Modeling of Phenix End-of-Life control rod withdrawal tests with the Serpent-DYN3D code system

E. Nikitin and E. Fridman*

Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden, Germany

Corresponding author: e.fridman@hzdr.de

Abstract. The nodal diffusion code DYN3D is under extension for Sodium cooled Fast Reactor (SFR) applications. As a part of the extension a new model for axial thermal expansion of fuel rods was developed. The model provides a flexible way of handling the axial fuel rod expansion that is each sub-assembly and node can be treated independently. In the current paper the new model is be described in details. The performance of the model is assessed with the help of the benchmark on the control rod withdrawal tests performed during the PHÉNIX end-of-life experiments. The DYN3D results are tested against the experimental data as well as against the numerical results provided by other participants to the benchmark.

Key Words: SFR, DYN3D, Serpent, Thermal expansion.

1. Introduction

DYN3D [1] is a state-of-the-art three-dimensional reactor simulation tool developed at Helmholtz-Zentrum Dresden-Rossendorf (HZDR). Initially, the code was developed for analyses of Light Water Reactors (LWRs). Currently, DYN3D is being extended for steady-state and transient analyses of Sodium cooled Fast Reactors (SFR). The code contains a nodal diffusion solver for hexagonal-z geometries and an internal thermal hydraulics (TH) model with single phase sodium flow modeling capability, which is necessary for SFR modeling. As a part of the code extension, an additional thermal mechanical (TM) model [2] was implemented to account for the effect of the thermal expansion of fuel rods because it provides an important reactivity feedback effect in transient and accident events.

For initial verification and validation purposes, the control rod (CR) withdrawal benchmark [3] was selected from the Phenix End-of-Life (EOL) experiments. In this study, the benchmark was calculated to assess the feasibility of using the nodal diffusion code DYN3D on real SFR cores.

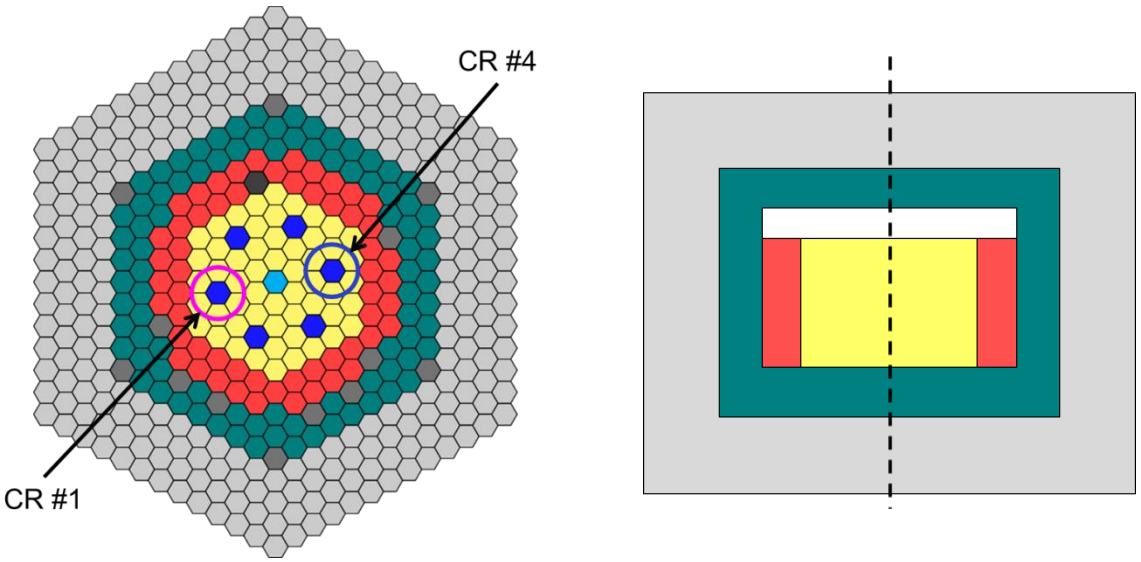
This paper is structured as follows. Section 2 provides an overview on the calculated benchmark. In Section 3, the calculation methodology is described. The details on the new TM model are given in Section 4. Selected results from the benchmark calculations are presented in Section 5. Section 6 summarizes the paper.

2. Overview on the Phenix EOL control withdrawal benchmark

The CR withdrawal tests [3] were conducted in the frame of the Phenix EOL experiments and were included in an IAEA Coordinated Research Project for code benchmarking. The 350 MWth Phenix EOL core comprises an inner and outer fissile zone, with 54 and 56 sub-

assemblies (SA), respectively. The fissile zone is surrounded with axial fertile blanket regions and 86 radial blanket SAs. The radial and axial core layout, including the reflector and control SAs, can be seen in Figure 1.

This paper concentrates on the second part of the tests, which was performed on-power at 340 MWth. In this phase, different CR configurations were used to create distorted radial power maps while preserving the sodium flow rates and the total power. Two CRs (#1 and #4) has been offset to distort the power map, whereas the remaining CRs remained in a bank. Four different CR configurations were used during the tests as presented in Figure 2. The assembly-wise power distribution was deduced from the sodium outlet temperature measurements of each SA in fissile zone. A more detailed description of the reactor core and the experiments can be found in the benchmark specification [3].



(a) Radial layout *(b) Axial layout*

FIGURE 1. Schematic view of Phenix EOL core (yellow – inner core, red – outer core, green – blanket, blue – control rods, grey – reflectors and white – sodium plenum).

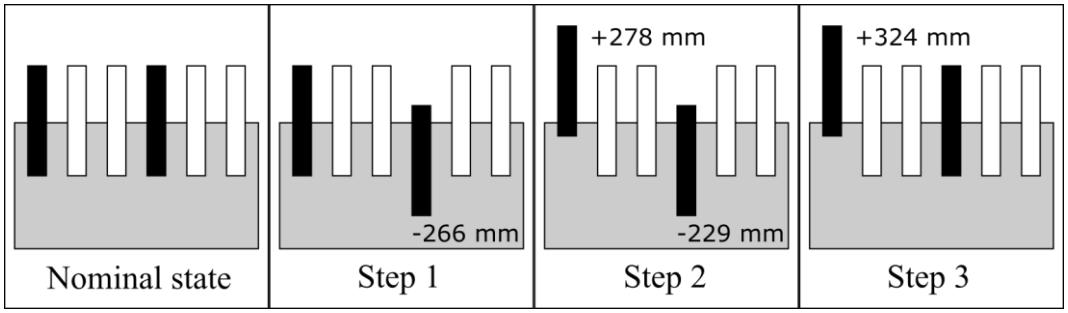


FIGURE 2. Schematic overview on different CR positions (grey – active core, black rectangles – shifted CRs, white rectangles – CRs in a bank).

3. Calculation methodology

The full core nodal diffusion solutions of the CR shift test were calculated the DYN3D code. The homogenized few-group cross sections (XS) needed for nodal calculations were generated with the Monte Carlo (MC) code Serpent [4]. It should be noted, that the feasibility of using Serpent as XS generator for SFR cores was already demonstrated in previous studies [5]–[7]. The applied XS methodology is summarized as follows:

- The XS for the fuel sub-assemblies are calculated using a 3D single sub-assemblies model with reflective radial and black axial boundary conditions (BC).
- The XS for blanket sub-assemblies and all non-multiplying regions (i.e. reflectors, sodium plenums, control rods and their empty channels) are prepared using 2D super-cell models depicted in Figure 3. All super-cells are constructed as central hexagonal region of interest surrounded by the fuel sub-assemblies. The XS are homogenized over the central hexagonal region only.
- The few-group energy structure used for the generation of the XS is a 24-group subset of the 33-group energy structure of the ERANOS code [8] obtained by collapsing 10 thermal energy groups (from 24 to 33) into a single thermal group. More details regarding the selection of the few-group energy structure can be found in [5], [6].
- For further improvement of the nodal diffusion solution additional equivalence techniques can be used. One of the recent studies [9] demonstrated the feasibility of using the Superhomogenization (SPH) method on SFR cores. In the Phenix calculations, the SPH factors were applied on CRs, first row of blanket regions and inside reflector SAs. The SPH factors are calculated using the Serpent and DYN3D codes. The detailed description of the SPH procedure can be found in [9].
- In order to perform steady-state neutronic calculations with TH and TM feedbacks, the XS are generated for different fuel temperatures, coolant temperatures and thermal expansion states. The XS are arranged in tables, thereafter used in calculations by DYN3D interpolation routines to acquire the XS for a certain temperature and expansion state.

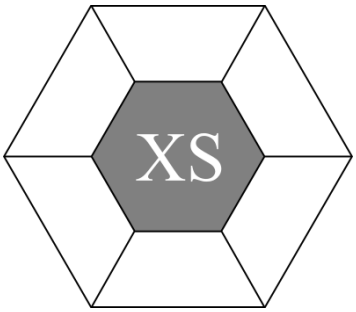


FIGURE 3. 2D super-cell model (gray – blanket or non-multiplying region, white – fuel, XS – where XS are generated).

4. Axial fuel rod expansion model

This new axial expansion model is designed to be flexible to resolve the restriction of the nodal mesh. The idea of the model was to preserve the axial size of the nodes and to account for the axial expansion effects by manipulation of XS. In this way the rigid nodal discretization can remain unchanged, and each node can be treated separately depending on its degree of expansion. The model recombines ("mixes") the XS for the affected nodes, depending on the contribution of the expanded materials inside of the node. It is done according to the following procedure:

- Initial axial discretization is specified to account for the material boundaries at some reference temperature (e.g. room temperature) as shown in Figure 4 (left).
- The obtained axial nodes are further subdivided into a smaller node with a height of the anticipated maximal possible axial expansion of a lower node and into a bigger one as shown in Figure 4 (right). The introduction of these smaller "mixing' nodes helps to reduce this dilution and smearing effect.
- For each sub-assembly, local nodal temperatures are used for the estimation of the axial expansion and new material interface levels. It should be noted that all new material levels are located within the "striped" regions as depicted in Figure 4 (right).
- When a new material interface within the "striped" regions is detected, the mixing of the XS is performed. For this purpose, volume weighted average of XS is used:

$$\Sigma = \frac{h_1\Sigma_1 + h_2\Sigma_2}{h_1 + h_2},$$

where h is the height of the material inside the node, Σ is the XS of the material, and the indices represent the lower and upper materials. The Σ includes all macroscopic reaction cross sections, group-to-group scattering matrices, and diffusion coefficients.

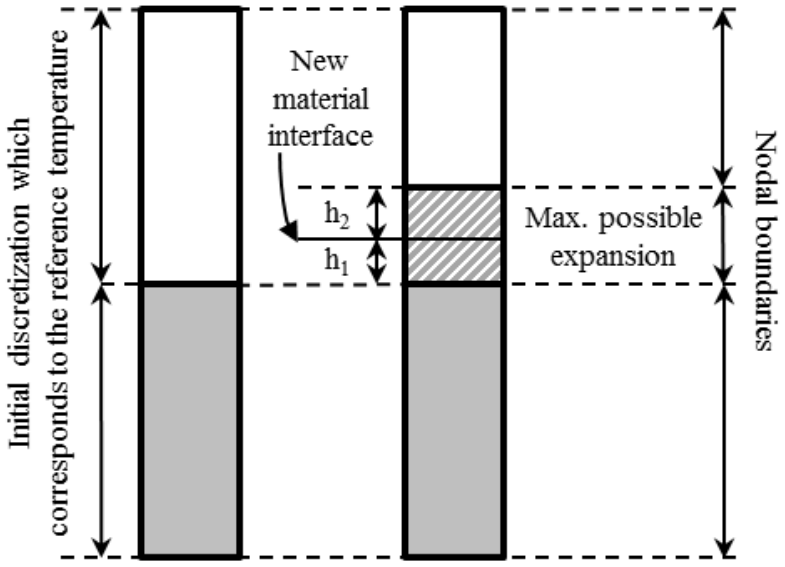


FIGURE 4. Subdivision of nodes for reduction of the dilution and smearing effect.

The estimation of the axial expansion is done assuming a pre-defined gas gap condition (open or closed gap). For the Phenix EOL core the closed gap condition is assumed. In this case, the expanding cladding is dragging the fuel pellets upwards, i.e., the fuel and cladding expand simultaneously driven by the cladding temperature. For a more accurate modelling of the fuel-cladding interaction a coupling with a fuel performance code is needed, which is only envisaged for the later stage of code extension.

5. Selected results from the benchmark calculations

First of all, it has to be noted, that the benchmark specification does not provide detailed assembly-wise material compositions, burnup map or flow rates, but only zone average values describing a large group of SAs. Additionally to the results of all participants using the averaged core description, the French Alternative Energies and Atomic Energy Commission (CEA) has also published results with a more detailed core model [3].

This benchmark was calculated with DYN3D using the XS generated with Serpent. The DYN3D results were compared with the full core MC solution Serpent, the results of the benchmark participants and the measurements. The TH and TM feedbacks were not considered in the code-to-code comparison, but in the comparison with the experiment. The solution of CEA using the averaged core model is a well representation of the benchmark outcome, therefore only the ERANOS [10] results of CEA are presented in this paper for comparison.

The calculated core reactivities obtained with ERANOS [3], Serpent, and DYN3D are compared in Table I. For all steps, the difference in the CEA results between the averaged and detailed core modeling indicate that around 700 pcm of discrepancy comes from model simplifications. The reactivity values predicted by Serpent and DYN3D, although in good agreement, are somewhat lower as compared to the CEA ERANOS solutions with the averaged core modeling.

TABLE I. CALCULATED CORE REACTIVITY AT ALL STEPS (PCM)

	CEA – ERANOS [3]		HZDR		
	Detailed core	Averaged core	Serpent	DYN3D	DYN3D vs. Serpent
Reference state	261	986	843	790	-53
Step 1	268	995	874	771	-103
Step 2	268	991	894	815	-79
Step 3	272	989	886	822	-64

The radial power distribution predicted by ERANOS [3], Serpent, and DYN3D are shown in Figure 5. Since the highest power distortions were observed when CR #1 and CR #4 were withdrawn and inserted respectively, only the results for Step 2 are presented here. The radial power distribution predicted by DYN3D is in a very good agreement with MC solution while the average/maximal difference is about 0.34/1.15%. Furthermore, the power distribution is also in a good agreement with the CEA ERANOS results using the averaged modeling, but high discrepancies can be observed in center core between DYN3D and the experiment. These discrepancies can be explained with averaged core modeling, since the measured power profile was well predicted with detailed modeling of CEA.

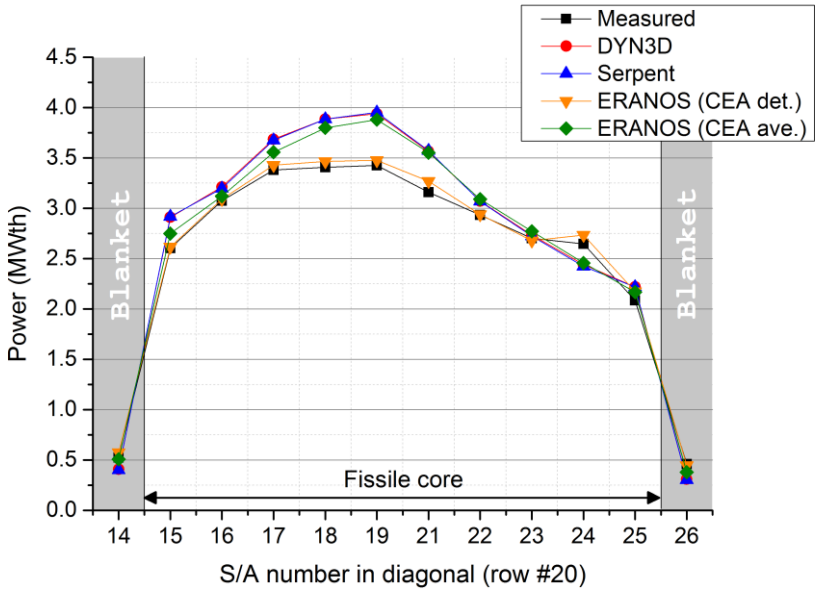
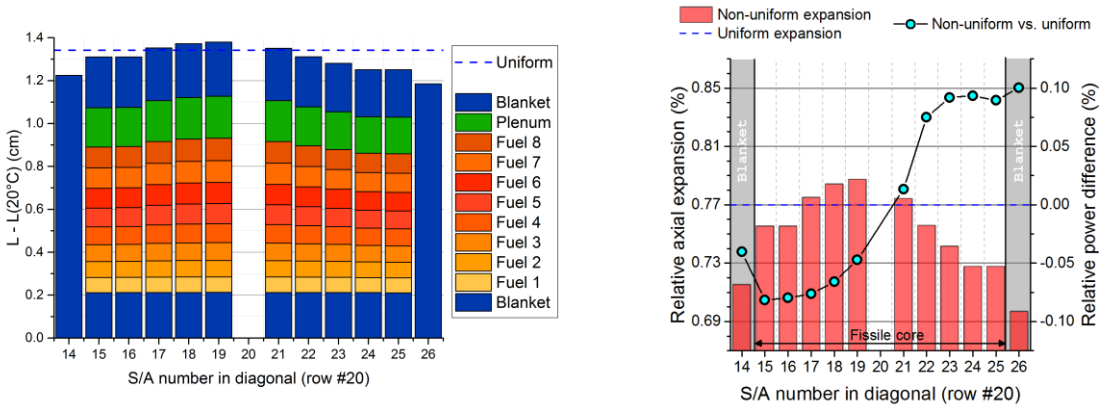


FIGURE 5. Radial power distribution along the diagonal, Step 2.

Using the new fuel rod expansion model of DYN3D the assembly-wise thermal expansion profile was also calculated as shown in Figure 6a. The radial profile of the axial fuel rod expansion clearly follows the power profile, and the materials at higher elevation are expanding more due to higher cladding temperature. The Figure 6b presents the relative radial power difference between the uniform expansion and the non-uniform expansion of the core. By the uniform expansion one core averaged temperature is used to expand the whole core, while by the non-uniform expansion the DYN3D is using the node-wise temperature distribution to expand each region separately. The maximal relative difference between expansion methods is around 0.05-0.10%. The use of the uniform expansion method leads to the power overprediction in the regions where the SAs expand above the core average expansion (Figure 6b left side), and to the power underprediction in regions where the SAs expand less (Figure 6b right side). These results are consistent with the negative feedback of axial fuel thermal expansion.



(a) Axial expansion profile *(b) Non-uniform vs. uniform expansion*

FIGURE 6. Axial expansion of the fuel rods at Step 2 calculated with DYN3D.

6. Conclusions

The Phenix EOL control rod withdrawal benchmark was calculated with the nodal diffusion code DYN3D. The XS were generated using the MC code Serpent and the SPH methodology was applied for the further improvement of the nodal diffusion solution. Additionally, Serpent was also used to calculate the full core MC solution of the problem.

The DYN3D results are in a very good agreement with the MC reference, and are in good agreement with the other benchmark participants. Nonetheless, high discrepancies can be observed in the power prediction compared to experimental results. The high discrepancies can be mainly explained with the averaged core modeling, therefore a calculation with a more detailed core and test description would be beneficial for a better understanding of the differences.

The new axial fuel rod expansion model was applied in the calculations. It was presented that the difference in power prediction is not insignificant when using the real temperature profile instead of one averaged temperature value. Nevertheless, the accounting for realistic temperature profile can be significantly more important in transient analyses. This new TM model is to be further assessed in transient SFR calculations, including Phenix natural circulation test.

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

[1] ROHDE, U., et al., "The reactor dynamics code DYN3D – models, validation and applications," Prog. Nucl. Energy, vol. 89, pp. 170–190, 2016.

[2] NIKITIN, E. AND FRIDMAN, E., "Axial fuel rod expansion model in nodal code DYN3D for SFR application," in PHYSOR 2016, 2016, pp. 3241–3251.

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Benchmark Analyses on the Control Rod Withdrawal Tests Performed during the PHÉNIX End-of-Life Experiments, IAEA-TECDOC-1742. Vienna, Austria: International Atomic Energy Agency, 2014.

[4] LEPPÄNEN, J., et al., "The Serpent Monte Carlo code: Status, development and applications in 2013," Ann. Nucl. Energy, vol. 82, pp. 142–150, Sep. 2015.

[5] FRIDMAN, E. AND SHWAGERAUS, E., "Modeling of SFR cores with Serpent-DYN3D codes sequence," Ann. Nucl. Energy, vol. 53, pp. 354–363, Mar. 2013.

[6] RACHAMIN, R., et al., "Neutronic analysis of SFR core with HELIOS-2, Serpent, and DYN3D codes," Ann. Nucl. Energy, vol. 55, pp. 194–204, May 2013.

[7] NIKITIN, E., et al., "Solution of the OECD/NEA neutronic SFR benchmark with Serpent-DYN3D and Serpent-PARCS code systems," Ann. Nucl. Energy, vol. 75, pp. 492–497, 2015.

[8] TOMMASI, J., "Création de pseudo-produits de fission pour ERANOS (BIBLIOTHEQUES JEFF-3.1)," 2006.

[9] NIKITIN, E., et al., "On the use of the SPH method in nodal diffusion analyses of SFR cores," Ann. Nucl. Energy, vol. 85, pp. 544–551, 2015.

[10] RUGGIERI, J. M., et al., "ERANOS 2.1: International code system for GEN IV fast reactor analysis," in Proceedings of the 2006 International Congress on Advances in Nuclear Power Plants, ICAPP'06, 2006, pp. 2432–2439.