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Rod Bundle Heat Transfer (RBHT) Project Phase I Summary Report

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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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List of abbreviations and acronyms

ARL	Applied Research Laboratory (United States)
ATF	Accident-tolerant fuel
DBA	Design basis accident
CEA	Commissariat à l'Energie Atomique et aux énergies alternatives (French Alternative Energies and Atomic Energy Commission)
CSN	Consejo de Seguridad Nuclear (Spain)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
ECCS	Emergency core cooling system
EDF	Electricité de France
ENSI	Swiss Federal Nuclear Safety Inspectorate
FOM	Figures of merit
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (French Institute for Radiological Protection and Nuclear Safety [ASNR since January 2025])
KAERI	Korea Atomic Energy Research Institute
KEPCO	Korea Electric Power Corporation
KINS	Korea Institute of Nuclear Safety
KHNP CRI	Korea Hydro and Nuclear Power – Central Research Institute
LOCA	Loss-of-coolant accident
MB	Bundle mass
NEA	Nuclear Energy Agency
NINE	Nuclear and Industrial Engineering
NRA	Nuclear Regulation Authority (Japan)
PCA	Permanent Court of Arbitration
PCT	Peak cladding temperature
PDF	Probability distribution functions
PSI	Paul Scherrer Institute
PSU	Pennsylvania State University
RBHT	Rod Bundle Heat Transfer
SE	Steam exhaust
SMR	Small modular reactors
SSM	Swedish Radiation Safety Authority
USNRC	United States Nuclear Regulatory Commission
VTT	Teknologian tutkimuskeskus VTT Oy (Finland)
WGAMA	Working Group on Accident Management and Analysis (NEA)

Executive summary

The NEA Rod Bundle Heat Transfer (RBHT) project focused on reflood thermal hydraulics. The project generated new and unique reflood experimental data and provided these data to the participants, who included members from 20 organisations from 12 countries. Simulations of the reflood experiments were performed and compared to the data, providing a useful and important assessment of the several different analytical codes involved.

Reflood thermal hydraulics remains a difficult and complex subject. Understanding the physical phenomena that occur during reflood is important to nuclear safety. Simulations of hypothetical large break loss-of-coolant accidents (LOCAs) often determine the core management strategies with respect to the sufficiency of the emergency core cooling system (ECCS). Inaccurate prediction of reflood thermal hydraulics can lead to an unnecessary restriction or critical operation of the reactor, or an unreliable expectation of ECCS performance.

The RBHT project was conducted to provide participants with new reflood data to assess analysis codes and improve their accuracy. The RBHT facility is well instrumented and records for given boundary conditions a detailed temperature distribution within the rod bundle as well as steam temperatures, spacer grid temperatures, void fraction below the quench front, and the liquid carryover and steam exhaust fractions. Of particular interest is the camera system that records droplet size, droplet velocity and the distribution of droplet sizes during a transient. The tests are unique in that the camera system provides information on droplet breakup as a dispersed droplet flow encounters a spacer grid.

The primary objective of the project was to generate a set of reflood data that covered a broad range of thermal-hydraulic conditions to be considered in code assessment. The secondary objective was to use the data to investigate code uncertainty analysis methods. These objectives were accomplished by conducting two series of tests.

The first series was considered the “open” test series. All measurements shared before these tests were simulated by participants and analytical results were compared to the data with the focus on several figures of merit (FOMs) to quantify code accuracy and allow possible improvements to achieve optimised results. The second test series was considered the “blind” test series. The “blind” test data were not immediately made available to the participants. Participants were provided with initial and boundary conditions for the tests. The participants were requested to simulate the experiments and apply a code uncertainty analysis method to capture the FOMs. The experimental campaign produced data for a total of 16 reflood tests. The “open” test series consisted of 11 experiments and the “blind” test series 5 experiments. Reflood rates ranged from 0.5 cm/sec to 15 cm/sec thus producing data applicable to dispersed flow film boiling and inverted annular flow film boiling. Inlet subcooling ranged from 2.8 K to 80 K. Tests with variable reflood rates and oscillatory reflood rates were included in the test matrix. Most tests were conducted at constant bundle power, but tests simulating a decay heat scenario were also performed. Evaluation of the data produced a detailed quench profile for each test in addition to bundle mass, carryover and steam exhaust fractions to characterise the mass distribution during the transient.

New experimental findings included the observation that entrainment and carryover could occur even at a very low reflood rate (0.5 cm/sec) and that spacer grids that rewet early in a transient could dry out later in time for variable reflood rate tests. Each participant used a code of their own selection and simulated the reflood tests. Codes used included APROS,

ATHLET, CATHARE, CTF, MARS, RELAP5, TRACE and SPACE. There were no guidelines on the modelling approach or on the uncertainty analysis method applied, but participants were requested to compare their analytical results to a set of FOMs to characterise code performance and accuracy. Extensive comparison of predicted and experimental results was made by the participants for all tests, and an in-depth evaluation of two types of experiments comparing the performance of the various codes was made. The evaluation of code performance was made for a low reflood rate test and a high reflood rate test for each of the "open" and "blind" test series.

The comparisons gave the following findings:

1. Most codes overpredicted the amount of carryover from the bundle, while underestimating the mass retained in the bundle and amount of steam exiting the bundle. This finding suggests that prediction of liquid entrainment at the quench front is overestimated and models for entrainment need improvement.
2. Many codes overpredicted the bundle peak cladding temperature (PCT) for low reflood rate tests. This suggests that the dispersed flow film boiling heat transfer model is conservative in those codes and could be improved.

The so-called "user effect" represents an important uncertainty in the simulation of a reflood test. Users were free to model the RBHT facility as they considered appropriate. However, it was clear that users of the same analysis code could obtain significantly different results. This suggests that the development of user guidelines for an analysis code should be developed and/or improved for analysis codes in association with the validation process. The participants recommend that research into reflood thermal hydraulics be continued. Results from this project showed that several analysis codes used for safety analysis do not predict some phenomena with sufficient accuracy. Additional experiments at low flooding rates would be beneficial to further code development and assessment activities.

This report was approved at the 72nd meeting of the NEA Committee on the Safety of Nuclear Installations (CSNI) in December 2022 (as recorded in the "Summary Record of the 72nd Meeting of the CSNI" [NEA/SEN/SIN(2022)6] [not publicly available]) and prepared for publication by the NEA.

All figures that do not include source information were created for the activity. The source in these cases is "NEA data, 2023".

1. Project description and participants

This report documents an international benchmark on reflood thermal hydraulics organised by the NEA Working Group on Accident Management and Analysis (WGAMA). Reflood experiments were conducted in the rod bundle heat transfer (RBHT) facility located at the Pennsylvania State University (PSU). The participants of the benchmark simulated the tests with the thermal-hydraulic code of their choice and compared the results to the data. Participants from 12 countries representing 20 organisations were involved.

The following participated in this project and contributed to the report:

- The United States Nuclear Regulatory Commission (USNRC), United States
- Tractebel Engineering S.A., Belgium
- Bel V, Belgium
- UJV Rez, Czechia
- Teknologian tutkimuskeskus VTT Oy (VTT), Finland
- Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France
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- Electricité de France (EDF), France
- Framatome, France
- Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany
- Nuclear and Industrial Engineering (NINE), Italy
- Nuclear Regulation Authority (NRA), Japan
- Korea Atomic Energy Research Institute (KAERI), Korea
- Korea Institute of Nuclear Safety (KINS), Korea
- Korea Hydro and Nuclear Power – Central Research Institute (KHNP CRI), Korea
- KEPCO Nuclear Fuel (KEPCO NF), Korea
- Consejo de Seguridad Nuclear (CSN), Spain
- Swedish Radiation Safety Authority (SSM), Sweden
- Swiss Federal Nuclear Safety Inspectorate (ENSI), Switzerland
- The Paul Scherrer Institute (PSI), Switzerland

The study was conducted in two major phases. In the first phase, 11 "open" tests were conducted and distributed to the participants. These experiments were simulated by most participants using an analysis code of their choice. Chapter 2 of this report describes the

RBHT facility, and the experimental findings are summarised in Chapter 3. Chapters 4 and 6 discuss modelling of the facility and the results of simulations. Chapter 5 discusses the figures of merit that were used to characterise agreement between predicted and measured results.

In the second phase of this study, five "semi-blind" tests were conducted. In these tests, thermal-hydraulic conditions like those in the "open" tests were imposed on the experiments and the test data recorded. However, only the as-measured initial and boundary conditions are provided to the participants. Simulations of these blind tests will use an uncertainty methodology of the participant's choice with the goal of capturing one or more of the several "figures of merit" that were defined based on measured quantities. Chapter 7 of this report documents the "blind" tests; the participant simulations of those tests and the uncertainty methods that were applied are discussed in Chapter 8.

Overall, the project can be characterised as having two distinct products. One major product is the experimental data, which provided participants with new and unique reflood data. The second product is comparative code assessment, where simulations of the data suggest strengths and weaknesses of the analysis codes used by the participants.

2. RBHT facility and experimental test matrix

The rod bundle heat transfer (RBHT) facility was designed, and has been generally operated, to provide data suitable for model and correlation development. Most previous reflood test facilities conducted tests to demonstrate the adequacy of an emergency core cooling system (ECCS) and provide data for code assessment. The RBHT facility includes extensive instrumentation to record a detailed temperature profile in a 45-rod bundle and quench front propagation. Optical ports and two cameras were used to measure droplet size and velocities upstream and downstream of spacer grids to provide data on droplet breakup. Steam probes and differential pressure cells measured steam temperatures and provide an estimate of void fraction distribution. Heater rod thermocouples and steam temperature measurements confirm the precursory cooling downstream of a spacer grid. This section contains a description of the RBHT facility and its instrumentation.

Two experimental campaigns were conducted as part of the project. The first campaign performed 11 reflood tests covering a range of conditions. In these tests flooding rates as high as 15 cm/sec and as low as 0.5 cm/sec were included. The inlet water subcooling ranged from 2.8 to 80 K. The system pressure was maintained at 0.276 kPa in all these tests. Table 2.1 lists the “open” tests.

The total bundle power was set at several values, each with the intent of obtaining high temperatures in the bundle while avoiding damage to the heater rods. The power was held constant in all except one test to prolong duration of the reflood transients. In one of the tests the power simulated a decay heat profile. Two cameras were used to record droplet size and velocity, and both cameras were generally positioned near the elevation of peak rod temperatures upstream and downstream of spacer grids. Droplet data were obtained for tests with low flooding rates.

Several of the tests in the open series were designed to provide sensitivities to important parameters. Tests O-3 and O-4 were both conducted with a flooding rate of 15 cm/sec, but with inlet subcooling of 10 and 80 K respectively. Tests O-2 and O-6 likewise provide a sensitivity to inlet subcooling, but at a constant flooding rate of 2.5 cm/sec. Tests O-1 and O-5 provide a sensitivity to flooding rate at an inlet subcooling of 10 K.

Test repeatability was verified by Tests O-5 and O-11. Test O-5 was conducted early in the test programme, and Test O-11 near the end. The results of these two tests were compared in order to demonstrate that tests could be reliably repeated.

Table 2.1. Open test matrix conditions

Open Matrix Condition	Experiment Number	Data Time @ Reflood Start (seconds)	Reflood Rate (cm/s)	Reflood Water Subcooling (K)	Bundle Power (kW)	Droplet Camera Locations (Upstream or Downstream)
O-5	9005	8846.40	5, constant	10	144	U/D Grid #6
O-8	9011	4374.85	8, 5, 3, 1.2, variable stepped	25	144	U/D Grid #6
O-7	9012	11505.90	2.5 ± 2.5, oscillatory, 4 s period	10	144	U/D Grid #6
O-4	9014	6822.00	15, constant	80	252	No cameras, high reflood rate
O-3	9015	9729.75	15, constant	10	252	No cameras, high reflood rate
O-1	9021	8931.98	2.5, constant	10	144	U/D Grid #5
O-2	9026	852.55	2.5, constant	80	144	U/D Grid #6
O-6	9027	8210.10	2.5, constant	30	144	U/D Grid #5
O-10	9029	14781.60	2.54, constant	47	222, decay	U/D Grid #6
O-11	9037	8820.60	5, constant	10	144	Down Grid #5, Up Grid #6
O-9	9043	13605.05	0.5 constant	2.8	35	U/D Grid #6

The second experimental campaign performed five additional reflood tests. These tests had boundary and initial conditions that were like the initial 11 "open" tests but were designed to be unique and represent a challenge to modelling and simulation. Following completion of the test series, the initial and boundary conditions of each test were released to the participants. Test data and other results were not released until participants completed simulation of the tests. Table 2.2 lists the "blind" tests.

Four of the five blind tests had a constant reflood rate, one with a 2.5 cm/sec flooding rate and the other three with a 10 cm/sec rate. In contrast to the open tests, the 10 cm/sec flooding rate is "bounded" by the 5 and 15 cm/sec flooding rate tests in the open test series. The blind test series varied the system pressure in another difference with the open tests. Test B-4 was conducted at 137 kPa (20 psia) and Test B-6 at 412 kPa (60 psia). The conditions in Test B-6 and open series Test O-6 provide a sensitivity to system pressure.

Tests in the blind test series had relatively low inlet subcooling, as low subcooling tests were found to be more difficult to accurately simulate. Test B-3, like Test O-7, investigated oscillatory reflood effects. Conditions in these two tests were the same except for the period of oscillation.

Table 2.2. Blind test matrix conditions

Blind Matrix Condition	Experiment Number	Data Time @ Reflood Start (seconds)	Reflood Delay (response on ch362, 363) (seconds)	Reflood Rate (cm/s)	Reflood Water Subcooling (K)	Pressure (kPa)	Bundle Power (kW)	Droplet Camera Locations (Upstream or Downstream)
B-1	9047	2 588.05	2 588.4	10, constant	10	276	252	No cameras, high reflood rate
B-2	9053	5 308	5 308.45	10, constant	5	276	252 decay	No cameras, high reflood rate
B-3	9064	6 143.5	6 148.3	2.5 ± 2.5, oscillatory, 2 s period	10	276	144	U/D Grid #6
B-4	9056	10 001.35	10 001.65	10, constant	5	137	252 decay	No cameras, high reflood rate
B-6	9059	16 155.4	16 160.4	2.5, constant	30	412	144	U/D Grid #6

3. Experimental findings

The primary objective of the present study was to obtain reflood data for a series of conditions and simulate those tests with several analytical codes. Participants selected an analysis code and then modelled and simulated the tests. However, the tests also provide unique experimental data suitable for model and correlation development to the participants. Some observations of the test results are provided below:

1. The high reflood rate tests, such as O-3 (9 015), O-4 (9 014) at a 15 cm/sec flooding rate, and Tests B-1 (9 047), B-2 (9 053) and B-4 (9 056) at a 10 cm/sec flooding rate, produced conditions where post-CHF inverted annular flow is likely to have occurred in significant portions of the bundle for a prolonged period of time. In Tests O-3 (9 015), O-4 (9 014) at a 15 cm/sec flooding rate, bundle quench did not occur for over 400 and 180 seconds, respectively.

2. The low reflood rate tests such as O-1 (9 021), O-2 (9 026), O-6 (9 027) and O-9 (9 043), resulted in slow-moving quench fronts and the likely heat transfer regimes in significant portions of the bundle were post-CHF dispersed droplet flow and steam cooling. Bundle quench did not occur for several hundred seconds.

3. A very low reflood rate test, Test O-9 (9 043), is unique in that it may be the lowest flooding rate test in any rod bundle test facility. The very low flooding rate combined with low inlet subcooling (2.8 K) resulted in a long duration experiment that required approximately 1 600 seconds for bundle quench. This test produced droplet data indicating lesser amounts of entrainment at low steam production rates.

4. Test O-8 (9 011) was a variable reflood rate test. The high flooding rate at the start of the transient caused all spacer grids to quickly rewet, but grid dry-out occurred once the flooding rate decreased for upper elevation grids of the bundle. These spacer grids then subsequently rewet again as the quench front progressed. The test is useful in examining the effect of grid rewet on bundle behaviour.

5. Tests O-7 and B-3 were reflood tests with controlled oscillatory injection with a nominal average of 2.5 cm/sec. Both had an inlet coolant temperature of 10 K. These tests complement Test O-1, which had a constant 2.5 cm/sec injection rate and 10 K inlet subcooling. A comparison of results indicates that oscillations increase carryover and delay bundle quench.

Further study of the data and results of these tests is expected to help develop new models and correlations for reflood thermal hydraulics. Droplet measurements upstream and downstream of spacer grids provide information that can improve correlations for droplet breakup and other spacer grid effects.

4. Modelling of the RBHT facility

Participants selected a code, performed simulations of the tests and reported comparisons of predicted and measured quantities against several figures of merit (FOMs). For the open test series, 14 organisations submitted the open test results using, in total, eight codes: TRACE, RELAP5, MARS-KS, SPACE, CATHARE, ATHLET, APROS and CTF. All these codes are system thermal-hydraulic codes, except for CTF, which is a subchannel code. The three-field model (liquid, steam and droplet) is allowed only in SPACE, CATHARE and CTF codes. PSI and CEA submitted results with three and two different simulation models, respectively. Table 4.1 summarises the participants and codes used in the study.

Table 4.1. Participants codes

Participant	Code	Type	Fields
NRA	TRACE (v5.0p5)	System Code	2
NRC-PSU	TRACE (v5.1341)	System Code	2
PSI-simexp	TRACE (v5.0p5)	System Code	2
PSI-v5p3uq	TRACE (v5.0p3uq)	System Code	2
PSI-v5p5	TRACE (v5.0p5)	System Code	2
UPV-ISIRYM	TRACE (v5.0p6)	System Code	2
UPV-IIE	TRACE (v5.0p5)	System Code	2
NINE	RELAP5/Mod3.3p5	System Code	2
UPC	RELAP5/Mod3.3p4	System Code	2
KINS	MARS-KS 1.5	System Code	2
KAERI	SPACE 3.22	System Code	3
KNF	SPACE 3.1.2	System Code	3
CEA-2field	CATHARE 3v2.1	System Code	2
CEA-3field	CATHARE 3v2.1	System Code	3
GRS	ATHLET 3.2	System Code	2
VTT	APROS 6.10.02.01	System Code	2
TRACTEBEL	CTF 4.2	Subchannel Code	3

There was considerable variation in the geometric modelling of the RBHT rod bundle and facility. Most participants modelled the RBHT test section as a single vertical channel with two radial regions identifying an inner and an outer zone. The UPV-IIE model included a 3x3 region in the central part of the bundle. The number of axial nodes in the heated region of the bundle ranged between 15 and 84, resulting in axial node heights between 24.4 and 4.4 cm (these numbers do not consider the mesh rezoning performed by some codes near the quench front).

All participants, except CEA, simulated the flow housing as heat structure. Several participants assumed an adiabatic boundary condition on the outer surface of the flow housing, while others simulated heat losses by assuming a constant heat transfer coefficient and exterior room temperature during the transient.

Participants simulated the spacer grids with a flow area reduction, also applying a form loss coefficient (either constant or Reynolds dependent) and, based on adopted code features, activating special models for the heat transfer enhancement.

Regarding the components outside the test section, no participant simulated the carryover tanks and the exhaust steam line. Several participants included the lower plenum and upper plenums in the input model. Nodalisations used by the participants are summarised in Table 4.2.

Different strategies were adopted to achieve the thermal-hydraulic conditions (heater rod temperatures, steam temperatures and flow housing wall temperatures) corresponding to the beginning of the reflood (i.e. start of transient). Few participants simulated a complete steady state process before the power ramp; most of the participants extracted the initial conditions from the experimental data at the time at which the water injection starts and applied them to the model (polynomial curves were generally used to fit the experimental data). Other participants instead simulated the experiment starting from the power ramp.

Table 4.2. Summary of nodalisations

Participant	Axial nodes	Radial zones	Heat structures	Heat structure radial nodes	Housing wall simulated (Y/N)	Heat losses simulated (Y/N)	Plenums simulated (Y/N)
NRA	15	1	1	9	Y	Y	Y
NRC-PSU	32	2	2	9	Y	Y	Y
PSI-simexp	30	2	2	9	Y	N	N
PSI-v5p3uq	30	2	2	9	Y	N	N
PSI-v5p5	30	2	2	9	Y	N	N
UPV-ISIRYM	30	2	2	9	Y	Y	Y
UPV-IIE	17	3	9	8	Y	Y	Y
NINE	70	1	5	21	Y	Y	Y
UPC	27	1	1	7	Y	N	Y
KINS	34	1	1	8	Y	Y	Y
KAERI	49	1	1	9	Y	Y	N
KNF	47	2	2	9	Y	N	Y
CEA-2field	84	1	1	5	N	N	N
CEA-3field	84	1	1	5	N	N	N
GRS	21	2	2	5	Y	Y	Y
VTT	52	1	45	10	Y	N	Y
TRACTEBEL	36	1	1	12	Y	N	N

5. Figures of merit

Several parameters were defined as figures of merit (FOMs) for simulations of the RBHT reflood tests and comparison to data. These FOMs were intended to characterise the experiment and provide challenging metrics for comparison of predicted and measured results.

The following two types of metrics were defined for the FOM:

- Punctual (i.e. a specific value or values at a fixed time)
- Temporal (i.e. time dependent)

There are two approaches to qualify the agreement (or accuracy) of the simulation results with the experimental results: the qualitative or quantitative. The former focuses on the general tendency of the "agreement" based on the difference of the FOM at a fixed time instant, while the latter is based on quantitative metrics during the transient.

For the present study, the following degree of agreement can be used to qualify the performance of the code used:

- "Excellent agreement" applies when the code exhibits no deficiencies in modelling a given FOM. Major and minor phenomena and trends are correctly predicted. The calculated results are judged to agree closely with data.
- "Good agreement" applies when the code exhibits minor deficiencies. Overall, the code provides an acceptable prediction. All major trends and phenomena are predicted correctly. Differences between calculated values and data are greater than are deemed necessary for excellent agreement.
- "Fair agreement" applies when the code exhibits significant deficiencies. Overall, the code provides a prediction that is not acceptable. Some major trends or phenomena are not predicted correctly, and some calculated values lie considerably outside the specified or inferred uncertainty bands of the data.
- "Poor agreement" applies when the code exhibits major deficiencies. The code provides an unacceptable prediction of the test data because major trends are not predicted correctly. Most calculated values lie outside the specified or inferred uncertainty bands of the data.

Numerical values for each level of agreement were defined and agreed upon by the participants.

Punctual metrics included:

- Peak cladding temperature: The peak cladding temperature (PCT) is the singular maximum cladding surface temperature measured in the rod bundle following the start of the transient. The PCT is often the parameter of most interest in a loss-of-coolant accident (LOCA) licensing analysis and thus becomes an important FOM. Since the PCT is a singular value, meaning that it is a uniquely identifiable measurement, the characterisation can be plus or minus a temperature difference.
- Peak cladding temperature elevation: The PCT elevation is the location in the bundle where the PCT occurs. In general, the PCT occurs at or near the peak power elevation (2.74 m). Prediction of the PCT elevation helps to indicate if a code is predicting the enthalpy rise correctly.

- Quench profile/time of quench at peak power elevation: The quench profile refers to the quench front elevation as a function of time. The quench profile was provided for each test, and this parameter helps to indicate if a code is predicting the correct heat release near the quench front. A parameter that is well quantifiable is the time at which the peak power elevation quenches (Rod D4 at 2.74 m). This was used as a metric in comparing predicted and measured results in addition to the quench profile.
- Bundle pressure drop (mass): The total bundle pressure drop is measured by Channel 362, and for most of a reflood test is a good indication of the total mass of liquid in the rod bundle. The total pressure drop can be converted to a collapsed liquid level or total bundle mass with appropriate assumptions on form and friction losses in the bundle. As a punctual characterisation, participants considered the bundle mass retained divided by the integral of liquid injected into the bundle at the time of peak power elevation (2.74 m) quench.
- Carryover fraction: The carryover fraction represents the quantity of coolant exiting the rod bundle in the liquid phase. The carryover fraction is defined as the liquid flow rate exiting the bundle divided by the inlet flow. Similarly to the bundle pressure drop (i.e. bundle mass) for a punctual characterisation, participants considered the carryover fraction at the time of peak power elevation (2.74 m) quench. To be comparable to the bundle mass, the carryover fraction was calculated as the integral of liquid exiting the bundle divided by the integral of liquid injected into the bundle.
- Exhaust steam flow rate: The exhaust steam flow rate is obtained from Channel 445, which records the exiting steam flow rate. To define a punctual parameter, the integral of the steam exit flow divided by the integral of liquid injected to the bundle at the time of peak power elevation quench was used.

It should be noted that the punctual parameters of bundle mass (MB), carryover fraction (CO) and steam exhaust (SE) at the time of peak power elevation quench provide an overall mass balance up until that time. The sum of the three parameters should be 1.0 and any imbalance in a prediction of the parameters indicates the tendency of a code to over or underpredict entrainment and/or interfacial heat transfer during the reflood transient.

The temporal FOMs represent parameters that vary considerably during a transient and provide useful information on code performance. Since the PCT occurs near the peak power elevation, several measurements and results near that location were selected for code to data comparison. Temporal parameters included:

- Rod surface temperature at 2.69 m: Using Channels 246, 238, 166, 30;
- Rod surface temperature at 2.89 m: Using Channels 194, 210, 226, 311;
- Rod heat transfer coefficient at 2.69 m;
- Rod heat transfer coefficient at 2.89 m;
- Shroud surface temperature: Using Channels 342, 349, 353, 354;
- Steam temperature at 2.93 m: Using Channels 326, 327;
- Spacer grid #6 droplet size: For low reflood rate tests only.

Note that the derivation of heat transfer coefficient accounts for both convection and radiation. The experimentally determined heat transfer coefficient is defined as:

$$h = \frac{q''_{surf}}{T_{surf} - T_{sat}}$$

where q''_{surf} is the heat flux, and T_{surf} is the cladding surface temperature and T_{sat} is the saturation temperature corresponding to the outlet pressure. Channel 393 is used to obtain the outlet pressure.

6. Simulations and comparison to data for the open test series

The open test series consisted of ten reflood experiments with boundary and initial conditions spanning a broad range of flooding rates and inlet subcooling. The data from these tests were made available to all participants and nearly all participants simulated the tests and compared their predictions to the experimental results.

A characterisation of agreement between predicted and experimental results can be summarised through consideration of low and high reflood rate tests separately. In low reflood rate tests the transient is relatively long and the peak cladding temperature can occur several hundred seconds following the start of reflood. Conditions in the rod bundle during low reflood rate tests are expected to be representative of post-CHF dispersed droplet film boiling and steam cooling in much of the bundle. The quench front moves slowly, and entrainment and de-entrainment at spacer grids can have a significant influence on the bundle thermal hydraulics.

Test O-1 (9 021) was a low reflood rate test with low inlet subcooling. In Test O-1 the flooding rate was 2.5 cm/sec with an inlet subcooling of 10 K. An evaluation of participants' simulations can be characterised as follows:

- The peak cladding temperature (PCT) is overestimated in all TRACE simulations, with a general poor agreement ($T_{calc} – T_{exp} > 100$ K). Better results are obtained by participants that used RELAP5, CATHARE (3-field) and ATHLET. A significant discrepancy between the two SPACE results is found. Finally, CTF also overpredicted the PCT. The comparison to peak cladding temperature is shown in Figure 6.1.
- Generally good prediction is achieved (except CTF result) for the PCT elevation, positioned very close to the peak power elevation as shown in Figure 6.2.
- The quenching time of rod D4 at 2.7 m (peak power elevation) depends on the simulation model developed by each TRACE participant. There was not a common behaviour in those results. Good results are obtained by NINE with RELAP5 and CEA with CATHARE (3-field). The other participants, tendentially, predicted a later quenching occurrence. These results are shown in Figure 6.3.
- The comparison of the carryover (CO) fraction (Figure 6.4), the steam exhaust (SE) fraction (Figure 6.5) and the bundle mass (MB) fraction (Figure 6.6) shows a common tendency for all the codes (except partially CATHARE (3-field) and ATHLET) to overpredict the CO fraction, while underpredicting the steam exhaust fraction and the mass retained in the bundle.
- There is a wide variation in results, even among participants using the same thermal-hydraulic code. Figure 6.7, showing the prediction of cladding temperatures near the peak power elevation, confirms that the "user effect" represents a major uncertainty in an analysis.

Figure 6.1. PCT, Test O-1

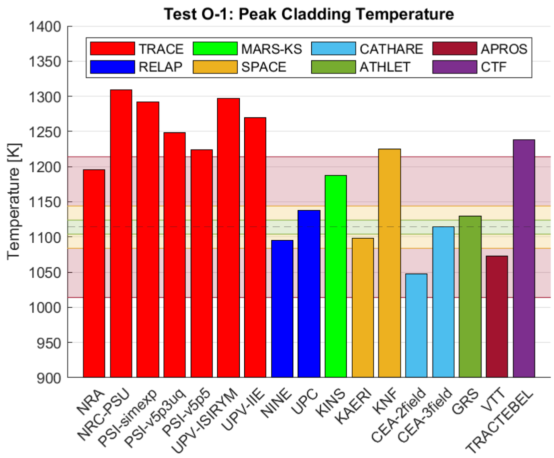


Figure 6.2. PCT elevation, Test O-1

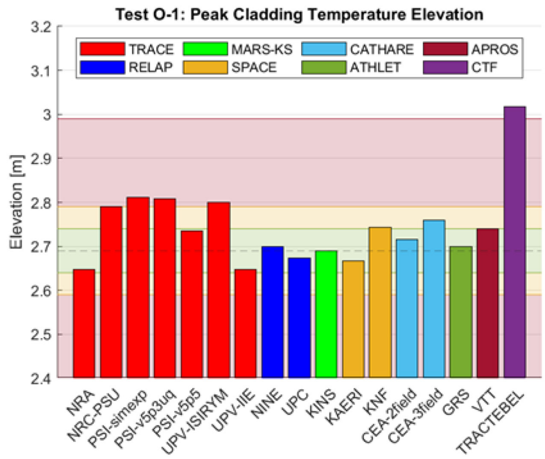


Figure 6.3. Quenching time, Test O-1

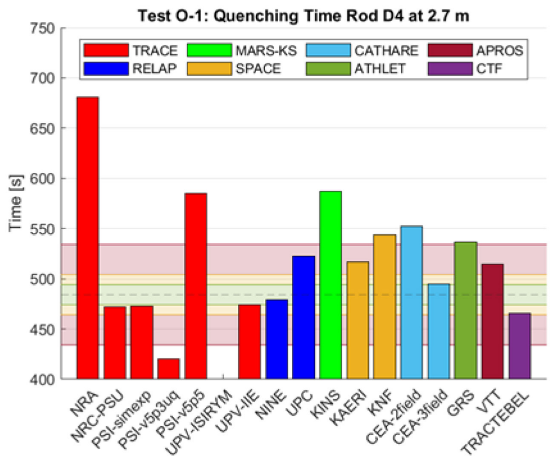


Figure 6.4. Carryover fraction, Test O-1

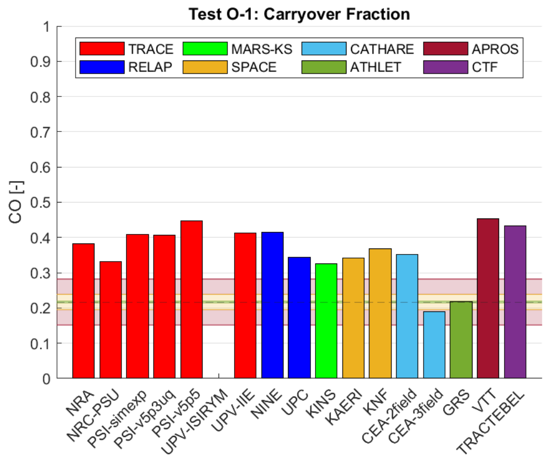


Figure 6.5. Steam exhaust fraction, Test O-1

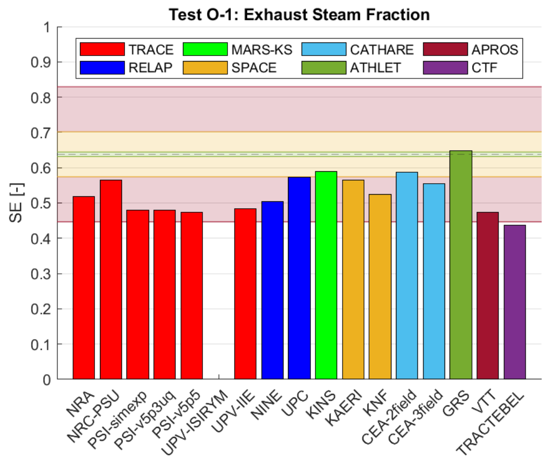


Figure 6.6. Mass bundle fraction, Test O-1

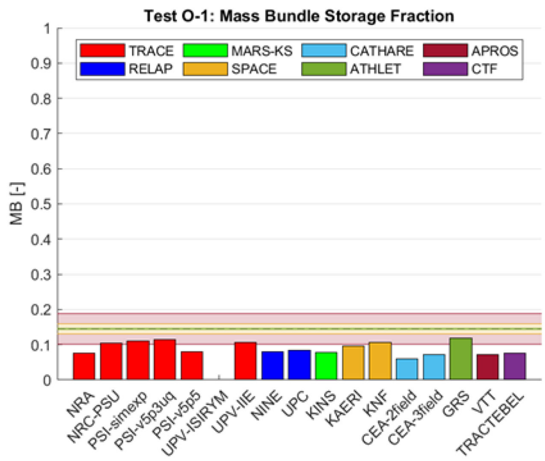
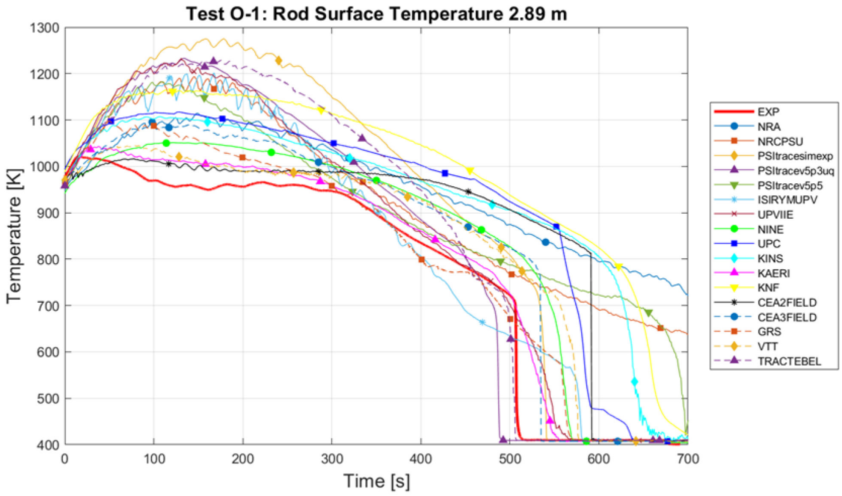


Figure 6.7. Rod surface temperature, 2.89 m – Test O-1



Test O-3 (9 015) was a high reflood rate test with a constant flooding rate of 15 cm/sec and inlet subcooling of 10 K. Results against Test O-3 were generally like the main findings made for the Test O-1 for the mass balance during the transient. KAERI with SPACE differs from the other participants with an underestimation of the CO fraction, and an overestimation of the SE fraction but a good value in terms of MB fraction. In addition, the follows considerations apply:

- The PCT is, at least, inside the poor range for all the participants, although big deviations in respect to the experimental data are not expected in a high flooding rate test (Figure 6.8).
- The PCT elevation is in excellent/good agreement for all participants, except for PSI TRACE models that predict the PCT at a lower elevation (Figure 6.9).
- The quenching time (rod D4, 2.7 m elevation) in Test O-3 is one of the results that highlighted deficiencies in almost all codes/simulation models. All the participants with TRACE predicted quench at that elevation about 100-150 s later than the experimental value (Figure 6.10). The opposite behaviour is recorded from RELAP5 and MARS-KS codes: quench is predicted much earlier than the experimental event. Good agreement is obtained by KNF with SPACE and VTT with APROS. It should be noted, also in this test, that a significant discrepancy exists between the two results obtained by SPACE.
- The mass balance, shown in Figures 6.11 to 6.13, suggests that carryover (CO) is overpredicted while the steam exhaust (SE) and bundle mass (MB) are underpredicted by most codes.
- The "user effect" is again observed in simulations of Test O-3 (9 015). Figure 6.14 presents the cladding temperature predicted by the participants. Again, there is a considerable variation in the temperature – time history and quench time for participants using the same thermal-hydraulic code.

Figure 6.8. PCT, Test O-3

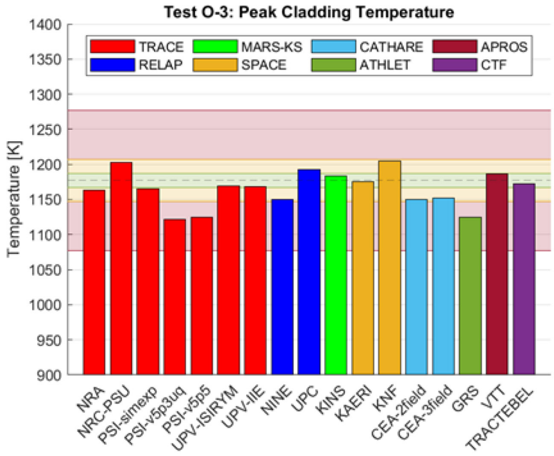


Figure 6.9. PCT elevation, Test O-3

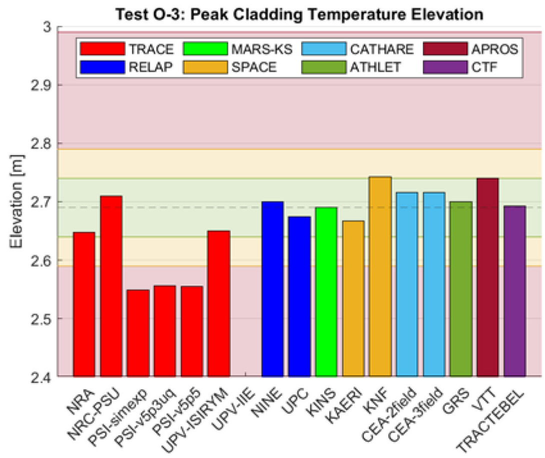


Figure 6.10. Quenching time, Test O-3

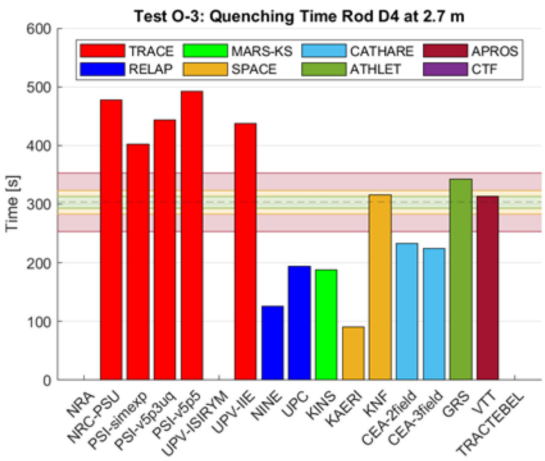


Figure 6.11. Carryover fraction, Test O-3

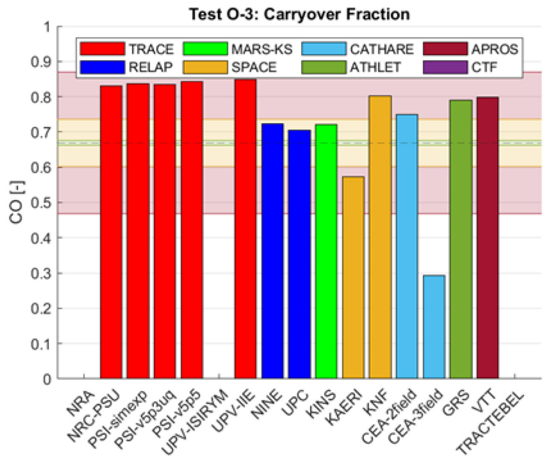


Figure 6.12. Steam exhaust fraction, Test O-3

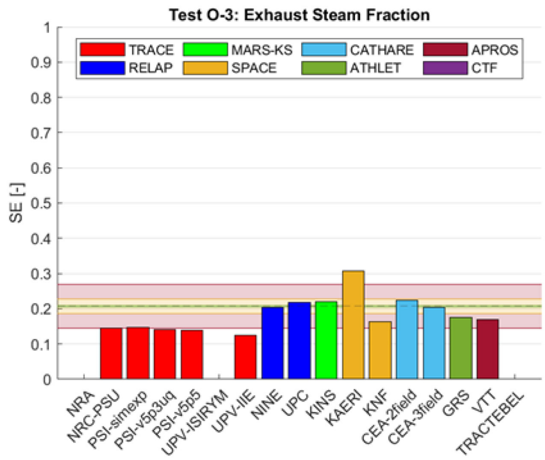


Figure 6.13. Mass bundle fraction, Test O-3

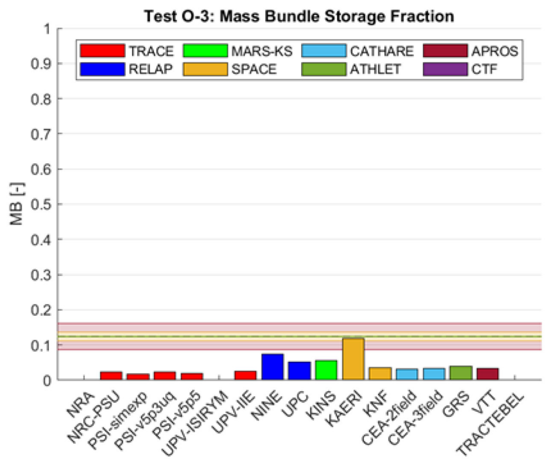
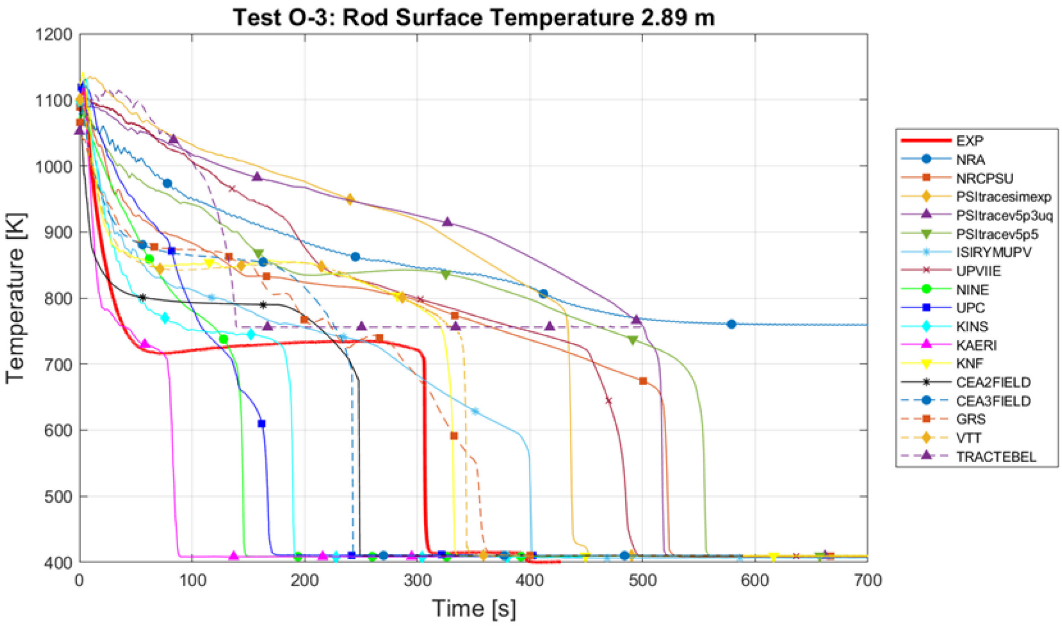


Figure 6.14. Rod surface temperature, 2.89 m – Test O-3



7. Simulations and comparison to data for the blind test series

The blind tests were simulated by 14 organisations using, in total, eight codes: TRACE, RELAP5, MARS-KS, SPACE, CATHARE, ATHLET, APROS and CTF (Table 7.1). PSI and CEA submitted results with four and two different simulation models/code versions, respectively. Simulations of the blind tests were performed without the benefit of the experimental results. Participants had access to only the initial and boundary conditions when simulations were performed. Experimental results were released afterward.

There were five tests in the blind test series, and these are listed in Table 7.1. Some participants simulated all five tests. However, the project requested that Tests B-2 (9 052) and B-6 (9 059) be simulated with an uncertainty methodology to capture the figures of merit.

Table 7.1. Participants codes

Participant	Code	Category
PSI-simexp	TRACE (v5.0p5)	System Code
PSI-simexp_Parposterior_biased	TRACE (v5.0p5)	System Code
PSI-simexp_Parposterior_unbiased	TRACE (v5.0p5)	System Code
PSI-v5p5	TRACE (v5.0p5)	System Code
UPV-ISIRYM	TRACE (v5.0p6)	System Code
UPV-IIE	TRACE (v5.0p5)	System Code
NINE	RELAP5/Mod3.3p5	System Code
UPC	RELAP5/Mod3.3p4	System Code
UJV	RELAP5/Mod3.3p5	System Code
KINS	MARS-KS 1.5	System Code
KAERI	SPACE 3.22	System Code
KNF	SPACE 3.1.2	System Code
CEA-2field	CATHARE 3v2.1	System Code
CEA-3field	CATHARE 3v2.1	System Code
IRSN	CATHARE 3v2.1	System Code
GRS	ATHLET 3.2	System Code
VTT	APROS 6.10.02.01	System Code
TRACTEBEL	CTF 4.2	Subchannel Code

Test B-6 can be characterised as a low flooding rate test with a flooding rate of 2.5 cm/sec with an inlet subcooling of 30 K. In Test B-6, however, the nominal system pressure was 412 kPa, which is higher than the pressure in any of the open series tests. Test B-6 complements Test O-6 from the open series as O-6 and had the same inlet conditions but had a system pressure of 276 kPa. Results summarising the comparison of code predictions against Test B-6 are presented in Figure 7.1 to Figure 7.7. The comparisons can be characterised as:

- The peak cladding temperature (PCT) is overestimated in all TRACE simulations, with a general poor/fair agreement. Excellent/good results are obtained using CATHARE (3-field model), ATHLET, MARS-KS and SPACE (KNF result). All the RELAP participants underpredict the PCT (Figure 7.1).
- Generally excellent/good prediction is achieved (except CTF result) for the PCT elevation, positioned very close to the peak power elevation (Figure 7.2).

- The quenching time (Figure 7.3) is inside the fair agreement bands for all the participants, with excellent/good predictions from UPC and UJV (RELAP5), KINS (MARS-KS), KAERI (SPACE) and VTT (APROS).
- The carryover fraction (at time of quench at peak power elevation) is overpredicted by all participants, except for CATHARE 3-field, which underpredicts it (Figure 7.4). The mass bundle fraction is instead underestimated by all participants (Figure 7.5).
- Figure 7.7 shows predictions of the cladding temperature at the 2.89 m elevation, which is just downstream of the peak power elevation. As can be seen in the figure, there is a large variation in the predictions, even for participants using the same code.

Figure 7.1. PCT, Test B-6

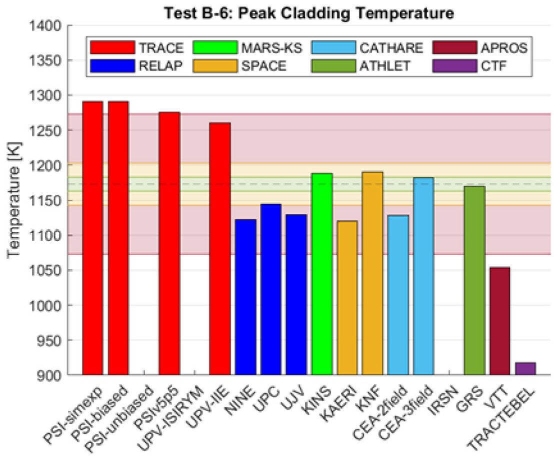


Figure 7.2. PCT elevation, Test B-6

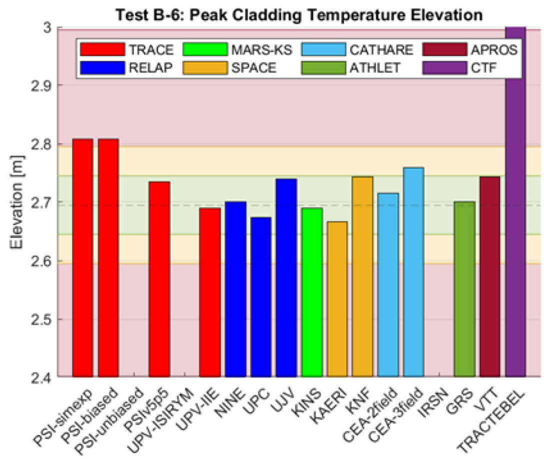


Figure 7.3. Quenching time, Test B-6

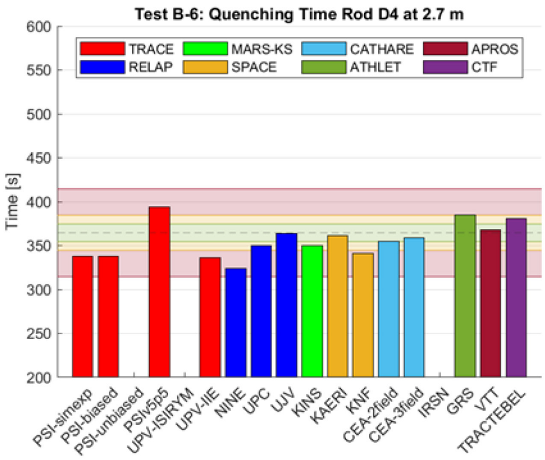


Figure 7.4. Carryover fraction, Test B-6

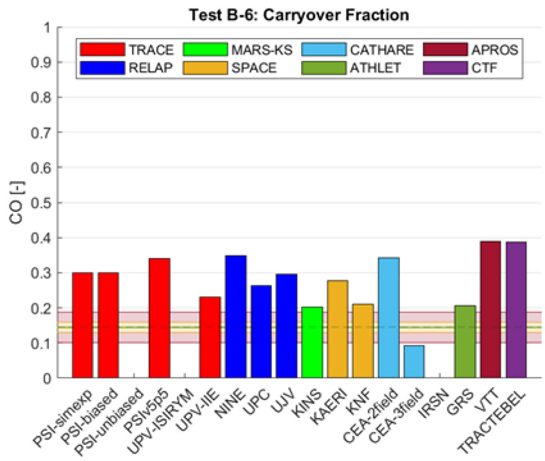


Figure 7.5. Steam exhaust fraction, Test B-6

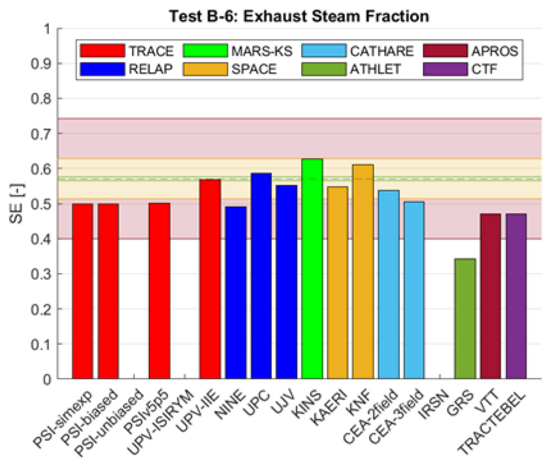


Figure 7.6. Mass bundle fraction, Test B-6

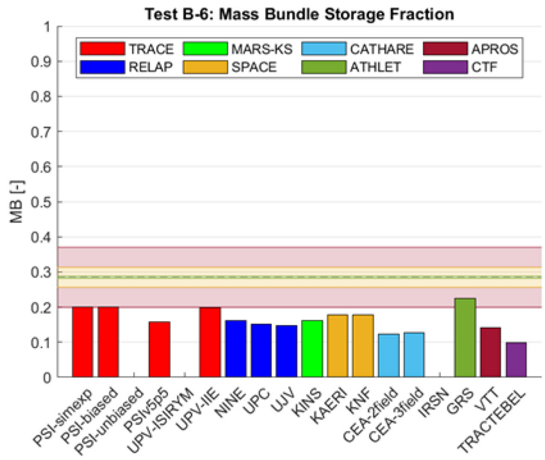
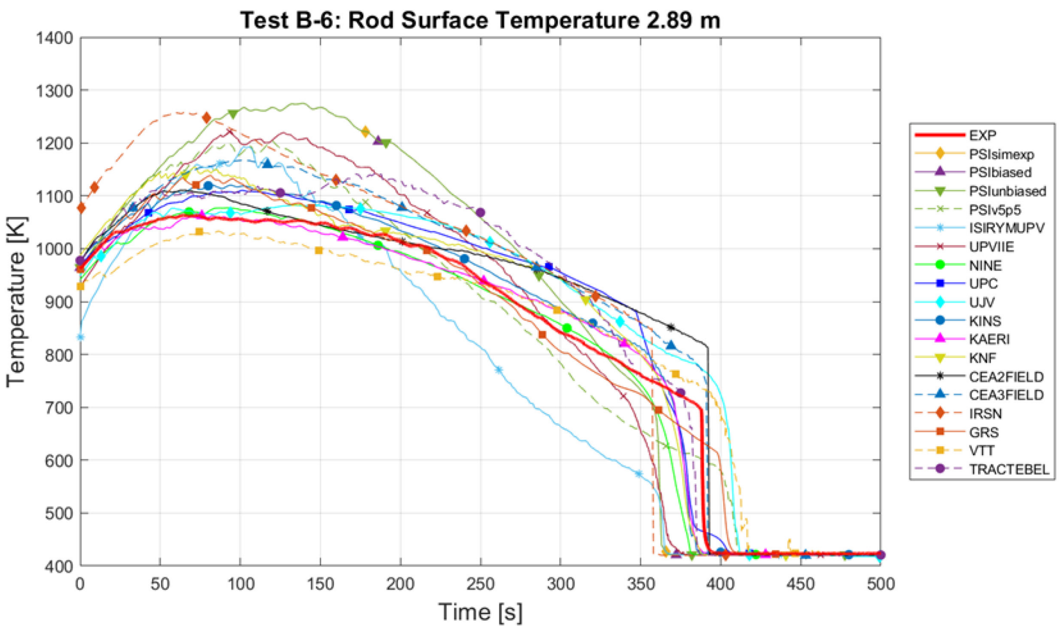


Figure 7.7. Rod surface temperature, 2.89 m – Test B-6



Test B-1 (9 047) is a relatively high flooding rate test, with an inlet flooding rate of 10 cm/sec and an inlet subcooling of 10 K. The system pressure for this test was 0.276 MPa, which was the pressure in nearly all the tests in this project. This test differed from all others in that the 10 cm/sec flooding rate did not match any of the other tests. It was bounded by open tests conducted at 5 and 15 cm/sec with a 10 K inlet subcooling. Thus, any benchmarking or calibration from open test simulations could be expected to benefit in modelling Test B-1. Results against Test B-1 are presented in Figure 7.8 to Figure 7.14. Some considerations can be drawn as follows:

- The PCT is, at least, inside the fair range for all the participants, although big deviations with respect to the experimental data are not expected in a high flooding rate test (Figure 7.8).

- The PCT elevation is similar for all participants, except for the PSI-v5p5 TRACE model and KINS MARS-KS model, which predict the PCT at a lower elevation (Figure 7.9).
- The quenching time (rod D4, 2.7 m elevation) in Test B-1 highlighted deficiencies in almost all codes/simulation models (Figure 7.10). Similar considerations also apply to the other high flooding rate tests. Participants with TRACE predicted quench at that elevation about 100 to 300 s later than the experimental value. The opposite behaviour was obtained by NINE, UPC and UJV with RELAP5 and by CEA with CATHARE: quench was predicted earlier (about 100 s) than the experimental event. Good agreement was obtained by KINS with MARS-KS. It should be noted that there was a significant discrepancy, presented also in the open test simulations, between the two results obtained by the SPACE code.
- The comparison about the carryover (CO) fraction (Figure 7.11), the steam exhaust (SE) fraction (Figure 7.12) and the bundle mass (MB) fraction (Figure 7.13) at time of quenching at peak power elevation shows a common tendency for TRACE results to overpredict the CO fraction, while underpredicting the steam exhaust fraction and the mass retained in the bundle (fair/poor agreement). Better results, in terms of mass balance at quenching time, are obtained using RELAP, MARS-KS, CATHARE (2-field), ATHLET and APROS.
- Figure 7.14 shows a comparison of predictions near the PCT elevation in Test B-1. As in other simulations, there is considerable variation in the predictions, even among participants using the same thermal-hydraulic code.

Figure 7.8. PCT, Test B-1

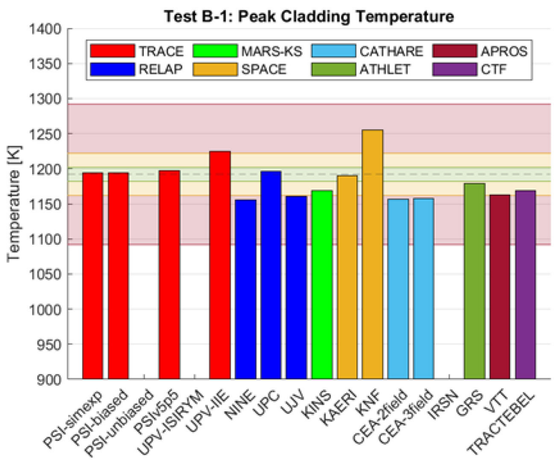


Figure 7.9. PCT elevation, Test B-1

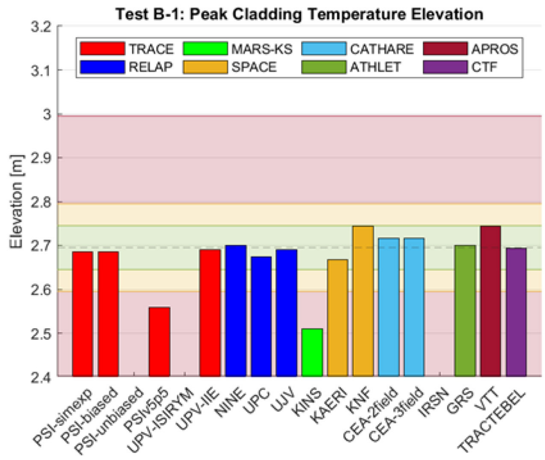


Figure 7.10. Quenching time, Test B-1

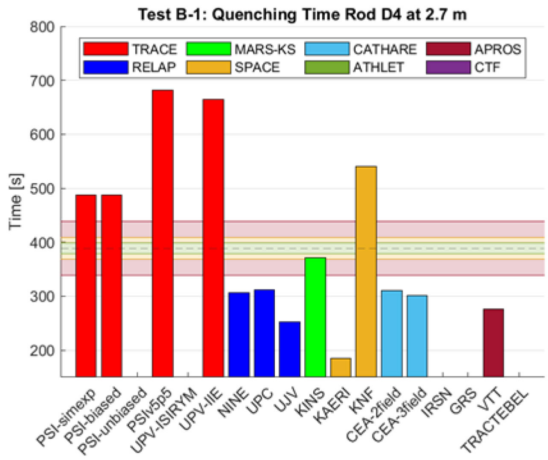


Figure 7.11. Carryover fraction, Test B-1

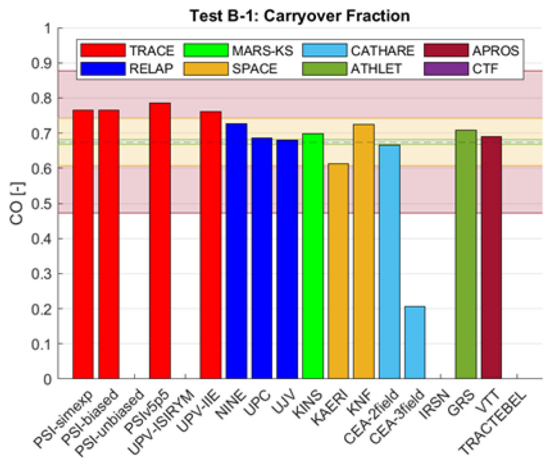


Figure 7.12. Steam exhaust fraction, Test B-1

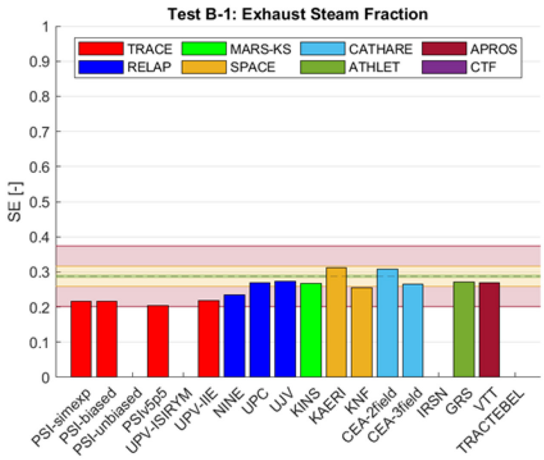


Figure 7.13. Mass bundle fraction, Test B-1

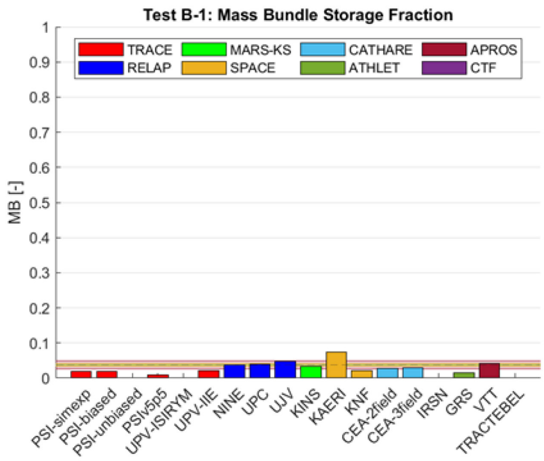
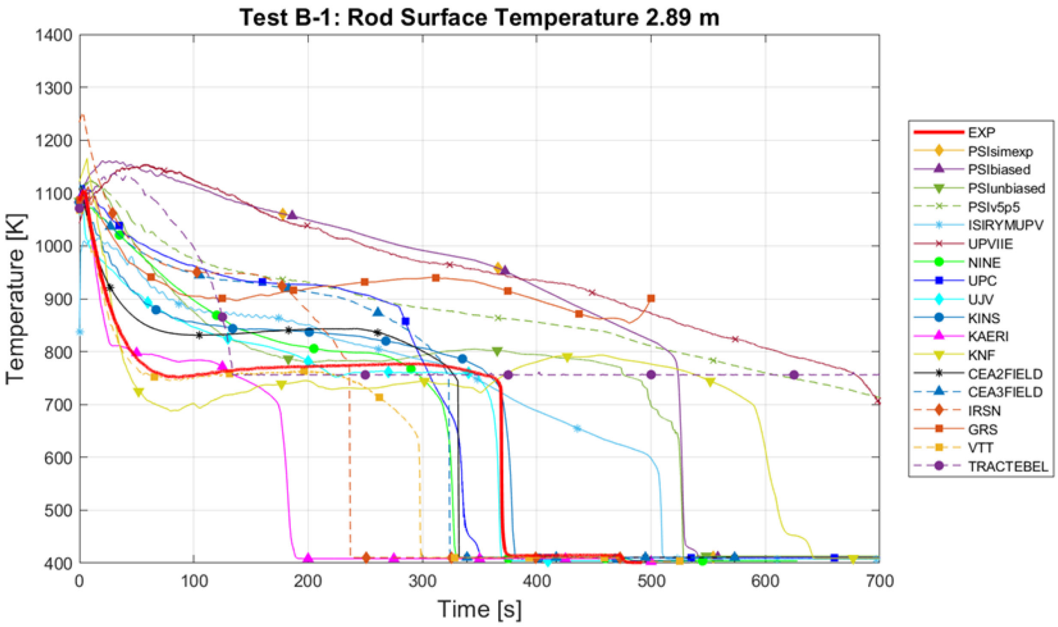


Figure 7.14. Rod surface temperature, 2.89 m – Test B-1



8. Uncertainty analysis

One of the objectives of the present project is to further the investigation of code uncertainty analysis methods. To provide a challenging exercise for the application of uncertainty methods, the initial and boundary conditions for the series of "blind" tests were provided to participants. Simulation of these tests, using an uncertainty analysis method, was performed and results compared to the figures of merit. Tests B-2 (9 053) and B-6 (9 059) were suggested as the two tests that all participants would simulate with uncertainties. Several participants reported simulations with uncertainties for all five of the blind tests. The uncertainty analysis results of each participant are presented in Chapter 4.

It should be noted that no specifications were made on the uncertainty analysis methods and the uncertainties to be considered from the benchmark organiser. Therefore, each participant has chosen their own method, uncertainty parameters, ranges and distributions.

A questionnaire (Annex A) was then prepared to facilitate the comparison of the uncertainty analysis methods used by the participants for the selected blind experiments of the RBHT. The questions were organised in different groups according to, as far as possible, the subdivision into six elements adopted in the SAPIUM project. In total, 12 participants performed uncertainty analyses and submitted the uncertainty questionnaires whose responses were reviewed and factored into conclusions on uncertainty analysis methods (Chapter 5 and Appendix A). Several different uncertainty methods were applied, with the "GRS method" based on ordered statistics and Wilk's formula being the most common approach, while five participants performed the inverse uncertainty analysis. Uncertainties of the model form, boundary and initial conditions, and other experimental uncertainties (such as those related to material properties) were considered and propagated in the uncertainty analysis.

With respect to Element 2 of SAPIUM (Development and Assessment of the Experimental Database), some participants used databases from other experiments to select important input uncertainty parameters and associated probability distribution functions (PDFs). Those databases were also assessed to evaluate the adequacy of those databases with respect to RBHT data. Similarity and scalability analysis and Sobol analysis were performed to assess the database adequacy.

The code applicability and nodalisation applicability were also evaluated by nine participants in response to Element 3 of SAPIUM (selection and assessment of the simulation model). A comparison of the simulation results to the experimental results was performed by participants to evaluate the quality of the developed model. Major discrepancies were identified and reported.

With respect to Element 4 of SAPIUM (input uncertainty quantification), some participants performed an inverse uncertainty quantification based on Bayesian inference to get the input parameter PDFs, while other participants obtained the input parameter PDFs from literature review, expert judgement, RBHT recommendations, etc.

Many participants used RBHT open tests for the model input uncertainty validation (and the RBHT FOM as the quantitative indicator for the validation Element 5 of SAPIUM).

The responses to the questionnaire identified the uncertainty parameters and their ranges for each participant. Most participants ranged models and correlations for:

- wall heat transfer, generally with emphasis on dispersed flow film boiling;
- interfacial heat transfer;
- interfacial drag;
- wall drag.

Also ranged, but not by all participants, were:

- nucleate boiling;
- minimum film boiling temperature;
- critical heat flux;
- droplet break up (critical Weber number and/or spacer grid effects);
- initial and boundary conditions.

Results of the RBHT blind simulations with uncertainties (Element 6 of SAPIUM: Application to RBHT) showed that in numerous cases the figures of merit were not captured within the uncertainty bands of the analysis. Carryover fraction was commonly identified as a parameter that was consistently overpredicted and outside the range of uncertainty (generally between the 5^{th} and 95^{th} percentiles). Other figures of merit were not bounded, depending on the test simulated.

The differences can be attributed to:

- the deficiency in some models of the used codes to realistically simulate some FOMs of the test; or
- the difference in the chosen uncertainty parameters, ranges and distributions.

Comparing analyses between participants using the same code, the so-called code "user effect" was found to be large and represents another source of uncertainty. Modelling flexibility and assumptions thus can result in significant variability of results. This should be further investigated in future activities.

9. Conclusions and lessons learnt

Reflood thermal hydraulics remains a complex area of interest in reactor safety and the phenomena are difficult to accurately simulate. While the thermal-hydraulic conditions in the RBHT tests have been investigated in previous experimental programmes, analytical codes do not necessarily provide accurate predictions of some important parameters. Significant improvements can and should be made to codes used for thermal-hydraulic analysis.

The reflood tests performed as part of this project considered a wide range of thermal-hydraulic conditions. Flooding rates varied from 0.5 cm/sec to 15 cm/sec, with inlet subcooling ranging from 2.8 to 80 K. The test results thus provide participants with conditions producing significant periods of post-CHF dispersed droplet flow and inverted annular flow. Both regimes are challenging to code validation, and the long durations of the tests provide valuable input for correlation development. The test matrix also included variable reflood rate tests and oscillatory injection tests. These tests provide data on spacer grid rewet, dry-out and subsequent rewet, thus providing new and unique information on spacer grid effects.

Most codes had difficulty predicting the figures of merit in certain tests, including the peak cladding temperature and timing of bundle quench, both of which are important in regulatory decision making. The PCT has a well-defined regulatory limit (1 204°C) and the quench time is related to the “time at temperature” that affects cladding oxidation. Both must be accurately predicted to ensure regulatory criteria are satisfied. This implies that further improvements are needed to the relevant models.

The mass balance figures of merit (mass retained in the bundle, carryover, steam exhaust) were useful in identifying deficiencies in the analysis codes. These parameters provide the relative split between water retained in the bundle, liquid mass entrained out of the bundle, and the mass of steam produced. In several of the codes used in the study, the results suggested that liquid carryover was overpredicted, indicating that entrainment models need improvement.

Participants used different uncertainty analysis methodologies and uncertainty modelling assumptions (parameters, ranges and distributions) to demonstrate that the various figures of merit could be bounded by the code predictions plus uncertainty. In many cases this was achieved; however, there were several examples in which the code predictions had significant deviations and the data fell outside the bounds of the estimate uncertainty range. This suggests that uncertainty analysis methods and uncertainty modelling assumptions need further study to ensure that best estimate plus uncertainty techniques appropriately bound the figure(s) of merit in an analysis. An uncertainty questionnaire based on SAPIUM methodology was prepared to facilitate the comparison of the uncertainty analysis methods adopted by the participants for the selected blind experiments of the RBHT.

Several participants used the same analysis code to model and simulate RBHT experiments. There was found to be a wide variation in the predictions, indicating that the code “user effect” can be an important uncertainty in a calculation. Expert users with a well-documented analysis code can obtain significantly different results.

10. Recommendations

Additional studies on reflood thermal hydraulics are warranted. While reflood has been studied extensively, simulation of the thermal-hydraulic phenomena that dominate reflood remains difficult. Some analysis codes found unexpectedly poor agreement with experimental data. There is the possibility that this is because the RBHT facility and tests differ from most previous reflood experiments (top-skewed power shape and constant bundle power), resulting in new thermal-hydraulic conditions. Poor agreement may be due to the inability of codes to simulate a broad range of conditions. More well-controlled tests with detailed measurements are recommended to improve the relevant key models.

The application of uncertainty analysis methods remains another area where additional study is necessary. There is no consensus on which uncertainty analysis methods and which uncertainty modelling assumptions work best for reflood thermal-hydraulics, and in many cases accounting for uncertainties did not capture the figures of merit. This does not necessarily indicate a shortcoming in uncertainty analysis methods but does suggest improvements are necessary in both analysis codes and the model input uncertainty quantification. The code "user effect" was apparent among users of the same analysis code. This suggests that code developers should better define user guidelines. Then an uncertainty analysis step is also recommended to be included in all thermal hydraulics benchmarks and exercises since the start of the project.

The participants of this RBHT project recommend continued support from the NEA CSNI for further experiments, code improvements and benchmarking on reflood heat transfer thermal-hydraulics, which is considered important for the continued safe and efficient operation of light water reactors.

Agreement between predicted and experimental results partly depended on the flooding rate. Most of the simulations predicted carryover poorly and usually overestimated that figure of merit. This suggests that the entrainment model might be the root cause, as the amount of entrainment affects the interfacial area of the entrained field and evaporation of that field into the steam. This is more of a challenge in the low flooding rate tests since small liquid dominates the steam production. It was also important to mention the user effect in the application of the same code by different experts. It is not clear how well spacer grid phenomena were captured in the simulations.

One idea for a future phase of the project is to carry out a series of low and high reflood rate tests. The low reflood rate tests might be an opportunity to see not only the inventory distribution and PCT, but also what type of temperature drop appears in the spacer grids, when they are wet and dry out again, and which kind of change in droplet diameter can be expected across the spacer grids. The high reflood rate should provide data on inverted annular flow with the objective of looking to the quench profile and inventory distribution, given that the PCT is not really the main interest because it turns around almost immediately and the carryover is high.

The power radial distribution within fuel assembly or between neighbouring fuel assemblies induces transverse velocities that participate in the overall cooling of the rods. Additionally, the perturbation coming from the unheated housing can be decreased by a properly defined radial power distribution. The radial power distribution can also be a source of investigation, not to mention the axial power shape.

Small modular reactors (SMRs) generally do not experience core uncover or a temperature excursion, at least for the typical design basis accident (DBA). In case of multiple failures or increases in power, this might result in boiloff where the bundle inventory decreases, even if there is flow from the bottom. The resulting void distribution below the water level is still challenging for the codes. Depending on the interest of the experts, in support of SMR evaluations, the proposal is to conduct a series of boiloff tests with low inlet coolant injection rates and ranges of bundle power and pressure. Simulations should focus on bundle mass, void distribution and temperature excursion. Accident-tolerant fuel (ATF) could also be addressed by replacing the inner 3x3 rods with rods simulating ATF (though this might be expensive) and repeating some constant reflood rate tests. In this case the focus would be on the quench profile.

The second phase of the project would be to focus on new experiments and simulations of phenomena that present difficulties, rather than uncertainty analysis, i.e. theoretical modelling aspects to focus on relevant physical phenomena (entrainment, spacer grid effects on droplet breakup and heat transfer enhancement) to improve models and correlations for computer codes.

Appendix A. Questionnaire to address Uncertainty Analysis of Thermal-hydraulic Simulations of the Blind Experiments in the Rod Bundle Heat Transfer (RBHT) facility

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The present questionnaire was prepared with the aim to facilitate the comparison of the uncertainty analysis provided by the participants for the selected blind experiments of the RBHT.

The answers from the participants will allow for characterising step-by-step the main features and assumptions of the proposed participants' uncertainty analysis methodologies and thus they will provide the bases for conducting an appropriate comparisons of participants' uncertainty bands and for explaining the reason for possible discrepancies.

The questions were prepared following the experiences gained and results achieved in international projects related with the uncertainty analysis and according to relevant framework for the uncertainty quantification, like:

- The Uncertainty Methods Study (UMS, 1998).
- The Best Estimate Methods - Uncertainty and Sensitivity Evaluation (BEMUSE, 2011).
- The Post-BEMUSE Reflood Model Input Uncertainty Methods Benchmark (PREMIUM, 2017).
- The Development of a Systematic Approach for Input Uncertainty quantification of the physical Models in thermal-hydraulic codes (SAPIUM, 2019).
- The USNRC Evaluation Model Development and Assessment Process (EMDAP, 2005).

The questions were organised in different groups according as far as possible to the subdivision in elements adopted in SAPIUM project.

The participants are encouraged to provide an answer for each question, limiting as much as possible replies based on the adoption of subjective engineering judgement. To facilitate the comparison between participants, please avoid skipping a question even if you have addressed it in some previous reply.

However, if any participants are not willing to share the information or not able to answer some of the questions, it is possible to skip questions associated with Elements 2-5 below.

ELEMENT 1: Specification of the Problem and Requirement

1.1 What type of uncertainty analysis method was applied in your analysis? Please provide a short description and indicate if there are specific changes applied for this specific study.

1.2 Which type of uncertainties (model form uncertainty, boundary and initial conditions uncertainty, nodalisation/representation uncertainty, experimental uncertainty of FOM) do you consider in your method for the RBHT?

1.3 Did you apply an inverse uncertainty quantification method for quantification of the model form input uncertainty? If yes, please describe the method and what are the assumptions adopted?

1.4 How have you identified important phenomena and key physical models? Have you performed a PIRT for the simulation of the RBHT tests (either based on the previous simulation of other rod bundle reflood heat transfer tests or new one)?

1.5 What key physical models have you considered for RBHT benchmark for uncertainty evaluation?

ELEMENT 2: Development and Assessment of the Experimental Database

2.1 Was the determination of the uncertainty parameters and associated range/distribution for your study of RBHT benchmark, based on the assessment of other experiments, and if so which experiments?

2.2 Do you assess the adequacy of the identified experimental database respect to the RBHT benchmark? If yes, please describe how you carried-out this analysis?

2.3 Do you assess the completeness of the identified experimental database respect to the RBHT benchmark? If yes, please describe how you carried-out this analysis?

2.4 Do you perform any scaling analysis to identify similarities/distortions between the identified experimental database and the RBHT benchmark? If yes, please describe.

2.5 Do you introduce any quantitative metrics to quantify the adequacy/representativeness of the identified experimental database respect to the RBHT benchmark?

ELEMENT 3: Selection and Assessment of the Simulation Model

3.1 How do you assess the applicability of your Simulation Model (i.e. applied code and developed nodalisation) for simulating the RBHT tests?

3.2 Do you introduce any quantitative metrics to quantify the agreement between the RBHT experimental results and the simulation results during the benchmark Open phase? If yes, please provide a description.

3.3 Which major discrepancies between simulation and experimental results of the open phase were identified? Which specific actions do you consider and implement for performing the uncertainty analysis during the blind phase?

ELEMENT 4: Input Uncertainty Quantification

4.1 In connection to the key physical models considered for RBHT benchmark (see question 1.5), which parameters have you considered to characterise the uncertainty in each identified key physical models?

4.2 Which other influential input parameters (in addition to the model input parameters addressed in question 4.1) have you considered and why?

4.3 Do you adopt any quantitative method to identify and support the identification of influential input parameters? If yes, please describe.

4.4 How do you derive the range of variation and the PDF for each identified influential input parameter? Please discuss separately the process adopted for parameters belonging to different type (e.g. Boundary and Initial Conditions, Model-Form, Nodalisation, Scaling considerations).

4.5 In case you have applied an inverse uncertainty quantification method for the quantification of the model form input uncertainty:

4.5.1 What are the experimental tests in the data base used for the quantification?

4.5.2 How do you aggregate/combine the information coming from different experiments to be used in the inverse propagation?

4.5.3 Do you apply any quantitative method to measure the disagreement between the experimental results in the database adopted for the quantification and the simulation results of those experiments, before "assimilating" the information and deriving the model form input uncertainty? If yes, how this works? If the disagreement is too high, what do you do?

4.5.4 Do you apply any scaling/distortion analysis between the experimental results in the database adopted for the quantification and the RBHT facility? If yes, how are the outcomes of this analysis quantitatively impacting the inverse uncertainty quantification?

4.5.5 How do you combine the model form input uncertainties if several quantifications are performed?

4.5.6 Do you apply any counterpart-test for confirming the results of the inverse uncertainty quantification methods? If yes, please describe. What happen if the confirmation test fails?

ELEMENT 5: Model Input Uncertainty Validation

5.1 What are the experimental tests in the data base used for the validation?

5.2 Do you adopt any quantitative metrics/criteria (validation indicators) to characterise the success of the validation process?

5.3 Is there any iteration between the quantification and the validation process in a loop-approach?

ELEMENT 6: Application to RBHT (or nuclear power plant - not in the present benchmark)

6.1 What are the final ranges and distributions used for the identified input uncertainties?

6.2 How do you propagate all identified input uncertainties through the simulation model? Please provide a description.

6.3 What is the chosen sample number? What happen do you do if some calculation fails?

6.4 Are the figures of merit (FOMs) estimated using a one-sided or two-sided uncertainty? How do you determine the upper and lower bounds with 95% level of confidence?

6.5 How do you treat the model bias if any?

6.6 Do you perform any scaling analysis with respect to your reference nuclear power plant? Do you think the model input uncertainty can be extrapolated for real plant applications?

6.7 Do you perform any sensitivity analysis? What method do you use? What are the sensitivity measures used for identifying/confirming the influential input parameters?