Neutronics analysis of demonstration and experimental fast reactors with transport methods

Response on the report by Áron Brolly

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First, I would like to thank Áron Brolly (Reviewer) for his time and work spent on his detailed review. The Reviewer formulated seven questions and made 22 specific and general remarks.

Remarks about the dissertation:

General remark:

In the general remark, the Reviewer expresses his general impressions about the dissertation, which is highly appreciated. I understand the Reviewer's message; however, I would like to reflect on his remark in some places. Thermal reactors are analysed in the dissertation as validation exercises to ensure the applicability of the methods for fast reactors where measurements and experiments are more limitable available. The transitions between the chapters might not indicate this necessity well in the dissertation. Furthermore, I believe that the main structure, how the chapters follow each other, is logical in their current state. Although, based on the feedback I have received, I might add a new chapter where I would write more about the code development and its structure, which might have received fewer emphases in the dissertation.

Specific remarks:

S1. On page 32 instead of "IE-6" I would use "10^{6}" as well in Tables 3.1, 4.1, 4.2, 4.3 and 5.1.

I prefer to use scientific notations in tables; it helps to compare the data and is easier to extract it for other use.

S2. In Figures 4.1 and 5.1 (and in Figure 1 in [P6]) "aaflxm/aaflux" can be read. According to the text, it shall be "raflxm/aaflxm". Do I understand correctly?

Yes, raflxm/aaflxm should be there.

S3. To Section 4.3.1, Figure 4.4: according to the caption, the figure shows the benchmark geometry with the void material. However, the figures are for the inserted absorber case. Colours and colour scale in the original publication [P6] are better and as a result of this more details can be seen.

The Caption in Figure 4.4 mentions the wrong material. The figures for the dissertation were recreated to avoid any licensing issues with the previous publications, and I tried to use similar colours and scales throughout the document. I chose "*parula"* colour scale because written text is more visible on this.

S4. To the same section on page 44: " ... the fission material is changed to the control rod material in the yellow region." In this case, according to Figure 4.2, the whole core will consist of absorber material and there will be no fission material in the reactor. Could the candidate clarify this? According to the original paper [P6], the yellow colour denotes the void region.

The text was not changed according to the figure. The text should mention "in the blue region".

S5. In equation 5.7 instead of summation until "Pb" and "Test" I would use i E V_{pb} and z E V_{rest} .

It could have been a better notation.

S6. To Figure 5.4: according to the text, the y-axis label shall be "Contribution to the reactivity" instead of "Reactivity".

"Contribution to the reactivity" would be better.

S7. In Figure 5.6, according to the legend, the reactor vessel is surrounded by lead, indeed?

The core specification of the ALFRED reactor mentions two reactor vessels. The legend in Figure 5.6 refers to the “inner vessel” in which the zone takes place, and in Figure 1, the “main vessel” is visible with the primary system. Figure 5.6 represents a schematic layout of the ALFRED reactor, mainly for neutronics modelling.

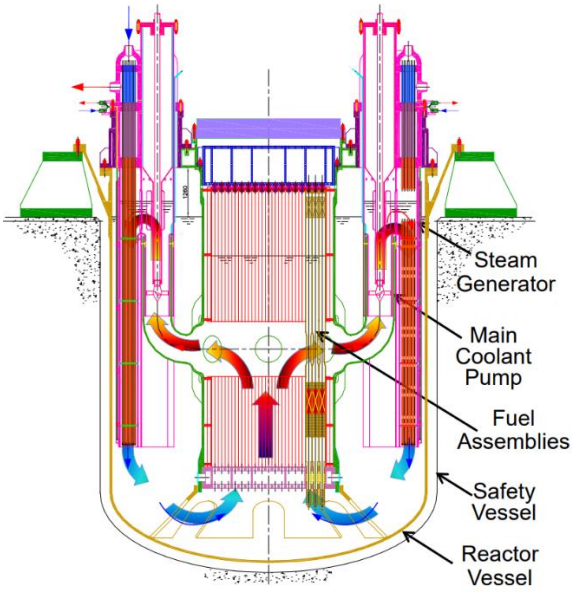

Figure 1. Primary system of the ALFRED reactor.

S8. On page 64 the candidate writes: "The coolant temperature coefficient tells the sensitivity of k_{eff} for the coolant temperature." It is about the sensitivity of the reactivity rather than k_{eff}.

Reactivity would have been the more appropriate word to use.

S9. On page 66 the candidate writes: "The pictures indicate that the contribution from the active region and from the inelastic scattering is highly dependent on the applied mesh[...]". According to the figure, the elastic scattering depends on the applied mesh size. In addition, denoting the active and the upper region on Figure 5.7 would be welcomed.

The text should state that “the elastic scattering depends on the applied mesh size”.

S10. On page 76: there is no reference to Figure 6.2 in the text.

A reference could have been placed at the end off section 6.2.2.

S11. On page 79 "data series III/2" is mentioned without any previous appearance in the text. The same in [P7].

The name of the data set does not contribute any meaning to the text. The sentence should have been rephrased without it.

S12. Figure 6.6 is too small in print, in addition it is rotated compared to Figure 6.3. It is hard to identify on the model the components of the reactor. E.g., what is the aluminium block in the upright corner of the core basket?

Not all Figures were test printed; therefore, some might be harder to read in the printed version. In the electronic version, many are vector graphic based to enable the reader to enlarge them.

The aluminium block is part of the irradiation channel in the model. When we performed this study, the MCNP model contained these aluminium blocks; later, it was found to be aluminium boxes.

S13. In Section 6.4 several times the word "zone" is used. I would rather use the word "core."

(See S22.)

S14. On page 87 "75 MWth thermal power" is written. First, the "MWth" is not an SI unit, second, it is redundant since thermal power is written explicitly. On page 63, correctly, only "MW" is used.

I agree with the redundancy; however, in many places in the literature "MWth" is used.

S15. In Section 6.4 the name of the thermal hydraulic code ATHLET is written like this and as ATHLETE as well.

ATHLET is the correct name of the code.

S16. References [82] and [83] are internal reports of the institute of the candidate and are not publicly available ones. Similarly to references [68] and [90], which are deliverables of an EU project.

These are indeed not publicly available documents; however, these contain the necessary information for the various core specifications.

S17. Axial cross section of the reactor geometry would be useful in Figures 5.6 and 6.13; [P2] and [P4] contain one for Figure 5.6.

Figures 5.6 and 6.13 shows the layout of the core, which describes the neutronics models.

S18. Legend would be useful for Figures 5.7 and 6.14 depicting the calculation model of the reactors.

(See S22.)

S19. There are several graphs hard to read in print: Figure 5.4, 5.5, 5.9, 5.10 (in [P2] and [P4] it was better), 6.3, 6.4 and 6.15.

Not all Figures were test printed; therefore, some might be harder to read in the printed version. In the electronic version, many are vector graphics based to enable the reader to enlarge them.

S20. The candidate uses the word "calculation" in several places. I suggest using alternatives since calculation is just a tool we use for an analysis, study, or investigation.

(See S22.)

S21. Chemical symbol of the elements is written in italics at several places with or without the mass number. I suspect that the candidate used the math environment of LaTeX without excluding the chemical symbol from the environment.

(See S22.)

S22. Equations are nicely edited. If the candidate would like to increase the level of the equations, I suggest to typeset running indices in italics, as already done however to typeset indices that denote properties in roman. E.g. for a multigroup fission cross section: $\Sigma_{f,g}$ This subtle difference would make Eqs. 2.6, 2.39-2.47 easier to follow.

I want to thank the Reviewer for his S13, S18, S20, S21, and S22 remarks. In the future, I will further improve my writing according to these suggestions.

Questions about the dissertation:

1. **Question:** On page 13 it is written that the product of υ and Σ_f is treated together in the candidate's analyses however there are methods in which these two quantities are treated separately. What is the effect, benefit or drawback, of the later methods?

The separation of the two quantities is possible; however, during the deterministic calculation $\upsilon\Sigma_f$ is employed. In Chapter 4, we only had an interest in the calculation of the product because the numerical accuracy of the applied method was in focus. However, later in chapter 5, sensitivity coefficients were calculated for υ and Σ_f separately. In this part, we were interested in the sensitivities of the reactivities to the original nuclear data, and the covariance matrix has the information separately. Therefore, the individual treatment of the two quantities was necessary.

2. **Question:** Section 3.2.2 investigates test cases with hypothetical square cores. To obtain the group constants the candidate uses Serpent 2 and the ECCO module of ERANOS. For the former he defines a rectangular pin cell while for the latter he uses an equivalent cylindrical pin cell. The candidate notes that the different geometry of the pin cells and the different boundary conditions can result differences between the groups constants obtained with the two codes. Why did not use the candidate the equivalent pin cell in Serpent 2 as well in order to minimize the differences between the obtained group constants? Did the candidate investigated this possibility?

The reference Serpent 2 Monte Carlo models for the different-sized cores consisted of the pin cells in a rectangular lattice; therefore, we preferred to use the most accurate representation during group constant generation. Furthermore, Serpent only allows the user to apply vacuum boundary conditions on a cylindrical surface. Due to its deterministic nature, the ECCO module does not allow this hybrid geometry description; therefore, we applied an equivalent cylindrical description.

To overcome the limitations of the Serpent code and check the equivalence between the two geometric descriptions, I placed the cylindrically approximated geometry inside a square where a reflective boundary can be applied and filled the remaining volume with void material. The most significant difference with the so-generated group constants was less than 0.5%.

3. Question: To Figure 4.6 but rather to Figure 4.9. As the order of expansion increases the reactivity difference curve does not show stabilization, instead of it has a maximum. Taking this into account, which expansion does the candidate suggest using? In addition, what kind of effect could have a wrongly chosen expansion on the result of a nuclear safety analysis?

In Figure 4.9. (and probably in Figure 4.6.), the decreasing trend corresponds to the slowly converging reactivity effect due to the increasing angular expansion in the numerical model. It might not be so evident in the dissertation. However, if we perform this analysis in even higher angular discretizations, it converges to a fixed value, as can be seen in the following figures:

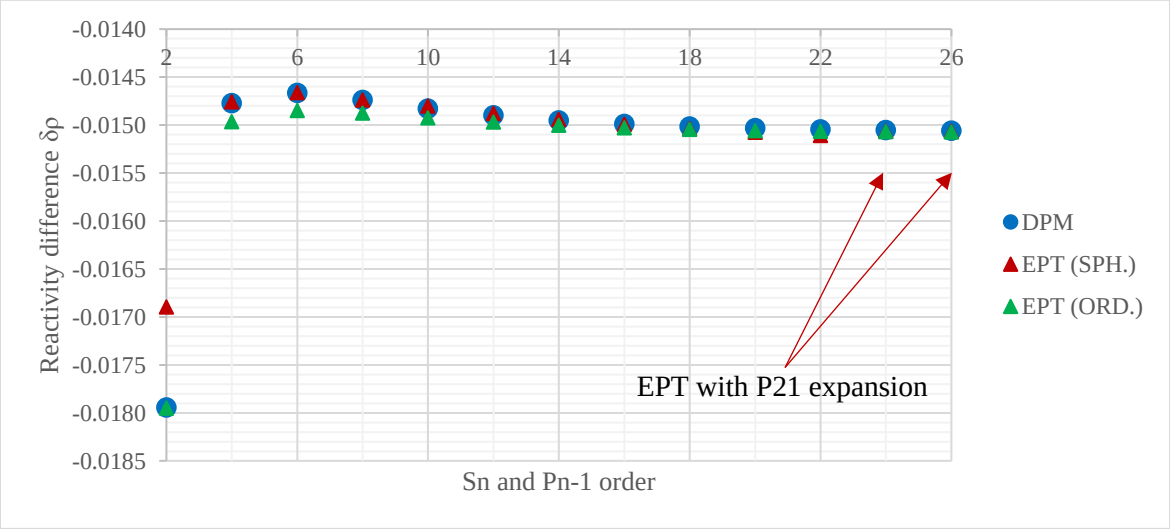

Figure 2. The effect of the higher-ordered expansion of the angular dependent flux in a curvilinear geometry.

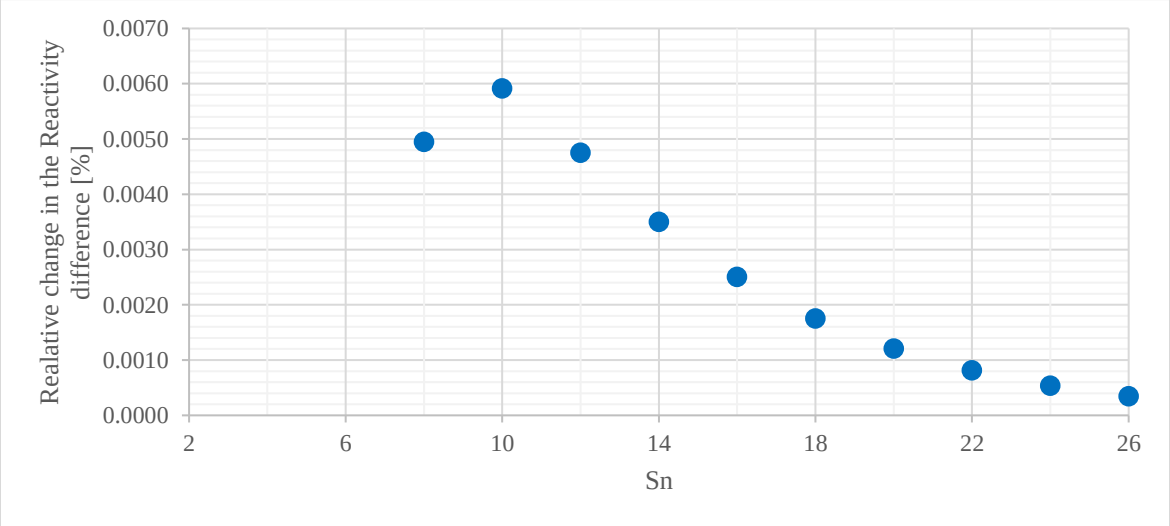

Figure 3. Convergence of the reactivity change

(Deviations start to arise at high angular expansion with the spherical harmonics (over P17). This is caused by the inaccurate estimation of the higher moments in the expansion from the given ordinate set. When S24

and S26 sets were used, the spherical harmonic expansion was set to P21, which corrected the coefficients resulting in a better agreement.)

There were no major differences between the results in Chapter 4, whether the spherical harmonic or the discrete ordinate representation was used. Therefore later, I mainly used the spherical harmonic representation as it was easier to implement the functions. I think a badly chosen set could affect the result in two ways:

1. The discrete ordinate set used in the deterministic calculation is not dense enough to accurately determine the flux solution; therefore, the flux will be inaccurate, which will highly affect the integration of the whole phase space.
2. Let's say we apply a dense enough ordinate set; then not necessary to expand the flux moment for a really high order as high momentum can affect the capture T1 and the scattering term T3. For the scattering, the spherical harmonic expansion to the 5th order should be sufficient, as I have not seen any scattering cross-section data going beyond that. Therefore the T1 term can depend on the higher moments; however, these examples did not have large angular anisotropies, which would require larger than L=5 expansion.

4. Question: To Figures 5.11 and 5.12. Actually, I don't understand what does mesh on the x-axis mean. Is it the mesh size in one direction? However, in this case, e.g., 20 cm is too large. An additional question to Figure 5.7 on which one can see different mesh sizes. Did the candidate use an adaptive mesh size?

During the calculation of the KENO Monte Carlo code of SCALE, spatial discretization is applied in all dimensions in a rectangular description. The angular moments of the flux solution for every material are determined in each voxel, and the integration (summations) are done for these regions.

In Figure 5.7, the geometric description of the PARTISN model can be seen, and the code allows the user to apply different mesh sizes in the axis for the finite-difference method. In the figures showing the PARTISN models, always a base mesh is visualized, and during the calculations, I used a multiple of this mesh. (The applied meshed would have been too dense for a visual representation.)

5. Question: In Section 6.2 the candidate presents several already existing transient solvers. What was the motivation to implement a new one?

When I started the development, I had access to the KIN3D transient solver (in ERANOS) to perform time-dependent calculations; however, I found it hard to use and not versatile enough. Many of the required programmings had already been done, and I thought I could learn a lot of things during the development. Furthermore, many time-dependent solvers perform the calculations in the diffusion approximation, and we wanted to perform our analysis with a higher transport solver.

6. Question: In Section 6.4 the candidate used Cartesian geometrical approximation of the hexagonal ALLEGRO core while for the hexagonal ALFRED core he used curvilinear one. What was the motivation for using different geometrical models?

The model specification of the ALFRED reactor consists of cylindrical elements (reactor vessel); therefore, it seemed that a cylindrical approximation was suitable. Later, when I was working at the KIT (Karlsruhe Institute of Technology), my colleagues suggested using a cartesian geometric description to approximate the individual hexagonal assemblies. (At that point, I developed an ALFRED reactor model with a cartesian

geometric description, but I did not use it later in my works as most of the calculation had already been performed and we did not need assembly wise power distributions.)

When I created the ALLEGRO model, I immediately chose the cartesian geometric description; because the suggested model does not have cylindrical elements and the assembly-wise power distribution can be determined in this way.

7. Question: In Section 6.4.4 "BASE" and "NOROD" states are defined. I couldn't understand the difference between the two states. Please clarify it.

In the BASE state, all the absorber assemblies are withdrawn from the core and are located above the active region. In the NOROD state, the absorber assemblies are completely removed and replaced with structural material. (This is more a hypothetical state. We were interested in whether we could achieve a better agreement between the different codes without any large absorber elements.)

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