SIMMER Analyses of the EBR-II Shutdown Heat Removal Tests

B. Vezzoni[1], M. Marchetti[1], L. Andriolo[1,•], F. Gabrielli[1], X.-N. Chen[1],
C. Matzerath Boccaccini[1], A. Rineiski[1], W. Maschek[1], K. Morita[2], T. Arima[2]

[1]Karlsruhe Institute of Technology, Eggenstein - Leopoldshafen, Germany

[2]Kyushu University, Fukuoka, Japan

E-mail contact of main author: barbara.vezzoni@kit.edu

Abstract. In the framework of the Coordinated Research Project (CRP) of the International Atomic Energy Agency (IAEA) on the Experimental Breeder Reactor II (EBR-II), two Shutdown Heat Removal Tests (SHRT-17 and SHRT-45R) representative, respectively, of Protected Loss of Flow (PLOF) and Unprotected Loss of Flow (ULOF) transients have been analyzed at KIT by using the SIMMER code.
An overview of the main results obtained for the two tests by employing the SIMMER-III ver. 3E is included in the paper. For SHRT-17 only the fluid-dynamics module of SIMMER was employed. The reduced calculation time has allowed testing several modeling options described in the paper. For SHRT-45R, an extended KIT SIMMER-III version including core thermal expansion reactivity feedbacks and new PARTISN-based spatial kinetics model has been adopted and validated.
The good agreement with the experimental data for the two tests has allowed a further validation of the KIT SIMMER code extensions.

Key Words: EBR-II, SIMMER validation, PLOF/ULOF transients

[•] Dr. L. Andriolo is actually working at EdF (France)

1. Introduction

In June 2012, the International Atomic Energy Agency (IAEA) initiated a four-year Coordinated Research Project (CRP) with the objective of improving state-of-the-art liquid metal cooled fast reactor codes and data used in neutronics, thermal hydraulics and safety analyses, by considering validation against whole-plant data recorded during landmark shutdown heat removal tests (SHRT) that were conducted at Argonne's Experimental Breeder Reactor II (EBR-II) in the 1980's. Several organizations representing eleven countries are participating in the CRP under the technical leadership of the Argonne National Laboratory (ANL) [1,2].

For the study, a protected loss-of-flow (PLOF, SHRT-17) and an unprotected loss of flow (station blackout, ULOF, SHRT-45R) transients, both initiated from full power and flow, were considered. The analysis of SHRT-17 has allowed focusing mainly on the prediction of the natural convective cooling, while the analysis of the unprotected loss-of-flow has provided more attention to the feedback effects as the core thermal expansion reactivity effects. An optional neutronics benchmark analysis was considered as part of the SHRT-45R simulations as support for the reactivity feedbacks evaluations [3].

The CRP activity was divided into different phases: 1) blind calculation (phase 1), and 2) improved calculation results after a first comparison with the recorded experimental data (phase 2).

The Karlsruhe Institute of Technology (KIT) together with Kyushu University (KU) has contributed to all the phases of the study by performing transient analyses with the SIMMER-III v.3E code [4]. An overview of the main results obtained is presented in the paper.

2. The EBR-II reactor

The EBR-II plant was a uranium metal-alloy-fueled sodium-cooled fast reactor (62.5 MWth) designed and operated by ANL for the U.S. Department of Energy at Argonne-West. Operation began in 1964 and continued until 1994. The original emphasis in the design and operation of EBR-II was to demonstrate the feasibility of a closed fuel cycle (breeding plutonium) with on-site pyro-metallurgical reprocessing. Later on, it has been dedicated to safety studies by performing several Shutdown Heat Removal Tests (SHRTs) and Inherent Safety Tests (ISTs).

The EBR-II reactor was an experimental pool type reactor characterized by a very large cold pool from which two primary pumps drew sodium to be provided to the two inlet plena (high-pressure and low-pressure zones) by piping systems. The high-pressure inlet plenum, accounting for approximately 85% of the total primary flow, was devoted to feeding inner core zone Subassemblies (SAs) while the low-pressure inlet plenum (15% of the total primary flow) was dedicated to the peripheral zone mainly accommodating the radial blanket SAs. The core outlet sodium was collected in a common upper plenum and after a mixing process it flowed, through the outlet pipe (so- called "Z-pipe"), into the intermediate heat exchanger (IHX). Sodium then exited the IHX returning into the large cold pool within the primary tank before entering the primary sodium pumps again (*FIG. 1*).

The two tests considered within the CRP show different core layouts (different types of SAs, different locations, etc.) as indicated in *FIG. 2* [1,2,5] that have been taken into account while preparing the dedicated SIMMER models.

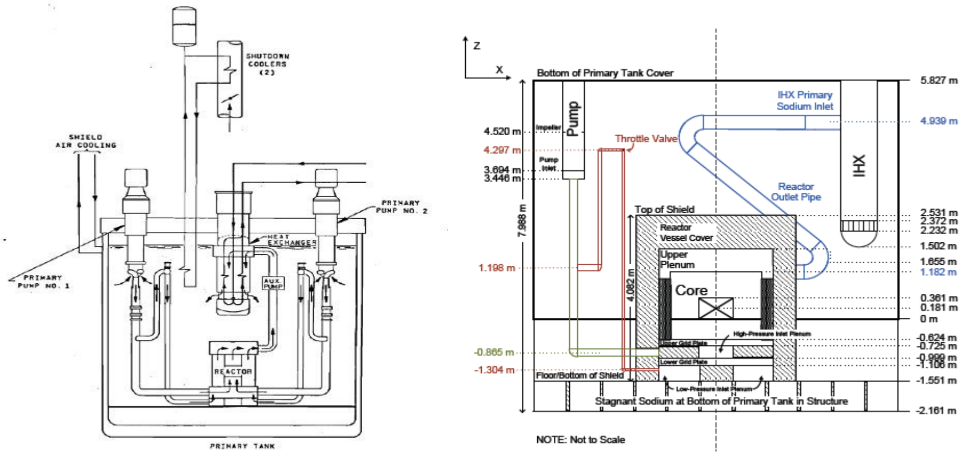
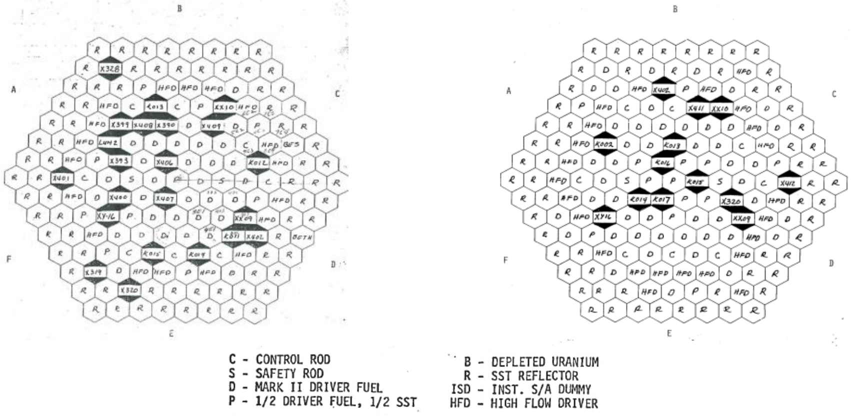


FIG. 1. *EBR-II Primary System Components and Sodium Flow Paths [1,2,5].*



(a) (b)

FIG. 2. Core layout: (a) SHRT-17 – PLOF (b) SHRT-45R – ULOF [1,2].

3. The EBR-II SIMMER model

All the reactor components (pumps, IHX, pipes) have been included in the SIMMER models by introducing some unavoidable approximations for taking into account the particular geometry of EBR-II in a 2D RZ model [6]. The main approximations are related to the reactor outlet "Z-pipe" and the sodium inlet pipes that have been modelled by means of virtual walls[1] (in green in *FIG. 3*, full tank model for SHRT-17). A simplified Intermediate Heat Exchanger (IHX), characterized by a constant sodium outlet temperature, and a single "equivalent" pump representing the two primary pumps and the Electromagnetic Pump, have been considered as well for the model. These modelling options are common for the two tests. The chosen axial meshes reasonably represent the relative position of the components as indicated in Table I.

The model of the core zone depends on the test considered (different core layouts and control rod axial positions). In total the SHTR-17 model consists of 30 radial (18 for the core zone) and 50 axial fluid-dynamic meshes while SHRT-45R model considers instead 49 radial (34 for core zone) and 52 axial fluid-dynamic meshes. In both cases, SAs have been grouped in rings according to their locations and type.

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[1] Virtual walls do not allow material and heat transfer between the sodium in the pipes and the cold pool around. The pressure losses due to the friction with the pipes are not modelled as well.

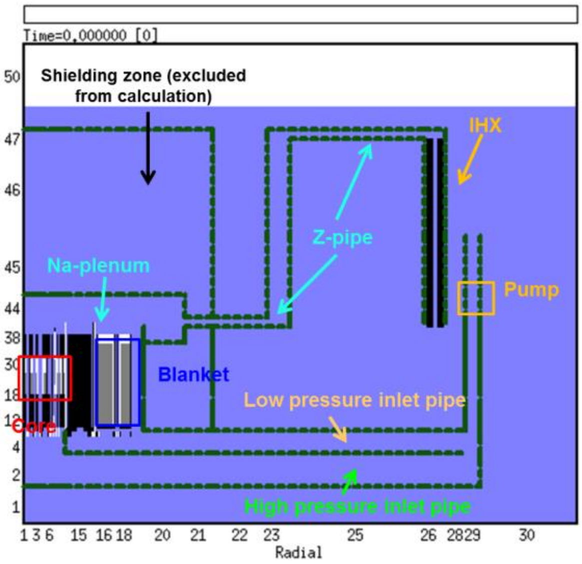


FIG. 3. SIMMER-III EBR-II RZ model (SHRT-17).

TABLE I: SIMMER-III 2d RZ model common to SHRT-17 and SHRT-45R

Components	**Reference**	**SIMMER-III Model**
	meter	
Total height	7.988	7.988
External radius	3.962	3.962
Sodium free surface level	6.941	6.941
Upper plenum upper boundary (z_{sup})	3.816	3.816
Upper plenum radial boundary (r_{ext})	1.1555	1.1555
Upper plenum lower boundary (z_{inf})	2.975	2.999
Radial position, IHX center	2.95	2.95
Radial position, pump center	3.251	3.22
Z-Pipe at upper plenum exit	3.57	3.421

4. SIMMER extensions adopted in the study

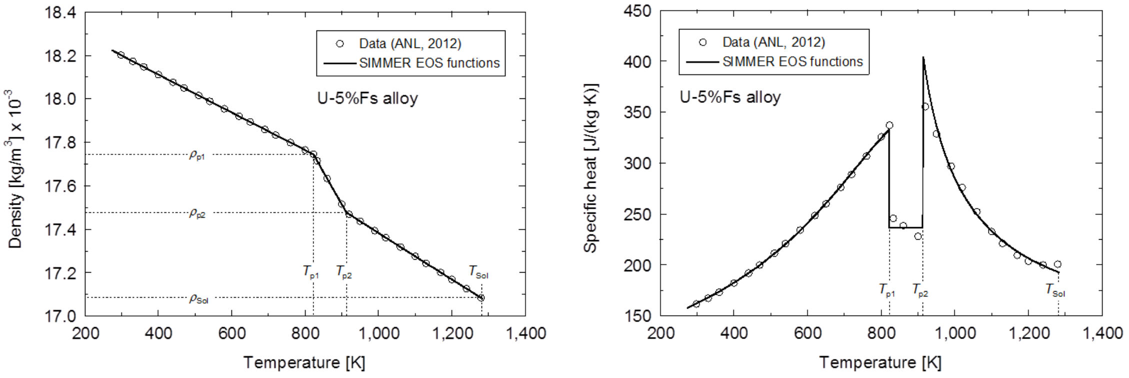
In order to carry out the EBR-II benchmark, an extended SIMMER version has been developed and used. The most important modifications introduced are the followings:

1. Specific Equations of State (EOS) and the Thermo-Physical Properties (TPP) for the EBR-II (67% U235) U-5%Fs alloy fuel (95% U and 5% Fissium) prepared by KU [4,7]. This extension has been used for both transients.
2. Core thermal expansion reactivity model developed at KIT [8]. Extension used only in SHRT-45R.
3. New PARTISN-based spatial kinetics model (instead of a TWODANT-based one) used in order to benefit from the SIMMER parallelization capability [9-10]. Extension used only in SHRT-45R.

4.1.Specific EOS and TPP for the EBR-II U-5%Fs alloy fuel

The thermodynamic properties of reactor-core materials in solid, liquid and vapour phases covering wide temperature and pressure ranges are calculated in SIMMER-III by using an analytical EOS model [4,7]. For simulating transients in EBR-II, only solid properties of metal fuel have been introduced (no melting was expected for the transients considered). The

SIMMER-III EOS functions for solid phase correlate the temperature (T) and the specific volume (υ) as a function of specific internal energy (e). For taking into account the solid-solid phase transitions of the EBR-II U-5%Fs alloy, the SIMMER EOS functions have been extended by introducing additional coefficients and a comparison with the data shows a very good agreement, see *FIG. 4*. Specific Equations of State (EOS) and the Thermo-Physical Properties (TPP) for the EBR-II (67% U235) U-5%Fs alloy fuel (95% U and 5% Fissium) prepared by KU [4,7]. This extension has been used for both transients.



(a) (b)

FIG. 4. Comparison SIMMER EOS Analytical Model and Input Data: A) Density - Temperature Correlation; B) Specific Heat - Temperature Correlation.

4.2.Treatment of Core Thermal Expansion Reactivity Feedbacks

In the original SIMMER version, the contributions to the net reactivity due to Doppler, fuel, coolant, steel and control material density variations are taken directly into account [4]. However, the correlated reactivity contributions due to core dimensional changes by thermal expansions were not considered because those feedbacks had no or minor importance for the accident evolution in case of already disrupted cores. New reactor designs are characterized by a delicate balance between reactivity effects and therefore, the simulation of the dominant feedbacks coefficients becomes more important in particular during the initiation phase of the accident. Therefore, the SIMMER-III code has been recently extended at KIT by introducing a methodology that allows to take into account the effects of core thermal expansion reactivity feedbacks within the constraints of the SIMMER code (Eulerian fluid-dynamic space time kinetics code, i.e. with fixed mesh and spatial kinetics) [8]. The implemented methodology is based on an "equivalence principle": this principle allows to transform a change in dimensions into an equivalent (in term of reactivity) change in densities. The procedure includes two steps:

1.Calculation of the expanded configuration. New geometry dimensions are evaluated based on local temperatures and expansion coefficients. Solid materials (e.g. can walls, clad, fuel pin) are expanded by considering a constant mass. On the other side, when the subassembly's can walls expand, more space is available for fluid components: the mass of liquid components (e.g. sodium) is therefore higher in this expanded configuration. This is accounted for while evaluating the expansion of all liquid components.

2.Application of the "equivalence principle". Based on the expanded dimensions (as evaluated in point 1) a new "equivalent" configuration is derived: the result is an "equivalent" configuration that has the original (i.e. not expanded) dimensions but different material densities.

For SHRT-45R simulations, clad driven core thermal expansion and conic modes (both grid and constraints plans expand) have been considered.

4.3. A new PARTISN-based spatial kinetics model

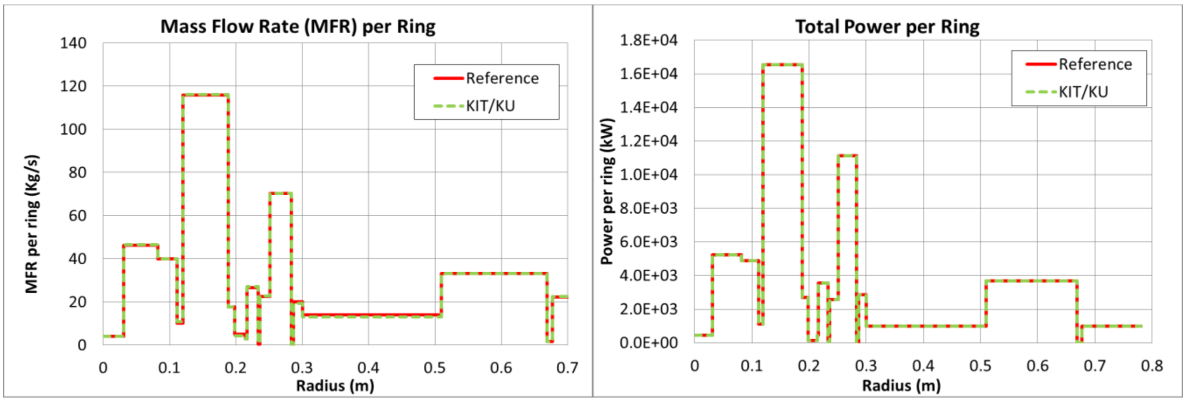
The PARTISN code is the evolutionary successor of the DANTSYS code package currently used in SIMMER-III as neutronics solver. The PARTISN code solves the time-dependent transport equation by using the SN method for 1D, 2D (RZ, XY, and R-θ), and 3D (XYZ, R-Z-θ) geometries.

The code has been extended at KIT [9,10] in order to be suitable for a coupling with the SIMMER code. This option has helped on reducing the total computational time significantly in particular for 3D calculations.

5. EBR-II results: comparison against experimental data

5.1. SHRT-17

SHRT-17 was oriented mainly to investigate the effectiveness of natural circulation. For reducing the calculation time, only the fluid-dynamics modules of SIMMER were considered (neutronics module deactivated) allowing performing several parametric studies. The results obtained at steady-state shows a good agreement between the calculated mass flow rate and the benchmark input values (*FIG. 5-a*). In the case without neutronics coupling, the ring-wise power has been imposed. The values adopted are consistent with the SA-wise data provided in the benchmark (*FIG. 5-b*). By employing this option it has been possible to take into account also the contribution to the power coming from gamma heating, mainly important for non-fuelled SAs (ca. 70% of the total [3]).



(a) (b)

FIG. 5. SHRT-17 (Steady-State): A) Mass Flow Rate per ring, B) Total Power per ring.

The parametric studies considered for SHRT-17 are summarized in Table II. The more important modifications are the following:

1.Total mass flow rate improvement (*FIG. 6*). At short term a slight tuning has been performed in order to overtake the limitation caused by the adoption of a single “equivalent” pump simulating the slightly different coast downs at the two pumps.

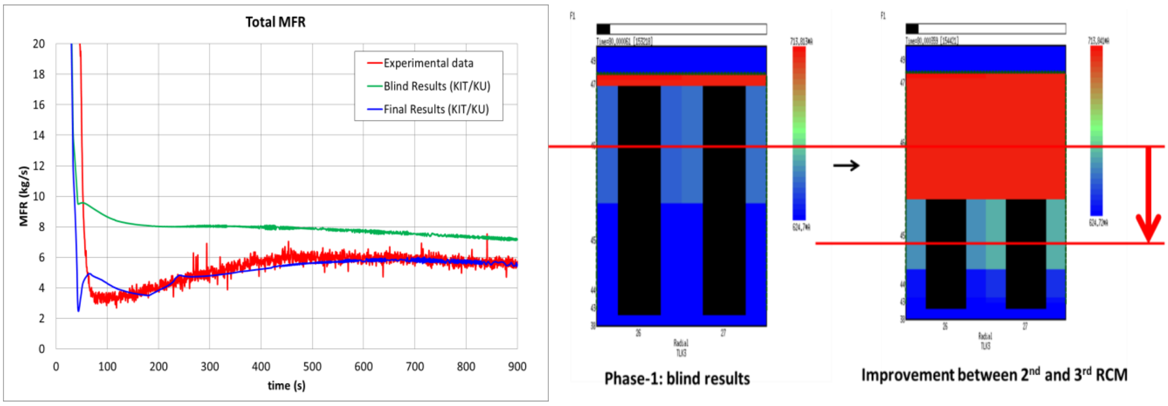
2.For long-term, the natural circulation in the blind calculations (see *FIG. 6-a*) was overestimated. Because of the IHX SIMMER model, the IHX thermal centre was found to be much higher than the real one. This aspect was corrected by changing modelling of IHX in SIMMER. The colour map in *FIG. 6-b* shows the sodium temperature along the IHX. The axial position of the thermal IHX centre is clearly lowered in the second phase.

3.The radial heat transfer from the neighbouring SA to the XX10 (instrumented steel SA) has been allowed by modelling explicitly the inter-wrapper sodium with dedicated rings (*FIG. 7*).

These modifications have allowed obtaining a better agreement with the experimental data either for global and local quantities. *FIG. 8-a* shows the average outlet coolant temperature behaviour and Fig. 8-b the coolant temperature at mid core in the XX10 instrumented steel SA. A significant improvement is achieved from blind to final results.

TABLE II: Overview of the modelling options considered for SHRT-17

Option number	**Options considered**	**Effect on the results**	**Adopted for Final Results**
1	Short-term mass flow rate tuning	High	yes
2	IHX position	High	yes
3	Different Gap Conductance	Limited	no
4	Axial conduction	Limited	no
5	Detail modelling of reactor shielding	Negligible	no
6	Radial conduction for XX10	High	yes
7	Fuel porosity	Limited	no



(a) (b)

FIG. 6. SHRT-17: a) Total Mass Flow rate improvement, b) Effect on IHX thermal center (red line).

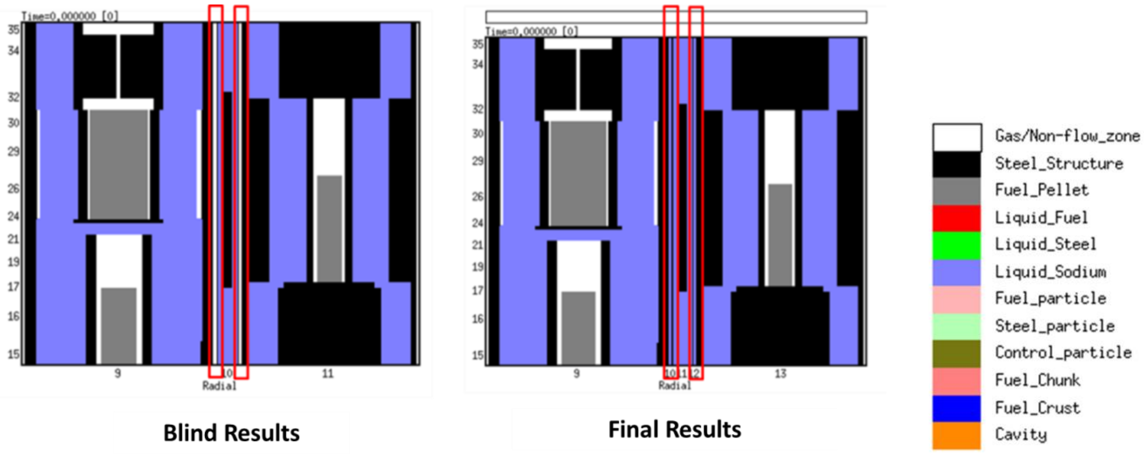
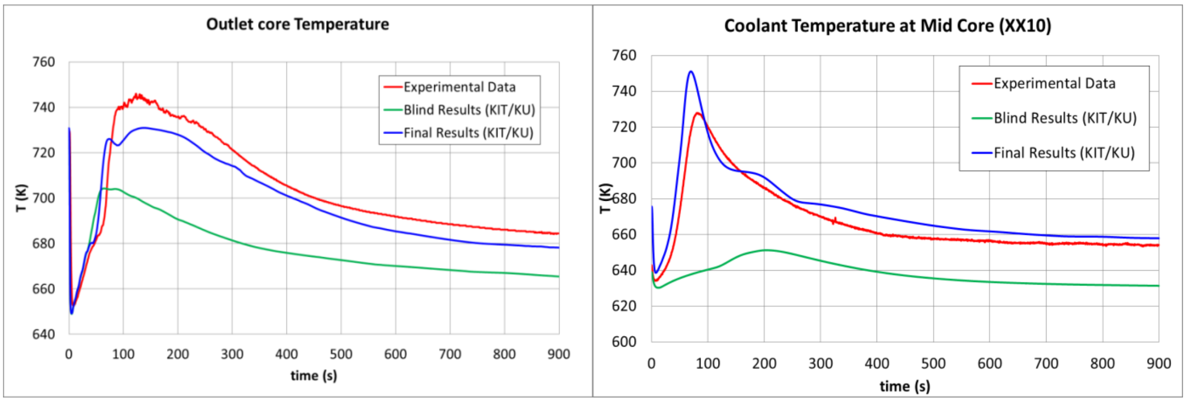


FIG. 7. SHRT-17: Improvement on the XX10 model: "explicit" modeling of inter-wrapper sodium



(a) (b)

FIG. 8. SHRT-17:a) average outlet core temperature, b) Coolant temperature at mid-core (XX10)

5.2. SHRT-45R

For SHRT-45R simulation, coupled neutronics-thermal hydraulic calculations have been performed. During the blind phase, the standard SIMMER version has been adopted. This version does not include reactivity feedbacks due to the core thermal expansion [4].

Also in this case, the steady-state (SS) conditions have been determined. The total SS mass flow rate (MFR) obtained is in good agreement with the benchmark input data. The power distribution is calculated on the basis of flux calculation in SIMMER. The comparison against the input data is shown in *FIG. 9-a*. Large discrepancies (ca. 60-70%) are observed for dummy and reflectors SA due to the missing gamma-heating contribution in standard SIMMER version. Results are in agreement with the ones obtained in the dedicated neutronics benchmark [3].

As with SHRT-17 studies, several improvements have been included for the final results:

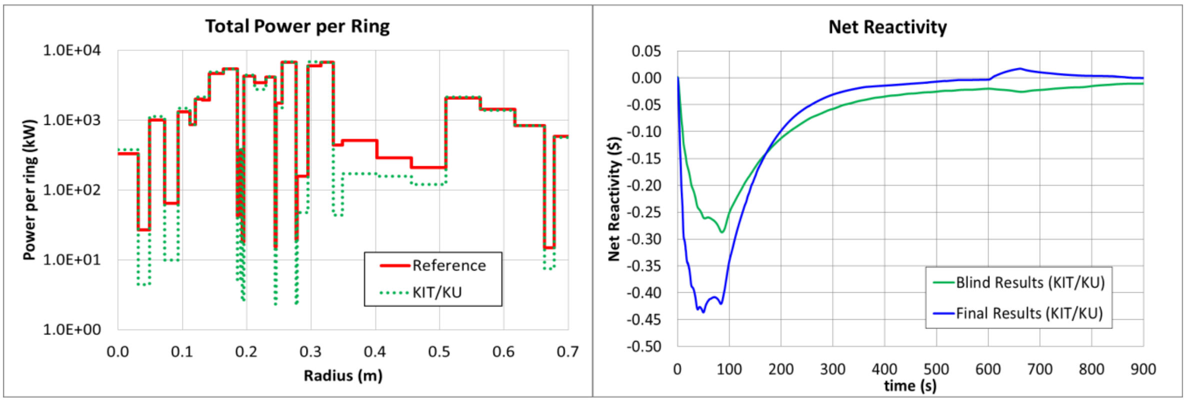
1. Total mass flow rate has been improved at short and long terms. The contribution to the total mass flow rate due to the on-battery operated Electromagnetic pump (EM) has also been included.

2. Core thermal expansion reactivity feedbacks have been considered in the simulation by using the recently extended SIMMER version of KIT [11-13], as described in Par. 4.2.

3. The radial heat transfer from the neighbouring SA to the XX10 (instrumented steel SA) has been allowed by an explicit model of the inter-wrapper sodium with dedicated rings, as for SHRT-17.

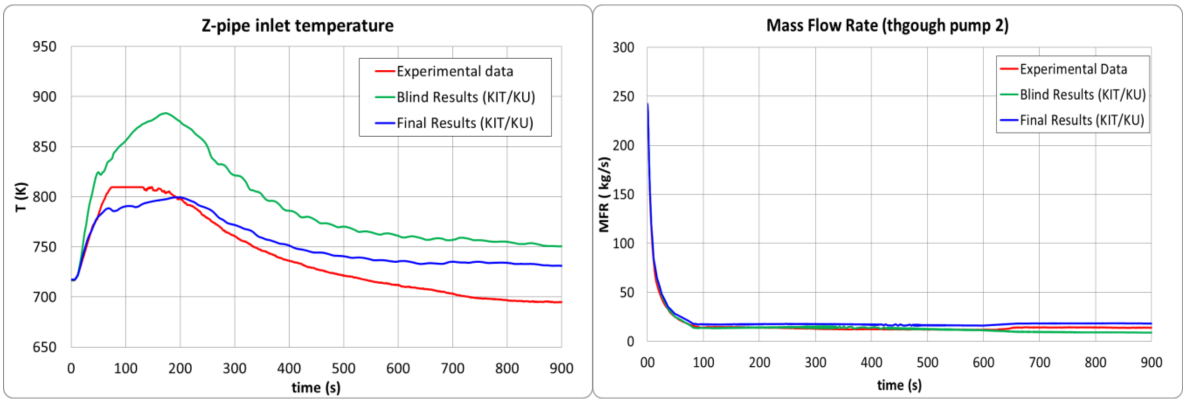
The net reactivity (that includes contribution from material density variation, Doppler and core thermal expansion) is shown in *FIG. 9-b*. Because of the negative expansion feedback, the net reactivity is lower compared to the blind results. The more accurate reactivity and power modelling leads to a considerable improvement in the Z-pipe inlet temperature behaviour as indicated in *FIG. 10-a*. The contribution due to modelling of the EM pump improves the long term mass flow rate (mainly after 600 s) as shown in *FIG. 10-b*.

At local level, the final results have been improved as shown by *FIG. 11-a* in which the coolant temperature in XX09 fuelled-instrumented SA is compared at core outlet. In *FIG. 11-b*, the coolant temperature in XX10 steel-instrumented SA at core top is shown. The same improvement indicated for SHRT-17 by modelling the radial heat transfer is achieved also in this case.



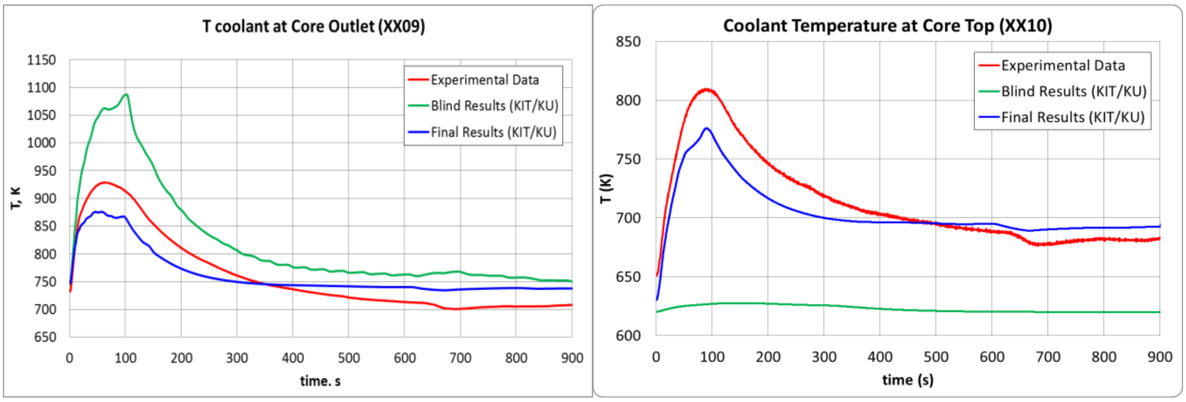
(a) (b)

FIG. 9. SHRT-45R: a) (steady-state) total power per ring, b) Net reactivity (contribution from material density variation, Doppler and core thermal expansion).



(a) (b)

FIG. 10. SHRT-45R: a) Z-pipe inlet temperature, b) mass flow rate through pump N.2.



(a) (b)

FIG. 11. SHRT-45R: a) XX09 coolant temperature at core outlet, b) XX10 coolant temperature at core top.

6. Conclusions

KIT together with KU has participated to the EBR-II shutdown heat removal benchmark activity by performing transient analyses with the SIMMER-III code.

Two RZ models representative for SHRT-17 and SHRT-45R have been assessed at KIT for taking into account the core configurations of the two tests. The specific fuel properties for the EBR-II core have been taken into account by a new set of Equations of State and the Thermo-Physical Properties implemented in the SIMMER code by Kyushu University.

Only thermal-hydraulic calculations have been carried out for SHRT-17 oriented to natural circulation investigations. Several modelling options have been tested and the more significant applied for the final results of both transients. The main modifications considered are related to the simulation of the total mass flow rate and to the possibility to allow radial heat transfer into non-fuelled instrumented SA (XX10). By these modifications a better agreement with global and local experimental data for SHRT-17 has been obtained.

An extended SIMMER version including a new core thermal expansion reactivity model has been developed and used for SHRT-45R. The results obtained with the extended SIMMER version in terms of reactivity effects are within the range of results obtained by other benchmark participants. The coolant temperature at the Z-pipe inlet is in very good agreement up to 70 s with the experimental data. Later on, the SIMMER results are within the range of results obtained by other benchmark participants. Good agreement is also obtained for the fuelled instrumented SA (XX09) temperature distribution at different axial positions and for XX10. By this study a more extended basis for a further validation of neutronics extensions for the SIMMER code carried out at KIT has been provided.

Acknowledgments

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