# Benchmark Analyses of EBR-II Shutdown Heat Removal Tests

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**Abstract**. In 2012, the International Atomic Energy Agency established a Coordinated Research Project on EBR-II Shutdown Heat Removal Tests. The objectives of the project, which concluded in 2016, were to improve design and simulation capabilities in fast reactor neutronics, thermal hydraulics, plant dynamics, and safety analyses through benchmark analysis of two landmark tests from the EBR-II Shutdown Heat Removal Tests program: SHRT-17 and SHRT-45R, the most severe protected and unprotected loss-of-flow transients, respectively, in the program. Nineteen organizations representing eleven countries participated in the project. Benchmark specifications were developed by Argonne for both transients, and a separate neutronics benchmark specification was assembled for the SHRT-45R test. Participant simulations were able to predict most plant parameters with acceptable accuracy, including the radial and axial temperature profiles within two instrumented subassemblies. A results qualification exercise was also performed for SHRT-17 results from ten of the participants and provided additional insight into the causes of discrepancies between the simulation predictions and the recorded data.

**Key Words**: EBR-II, SHRT-17, SHRT-45R, sodium-cooled fast reactors.

## 1. Introduction

From June 2012 to June 2016, the International Atomic Energy Agency (IAEA) conducted the Coordinated Research Project (CRP), "Benchmark Analyses of EBR-II Shutdown Heat Removal Tests", with the principal goal being to improve validation of state-of-the-art sodium-cooled fast reactor (SFR) computer codes. A secondary goal was training of the next generation of fast reactor analysts and designers. The CRP used whole-plant data recorded as part of a series of landmark shutdown heat removal tests (SHRT) [1] conducted by Argonne National Laboratory at its Experimental Breeder Reactor-II (EBR-II) facility in the 1980's. Argonne was the lead technical organization in the CRP, as well as a participant in the simulations, and developed benchmark specifications for the most severe protected loss-of-flow (LOF) SHRT test, SHRT-17, and the most severe unprotected LOF test, SHRT-45R. A neutronics benchmark specification was also created for SHRT-45R. These specifications were used by the nineteen CRP participants, representing eleven countries, to develop models and perform simulations of these two tests using a variety of SFR analysis codes.

The CRP was divided into two phases: initial blind calculations (phase 1) [2], followed by distribution of the recorded data to the participants and subsequent modelling improvements (phase 2) [3]. A results qualification exercise was also performed on the final results. This paper gives a summary of the tests analysed, the results achieved, and lessons learned during the CRP. Details of the models and modelling assumptions used by all participants, plus full final results of the simulations and the qualification process, will appear in an IAEA TECDOC [4].

## 2. Tests Analyzed

Participants had the option of analyzing both SHRT-17 and SHRT-45R or of analyzing just one transient. Nearly all participants analyzed SHRT-17. Participants also had the option of taking part in the neutronics benchmark exercise and generating their own neutronics parameters to apply to analysis of SHRT-45R. Alternatively, they could use neutronics parameters made available by Argonne.

### 2.1.EBR-II

The EBR-II plant was designed and operated by Argonne National Laboratory for the U.S. Department of Energy. EBR-II was a 62.5 MWth sodium-cooled fast reactor that was operated with metal fuel. The plant was a pool design, with all major primary system components submerged in sodium in the primary tank. The reactor operated for 30 years, beginning in 1964. During the last 15 years of operation, much of the EBR-II mission was focused on experiments that demonstrated the passive safety characteristics of liquid metal reactors. Of these, the SHRT series was the most extensive and prominent.

More detailed information about EBR-II can be found in [5].

### 2.2.SHRT-17

SHRT-17 was conducted on June 20, 1984. It was a full power LOF test that was run to demonstrate the effectiveness of natural circulation in the EBR-II plant. The test was initiated from full power and flow conditions, with both primary coolant pumps and the intermediate loop pump being tripped. The plant protection system remained on and simultaneously scrammed the reactor. To fully demonstrate the effectiveness of natural circulation, the primary system auxiliary coolant pump, which normally was connected to an emergency battery power supply, was turned off for the SHRT-17 test. The drop in coolant flow resulted in reactor temperatures rising initially to high levels that, nonetheless, remained well within safety limits. As the reactor transitioned into natural circulation, the effect was that the reactor safely cooled itself down and temperatures declined down to decay heat power levels.

### 2.3.SHRT-45R

SHRT-45R was performed on April 3, 1986, nearly two years after SHRT-17. It was a station blackout test, run from full power and flow, and was a demonstration of the effectiveness of the EBR-II reactor passive reactivity feedback in bringing the reactor down to decay heat power. For this test, the plant protection system was disabled so that a scram would not be initiated when the loss of flow occurred. The test was initiated by tripping the primary coolant pumps and the intermediate loop pump simultaneously at full power and flow. Because the intention was to simulate a station blackout, the primary system auxiliary coolant pump was left connected to its emergency battery power supply. Since the control rod drives had been deactivated, no control rod movement occurred following the pump trips.

As with SHRT-17, the initial drop in flow resulted in temperatures rising for the first ~100 seconds. Meanwhile, reactor power decreased due to reactivity feedbacks, causing the temperatures to begin to fall and eventually reach decay heat levels.

### 2.4.Instrumented Subassemblies

Throughout the SHRT series, instrumented subassemblies were inserted into control rod positions in the core to record detailed axial and radial temperature profiles and flow rate within the subassembly. These subassemblies recorded data that could be used to validate simulation results at a finer level of detail.

Two instrumented subassemblies, XX09 and XX10, were used during both SHRT-17 and SHRT-45R. XX09 was a fueled subassembly with two flowmeters at the subassembly inlet and thermocouples at the inlet and five additional axial locations. XX10 was a non-fueled subassembly, again with two flowmeters at the inlet, plus thermocouples at the inlet and four additional axial locations.

## 3. Benchmark Specifications

Argonne assembled benchmark specifications for both transients that provided detailed information on the core and the primary circuit, as well as boundary conditions for both transients. In addition, Argonne developed a separate neutronics benchmark specification that provided the data needed to construct neutronics models for SHRT-45R.

The SHRT-17 and SHRT-45R specifications included separate model details for each of the ten types of subassemblies that were in the core during these transients, as well as fuel properties. They also provided representations of the inlet and outlet plena, the primary circuit components (pumps, intermediate heat exchanger (IHX)), and the primary circuit piping.

Each specification included boundary conditions for the transient: pump speeds for the primary pumps, the intermediate sodium loop flow rate, and the sodium temperature at the intermediate loop inlet to the IHX. For SHRT-17, the total power is also a boundary condition. For SHRT-45R, the auxiliary EM pump current is a boundary condition, and for participants who chose not to perform a SHRT-45R neutronics analysis, the total power was also provided as a boundary condition.

The benchmark model of the EBR-II primary vessel components is diagrammed in FIG. 1.

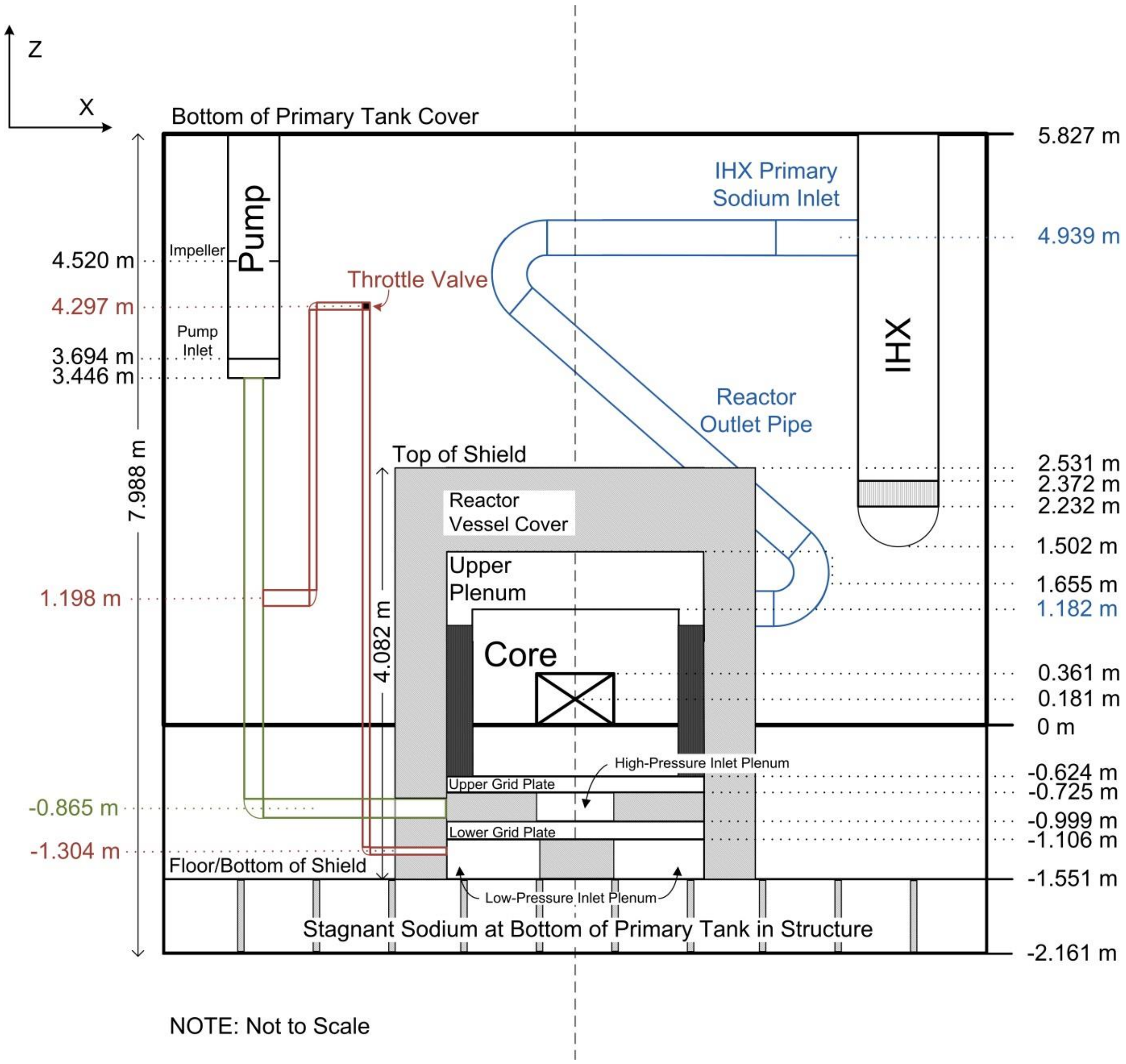


*FIG. 1. Benchmark model of EBR-II primary vessel components, elevation view.*

## 4. Results Summary

Participants overall achieved good simulation results for both transients for primary loop flow and for temperatures in the core and throughout much of the primary loop. A particular simulation challenge was the complex geometry of the reactor, especially in the upper and lower plena and in the instrumented subassemblies. FIG. 2 shows the collective final results and the recorded data for the temperature at the top of the fueled instrumented subassembly XX09. The simulations marked “Ave” calculated an average outer cladding temperature at each axial node; other simulations used subchannel modeling to create a radial temperature profile across the subassembly. The models that predicted the smallest discrepancies with the recorded data were those that included radial heat transfer with the neighbouring subassemblies and achieved an accurate simulation of the primary pump flow rate.

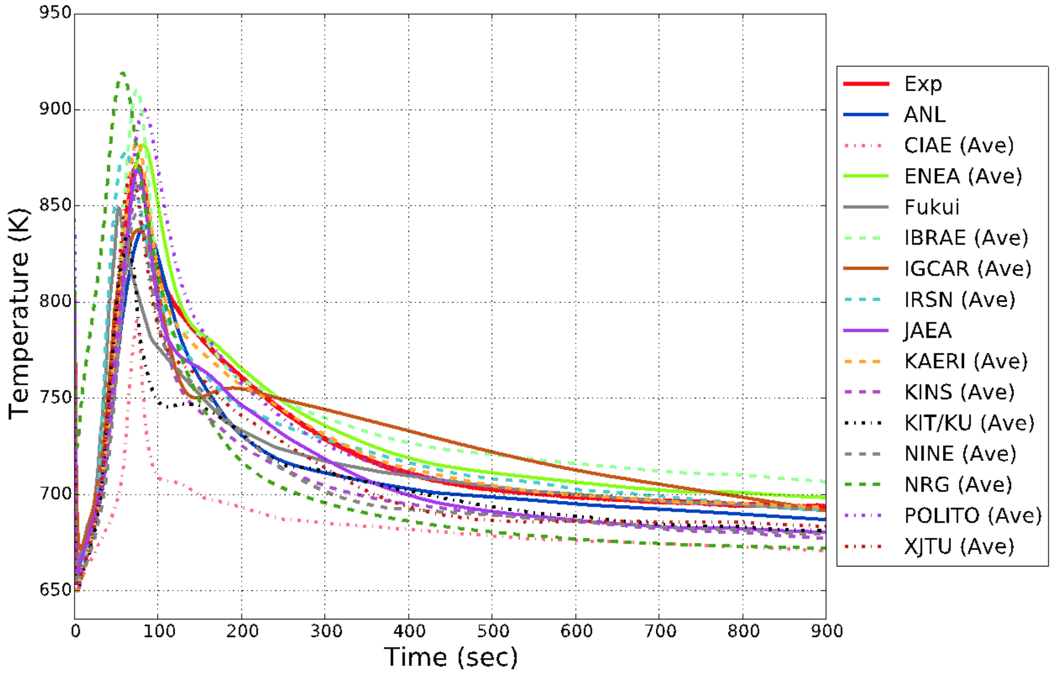


*FIG. 2. SHRT-17 XX09 sample top of core temperature*

Some aspects of both transient analyses were beyond the abilities of systems analysis codes. Modeling of the inner structure of the upper plenum was limited by a lack of detailed geometric information, and the effect of this structure on the flow of sodium through the plenum could not be simulated well with a 0-dimensional component model, typically used by systems codes. The greatest deviation from the recorded data occurred at the inlet to the primary side of the IHX. This portion of the IHX was again a plenum region with a complex structure, and although data were recorded by four thermocouples, none of the readings represented an average inlet temperature. Modifications made by two of the participants addressed this problem to some extent; in one case (the NRG model), the analysis was performed using coupled systems thermal-hydraulic/computational fluid dynamics codes, and in the other (the IBRAE model), two-dimensional heat structures were used in the IHX inlet plenum. FIG. 3 below presents the collective final results for the IHX inlet temperature for SHRT-45R.

More information on the simulation results for the two transients is presented in papers [6], [7], [8], and [9] in this conference.

## 5. Results Qualification

At about the midway point of the CRP, the participants from N.IN.E. suggested performing a qualification evaluation of the final results achieved by the CRP participants. Such an evaluation would provide support for the results interpretation by establishing quantitative measures of the discrepancies between the modeling assumptions made by each analysis and the reference specification data. These measures, in turn, would inform an understanding of the differences among the participants' results and also the differences between analysis results and the measured data. It should be understood that the qualification process would in no way be a ranking of the participant results.

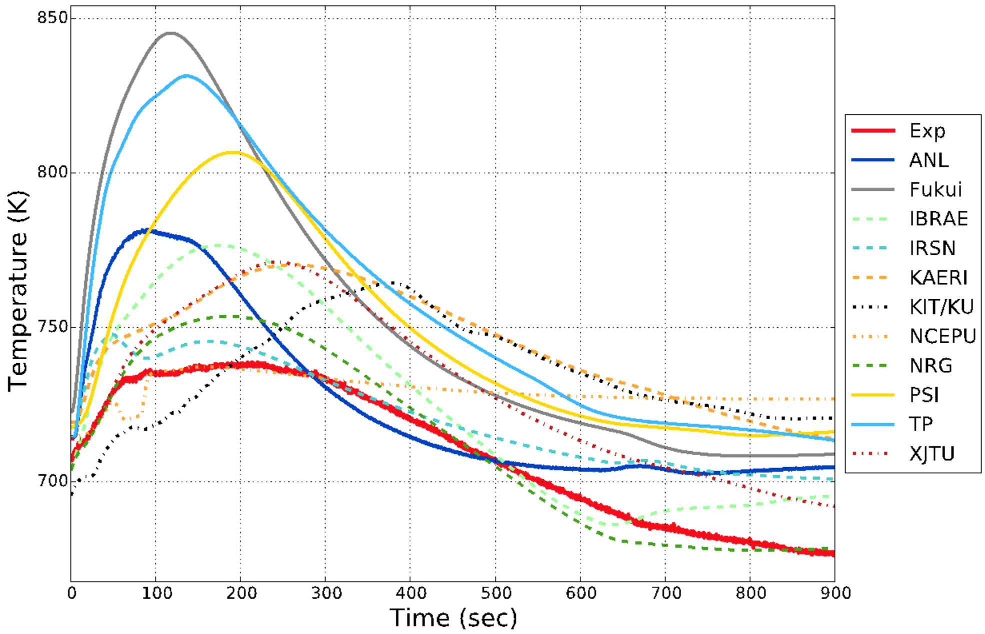


*FIG. 3. SHRT-45R IHX primary inlet temperature.*

It was agreed by the participants that performing a results qualification would be a worthwhile exercise. It was also agreed that this exercise would be performed only for the SHRT-17 transient results.

The Standardized Consolidated Calculated & Reference Experimental Database (SCCRED) method [10] was selected for the analysis. Only a quantitative analysis using the Fast Fourier Transport Based Method (FFTBM) was performed, whereas a full application of the process also requires an extensive qualitative analysis, as described in [10].

The qualification process was initiated by extracting a set of reference values from the geometric information and steady-state parameters of the SHRT-17 benchmark specification – a lengthy exercise. Participants were then sent a list of parameters required from their analyses for the evaluation. These parameters included details about the nodalization used; material densities used at steady state; a set of steady-state values for temperatures, pressures, and flows; and a set of transient values at various locations within the primary loop. Ten of the CRP participants provided input for the qualification process.

The SCCRED process concluded that the participant models generally showed good geometrical fidelity and predicted the steady-state values well. The FFTBM analysis of the transient results represented the discrepancies between calculated values and experimental data with a dimensionless number called the Average Amplitude (AA). AA is an indication of the relative magnitude of these discrepancies, so the lower the AA value, the better the agreement between the simulation results and the recorded data.

As an example of the qualification process results, FIG. 4 presents AA values for the reactor inlet and outlet plena temperatures. As can be seen from the figure, the inlet plena temperature results for all models are characterized by low AA values, with the outlet plena temperatures having somewhat larger AA values. This is to be expected, given the relatively high fidelity of the inlet plena models and the lower fidelity of the outlet plenum model for most of the simulations. The AA values for the IHX inlet and outlet temperatures are presented in FIG. 5 and are representative of the difficulties described above with accurately predicting the measured IHX primary side inlet temperature.

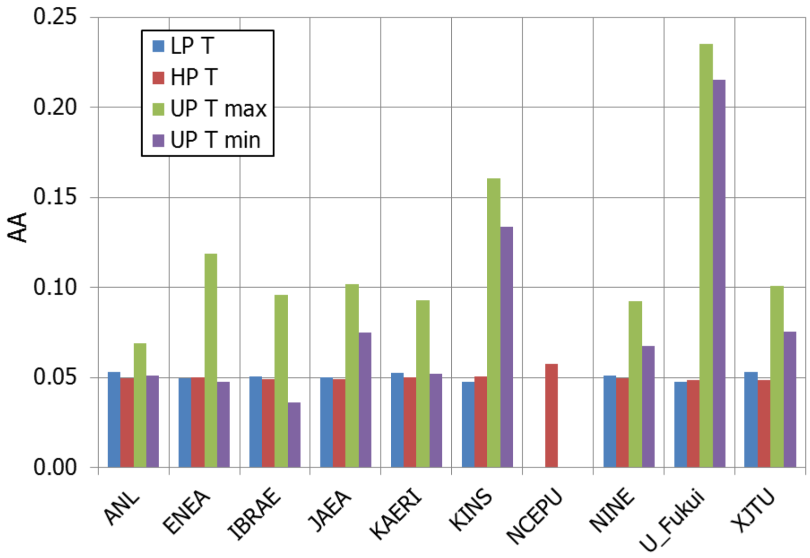


*FIG. 4. FFTBM results, low-pressure and high-pressure inlet plena and upper plenum temperatures.*

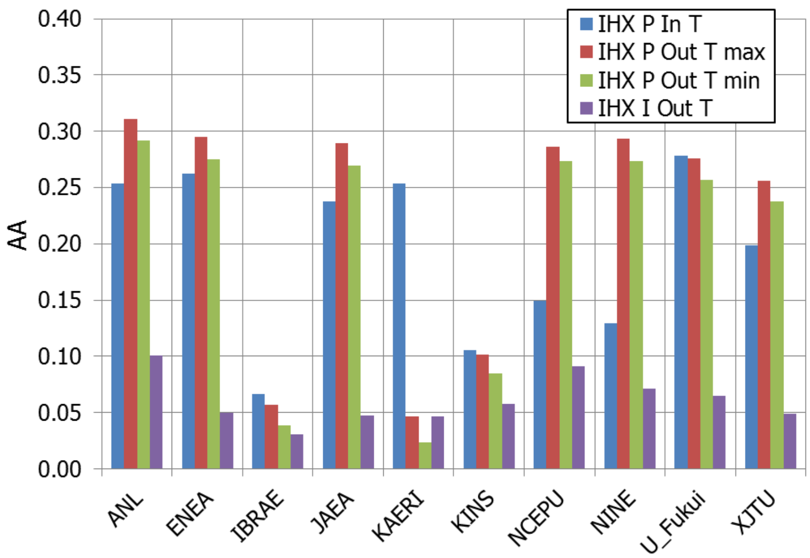


*FIG. 5. FFTBM results, IHX primary side inlet and outlet temperatures and intermediate side outlet temperature.*

Applying the qualification methodology to the CRP SHRT-17 results was felt to have been a worthwhile exercise. The results of the qualification process gave added insights into the relative importance of various types of discrepancies between the simulation results and the recorded data. The exercise also gave experience in addressing the two main challenges in applying the methodology to this CRP: (1) defining the data required from all the models in a way that was applicable to all the different computer codes that were used by the participants and (2) applying to a fast reactor system a methodology that had been developed for and previously applied only to light water reactor systems. This experience will contribute to expanding the application of the SCCRED methodology to a wider range of computer codes and reactor systems.

## 6. Lessons Learned

CRP participants derived a number of lessons learned from the four years of working on the project. Some of these reflected the large size of the group of participants, and some resulted from incorporating into the CRP some processes that had not been tried with earlier CRPs. The major lessons learned were the following:

- Include in the benchmark specifications the parameters that will be needed for uncertainty analysis and results qualification, and devote a phase of the CRP to preparing the information needed for such analyses. For this CRP, the extent of the results qualification was limited, in part, by the fact that the qualification process was added about halfway through the CRP.
- Plan to issue a revision to the original benchmark specification(s) during the first 6 or so months of the CRP; this gives participants a chance to exercise the original specifications and provide feedback for revisions. This was done in this CRP and was found to be very valuable.
- A CRP is a valuable driver for adding new models to systems analysis codes, as well as a useful means of expanding code validation and adding confidence in model generation.
- A CRP is a beneficial way to engage early career researchers and students in a range of modeling approaches and to increase their awareness of a range of codes and experiments. It also introduces them to an international community of experienced researchers and can be an opportunity for them to expand their expertise into a different type of reactor system than what they have worked with previously.
- Since the CRP included analysis of an unprotected transient, it was valuable to include an optional separate neutronics benchmark specification and exercise.
- For CRPs with a large (say, greater than eight) number of participants, it is recommended to consider forming subgroups to address specific modeling challenges. The participants should also consider using a project management tool to manage project timelines and participant progress, and it would probably be helpful to create an online forum for group communications between Research Coordination Meetings.

## 7. Conclusions

The EBR-II benchmarks CRP was successful both in furthering validation of fast reactor safety codes and in providing early career researchers and students with the opportunity to develop their fast reactor safety knowledge and contacts. Both the thermal-hydraulic and the neutronics modelling that was undertaken faced significant challenges due to the complex geometry of the EBR-II reactor, limited detailed information regarding some of the primary system components, and inherent limitations on the 1980s technology that was used to record the data. Within these constraints, the CRP participants collectively produced simulations that predicted most plant parameters with reasonable accuracy.

At nineteen participants, this was the largest fast reactor CRP to date ever undertaken by the IAEA. The unusually large size offered the opportunity to consider project management innovations that would be helpful to future large CRPs.

This group of participants also decided to add a results qualification exercise to the CRP tasks. This opportunity was made possible by the expertise in results qualification of the participant group from N.IN.E. This was an experiment all around, since the qualification method had never before been applied to a fast reactor system, nor had it been applied to such a diverse group of codes. The process proved to be a useful learning experience for everyone involved and is recommended to future CRPs.

Finally, the inclusion of a separate, optional neutronics benchmark for the SHRT-45R transient was regarded favourably by the participants and created an added dimension to the CRP.

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