EBR-II PASSIVE SAFETY DEMONSTRATION TESTS BENCHMARK ANALYSES – PHASE 2

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ABSTRACT

The International Atomic Energy Agency Coordinated Research Project, "Benchmark Analyses of an EBR-II Shutdown Heat Removal Test" is in the third year of its four-year term. Nineteen participants representing eleven countries have simulated two of the most severe transients performed during the Shutdown Heat Removal Tests program conducted at Argonne's Experimental Breeder Reactor II. Benchmark specifications were created for these two transients, enabling project participants to develop computer models of the core and primary heat transport system, and simulate both transients. In phase 1 of the project, blind simulations were performed and then evaluated against recorded data. During phase 2, participants have refined their models to address areas where the phase 1 simulations did not predict the experimental data as well as desired. This paper describes the progress that has been made to date in phase 2 in improving on the earlier simulations and presents the direction of planned work for the remainder of the project.

KEYWORDS
EBR-II, SHRT, LOF, benchmark, sodium

1. INTRODUCTION

The International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP), "Benchmark Analyses of an EBR-II Shutdown Heat Removal Test" was formally initiated in June 2012. The goals of the CRP are 1) improved validation of state-of-the-art sodium-cooled fast reactor (SFR) computer codes through comparisons of the analytical predictions against whole-plant recorded test data and 2) training of the next generation of SFR analysts and designers through participation in international benchmark exercises. The data used in the CRP were acquired as part of a series of landmark shutdown heat removal tests (SHRT) conducted by Argonne National Laboratory at its Experimental Breeder Reactor II (EBR-II) facility in the 1980's. Nineteen organizations representing eleven countries are participating in the CRP, which will conclude in 2016.

To date, CRP participants have performed blind calculations on two of the most severe SHRT transients (phase 1 of the CRP) and have then made a first round of modeling improvements based on insights acquired through comparisons against the recorded data and through comparisons between codes (phase 2 of the CRP). A summary of the current status of simulation of the primary loop behavior during both transients and future work to be performed by the participants are described below. Detailed descriptions of the models and modeling assumptions made by each participating organization, plus additional results, will be presented in the CRP TECDOC that will be published by the IAEA after the CRP ends.

2. EBR-II AND THE SHUTDOWN HEAT REMOVAL TESTS

EBR-II was a prototype fast reactor plant that was rated for 62.5 MWth and generated approximately 20 MWe. It was designed and operated by Argonne for the U.S. Department of Energy and was located at the Argonne-West site (now the Materials and Fuels Complex at the current Idaho National Laboratory). EBR-II was a sodium-cooled reactor fueled with uranium metal alloy fuel, with a pool type primary system. Figure 1 shows the configuration of the main components in the EBR-II primary system.

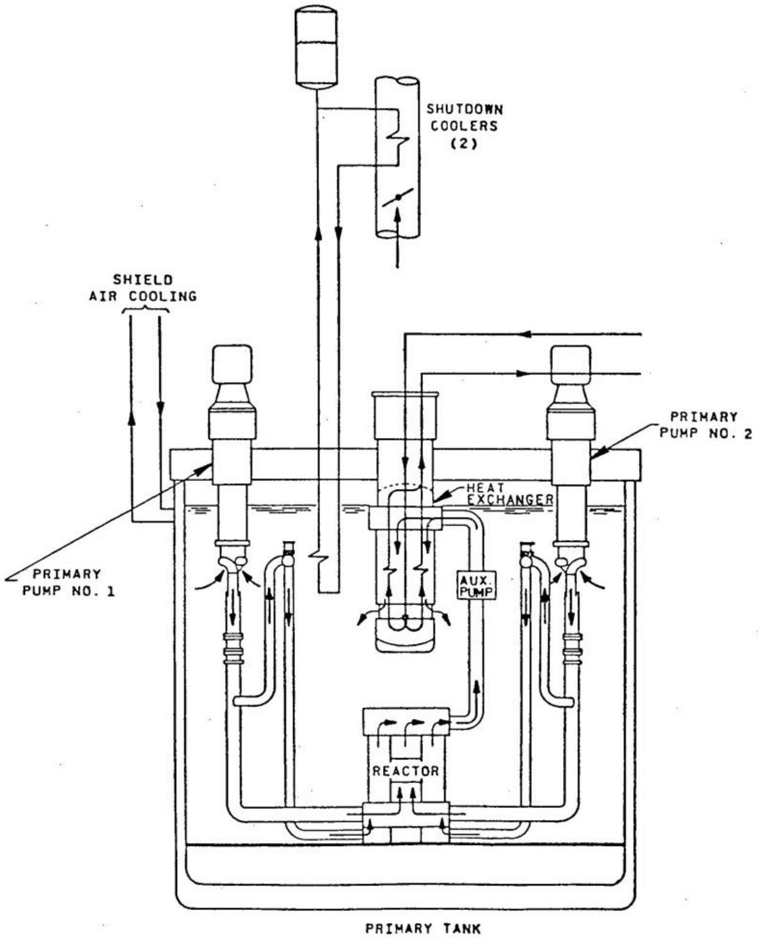

Figure 1. EBR-II Primary System

The EBR-II SHRT testing program demonstrated the ability of a SFR to survive severe loss-of-flow and loss-of-heat sink accident initiators with no core damage. The program was conducted from 1984 to 1986. In addition to data collected throughout the primary and intermediate loops, two instrumented subassemblies, one (XX09) a fueled subassembly in the inner core and one (XX10) a non-fueled subassembly in the reflector region, were in place during the transients and recorded extensive radial and axial temperature measurements, plus flow data. The tests thus provide a unique set of whole-plant data taken during severe accident sequences.

For this CRP, the two tests selected for analysis were SHRT-17, the most severe of the protected (with scram) loss-of-flow tests, and SHRT-45R, a station blackout and the most severe of the unprotected (without scram) loss-of-flow tests in the program. These tests were selected because of the wide range of conditions that occurred during the transients. Both were initiated from full power and flow, with a total loss of pumping power. More detailed descriptions of these tests are available in [1] and [2].

3. THE CRP BENCHMARKS

Phase 1 began with development by Argonne of the benchmark specifications for both transients. Argonne, as the organization that conducted the SHRT program and the owner of the data from these tests, is the sponsor and lead technical organization for the CRP, as well as a participant in the benchmark analyses. The benchmark specifications provided participants with 1) a complete description of both tests; 2) detailed descriptions of the reactor core for each transient, including subassembly dimensions; 3) primary system component dimensions; 4) isotopic compositions; 5) material properties; and 6) data needed for calculating reactivity feedback coefficients in the case of SHRT-45R. The benchmark model of the EBR-II primary circuit is diagrammed below in Fig. 2. Further details about the benchmark specifications are given in [1] and [3].

CRP participants could elect to simulate one or both of the transients. In the case of the unprotected loss-of-flow test SHRT-45R, a neutronics benchmark specification was also created, and participants who analyzed SHRT-45R had the option of also participating in the neutronics benchmark. Participants were asked to calculate the following values:

- For comparison against plant data:
    - High-pressure and low-pressure inlet plena temperatures
    - Z-pipe (reactor outlet pipe) inlet temperature
    - IHX primary side inlet temperature
    - IHX intermediate side outlet temperature
    - Mass flow rates at the primary pumps
    - XX09 and XX10 temperatures
    - XX09 and XX10 mass flow rates
    - SHRT-45R: Fission power
- For code-to-code comparison:
    - Peak fuel temperature
    - Peak cladding temperature
    - Peak in-core coolant temperature
    - SHRT-45R: Decay heat power
    - SHRT-45R: Total power
    - SHRT-45R: Reactivity feedbacks

4. MODELING TOOLS

In the tables and plots below, participants are identified only by number, not by institution name. This is done so as to focus on the results collectively and on how the various simulations compare with each other and with the experimental data. This also avoids any appearance of judging the performance of individual models. Table I below summarizes, by type, the codes used by the CRP participants.

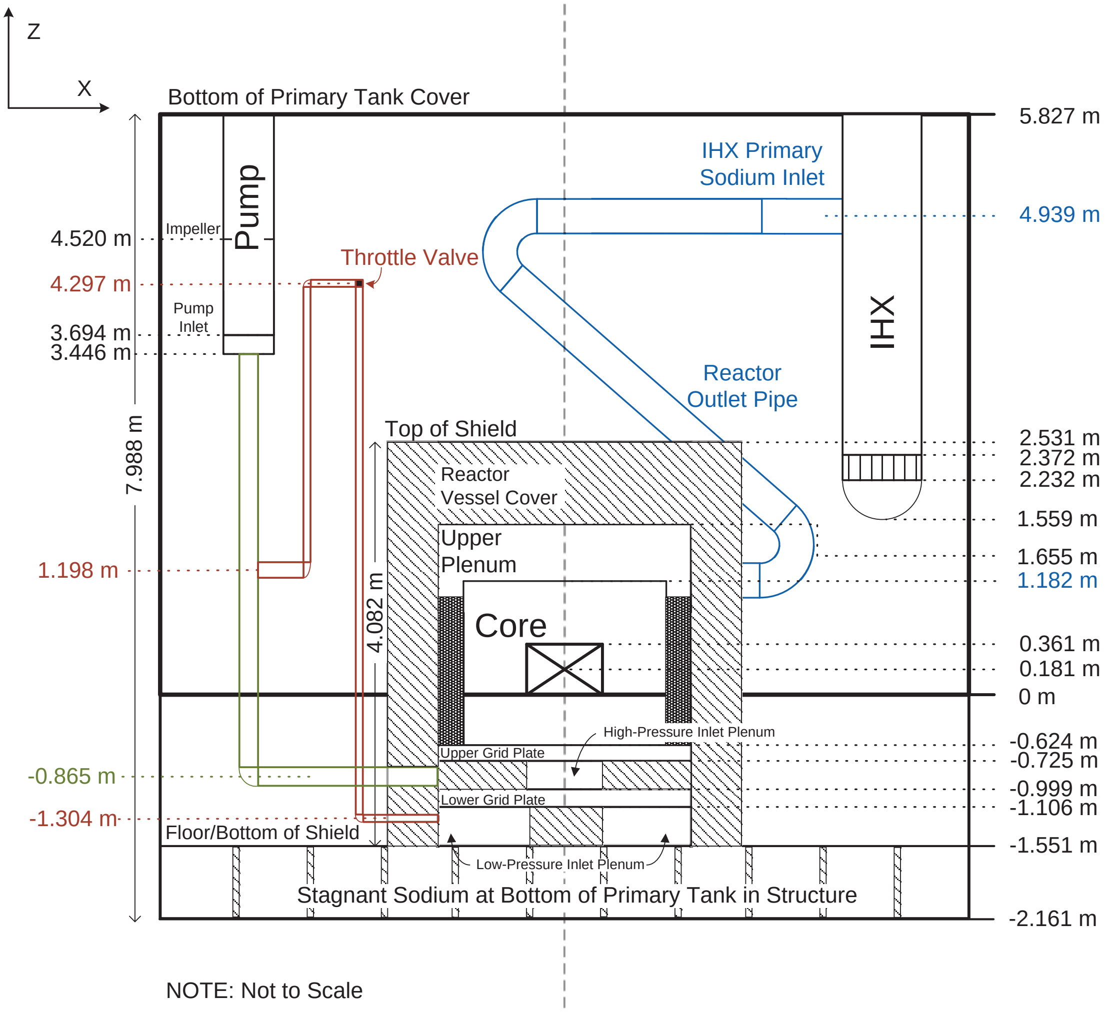

Figure 2. EBR-II Primary System Benchmark Model

5. SUMMARY OF PHASE 1

5.1. Conduct of Phase 1

During phase 1, participants generated blind simulation results for both transients. These results were evaluated collectively by the participants against plant data during the second Research Coordination Meeting (RCM) of the CRP, with final blind results submitted in February 2014. These combined results showed generally good agreement with plant data for some parameters, such as the SHRT-17 inlet plena temperatures and the SHRT-45R primary pump flow. For other parameters, such as the SHRT-45R inlet plena temperatures and the SHRT-17 primary pump flow, a number of models agreed well with each other but showed consistent differences with the data. For a third group of parameters, the results differed significantly among models, and none of the models showed good agreement with the data. These included the Z-pipe inlet temperature, the IHX primary side inlet temperature, and the IHX secondary side outlet temperature.

Table I. Codes used for CRP models

Participant	Code(s)
1	Thermal-Hydraulic Systems Analysis/Subchannel: SAS4A/SASSYS-1 Neutronics: MC^2-3, TWODANT, DIF3D, VARI3D, ORIGEN-2
2	Thermal-Hydraulic Systems Analysis: SAS4A/ SASSYS-1 Subchannel: COBRA-SFR
3	Thermal-Hydraulic Systems Analysis: RELAP5-3D Computational Fluid Dynamics: CFX Neutronics: PHISICS, SCALE, MCNPX
4	Thermal-Hydraulic Systems Analysis: RELAP5-3D, NETFLOW++ Computational Fluid Dynamics: CFX Neutronics: ERANOS 2.0
5	Thermal-Hydraulic Systems Analysis: SOCRAT-BN
6	1-D Plant Dynamics: EBRDYN Computational Fluid Dynamics: STAR-CD
7	Thermal-Hydraulic Systems Analysis: CATHARE
8	Thermal-Hydraulic Systems Analysis: Super-COPD Subchannel: ASFRE
9	Thermal-Hydraulic Systems Analysis: MARS-LMR
10	Thermal-Hydraulic Systems Analysis: TRACE
11	Thermal-Hydraulic Systems Analysis: SIMMER Neutronics: ERANOS, ECCO, KIN-3D, PARTISN
12	Fuels: CALPHAD
13	Thermal-Hydraulic Systems Analysis: SAC-CFR
14	Thermal-Hydraulic Systems Analysis: SPECTRA Subchannel: COBRA Computational Fluid Dynamics: CFX
15	Thermal-Hydraulics + Neutronics: FRENETIC
16	Thermal-Hydraulic Systems Analysis: TRACE 5.0 Computational Fluid Dynamics: OPENFOAM Fuels: FRED Neutronics: SERPENT 2.1.5, PARCS
17	Thermal-Hydraulic Systems Analysis: SASA4A/SASSYS-1 Subchannel: COBRA-4i
18	Thermal-Hydraulic Systems Analysis: RELAP5-3D
19	Thermal-Hydraulic Systems Analysis: THACS

Twelve participants analyzed SHRT-17 during phase 1 and eight analyzed SHRT-45R (with some participants simulating both transients). A few also performed the neutronics benchmark. Some participants implemented detailed models for the instrumented subassemblies, in addition to modeling the primary circuit components.

5.2. Phase 1 Simulation Results That Agreed Well with the Data

Because the variety of simulation results produced by the CRP participants are too numerous to cover in one conference paper, the results to be presented in this paper will be limited to thermal-hydraulic parameters in the primary circuit outside the core and will include only parameters for which recorded data are available. Temperature and flow simulation results within the core, including comparisons against data from the instrumented subassemblies and inter-code comparisons of peak fuel, cladding, and coolant temperatures, will be presented in a future paper. Neutronics benchmark results will also be covered in another paper. As mentioned above, detailed discussions of all CRP models and results will be presented in the CRP TECDOC that will be published by the IAEA after the CRP ends in 2016.

5.2.1. SHRT-17 inlet plena temperatures

Of the twelve participants who simulated the SHRT-17 primary loop during phase 1, seven predicted temperatures for the high-pressure inlet plenum that were within 1K of the data throughout the transient, and only two of the remaining five were significant outliers. Results were not quite as good for the low-pressure inlet plenum temperature, for which the data showed a slow, steady decline beginning about 400 seconds into the transient. Most participants predicted the temperature up to 400 seconds well but did not capture the slow temperature drop. This drop may be due to thermal stratification in the cold pool and thus heat loss to the pool from the lower portion of the low-pressure plenum inlet piping. Since most phase 1 simulations did not model thermal stratification of the cold pool, the simulation results did not show this decline in temperature.

5.2.2. Primary pump flow in SHRT-45R

Eight participants analyzed the SHRT-45R transient during phase 1. Figure 3 below plots the simulation results against recorded data (solid red line in Fig. 3) for pump #2 (the pump #1 flowmeter was no longer operational at the time of the SHRT program, and so data were recorded only for pump #2). Half of these showed the correct shape of the curve and came within 10% of the recorded data throughout the transient. The jump in flow just after 600 seconds occurred because the EBR-II auxiliary electromagnetic pump current was increased at that point. Only the lowest flow portion of the transient is plotted in Fig. 3; the initial flow rate was 242 kg/s, and so the high flow rate portion of the curves is not shown in order to make the spread among the simulation results easy to see. It should be noted that, at these low flows, the uncertainty in the EBR-II flowmeter measurements is significantly greater than at full flow.

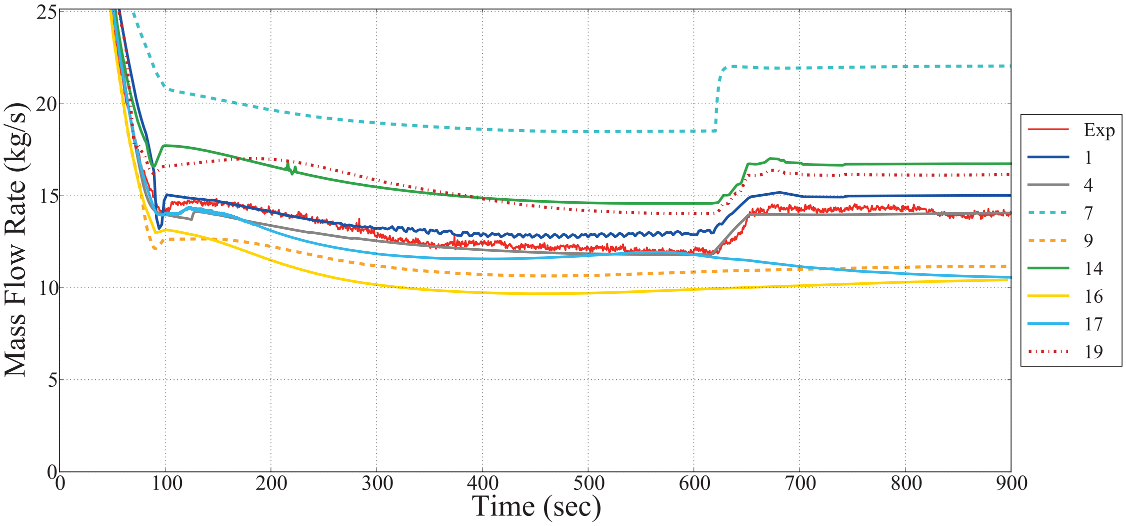

Figure 3. Phase 1 Simulation Results vs. Recorded Flow Data for Pump #2, SHRT-45R.

5.3. Phase 1 Modeling Shortfalls

5.3.1. SHRT-17 primary pump flow

As indicated in Fig. 4, most of the simulations overpredicted the flow through pump #2 for SHRT-17 once the main coastdown was over. Only participant 4 was fairly successful at predicting both the SHRT-45R flow through pump #2 and also the SHRT-17 flow.

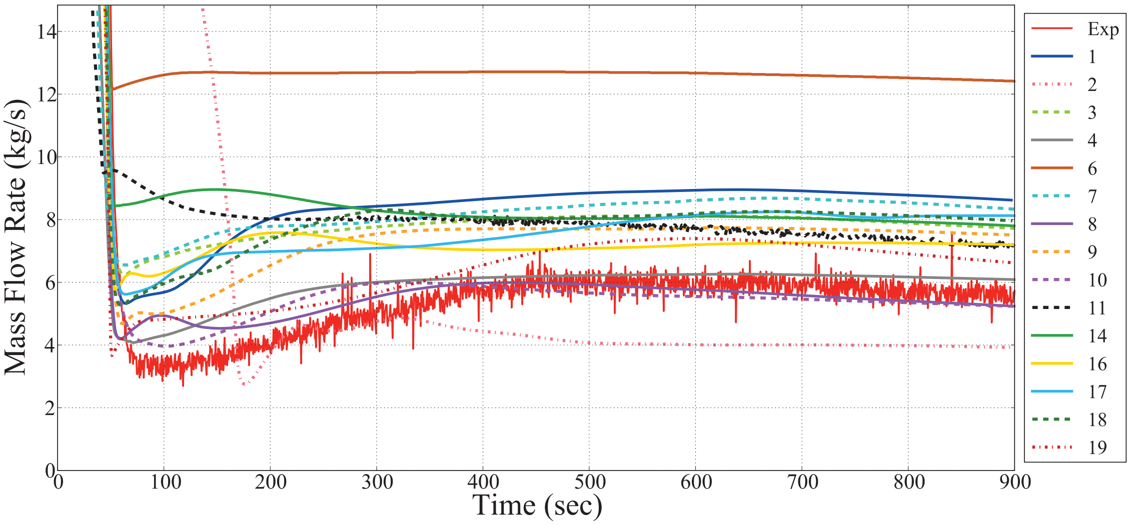

Figure 4. Phase 1 Simulation Results vs. Recorded Flow Data for Pump #2, SHRT-17.

5.3.2. SHRT-45R inlet plena temperatures

The SHRT-45R low-pressure inlet plenum temperature started dropping at the beginning of the transient and had dropped about 3K by 900 s, whereas the high-pressure inlet plenum temperature rose throughout the transient and had increased about 3K at 900 s. Nearly all the simulations overpredicted the low pressure inlet plenum temperature by 2-4K by 400 seconds into the transient. The simulation results were mixed for the high-pressure inlet plenum temperature, but nearly all underpredicted the temperature in the last half of the transient. As with the SHRT-17 low-pressure inlet plenum temperature, the differences between the simulation results and the data may be due to the fact that the simulations did not account for thermal stratification in the cold pool.

5.3.3. Z-pipe inlet temperature and IHX primary side inlet temperature

As explained in [2], no direct measurement of the Z-pipe inlet temperature is available for SHRT-17. Therefore, comparisons between data and simulation results for the Z-pipe inlet temperature will be discussed just for SHRT-45R. As seen in Fig. 5 below, all the simulations predicted the correct shape for the temperature curve but varied widely in the predicted peak temperature, and most results overpredicted the temperature following the peak. The gap in the experimental data curve is due to an instrumentation error that resulted in the temperature not being recorded correctly from about 75 to 200 seconds during SHRT-45R.

The inaccuracy of the Z-pipe inlet temperature simulation results meant that, of course, the simulations would also overpredict the IHX primary side inlet temperature. However, as Fig. 6 shows, the disagreement between simulations and experimental data is significantly worse for this temperature. The heat loss from the Z-pipe to the cold pool that was included in some of the models is insufficient to account for the temperature difference between the Z-pipe inlet and the IHX inlet/Z-pipe outlet. Clearly other phenomena that were not modeled acted to lower the IHX inlet temperature.

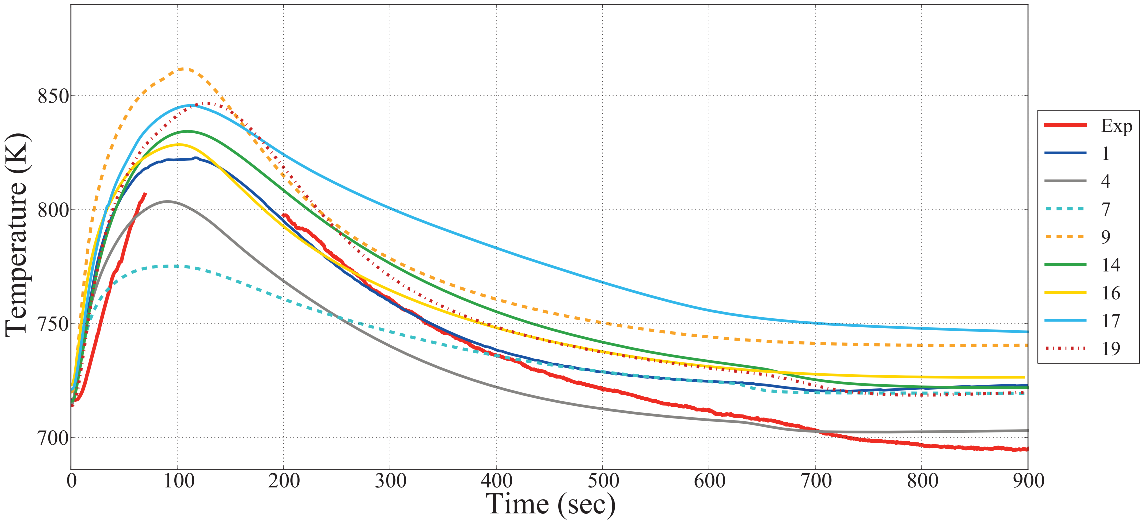

Figure 5. Phase 1 Simulation Results vs. Recorded Inlet Temperature Data for Z-Pipe, SHRT-45R.

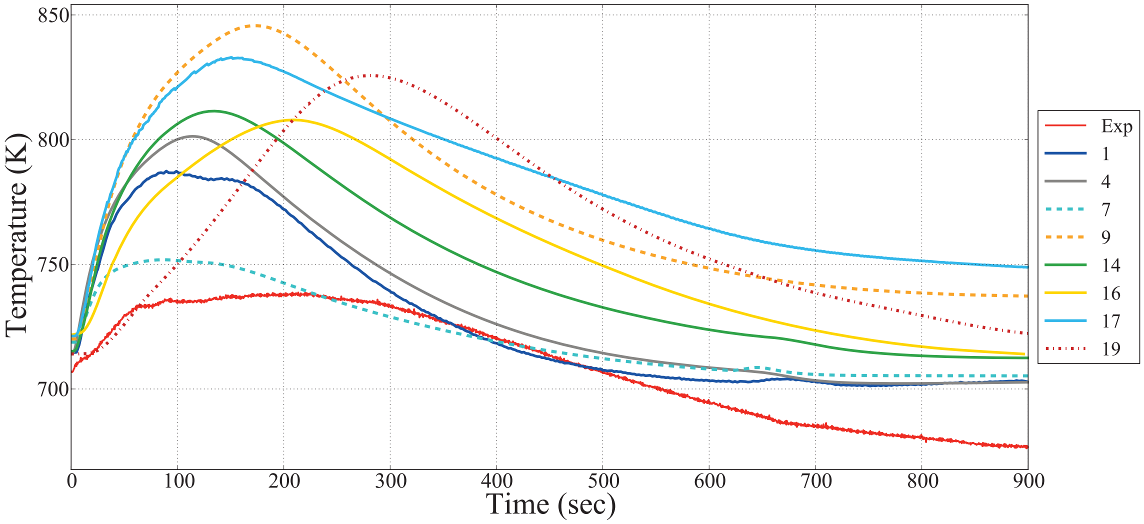

Figure 6. Phase 1 Simulation Results vs. Recorded IHX Primary Side Inlet Temperature Data, SHRT-45R.

5.4. Lessons Learned During Phase 1

Evaluation of the blind simulation results against the recorded data at the end of phase 1 and consequent reevaluation of the simulation models provided direction for modeling refinements to be pursued during phase 2 of the CRP. The more prominent among those applicable to the primary circuit modeling are:

- The two primary pumps and associated piping must be modeled individually. Some of the models made the simplification of combining the two pumps into one. However, although the two pumps and piping are nominally identical, they are not located symmetrically with reference to the IHX and do not behave identically, particularly during the natural convection portion of SHRT-17.

- Mass flow results led to the conclusion that both pumps locked for SHRT-17 and neither pump locked for SHRT-45R, contrary to what was originally thought. See [2] for details.
- A perfect mixing model of the upper plenum does not appear to be adequate.
- Some results would be improved by modeling thermal stratification in the cold pool.
- Heat transfer between the Z-pipe and the cold pool must be modeled. While the Z-pipe double-walled design, with stagnant sodium between the inner and outer pipes, was intended to minimize heat loss to the cold pool, the heat loss that still occurred was significant enough to need to be accounted for in the modeling.

There were also a number of lessons learned with respect to the core modeling and level of detail required to model the instrumented subassemblies; these will be covered in a future paper.

6. PHASE 2 MODELING REFINEMENTS AND RESULTS

6.1. Modeling Refinements Implemented in Phase 2

Based on the outcomes of the phase 1 modeling, participants implemented and tested a number of modeling refinements during phase 2. Multidimensional effects modeling was explored for both the cold pool and the reactor outlet plenum. Cold pool model refinements ranged from a 3-level 1-D model to 3-D models with coarse radial and azimuthal meshes and finer axial meshes. Some simple upper plenum model refinements, including limited modeling of the upper plenum baffle plate, were tried. Primary pump modeling was improved by adjusting the locked rotor flow rate threshold and the locked rotor loss coefficient. To address the increased uncertainty in the flowmeter readings at low flow rates, parametric studies on mass flow rate or on pump coastdown were performed by some participants. More participants modeled each primary pump separately and modeled heat loss from the Z-pipe to the cold pool.

Table II summarizes the principal modeling revisions made from phase 1 to phase 2 by each participant.

6.2. Improvements in Phase 2 Results Compared with Phase 1

6.2.1. SHRT-17 primary pump flow

Primary pump #2 mass flow rate simulation results for phase 2 are plotted in Fig. 7, along with the recorded flow measurements. Comparison with Fig. 4 shows significant improvement for most of the simulations, with several matching the data quite well from about 200 seconds on.

6.2.2. SHRT-45R primary pump flow

Several of the simulations already had done a good job in phase 1 of predicting the mass flow rate for primary pump #2 during SHRT-45R. The results for phase 2 are shown in Fig. 8, and comparison with Fig. 3 shows that, collectively, the phase 2 results are a significant improvement over phase 1. In particular, the large improvement for participant 7 appears to be due to modeling the primary pumps separately in phase 2, instead of as a single average pump as was done in phase 1.

6.2.3. SHRT-45R inlet plena temperatures

Simulation results overall improved slightly in phase 2 for the high-pressure inlet plenum temperature, with most simulations moving closer to the recorded data but still underpredicting the temperature for the last 250 seconds of the transient. For the low-pressure inlet plenum, two of the simulations matched the data to generally better than 1 K throughout the transient, while others showed little improvement or, in a few cases, were in poorer agreement with the data than were the phase 1 results.

Table II. Phase 2 modeling revisions

Participant	Modeling Revision(s)
1	• Refined homologous pump model for primary pumps • Identified an incorrect thermocouple location in the upper plenum
2	• No phase 2 primary loop results
3	• Cheng & Todreas wire-wrapped bundle pressure drop correlation • Sodium properties based on measured experimental data
4	• CFD steady-state analysis of cold pool, output error correction
5	• Did not join CRP until phase 2
6	• 3-D steady-state CFD modeling of XX09
7	• Primary pumps and associated piping modeled individually • Increase singular head loss coefficients at low flowrates • Modeled EM pump using voltage evolution
8	• Radial heat transfer between inner and outer core • Modeled high-pressure and low-pressure inlet plena separately • Pressure loss coefficient in minor subassemblies improved
9	• Modeled thimble flow in instrumented subassemblies • Parametric evaluation of Z-pipe heat structure model
10	• Modeled radial heat transfer between neighboring subassemblies • Heat structures added in upper plenum shield, Z-pipe, IHX
11	• Tuned pump parameters so pump coastdown matches transient flow • S_8 used for reactivity coefficients
12	• Thermodynamic properties developed for U-5Fs, used by participant 11
13	• 3-D cold pool model
14	• Cosine axial power profile, heat loss through cold pool floor • Change in assumed location of IHX primary inlet thermocouple
15	• Did not join CRP until phase 2, analyzed only the core
16	• 3D cold pool model
17	• Refined core nodalization and COBRA subchannel modeling • Control rod drive expansion + coolant reactivity feedback coefficient • Adjusted primary pump models to match steady state • Included heat loss from Z-pipe and IHX to cold pool
18	• Each inner core subassembly modeled separately • 3-D cylindrical cold pool nodalization • Thimble flow modeled in instrumented subassemblies
19	• 3-layer cold pool model, heat transfer between Z-pipe and cold pool

6.2.4. SHRT-17 inlet plena temperatures

Phase 2 results for the SHRT-17 high-pressure inlet plenum temperature were consistently an improvement over phase 1. Thirteen participants produced phase 2 SHRT-17 predictions, with eleven of these having also produced phase 1 results for this transient. There were no outliers among the predictions, and over half the results came within less than 1 K of the recorded data throughout the transient. The phase 2 results for the low-pressure inlet plenum temperature did not show as much improvement over phase 1 for most of the participants, but the three outliers from phase 1 improved their results significantly, and their phase 2 results are in line with the predictions from the other simulations.

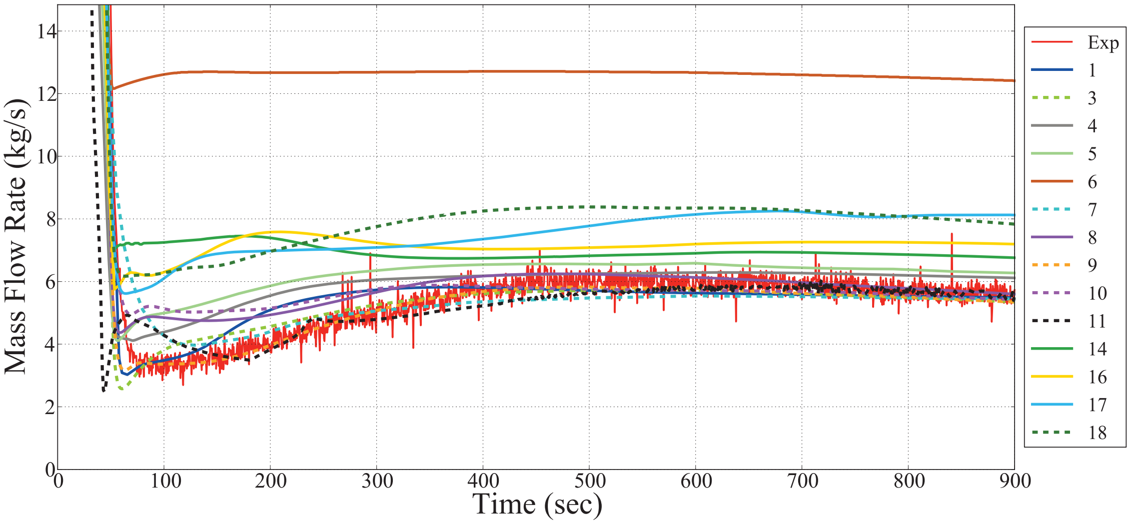

Figure 7. Phase 2 Simulation Results vs. Recorded Flow Data for Pump #2, SHRT-17.

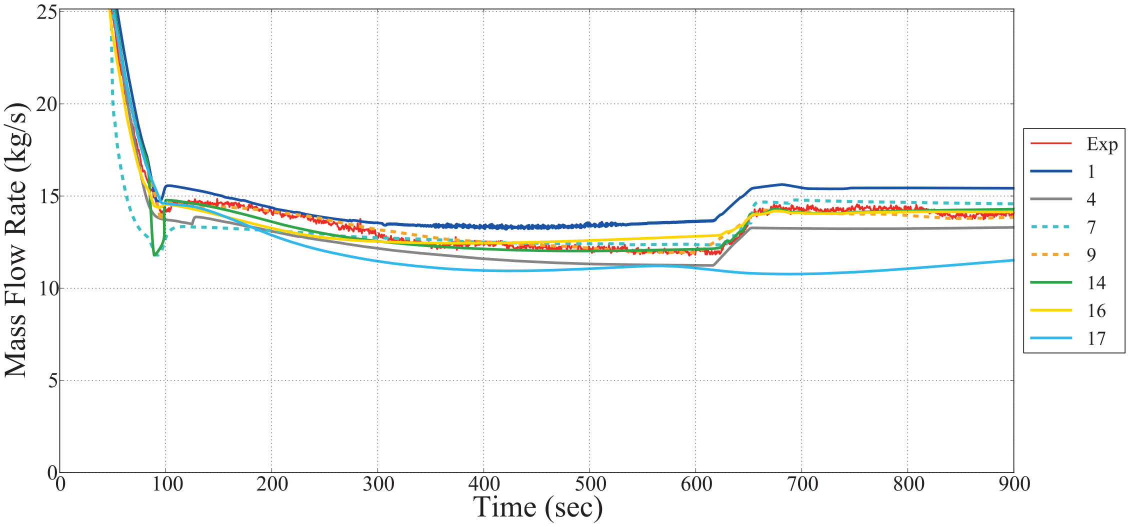

Figure 8. Phase 2 Simulation Results vs. Recorded Flow Data for Pump #2, SHRT-45R.

7. REMAINING MODELING ISSUES AND FUTURE WORK

The most significant modeling difficulty for all participants remains predicting the Z-pipe inlet temperature and the IHX primary side inlet temperature for both transients. Figure 9 plots phase 2 Z-pipe inlet temperature results for SHRT-45R. Comparison of these curves with the phase 1 results displayed in

Fig. 5 shows that, while phase 2 results from most of the simulations were closer to the data from 300 seconds on, some of the phase 2 temperatures were less accurate in the early part of the transient. The phase 2 IHX primary side inlet temperature results shown in Fig. 10 exhibit this same behavior. Comparing against the phase 1 results plotted in Fig. 6 shows that the models improved significantly after 300 seconds but still overpredicted the temperature throughout the transient.

One participant (identified in the graph as #14) achieved significantly better agreement with the measured IHX primary side inlet temperature by comparing the data against the calculated temperature from an upper node in the IHX primary side model, rather than against the calculated IHX inlet temperature. This may be an indication that the thermocouple that was intended to measure the average IHX inlet temperature is instead measuring only a colder portion of the sodium flow and that thermal stratification is occurring at the IHX inlet region.

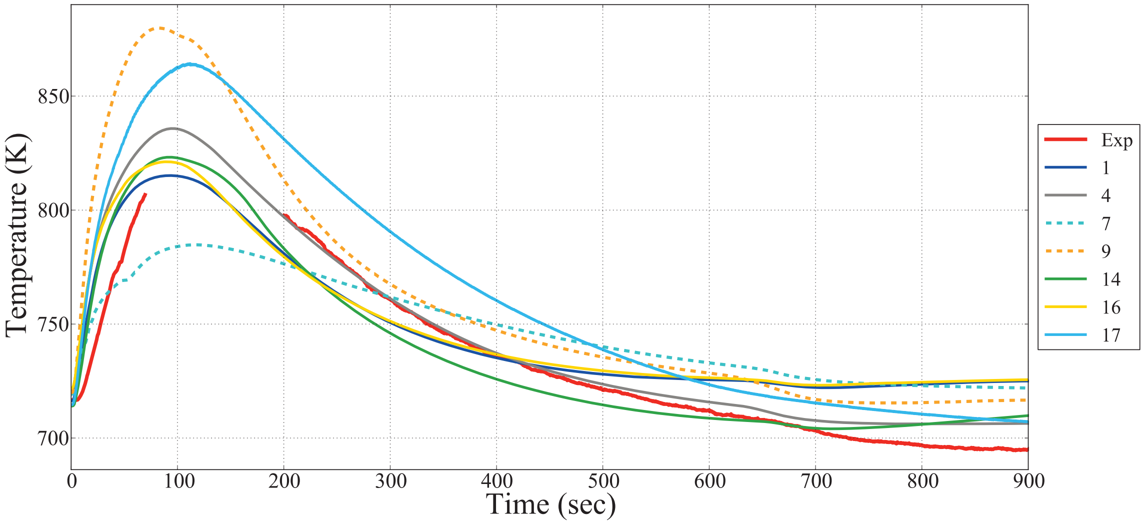

Figure 9. Phase 2 Simulation Results vs. Recorded Inlet Temperature Data for Z-Pipe, SHRT-45R.

Leakage between the outlet plenum and the cold pool, combined with thermal stratification in the outlet plenum and Z-pipe, may explain the inaccuracy of the Z-pipe and IHX inlet temperature predictions. This combined effect may have caused a significant shift in the sodium temperature as it traveled from the core exit through the Z-pipe and then entered the IHX. The perfect mixing and 1-D models used to date by the participants to model the outlet plenum and the Z-pipe do not allow simulation of thermal stratification. Several participants plan to create computational fluid dynamics (CFD) models of the upper plenum and the Z-pipe and couple them to the system codes in order to better model these regions, including the effect of leakages between the outlet plenum and the cold pool. Since no detailed information is available on sizes and exact locations of leakages or on the dimensions of the upper plenum baffle plate and the orifices in the plate, parametric studies will then be performed on leakage sizes and the baffle plate structure to see if the inlet temperatures to the Z-pipe and IHX can be more accurately modeled.

Several participants also plan to implement a full CFD model of the cold pool for the next round of simulations.

The CRP will conclude with a model qualification and accuracy quantification exercise to evaluate models and results from all participants. The qualification process will include 1) assessment of geometry fidelity through evaluation of geometrical data and numerical values implemented in the nodalization used by each model, 2) qualification of steady-state calculated values against experimental data and 3) qualitative and quantitative analysis using the Fast Fourier Transform Based Method, to quantify the accuracy of the simulations against the transient data.

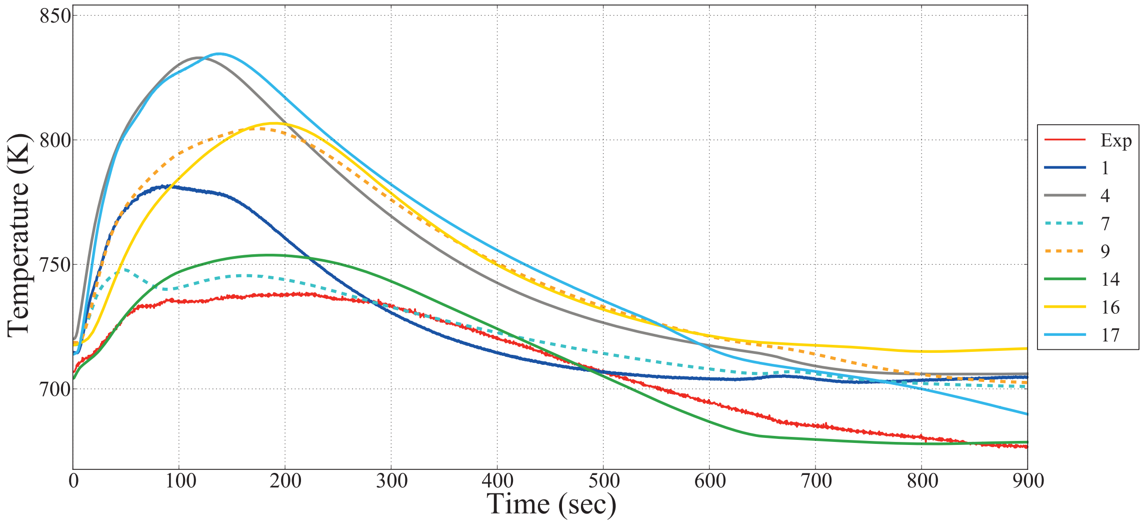

Figure 10. Phase 2 Simulation Results vs. Recorded IHX Primary Side Inlet Temperature Data, SHRT-45R.

8. CONCLUSIONS

Participants in the IAEA CRP, "Benchmark Analyses of an EBR-II Shutdown Heat Removal Test", have completed significant improvements in modeling the SHRT-17 and SHRT-45R transients, as shown by comparisons of the simulation results against the recorded plant data. Investigations are underway to determine how to further improve the models so as to achieve acceptable predictions for the Z-pipe and IHX primary side inlet temperatures, as well as to improve predictions with data from the instrumented subassemblies. Detailed final model descriptions and results will be published in an IAEA TECDOC once the CRP has concluded.

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