Extension of the reactor dynamics code DYN3D to SFR applications – Part III: validation against the initial phase of the Phenix EOL natural convection test

Nikitin, E.; Fridman, E.;

Originally published:

May 2018

Annals of Nuclear Energy 119(2018), 390-395

DOI: https://doi.org/10.1016/j.anucene.2018.05.017

Extension of the reactor dynamics code DYN3D for SFR applications – Part III: validation against the initial phase of the Phenix EOL natural convection test

E. Nikitin [a,b,*], E. Fridman [a], and A. Pautz [b]

[a] *Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany*

[b] *Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*

Keywords:

SFR, Phenix EOL tests, thermal expansion, nodal diffusion, transient analysis, DYN3D, Serpent

Abstract

The reactor dynamics code DYN3D, initially developed for LWR applications, is being extended for steady state and transient analyses of Sodium cooled Fast Reactor (SFR) cores. The extension includes the development of the few-group cross section generation methodology, updating of the thermal-hydraulic database with thermal-physical properties of sodium, and development of the thermal-mechanical model to account for thermal expansion effects of the core components.

Part I of the paper provided a detailed description of the recently implemented thermal expansion models able to treat axial expansion of fuel rod and radial expansion of diagrid. The results of the initial verification test were also presented in Part I of the paper.

The capability of the extended version of DYN3D to perform steady state and transient analyses of SFR cores was validated using selected tests from the end-of-life experiments conducted at the Phenix reactor. Steady state analysis of the control rod withdrawal tests is covered in Part II of the paper.

Part III of the paper reports on the results of the transient analysis of the initial stage of the natural circulation test from the Phenix end-of-life experiments.

[*] Corresponding author: e.nikitin@hzdr.de

1. Introduction

The reactor dynamics code DYN3D (Rohde et al., 2016), initially developed for LWR applications, is being extended for steady-state and transient analyses of Sodium cooled Fast Reactor (SFR) cores. The extension includes the development of the few-group cross section (XS) generation methodology (Fridman and Shwageraus, 2013; Rachamin et al., 2013; Nikitin et al., 2015a, 2015b), the updating of the thermal-hydraulic (TH) database with thermal-physical properties of sodium, and the development of the thermal-mechanical (TM) model to account for thermal expansion effects of the core components.

Part I of the paper (Nikitin et al., 2018a) provided a detailed description of the thermal expansion models that have recently been implemented in DYN3D. The models enable the treatment of important thermal expansion effects occurring within the SFR core, in particular axial expansion of fuel rod and radial expansion of diagrid. The axial expansion model is capable of modeling non-uniform core expansions by using the spatial temperature distribution of the fuel rods. The radial diagrid expansion model utilizes the average inlet sodium temperature to uniformly expand the core in the radial direction. The initial verification study, summarized in Part I of the paper, demonstrated an adequate performance of the newly implemented models.

Part II of the paper (Nikitin et al., 2018b) presented the verification and validation of the extended version of DYN3D against the IAEA benchmark on the control rod (CR) withdrawal tests from the end-of-life (EOL) experiments conducted at the Phenix reactor (IAEA, 2014). The benchmark results, summarized in Part II of the paper, were used to validate the few-group XS generation methodology and the neutronic performance of DYN3D in steady state analyses.

Part III of the paper focuses on validation of DYN3D against a transient scenario taken from the IAEA benchmark on the Phenix EOL natural circulation test (IAEA, 2013). Initially, the benchmark targeted sodium capable TH system codes utilizing point kinetics models for validation. However, by combining this benchmark with the detailed core description of the CR withdrawal benchmark, the point kinetics model can be exchanged with a spatial neutron kinetics code for a more detailed evaluation of the test, as it was also done in (Chenu et al., 2012). Similarly, the initial stage of the natural convection test was calculated with DYN3D using the 3D nodal diffusion solver together with the intrinsic TH model and the new TM models. This study provides an assessment of DYN3D for coupled neutron kinetics thermal-hydraulics (NK/TH) transient analyses of SFR cores in general, and presents the impact of using uniform axial expansion profiles instead of simulating a more realistic non-uniform core expansion for this particular test.

The following section provides a brief overview on the initial phase of the natural circulation test. The computational methodology and the modeling assumptions are presented in Section 3. The numerical results obtained with the DYN3D are compared to the experimental data in Section 4. Section 5 summarizes the paper and presents possible directions for the future work.

2. Description of the initial phase of the natural convection test

The natural circulation test (IAEA, 2013) was dedicated to investigate the onset and development of natural circulation in pool-type SFR systems. In the framework of the benchmark, the experimental data were made available for qualification and validation of thermal-hydraulic system codes that are aimed for modeling liquid sodium systems.

The test was initiated by manual dry out of the two steam generators at the reduced power of 120 MWth. This caused a loss of heat removal from the secondary, and consequently, from the primary side. After the initial phase, which lasted 458 seconds, the reactor was manually scramed. Eight seconds later, the primary pumps were tripped and the characteristics of natural circulation were measured in the primary system.

In the unprotected phase, while the total mass flow rate remained constant, the core inlet temperature has increased by around 40°C. As a result, the total power has dropped from 120 MWth to 50 MWth, and the inner core outlet temperature by around 10°C, as shown in Fig. 1. The power reduction driven by the core reactivity was initiated by the thermal expansion of the core diagrid. The further development of the total reactivity (Fig. 1) was mainly influenced by the thermal expansion of the diagrid and fuel rods, the Doppler effect, and the relative CR movement caused by the simultaneous expansion of the core, CR drivelines and vessel. The measured core characteristics, shown in Fig. 1, include time-dependent inlet and outlet coolant temperatures, reactivity, and total power.

The temperature increase of the core inlet is mainly driven by the loss of heatsink in the steam generators. The small and slow change of the outlet coolant temperature has only a minor influence on the core inlet during the unprotected phase. Therefore, to a certain extent, the core TH behavior may be considered decoupled from the primary circuit, and can be modeled with a core simulator by using the inlet temperature curve as time-dependent boundary condition (Fig. 1, top). In this study, the unprotected stage of the test was calculated in such way with DYN3D, and the numerical results were compared with the experimental data provided by the benchmark specification (IAEA, 2013).

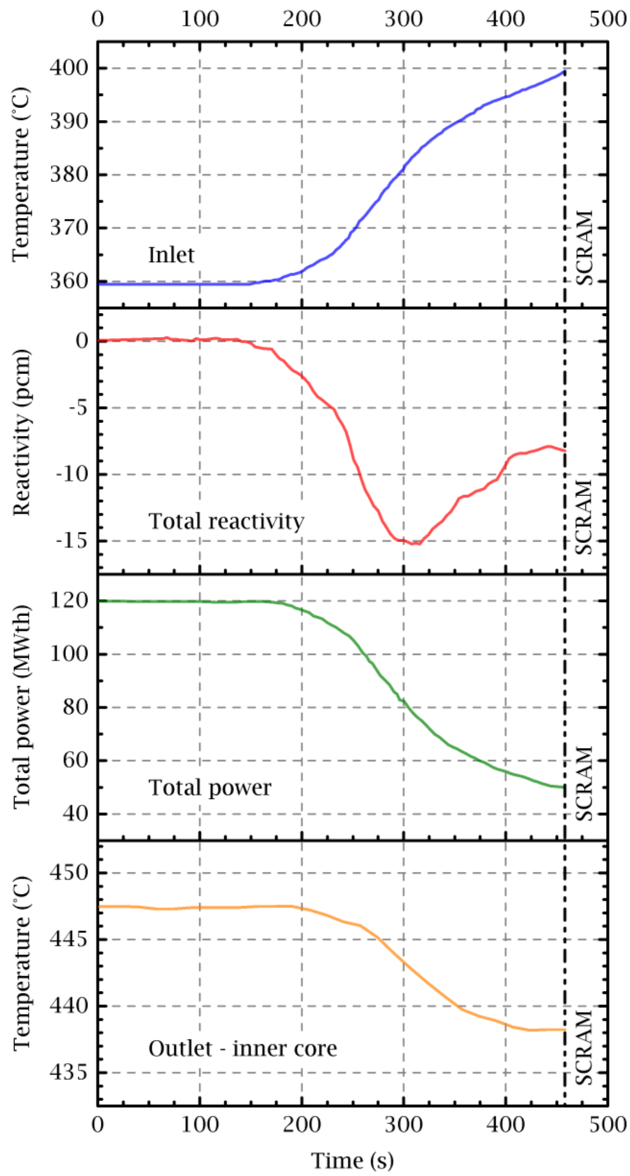


Fig. 1. Measurements in the initial phase of the natural convection test. *Top* to *bottom*: inlet coolant temperature, reactivity, total thermal power, outlet coolant temperature of the inner core. Data are extracted from the benchmark report.

3. Computational methodology

The calculations were done in a two-step approach using the Serpent-DYN3D codes sequence. In the first step, the homogenized few-group cross sections (XS) were generated on lattice level with Serpent, and in the second step, the full core nodal calculations were performed with DYN3D.

3.1 Generation of parametrized cross section libraries

A parametrized cross section library was generated for DYN3D that covers the full range of reactor conditions of the CR shift tests and the natural circulation test. In this way, the same library was utilized in all calculations presented in Part II and III of the paper.

The XS were calculated with Serpent at different fuel temperatures, coolant temperatures, axial expansion and radial diagrid expansion states. Table 1 presents the selected states that span the parameter space of the XS-library. In Table 1, the temperature-dependent expansion coefficients are defined as:

$$\varepsilon(T) = \frac{L(T)}{L(T_0)} = 1 + \alpha(T) \cdot (T - T_0), \tag{1}$$

where L is the linear dimension and α is the linear expansion coefficient corresponding to the temperature T, and T_0 is the reference temperature of the used linear expansion correlation. In this case, the correlation for the temperature-dependent linear expansion coefficients was provided in the benchmark specification.

Table 1. Conditions used for cross section parametrization.

Fuel temp. (K)	Coolant temp. (K)	Axial expansion	Radial expansion
523 900	523	ε(523)	ε(523)
1500 1800	900	ε(1200)	ε(900)

The coolant density effect is implicitly considered in the coolant temperature variation. In case of the axial expansion effect, the change of dimensions and densities is considered for both fuel and cladding. Furthermore, the radial expansion of the pins, the reduction in the liquid sodium amount between the pins, and the temperature effect of the cladding are taken into account. The axial expansion is assumed to be driven by the cladding temperature. When the diagrid is radially expanded, the assembly pitch size is increased. At the same time, the dimensions of the pins and assembly wrapper remain unchanged, i.e. the increase of sodium gap between assemblies is modeled when the homogenized XS are generated.

The JEFF-3.1 based homogenized XS were obtained in the 24-group energy structure as suggested in (Fridman and Shwageraus, 2013). For further improvement of the nodal diffusion solution, the Superhomogenization (SPH) method (Kavenoky, 1978; Hebert, 1993) was applied for blanket and non-multiplying regions adjacent to the fuel nodes. The XS generation procedure for the Phenix core is presented in more details in Part I of the paper. The methodology to create Monte Carlo based homogenized XS for SFRs in general is discussed in the preceding papers by the authors (Nikitin et al., 2015a, 2015b).

3.2 DYN3D model

The Phenix EOL core model was constructed in DYN3D based on the data provided in the benchmark reports of the CR shift test and the natural circulation test. The fuel rods were modeled as described in the benchmark, but instead of having 90% of linked and 10% of free fuels, all fuel pins were considered to have a closed gas gap in the 3D DYN3D model. This approximation is based on the fact that the positions of the linked and free fuel pins are not available in the specification, since the natural circulation benchmark was aimed for system analyses by not modeling spatial neutronics and mechanics.

At the core inlet, a constant mass flow rate and a time-dependent coolant temperature boundary condition was defined. The inlet flow resistance coefficients of the assemblies were set to reproduce the zone-wise mass flow rate distribution given by the benchmark specification. Within the zones, the total mass flow rate of the zone was evenly distributed to the assemblies. The total mass flow rate of the core had to be adjusted, in order to match the initial coolant temperature measured at the outlet of the inner core (Fig. 1). In DYN3D, the total mass flow rate was set to 1275 kg/s instead of 1254 kg/s, which is still within the 5% of reported measurement uncertainty. Furthermore, it is assumed that the diagrid expansion in the Phenix reactor is directly driven by the average sodium inlet temperature without significant delay, since the thermal inertia of the diagrid heat-structure is very small (Chenu et al., 2012).

The initial phase of the test was computed with DYN3D by using the Serpent-generated parametrized XS-library and the newly implemented TM models of thermal expansion. The calculation was repeated twice with different treatments of axial fuel rod expansion:

- Case A: The newly implemented axial fuel rod expansion model was employed, where the axial expansion of the fuel rods was driven by local cladding temperatures. Hereafter referred to as the non-uniform expansion model.
- Case B: The same mixing based model (Nikitin et al., 2018a) as in Case A, but the layer-average cladding temperature is used to expand the sections of the fuel rods located in the same layer. Hereafter referred to as the layer-uniform expansion model.

The solution of Case A is considered as the reference solution of DYN3D. Case B is a simplified approach of Case A, since the radial averaging of thermal expansions covers up the local effects. Nevertheless, the layer-uniform expansion model can be a compromise for other spatial neutronic codes that also utilize a regular axial grid, and prefer an explicit expansion of the mesh.

4. Numerical results

Before the transient analyses, the reactivity coefficients obtained by DYN3D were compared with values provided by the benchmark specification. The feedback parameters are in good agreement as show in Table 2.

Table 2. Reactivity coefficient of the Phenix EOL core.

	Doppler-effect (pcm)	Diagrid expansion (pcm/K)	Fuel axial expansion (pcm/K)	Coolant temperature (pcm/K)
Benchmark spec.	-680	-1.21	-0.31	-0.02
DYN3D	-661	-1.00	-0.29	-0.05

4.1 Case A – Non-uniform thermal expansion modeling

The calculated total reactivity, power and core outlet temperature evolutions over time are presented in Fig. 2, along with the measured data. The power and core outlet temperature curves are completely aligned with experimental data, while the calculated values remain within measurement uncertainties. In the first ~300 s the calculated reactivity remains in a good agreement with measurements, whereafter the DYN3D underestimates the total reactivity, and reaches 7 pcm discrepancy at the end of the transient. The underestimation can be explained with the missing model of vessel expansion. After 300 s, the increasing sodium temperature of the cold pool warms up enough to induce vessel expansion, which acts as a relative extraction of the control rods (IAEA, 2013). By modeling the vessel expansion effect, the discrepancy can be reduced, as it was demonstrated by (Chenu et al., 2012).

As it is presented in Fig. 3a, the two main contributors to the reactivity evolution are the diagrid expansion and the Doppler-effect. The increase of the inlet temperature triggers the diagrid expansion, which initiates the power reduction. The fuel temperature of the fissile zone is decreasing (Fig. 4a) due the power reduction, while the blanket temperature of the fertile zone is increasing (Fig. 4b) due to the sodium heat-up. In total, the observed positive Doppler reactivity (Fig. 3a) is actually the combination of the dominant positive effect from the fissile core and the slightly negative effect from the blanket region, as shown in Fig. 3b. An overall temperature rise in fuel rod cladding is observed (Fig. 4), causing a moderate negative reactivity contribution by axially expanding the fuel rods, as seen in Fig. 3a. The coolant temperature effect remains insignificant during the whole transient.

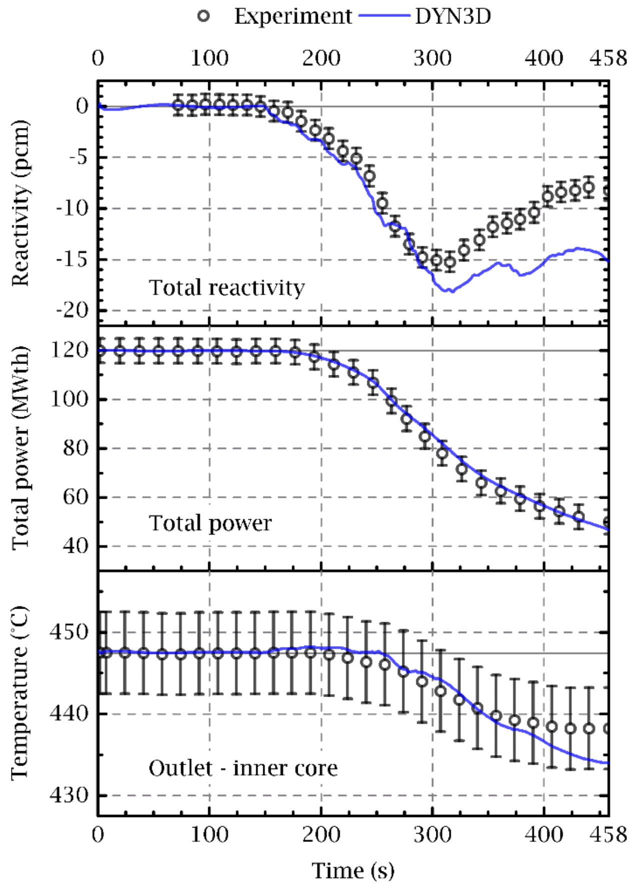
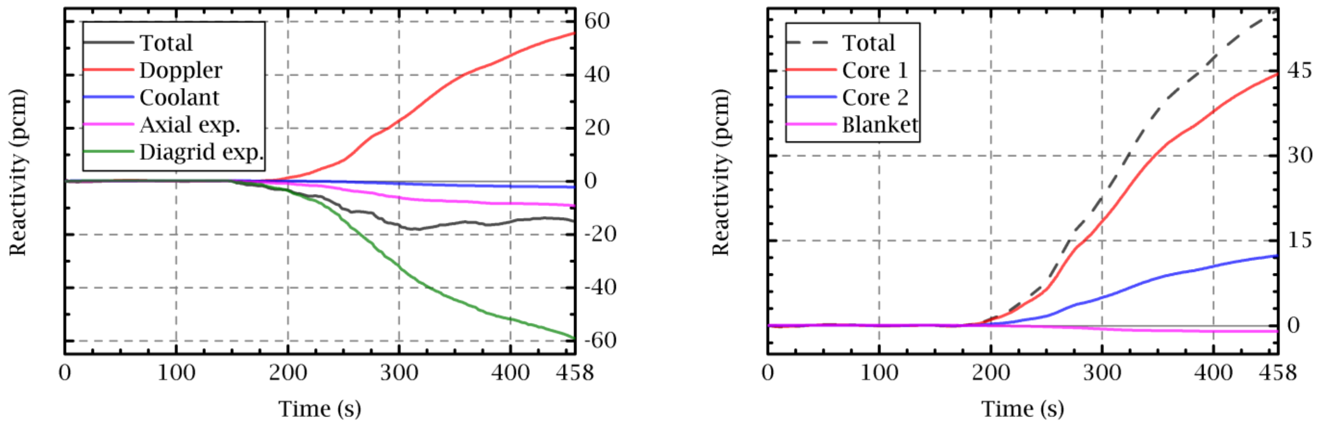
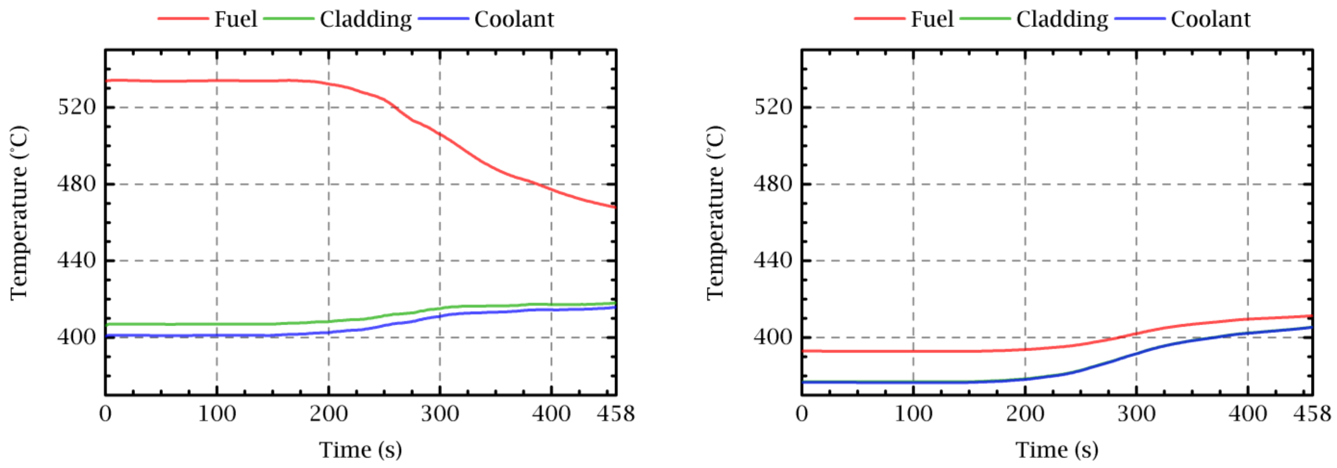


Fig. 2. DYN3D results on the initial phase of the natural circulations test (compared with the experimental results). *Top* to *bottom*: reactivity, total thermal power, outlet coolant temperature of the inner core.



a) Total reactivity decomposition *b) Doppler-effect decomposition by regions*

Fig. 3. Reactivity effect decompositions with DYN3D.



a) Fissile core *b) Radial blanket*

Fig. 4. Averaged fuel rod temperature evolution calculated with DYN3D.

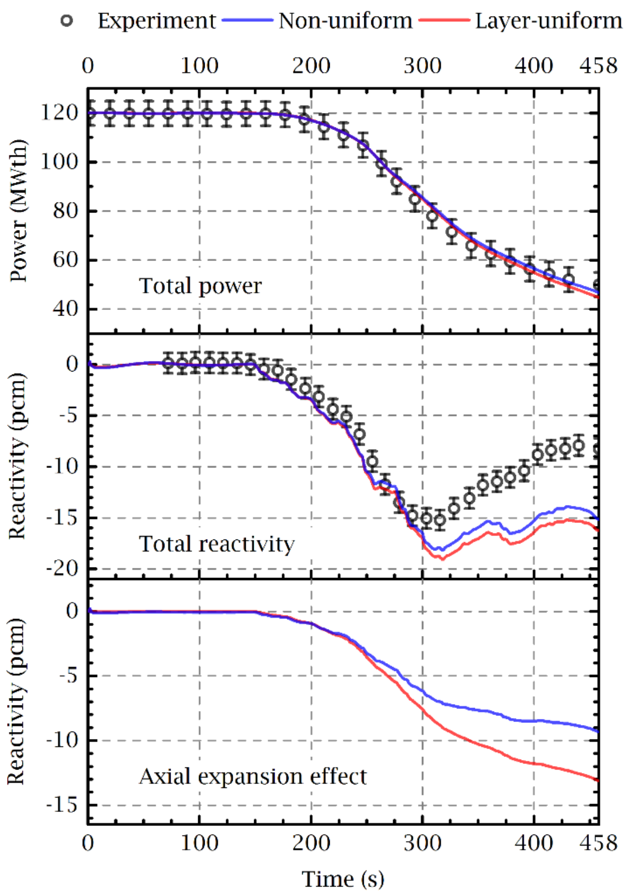
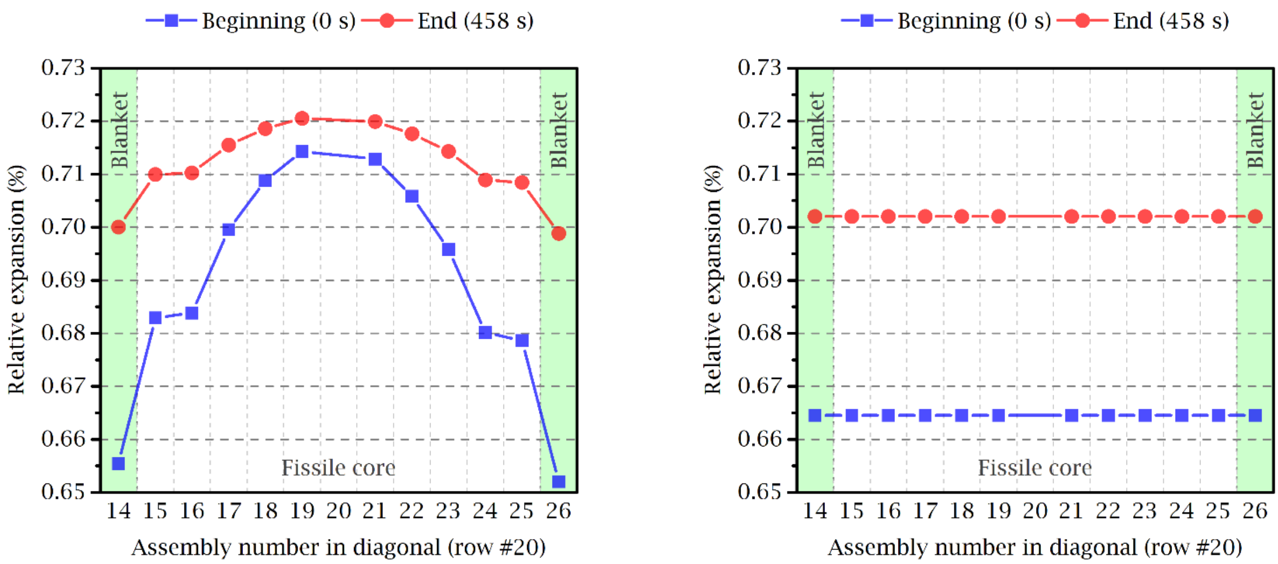


Fig. 5. Difference in the results by using non-uniform and layer-uniform expansion models. *Top* to *bottom*: total power, total reactivity, and axial expansion effect.

4.2 Case B – Layer-uniform thermal expansion modeling

The transient calculation was repeated once more with the layer-uniform expansion model. The differences between the results of Case A and B are summarized in Fig. 5. In Case B, the DYN3D predicts at the end a lower power of ~2 MW, which corresponds to 1.7% of the initial state. This reduction in power is caused by the larger axial expansion reactivity effect (Fig. 5, bottom) that is somewhat compensated by the Doppler-effect, and yielding a 2 pcm lower reactivity in total (Fig. 5, center).

The overestimation of axial expansion effect can be explained by comparing the evolution of the radial profiles of the assembly expansions, as presented in Fig. 6. With the layer-uniform model, all assemblies expand by additional 0.038% during the transient, while with the non-uniform model by only 0.023% in average. Since the transient is driven by a radially uniform heat-up of the coolant, the non-uniform profiles flattens out in time, and even would become uniform if transient would continue without external interaction. In this core-symmetric transient scenario, the discrepancies seen in the results can be originated from the differences of expansion profiles present at the beginning.



a) Non-uniform model *b) Layer-uniform model*

Fig. 6. Change of the axial expansion profile between the beginning and the end of the transient. The profiles are depicted along the diagonal closest to CRs #1 and #4.

5. Summary and conclusions

This study presented the validation of the extended version of DYN3D against the initial stage of natural circulation test from the Phenix EOL experiments. The test was simulated with the Serpent-DYN3D codes sequence, i.e. the parametrized cross section library was generated with Serpent and the coupled NK/TH time-dependent solution was obtained with DYN3D. The numerical results were compared against the experimental data. The following conclusions can be made from the validation study:

- In general, the DYN3D solutions were in very good agreement with the experimental data indicating the feasibility of using DYN3D in coupled NK/TH transient analyses of SFR cores.
- The deviations from the measurements were only observed when out-of-core thermal expansion effects, such as vessel expansion, start to influence the CR position relatively to the core. In order to account for the correct magnitude and time delay of such relative CR movements, the change in thermal-mechanical conditions of the supporting structures has to be modeled. The development of TM models for the supporting structures is an ongoing research topic at HZDR that will be based on a coupling of DYN3D with a TH system code capable of sodium flow modeling.
- The study demonstrated that by utilizing the newly implemented fuel rod thermal expansion model, the non-uniform thermal expansion effects can be modeled in transient simulations. As compared to the layer-uniform fuel rod expansion modeling, the discrepancies between the numerical results and the measurements did not change significantly. This can be attributed to a relatively small variation in sodium heat-up over the course of transient (about 40°C). In more severe cases (e.g. accident scenarios with significantly higher or/and asymmetric sodium heat-up) the selection of one thermal expansion model over the other can lead to much higher deviations in the results.
- This study also demonstrated that the MC code Serpent can be successfully applied to generate few-group XS for transient analyses of SFR cores.

Acknowledgements

The work carried out by HZDR was partly supported by a project of the German Federal Ministry for Economic Affairs and Energy (BMWi) (registration number 150 1462).

References

Chenu, A., Mikityuk, K., Chawla, R., 2012. Analysis of selected Phenix EOL tests with the FAST code system – Part II: Unprotected phase of the Natural Convection Test. Annals of Nuclear Energy 49, pp. 191–199.

Fridman, E., Shwageraus, E., 2013. Modeling of SFR cores with Serpent-DYN3D codes sequence. Annals of Nuclear Energy 53, pp. 354–363.

Hebert, A., 1993. Consistent technique for the pin-by-pin homogenization of a pressurized water reactor assembly. Nuclear Science and Engineering 113, pp. 227–238.

IAEA, 2014. Benchmark Analyses on the Control Rod Withdrawal Tests Performed during the PHENIX End-of-Life Experiments, IAEA-TECDOC-1742, International Atomic Energy Agency, Vienna, Austria.

IAEA, 2013. Benchmark Analyses on the Natural Circulation Test Performed During the PHENIX End-of-Life Experiments, IAEA-TECDOC-1703, International Atomic Energy Agency, Vienna, Austria.

Kavenoky, A., 1978. The SPH Homogenization Method, in Proc.: A Specialists' Meeting on Homogenization Methods in Reactor Physics, IAEA-TECDOC-231, Lugano, Switzerland.

Nikitin, E., Fridman, E., Mikityuk, K., 2015a. Solution of the OECD/NEA neutronic SFR benchmark with Serpent-DYN3D and Serpent-PARCS code systems. Annals of Nuclear Energy 75, pp. 492–497.

Nikitin, E., Fridman, E., Mikityuk, K., 2015b. On the use of the SPH method in nodal diffusion analyses of SFR cores. Annals of Nuclear Energy 85, pp. 544–551.

Nikitin, E., Fridman, E., Pautz, A., 2018a. Extension of the reactor dynamics code DYN3D for SFR applications – Part I: thermal expansion models. Annals of Nuclear Energy, submitted.

Nikitin, E., Fridman, E., Pautz, A., 2018b. Extension of the reactor dynamics code DYN3D for SFR applications – Part II: validation against the Phenix EOL control rod shift tests. Annals of Nuclear Energy, submitted.

Rachamin, R., Wemple, C., Fridman, E., 2013. Neutronic analysis of SFR core with HELIOS-2, Serpent, and DYN3D codes. Annals of Nuclear Energy 55, pp. 194–204.

Rohde, U., Kliem, S., Grundmann, U., Baier, S., Bilodid, Y., Duerigen, S., Fridman, E., Gommlich, A., Grahn, A., Holt, L., Kozmenkov, Y., Mittag, S., 2016. The reactor dynamics code DYN3D – models, validation and applications. Progress in Nuclear Energy 89, pp. 170–190.