Reviewer's opinion on the PhD thesis
"Neutronics analysis of demonstration and experimental fast reactors with transport methods"
submitted by Zoltán Böröczki

Overview

The dissertation deals with the following topics: investigation of weighting methods of linearly anisotropic scattering matrices for thermal reactor cores; the effect of angular and spatial discretization on perturbation calculations for a critical assembly; then sensitivity and uncertainty analyses of lead-cooled fast reactor cores and finally transient simulation for a low power thermal and for a gas-cooled fast reactor. Investigations are presented for altogether seven cores or reactors, among which there are fast ones. The rationale of the studies can be summarised as comparison the effect of using different approximations or calculation methods.

The dissertation

The dissertation consists of eight chapters, including the *Introduction*, a *Summary and outlook* and *Thesis statements*. These are followed by the *List of publications* with the candidate's nine publications and a comprehensive *Bibliography* with 92 references. The dissertation counts 115 pages.

Chapter 1 is an introduction however without formulating the goal of the dissertation. It is more like a summary of the candidate's work even presenting some conclusions. I miss the big picture, the scientific question addressed. What is the common base of the investigations performed?
Chapter 2 is a comprehensive and at the same time a concise presentation of the theory and the methods used. It has a logical structure, except the subsection entitled *Flux moments collapsing*. The candidate presents benefits and drawbacks of the methods as well and proofs that he has a solid knowledge of the applied methods.
Chapter 3 deals with different weighting methods of linearly anisotropic scattering matrices used in the analyses of a VVER-440 reactor benchmark and used for hypothetical, PWR like cores with different size built from square fuel assemblies. Two energy group and multigroup cases are investigated revealing in the latter cases the applicability of the approximations.
In Chapter 4 different spatial and angular flux discretisation options are used and their effect on the results of perturbation theory calculations is studied. The candidate compares his calculation results to measured data from the Kyoto University Critical Assembly (KUCA) benchmark. Actually, the scientific value of this chapter is not obvious for the first sight.
Chapter 5 first presents sensitivity analysis for the lead void coefficient of the Comet Critical Assembly as validation of the method developed and applied by the candidate. This is followed by the uncertainty analysis of the same critical assembly and of the lead-cooled ALFRED reactor. Explanation and interpretation of the obtained results are more established in this chapter than in previous ones.
Chapter 6 deals with time dependent analyses. First, the candidate presents his simulation of a measurement performed on the BME Training Reactor. Then he does code-to-code analysis from which he derives requirements for spatial and temporal resolution of future experiments serving validation purposes. I found this part of the dissertation the best one. Final part of the chapter presents simulation of an unprotected transient on the ALLEGRO reactor. Although the candidate's code currently doesn't have full functionality for a complete, standalone simulation, the obtained results – through a code-to-code comparison – serve as validation of the current state of the code.
Finally, Chapter 7 is a good summary and outlook where we find, for the first time, the focus of the dissertation.
Chapter 8 is the last numbered chapter containing the thesis statements of the candidate.

General remarks

The dissertation does not show a coherent picture. According to the title, it is about fast reactors however more than half of the analysed reactors are thermal ones. The goal of the dissertation is not set therefore there is no target to head for. The common feature that connects the studies is not stated explicitly;

chapters follow each other with loose coupling. The structure of several chapters reflects the one of a scientific paper, starting with the first sentence containing a common knowledge, than we find some previous work from the candidate and a literature overview, than the lack on the field is identified. Where are we heading, actually? How does the current chapter fit to the big picture of the dissertation? Indeed, text copied from the candidate publications can be identified and in some cases keeping references to text not copied from the original paper. From this aspect, text from earlier papers and spent nuclear fuel has a common feature: both can be recycled. To be serious, I do not have any objection to reuse already written text however it should not do in this way.

If the dissertation was submitted for the internal debate or if I were the candidate's supervisor, I would suggest a restructuring of the chapters. A dissertation has a different role than a scientific paper. At a certain point we finish our research, more or less as we all know, and look back on the path we made. Not the chronology is important, e.g., extension of our own tool again and again however the work we done, the outcome, the findings and now we synthesize, compile what we have achieved. We search for the common feature, the glue that connects our research and we present it in the dissertation along this guideline. Writing a dissertation serves also to acquire this skill as well.
If I could make a suggestion to the candidate, I would suggest the following structure. Chapter 2 is an outstanding presentation of theory and methods. In Chapter 3 I would compile how the methods are implemented in his own code. I would share some technical features as well, like coding language, operating system the code runs on, typical running time. Then in following chapters, validation of the code could be presented and later on application. But always keeping in mind the common feature and emphasize what connects the whole material. As one can notice, my suggestion lacks placing the literature overview, which is difficult in that case, since the candidate deals with a lot of loosely coupled topics. This is a sign of a too broadly chosen research area.

Concerning the format of the dissertation, it is of high quality, the text is well written, equations are carefully edited, free from errors. Tables and figures have a uniform style and are aesthetic. The text contains some typos, not more than usual, however in Section 6.3 on page 78 there are around four lines of text written two times.

Specific remarks
S1) On page 32 instead of "1E-6" I would use "10^6" as well in Tables 3.1, 4.1, 4.2, 4.3 and 5.1.
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?
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.
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.
S5) In equation 5.7 instead of summation until "*Pb*" and "*Test*" I would use $i \in V_{\mathrm{Pb}}$ and $z \in V_{\mathrm{Test}}$.
S6) To Figure 5.4: according to the text, the y-axis label shall be "Contribution to the reactivity" instead of "Reactivity".
S7) In Figure 5.6, according to the legend, the reactor vessel is surrounded by lead, indeed?
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}.
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.
S10) On page 76: there is no reference to Figure 6.2 in the text.
S11) On page 79 "data series III/2" is mentioned without any previous appearance in the text. The same in [P7].

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?
S13) In Section 6.4 several times the word "zone" is used. I would rather use the word "core."
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.
S15) In Section 6.4 the name of the thermal hydraulic code ATHLET is written like this and as ATHLETE as well.
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.
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.
S18) Legend would be useful for Figures 5.7 and 6.14 depicting the calculation model of the reactors.
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.
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.
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.
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.

Questions to the candidate
Q1) On page 13 it is written that the product of ν 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?

Q2) 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?

Q3) 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?

Q4) 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?
Q5) In Section 6.2 the candidate presents several already existing transient solvers. What was the motivation to implement a new one?

Q6) 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?

Q7) In Section 6.4.4 "BASE" and "NOROD" states are defined. I couldn't understand the difference between the two states. Please clarify it.

Thesis statements and publications

The thesis statements provide a fair summary of the results presented in the dissertation. I accept all of them as new scientific results however I have to note that the Statement 6 is not supported by a paper, as the connecting Section 6.4 in the dissertation. Other thesis statements are supported by nine documents authored by the candidate. Five of these are journal articles published in English language and the candidate is the first author in three of these five papers. Several further papers were published in proceedings of significant conferences. This list of papers satisfies abundantly the requirements prescribed by the Doctoral School of Physical Sciences.

Conclusion

Having reviewed the dissertation and the thesis statements, my general opinion is that the candidate has a comprehensive overview on his research field, he has acquired a solid knowledge of the applied theoretical methods, he has achieved high-level skills in using several computational tools and capable to conduct independent research work. Based on this, I suggest that the dissertation be released for public debate in order to assess the PhD degree.

Paks, 2nd December 2022
Just 80 years after the first human-made self-sustaining nuclear chain reaction

Áron Brolly, Ph.D.