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International Agreement Report

Assessment of NEPTUN Reflooding Experiments 5050 and 5052 with TRACE V5.0 Patch 5

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ABSTRACT

NEPTUN experiments 5050 and 5052 have been simulated with TRACE V5.0 Patch 5. Calculation results were compared to experiment data received from OECD/NEA databank but, unfortunately, not all original experiment data was available. Uncertainties of the experimental data were not quantified in the original material nor were there enough available data in order to form an estimate. There is also uncertainly about radial placement of those thermocouples for which data is available.

Both simulations show qualitatively similar results: TRACE predicts higher temperature in the lower parts of the test section which leads to later quenching than in the experiment. In higher elevations temperatures are a closer match but there is still a significant difference in quenching times. Collapsed water level prediction is in reasonably good agreement in both experiments.

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ABBREVIATIONS AND ACRONYMS

CAMP	Code Applications and Maintenance Program
EIR	Eidgenössisches Institut für Reaktorforschung
LOCA	Loss Of Coolant Accident
PSI	Paul Scherrer Institute
PWR	Pressurized Water Reactor
SIN	Schweizerisches Institut für Nuklearphysik
TRACE	TRAC/RELAP Advanced Computational Engine
U.S. NRC	United States Nuclear Regulatory Commission
VTT	VTT Technical Research Centre of Finland Ltd

1 INTRODUCTION

This report is based on NEPTUN reflooding data, experiments 5050 and 5052, received from OECD/NEA databank (Ref. 1, Ref. 2). The simulations were performed using TRACE V5.0 Patch 5 and SNAP 2.5.8. This report is produced as in-kind contribution to the U.S. NRC CAMP program (Code Applications and Maintenance Program). The funding for this work has been provided by VTT's COVA project (Comprehensive and systematic validation of independent safety analysis tools) which is a part of the SAFIR2018 programme (The Finnish Research Programme on Nuclear Power Plant Safety 2015-2018). The two cases have been previously calculated in NUREG/IA series in 1992 RELAP5 validation (Ref. 3). Unfortunately it was not possible to digitalize this data into this report for comparison purposes as the quality of the graphs has been greatly deteriorated during the previous printing and scanning processes.

2 DESCRIPTION OF THE NEPTUN TEST FACILITY

The NEPTUN experimental facility was designed and built at Eidgenössisches Institut für Reaktorforschung (EIR) that merged with Schweizerisches Institut für Nuklearphysik (SIN) to form Paul Scherrer Institute (PSI) in 1988. NEPTUN facility was completed around 1980 and the experiments made were the full-length emergency cooling heat transfer tests for LOFT (Loss of Fluid Tests) test facility. The heater bundle of NEPTUN facility holds 33 electrical heater elements and 4 guide tubes that simulate a section of the LOFT nuclear core. The outer dimensions of the rods were similar to those of a PWR fuel rods except being half length in size (1.68 m heated length, heated rods with diameter of 10.7 mm, p/d = 1.33). (Ref. 3, Ref. 4)

The general objective of the NEPTUN tests was to contribute to the understanding of thermal-hydraulic and heat transfer behavior during the reflood phase of a loss of coolant accident (LOCA) in a pressurized water reactor (PWR). 40 reflooding experiments were performed in this facility during 1981-1983. Flow diagram and geometry of the NEPTUN facility are presented in Figures **1-4** (Ref. 4, Ref. 5). Rod cladding temperatures, fluid temperatures and differential pressures were measured at eight measurement levels, which are presented in Table **1**. Only cladding temperature readings of unknown radial placement are available in the NEA datasets (Ref. 1, Ref. 2).

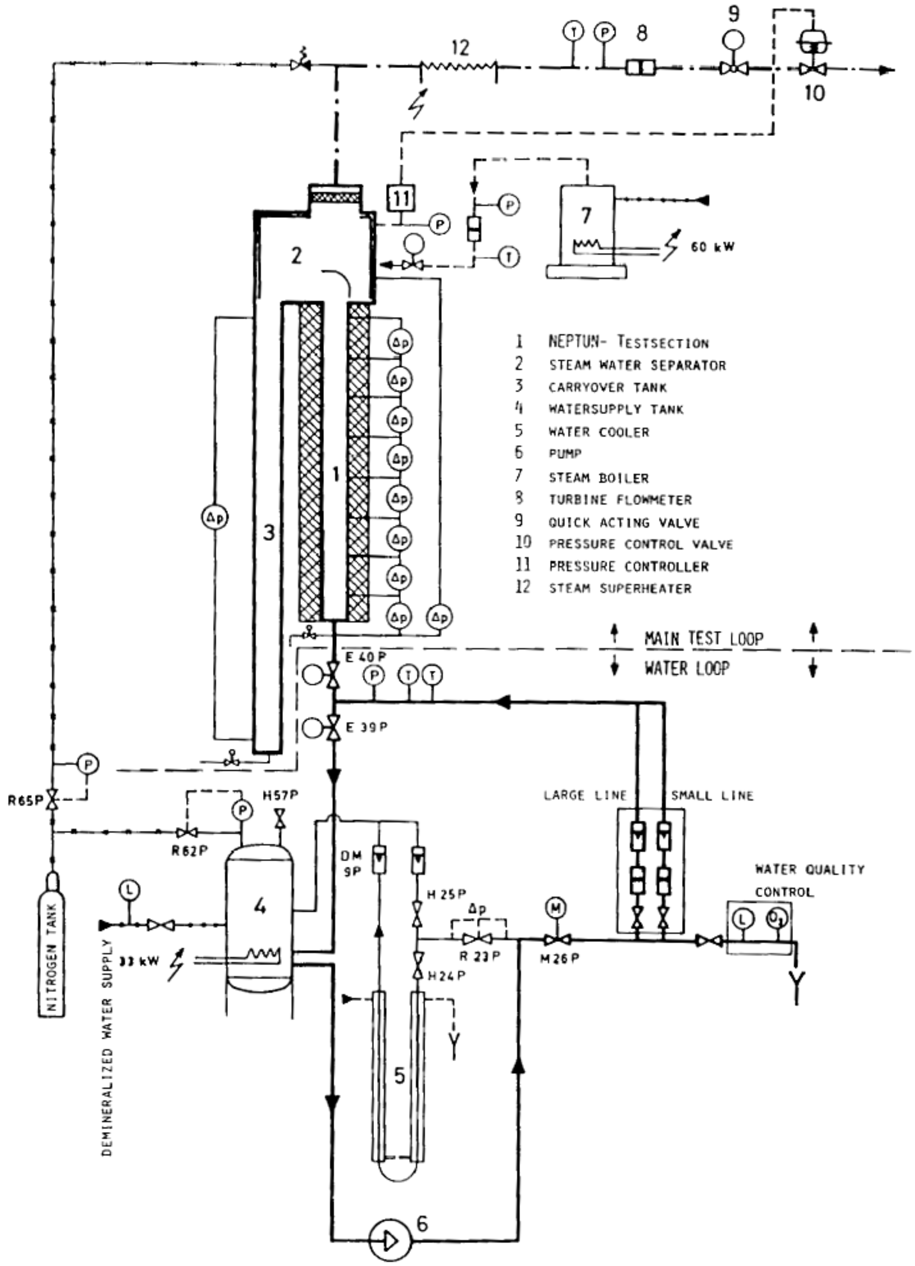

Figure 1 Flow Diagram of the NEPTUN Facility

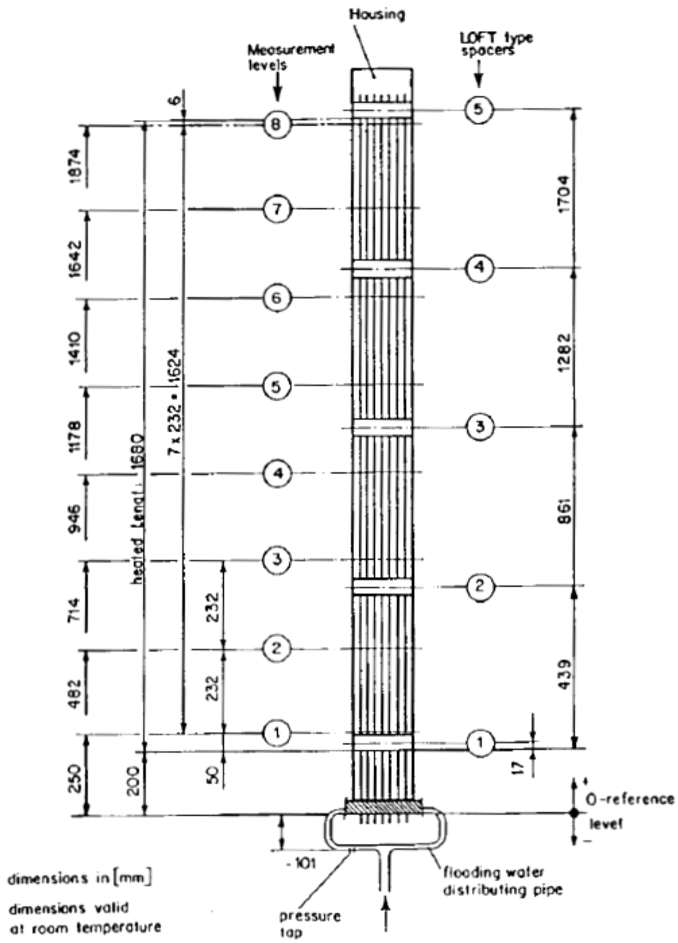

Figure 2 NEPTUN Rod Bundle Test Section and Measurement Elevations

Table 1 Measurement Level Elevations from the Bottom of Heated Section

Measurement level	Elevation [mm]
1	50
2	282
3	514
4	746
5	978
6	1210
7	1442
8	1674

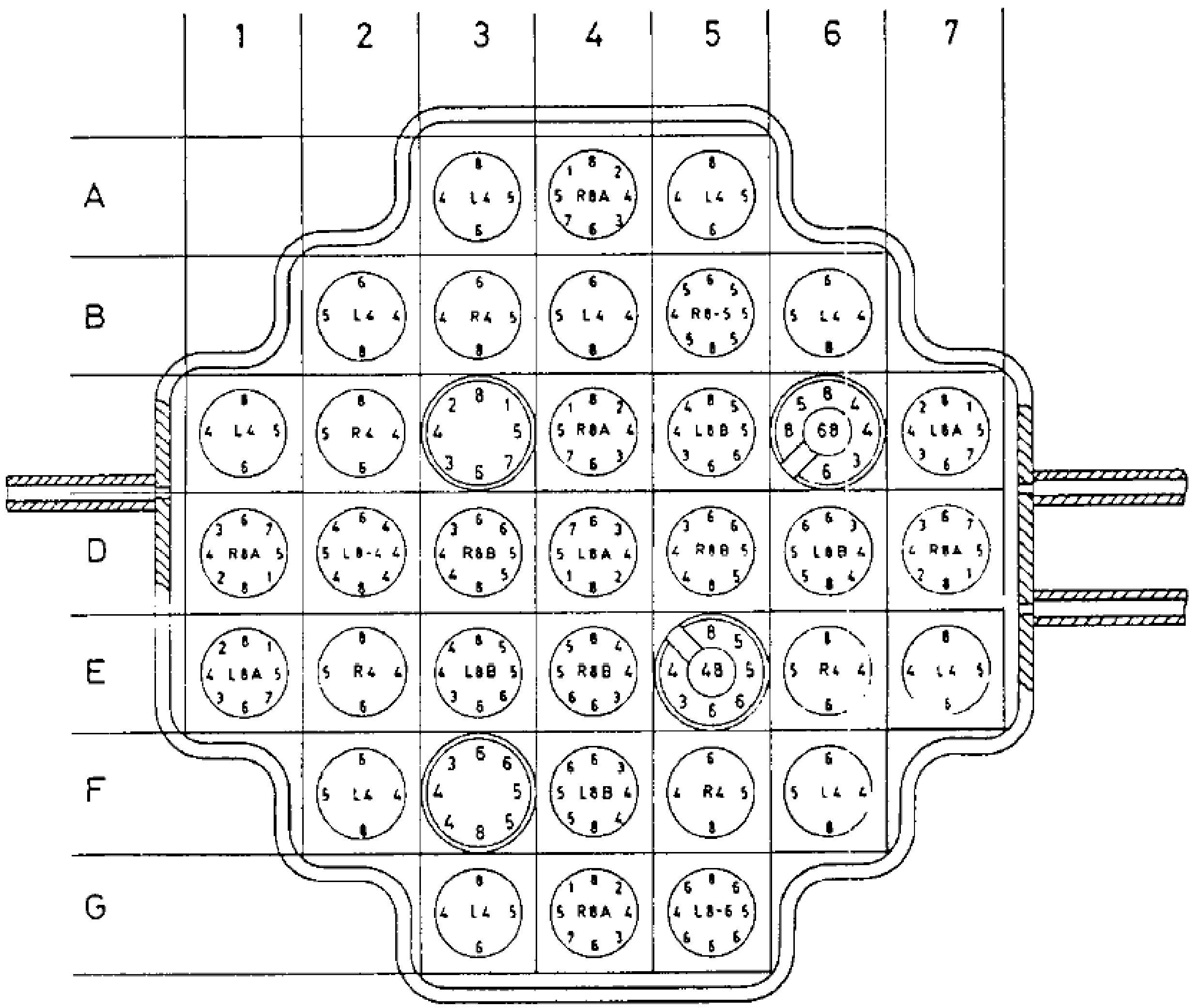

Figure 3 Heater Bundle of the NEPTUN Facility

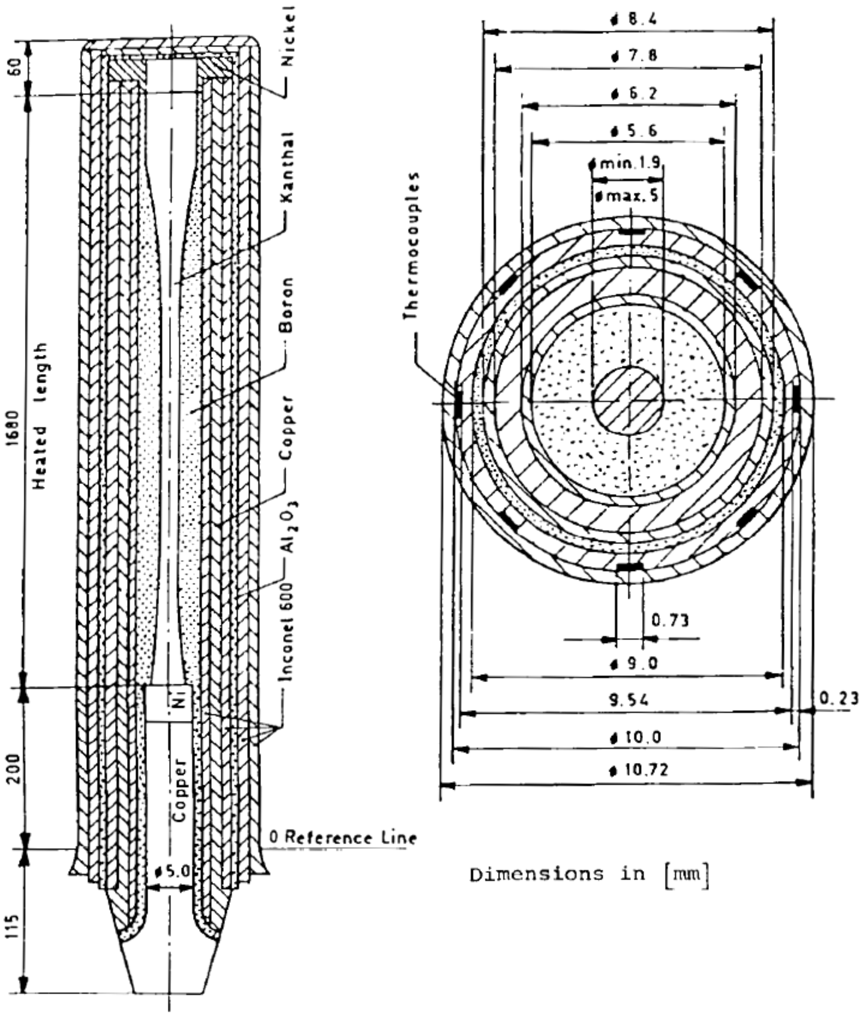

Figure 4   A Heater Rod of the NEPTUN Heater Bundle

3 REFLOODING EXPERIMENTS 5050 AND 5052

40 reflood experiments were performed in the NEPTUN facility from 1981 to 1983. Unfortunately data for only two of these experiments is available through OECD/NEA databank. Experiment procedure started by bringing the flooding water in the circuit to desired conditions. The test section was kept at a defined experiment pressure and was filled with saturated steam. Power to the heater rods was then switched on. A short time before the cladding temperatures reached the desired value, a valve was opened and water was allowed into the test section. The power at the bundle was held constant until the end of of the experiment. (Ref. 3)

Experiments 5050 and 5050 are similar to each other in every way except flooding rate which is 15 cm/s n 5050 and 2.5 cm/s in 5052. Initial conditions of the experiments are presented in Table 2. (Ref. 1, Ref. 2).

Table 2 Initial Conditions of the Experiments

	Experiment 5050	Experiment 5052
Pressure [bar]	4.1	4.1
Flood velocity [cm/s]	15	2.5
Subcooling temperature [ºC]	78	78
Single rod power [kW]	2.45	2.45
Maximal initial cladding temperature [ºC]	867	867

3.1 Estimation of Uncertainties

No estimation of uncertainties is presented in the available technical documentation. In 1992 NEPTUN data was used in validation of RELAP5 (Ref. 3) and probable errors were estimated using the available data from the experiment. For example data from individual pressure differential measurements were compared to the ones from the top and bottom of the bundle. The full data set was not available when writing this report so therefore similar estimation could not be performed. Estimations made in 1992 are presented in Table 3 to provide background information to the reader but they are not used elsewhere in this report.

Table 3 Probable Errors According to Ref. 3

Quantity	Probable error	Largest scattering min. to max of the data
Flooding water mass flow	± 5.3 %	
Flooding water temperature	± 0.5 ºC	
Test section pressure	± 0.03 bar	0.42 bar during exp. 5050
Collapsed water level	± 1.8 %	
Void fractions	± 0.04	
Rod cladding temperatures between all rods without external thermocouples	± 5 ºC	48 ºC during exp. 5050
Quench times between all rods without external thermocoules at measurement points 4 and 5	± 1.2 s	2.5 s during exp. 5050

4 SIMULATION MODEL

The simulation model consists of fill and break boundary conditions, 20 cm inlet and outlet pipes, a 1.68 m long heated section of flow channel modelled with a vessel component and heat structures for heater elements, channel wall and guide tubes. The heated section was divided into 20 thermal-hydraulic cells while the inlet and outlet pipes consisted of single cells. Channel wall was modelled as 2 mm thick slab heat structure while the guide tubes are cylindrical heat structures. Thickness of the guide tubes is not revealed in the documentation so value of 1 mm was used as this was seen as a reasonable estimation of the probable thickness. Material of both of these heat structures is Inconel 600. Fill rate in the simulations was given as a constant velocity boundary condition while the exit break component maintained steady pressure. Unlike the static pressure and fill rate, measured heater element power was used in the simulations. Test section flow area was 0.00435 m^2 and hydraulic diameter was 1.17 cm. The simulation model and radial geometry of the heater element heat structures are presented in Figure **5** and Table 4 (Ref. 4, Ref. 6, Ref. 7, Ref. 8).

The model was first initialized by setting all heat structures to the same saturation temperature of both tests and then full power was turned on to the heater elements with no flow entering the test section. Once the maximum cladding temperature reached the specified value of 867 ºC simulation was stopped, fine mesh reflood model was enabled and the state of the model was used as the initial state for both simulations. As radiation heat transfer was not modelled (due to difficult implementation and lack of all housing measurement data), heat transfer from the heating elements to the housing and guide tubes was possible only through the thermal-hydraulic cells. This affected the guide tube and housing temperatures - the guide tubes likely being colder than in the experiment while the housing being an unknown, as no heat flow to the insulation, due to insufficient data, was modelled. In NEPTUN experiments many temperature sensors were used but no data on housing or guide tube temperatures is available in the OECD/NEA data.

For each coarse mesh cell three permanent fine mesh cells were added. Cladding temperature measurement were taken from the closest permanent (2.8 cm long) fine mesh cell (see **Table 1**).

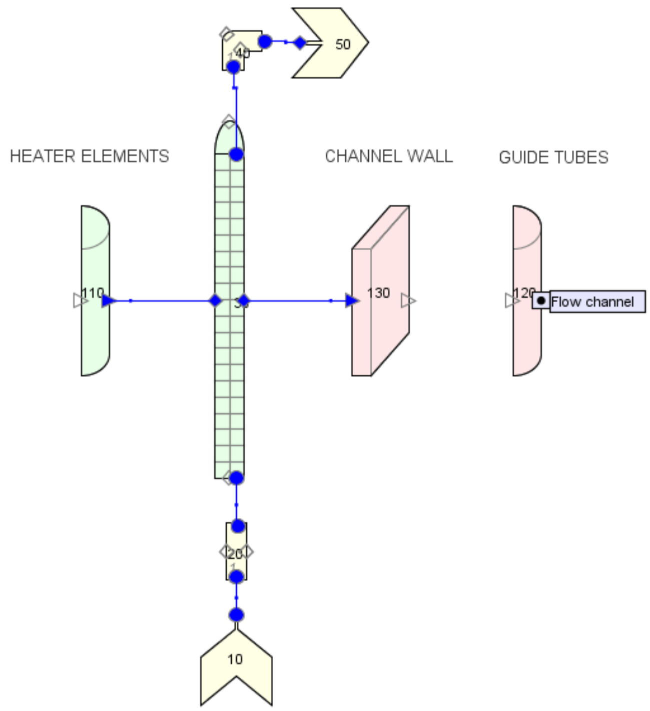

Figure 5 NEPTUN Smulation Model

Table 4 Radial Geometry of the Heater Element Heat Structures

Material	Inner radius [m]	Outer Radius [m]	Thickness [m]	Node count []
Kanthal A1	0	2.50E-03	2.50E-03	2
Boron-Nitride	2.50E-03	2.80E-03	3.00E-04	2
Inconel 600	2.80E-03	3.10E-03	3.00E-04	2
Copper	3.10E-03	3.90E-03	8.00E-04	2
Inconel 600	3.90E-03	4.20E-03	3.00E-04	2
Al_2O_3	4.20E-03	4.50E-03	3.00E-04	2
Inconel 600	4.50E-03	5.00E-03	5.00E-04	2
Inconel 600	5.00E-03	5.36E-03	3.60E-04	2

Only the active length of the heater elements is modelled. This probably has some minor initial effect on quenching as axial conduction is not possible to (and possibly from) the non-heated sections of the rods. Additionally this has some effect on the initial temperature distribution. The axial power profile and initial temperature distributions before enabling the fine mesh reflood model are presented in Figures **6** and **7**.

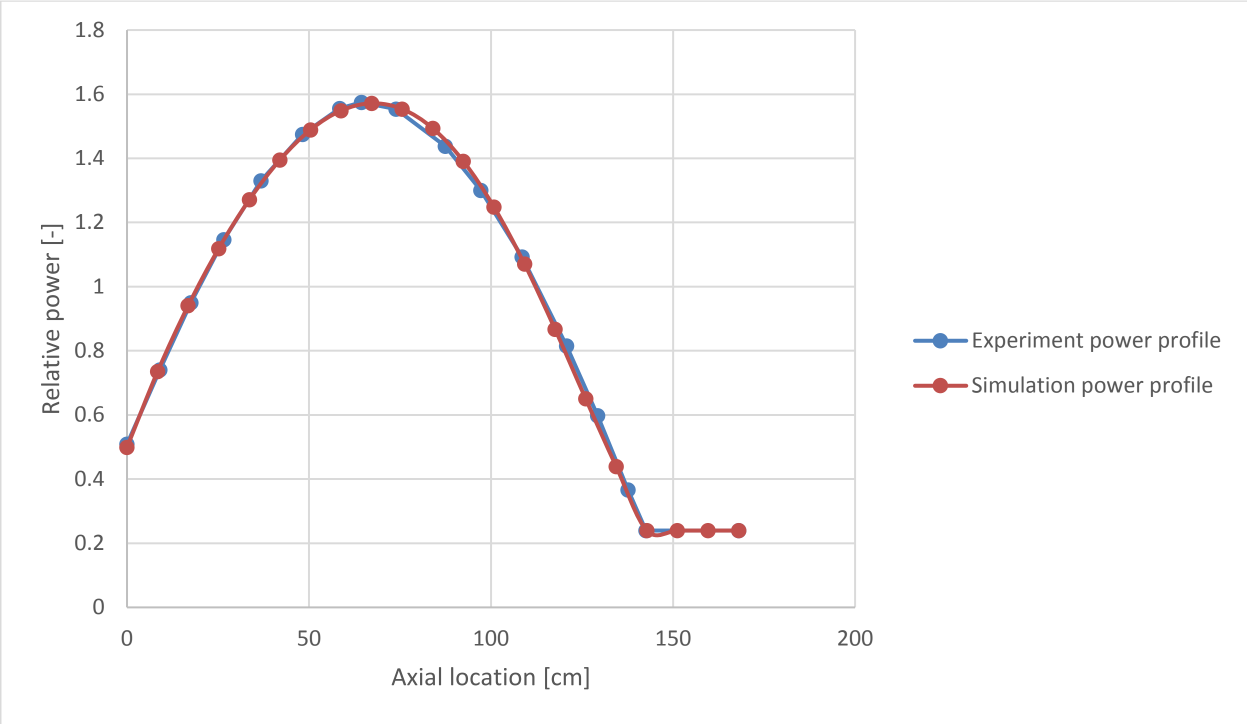

Figure 6 5050 and 5052 Axial Power Profiles

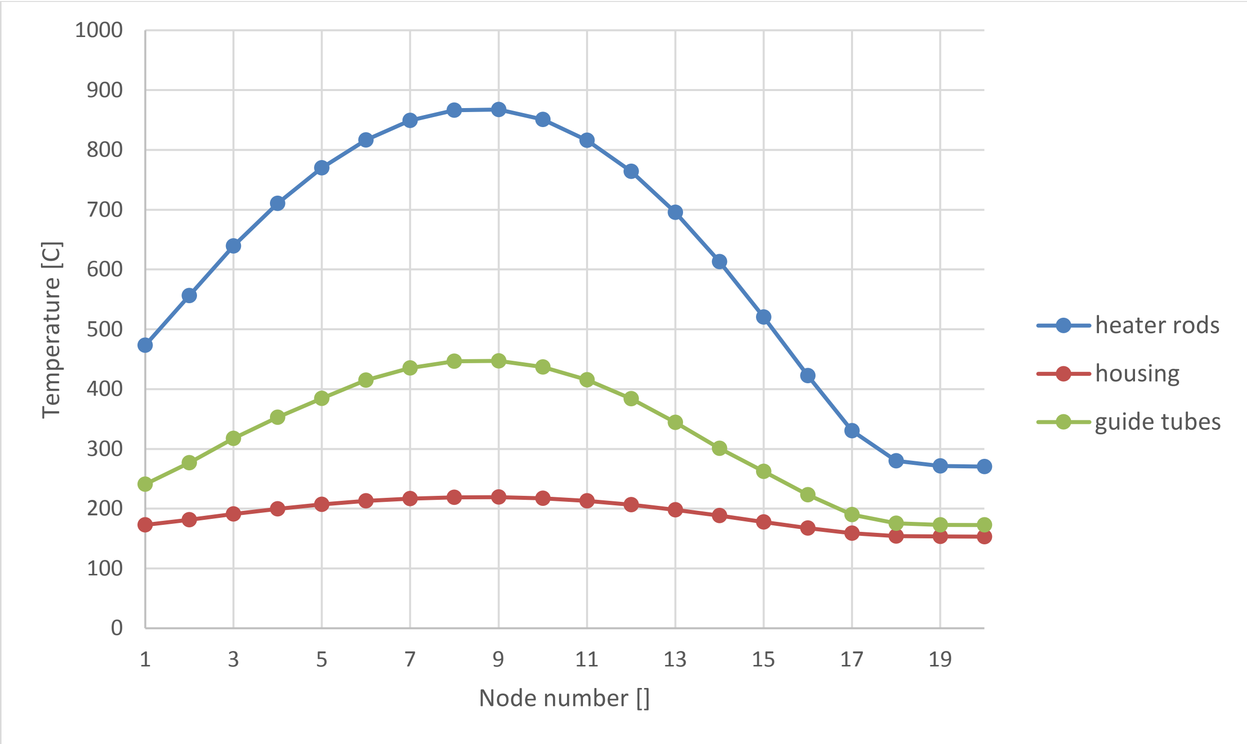

Figure 7 Initial Cladding Temperatures for Simulation of Experiments 5050 and 5052

5 SIMULATION RESULTS

5.1 Experiment 5050

Experiment 5050 is a high flood rate case with inlet velocity of 15 cm/s. Test section pressure, flooding rate, flooding water temperature and total bundle power area presented in Figures 8-11. Pressure, flooding rate and temperature are given as fixed boundaries while the test section power is used as shown in the data. All experimental data of 5050 is from Ref. 1.

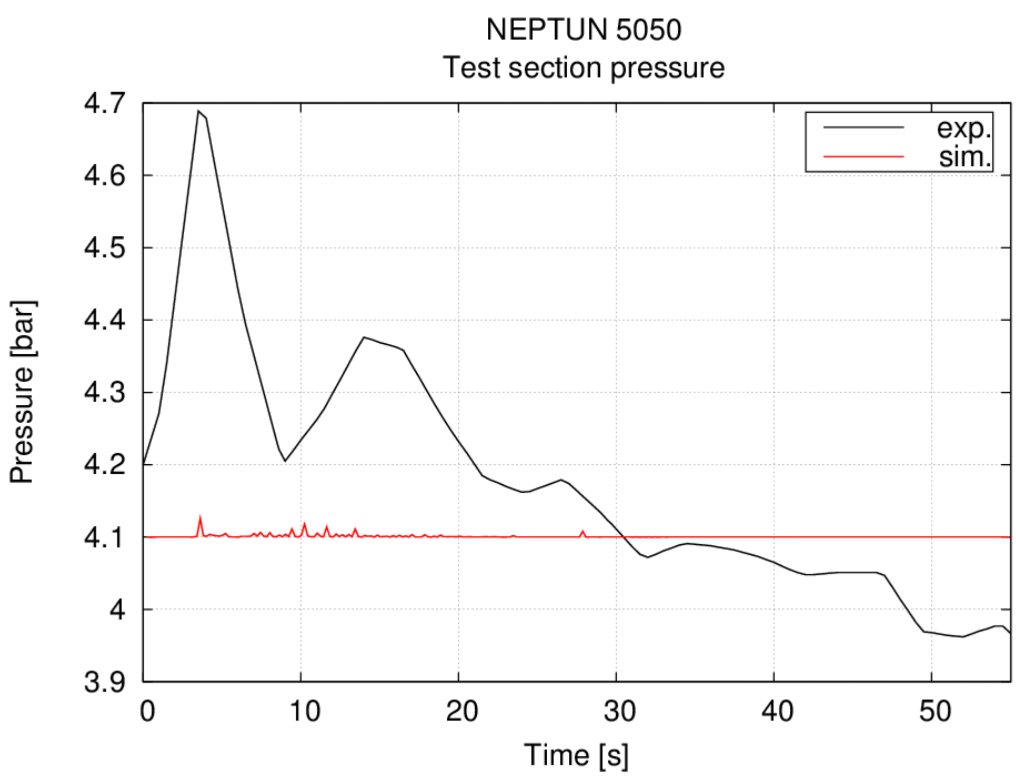

Figure 8 Test Section Pressure (5050)

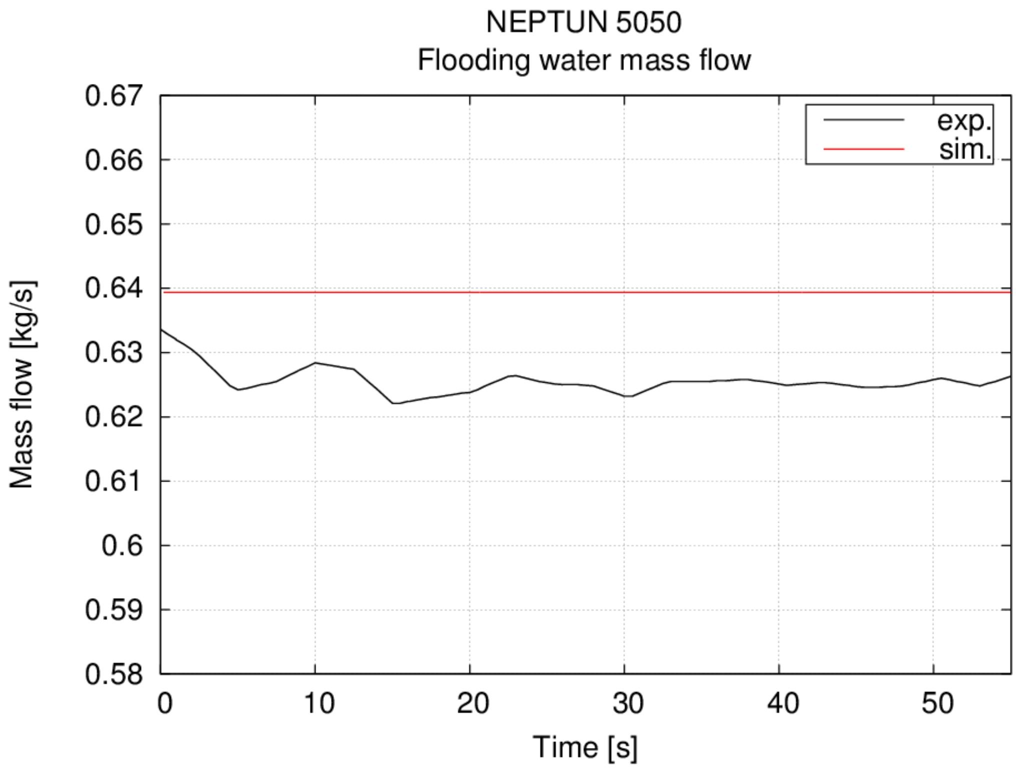

Figure 9 Flooding Water Mass Flow (5050)

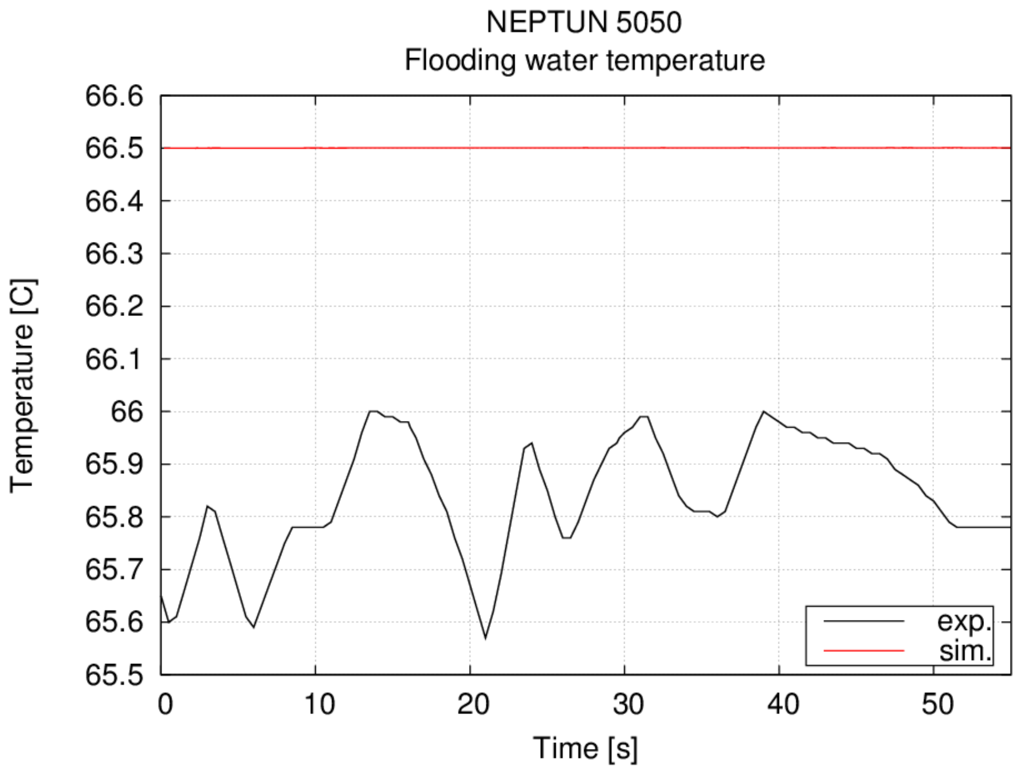

Figure 10 Flooding Water Temperature (5050)

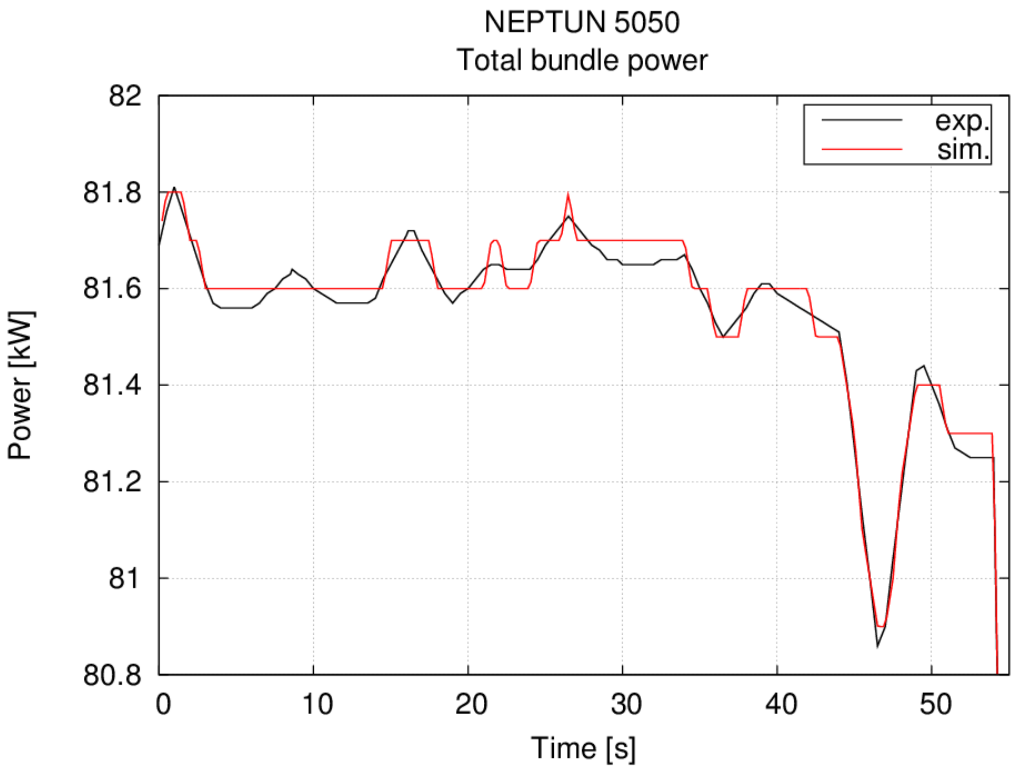

Figure 11 Total Bundle Power (5050)

Collapsed water level, shown in Figure 12, shows relatively good agreement with test data. As the experiment initial water level is in the heated section it is possible that in the experiment flooding was started slightly prematurely. For the simulation initial water level was set to fill only the inlet tube. During the simulation heated section doesn't fully quench unlike in the experiment (Figure 13). Experiment quench times for Figure 13 are estimated from cladding temperatures (which are presented later). Heat flow from heater elements dominates total heat structure heat release but during the first 15 seconds of the simulation other heat flows are not insignificant (Figure 14). It is, however, notable that uncertainties related to channel wall and guide tubes are relatively large, as discussed earlier.

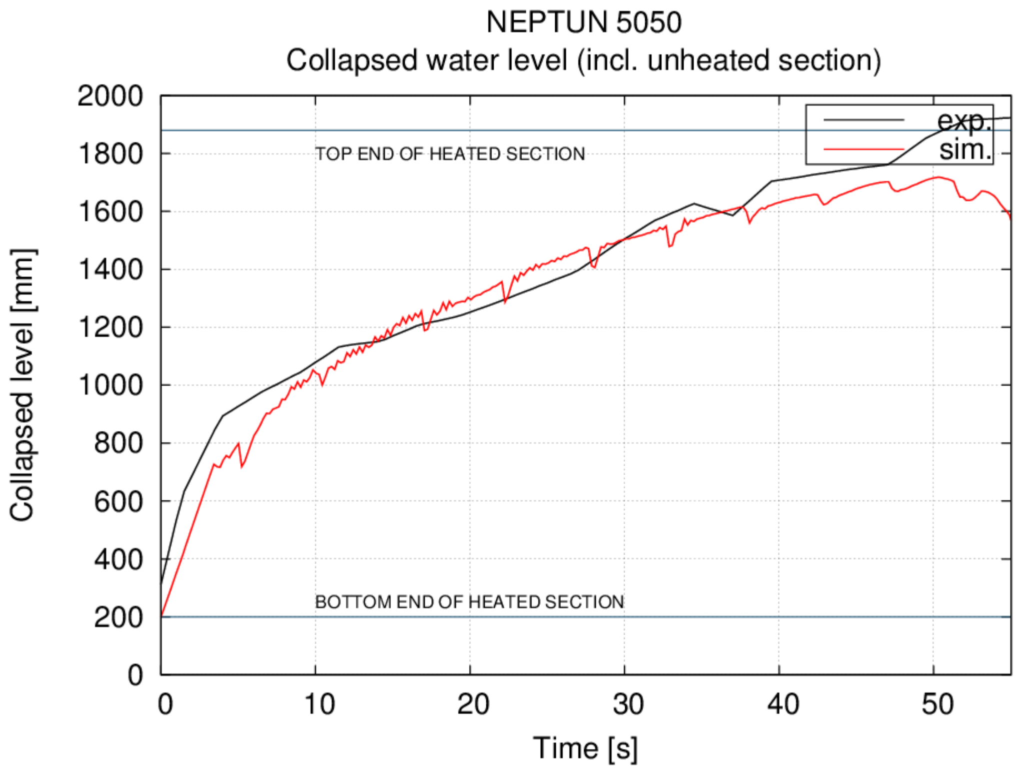

Figure 12 Collapsed Water Level (5050)

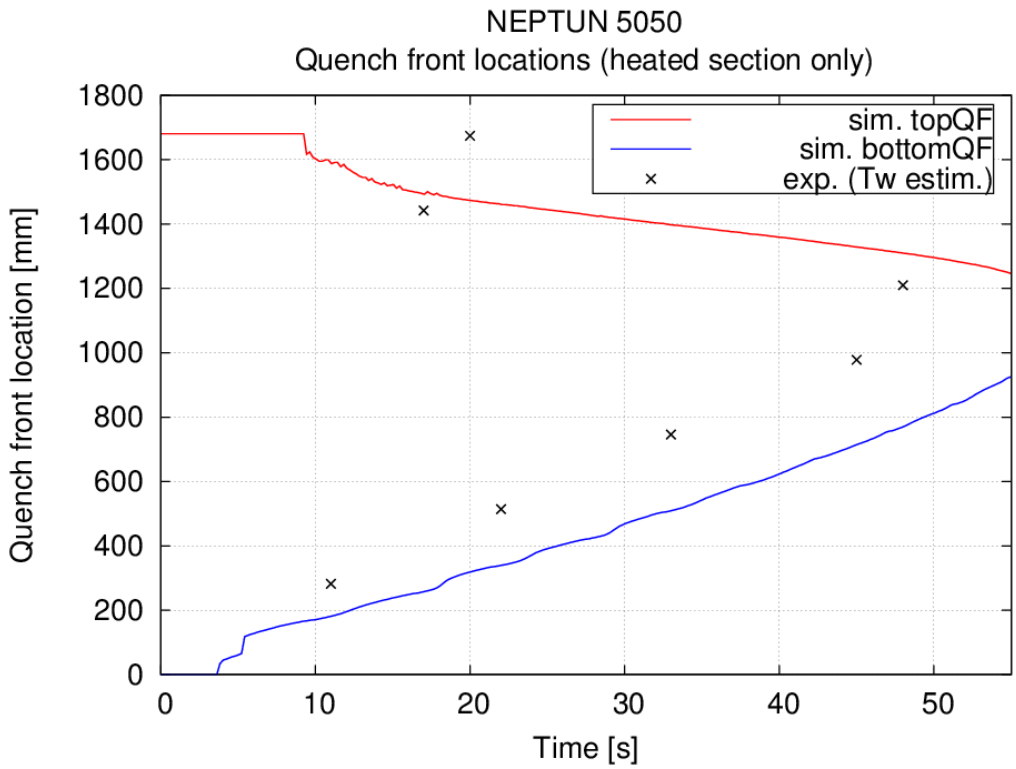

Figure 13 Quench Front Locations (5050)

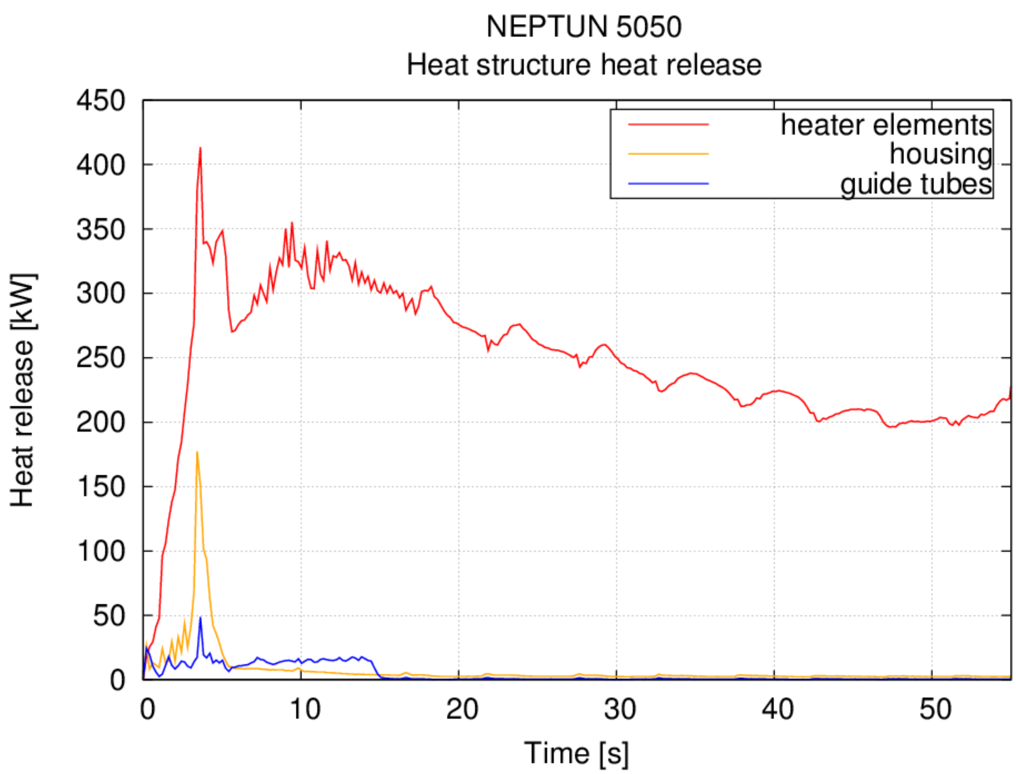

Figure 14 Heat Structure Heat Release (5050)

Temperature measurements from levels 2-8 are presented in Figures 15-21. In general, TRACE predicts higher temperatures and later quenching in the first two thirds of the test section. Both experiment and simulation agree that measurement levels 7 & 8 are quenched by the upper quench front but difference in timing is significant. In experiment measurement from level 7 shows earlier quenching than in level 8 which is probably caused by a difference in rod bundle sensor placement. TRACE predicts reasonably similar entrainment to the experiment (Figure 22).

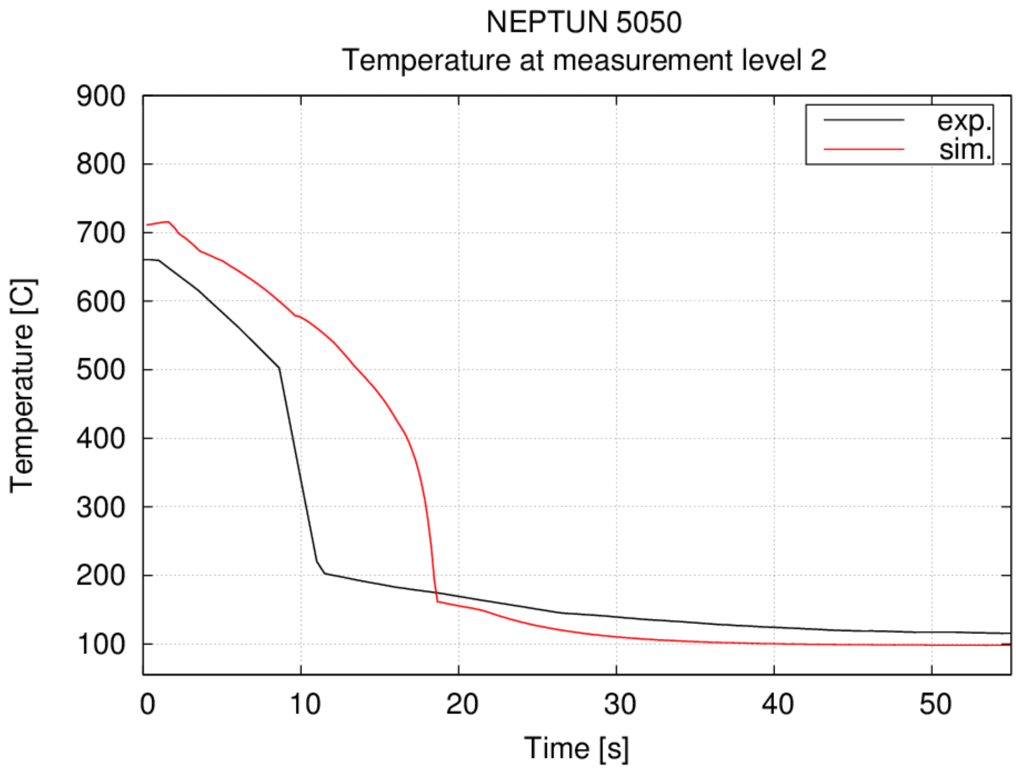

Figure 15 Temperature at Measurement Level 2 (5050)

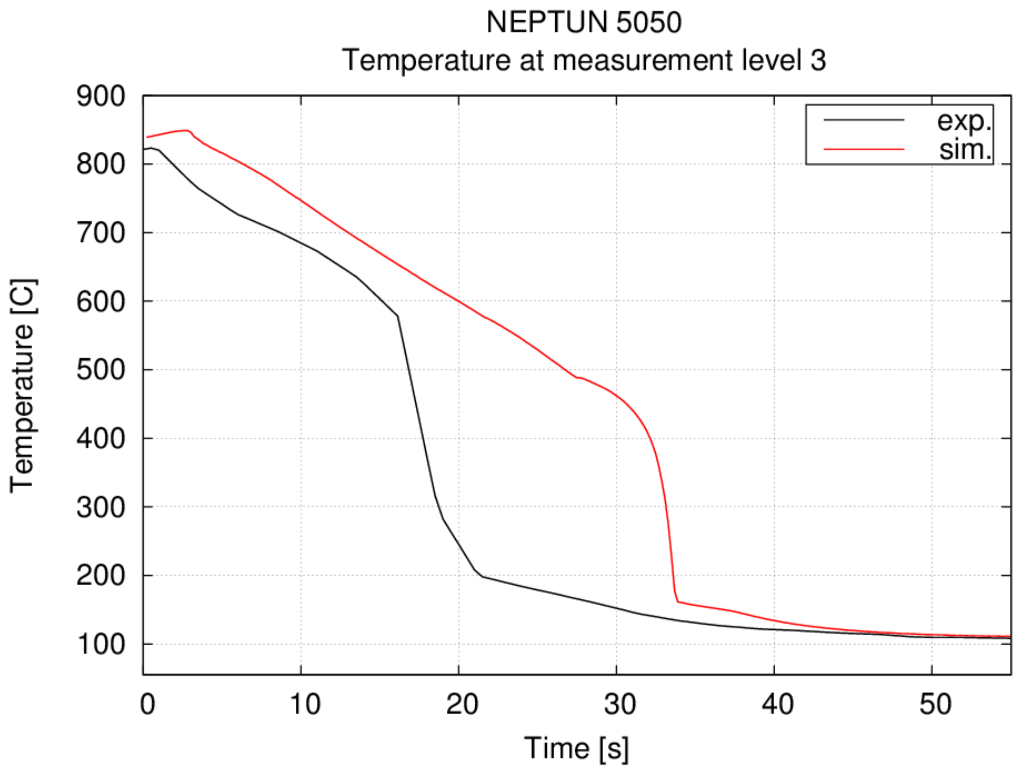

Figure 16 Temperature at Measurement Level 3 (5050)

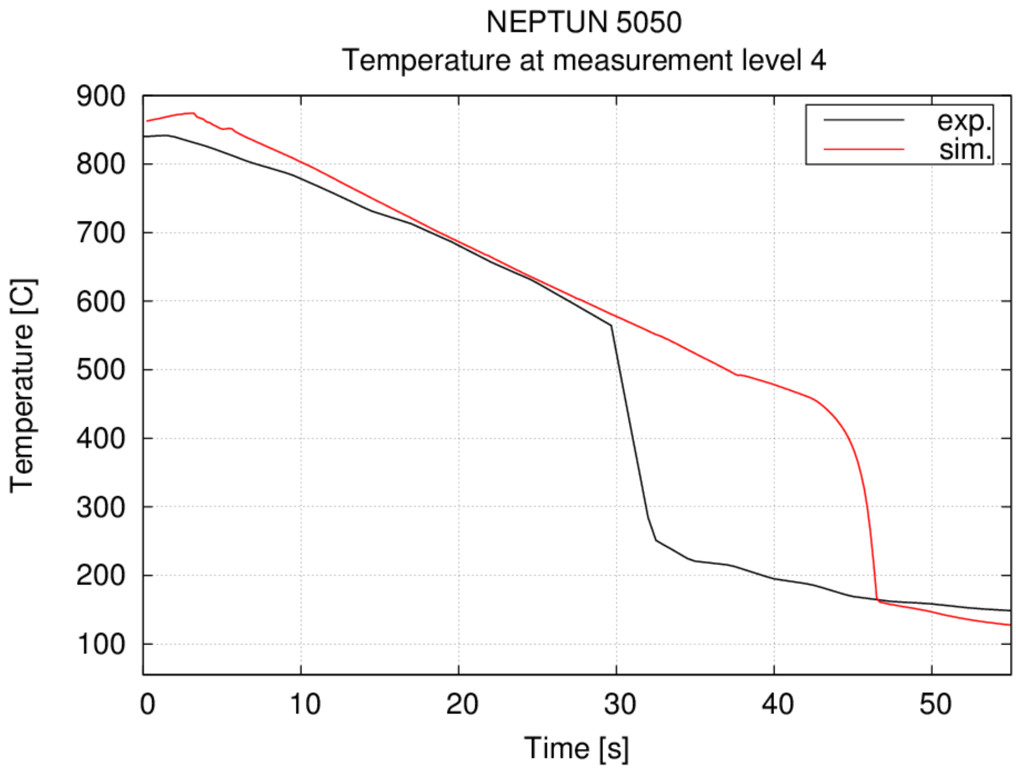

Figure 17 Temperature at Measurement Level 4 (5050)

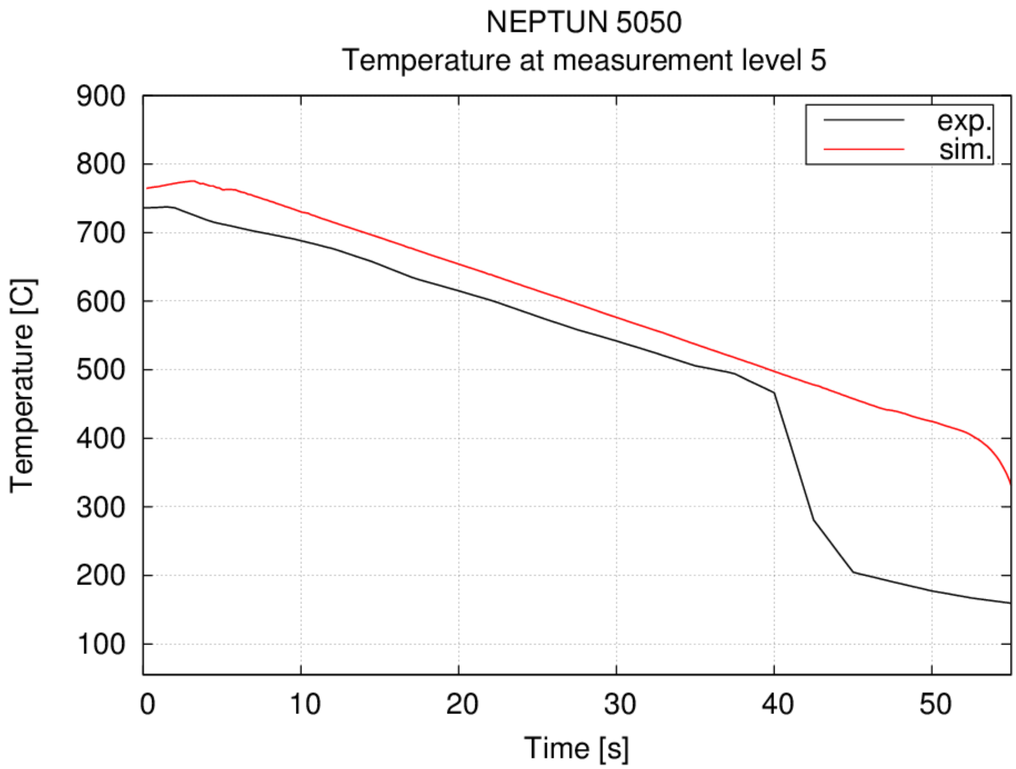

Figure 18 Temperature at Measurement Level 5 (5050)

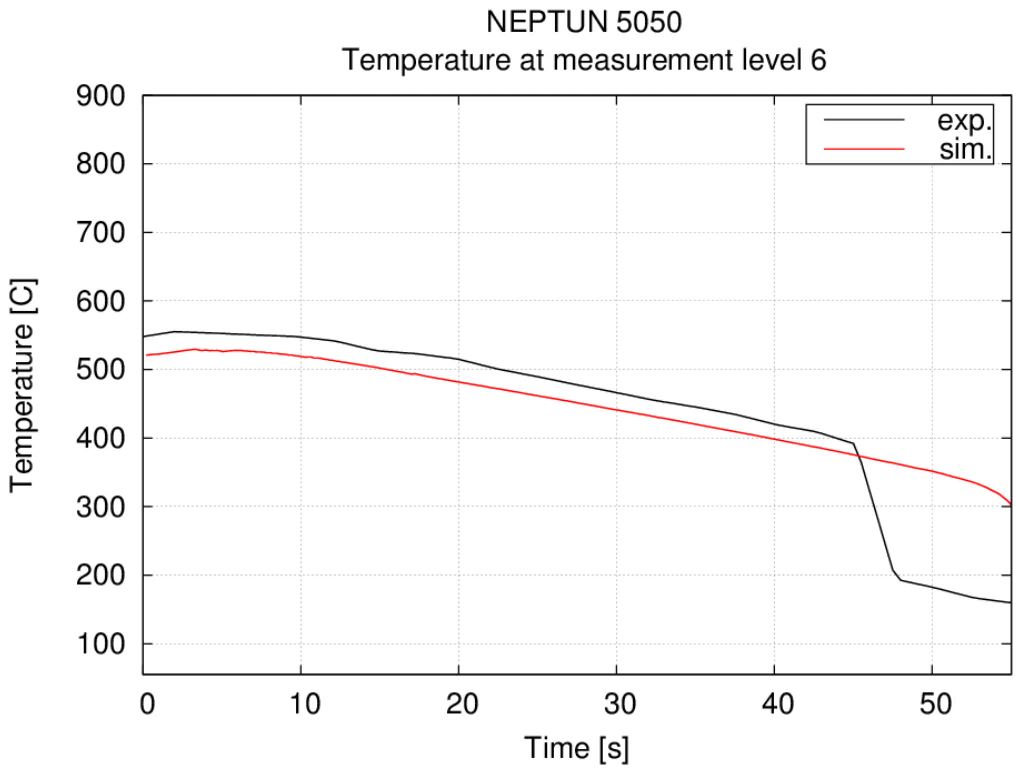

Figure 19 Temperature at Measurement Level 6 (5050)

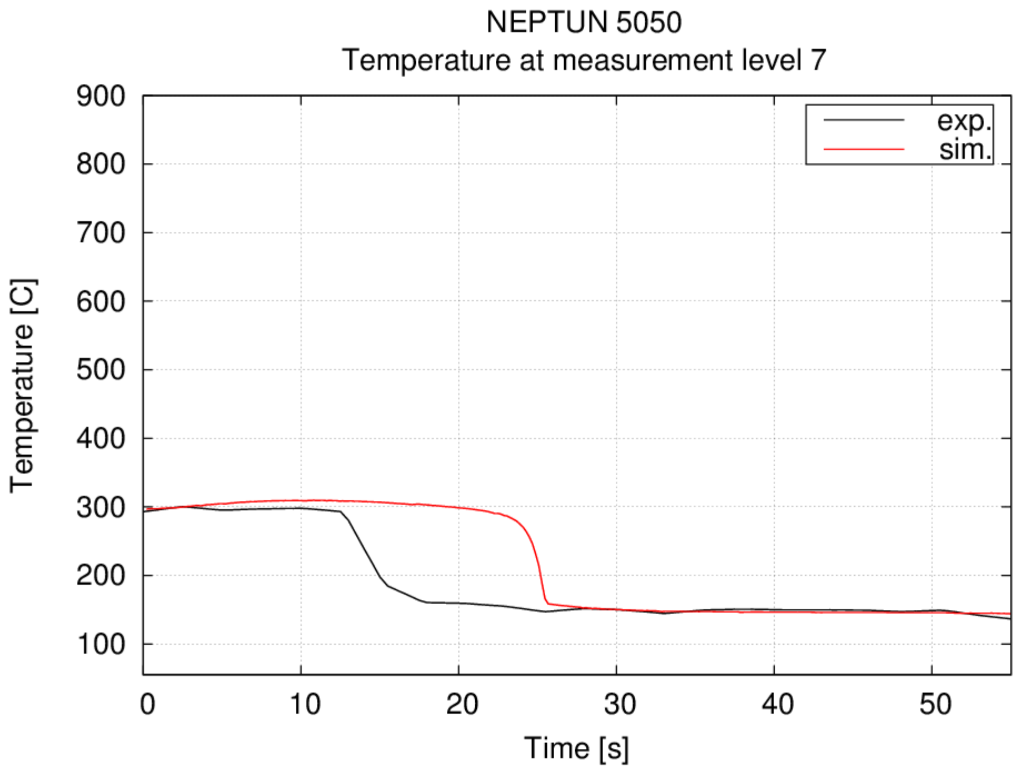

Figure 20 Temperature at Measurement Level 7 (5050)

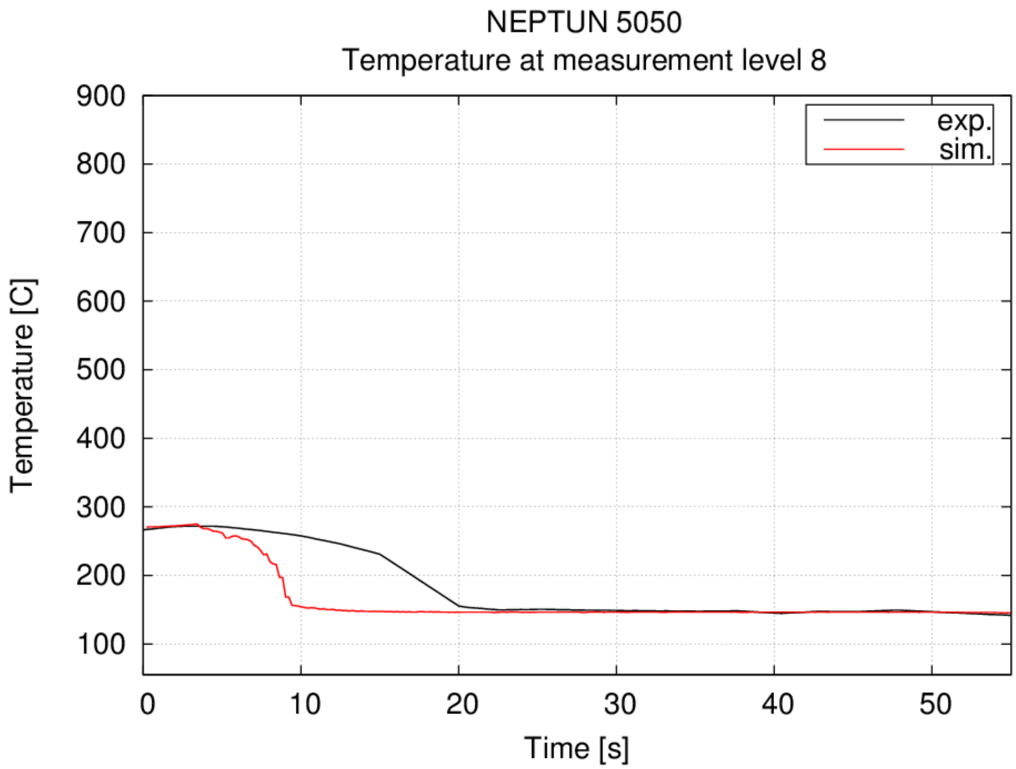

Figure 21 Temperature at Measurement Level 8 (5050)

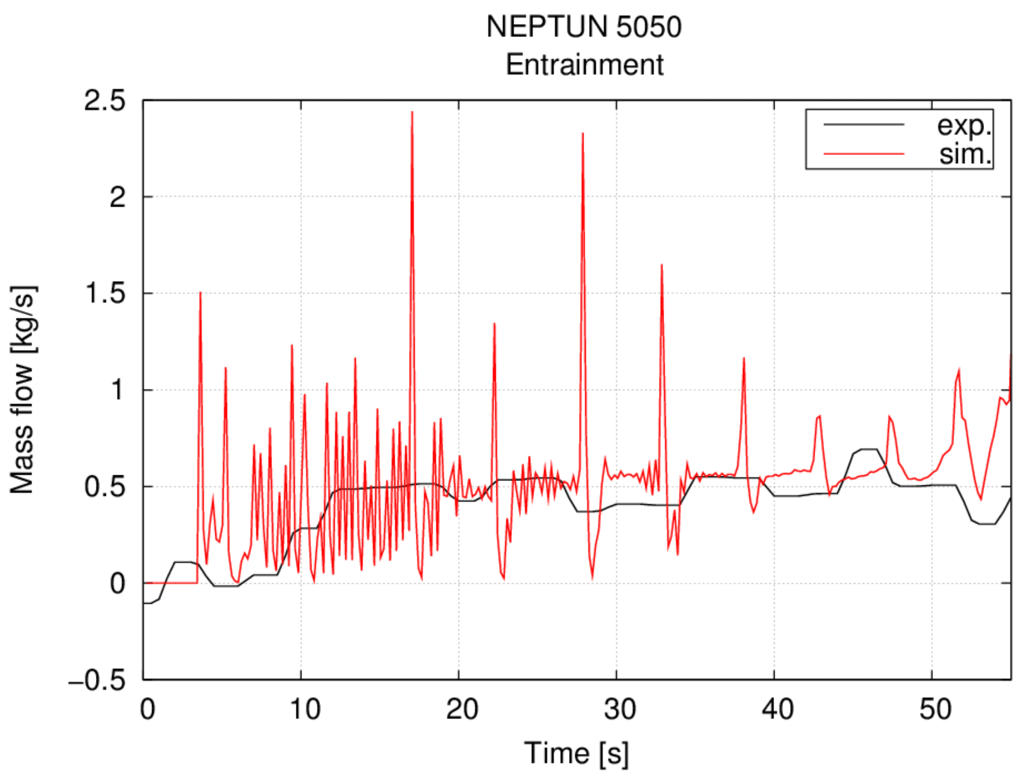

Figure 22 Entrainment in the Experiment and in the Simulation (5050)

5.2 Experiment 5052

Experiment 5052 is a low flood rate (2.5 cm/s) case with otherwise similar conditions to experiment 5050. Test section pressure, flooding rate, flooding water temperature and total bundle power area presented in Figures 23-26. Inlet temperature is measured from the unheated inlet cell. As the initial water level is set to be in this same partially steam-filled cell, mass and heat transfer occurs and temperature rises from the initial value. It is likely that the same behavior has occurred also in the actual test although the relatively large 20 cm single cell size neglects temperature stratification within this volume. As in the test 5050, pressure, flooding rate and temperature are given as fixed boundaries while the test section power is used as shown by the data. All experimental data of 5052 is from Ref. 2.

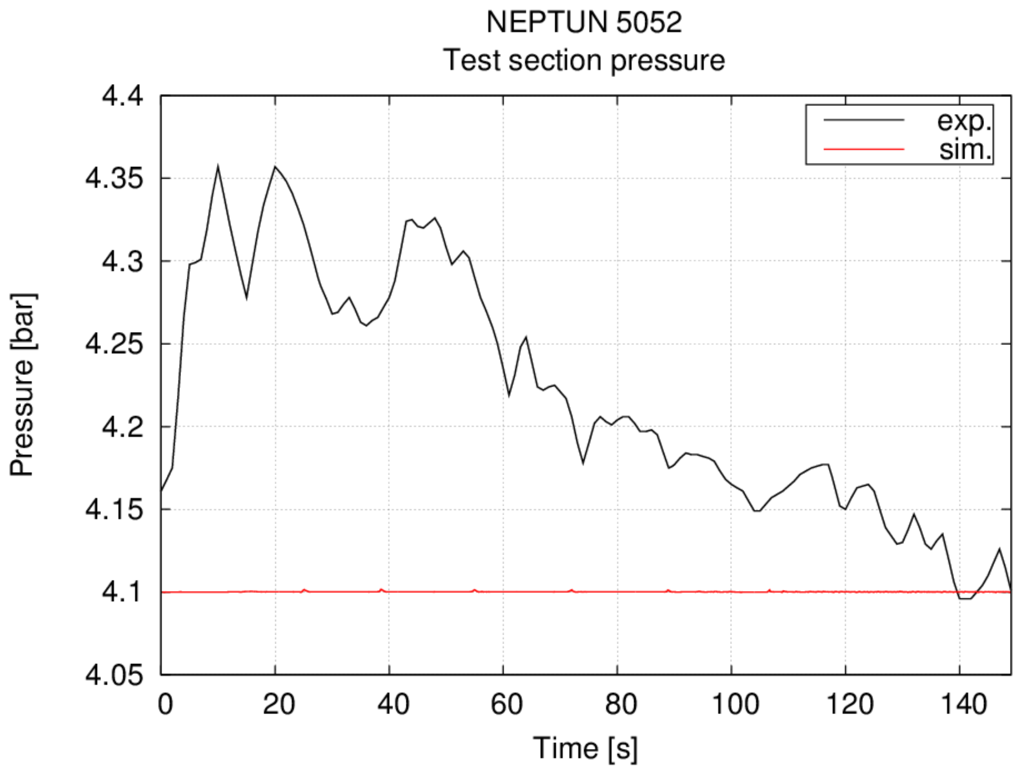

Figure 23 Test Section Pressure (5052)

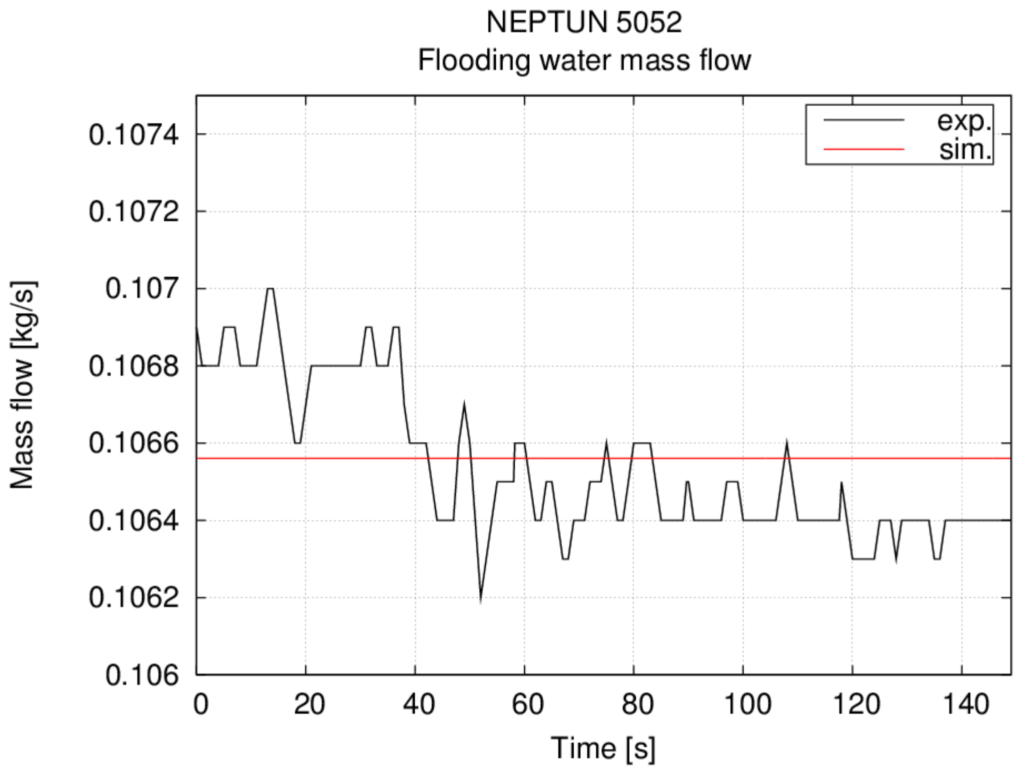

Figure 24 Flooding Water Mass Flow (5052)

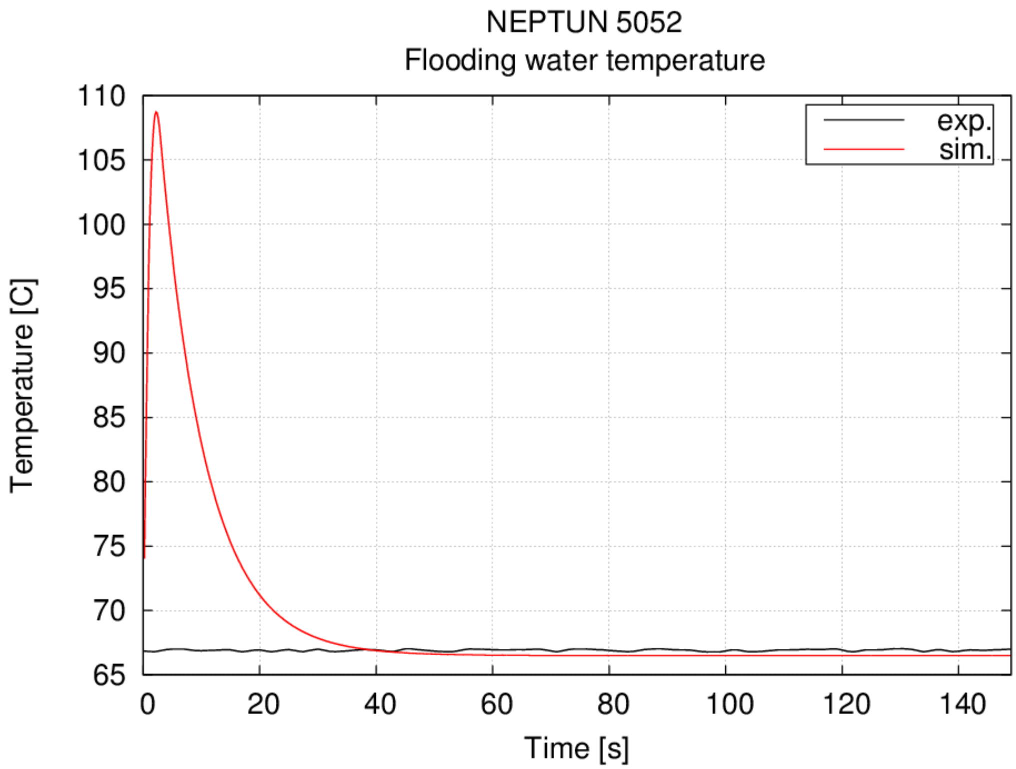

Figure 25 Flooding Water Temperature (5052)

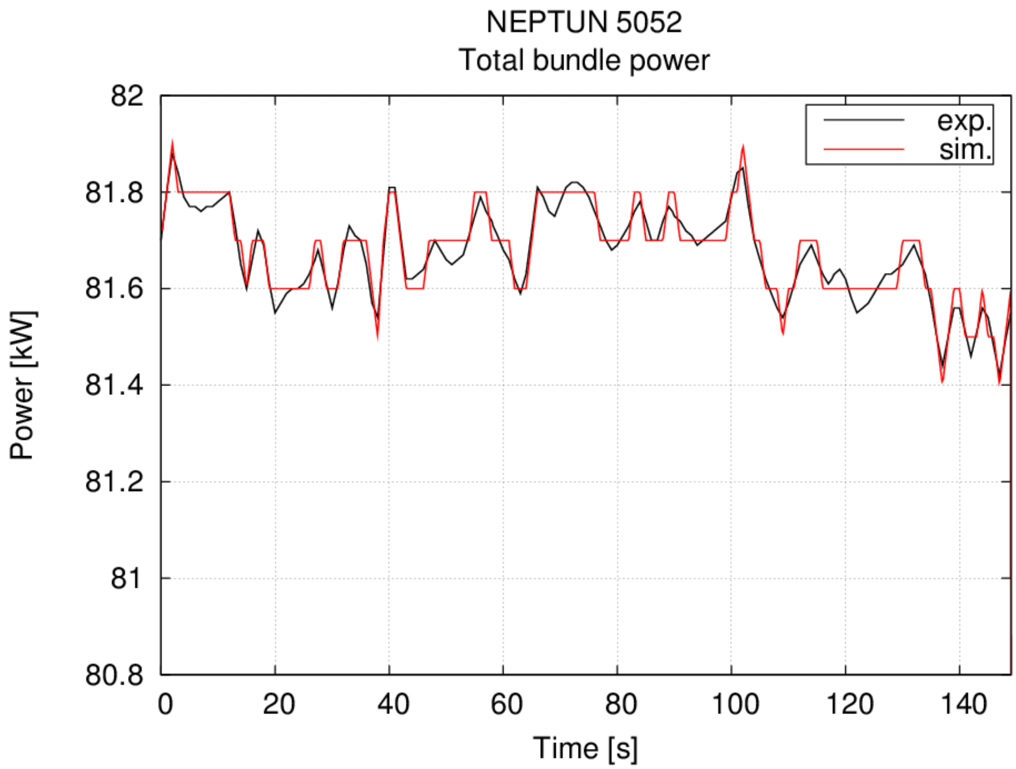

Figure 26 Total Bundle Power (5052)

Like in test 5050, there is a good agreement between collapsed water level prediction and test result (Figure 27). Calculated quench fronts (with estimation of experiment quench times based on cladding temperatures) and energy releases are presented in Figures 28 and 29.

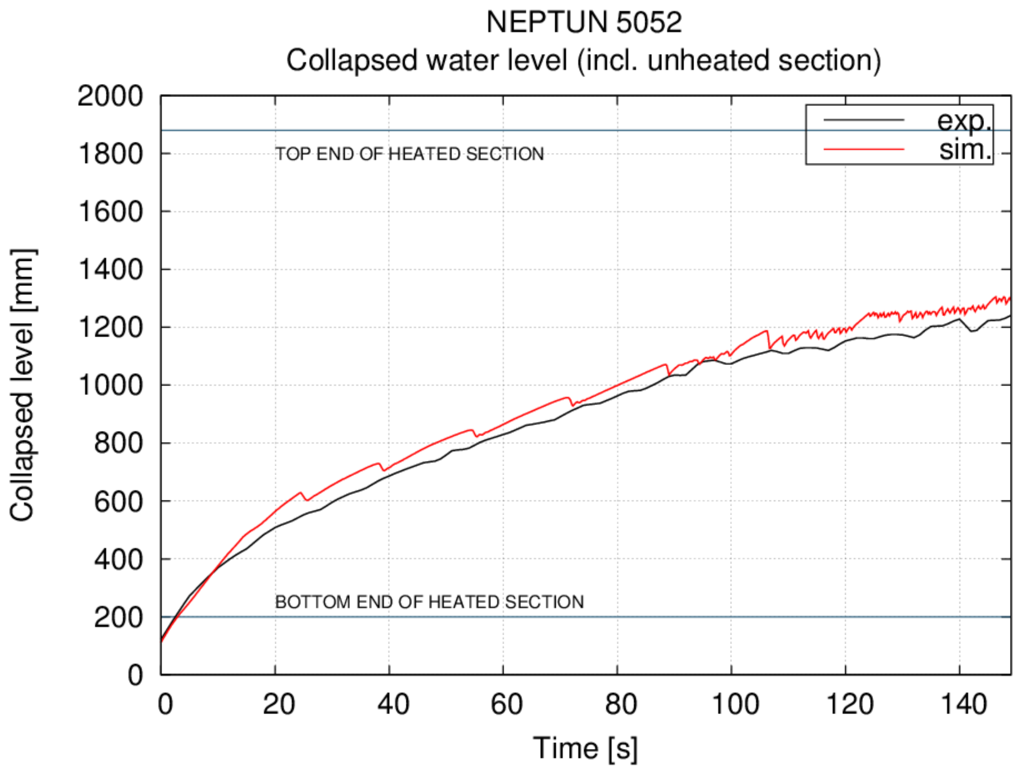

Figure 27 Collapsed Water Level (5052)

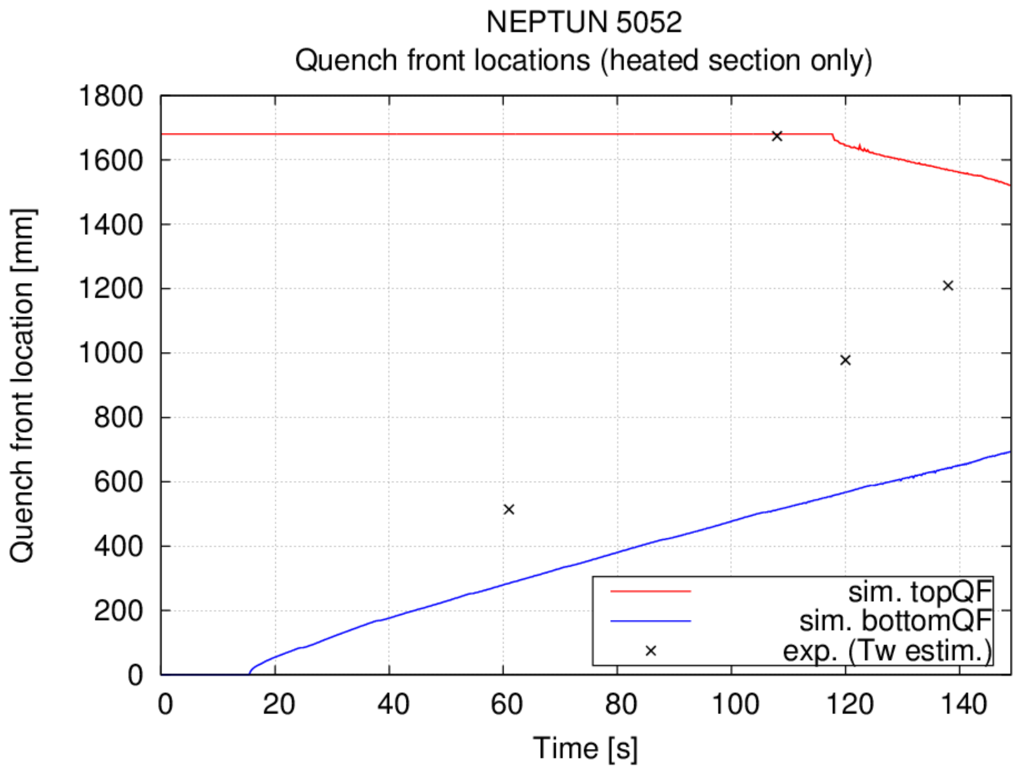

Figure 28 Quench Front Locations (5052)

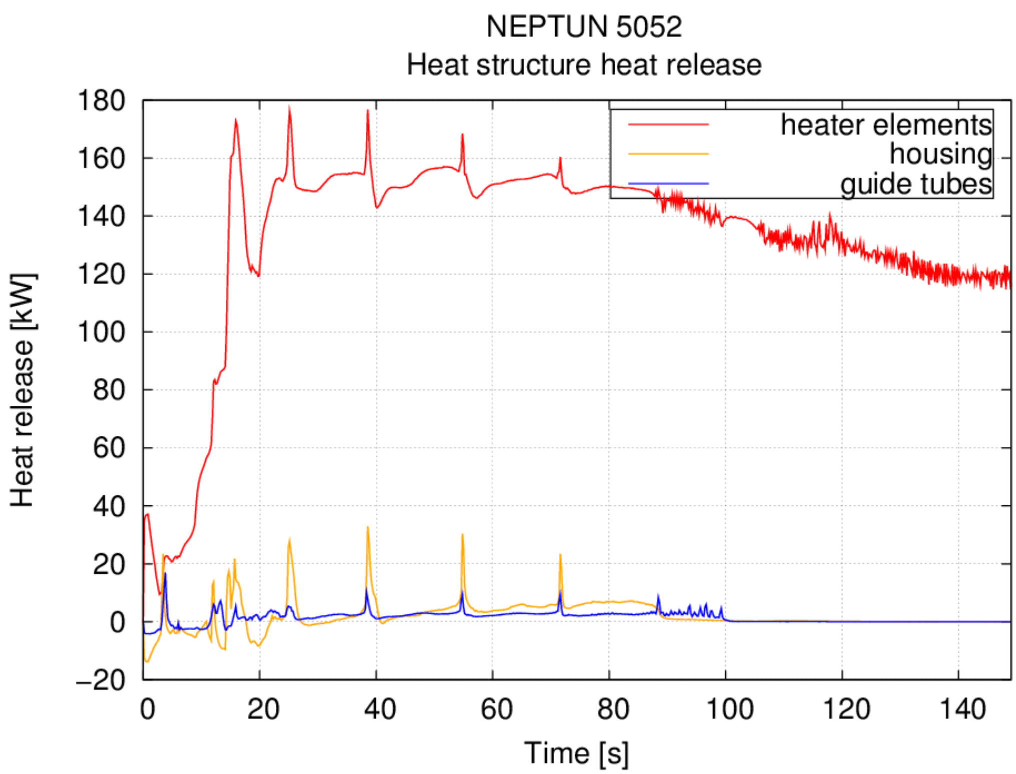

Figure 29 Heat Structure Heat Release (5052)

Few temperature measurements are available for 5052, and for this analysis, one of them was discarded due to inconsistent behavior[1], perhaps due to sensor placement. Cladding temperatures of elevations 3, 5, 6 and 8 are presented in Figures 30-33. Results of the simulation are qualitatively similar to 5050 as in the lower parts of the test section predicted temperature tends to be higher and quenching is occurring later. Temperatures in elevations 6 & 8 are a better match to experiment although there is still a significant difference in quench times. TRACE predicts correctly that elevation 8 is quenched by the upper quench front. Entrainment is presented in Figure 34.

[1] Cladding temperature at measurement level 7 shows quenching significantly before upper or lower quench fronts reach the elevation.

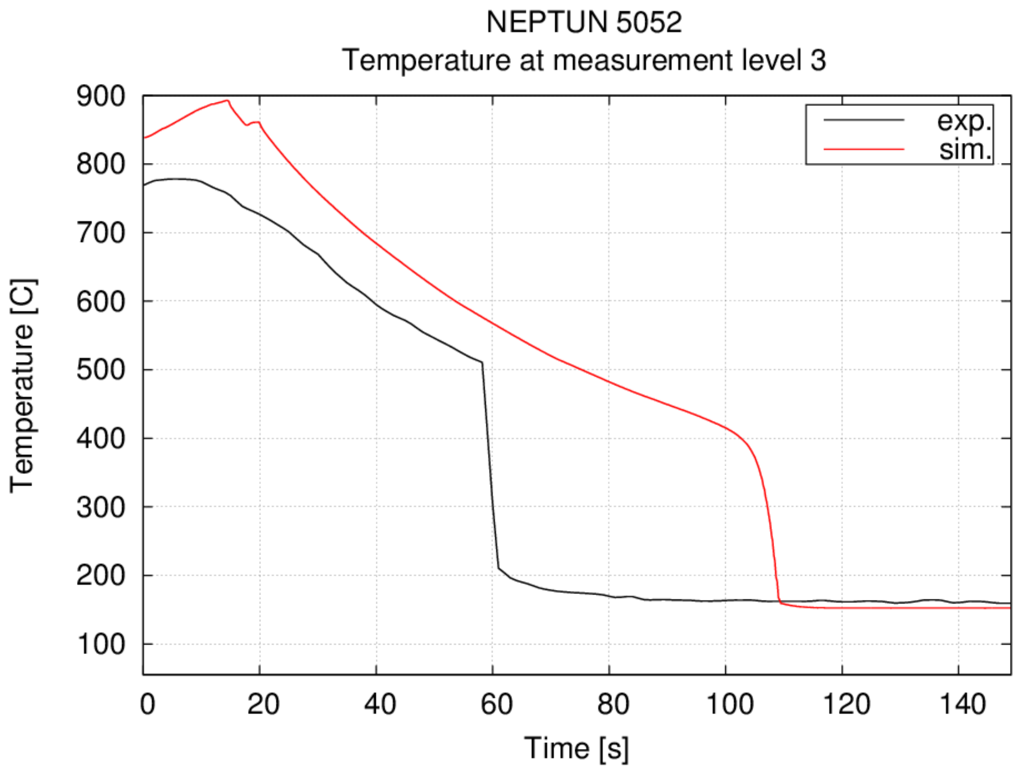

Figure 30 Temperature at Measurement Level 3 (5052)

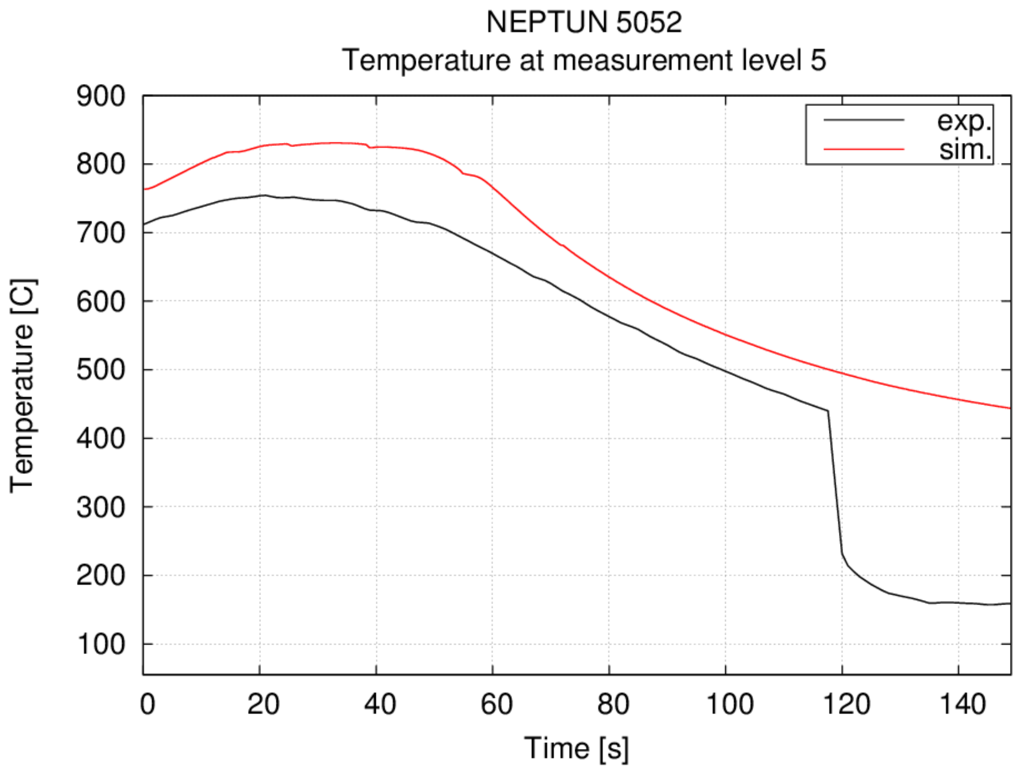

Figure 31 Temperature at Measurement Level 5 (5052)

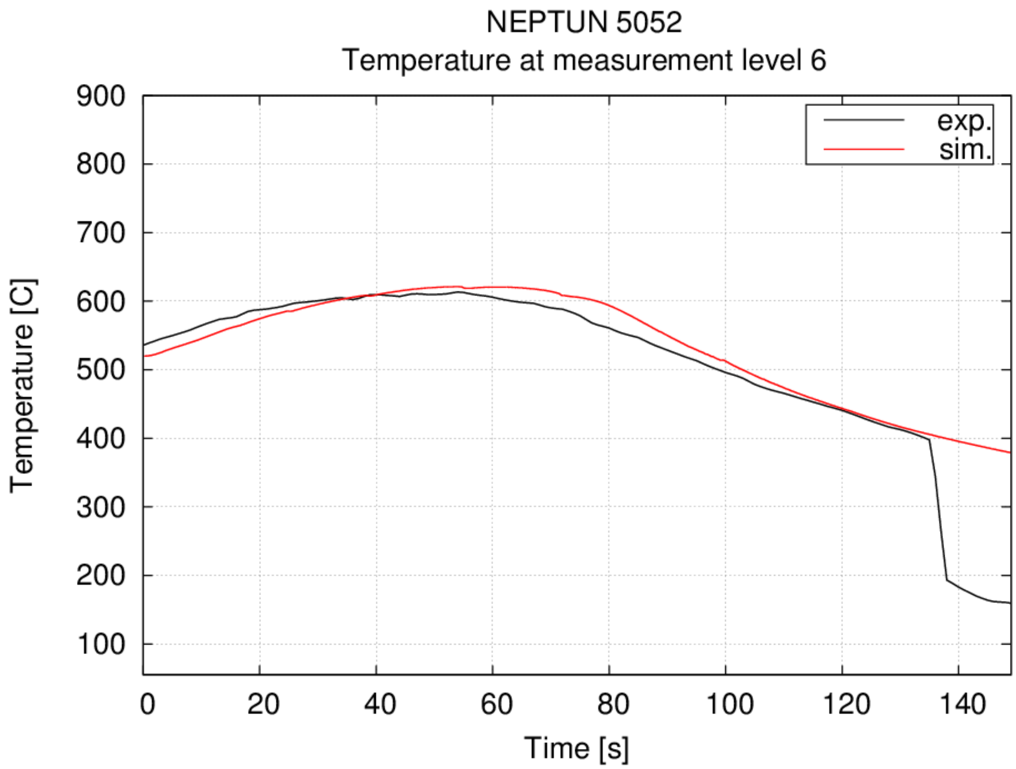

Figure 32 Temperature at Measurement Level 6 (5052)

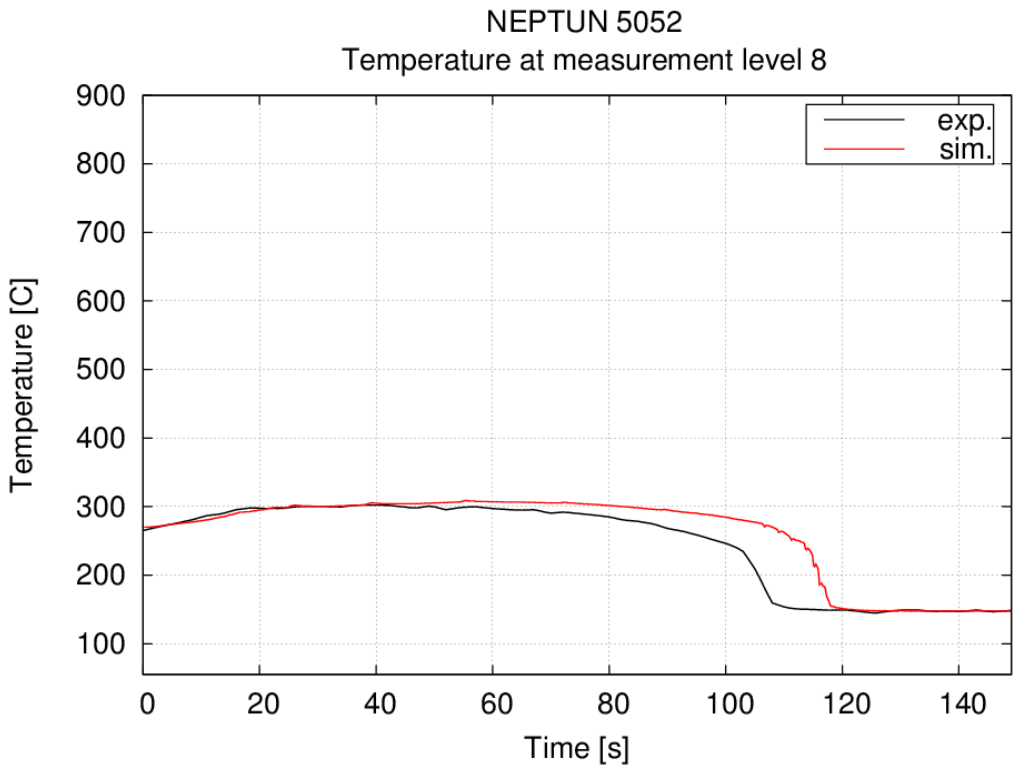

Figure 33 Temperature at Measurement Level 8 (5052)

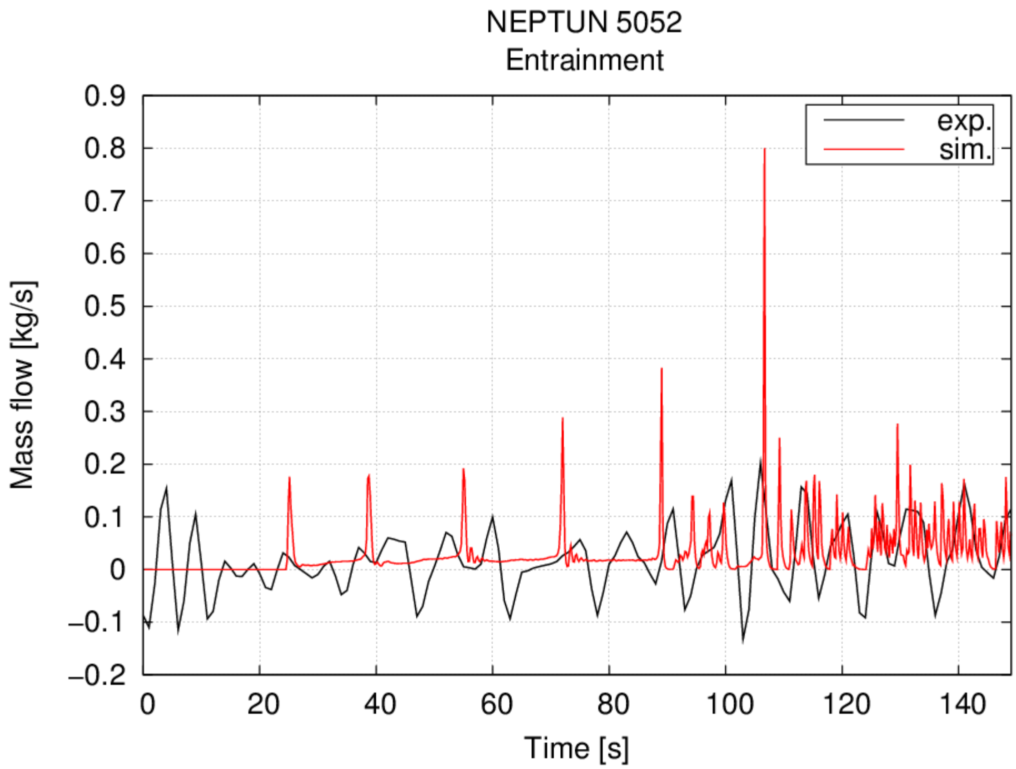

Figure 34 Entrainment in the Experiment and in the Simulation (5052)

6 CONCLUSIONS

NEPTUN experiments 5050 and 5052 have been simulated with TRACE V5.0 Patch 5. Calculation results were compared to experiment data received from OECD/NEA databank but, unfortunately, not all original experiment data was available. Uncertainties of the experimental data were not quantified in the original material nor were there enough available data in order to form an estimate. There is also uncertainly about radial placement of those thermocouples for which data is available. Location of these thermocouples could provide insight into some of the behavior observed in experiments.

Both simulations show qualitatively similar results: TRACE predicts higher temperature in the lower parts of the test section which leads to later quenching than in the experiment. In higher elevations temperatures are a closer match but there is still a significant difference in quenching times. Collapsed water level prediction is in reasonably good agreement in both experiments. Detailed sets of measurement data would be needed for a more conclusive analysis.

7 REFERENCES

1. CSNI1012 NEPTUN/5050 data. OECD/NEA databank. Available at: http://www.oecd-nea.org/tools/abstract/detail/csni1012/

2. CSNI1013 NEPTUN/5052 data. OECD/NEA databank. Available at: http://www.oecd-nea.org/tools/abstract/detail/csni1013/

3. Richner, M., Analytis, G. Th., Aksan, N., 1992. Assessment of RELAP5/MOD2, Cycle 36.02, Using NEPTUN Reflooding Experiment Data. USNRC International Agreement Report, NUREG/IA-0054.

4. Grütter, H., Stierli, F., Aksan, S. N., Varadi, G., 1980. Neptun Bundle Reflooding experiments: Test Facility Description. Würenlingen, Switzerland.

5. Aksan, S. N., Stierli, F., Analytis, G. Th. Boil-Off Experiments with the EIR-NEPTUN Facility: Analysis and Code Assessment Overview Report. USNRC International Agreement Report, NUREG/IA-0040.

6. Kanthal A-1. Resistance heating wire and resistance wire. Datasheet. Available at: http://www.kanthal.com/en/products/material-datasheets/wire/resistance-heating-wire-and-resistance-wire/kanthal-a-1/

7. Thermal properties of aluminium oxide. Available at: http://accuratus.com/alumox.html

8. Thermal properties of copper. Available at: https://www.engineersedge.com/properties_of_metals.htm

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11. ABSTRACT (200 words or less)

NEPTUN experiments 5050 and 5052 have been simulated with TRACE V5.0 Patch 5. Calculation results were compared to experiment data received from OECD/NEA databank but, unfortunately, not all original experiment data was available. Uncertainties of the experimental data were not quantified in the original material nor were there enough available data in order to form an estimate. There is also uncertainly about radial placement of those thermocouples for which data is available. Both simulations show qualitatively similar results: TRACE predicts higher temperature in the lower parts of the test section which leads to later quenching than in the experiment. In higher elevations temperatures are a closer match but there is still a significant difference in quenching times. Collapsed water level prediction is in reasonably good agreement in both experiments.

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