhW3 in the experiment. GRS and more significantly KAERI_b and UNIROMA1 start the temperature increase in the final part of the PhW determining an anticipation with respect to the experimental data. In the case of UNIROMA1, it is due to the shorter quasi-steady state operation, as previously mentioned. Indeed, the level within the HXP decreases before the experimental one uncovering the header; this leads to the early temperature increase. KAERI_b, UNIROMA1 and USNRC calculations overpredict the temperature in this phase.

Analysis of the third phenomenological window (11 845 s – 14 784 s)

In the last PhW the boil-off in the HXP occurs with a consequent level reduction. Therefore, the HX power gradually decreases and consequently also the steam and condensate flow rates. The decreasing steam production in the HXP causes a reduction of the pool pressurisation and of the steam directed to the OP.

The HXP level (Figure 7.1) gradually reduces to around 1.13 m due to the boil-off of the water present in the HXP. Its behaviour is qualitatively predicted by all the participants. IBRAE and USNRC slightly overestimate the HXP level. KAERI_a and KAERI_b and UJV slightly underestimate the results at the beginning of the PhW. VTT underestimates the level at the beginning of the PhW, then overestimate it in the second part. The other participants intersect the experimental HXP level along the PhW. As in the previous PhW, USNRC shows some level oscillations.

The steam produced in the HXP is directed to the OP causing a gradual OP level increment (Figure 7.2), up to around 4.53 m. All the codes qualitatively predict its behaviour with the exception of KAERI_a, which predicts in final phase a slight level reduction after around 13 500 s. The experimental data present significant oscillations not reproduced by any participant.

The reduction of the HX power is followed also by the reduction of the steam and condensate flow rates (Figure 7.3 and Figure 7.4) which is qualitatively predicted by all the participants. Similarly, to the HX power, KAERI_a, KAERI_b, UJV, UNIROMA1 and VTT underestimate the flow rates at the beginning of the PhW, while POLITO and USNRC overestimate them. In addition, some oscillations are present in USNRC results. UofU in general overestimates the flow rate while at the end of the PhW shows consistent quantitative results. NRG, though imposing the steam flow rate, obtains an underestimation of the condensate flow rate in the initial part of PhW3. This is due to the lower power exchanged compared to the experiment and therefore part of the steam is not condensed.

The progressive uncovering of the HX tubes causes a reduction of the HX power (Figure 7.5). The power reduction is qualitatively predicted by all the participants. UofU and USNRC show oscillations in the initial part of the PhW3. In the initial part of PhW3 the power is underestimated by KAERI_a, KAERI_b, NRG, UJV, UNIROMA1 and VTT consistently with the underestimation of the HXP level. POLITO slightly overestimates the HX power in the initial part of the PhW due to the overestimation of the HXP level. USNRC overestimates the power in the central part of the PhW, showing also significant oscillations. The HX power at the end of the PhW lower than the experimental data for all the participants; this could be due to the uncertainty on the mass flow rate measurement used to derive the HX power, as in the initial part of the test.

The primary pressure (Figure 7.6) is kept constant until the end of the test and it is imposed by the various participants. Only KAERI_a shows a primary pressure not in agreement with the experimental data since, as previously mentioned, a time-dependent steam flowrate was imposed instead of a time-dependent pressure.

The steam and condensate temperatures (Figure 7.7 and Figure 7.8) present the same discrepancies of the previous PhW. The experimental steam temperature measurement is superheated while most of the participants found saturated values, with the exception of NRG and VTT, which imposed the experimental temperature. The IBRAE results, following the overestimation in the final part of the previous PhW, show a temperature higher than the other participants; along the PhW the temperature tends to the saturation temperature and match it at the end of the PhW. USNRC shows a temperature which initially decreases, then slightly rises in the final part of the PhW. For KAERI_a the temperature follows the calculated pressure behaviour. The condensate temperature is at saturation conditions for almost all the participants even if the experimental measurement is superheated. The main discrepancies are found again by KAERI_a, with a temperature following the calculated pressure behaviour. POLITO results show discrepancies at the beginning of the PhW since a mixture temperature has been considered; a similar behaviour is present in the VTT results.

The temperature in the lower part of the HXP (T-Q037 in Figure 7.9) remains at saturation condition since the HXP level remains higher than the thermocouple position. All the participants correctly predict the quantitative value, with the exception of UofU, as in PhW2. UNIROMA1, consistently with the observation in PhW2, reaches the saturation in this PhW. The progressive uncovering of the HXP causes the rising of the temperatures in the middle and top part of the HXP (T-Q034 in Figure 7.10 and T-Q031 in Figure 7.11). The GRS and partially the IBRAE calculations better predict the temperature behaviour. All the other codes show major discrepancies: anticipating the temperature increase, predicting oscillations not observed in the experimental data, missing the thermal stratification in the HXP (predicting similar values for T-Q034 and T-Q031) and showing very large quantitative discrepancies.

The HXP relative pressure (Figure 7.12) gradually decreases due to the reduction of the steam produced in the HXP caused by the reduction of the HX power, reaching a value

close to 12 kPa at the end of the test. All the participants qualitatively reproduce the experimental behaviour with the exception of UofU, due to the missing prediction of the pressure peak in PhW2. Large oscillations are present in KAERI_a and USNRC results.

The temperature in the lower part of the OP (T-P008 in Figure 7.13) after an increase at the beginning of the PhW, sharply decreases and then stabilises when the flow rate of steam from the HXP becomes negligible. This behaviour is qualitatively predicted only by IBRAE even if the quantitative value is underpredicted. GRS and NRG do not predict the heating up of the lower part of the OP while all the other participants show a continuously increasing temperature, overestimating the values at the end of the transient. This is probably caused by the missing prediction of the thermal stratification that becomes relevant after around 12 400 s. Considering the temperature in the upper part of the OP (Figure 7.14), all the participant are able to capture the qualitative behaviour only up to the slope change occurring at around 13 450 s. GRS significantly overpredicts the temperature; this is probably due to a low mixing in the OP, which is also the cause of the underestimation of the temperature in the lower part. KAERI_a, POLITO, UNIPI and UofU are almost able to predict also the quantitative behaviour but only until the slope variation, then they show an underprediction. A slight overestimation is predicted by IBRAE, USNRC and VTT; KAERI_b, UJV and UNIROMA1 underpredict the experimental results.

The HX differential pressure (Figure 7.15) rises at the beginning of the PhW and then it is almost constant. At the beginning of the window it is overestimated by NRG and underestimated by IBRAE, UJV and USNRC. As a consequence of the sensible underestimation in PhW2, GRS underpredicts the differential pressure at the beginning of the PhW, while it correctly predicts the final value. KAERI_a and VTT show significant oscillations, which are also present in UofU results at the end of the PhW.

The reduction of the HX power causes a reduction of the steam produced in the HXP and directed to the OP and therefore a gradual reduction of the injector differential pressure (Figure 7.16), which tend to zero. UofU does not predict the qualitative behaviour since the calculated results are close to zero for the entire transient duration. The other participants qualitatively predict the parameter behaviour. KAERI_b, POLITO, UJV, UNIPI and UNIROMA1 predict high oscillations at the beginning of the PhW; UNIROMA1 predicts also oscillations in the final phase of the PhW. USNRC predicts oscillations in the central part of the PhW.

The HX lower header remains completely flooded also in the present PhW. Therefore, the wall temperature (Figure 7.17) remains almost constant and the qualitative behaviour is predicted by all the participants with some quantitative discrepancies. The level reduction in the HXP causes the uncovering of the HX upper header which experience a gradual heating up (Figure 7.18). With the exception of GRS, NRG, KAERI_b and UNIROMA1, which predict the heating up of the upper header already in PhW2, all the other participants qualitatively predict the behaviour of the upper header wall temperature. KAERI_a and UNIPI show some oscillations at the beginning of the PhW. KAERI_b, POLITO, UNIPI and VTT slightly underestimate the quantitative value during the heating up, while all the other participants overestimate it with the exception of KAERI_a and UofU, which also underestimate the value between 12 150 and 12 750 s. Large oscillations are present in USNRC results at the beginning of the PhW, which show an almost stepwise increase of the temperature instead of a gradual rise. At the end of the transient all the participants' results tend to the experimental value.

Figure 7.1. Test 7 Part 1, HXP level L_VQ

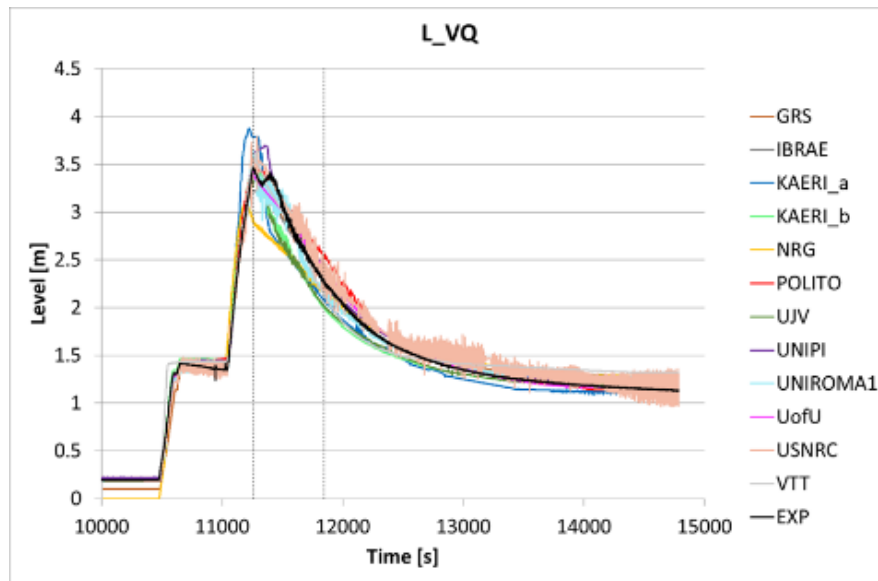


Figure 7.2. Test 7 Part 1, OP level L_VP

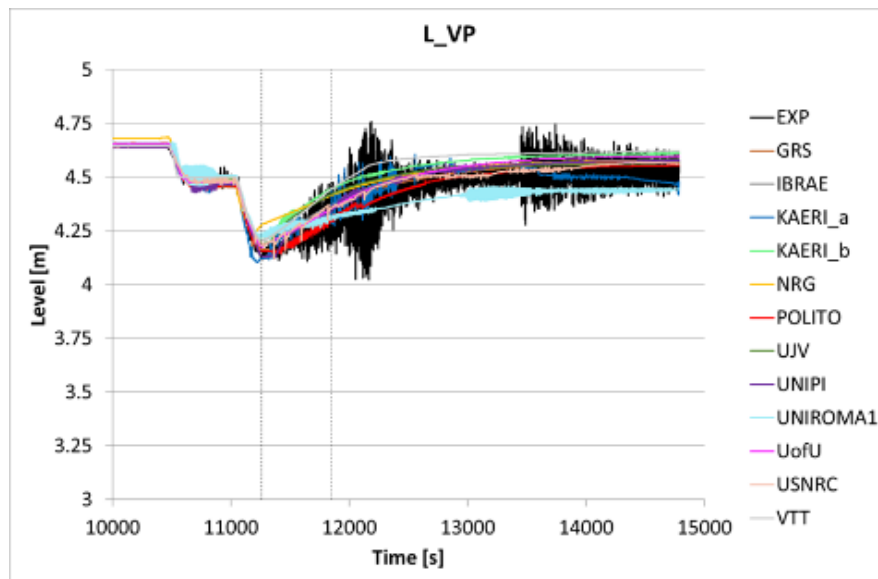


Figure 7.3. Test 7 Part 1, steam flow rate F_A001

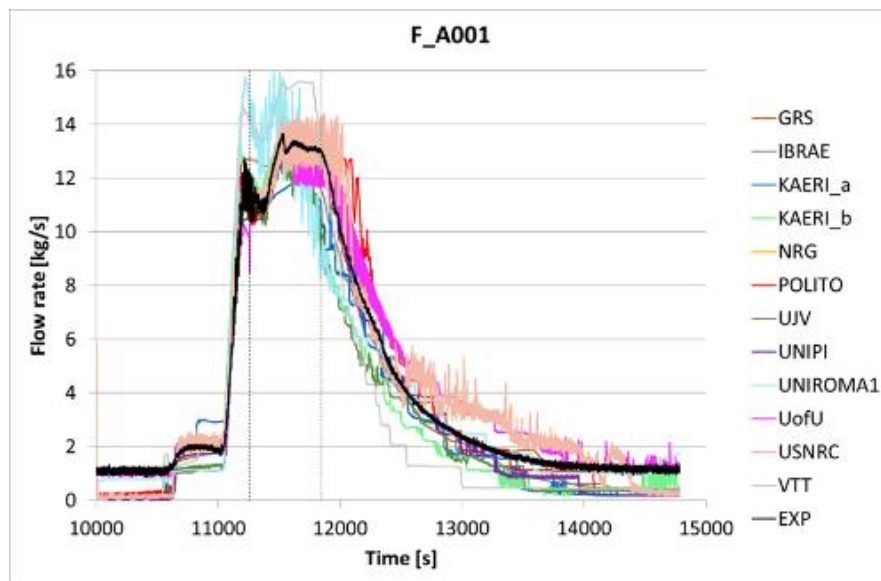


Figure 7.4. Test 7 Part 1, condensate flow rate F_E001

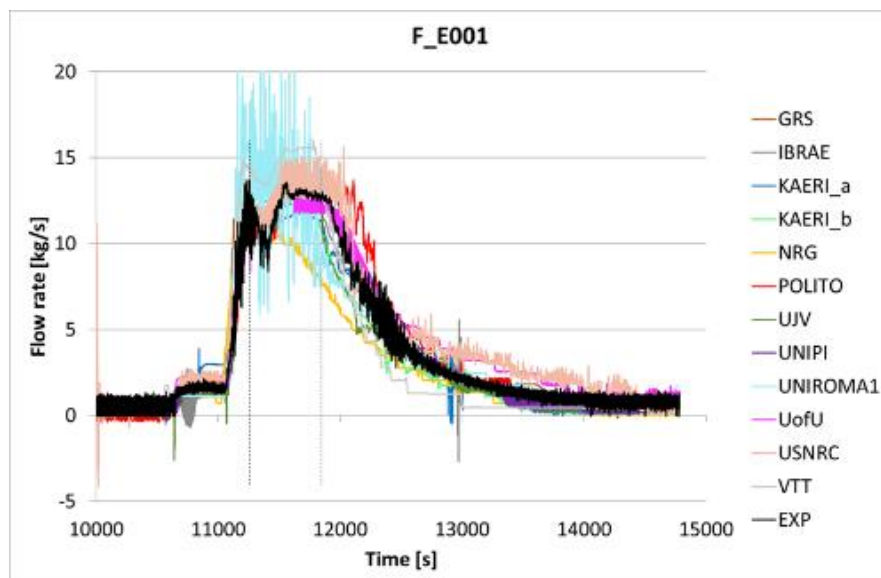


Figure 7.5. Test 7 Part 1, HX power W_IC

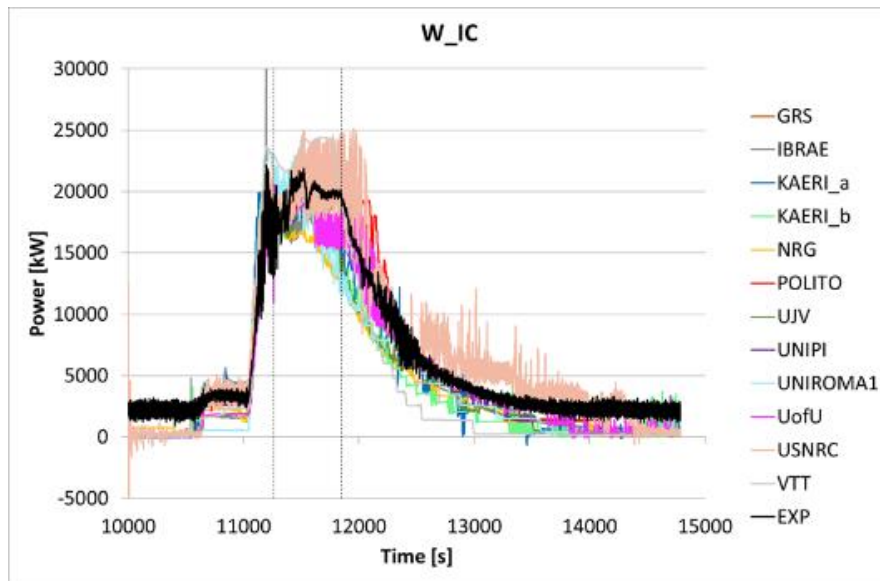


Figure 7.6. Test 7 Part 1, primary pressure P-I001

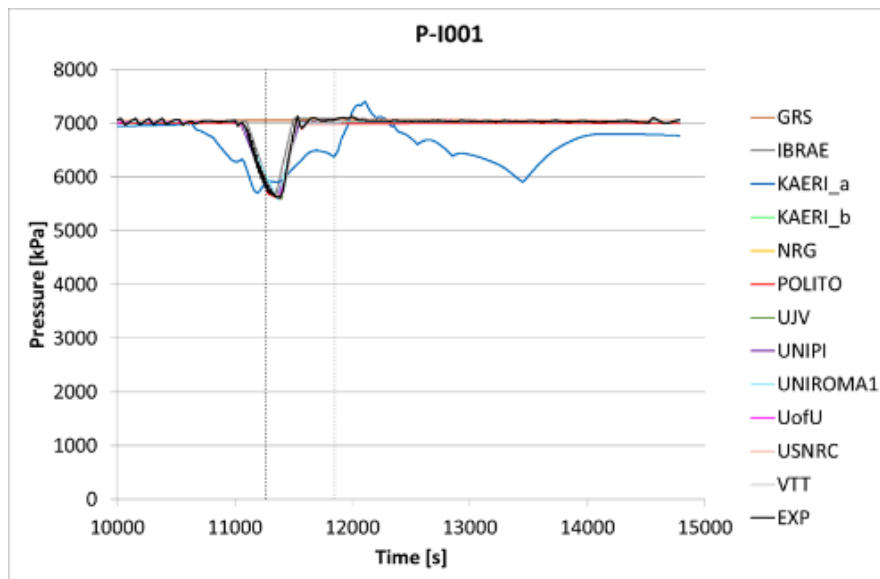


Figure 7.7. Test 7 Part 1, steam temperature T-A005

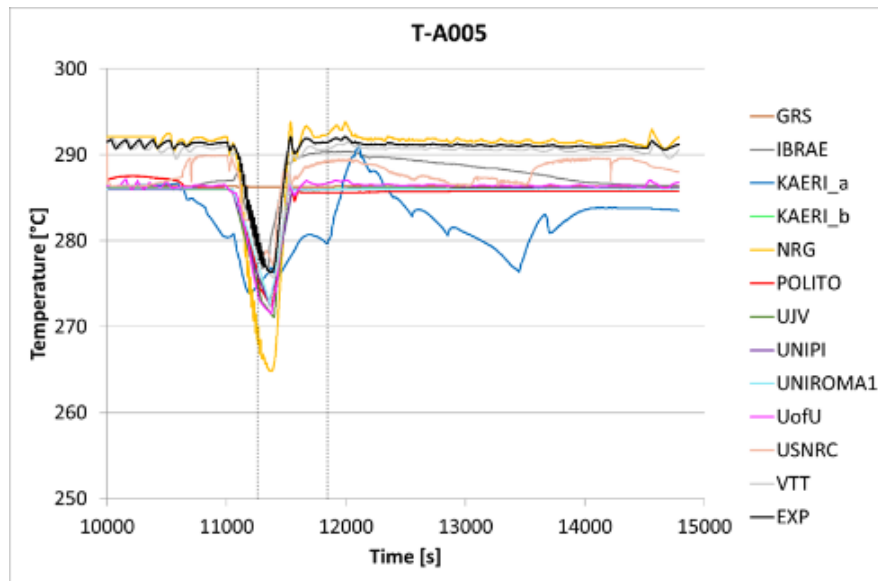


Figure 7.8. Test 7 Part 1, condensate temperature T-E001

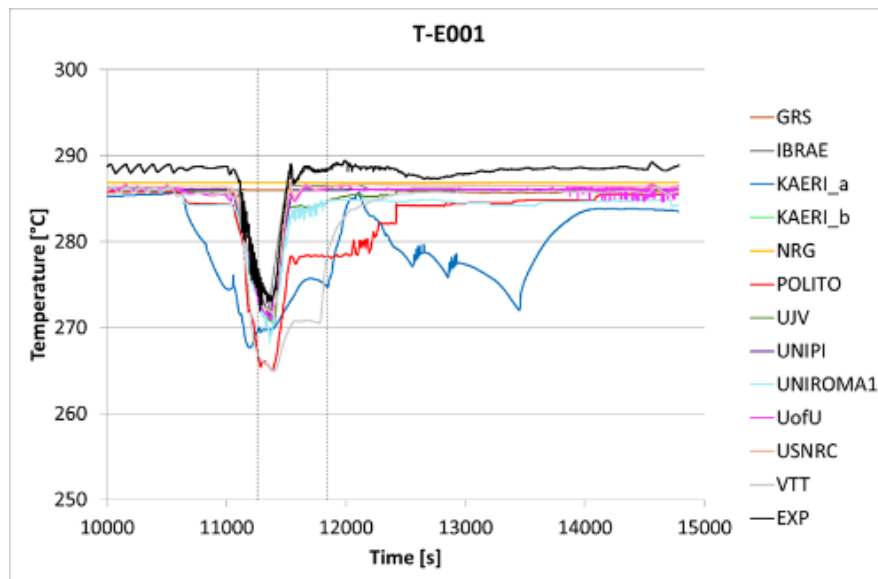


Figure 7.9. Test 7 Part 1, HXP temperature bottom T-Q037

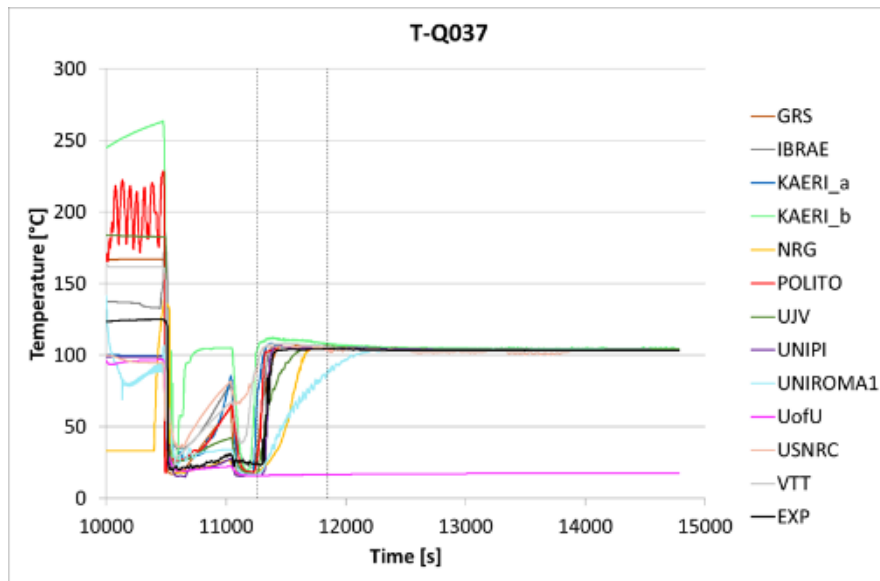


Figure 7.10. Test 7 Part 1, HXP temperature middle T-Q034

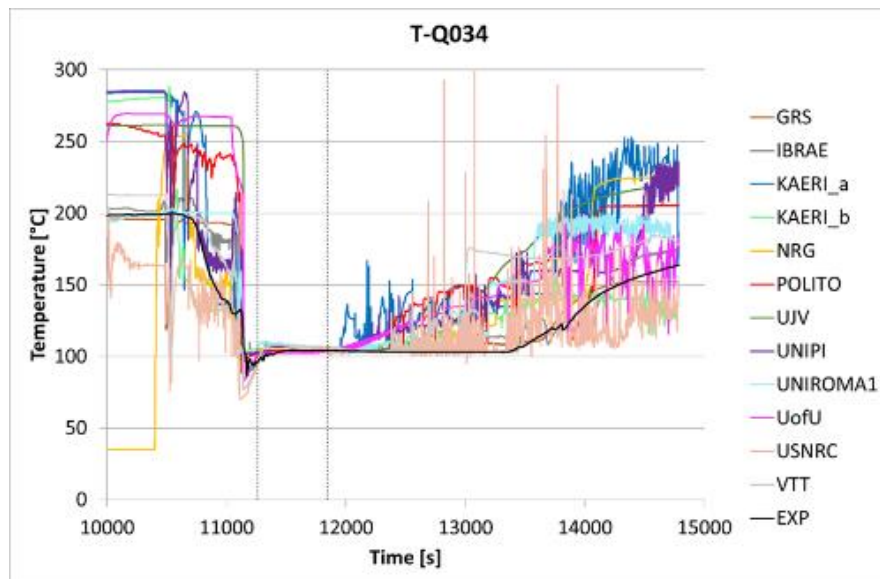


Figure 7.11. Test 7 Part 1, HXP temperature top T-Q031

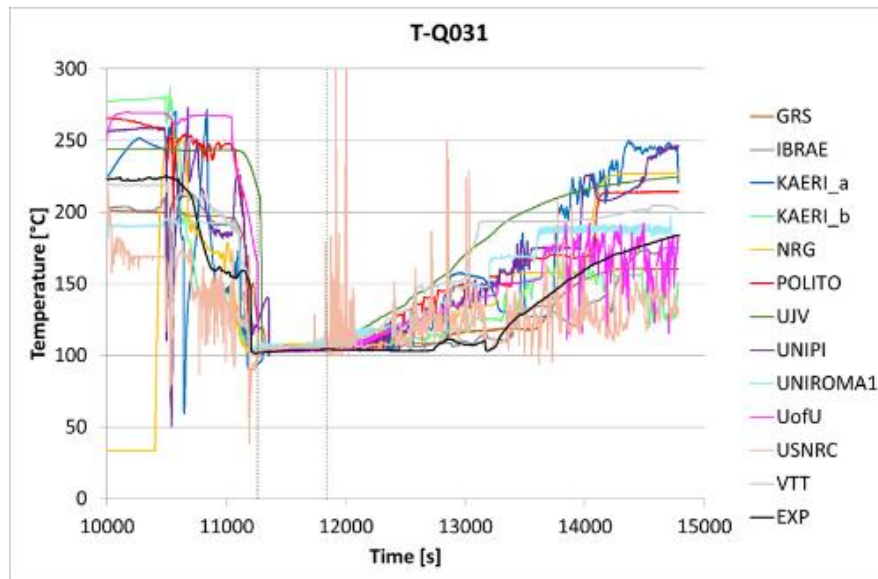


Figure 7.12. Test 7 Part 1, HXP relative pressure P-Q001

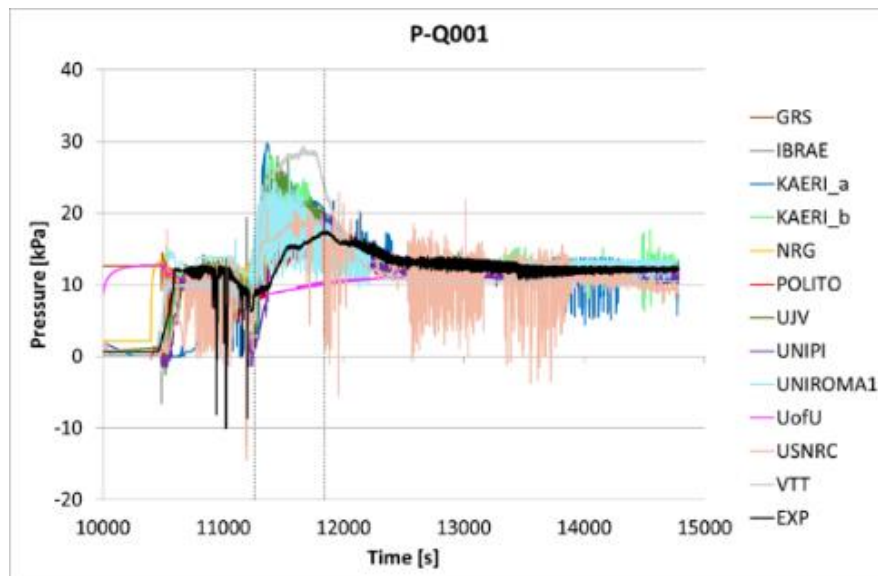


Figure 7.13. Test 7 Part 1, OP temperature bottom T-P008

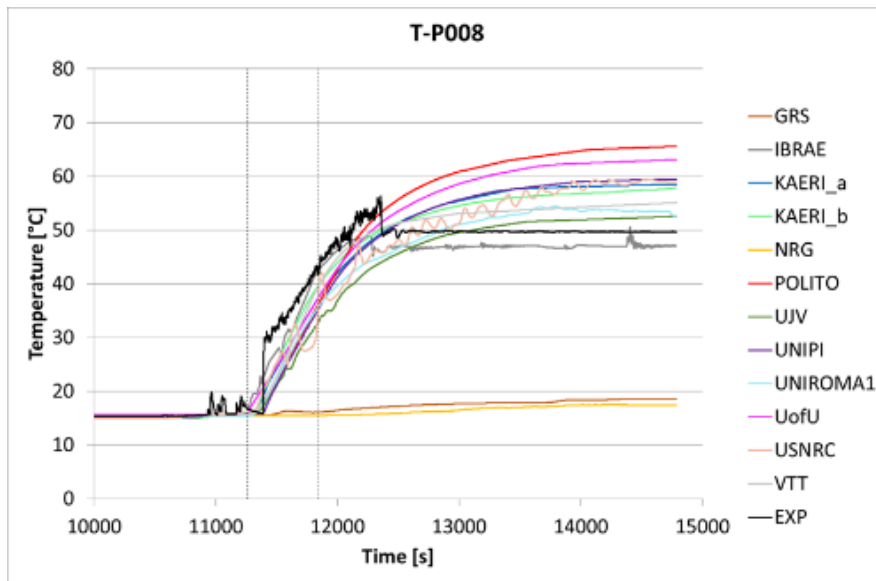


Figure 7.14. Test 7 Part 1, OP temperature top T-P021

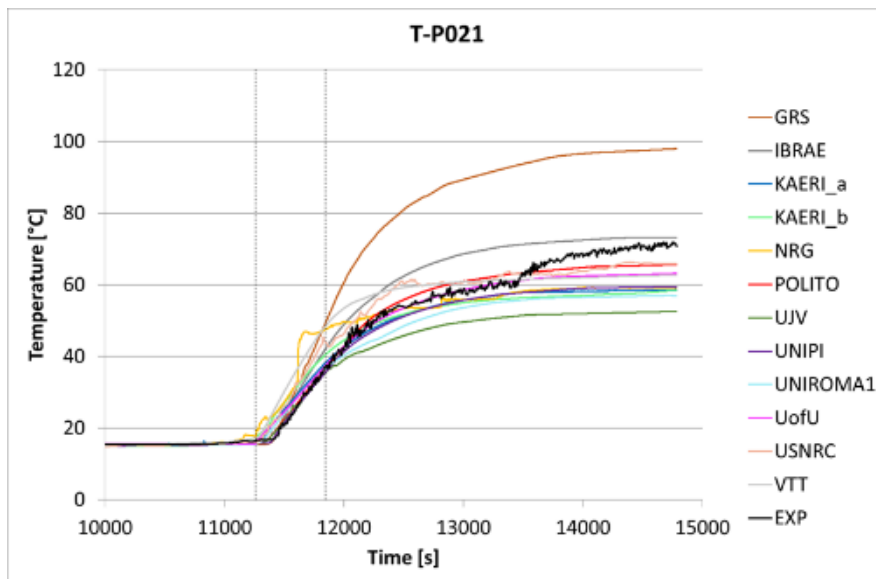


Figure 7.15. Test 7 Part 1, HX differential pressure DP-003

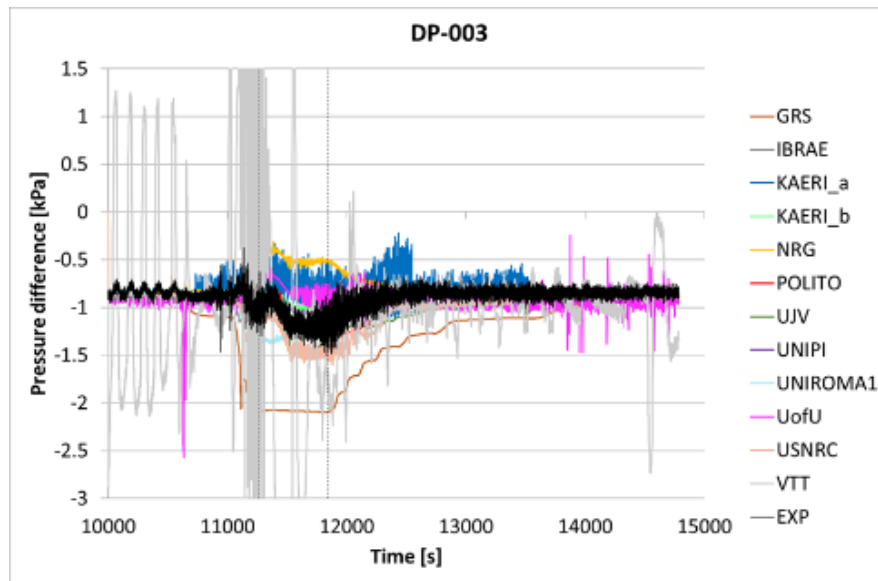


Figure 7.16. Test 7 Part 1, injector differential pressure DP-J001

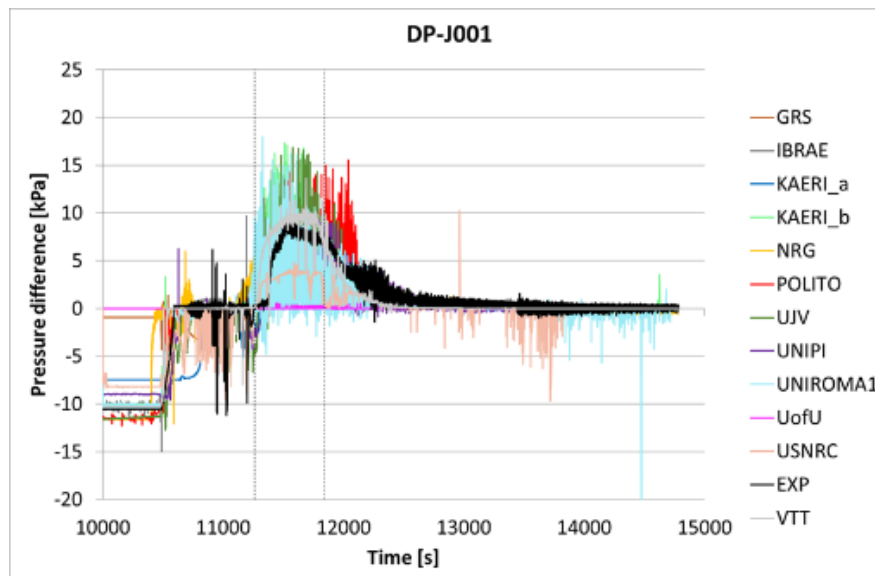


Figure 7.17. Test 7 Part 1, HX lower header outer wall temperature
TW-D001

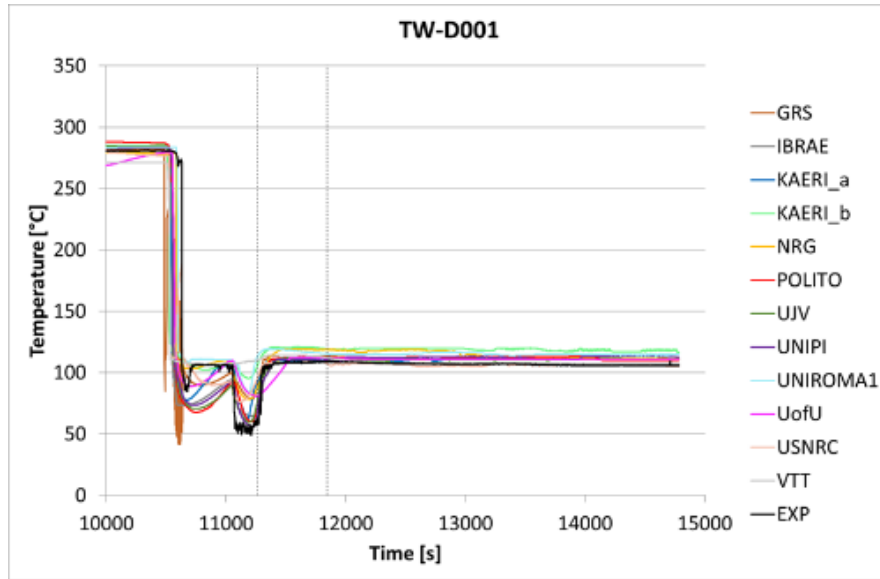
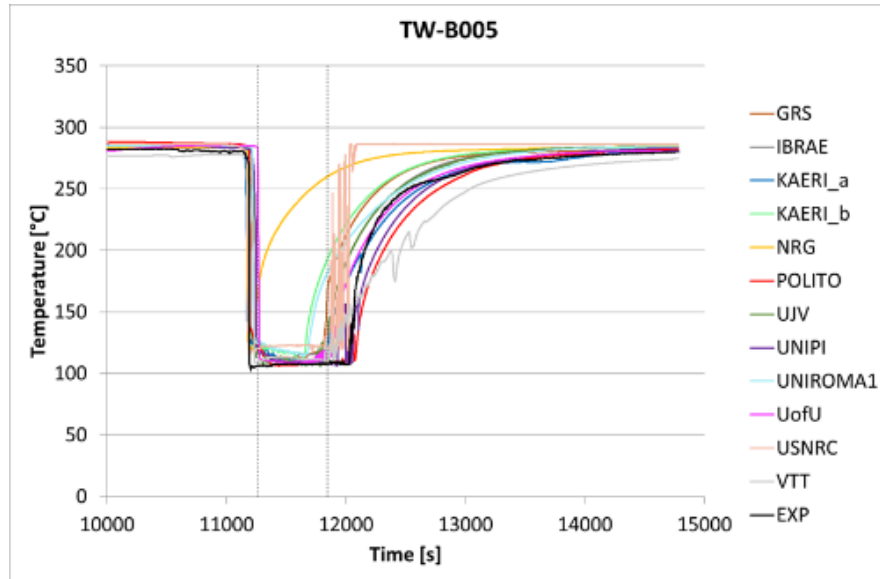


Figure 7.18. Test 7 Part 1, HX upper header outer wall temperature
TW-B005



7.1.2. Test 7 Part 2

Analysis of the first phenomenological window (0 – 53 s)

Test 7 Part 2 is performed starting from the end of Part 1. The first PhW represents the passive system activation. The HXP is flooded in one step by the opening of the triggering valve at 300 s. The flooding of the HX tubes causes the inception of significant heat transfer between the HX and the HXP with a consequent increase of the primary side flow rate.

Before the opening of the triggering valve, the HXP level (Figure 7.19) is correctly predicted by all the participants with a slight underprediction by KAERI_a (as shown in

Table 6.7). A slight overprediction is present in IBRAE and UNIROMA1 results (as shown in Table 6.7), which performed the calculation of Test 7 Part 1 and Part 2 together, and UJV. At the triggering valve opening the HXP is flooded and the HXP level reaches a maximum of 3.3 m. The HXP level increase is qualitatively predicted by all the participants. NRG underestimates the maximum HXP level, around 2.7 m, because at around 450 s the steam production in the HXP is sufficiently high to pressurise the pool, preventing additional water to enter the HXP from the OP. Discrepancies with respect to the experimental data are present also in GRS, IBRAE and UJV results, which slightly underestimate the maximum value, KAERI_b, POLITO and USNRC, which anticipate the maximum, and UNIPI and UofU, which anticipate and overestimate the maximum.

The initial OP level (Figure 7.20) is correctly simulated by almost all the participants and slightly overestimated by NRG (as shown in Table 6.7). The flooding of the HXP causes a level reduction in the OP which is qualitatively predicted by all the participants.

Before the opening of the triggering valve, negligible power is transferred from the HX to the HXP, therefore the primary steam and condensate flow rates (Figure 7.21 and Figure 7.22) are close to zero for almost all the participants. The experimental data shows non-zero values for these two parameters probably due to the uncertainty of measurements at low flow rates. Only NRG, which imposes the steam flow rate, UNIROMA1 and UofU predict a flow rate close to the experimental one in this phase. The mass flow rate increase is qualitatively predicted by all the participants. Considering the condensate flow rate, NRG underestimates the maximum value, even if the steam flow rate is imposed according to the experimental data, as in Test 7 Part 1.

The uncertainty on the flow rate also affects the HX power (Figure 7.23), which is experimentally derived from the flow rate; therefore, almost all participants predict a HX power lower than the experimental one before the opening of the triggering valve. The flooding of the HXP causes the inception of significant heat transfer between the HX and the HXP with a maximum exchanged power around 20 MW at the end of PhW1. All the codes are capable to predict the increase of the HX power and the consequent steam and condensate flow rates increment. IBRAE, USNRC and VTT results show a power peak at around 25-26 MW when the maximum HX power is reached.

In the present PhW, the primary pressure (Figure 7.24) is almost stable with limited oscillations and all the participants imposed it as a boundary condition.

The steam temperature (Figure 7.25) is underestimated by all the participants since saturation conditions have been set, with the exception of NRG and VTT, which imposed the experimental values. When the system is activated, IBRAE results show an increase of the steam temperature. The condensate temperature (Figure 7.26) is also underestimated by all the participants since the experimental value is superheated, probably due to a measurement uncertainty, as underlined in the previous sections. When the HX power becomes relevant, UJV and in particular KAERI_a, POLITO, UNIROMA1 and VTT predict a decrease of the temperature. In the case of KAERI_a, this is due to an underprediction of the pressure and therefore to an underprediction of the saturation temperature. In the case of POLITO, UJV and VTT this is due to the use of a mixture temperature for the post processing of the data since both liquid and gas phases are present with different temperatures. All the other participants predict an almost constant condensate temperature.

The HXP starts in saturation condition in the lower part where liquid is present (T-Q037 in Figure 7.27) and with superheated steam above the liquid level (T-Q034 in Figure 7.28 and T-Q031 in Figure 7.29). GRS, IBRAE and VTT are qualitatively able to predict the thermal stratification before the opening of the triggering valve. All the other participants highly

overestimate the steam temperature, do not predict the thermal stratification or show oscillations not observed in the experimental data. However, it should be noted that a not accurate prediction of the initial steam temperatures does not significantly affect the remaining part of the transient since the energy stored in the fluid is negligible.

When the HXP is flooded, T-Q037 (in the lower part of the HXP) reduces to around 60°C due to the income of colder water from the OP. The reduction is not qualitatively predicted by UofU, which starts with a very low temperature, while it is foreseen by all the other participants. Quantitative discrepancies regarding the minimum value reached by T-Q037 are present in all the results. After the initial reduction, the temperature rises again to the saturation value due to the heat transfer from the HX to the HXP. This behaviour is qualitatively predicted by all the participants which predicted the previous decrease. The main discrepancy with respect to the experiment is the delay present in GRS and NRG results regarding the temperature rise, which occurs mostly in PhW2 (NRG shows a major delay in the temperature rise in PhW2). The temperature in the middle and top part of the HXP (T-Q034 in Figure 7.28 and T-Q031 in Figure 7.29) is initially better predicted by GRS and IBRAE. After the HXP flooding the temperatures drop to the saturation value and the behaviour is qualitatively and quantitatively predicted by all the participants with a slight underestimation by UofU and USNRC at the end of T-Q034 reduction.

The HXP relative pressure (Figure 7.30) is at around 12 kPa at the beginning of the transient due to the pressurisation that occurred during Test 7 Part 1 (as shown in Table 6.7). After the opening of the triggering valve the pressure decreases at around 9 kPa; the income of colder water from the OP causes an initial condensation of the steam present in the HXP. Then the production of steam in the HXP causes a pressure increase, which occurs between PhW1 and PhW2. The pressure behaviour in this phase is qualitatively predicted by all the participants. Quantitative discrepancies are shown by KAERI_a, with strong oscillations at the beginning of the test, NRG, which starts from a lower initial condition and foresees an early pressure increment and UJV, which predicts significant oscillations and anticipates the pressure rise finding a higher peak with respect to the experimental data. Also UNIROMA1 anticipates and overestimates the pressure peak. USNRC results show large oscillations with negative pressure values at the end of the PhW.

The temperature in the lower part of the OP pool (T-P008 in Figure 7.31) is almost constant in this PhW. IBRAE, KAERI_b, NRG, UNIPI and VTT are able to predict the qualitative and quantitative behaviour of the temperature. KAERI_a and UJV predict the qualitative behaviour but overestimate the quantitative value, starting from a higher initial value. GRS, IBRAE, POLITO and UofU show temperature increases in this PhW not observed in the experimental data. POLITO and UofU show a significant quantitative overestimation since they start from a higher initial value; IBRAE shows small oscillations along the temperature increase in the final part of the PhW. OP temperature T-P021 (Figure 7.32) is stable at the beginning of the transient and then it rises in the final part of the PhW, probably due to the income of hot steam from the HXP. This behaviour is qualitatively predicted by IBRAE and KAERI_b and NRG, even if they do not foresee the temperature plateau at the end of the PhW (in particular NRG shows an increase of temperature which continues in the initial part of PhW2). All the other participants do not predict the qualitative behaviour of T-P021 in the present window.

The HX differential pressure (Figure 7.33) is around -0.8 kPa at the beginning of the transient (as shown in Table 6.7), then it reduces in this PhW due to the gravitational contribution of a condensate level which is formed in the HX tubes. The behaviour is correctly predicted by IBRAE, POLITO and UNIROMA1. The qualitative behaviour is predicted by KAERI_b and UNIPI but quantitatively slightly overestimated. Similarly, it is qualitatively predicted by UJV and USNRC but quantitatively slightly underestimated.

A more noticeable underestimation is present in GRS results. UofU does not predict any significant variation of the HX differential pressure. NRG does not predict the qualitative behaviour of the parameter, since a differential pressure increase is foreseen, as in Test 7 Part 1. VTT results show very large oscillation for this parameter throughout all the transient, since the experimental fluctuating pressure was used as a boundary condition for the PV pressure. Consequently, the steam flow rate and HX differential pressure show fluctuations.

The injector differential pressure (Figure 7.34) is almost constant and close to zero at the beginning of the PhW and then it starts to rise at the end of the window due to the increase of the steam flow rate from the HXP to the OP. Discrepancies are present in NRG and POLITO results at the beginning of the transient due to the initial conditions (as shown in Table 6.7), and a lower discrepancy is present in GRS initial condition. When the system is activated almost all the participant correctly reproduce the experimental data with a slight anticipation by NRG and VTT. Localised oscillations are present in GRS, UJV and USNRC results. UofU predicts an almost null differential pressure during the entire transient. In the case of UofU this could be due to the fact that MELCOR does not have dedicated models to capture the behaviour of the injector component.

The HX lower header is flooded at the beginning of the transient so the wall temperature Figure 7.35 is almost constant and slightly higher than the saturation one in the HXP. At the opening of the triggering valve the income of colder water from the OP causes a reduction of the fluid temperature in the lower part of the HXP (T-Q037) and also the HX lower header experiences a temperature reduction, even if not significant as the fluid one. The behaviour is correctly predicted by almost all the participants. IBRAE underestimates the temperature during its decrease in the second part of PhW1. NRG starts with a very high wall temperature then predicts the reduction after the opening of the triggering valve. The uppermost HS is initially not flooded (i.e. at around the steam temperature inside the tubes); then, when the HS is flooded the temperature goes to around 100°C.

The HX upper header is initially surrounded by superheated steam; when the HXP is flooded its wall temperature (Figure 7.36) drops to around 106°C and the slightly rises to around 109°C. The behaviour is qualitatively predicted by almost all the participants. NRG does not predict the reduction of the header temperature because the maximum HXP level is 2.75 m, which is some 50 cm lower than the experiment. For this reason, the HX upper header is never flooded, thus the corresponding wall temperature remains approximatively the same throughout the whole transient. UNIROMA1 predicts a gradual temperature reduction, which ends in PhW2, instead of a stepwise behaviour. All the participants which qualitatively predict the temperature reduction slightly overestimate the minimum quantitative value.

Analysis of the second phenomenological window (531 – 2 282 s)

The second PhW represents the phase with the maximum exchanged power between the HX and the HXP. The HXP level is sufficiently high to exchange the maximum power (around 20 MW). In this PhW the triggering valve remains open, so the water evaporated in the HXP is reintegrated by the OP. At 1 150 the OP discharge valve is opened to accelerate the OP level decrease.

The HXP level (Figure 7.19), after its maximum reached at the end of PhW1, significantly decreases due to the pressurisation of the HXP. Then few high amplitude and long period oscillations are present in the experimental data, which disappear after around 1 600 s. After the level slightly decrease until the end of the PhW. The level behaviour is qualitatively predicted by almost all the participants. UofU, after a small initial level decrease, significantly overpredicts the level then, at around 1 800 s, a sharp reduction and

a subsequent rise and second reduction is observed. Only GRS and UNIPI are qualitatively able to predict the high amplitude oscillations observed in the experimental data even if with quantitative discrepancies. The level is overestimated by NRG and VTT and, in the final part of the PhW, also by IBRAE. In the final part of the PhW, UJV and UNIPI underestimate the level.

At the beginning of the PhW, the OP level (Figure 7.20) tend to increase even if strong oscillations are observed in the experimental data. Then, after the opening of the OP discharge valve, it decreases at a constant rate. Almost all the participants are able to predict the average level behaviour and do not predict the oscillations. KAERI_a shows small oscillations in the central part of the window. UofU, after a correct prediction of the average behaviour in the initial part of the window, shows a significant sharp level drop and then a gradual reduction.

The steam and condensate mass flow rate behaviours (Figure 7.21 and Figure 7.22) follow the HX power. When power is exchanged, the steam is condensed inside the HX tubes and new steam is sucked from the PV. The two flow rates have analogous trends and they are qualitatively predicted by all the participants. The steam flow rate is in general slightly underestimated; UJV in the final part of the PhW shows a higher underestimation of the steam flow rate and, as UNIROMA1, UofU and USNRC, shows some oscillations along the PhW. The condensate flow rate is underestimated by NRG and VTT. The steam flow rate is more underestimated by VTT.

As previously mentioned, in this phase the maximum HX power is exchanged (Figure 7.23), around 20 MW. The behaviour is qualitatively predicted but slightly underestimated by all the participants, in particular VTT. UofU and USNRC show relevant oscillations in this phase.

The primary pressure (Figure 7.24) remains almost stable with limited oscillations and almost all the participants imposed it as a constant boundary condition. KAERI_a, starting with an accurate prediction of the pressure at the beginning of the PhW, along the PhW2 shows an increase of the discrepancy with respect to the experimental data. As in Test 7 Part 1, this is due to the fact that a time-dependent steam flowrate was imposed instead of a time-dependent pressure.

Considering the steam temperature (Figure 7.25), the measurement is superheated probably due to a measurement uncertainty. The temperature predicted by almost all the participants follow the constant saturation temperature. NRG and VTT, which imposed the superheated steam temperature along the transient, and USNRC show the better quantitative agreement with respect to the experimental data. IBRAE temperature is higher than the saturation value since, to match the experimental data, the boundary condition for the steam injected in the PV is superheated of 10 K. KAERI_a temperature follows the behaviour of the calculated primary pressure. Considering the condensate temperature (Figure 7.26) almost all participants found a constant temperature close to the saturation one. KAERI_a, POLITO, UJV (with a minor discrepancy), UNIROMA1 and VTT predict a lower temperature due to the temperature reduction at the end of PhW1. In the case of KAERI_a this is due to an underprediction of the pressure and therefore to an underprediction of the saturation temperature. In the case of POLITO, UJV and VTT since the liquid and gas phase are not at equilibrium, a mixture temperature has been computed for the post processing at the HX outlet and the resulting temperature is lower than the saturation one.

In the present PhW all the HXP temperatures (Figure 7.27, Figure 7.28 and Figure 7.29) are at the saturation value, with small localised decrease of T-Q037, which senses the income of colder water from the OP since it is located in the lower part of the pool. Considering T-Q037 the behaviour is predicted by almost all the participants. GRS predicts

the rising of the temperature in this PhW instead of PhW1. NRG and UofU results show significant delay in reaching the saturation temperature. In the case of NRG, due to the limited mixing of the water, the cold water stays at the bottom and is slowly heated by the volumes above that are warmer. Considering T-Q034 and T-Q031 in the middle and upper part of the HXP all the participant correctly predicts the temperatures behaviour.

The HXP relative pressure (Figure 7.30) increases during this phase up to around 23 kPa to the pressurisation of the HXP caused by the production of steam. The pressurisation is qualitatively predicted by all the participants with the exception of UofU (in PhW2 in the first part shows a plateau, then a localised peak and a sharp drop and a subsequent plateau close to 0 kPa). KAERI_a, POLITO, USNRC and VTT underestimate the pressure increase in the initial part of this PhW, then all the participants, with the exception of GRS, UJV and USNRC underestimate the quantitative value in the final part of the PhW. GRS, UNIPI and USNRC are qualitatively able to predict the high amplitude and low frequency oscillations that are linked to the HXP level oscillations.

The steam produced in the HXP is directed to the OP, causing the increase of the OP temperatures (Figure 7.31 and Figure 7.32), which reach the saturation value at around 1 500 s. Considering T-P008 the experimental data shows a reduction in the central part of the PhW, probably due to the mixing with colder water, then it rises again. This is only minimally qualitatively predicted by GRS, IBRAE and USNRC and not predicted by all the other participants that only foresee the overall temperature increase. POLITO, UofU and USNRC are able to predict the time at which the temperature reaches the saturation value. All the other participants show a delay which is particularly significantly for NRG, which reaches the saturation temperature in PhW3, and VTT. In the case of NRG, similarly to what observed for the bottom HXP temperature, due to the limited mixing of the water, the cold water stays at the bottom and is slowly heated by the volumes above. T-P021 decreases at the beginning of PhW2 probably due to the mixing with colder water in the pool, then it rises up to the saturation temperature. Only IBRAE is able to qualitatively predict the initial reduction; the overall temperature increase and the reaching of the saturation value is qualitatively predicted by all the participants. NRG significantly anticipates the reaching of the saturation, since the temperature is measured in the proximity (axial direction) of the injector, while KAERI_a, UJV, UNIPI and UNIROMA1 slightly delay it.

The HX differential pressure (Figure 7.33) remains almost constant during this PhW. With the exception of VTT, which shows significant oscillations, no participant predicts particular variations of the HX differential pressure in this phase so the main discrepancies are due to the discrepancies already underlined at the end of PhW1.

The injector differential pressure (Figure 7.34) increases at the beginning of this PhW due to the flowing of the steam produced in the HXP that becomes relevant, showing also significant oscillations. The experimental average behaviour is qualitatively predicted by almost all the participants. Only UofU predicts a null differential pressure throughout all the transient as previously described. All the other participants show results almost within the experimental oscillation band at the beginning of the PhW. At the end of the PhW, GRS, KAERI_a, UNIPI, UNIROMA1, USNRC and VTT underpredict the average experimental value.

The HX upper and lower headers wall temperature (Figure 7.35 and Figure 7.36) in the present PhW remains almost constant slightly above the fluid saturation temperature in the HXP. Considering the lower header temperature, the behaviour is correctly predicted by all the participants with a slight overestimation by KAERI_b, NRG and UNIROMA1. Considering the upper header temperature NRG predicts a very significant discrepancy since the temperature remains approximatively the same throughout the whole transient, as

previously mentioned. GRS and KAERI_b greatly anticipate the temperature rise, which experimentally occurs in PhW3. In the case of GRS this is due to the fact that the heat conduction object is wetted only at the peaks of the liquid level progress. Later on, without any fluctuations, the heat conduction object stays dry until the end of the simulation, leading to higher temperatures than in the experiment. IBRAE slightly overpredicts the temperature while UJV, UNIPI and UofU show some oscillations.

Analysis of the third phenomenological window (2 282 – 5 735 s)

In the last PhW, the decrease of the HXP level occurs and consequently HX power decreases and so also the steam and condensate flow rates. The HXP level decrease is accelerated at 3 338 s when the triggering valve is closed. Therefore, the water evaporated in the HXP is no longer reintegrated by the OP. The decreasing steam production in the HXP causes a reduction of the pool pressurisation and of the steam directed to the OP.

The HXP level (Figure 7.19) gradually decreases at the beginning of the PhW, then the decrease is accelerated after the closure of the triggering valve. The behaviour is qualitatively predicted by all the participants, in particular the increased HXP level decrease rate after the closure of the triggering valve. IBRAE, NRG and more significantly VTT overestimate the level in the entire PhW. KAERI_a, POLITO and UofU slightly overestimate the level only at the beginning of the PhW, while UJV, UNIPI and USNRC slightly underestimate it at the beginning of the window.

The OP level (Figure 7.20) decreases along the window, with a slight slope change after the closure of the triggering valve. The qualitative behaviour is correctly predicted by all the participants with some quantitative discrepancies. NRG and VTT slightly overestimate the level in the whole PhW, while KAERI_a underestimates it. UofU starts with a low level at the beginning of PhW3 and the rate of reduction is lower compared to the experimental one. In the final part of the window the level calculated by UofU becomes higher than the experimental one.

The steam and condensate mass flow rate behaviours (Figure 7.21 and Figure 7.22) follow the HX power trend with a reduction in PhW3. The behaviour is qualitatively predicted by all the participants with some quantitative discrepancies. IBRAE, KAERI_a POLITO and UNIPI overestimate the flow rates at the beginning of the PhW, while UofU and USNRC underestimate the flow rates and present oscillations. The steam flow rate is also underestimated by VTT at the beginning of the PhW. NRG, which imposes the steam flow rate, and VTT underestimate the condensate flow rate at the beginning of the PhW. IBRAE and KAERI_a show a significant localised oscillation in the condensate flow rate during its reduction. This is an artefact of momentum equation linearisation in case of partially vertical stratified flow. At the end of the PhW, many participants underestimate the steam flow rate, probably due to an uncertainty in the mass flow rate measurement at low flow rate values, as already mentioned.

The HX power (Figure 7.23) gradually reduces due to the reduction of the HXP level. The behaviour is qualitatively predicted by all the participants. In the initial part of the PhW UofU underestimated the HX power and present significant oscillations, which are also present in USNRC results. VTT underestimates the HX power at the beginning of the PhW. Some localised oscillations are also present in KAERI_a calculation. Many participants slight underestimate the power at the end of the transient. This can be due to an uncertainty in the mass flow rate measurement at low flow rate values that affects also the power, which is derived from the flow rate.

The primary pressure (Figure 7.24) is almost constant with small oscillations until around 4 670 s. Then the system is gradually depressurised to end the test. The reduction is

predicted or imposed by almost all the participants with a slight overestimation by UJV and an underestimation by GRS and VTT. KAERI_a calculation shows a significant discrepancy with respect to the experimental data since, as previously mentioned, a time-dependent steam flowrate was imposed instead of a time-dependent pressure. In the case of GRS and VTT, the depressurisation of the system is done by closing the connection to the pressure and enthalpy boundary for the pressure vessel and not by following the experimental determined pressure, leading to a pressure drop, which is larger than in the experimental case.

The steam temperature (Figure 7.25) is almost constant with small oscillations, and superheated as already underlined, until the system depressurisation begins. Almost all the participants qualitatively predict the temperature behaviour, close to the saturation value, with some quantitative discrepancies. IBRAE, NRG, USNRC and VTT predict a temperature higher than the other participants and close to the experimental one in the initial part of the window. During the depressurisation phase, GRS, NRG, UJV, UNIROMA1, UofU, USNRC and VTT underpredict the experimental temperature. IBRAE, KAERI_b, POLITO and UNIPI are closer to the experimental temperature with some quantitative underprediction or overprediction in the last part of the window. The main discrepancies are found by KAERI_a, with a temperature following the calculated pressure behaviour.

The condensate temperature (Figure 7.26) in the initial part of the PhW is almost constant with small oscillations. Almost all the participants predict a constant temperature close to the saturation one. As already mentioned, the experimental temperature is slightly superheated, probably due to an uncertainty in the measurement. POLITO, UJV, UNIROMA1 (more significantly) and VTT, in the initial part of the PhW, predict a lower temperature as in PhW2; in the case of POLITO, UJV and VTT, since the liquid and gas phase are not at equilibrium, a mixture temperature has been computed for the post processing at the HX outlet and the resulting temperature is lower than the saturation one. KAERI_a in general underestimates the temperature since the pressure and therefore the saturation temperature are underestimated. During the system depressurisation phase at the end of the PhW, almost all the participants predict the temperature reduction, which is in general slightly underestimated. NRG does not predict the temperature reduction and foresees a constant temperature since there is a time-independent volume with constant temperature.

The bottom HXP temperature (Figure 7.27) remains in saturation condition since the water level is higher than the thermocouple elevation. It slightly reduces in the PhW due to a reduction of the HXP pressurisation and therefore of the saturation temperature. All the participants are able to correctly predict the temperature behaviour. The middle and top HXP temperatures (Figure 7.28 and Figure 7.29) increase due to the HXP gradual uncovering and the superheating of the steam present in the pool. GRS and KAERI_b show the better qualitative and quantitative agreement with the experimental data for the thermal stratification in the HXP. Though all the participants generally predict the temperature increase, the correct behaviour is generally not predicted with several discrepancies: anticipation of the temperature increase, prediction of oscillations not observed in the experimental data, missing prediction of the thermal stratification in the HXP (predicting the similar values for T-Q034 and T-Q031) and presence of very large quantitative discrepancies.

The reduction of the power exchanged between the HX and the HXP causes a reduction of the HXP pressurisation (Figure 7.30). At the beginning of the PhW the reduction is almost linear then it accelerates after the closure of the triggering valve. The behaviour is qualitatively predicted by almost all the participants with the exception of UofU, which

predicts an almost null relative pressure already in the second part of PhW2. Almost all the participants quantitatively underestimate the pressure in the initial part of the PhW, with the exception of UJV and USNRC; after the close of the triggering valve all the participants in general quantitatively underestimate the pressure. UJV and UNIROMA1 show oscillations in the initial part of the PhW.

The OP temperatures (Figure 7.31 and Figure 7.32) are almost constant and in saturation condition during this PhW. T-P008 remains always below the water level so it measures the liquid temperature. The T-P021 thermocouple becomes uncovered due to the OP level reduction so it measures the temperature of the steam that is present in the upper part of the OP, which is in saturation condition. Almost all the participants are able to predict the behaviour of T-P008. NRG and VTT predict the reaching of the saturation temperature in PhW3 instead of PhW2. In the case of NRG, the delay is due to a poor mixing within the pool. Considering T-P021 all the participants correctly predict the temperature behaviour at the beginning of the PhW. Then GRS, NRG, UJV, USNRC and VTT predict a temperature increase. In the case of GRS this could be due to the fact that the superheated steam flowing through the injector does not reach the probe in the experiment, but due to the applied nodalisation it does in the simulation. Another possibility could be that a water droplet got caught on the temperature probe. In the case of NRG this is due to the fact that since the void fraction becomes higher than 0.95 the steam temperature is detected. In the case of UJV this can be due to the fact that when the injector is uncovered, superheated steam is flowing through the upper part of both channels simulating the OP (maybe due to overpredicted inner circulation). In the case of VTT, when the injector (at elevation 3.3 m) is uncovered and water level drops below the measuring point (2.695 m) superheated steam coming from the injector reaches the measurement point; the OP is modelled with only one stack of nodes, i.e 1D model.

The HX differential pressure (Figure 7.33) gradually increase due to the reduction of the condensate level inside the HX tubes which gives a negative contribution to the pressure difference. The behaviour is qualitatively predicted by almost all the participants with the exception of KAERI_a, which predicts an almost constant pressure, NRG, which predicts a decrease in the initial part of the PhW, as in Test 7 Part 1, UofU, which predicts an almost constant differential pressure at the beginning of the PhW and VTT, which shows significant oscillations. At the beginning of the PhW, UJV and USNRC slightly underpredict the differential pressure while GRS underpredict it more significantly. NRG and UofU show localised oscillations in the final part of the window but are able to qualitatively predict the final differential pressure increase.

The injector differential pressure (Figure 7.34) decreases due to the reduction of the flow rate of steam produced in the HXP and directed to the OP. The reduction becomes faster after the closure of the triggering valve and the faster level decrease in the HXP. Almost all the participants qualitatively predict the differential pressure behaviour with the exception UofU, which predicts an almost null value throughout all the transient. GRS, KAERI_a, UNIROMA1, USNRC and VTT underestimate the quantitative value at the beginning of the PhW. In VTT simulation the heat transfer from HX was underpredicted, consequently the steam flow through the injector and the differential pressure was also underpredicted. NRG, UJV and UNIP1 shows relatively high amplitude oscillations in the initial and central part of the PhW.

The HX lower header remains completely flooded also in the present PhW. Therefore, the wall temperature (Figure 7.35) remains almost constant and the qualitative behaviour is predicted by all the participants with some quantitative discrepancies. The level reduction in the HXP causes the uncovering of the HX upper header which experience a gradual heating up (Figure 7.36). NRG does not predict the qualitative behaviour since it foresees

an almost constant temperature throughout all the transient. GRS and KAERI_b predict the temperature increase in PhW2 instead of the present PhW. POLITO, UNIPI, UNIROMA1, UofU and USNRC anticipate the temperature increase; in addition, in USNRC results, the increase is very sharp. VTT delays the temperature increase, showing also a temporary reduction. In fact, steam is present on both sides of the upper header wall with slightly superheated steam on the outer surface (temperature around 130°C) and hot steam (temperature 290°C) on the inner surface. The steam flow to HX is reducing and steam flows are quite small on both sides; due to some spurious, weak, convective flows, the heat transfer on the outer surface is temporarily higher than on the inner surface and consequently HX wall temperature decreased. IBRAE, KAERI_a and UJV predict a better quantitative agreement with respect to the experimental data. In the case of POLITO the anticipation of the heating up is due to the fact that a single heat structure has been used for the wall header while the thermocouple is placed in the lower part of the header, therefore it experiences later the uncovering due to the HXP level reduction. While within the experiment, the thermo probe TW-B005 at the upper header is wetted all the time until 3 400 s, keeping the temperature low, in the GRS case it is only wetted at the peaks of the liquid level progress. Later, the temperature stays high, since the heat conduction object is unwetted. The difference with the experimental data could be explained by the coarse nodalisation of the lower header (one node) compared with the exact location of the thermo probe.

Figure 7.19. Test 7 Part 2, HXP level L_VQ

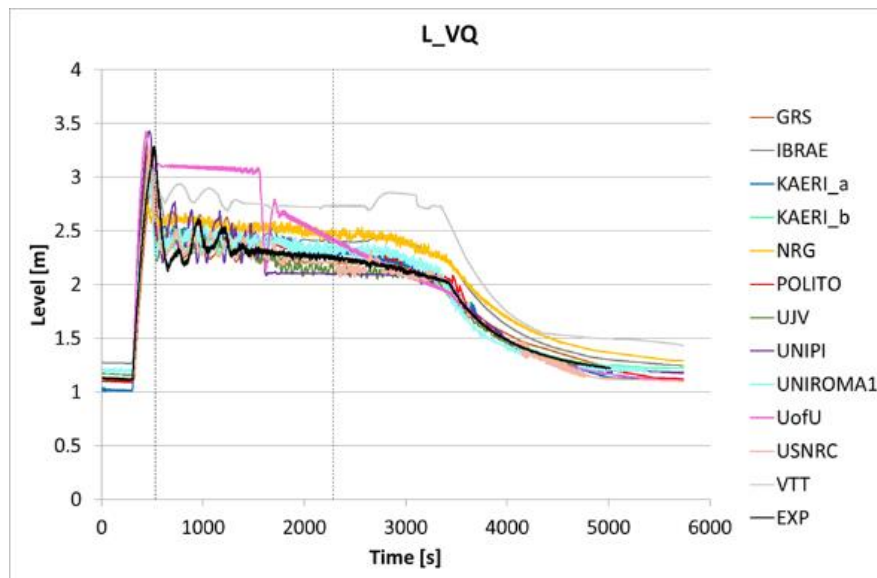


Figure 7.20. Test 7 Part 2, OP level L_VP

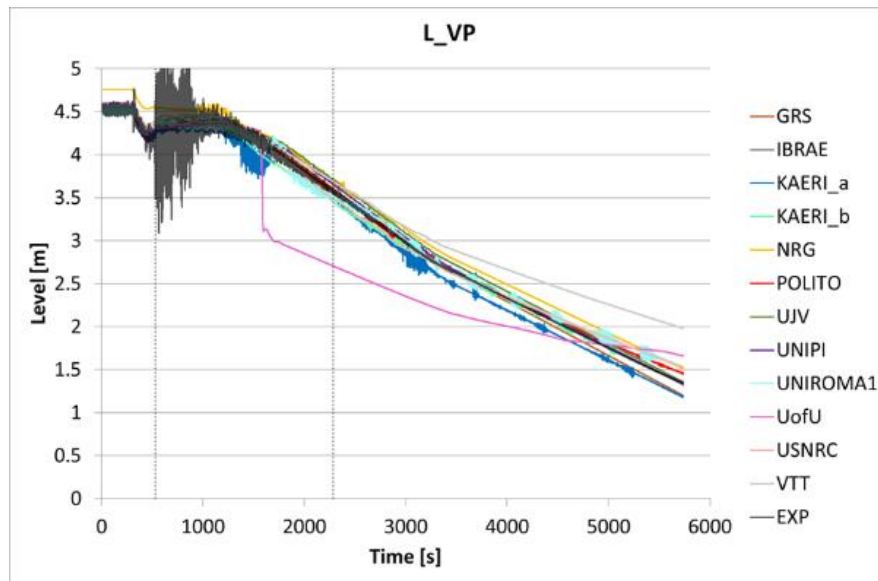


Figure 7.21. Test 7 Part 2, steam flow rate F_A001

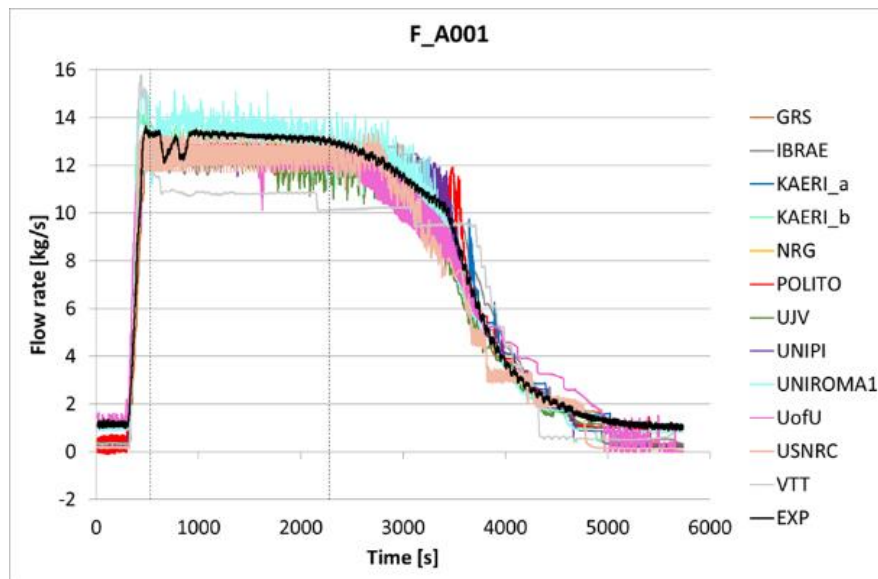


Figure 7.22. Test 7 Part 2, condensate flow rate F_E001

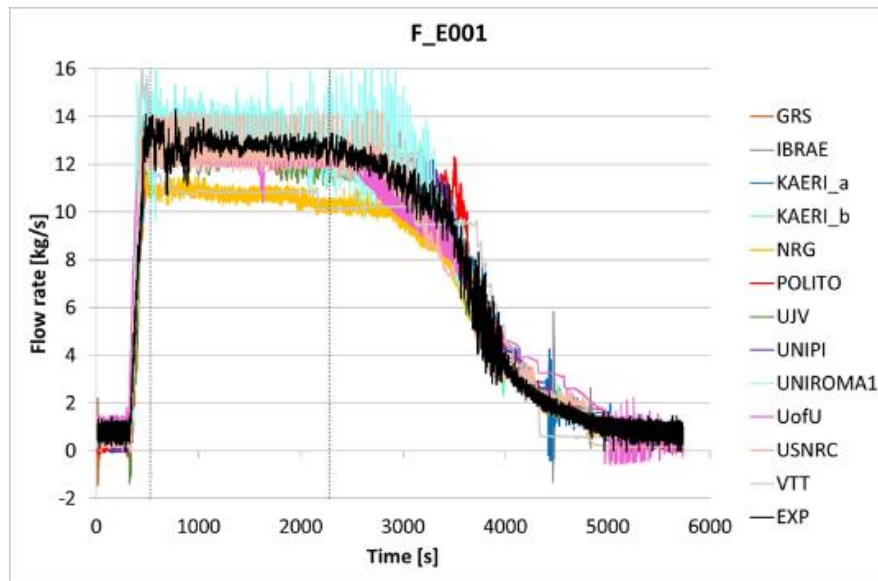


Figure 7.23. Test 7 Part 2, HX power W_IC

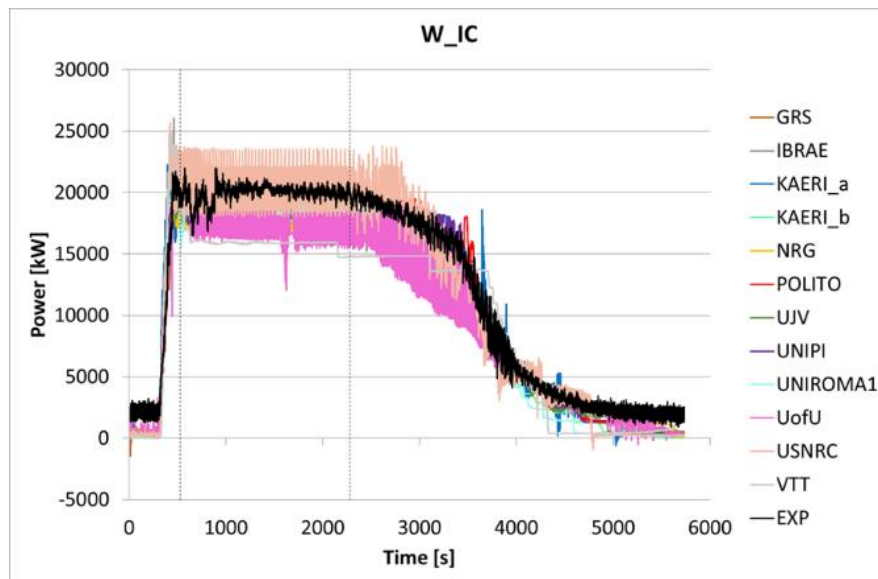


Figure 7.24. Test 7 Part 2, primary pressure P-I001

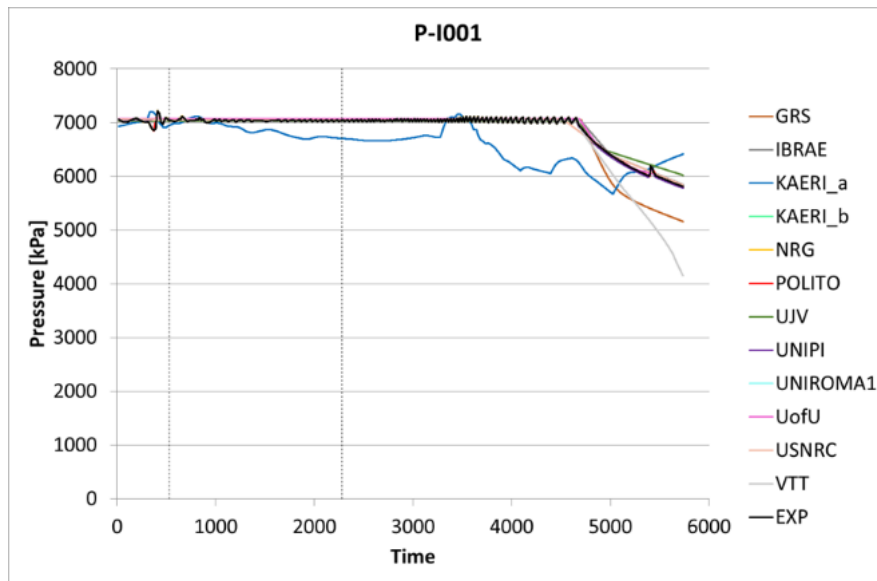


Figure 7.25. Test 7 Part 2, steam temperature T-A005

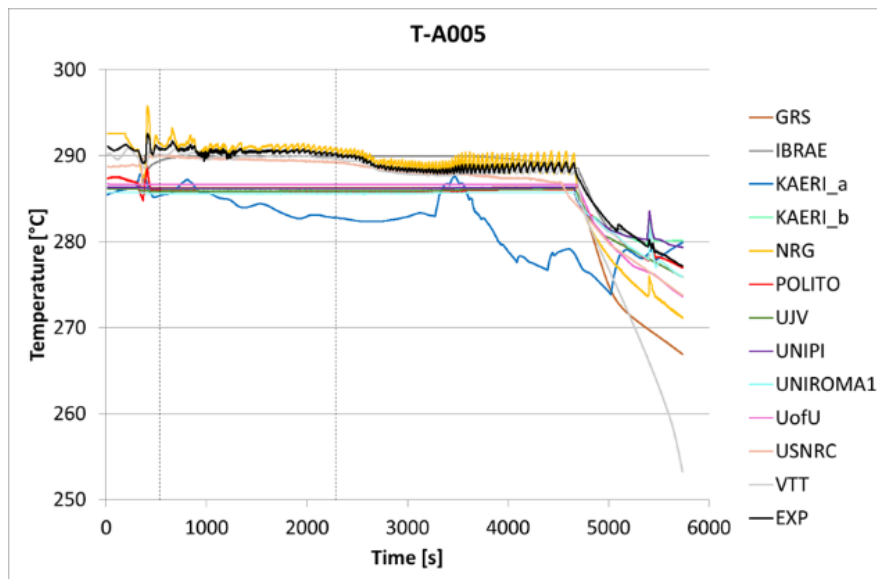


Figure 7.26. Test 7 Part 2, condensate temperature T-E001

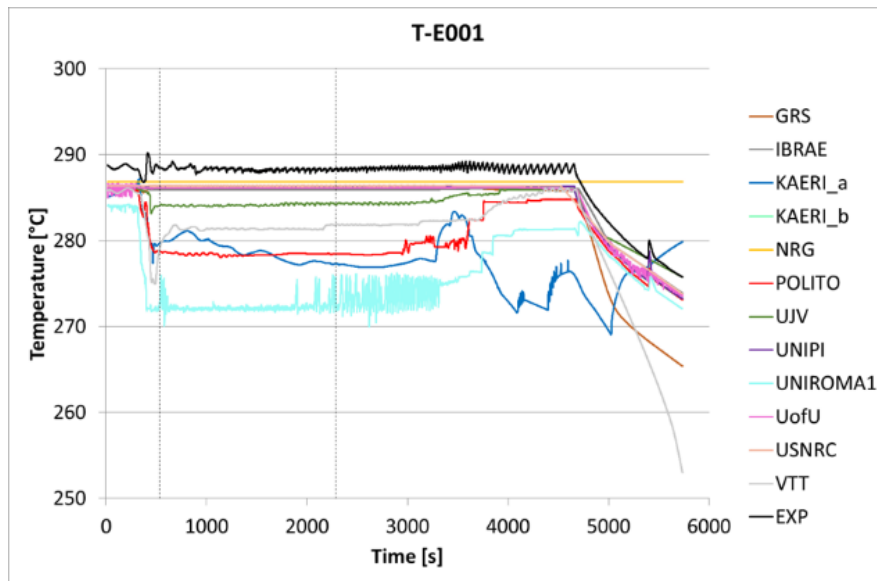


Figure 7.27. Test 7 Part 2, HXP temperature bottom T-Q037

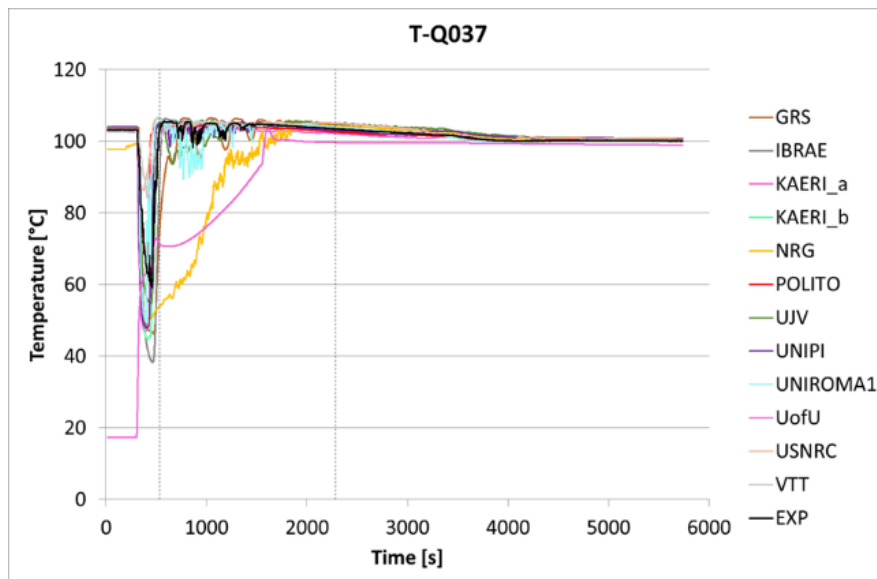


Figure 7.28. Test 7 Part 2, HXP temperature middle T-Q034

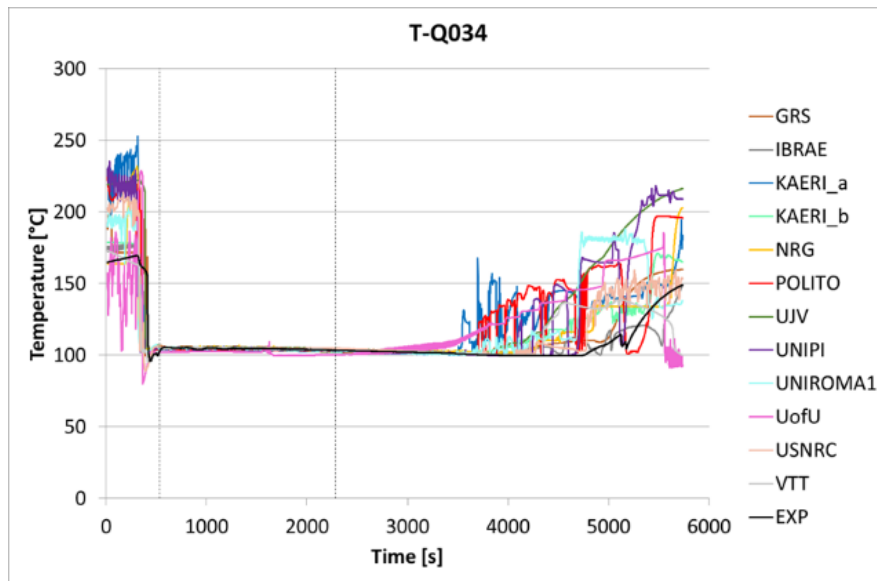


Figure 7.29. Test 7 Part 2, HXP temperature top T-Q031

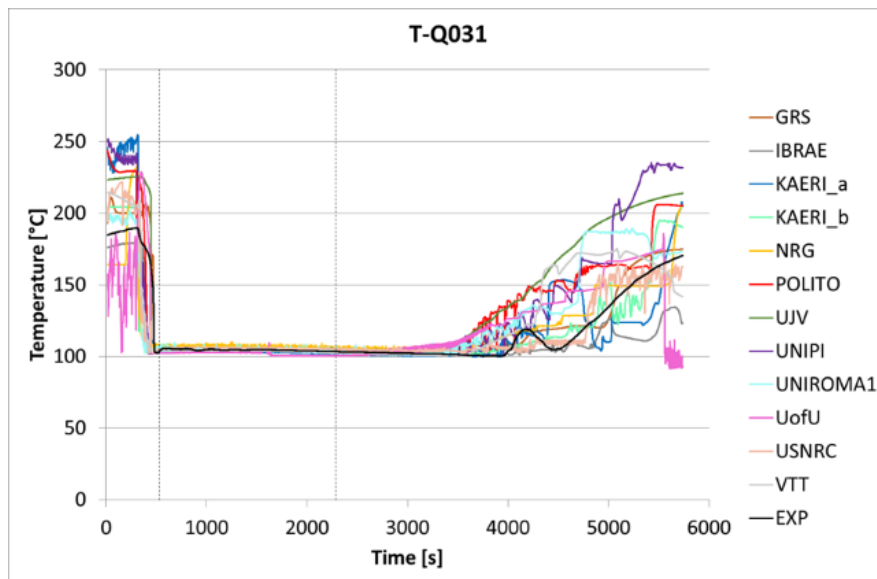


Figure 7.30. Test 7 Part 2, HXP relative pressure P-Q001

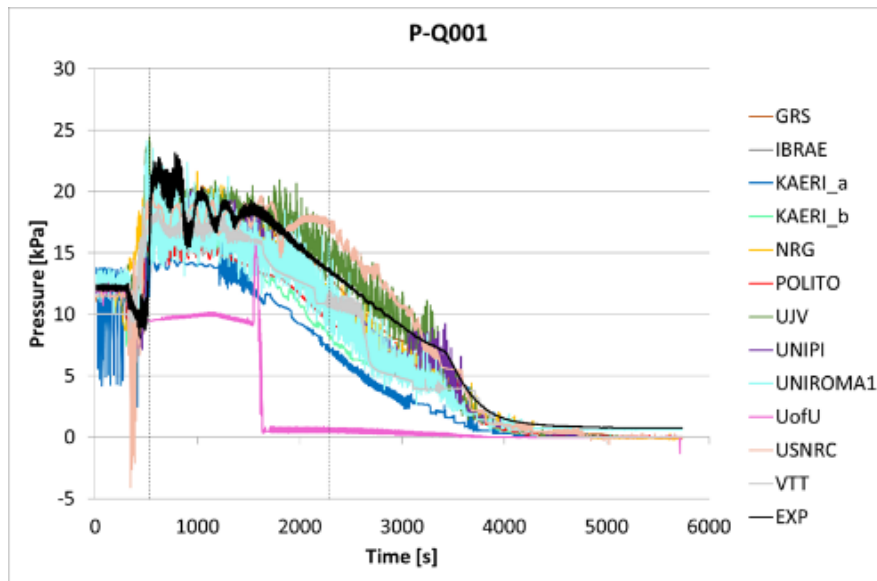


Figure 7.31. Test 7 Part 2, OP temperature bottom T-P008

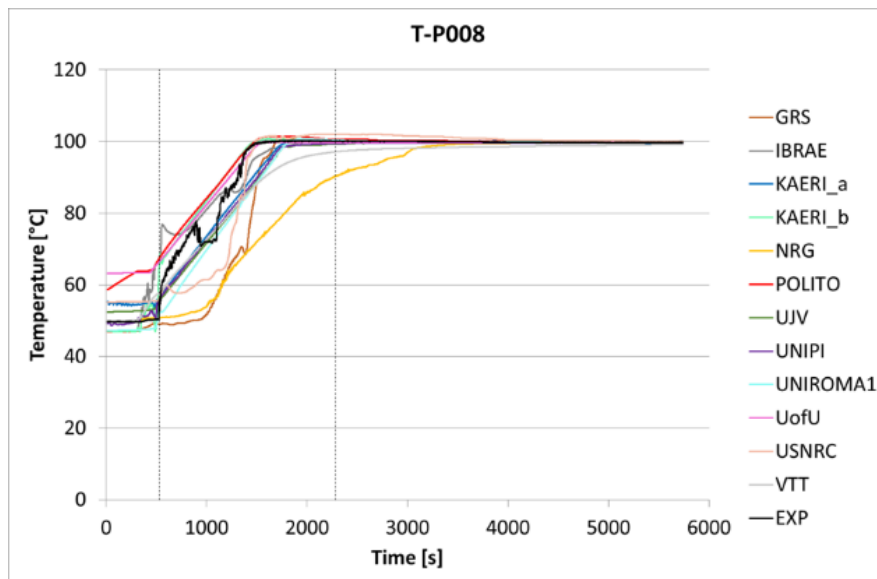


Figure 7.32. Test 7 Part 2, OP temperature top T-P021

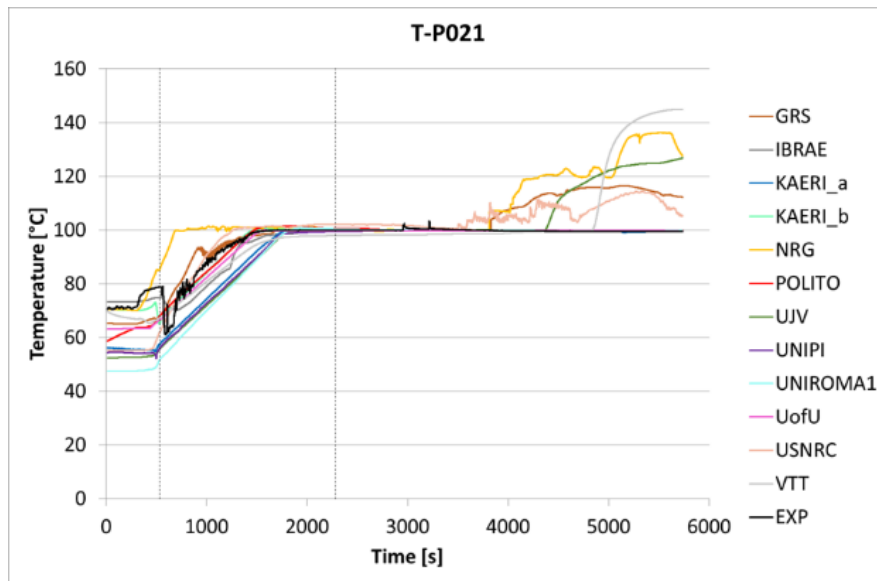


Figure 7.33. Test 7 Part 2, HX differential pressure DP-003

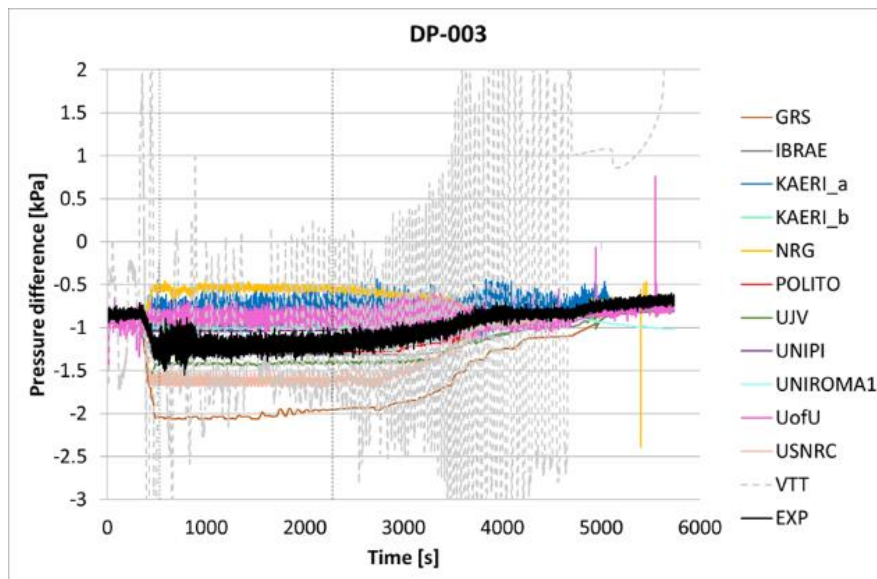


Figure 7.34. Test 7 Part 2, injector differential pressure DP-J001

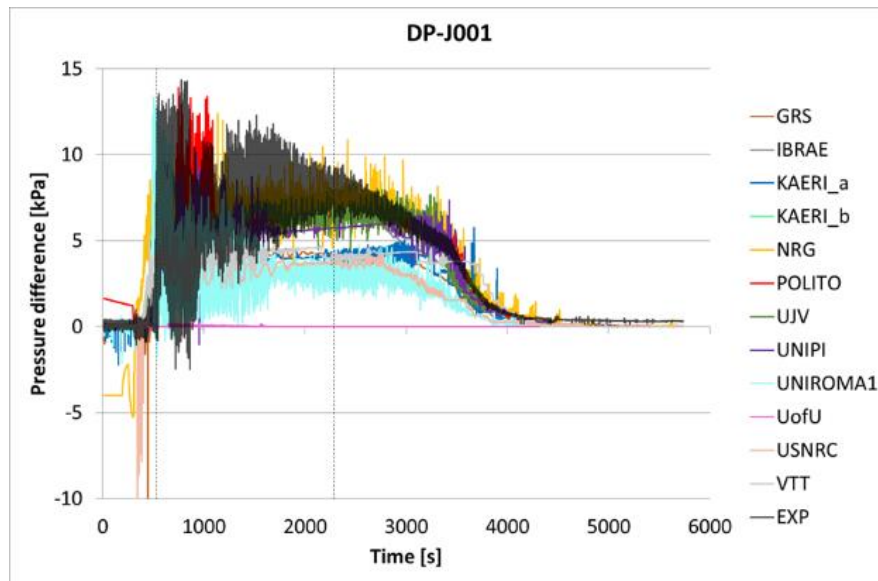


Figure 7.35. Test 7 Part 2, HX lower header outer wall temperature TW-D001

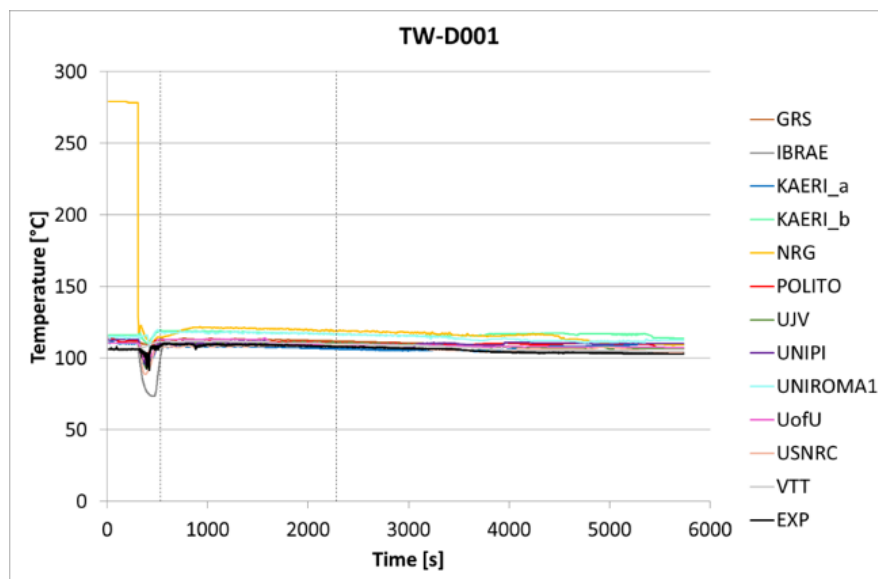
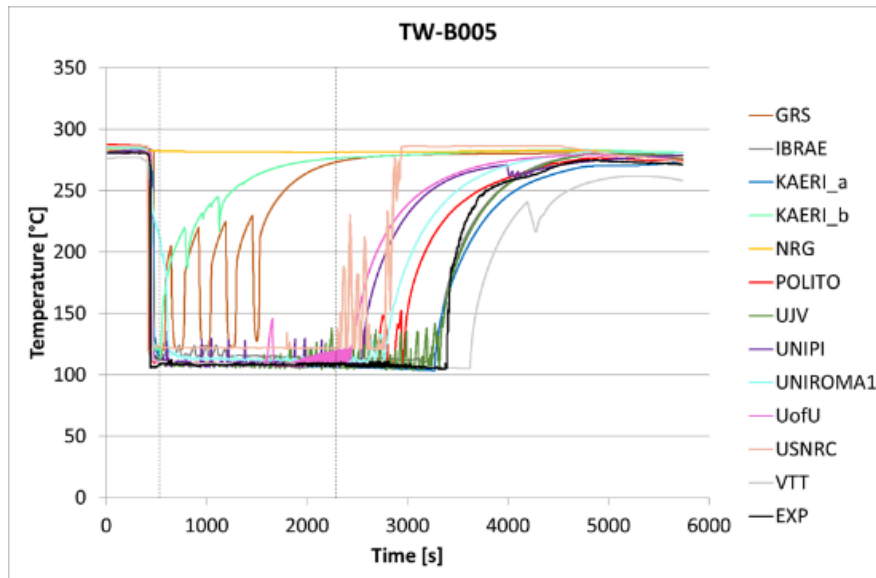


Figure 7.36. Test 7 Part 2, HX upper header outer wall temperature TW-B005



7.2. Analyses of the qualitative code accuracy

The qualitative code accuracy has been evaluated considering the main phenomena characterised in PERSEO Test 7 Part 1 and 2 based on the four subjective marks proposed in Table 4.2. The results are reported in Table 7.1 for Test 7 Part 1 and in Table 7.2 for Part 2. In the tables the participant evaluation is reported (U=user) together with an independent evaluation (I). The independent evaluation was performed by the lead authors of the present report to have an external and possibly uniform point of view in addition to the one of the users who performed the calculation.

7.2.1. User qualitative accuracy evaluation

“Natural circulation in one-phase and two-phase flow in-tube side” has been marked with a “+” by almost all the participants for both Part 1 and 2. NRG marked this phenomenon with a “-” since the PV is not modelled.

“Natural circulation in HXP and OP coupled circuit” has been marked with a “+” by almost all the participants in Part 1 with the exception of NRG and USNRC, which marked it with a “o” and GRS, which marked it with “+/o”. In the case of NRG this is due to the fact that the phenomenon is only reasonably modelled. The triggering valve opening fraction was modified in order to improve the quality of the inter-pool flow rate. In the case of GRS “+/o” has been chosen since while between both pools the circulation itself is in a good agreement with the experimental data, the mixing within the OP was not well predicted. In Part 2 also KAERI_a and KAERI_b marked this phenomenon with an “o”.

“Thermo-fluid dynamics and pressure drops in various geometrical configurations” has been marked with a “+” by almost all the participants in both Part 1 and 2. GRS marked it with “+/o”, since the power of the heat exchanger is still underestimated by approximately 5 – 10%. KAERI_a, KAERI_b and NRG marked this phenomenon with an “o”. In Part 2 VTT marked it with a “+/o”. In the case of NRG this is due to the fact that some discrepancies were observed for pressure differences and an improvement might involve modification of loss factors or other parameters tuning.

“Behaviour of emergency heat exchangers and isolation condensers: Tube-side convection heat transfer” has been marked with a “+” by GRS, IBRAE, UNIROMA1, UofU and USNRC for both parts. VTT marked it with a “+” in Part 1 and “+/o” in Part 2 HX since power was firstly overpredicted and later on underpredicted by 20%, which is still within the general accuracy of heat transfer correlations. All the other participants marked this phenomenon with an “o” in both parts. In the case of POLITO and UJV this is due to the underestimation of the condensation heat transfer coefficient and to the needing of increase it through fouling factors. In the case of NRG, the equivalent condensation length was modified to increase the heat transfer coefficient.

“Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer” has been marked with a “+” by IBRAE, UofU and USNRC for both Part 1 and 2. GRS marked it with a “+/o” in Part 1 and “+” in Part 2. UNIROMA1 and VTT marked the phenomenon with “+” in Part 1 and “o” and “+/o” respectively in Part 2. In the case of VTT this is due to the fact that the upper part of the tubes went in dry out condition on the pool side, which requires further evaluation although there was not detailed instrumentation in the experiment to assess the phenomena. All the other participants marked the phenomenon with an “o” in both parts. In the case of POLITO and UJV this is due to the underestimation of the heat transfer. In the case of NRG, the equivalent condensation length was modified to increase the heat transfer coefficient.

“Behaviour of large pool: Thermal stratification” has been marked in both Part 1 and 2 with a “+” by IBRAE and UofU, “-” by POLITO and UNIPI, “NA” by NRG and “o” by all the other participants. For GRS, Part 1 has been marked with “o” and Part 2 with “+”, since in Part 1 the mixing within the OP is not well predicted. VTT marked the phenomenon with “+” in Part 1 and “+/o” in Part 2. In the case of POLITO, the missing prediction of the thermal stratification could be due to the code numerical solving scheme or to the adopted nodalisation. In the case of UJV, since some thermal stratification was observed, an “o” has been marked instead of “-”. In the case of NRG, it has been marked with NA since the nodalisation used is not really effective to predict thermal stratification.

“Behaviour of large pool: Natural convection (within a single pool)” has been marked with a “+” by GRS, POLITO, UJV, UNIPI, UNIROMA1 and UofU in both parts. VTT marked it with “+” in Part 1 and “o” and “+/o” respectively in Part 2. IBRAE marked the phenomenon with a “+/o” in both parts. KAERI_a, KAERI_b, NRG and USNRC marked the phenomenon with an “o”. In the case of NRG this is due to the observed discrepancies with measured temperatures.

“Steam-liquid interaction: Direct contact condensation of steam in pool water” has been marked with a “+” by POLITO, UJV, UNIPI, UofU and USNRC, while it has been marked with a “+/o” by IBRAE, since they believe that the experimental data are not enough to properly evaluate the phenomenon. UNIROMA1 marked the phenomenon with “+” in Part 1 and “o” in Part 2. All the other participants marked it with an “o” in both parts with the exception of GRS and VTT, which marked it with “+/o” in Part 2. In the case of NRG this is due to the fact that the phenomenon is reasonably captured, but limited to the CV where it occurs and the steam jet is not axially resolved.

“Structural heat was marked in both Part 1 and Part 2 with a “+” by almost all the participants with the exception of KAERI_a and KAERI_b, which marked it with a “o” in both parts and GRS, which marked Part 2 with an “o”, since the wall temperature at the upper header does not suit the experimental data well.

7.2.2. Independent qualitative accuracy evaluation

The independent qualitative accuracy evaluation has been performed by judging the code capability to predict the various parameters characterising each phenomenon (Table 4.1) and then evaluating the phenomenon itself. This independent evaluation should not be considered as an endorsement or not endorsement of any code for each specific phenomenon, but it is only an attempt to evaluate the results of the various codes for this specific experiment, in a uniform way from an external point of view, and independently of who performed the calculation. Also, in this case, this is not an objective evaluation of the qualitative code's capability to predict the phenomena but a subjective one.

For phenomenon A in both parts, a “NA” has been given to NRG and UofU, which do not simulate the vessel and therefore a closed primary system loop is not present. KAERI_a has been marked with “o” considering the general evaluation of the parameters characterising this phenomenon, in particular the primary pressure and temperatures. A “+” has been given to all the other participants.

For phenomenon B in Part 2, an “o” has been given to NRG and UofU considering the general evaluation of the parameters characterising this phenomenon. A “+” has been given to all the other participants.

Considering phenomenon C, an “o” has been given to NRG and UofU in both parts and KAERI_a, UNIROMA1 and VTT in Part 2, mostly due to discrepancies in the prediction of one or more of the following parameters: HX and injector differential pressures and HXP relative pressure. A “+” has been given to all the other participants.

For phenomenon D in both parts, a “+” has been given to GRS, IBRAE, USNRC and VTT, which do not adopt any correction factor to quantitatively predict the HX power. An “o” has been given to all the other participants that are able to predict the HX power only after the application of proper correction factors.

For phenomenon E an approach similar to phenomenon D has been adopted with the exception of an “o” given to VTT in Part 1, considering the general evaluation of the parameters characterising this phenomenon and in particular the HXP temperatures (middle and top) and HX power.

Phenomenon F has been marked with a “+” for IBRAE and KAERI_b in both parts and GRS in Part 2 since they are able in general to capture some thermal stratification in the pools. An “o” has been given to all the other participants due to the discrepancies present in the HXP and OP temperatures.

For phenomenon G, UofU has been marked with “o” in Part 2 considering the general evaluation of the parameters characterising this phenomenon. A “+” has been given to all the other participants.

Considering phenomenon H, a “+” has been given to all the participants with the exception of UofU, which has been marked with “o” considering the general evaluation of the parameters characterising this phenomenon; in relation to Part 1, it is to underline the discrepancies in the HXP relative pressure and the injector differential pressure; in relation to Part 2, it is to underline the discrepancies in the OP level, in the HXP relative pressure and the injector differential pressure.

Finally, for phenomenon I, a “o” has been given to GRS and KAERI_b in Part 2 and to NRG in both parts due to the discrepancies mainly on the HX upper header wall temperatures, which experience the temperature drop and subsequent temperature increase. A “+” has been given to all the other participants.

Table 7.1. Qualitative code accuracy evaluation Test 7 Part 1

Phenomenon		GRS		IBRAE		KAERI _a		KAERI _b		NRG		POLITO		UJV		UNIPI		UNIROMA1		UofU		USNRC		VTT	
		U	I	U	I	U	I	U	I	U	I	U	I	U	I	U	I	U	I	U	I	U	I	U	I
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	+	+	+	o	+	+	-	N A	+	+	+	+	+	+	+	+	+	N A	+	+	+	+
B	Natural circulation in HXP and OP coupled circuit	+/o	+	+	+	+	+	+	+	o	+	+	+	+	+	+	+	+	+	+	+	o	+	+	+
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+/o	+	+	+	o	+	o	+	o	o	+	+	+	+	+	+	+	+	+	o	+	+	+	+
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	+	+	o	o	o	o	o	o	o	o	o	o	o	o	+	o	+	o	+	+	+	+
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+/o	+	+	+	o	o	o	o	o	o	o	o	o	o	o	o	+	o	+	o	+	+	+	o
F	Behaviour of large pool: Thermal stratification	o	o	+	+	o	o	o	+	N A	o	-	o	o	o	-	o	o	o	+	o	o	o	+	o
G	Behaviour of large pool: Natural convection (within a single pool)	+	+	+/o	+	o	+	o	+	o	+	+	+	+	+	+	+	+	+	+	+	o	+	+	+
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	o	+	+/o	+	o	+	o	+	o	+	+	+	+	+	+	+	+	+	+	o	+	+	o	+
I	Structural Heat	+	+	+	+	o	+	o	+	+	o	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Table 7.2. Qualitative code accuracy evaluation Test 7 Part 2

Phenomenon		GRS		IBRAE		KAERI _a		KAERI _b		NRG		POLITO		UJV		UNIPI		UNIROMA1		UofU		USNRC		VTT	
		U	I	U	I	U	I	U	I	U	I	U	I	U	I	U	I	U	I	U	I	U	I	U	I
A	Natural circulation in one-phase and two-phase flow in-tube side	+	+	+	+	+	o	+	+	-	NA	+	+	+	+	+	+	+	+	+	NA	+	+	+	+
B	Natural circulation in HXP and OP coupled circuit	+	+	+	+	o	+	o	+	o	o	+	+	+	+	+	+	+	+	+	o	o	+	+	+
C	Thermo-fluid dynamics and pressure drops in various geometrical configurations	+/o	+	+	+	o	o	o	+	o	o	+	+	+	+	+	+	+	o	+	o	+	+	+/o	o
D	Behaviour of emergency heat exchangers and isolation condensers: Tube side convection heat transfer	+	+	+	+	o	o	o	o	o	o	o	o	o	o	o	o	+	o	+	o	+	+	+/o	+
E	Behaviour of emergency heat exchangers and isolation condensers: Pool side convection heat transfer	+	+	+	+	o	o	o	o	o	o	o	o	o	o	o	o	o	o	+	o	+	+	+/o	+
F	Behaviour of large pool: Thermal stratification	+	+	+	+	o	o	o	+	NA	o	-	o	o	o	-	o	o	o	+	o	o	o	+/o	o
G	Behaviour of large pool: Natural convection (within a single pool)	+	+	+/o	+	o	+	o	+	o	+	+	+	+	+	+	+	+	+	+	o	o	+	+/o	+
H	Steam-liquid interaction: Direct contact condensation of steam in pool water	+/o	+	+/o	+	o	+	o	+	o	+	+	+	+	+	+	+	o	+	+	o	+	+	+/o	+
I	Structural heat	o	o	+	+	o	+	o	o	+	o	+	+	+	+	+	+	+	+	+	+	+	+	+	+

7.3. Analyses of the quantitative code accuracy

7.3.1. Test 7 Part 1

The results of the FFTBM application for the evaluation of the quantitative code accuracy related to PERSEO Test 7 Part 1 are presented in Table 7.3 regarding the total AA and WF (See Annex 1). It should be reminded that the AA is used as an indication of the code accuracy; the lower the AA is, the more accurate the result. The WF gives information about the frequencies that more significantly contribute to the discrepancies between the calculated and the experimental data. The accuracy evaluation is mainly based on the AA parameter, while the WF is an additional qualitative information that may be considered for the accuracy evaluation.

The AA and the WF of the single parameters adopted in the analysis are presented from Table 7.4 to Table 7.15. In the following sections, only the parameters with a high AA (>0.5) are described in detail to support the qualitative analysis discussion. This is a standard application of the FFTBM with the default value of 0.4 Hz for f_{cut} (See Annex 1).

PhW1

In PhW1, AA_{tot} (Table 7.3) is between 0.41 and 0.47 for almost all the participants, with the exception of IBRAE and POLITO, which show a lower value (0.25 and 0.34 respectively), and VTT, which shows a higher value (0.65).

The HX power shows high AA values for KAERI_a, KAERI_b, UNIROMA1 and USNRC (Table 7.5) due to the oscillations present in the calculated data. Also VTT shows a relatively high AA value due to the overestimation of the HX power.

Regarding the middle HXP temperature AA (T-Q034, Table 7.9) low values are shown by GRS, IBRAE, UNIROMA1 and VTT, which present the better agreement with the experimental data. The AA is high for KAERI_b, POLITO and USNRC and very high for all the other participants. As noticed in the qualitative analysis, at the beginning of the transient the temperature profile in the HXP is a critical point in several calculations.

The AA related to the HXP relative pressure (Table 7.10) is low for IBRAE and UNIROMA1; it is high for NRG and VTT and very high for all the other participants. In fact, as highlighted in the results comparison, relevant discrepancies are present in the initial conditions, in the pressure rise timing and in the missing prediction of the pressure oscillations due to the opening of the vacuum breaker valve.

The HX differential pressure AA (Table 7.13) is high for IBRAE, POLITO and UNIP. It is very high for all the other participants due to the missing prediction of the oscillations present in the experimental data and the qualitative and the quantitative discrepancies. The AA is particularly high for VTT due to the large oscillations present in the calculated data (due to chosen fluctuating boundary condition for the upstream pressure).

The injector differential pressure AA (Table 7.14) is high for IBRAE, KAERI_b and UNIP and very high for all the other participants due to discrepancies in the initial conditions and to the missing prediction of the experimental oscillations. UofU has an AA equal to 1.00 for this parameter since it predicts a null value.

The upper header wall temperature AA (Table 7.15) is high for UofU, due to the delay in the temperature reduction which occurs in PhW2.

PhW2

In PhW2, AA_{tot} (Table 7.3) is particularly low for IBRAE (0.27) and POLITO (0.29), while it is slightly higher for almost all the participants. NRG and VTT show a high AA_{tot} value (0.70 and 0.75 respectively).

The steam flow rate AA (Table 7.4) is high for UNIROMA1 due to the presence of oscillations not observed in the experimental results.

The HX power AA (Table 7.5) is high for KAERI_b, NRG, UJV, UofU and VTT and very high for UNIROMA1 and USNRC due to quantitative discrepancies in the prediction of the experimental results and the presence of oscillations in particular in the final part of the PhW.

The HXP relative pressure AA (Table 7.10) is high for NRG and UofU, for the discrepancies underlined in the qualitative analysis; it is very high for all the other participants, caused by the overprediction of the pressure in the central part of the PhW and the predicted oscillations, as underlined in the qualitative evaluation.

The bottom OP temperature AA (Table 7.11) is very high for GRS and NRG which do not predict the temperature increase in the lower part of the pool.

The HX differential pressure AA (Table 7.13) is very high values for GRS and UNIROMA1, for the quantitative discrepancies, KAERI_a and NRG, for the qualitative and quantitative discrepancies, and VTT for the large predicted oscillations. The AA is high for all the other participants.

The injector differential pressure AA (Table 7.14) is high for GRS and IBRAE while it is very high for all the other participants due to the prediction of oscillations not observed in the experimental data and quantitative discrepancies. UofU shows an AA of 0.99 since the calculation is very close to zero.

The upper header wall temperature AA (Table 7.15) is high for GRS, due to the slight anticipation of the temperature increase at the end of the PhW, and very high for KAERI_b, NRG and UNIROMA1, which significantly anticipates the temperature rise, and UofU, which slightly delays the temperature reduction occurring in PhW1 in the experimental data.

PhW3

In PhW3, AA_{tot} (Table 7.3) is particularly low for IBRAE (0.23), low for GRS (0.37), while it is slightly higher for almost all the participants. USNRC shows a very high AA_{tot} value (0.94).

The HX power AA (Table 7.5) is very high for USNRC due to the power oscillations present in the PhW. The AA is high for KAERI_a, KAERI_b and UofU.

The middle HXP temperature AA (Table 7.9) is low for GRS (0.15), IBRAE (0.22) and KAERI_b (0.46) since they are able to qualitatively predict the temperature behaviour and the quantitative discrepancies are limited. The AA is very high for all the other participants due to the discrepancies observed in the qualitative analysis: anticipation of the temperature increase, prediction of oscillations not observed in the experimental data, missing prediction of the thermal stratification in the HXP and presence of large quantitative discrepancies.

The HXP relative pressure AA (Table 7.10) is low for GRS, IBRAE, NRG and POLITO. It is high for UJV and very high for all the other participants due to qualitative and quantitative discrepancies.

The bottom OP temperature AA (Table 7.11) is low for IBRAE, which is able to predict the qualitative behaviour, UNIROMA1 and VTT. The AA is high for KAERI_a, KAERI_b, UJV and USNRC and very high for all the other participants due to the significative quantitative discrepancy.

The HX differential pressure AA (Table 7.13) is high for IBRAE, KAERI_b, POLITO, UNIPI and UNIROMA1, while it is very high for all the other participants, due to discrepancies in the results.

The injector differential pressure AA (Table 7.14) is high for GRS, IBRAE and VTT; it is very high for all the other participants due to the prediction of oscillations not observed in the experimental data and quantitative discrepancies. UofU shows an AA of 0.99 since the calculation is very close to zero.

The upper header wall temperature AA (Table 7.15) is low for almost all the participants, while it is high for NRG, which anticipates the temperature rise in PhW2 instead of PhW3 as observed in the experimental data, and USNRC, for the stepwise temperature increase.

Table 7.3. Test 7 Part 1, FFTBM result for the total AA and WF

	PhW1		PhW2		PhW3	
Participant	AA _{tot}	WF _{tot}	AA _{tot}	WF _{tot}	AA _{tot}	WF _{tot}
GRS	0.43	0.06	0.54	0.06	0.37	0.05
IBRAE	0.25	0.06	0.27	0.06	0.23	0.06
KAERI_a	0.44	0.05	0.44	0.05	0.66	0.07
KAERI_b	0.36	0.06	0.56	0.06	0.42	0.06
NRG	0.47	0.05	0.70	0.07	0.51	0.06
POLITO	0.34	0.06	0.29	0.07	0.50	0.06
UJV	0.41	0.06	0.44	0.06	0.43	0.06
UNIPI	0.41	0.06	0.38	0.07	0.49	0.07
UNIROMA1	0.32	0.06	0.64	0.07	0.49	0.06
UofU	0.46	0.06	0.47	0.07	0.52	0.07
USNRC	0.42	0.07	0.38	0.07	0.94	0.09
VTT	0.65	0.06	0.75	0.05	0.44	0.06

**Table 7.4. Test 7 Part 1, FFTBM result for the steam flow rate
F_A001**

F_A001	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.32	0.06	0.30	0.07	0.13	0.07
IBRAE	0.25	0.06	0.24	0.07	0.13	0.07
KAERI_a	0.30	0.05	0.31	0.06	0.28	0.08
KAERI_b	0.35	0.06	0.44	0.08	0.29	0.07
NRG	0.05	0.13	0.06	0.09	0.01	0.21
POLITO	0.25	0.08	0.20	0.10	0.26	0.05
UJV	0.24	0.07	0.45	0.08	0.28	0.06
F_A001	PhW1		PhW2		PhW3	
UNIROMA1	0.44	0.07	1.08	0.08	0.36	0.06
UofU	0.23	0.08	0.29	0.08	0.28	0.09
USNRC	0.34	0.10	0.43	0.17	0.50	0.10
VTT	0.43	0.06	0.42	0.06	0.20	0.05

Table 7.5. Test 7 Part 1, FFTBM result for the HX power W_IC

W_IC	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.50	0.08	0.40	0.08	0.34	0.10
IBRAE	0.49	0.11	0.48	0.09	0.33	0.10
KAERI_a	0.55	0.08	0.42	0.08	0.55	0.10
KAERI_b	0.52	0.09	0.62	0.09	0.52	0.11
NRG	0.46	0.09	0.68	0.06	0.46	0.08
POLITO	0.44	0.09	0.37	0.09	0.45	0.08
UJV	0.44	0.09	0.54	0.08	0.44	0.09
UNIP1	0.41	0.10	0.40	0.08	0.39	0.09
UNIROMA1	0.57	0.08	0.98	0.08	0.48	0.08
UofU	0.42	0.10	0.57	0.09	0.57	0.11
USNRC	0.75	0.10	0.90	0.17	0.98	0.11
VTT	0.59	0.08	0.56	0.07	0.40	0.09

Table 7.6. Test 7 Part 1, FFTBM result for the primary pressure P-I001

P-I001	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.28	0.06	0.35	0.05	0.03	0.03
IBRAE	0.08	0.06	0.09	0.04	0.03	0.05
KAERI_a	0.14	0.03	0.23	0.05	0.28	0.03
KAERI_b	0.05	0.06	0.06	0.04	0.03	0.03
NRG	0.01	0.04	0.00	0.11	0.00	0.09
POLITO	0.06	0.06	0.05	0.06	0.03	0.03
UJV	0.05	0.06	0.04	0.06	0.03	0.03
UNIPi	0.05	0.06	0.06	0.04	0.03	0.03
UNIROMA1	0.07	0.07	0.07	0.07	0.03	0.03
UofU	0.04	0.06	0.03	0.06	0.01	0.07
USNRC	0.04	0.06	0.03	0.07	0.03	0.04
VTT	0.04	0.07	0.04	0.05	0.01	0.07

Table 7.7. Test 7 Part 1, FFTBM result for the HXP level L_VQ

L_VQ	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.06	0.03	0.13	0.07	0.06	0.10
IBRAE	0.06	0.06	0.13	0.08	0.11	0.06
L_VQ	PhW1	PhW2	PhW3	L_VQ	PhW1	PhW2
KAERI_a	0.15	0.04	0.32	0.05	0.14	0.08
KAERI_b	0.06	0.05	0.18	0.06	0.19	0.06
NRG	0.14	0.04	0.27	0.06	0.18	0.06
POLITO	0.05	0.05	0.16	0.07	0.20	0.06
UJV	0.04	0.05	0.21	0.06	0.18	0.06
UNIPi	0.06	0.06	0.14	0.06	0.09	0.08
UNIROMA1	0.07	0.07	0.24	0.14	0.17	0.08
UofU	0.02	0.06	0.12	0.08	0.11	0.08
USNRC	0.07	0.14	0.20	0.15	0.47	0.21
VTT	0.09	0.05	0.13	0.08	0.24	0.05

Table 7.8. Test 7 Part 1, FFTBM result for the OP level L_VP

L_VP	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.05	0.12	0.14	0.16	0.33	0.17
IBRAE	0.05	0.11	0.15	0.15	0.33	0.17
KAERI_a	0.06	0.12	0.16	0.14	0.35	0.16
KAERI_b	0.05	0.12	0.16	0.14	0.34	0.16
NRG	0.07	0.09	0.16	0.14	0.33	0.16
POLITO	0.05	0.12	0.14	0.16	0.33	0.17
UJV	0.05	0.11	0.16	0.14	0.34	0.16
UNIPi	0.06	0.15	0.14	0.16	0.33	0.17
UNIROMA1	0.07	0.13	0.17	0.14	0.34	0.16
UofU	0.05	0.12	0.14	0.16	0.33	0.16
USNRC	0.05	0.12	0.15	0.16	0.33	0.17
VTT	0.06	0.10	0.16	0.14	0.34	0.16

Table 7.9. Test 7 Part 1, FFTBM result for the HXP temperature (middle) T-Q034

T-Q034	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.50	0.05	0.09	0.05	0.15	0.05
IBRAE	0.33	0.05	0.15	0.07	0.22	0.03
KAERI_a	0.84	0.05	0.14	0.06	1.42	0.06
KAERI_b	0.70	0.04	0.16	0.06	0.46	0.04
NRG	1.30	0.04	0.16	0.07	0.78	0.04
POLITO	0.67	0.04	0.09	0.07	0.94	0.04
UJV	0.82	0.04	0.10	0.03	0.72	0.04
UNIPi	0.92	0.05	0.12	0.06	0.97	0.07
UNIROMA1	0.44	0.06	0.23	0.06	0.72	0.04
UofU	0.82	0.05	0.12	0.07	1.00	0.07
USNRC	0.60	0.07	0.10	0.04	1.85	0.12
VTT	0.43	0.04	0.10	0.02	0.67	0.02

Table 7.10. Test 7 Part 1, FFTBM result for the HXP relative pressure P-Q001

P-Q001	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	1.16	0.05	1.65	0.05	0.49	0.05
IBRAE	0.43	0.09	1.06	0.08	0.35	0.05
KAERI_a	1.09	0.06	2.72	0.05	1.50	0.10
KAERI_b	0.58	0.07	2.10	0.07	0.97	0.13
NRG	0.56	0.04	0.69	0.14	0.48	0.08
POLITO	0.73	0.06	1.14	0.09	0.48	0.08
UJV	0.96	0.07	2.48	0.07	0.57	0.09
UNIPi	0.90	0.07	2.28	0.07	0.83	0.13
UNIROMA1	0.41	0.09	2.73	0.16	1.41	0.13
UofU	1.04	0.04	0.53	0.05	0.76	0.05
USNRC	1.65	0.10	1.68	0.10	3.64	0.17
VTT	0.61	0.08	2.75	0.05	0.80	0.06

Table 7.11. Test 7 Part 1, FFTBM result for the OP temperature (bottom) T-P008

T-P008	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.38	0.05	0.80	0.05	0.72	0.02
IBRAE	0.34	0.05	0.26	0.03	0.29	0.05
KAERI_a	0.36	0.04	0.30	0.04	0.64	0.05
KAERI_b	0.36	0.04	0.27	0.03	0.53	0.05
NRG	0.38	0.05	0.82	0.05	0.75	0.02
POLITO	0.38	0.04	0.34	0.03	0.97	0.04
UJV	0.37	0.04	0.40	0.04	0.55	0.05
UNIPi	0.36	0.04	0.36	0.03	0.73	0.05
UNIROMA1	0.38	0.04	0.34	0.03	0.47	0.05
UofU	0.37	0.05	0.31	0.03	0.83	0.04
USNRC	0.35	0.04	0.37	0.03	0.65	0.04
VTT	0.37	0.04	0.31	0.03	0.41	0.05

**Table 7.12. Test 7 Part 1, FFTBM result for the OP temperature
(top) T-P021**

T-P021	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.13	0.06	0.48	0.06	0.45	0.03
IBRAE	0.07	0.03	0.21	0.05	0.19	0.03
KAERI_a	0.12	0.05	0.17	0.03	0.31	0.04
KAERI_b	0.18	0.06	0.20	0.03	0.35	0.05
NRG	0.20	0.05	0.51	0.04	0.42	0.05
POLITO	0.11	0.05	0.10	0.04	0.16	0.04
T-P021	PhW1		PhW2		PhW3	
UJV	0.10	0.05	0.10	0.05	0.39	0.04
UNIP	0.07	0.04	0.09	0.05	0.26	0.04
UNIROMA1	0.12	0.05	0.13	0.03	0.32	0.04
UofU	0.13	0.06	0.14	0.03	0.21	0.04
USNRC	0.07	0.03	0.33	0.05	0.24	0.05
VTT	0.11	0.05	0.47	0.05	0.37	0.05

**Table 7.13. Test 7 Part 1, FFTBM result for the HX differential
pressure DP-003**

DP-003	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	1.48	0.07	0.95	0.09	1.11	0.10
IBRAE	0.67	0.12	0.53	0.16	0.67	0.16
KAERI_a	0.99	0.14	1.01	0.15	1.27	0.16
KAERI_b	0.62	0.14	0.55	0.15	0.70	0.16
NRG	0.87	0.11	0.76	0.11	0.91	0.13
POLITO	0.60	0.14	0.52	0.16	0.69	0.16
UJV	0.74	0.12	0.59	0.14	0.71	0.15
UNIP	0.61	0.14	0.51	0.16	0.68	0.16
UNIROMA1	0.79	0.11	0.75	0.12	0.63	0.17
UofU	1.43	0.10	0.67	0.14	1.11	0.15
USNRC	0.85	0.12	0.65	0.15	0.81	0.14
VTT	13.13	0.06	11.63	0.05	2.12	0.07

Table 7.14. Test 7 Part 1, FFTBM result for the injector differential pressure DP-J001

DP-J001	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.98	0.06	0.55	0.07	0.66	0.14
IBRAE	0.66	0.10	0.52	0.11	0.58	0.16
KAERI_a	0.83	0.07	0.75	0.06	0.85	0.13
KAERI_b	0.70	0.09	2.04	0.16	0.73	0.14
NRG	0.93	0.08	1.08	0.09	0.72	0.13
POLITO	0.71	0.08	1.25	0.16	1.33	0.17
UJV	0.79	0.09	1.90	0.17	0.97	0.15
UNIPI	0.69	0.09	1.33	0.15	1.07	0.16
UNIROMA1	0.71	0.10	2.84	0.15	1.47	0.15
UofU	1.00	0.06	0.99	0.05	0.99	0.10
USNRC	1.07	0.10	0.81	0.07	1.36	0.12
VTT	0.75	0.09	0.84	0.12	0.66	0.16

Table 7.15. Test 7 Part 1, FFTBM result for the HX upper header wall temperature TW-B005

TW-B005	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.40	0.05	0.68	0.07	0.29	0.04
IBRAE	0.18	0.09	0.18	0.04	0.18	0.03
KAERI_a	0.35	0.05	0.27	0.04	0.17	0.05
KAERI_b	0.35	0.06	1.51	0.05	0.36	0.05
NRG	0.38	0.06	2.66	0.04	0.59	0.05
POLITO	0.21	0.09	0.28	0.06	0.16	0.03
UJV	0.44	0.04	0.40	0.07	0.19	0.03
UNIPI	0.46	0.04	0.29	0.07	0.19	0.07
UNIROMA1	0.43	0.04	1.26	0.05	0.31	0.05
UofU	0.63	0.06	2.13	0.09	0.15	0.03
USNRC	0.35	0.05	0.26	0.08	0.68	0.07
VTT	0.37	0.05	0.24	0.05	0.21	0.03

7.3.2. Test 7 Part 2

The results of the FFTBM application for the evaluation of the quantitative code accuracy related to PERSEO Test 7 Part 2 are presented in Table 7.16 regarding the total AA and WF. The AA and the WF of the single parameters adopted in the analysis are presented from Table 7.17 to Table 7.28. In the following sections, only the parameters with a high AA (>0.5) are described in detail for supporting the qualitative analysis discussion. This is a standard application of the FFTBM with the default value of 0.4 Hz for f_{cut} (See Annex 1).

PhW1

In PhW1, AA_{tot} (Table 7.16) is below 0.5 for almost all the participants, with the exception of VTT, for which is slightly higher (0.52).

The HX power AA (Table 7.18) is slightly high for USNRC due to the presence of oscillations at the end of the PhW, after the power increase.

The middle HXP temperature AA (Table 7.22) shows high or very high values for almost all the participants, with the exception of GRS, IBRAE, KAERI_b and VTT, which have a low AA for this parameter, since they show the better agreement with the experimental data. In fact, as noticed in the qualitative analysis, at the beginning of the transient the temperature profile in the HXP is a critical point in several calculations.

The HXP relative pressure AA (Table 7.23) is high for GRS, KAERI_b, POLITO, UNIPI and UofU. It is very high for KAERI_a, due to the relevant predicted oscillations, and NRG, UJV, UNIROMA1, USNRC and VTT which predict the pressure rising in PhW1 instead of PhW2 as in the experimental data. IBRAE shows a low AA for this parameter in PhW1.

The bottom OP temperature AA (Table 7.24) is relatively low for almost all the participants with the exception of IBRAE, which shows a high value.

The HX differential pressure AA (Table 7.26) is very high for GRS, due to the large quantitative discrepancy at the end of the PhW, and NRG, UofU and VTT, for the qualitative discrepancies in the results behaviour. In addition, VTT shows also large oscillations, which can explain the very high AA value (7.69). The AA is high also for USNRC due to the quantitative discrepancy with respect to the experimental results.

The injector differential pressure AA (Table 7.27) is very high for all the participants, due to discrepancies in the initial conditions, anticipation of the differential pressure rise and prediction of oscillations not observed in the experimental data. UofU shows an AA of 1.00 for this parameter since the calculation result is zero.

The upper header wall temperature AA (Table 7.28) is high for NRG, which do not predict the temperature reduction, and UNIROMA1, which delays the reduction in PhW2.

PhW2

In PhW2, AA_{tot} (Table 7.16) is between 0.25 and 0.46 for almost all the participants. The AA_{tot} is slightly higher UNIROMA1 (0.55) and very high for GRS (0.77) and KAERI_b (0.70).

The steam flow rate AA (Table 7.17) is high for UJV and USNRC, in agreement with the qualitative analysis, very high for UNIROMA1, for the presence of oscillations, and low for the other participants.

The HX power (Table 7.18) shows high AA values for NRG, UJV and VTT, due to the underestimation of the power and very high values for UNIROMA1, UofU and USNRC, due also to the oscillations present in the calculated results, not observed in the experimental ones.

The HXP level AA (Table 7.20) is high for UofU, due to the missing qualitative prediction of the level, and UNIROMA1, for the presence of oscillations in the calculated results.

The OP level AA (Table 7.21) is high for all the participants due to the missing prediction of the oscillations present in the experimental data at the beginning of the PhW. The AA is very high for UofU due to the sharp OP level reduction occurring in the window, as highlighted in the qualitative analysis.

The HXP relative pressure AA (Table 7.23) is very high for UJV, UNIROMA1 and UofU. It is high for all the participants due to the quantitative discrepancies of the calculated results with the exception of IBRAE, which has a slightly lower AA.

The HX differential pressure AA (Table 7.26) is high for IBRAE, KAERI_b, POLITO, UJV, UNIPi and UNIROMA1 and it is very high for GRS, KAERI_a, NRG and UofU due to quantitative discrepancy with respect to the experimental data. The AA is very high for VTT due to the large oscillations in the calculated results.

The injector differential pressure AA (Table 7.27) is very high for all the participants, due to quantitative discrepancies and the missing prediction of the oscillations observed in the experimental results. UofU shows an AA of 1.00 for this parameter since the calculation result is zero.

The upper header wall temperature AA (Table 7.28) is high for UJV, UNIPi and UofU due to the prediction of some oscillations not present in the experimental data. The AA is very high for GRS and KAERI_b, which predict the temperature rise in this PhW instead of PhW3, and for NRG, which do not predict the temperature reduction in the transient. The AA is very high also for UNIROMA1 due to the prediction of the temperature reduction in the present PhW instead of PhW1.

PhW3

In PhW3, AA_{tot} (Table 7.16) is low for IBRAE (0.14) while it is slightly higher for the other participants between 0.30 and 0.50. VTT shows a higher AA around 0.76.

The HX power shows relatively high AA values for UofU and USNRC (Table 7.18) due to the oscillation observed in the calculated data. The AA is low for the other participants.

The middle HXP temperature AA (Table 7.22) is low for GRS, IBRAE and KAERI_b, which show the better qualitative and quantitative agreement with the experimental data. The AA is high for NRG, USNRC and VTT and very high for all the other participants due to the large qualitative and quantitative discrepancies: anticipation of the temperature increase, prediction of oscillations not observed in the experimental data, missing prediction of the thermal stratification in the HXP and presence of very large quantitative discrepancies.

The HXP relative pressure AA (Table 7.23) is high for KAERI_a, UJV and UNIROMA1. UofU shows a very high AA due to the missing qualitative prediction of the pressure behaviour, as highlighted in the qualitative analysis.

The top OP temperature AA (Table 7.25) is low for almost all the participants, while it is very high for NRG, UJV and VTT, which shows the largest quantitative discrepancies at the end of the transient.

The HX differential pressure AA (Table 7.26) is high for almost all the participants. It is very high for GRS, due to significant quantitative discrepancy with respect to the experimental data, and KAERI_a, NRG and UofU, due to the missing prediction of the qualitative behaviour at the beginning of the PhW and to the prediction of strong oscillations not observed in the experimental results. VTT has a very high AA due to the presence of very large oscillations in the calculated results.

The injector differential pressure AA (Table 7.27) is high almost all the participants with the exception of IBRAE, KAERI_b and POLITO. UofU shows an AA of 1.00 for this parameter since the calculation result is zero.

The upper header wall temperature AA (Table 7.28) is low for almost all the participants. The AA is very high for GRS and KAERI_b, which predict the temperature rise in PhW2

instead of PhW3, and for NRG, which do not predict the temperature reduction and the subsequent increase in the transient. The AA is high for USNRC due to the stepwise increase of the temperature.

Table 7.16. Test 7 Part 2, FFTBM result for the total AA and WF

Participant	PhW1		PhW2		PhW3	
	AA _{tot}	WF _{tot}	AA _{tot}	WF _{tot}	AA _{tot}	WF _{tot}
GRS	0.33	0.07	0.77	0.06	0.30	0.05
IBRAE	0.33	0.07	0.26	0.07	0.14	0.06
KAERI_a	0.49	0.06	0.30	0.07	0.34	0.07
KAERI_b	0.36	0.06	0.70	0.07	0.24	0.08
NRG	0.40	0.07	0.46	0.08	0.50	0.07
POLITO	0.39	0.05	0.25	0.08	0.33	0.07
UJV	0.42	0.06	0.35	0.07	0.44	0.06
UNIFI	0.41	0.06	0.34	0.07	0.35	0.06
UNIROMA1	0.43	0.06	0.55	0.08	0.31	0.08
UofU	0.43	0.06	0.40	0.07	0.43	0.06
USNRC	0.47	0.05	0.31	0.07	0.34	0.05
VTT	0.52	0.05	0.32	0.07	0.76	0.05

**Table 7.17. Test 7 Part 2, FFTBM result for the steam flow rate
F_A001**

F_A001 Participant	PhW1		PhW2		PhW3	
	AA	WF	AA	WF	AA	WF
GRS	0.14	0.05	0.29	0.05	0.14	0.06
IBRAE	0.12	0.05	0.25	0.05	0.14	0.06
KAERI_a	0.18	0.04	0.23	0.06	0.21	0.09
KAERI_b	0.25	0.04	0.29	0.06	0.13	0.07
NRG	0.02	0.15	0.04	0.18	0.02	0.16
POLITO	0.17	0.06	0.19	0.06	0.20	0.07
UJV	0.16	0.05	0.54	0.07	0.26	0.07
UNIFI	0.18	0.04	0.34	0.05	0.25	0.08
UNIROMA1	0.26	0.05	0.77	0.10	0.33	0.10
UofU	0.22	0.06	0.52	0.09	0.35	0.10
USNRC	0.25	0.07	0.66	0.08	0.30	0.07
VTT	0.26	0.04	0.47	0.05	0.28	0.05

Table 7.18. Test 7 Part 2, FFTBM result for the HX power W_IC

W_IC	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.25	0.10	0.48	0.08	0.34	0.09
IBRAE	0.24	0.10	0.46	0.08	0.32	0.10
KAERI_a	0.39	0.07	0.43	0.09	0.47	0.10
KAERI_b	0.33	0.08	0.48	0.08	0.33	0.10
NRG	0.24	0.09	0.54	0.09	0.36	0.10
POLITO	0.26	0.08	0.39	0.09	0.36	0.09
UJV	0.26	0.08	0.61	0.08	0.41	0.09
UNIPI	0.27	0.08	0.48	0.08	0.41	0.09
UNIROMA1	0.28	0.08	0.72	0.11	0.43	0.10
UofU	0.35	0.09	0.86	0.10	0.64	0.11
USNRC	0.52	0.09	1.15	0.09	0.61	0.09
VTT	0.37	0.06	0.58	0.07	0.45	0.08

Table 7.19. Test 7 Part 2, FFTBM result for the primary pressure P-I001

P-I001	PhW1		PhW2		PhW3	
GRS	0.05	0.02	0.03	0.04	0.21	0.04
IBRAE	0.05	0.02	0.03	0.04	0.07	0.04
KAERI_a	0.08	0.02	0.12	0.04	0.32	0.04
KAERI_b	0.05	0.02	0.03	0.04	0.05	0.06
NRG	0.01	0.03	0.00	0.09	0.00	0.11
POLITO	0.03	0.03	0.03	0.04	0.05	0.06
UJV	0.05	0.02	0.03	0.04	0.09	0.05
UNIPI	0.05	0.02	0.03	0.04	0.05	0.06
UNIROMA1	0.05	0.02	0.03	0.04	0.05	0.05
UofU	0.05	0.02	0.03	0.04	0.06	0.05
USNRC	0.05	0.02	0.03	0.04	0.07	0.04
VTT	0.03	0.03	0.02	0.06	0.42	0.05

Table 7.20. Test 7 Part 2, FFTBM result for the HXP level L_VQ

L_VQ	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.14	0.06	0.29	0.06	0.07	0.09
IBRAE	0.14	0.06	0.29	0.06	0.12	0.06
KAERI_a	0.25	0.06	0.42	0.07	0.12	0.10
KAERI_b	0.22	0.06	0.35	0.07	0.08	0.10
NRG	0.23	0.06	0.48	0.07	0.18	0.08
POLITO	0.24	0.06	0.40	0.07	0.12	0.07
UJV	0.29	0.07	0.48	0.07	0.13	0.07
UNIP	0.22	0.05	0.44	0.05	0.14	0.07
L_VQ	PhW1		PhW2		PhW3	
UNIROMA1	0.31	0.07	0.52	0.08	0.18	0.13
UofU	0.17	0.02	0.52	0.03	0.15	0.07
USNRC	0.19	0.08	0.32	0.07	0.14	0.11
VTT	0.10	0.07	0.50	0.06	0.26	0.03

Table 7.21. Test 7 Part 2, FFTBM result for the OP level L_VP

L_VP	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.18	0.16	0.51	0.16	0.07	0.08
IBRAE	0.18	0.16	0.51	0.16	0.05	0.09
KAERI_a	0.18	0.16	0.55	0.16	0.11	0.16
KAERI_b	0.19	0.15	0.54	0.16	0.08	0.17
NRG	0.23	0.13	0.53	0.16	0.06	0.09
POLITO	0.19	0.16	0.51	0.16	0.07	0.12
UJV	0.19	0.16	0.52	0.16	0.06	0.08
UNIP	0.18	0.17	0.52	0.16	0.05	0.10
UNIROMA1	0.22	0.16	0.53	0.16	0.15	0.12
UofU	0.18	0.16	0.72	0.12	0.41	0.05
USNRC	0.20	0.15	0.53	0.16	0.10	0.06
VTT	0.19	0.16	0.52	0.16	0.21	0.05

Table 7.22. Test 7 Part 2, FFTBM result for the HXP temperature (middle) T-Q034

T-Q034	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.40	0.08	0.06	0.06	0.25	0.03
IBRAE	0.30	0.05	0.06	0.07	0.24	0.02
KAERI_a	0.92	0.05	0.06	0.07	0.89	0.07
KAERI_b	0.38	0.03	0.07	0.07	0.39	0.03
NRG	0.57	0.03	0.09	0.13	0.64	0.05
POLITO	0.75	0.05	0.05	0.07	1.25	0.05
UJV	0.79	0.04	0.06	0.07	0.96	0.04
UNIPi	0.81	0.05	0.08	0.09	1.24	0.04
UNIROMA1	0.55	0.04	0.08	0.13	0.80	0.02
UofU	0.96	0.07	0.14	0.08	1.09	0.04
USNRC	0.64	0.04	0.05	0.06	0.54	0.04
VTT	0.36	0.03	0.03	0.05	0.64	0.05

Table 7.23. Test 7 Part 2, FFTBM result for the HXP relative pressure P-Q001

P-Q001	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.61	0.09	0.51	0.09	0.09	0.05
IBRAE	0.46	0.10	0.49	0.09	0.24	0.04
KAERI_a	1.34	0.10	0.66	0.09	0.55	0.06
KAERI_b	0.62	0.11	0.62	0.08	0.39	0.05
NRG	1.02	0.07	0.70	0.12	0.43	0.13
POLITO	0.57	0.08	0.61	0.10	0.31	0.05
UJV	1.35	0.07	0.79	0.11	0.61	0.12
UNIPi	0.69	0.10	0.68	0.09	0.41	0.10
UNIROMA1	1.15	0.09	1.16	0.15	0.69	0.14
UofU	0.55	0.09	1.12	0.06	0.96	0.05
USNRC	1.66	0.09	0.54	0.09	0.39	0.08
VTT	0.85	0.08	0.55	0.10	0.33	0.06

**Table 7.24. Test 7 Part 2, FFTBM result for the OP temperature
(bottom) T-P008**

T-P008	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.15	0.06	0.27	0.02	0.01	0.08
IBRAE	0.66	0.05	0.21	0.05	0.01	0.07
KAERI_a	0.20	0.06	0.14	0.03	0.02	0.06
KAERI_b	0.44	0.07	0.19	0.05	0.01	0.09
NRG	0.11	0.11	0.26	0.02	0.26	0.05
POLITO	0.43	0.03	0.19	0.05	0.01	0.08
UJV	0.14	0.06	0.15	0.03	0.03	0.06
UNIPi	0.17	0.06	0.15	0.03	0.02	0.06
UNIROMA1	0.15	0.06	0.17	0.03	0.01	0.10
UofU	0.35	0.02	0.18	0.05	0.01	0.08
USNRC	0.19	0.06	0.20	0.02	0.05	0.04
VTT	0.25	0.04	0.17	0.04	0.07	0.05

**Table 7.25. Test 7 Part 2, FFTBM result for the OP temperature
(top) T-P021**

T-P021	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.26	0.04	0.28	0.05	0.43	0.04
IBRAE	0.16	0.06	0.25	0.04	0.04	0.09
KAERI_a	0.37	0.03	0.36	0.06	0.05	0.09
KAERI_b	0.31	0.06	0.25	0.06	0.05	0.09
NRG	0.16	0.06	0.37	0.03	0.93	0.04
POLITO	0.19	0.01	0.24	0.06	0.05	0.08
T-P021	PhW1	PhW2	PhW3	T-P021	PhW1	PhW2
UJV	0.37	0.02	0.39	0.06	0.78	0.05
UNIPi	0.39	0.03	0.38	0.06	0.05	0.08
UNIROMA1	0.41	0.01	0.45	0.06	0.05	0.08
UofU	0.24	0.03	0.25	0.06	0.05	0.08
USNRC	0.29	0.01	0.29	0.06	0.35	0.04
VTT	0.31	0.05	0.26	0.05	1.32	0.05

Table 7.26. Test 7 Part 2, FFTBM result for the HX differential pressure DP-003

DP-003	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.96	0.07	0.91	0.11	1.05	0.08
IBRAE	0.37	0.12	0.62	0.16	0.52	0.15
KAERI_a	0.80	0.12	1.23	0.16	1.39	0.15
KAERI_b	0.45	0.10	0.66	0.15	0.57	0.14
NRG	0.91	0.07	0.87	0.12	0.98	0.11
POLITO	0.29	0.15	0.61	0.16	0.50	0.16
UJV	0.50	0.09	0.66	0.15	0.59	0.13
UNIP	0.47	0.10	0.64	0.15	0.54	0.14
UNIROMA1	0.38	0.12	0.59	0.17	0.63	0.12
UofU	0.92	0.12	0.94	0.15	1.37	0.14
USNRC	0.63	0.09	0.84	0.13	0.80	0.11
VTT	7.69	0.04	3.18	0.06	9.78	0.05

Table 7.27. Test 7 Part 2, FFTBM result for the injector differential pressure DP-J001

DP-J001	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	1.30	0.16	0.94	0.16	0.56	0.09
IBRAE	0.86	0.13	0.91	0.17	0.38	0.14
KAERI_a	1.07	0.14	0.95	0.16	0.69	0.11
KAERI_b	1.13	0.11	0.90	0.17	0.33	0.15
NRG	1.85	0.07	0.94	0.17	0.60	0.16
POLITO	1.06	0.09	1.07	0.17	0.41	0.13
UJV	1.09	0.10	0.91	0.17	0.62	0.13
UNIP	1.23	0.14	1.03	0.16	0.58	0.12
UNIROMA1	1.81	0.15	1.17	0.16	0.84	0.10
UofU	1.00	0.13	1.00	0.15	1.00	0.06
USNRC	1.90	0.11	0.95	0.16	0.63	0.09
VTT	0.93	0.12	0.94	0.16	0.59	0.09

Table 7.28. Test 7 Part 2, FFTBM result for the HX upper header wall temperature TW-B005

TW-B005	PhW1		PhW2		PhW3	
Participant	AA	WF	AA	WF	AA	WF
GRS	0.50	0.05	4.44	0.04	0.78	0.04
IBRAE	0.43	0.06	0.31	0.05	0.16	0.04
KAERI_a	0.44	0.05	0.17	0.10	0.17	0.04
KAERI_b	0.38	0.06	3.93	0.05	0.77	0.04
NRG	0.67	0.06	1.54	0.01	0.80	0.04
POLITO	0.40	0.06	0.14	0.10	0.32	0.02
UJV	0.24	0.10	0.57	0.07	0.24	0.05
UNIP	0.38	0.06	0.65	0.08	0.37	0.02
UNIROMA1	0.51	0.05	1.81	0.06	0.31	0.02
UofU	0.33	0.07	0.60	0.06	0.37	0.02
USNRC	0.46	0.06	0.27	0.08	0.63	0.03
VTT	0.37	0.06	0.13	0.10	0.29	0.02

8. Conclusions

8.1. Framework

In the framework of the Working Group on Analysis and Management of Accidents (WGAMA) of the Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI), an activity on the design and safety assessment of thermal-hydraulic passive systems was conducted and a status report was drafted. Within this activity, a benchmark exercise was carried out on the experimental data developed in the full-scale component separate effect test facility PERSEO (which stands for in-pool energy removal system for emergency operation). An “open” benchmark exercise, hosted by ENEA, was conducted.

PERSEO is a full-scale facility aimed at studying a new passive decay heat removal system operating in natural circulation. It was built at the SIET laboratory in Piacenza (Italy), modifying the existing PANTHERS IC-PCC facility. It should be underlined that there is not a direct scaling relation between PERSEO and the PRHR of the AP-600, the IC of the SBWR or other designs. However, the heat transfer data developed in the PERSEO facility could be useful for the generic assessment of system codes for the full-scale heat transfer phenomena in HX in the pool (in-tube side and pool side) of passive systems. Among the four actual tests performed in the PERSEO experimental campaign, Test 7, which is divided into two parts, was chosen for its completeness: the system stability and the long-term cooling capability.

The main targets for the benchmark proposed by ENEA and agreed by the partners were:

- investigation of the exchanged power from the HX to the HXP versus the HXP level;
- prediction of the mass transfer between the two pools when the triggering valve is open and of the steam flow accelerated into the OP through the injector, as well as characterisation of possible instabilities due to the steam/cold water interface in the injector;
- test of the 1D nodalisation, fictitious 2D nodalisation and 3D component, which is available in some codes, against natural circulation and thermal mixing in large pools;
- characterisation of the “user effect” for the simulation of heat transfer in HX submerged in large pools and the thermal-hydraulic behaviour of large pools.

Nineteen organisations worldwide expressed an interest to participate in the PERSEO Test 7 benchmark. In this report, 12 results from 11 organisations are presented.

8.2. Main general conclusions

The benchmark of the PERSEO Test 7 Parts 1 and 2 was successful and valuable to highlight some of the main capabilities and limitations of the codes used by the benchmark participants in the simulation of a passive system operating in natural circulation.

In general, it was found that almost all codes are qualitatively able to predict the phenomena that occurred in PERSEO Test 7. However, some qualitative and quantitative discrepancies with respect to the experimental data have been found.

The main limitation, observed in almost all the adopted codes, is the significant underestimation of the heat transfer between the HX and the HXP. Most participants attributed this to the underestimation of the condensation heat transfer coefficient on the tube side, and in some cases, also to the underestimation of the nucleate boiling heat transfer coefficient on the pool side.

With the exception of IBRAE, which adopted the SOCRAT code, USNRC, which adopted the TRACE code, and VTT, which adopted the Apros code, all the other participants decided to modify the code or the nodalisation to correctly predict the heat transfer:

- GRS (ATHLET) used a developer version of ATHLET introducing a Nusselt correlation (for laminar condensation), a Kutateladze correlation (for laminar wavy condensation) and a Chen correlation (for turbulent condensation);
- KAERI_a (MARS), KAERI_b (SPACE), POLITO (RELAP5-3D), UJV (RELAP5), UNIPI (RELAP5) and UNIROMA1 (RELAP5-3D) multiplied the heat transfer coefficient by a factor ranging from 2.2 to 3.0;
- NRG (SPECTRA) set the characteristic length for the film condensation to 5 cm, corresponding to a multiplier of 2.44 for the heat transfer coefficient;
- UofU (MELCOR) modified several sensitivity coefficients in the Heat Structure Package and set a multiplier of 180 instead of 120 for the number of tubes.

The other phenomenon that presented a significant challenge is the prediction of the thermal stratification in the pools, which was underlined in particular by POLITO, UJV, UNIPI and UNIROMA1. However, it should be mentioned that in PERSEO Test 7 Parts 1 and 2 the thermal stratification is present mainly at the beginning and at the end of the transients, when the passive system is not in operation. It should be noted also that the missing prediction of the thermal stratification did not prevent the correct prediction of the behaviour of the passive system during the operation phase.

The coupling between the two pools and the mass transfer when the triggering valve is open were qualitatively simulated by all the participants with minor quantitative discrepancies. The instabilities at the injector, which can be seen in the injector differential pressure, were partially predicted only by a few participants. However, the missing prediction of the instabilities at the injector did not prevent correct simulations of the overall transient behaviour.

Regarding the nodalisation strategy for the pools, the majority of participants adopted a fictitious 2D nodalisation for the pools: two vertical hydraulic regions laterally connected through cross-flow junctions. This approach resulted in a more accurate prediction of the main phenomena occurring in the pools in PERSEO Test 7. UNIROMA1 and USNRC adopted three vertical hydraulic regions connected through cross-flow junctions, which provided results comparable to two vertical hydraulic regions. KAERI_a adopted a 3D approach for the OP, but no evident improvement with respect to the 2D approach is shown in the calculation results, taking into account the two OP temperatures considered in the analysis. VTT used a 1-D modelling approach for the OP with a novel diffusion model taking in account the steam velocity in the injector to simulate mixing of the pool. UofU adopted one control volume for the OP to avoid inadvertently defining artificial, non-physical natural circulation loops. VTT noted that the sensitivity calculation of Test 7 Part 2, with modified form loss coefficients in the open pool area of HXP, shows a limitation of a quasi-2D modelling approach with a 1D code. Attempts to improve some aspects of modelling, i.e. initial temperature distribution, may have drawbacks in overall behaviour of the model. User effects in modelling this kind of phenomena, which is beyond the

original application area of a thermal-hydraulic system code, i.e. the 2D modelling approach with a 1D code, may be strong.

The user effect was investigated considering the submitted results. User effect can be relevant in particular regarding the nodalisation strategy of the pools (1D, fictitious 2D and 3D approaches), as underlined by some participants, and in setting the initial and boundary conditions. Considering the four participants that adopted RELAP5 (UJV and UNIPI) and RELAP5-3D (POLITO and UNIROMA1), it is possible to note that similar choices were made in the development of the nodalisation (e.g. primary pressure imposed as boundary condition, HXP and OP modelled with two or three vertical pipes connected by cross-flow junctions). The main difference is the adoption of a single pipe for the modelling of the HX by POLITO, UJV and UNIROMA1 and 15 pipes by UNIPI. The results of the three calculations are similar both considering the qualitative and the quantitative analysis and the same limitations emerged (in particular the underestimation of the heat transfer between the HX and the HXP and the missing prediction of the thermal stratification). Therefore, the user effect related to the nodalisation strategy has a minimal influence in this case. The use of a higher level of detail for the simulation of the HX tubes seems to not give any particular advantage in this case. However, it should be noted that avoiding HX tubes lumping may be a way to capture TH instabilities, which are one of the sources of unreliability in passive systems. The analysis of a single calculation for a specific code does not allow an immediate characterisation of the user effect for that specific code. However, as underlined in the previous paragraph a 2D approach to the pools' nodalisation provided in general a more accurate calculation result.

Some discrepancies emerged in the comparison of the initial conditions obtained by the various participants. However, comparing the calculated results during the transient, few discrepancies related to the initial conditions emerged and they are limited mainly to PhW1 of Test 7 Part 1 and 2 when the system is not in operation. Therefore, a discrepancy on the initial conditions that may be considered unacceptable in other cases, may be considered acceptable in this case.

The authors would like to emphasise the importance of the adopted methodology in the comparison of the calculated results and in the evaluation of the code accuracy. The use of both a qualitative and a quantitative approach is fundamental to properly assure the quality of a code calculation. In the quantitative analysis a method should be selected to quantify the error between the experimental and the calculated results as the FFTBM, adopted in a default way ($F_{cut}=0.4$ Hz) in the present benchmark. In relation to the adoption of the FFTBM method it is to underline that the presence of oscillations in the experimental and/or calculated data could give relatively high values of AA even if the curves, from a visual observation, seem in reasonable agreement. These oscillations in fact can introduce higher frequencies that in principle could be not physical but add spurious contributions in the AA computation, increasing its value. Therefore in a validation process for safety review purpose, more detailed analysis could be necessary to analyse the nature of the oscillations both in the experimental and/or calculated signals (e.g. comparing the amplitude of the experimental oscillations with the average value and the measurement uncertainty, and e.g. comparing the frequency of the calculated oscillations with the time step adopted by the code) and by investigating the AA values as a function of the cut-off frequencies (more details about FFTBM application and F_{cut} can be found in [4] [22] [23] [24]). In this regard it is also important to underline the role of the weight of each parameter for the calculation of the total accuracy in the FFTBM; this weight determines the contribution of each parameter for the computation of the total accuracy (e.g. a parameter that has a very high AA could have a minor contribution to the evaluation of the total accuracy due to its weight). Therefore, qualitative and quantitative accuracy evaluations have to be considered complementary and they should be applied together to have a solid and rigorous accuracy

evaluation. This must be coupled with an understanding of the phenomenology, which is a prerequisite before starting the analyses.

The PERSEO benchmark showed the limitations of most of the codes in predicting the full-scale experimental results without modifications of the code models or of the nodalisation, which in this case were possible thanks to the “open” nature of the benchmark, with the experimental data distributed to the participants before the beginning of the calculation phase. Therefore, an accurate evaluation of the validation domain and of the related scaling issues is fundamental for the application of the codes in the simulation of full-scale passive systems and a precondition for any reliability assessment of passive systems on the basis of these codes.

Considering previous related activities, and in particular the publication entitled “A state-of-the-art report on scaling in system thermal hydraulics applications to nuclear reactor safety and design” (NEA, 2017^[8]) developed in the framework of the WGAMA, the PERSEO benchmark activity supports and highlights some of the recommendations consolidated in the report. In particular:

- the database of existing SETF and ITF CCVM (computer code validation matrix) should be extended to include advanced reactors using passive safety systems;
- there is a need for well-instrumented tests for validating CFD for water-cooled reactors in relation to mixing problems, such as mixing with buoyancy effects in some passive systems (e.g. large pool of liquid as in the case of PERSEO);
- full-height scaling and suitable flow areas (and volume sizes) are recommended for experimental simulation of passive systems wherein the important phenomena are the boiling and condensation processes and the buoyancy effect due to density change. Full height will provide an accurate characterisation of phenomena, such as natural circulation and related stability;
- revisiting systematically the scalability of system codes at the basic level of each closure law may be a good practice to improve the understanding of code scaling uncertainty and to improve the code’s documentation.

8.3. Code-specific conclusions

Some additional specific conclusions by the various participants, not already included in the general ones, are presented here.

In relation to ATHLET, GRS underlined that some minor problems were seen in the circulation and the mixing within the OP, especially in the subcooled case (Part 1). To improve the results concerning the temperature distribution within the OP, a 3D representation of the pool could be generated and used with the 3D component model of ATHLET.

In relation to SOCRAT, IBRAE underlined that the main lesson learnt from the PERSEO data was the modelling of pool fast filling with an immersed heat exchanger and the modelling of steam discharge in OP.

In relation to SPECTRA, NRG underlined that the “non-sliced” nodalisation approach adopted to model the pools revealed some weak points, in particular related to the condensation of the steam coming from the HXP to the OP and to the water mixing occurring in the HXP when the triggering valve is open. As a consequence, a “sliced” nodalisation approach might be investigated for the pool volumes. In general, the nodalisation strategy adopted can greatly affect the model of transient scenarios. Nevertheless, it is difficult to design a system thermal-hydraulic model a priori that is

suitable for all possible conditions of operation for a system like PERSEO. Concerning specifically the SPECTRA code, the lack of capability to track water levels in contact with a set of structures stacked vertically may result in a not very accurate estimation of the power exchanged under dynamic conditions of the liquid level on the opposite side of the structures.

In relation to TRACE, USNRC underlined that TRACE has a lesser performance on direct steam condensation. It shows on the deviation of the heat exchanger pool relative pressure and steam injector pressure drop. However, the instability of direct steam condensation was captured well through a smaller separate pipe component to model the fluid directly under the steam injector. The steam condensation below the steam injector creates a low pressure point to relieve the pressure buildup in the heat exchanger pool. This is important in determining the level response in the heat exchanger pool.

8.4. Proposals for future activities

Considering the analysis of the results, the main lessons learnt in the present benchmark and the discussion in the third meeting of the WGAMA task group on thermal-hydraulic passive systems design and safety assessment in water-cooled reactors (Tirrenia, 11- 13 December, 2019), the authors propose as possible future research activities:

- 1) to make a detailed analysis of the condensation heat transfer coefficient and direct contact condensation (namely downstream of the injector/sparger location with or without specific correlation) used by the various participants;
- 2) to make an uncertainty and sensitivity analysis of Test 7 Part 2;
- 3) to evaluate whether 3D modelling brings tangible improvements in comparison with experimental data;
- 4) to check the qualification of any procedure used to analyse the current tests at different pressures, or even using any other test condition (using experimental data already available by ENEA);
- 5) to make “extreme case” analyses (currently only UNIPI together with POLITO has made those analyses)⁸.

8. Extreme cases are defined within the space of the variation of parameters that are selected as the origin of reliability of the concerned passive system; the low value of the probability envisaged for each concerned parameter value and the combination of those values are expected to challenge the performance of the system and justify the word “extreme”.

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Annex 1: FFTBM method description

The quantitative evaluation of the code results obtained within the PERSEO benchmark has been performed adopting the fast Fourier transform based method (FFTBM) [6] [18] [25]. This method is used to assess the quantitative accuracy of code calculations against experimental results.

The evaluation is performed considering two parameters: the average amplitude (AA) and the weighted frequency (WF). FFTBM can be improved by signal mirroring [5] [7].

The function must be identified by a number of values that is a power of two to apply the FFTBM. Therefore, in the time domain the function is defined by N point such that:

$$N = 2^{m+1} \quad \text{Eq. (1)}$$

with $m=0,1,2,\dots,M$

In the frequency domain the function is defined by 2^m+1 values corresponding to the frequencies

$$f_n = \frac{n}{T_d} \quad \text{Eq. (2)}$$

with $n=1,2,\dots,2^m$ and T_d the time duration of the signal.

It is defined an error function $\Delta F(t)$ in the time domain as:

$$\Delta F(t) = F_{cal}(t) - F_{exp}(t) \quad \text{Eq. (3)}$$

Where $F_{cal}(t)$ and $F_{exp}(t)$ are the calculated signal and the experimental signal in the time domain respectively.

The AA is calculated after having performed the fast Fourier transform as:

$$AA = \frac{\sum_{n=0}^{2^m} |\tilde{\Delta F}(f_n)|}{\sum_{n=0}^{2^m} |\tilde{F}_{exp}(f_n)|} \quad \text{Eq. (4)}$$

Where $|\tilde{\Delta F}(f_n)|$ is the error function amplitude at frequency f_n and $|\tilde{F}_{exp}(f_n)|$ the experimental signal amplitude at frequency f_n . AA is an indication of the error and closer AA is to 0, the more accurate is the result.

The WF is defined as the sum of frequency multiplied by the error function amplitude and divided (normalised) by the sum of error function amplitudes

$$WF = \frac{\sum_{n=0}^{2^m} |\tilde{\Delta}F(f_n)| f_n}{\sum_{n=0}^{2^m} |\tilde{F}_{exp}(f_n)|} \quad \text{Eq. (5)}$$

The global accuracy index for a code calculation is defined by the total weighted average amplitude and the total weighted frequency

$$AA_{tot} = \sum_{i=1}^{N_{var}} (AA)_i (w_f)_i \quad \text{Eq. (6)}$$

$$WF_{tot} = \sum_{i=1}^{N_{var}} (WF)_i (w_f)_i \quad \text{Eq. (7)}$$

With

$$\sum_{i=1}^{N_{var}} (w_f)_i = 1 \quad \text{Eq. (8)}$$

Where N_{var} is the number of parameters considered in the analysis and $(w_f)_i$ the weighting factor for the i -th parameter that considers the experimental accuracy, the safety relevance and the parameter contribution to the primary pressure [7].

In relation to the adoption of the FFTBM method it is to underline that the presence of oscillations in the experimental and/or calculated data could give relatively high values of AA even if the curves, from a visual observation, seems in reasonable agreement. These oscillations in fact can introduce higher frequencies that in principle could be not physical but add spurious contribution in the AA computation increasing its value. A cut-off frequency (f_{cut}) is introduced as input in the FFTBM method in order to filter these contributions [4] [23]. The default value of f_{cut} is 0.4 Hz.

For the PERSEO benchmark the tool that has been used is the JSI FFTBM Add-In 2007 developed at Jožef Stefan Institute (Slovenia) [4] [5] [6] [7]. The data series provided by the participants must be no longer than 10 000 points. As decided at the meeting in Karlstein (26-27 June 2018) the participants provided the results with a time step of one second to avoid user effect error on the FFTBM application.

The reference threshold values usually adopted for the accuracy evaluation with FFTBM, which have also been applied in the present benchmark, are [18]:

- $AA_{tot} \leq 0.3$: very good code prediction;
- $0.3 < AA_{tot} \leq 0.5$: good code prediction;

- $0.5 < AAtot \leq 0.7$: poor code prediction;
- $AAtot \geq 0.7$: very poor code prediction.

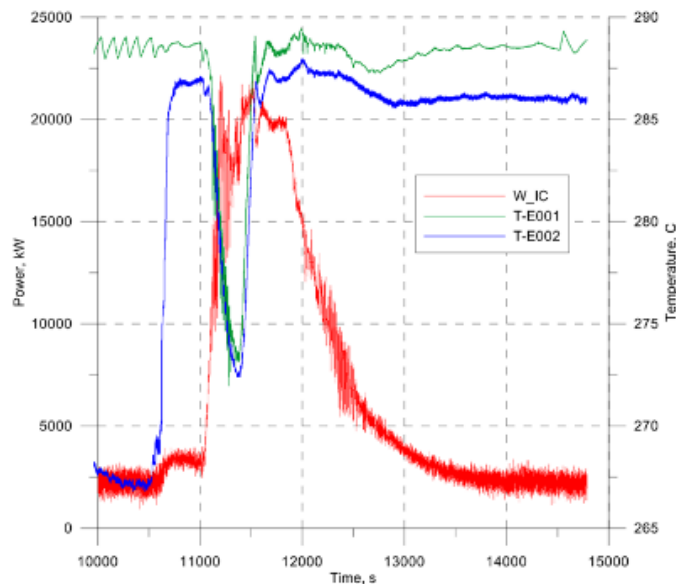
Annex 2: Questions and answers

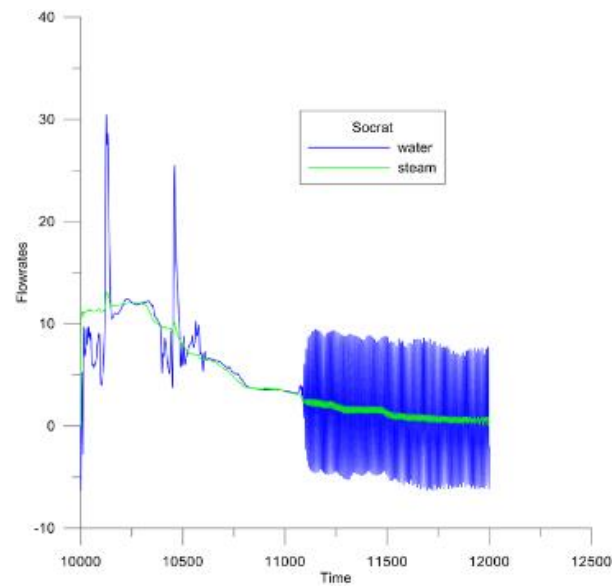
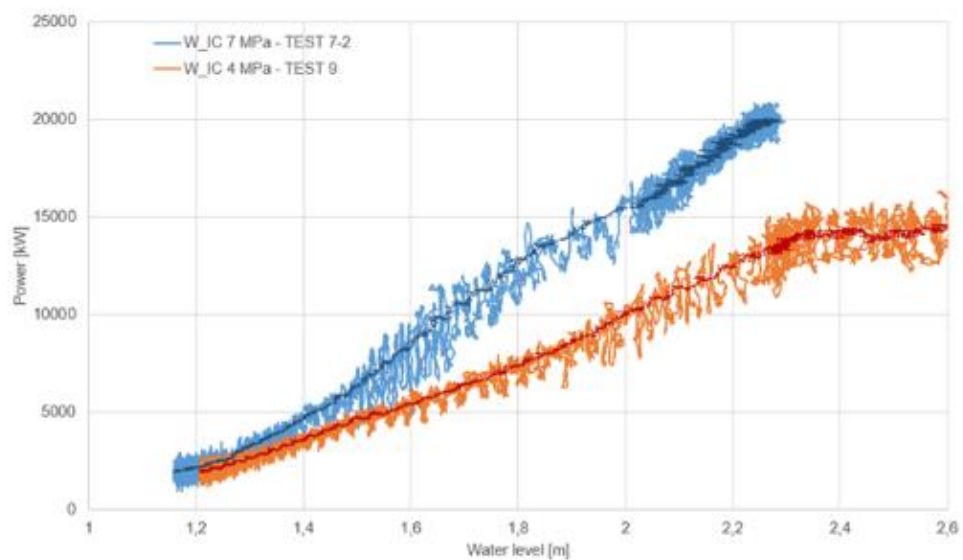
QUESTION 1

Let's exclude several time intervals from comparison (flowrates and IC power). Picture 1 shows that from 10 000 s till 10 550 s there is no circulation in primary side because condensate temperature is significantly below saturation. For data from 10 600 s all seems okay except uncertainty in flowrate calculations. One may obtain oscillation of water or steam flows due to logic of steam addition to steam pressure vessel (SPV). Yes, I may obtain this data from primary side pressure (top left corner of picture 1 shows steam temperature oscillation like in MASLWR then valve opens)? But it is usable only for low power, not for 11 000-11 500 s time interval. It would be nice to know if anybody has already done this work. Picture 2 shows SOCRAT oscillation of condensate drain line flow powered by SPV level oscillation. This is not a PERSEO 7 test, only HX poll evaporation like in picture three. One can see reverse flow in condensate line.

(Dmitrii Tomashcik, IBRAE)

Picture 1: PERSEO 7-1 test data



Picture 2: SOCRAT flow oscillation**Picture 3: PERSEO IC power vs. level**

ANSWER 1

We can discuss the phenomenological windows to apply the qualitative and quantitative accuracy analyses. I think that we can still discuss also the parameters selected if the analyses show that there is too much uncertainty or measurement error. A deeper discussion could be had at the next meeting.

QUESTION 2

Maybe DP in formula below can change sign? And this is a reason for NaN in .xls file for PERSEO Test 7 Part 1?

(Dmitrii Tomashcik, IBRAE)

Flowrate measured by orifices with taps at D and D/2, at corners, at flanges [12]

The reduction formula used to obtain the flowrate is:

$$F = \alpha * \varepsilon * \frac{\pi * d^2}{4} * \sqrt{2 * \rho * DP}$$

where:

- F = mass flowrate;
- α = flowrate coefficient;
- ε = compressibility coefficient (for liquid $\varepsilon = 1$);
- d = orifice throat diameter;
- ρ = fluid density upstream of the nozzle;
- DP = local pressure drop across the nozzle.

ANSWER 2

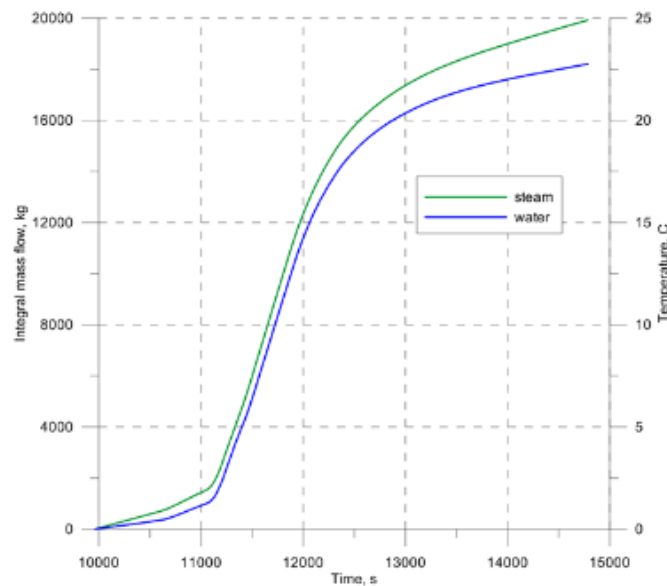
In PERSEO Test 7 Part 1, negative values of FE-001a (kPa) are recorded when the mass flowrate is zero and they are due to the measurement uncertainty. NaN values of mass flowrate are due to negative DP and they have to be considered 0.

QUESTION 3

Uncertainty in flowrates determination. Picture four is an integrated value of F_A001 and F_E001. One can see that data is not consistent at intervals 10 000-10 700 s and after 13 500 s. From 10 700 to 13 500 relative error is about 5% or less and I think only this interval of Part 1 can be used for comparison. For Part 2 the situation is the same: we need to shrink time interval. It is a good idea to set relative and absolute error for flowrate and power determination before comparison with codes.

(Dmitrii Tomashcik, IBRAE)

Picture 4

**ANSWER 3**

As I understand the uncertainty for steam flow rate and water flow rate is not constant along the transient and this determines some error. For the qualitative code accuracy analyses this should be not a problem, from a quantitative code accuracy analyses we can discuss and agree in the next meeting how to manage along the FFTBM application.

QUESTION 4

I am catching up the PERSEO model and found much data missing from the report, i.e. vacuum breaker in HX pool, valve info. between the pools. Has anyone in the group raised questions on the model development?

(Peter Lien, USNRC)

ANSWER 4

Vacuum breaker valve characterisation:

Check valve type Europa

Size 2½ inch

Full area 1.0116E-3 m²

Opening DP 0.05 kPa

Installation horizontal

Valve between the pools characterisation:

Gate valve

Size 8 inch

Full Area 0.0323 m²

CV versus normalised area:

Norm. area	CV
0	0
0.315	446
0.652	1 695
0.949	4 000
1	5 800

QUESTION 5

Based on the plots provided by ENEA, the steam/condensate flows are on in the primary loop for about 400 s in Test 7 Part 1. The controller is trying to control the RPV pressure at 70 bar. However, is the RPV level under control? If not, the condensate flows back to RPV from HX, the RPV level will be rising all the time unless the RPV drain line is open. Unfortunately, we do not have data for RPV drain line, RPV level; and do not know the drain line controller details. Please provide the overall RPV controller function details (pressure and level) if available or assumptions to make.

(Peter Lien, USNRC)

ANSWER 5

The RPV level was controlled by means of the valve F114 that is a 2-inch valve. During the phases of high condensate flowrate from the heat exchanger, the valve is not sufficient to discharge all the liquid entering the vessel and the level increases as it can be seen from the graph below for Test N. 7 Phase 1.

The controller parameters are not available.

The vessel can be considered as a steam source which internal differential pressure is measured by DP-010 that included the two terms: gravity head (water level) and pressure drops of steam crossing the vessel from the inlet to the outlet.

The pressure in the vessel is controlled by means of the valve F103 on the basis of PI001.

Pressure decreases in the vessel during the high condensation phase.

QUESTION 6

Is it necessary to provide the calculation data with fix timesteps of one second as given in the ENEA_PERSEO_results.xlsx template?

(Sebastian Buchholz, GRS)

ANSWER 6

The participants should provide the results with a time step of one second to avoid user effect error on the FFTBM application

QUESTION 7

Another question is regarding the initial temperature in the bottom of HX pool T-Q016. It starts with 80°C for about 500 s in Test 7 Part 1 according to Figure 4.7. Does it mean the fluid in the pipe between OP and HXP, after valve F045 was maintained at about same temperature? According to Figure 4.7, the temperature drops immediately to about 20°C after FO45 opens. It implies very cold water mixes immediately as it goes into HXP. Do we have measurement of the fluid temperature in the connection pipe, particular after valve FO45?

(Peter Lien, USNRC)

ANSWER 7

There is a temperature measurement upstream (overall pool side) of the triggering valve F045. The valve is close to the overall pool, so the T-N001 is far from the HX pool.

Water temperature in the HX (TQ016) pool decreases as soon as colder water enters through the connection pipe, after the valve opening.

The pipe is not thermally insulated, so it is reasonable to have cold water in the pipe and hotter water in the pool with F045 closed.

QUESTION 8

What do you mean by “slow water consumption in the HX pool” (Table 2.1) of the PERSEO Benchmark results document? Is it the integral amount of steam produced in the first phase? Or the water mass flowing into the HXP?

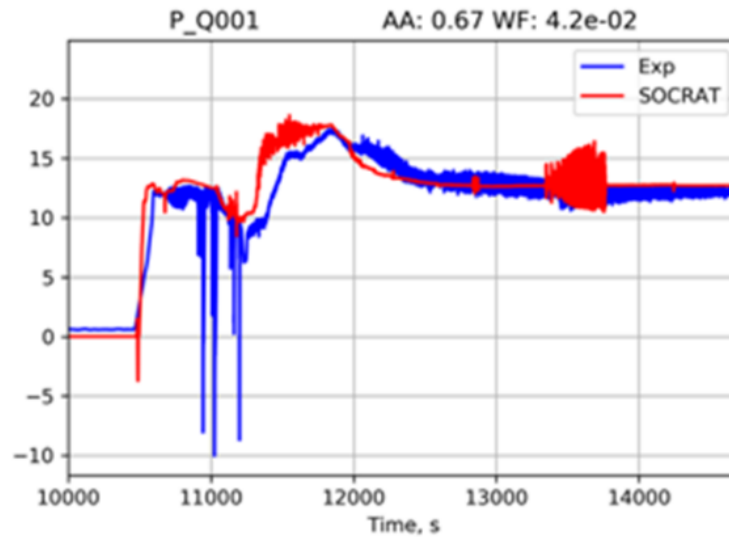
(Sebastian Buchholz, GRS)

ANSWER 8

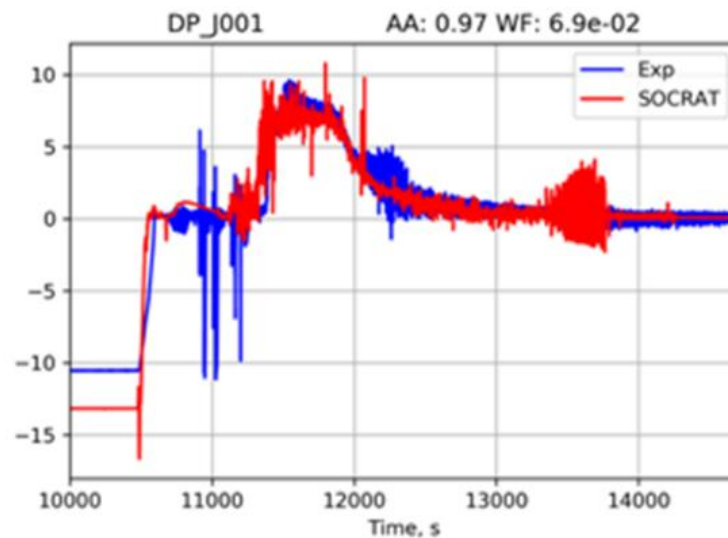
Slow water consumption, lasting until the triggering valve is reopened (so no water flow from the overall pool), means that water contained in the pool is evaporated by the heat exchanger flown by steam. Evaporation is slow because only the lower header of the HX and a short portion of the tubes, at bottom, is covered and transferred power is relatively low.

QUESTION 9

Level of steam line axis (HX to overall poll) is 5 150 mm, Nozzle depth in OP is 1 880 mm, OP initial level 4 650 mm. So water level above bottom of nozzle is $4\,650 - (5\,150 - 1\,880) = 1\,380$ mm (~ 13.8 kPa) because pressure in HX is about one atm.



I expected that initial value of DP-J001 should be -13...-14 kPa,



But measured value is -10. What is wrong?

(Dmitrii Tomashcik, IBRAE)

ANSWER 9

The DPJ001 is installed according to the scheme below, leftmost case where $DP = P1 \text{ press} - P2 \text{ press}$.

The elevations of the pressure taps are:

P1 4 400 mm

P2 3 340 mm

that provide $H = (4\,400 - 3\,340) = 1\,060 \text{ mm}$ corresponding to 10.39 kPa

Being the OP level above P1 (initial level 4 650 mm), the DP_{inst} is = 0 Pa because both branches (P1 to P-) and (P1 to P+) are full of water and balanced.

Being $DP_{inst} = 0 \Rightarrow DPJ001 = 0 - H = 0 - 10.39 \text{ kPa}$

Scheme of Differential pressure instrument installation

P1 and P2 represent the pressure tap locations on a component or pipe.

P+ and P- represent the instrument hydraulic connections.

$DP = P(P1) - P(P2)$ is the differential pressure measurement.

QUESTION 10

Time 147 850 s in 7-1 test equal to 0 s in 7-2 test?

(Dmitrii Tomashcik, IBRAE)

ANSWER 10

Yes, the test 7-2 follows the test 7-1.

QUESTION 11

Can we know the temperature and flow rate of steam supplied to the steam vessel?

(ByongGuk Jeon, KAERI)

ANSWER 11

In the spreadsheets experimental data there is temperature T-1003 and the flowrate is measured by FA001.

QUESTION 12

Can we know the flow rate of water drained from the overall pool in the Test Part 2? Should we arbitrarily decide the opening area of valve F031 to match the overall pool water level trend?

(ByongGuk Jeon, KAERI)

ANSWER 12

The flow rate drained from the overall pool is not given, the only available information is the level in the pool itself. Yes, open the valve to match the level.

QUESTION 13

Can we know the opening area (percent) of the triggering valve during the test?

(ByongGuk Jeon, KAERI)

ANSWER 13

The triggering valve was fully open during the tests and the opening time is declared in the table of the events, test by test. The valve characteristics were provided in the past to ENEA.

QUESTION 14

Can we trust the flow rate values from F_A001 at the beginning (~ 1 kg/s)? It seems that the early flow rate needs to be near 0 kg/s. If the flowrate at the beginning was overly measured, should we reduce the flow rate slightly throughout the test period?

(ByongGuk Jeon, KAERI)

ANSWER 14

The initial value of the flow rate is affected by uncertainty due to the uncertainty on the pressure drop measurement at low values from which the flow rate is derived. The flow rate when the system is in operation should have a lower uncertainty.

QUESTION 15

In Figure 4.4 of the test facility report, the steam line from T-A004 to TA005 is missing. Can we get the information?

(ByongGuk Jeon, KAERI)

ANSWER 15

As it is shown in Figure 4.1 that part of the line is 12" SCH 80 and it is a vertical.