RERTR 2016 – 37TH INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

OCTOBER 23-27, 2016
RADISSON BLU ASTRID HOTEL
ANTWERP, BELGIUM

Adopting the Monte-Carlo Methodology in Dynamic Reactor Core Analysis

[1,2]Antonios G. Mylonakis, [1]Melpomeni Varvayanni, [1]Nicolas Catsaros
[1]National Centre for Scientific Research Demokritos, Institute for Nuclear and Radiological Sciences, Energy, Technology and Safety, Nuclear Research Reactor Laboratory, 15310, Aghia Paraskevi, Attiki - Greece

[2]Aristotle University of Thessaloniki, Faculty of Engineering, School of Electrical and Computer Engineering, Nuclear Technology Laboratory, 54124 Thessaloniki - Greece

ABSTRACT

The dynamic analysis of the reactor behavior is crucial regarding design safety issues. Especially for a nuclear reactor core conversion, the study of the behavior of the "new" core configuration under various transient circumstances, normal or accidental, is a major requirement. So far, the transient analysis of the reactor core is performed with deterministic models that make use of various approximations in combination with point kinetics models. The latter are very flexible and easy to use but very simplified and with limited spatial applicability. The Monte-Carlo methodology is currently very extensively utilized in rigorous static analysis. The main constraint that limits its use is its burdensome computational nature. However, the continuous increase of the available computational resources makes its potential use in the field of reactor transient analysis quite attractive, especially for benchmarking and reference calculations. In this work, a pure Monte-Carlo tool for dynamic analysis that is under development in NCSR "Demokritos" is tested in some small-scale test cases. The presented results are encouraging and give motivation for further investigation.

1. Introduction

The conversion of a reactor core from HEU to LEU requires the rigorous analysis of the new core configuration as part of the safety assessment procedure. During this phase, transient analysis plays a crucial role because it can generate useful information that regards, for example, the maximum heat generation during regular and/or accidental operation. So far, for transient analysis deterministic methodologies are mainly used in combination with point-kinetic models that are quite flexible but also significantly simplified. On the other hand, the Monte-Carlo

methodology [1] that is inherently free of significant approximations is mainly employed in static analysis (eigenvalue/fixed-source). Some algorithms that attempt to perform transient analysis utilizing Monte-Carlo are again based on Point-kinetics for the transient part. An example of a conversion study using such a scheme can be seen in [2]. It is known that the main disadvantage of the Monte-Carlo methodology in reactor physics is the high computational cost. However the continuous increase of the available computational resources together with the fact that Monte-Carlo is not commonly used for handy and daily calculations but mostly for reference and benchmarking ones makes its expansion to transient analysis attractive. In [3] the authors have presented the on-the-fly procedure of the development of a pure Monte-Carlo tool for transient analysis. The general theory behind the current status of this tool has been developed in [4] and [5]. Main aim of this tool is to serve as a platform for research on new developments and methodologies related to the field of transient Monte-Carlo simulations. Main purpose of the current work is to analyze two additional small-scale test-cases, of subcritical nature, in order to demonstrate the applicability of this, under development, tool in this kind of problems.

2. Brief description of the module

The described module has been developed on the Monte-Carlo code OpenMC [6]. OpenMC has been selected as a platform for the development of this tool mainly because it is open-source and as a result it can facilitate the developing procedure without any constraint. In addition it is written in modern Fortran making use of “type” structures and other modern programming features and finally because it includes various others utilities as restarting files, XML (Extensible Markup Language) format of the input files, etc.

The development of this new module was based on the fixed-source scheme of OpenMC following the general flowchart of that module. Consequently, the simulation of the whole phenomenon is performed in each batch. Since OpenMC calculates statistics considering each batch as a single realization of the random variable, the selected approach is compatible and can take advantage of the already existing tallying capabilities.

A simplified flowchart of the developed module is illustrated in Fig.1. The first step concerns the generation of a particle source. Transient phenomena of interest, are created when some cause (normal or accidental) perturbs a reactor steady-state imposing a time-dependent evolution of the neutron flux and thus of the power of the reactor core. In these cases a *k*-eigenvalue calculation may be used for the generation of the transient source. Because the straight-forward analysis of a reactor core transient behavior requires the total treatment of the involved physical phenomena, taking into account the involved time-scales, the initial critical neutron source is transformed in a precursor/prompt-neutron source where the appearance of the delayed neutrons will result naturally from the simulation of the behavior of the precursors. When the neutron source (prompt/delayed) is ready, the simulation starts. The simulation of the precursors is performed using a technique developed in [5] that tries to reduce the variance inserted by the fact that in a limited statistics context the number of delayed neutrons produced from precursor-decay is limited. More specifically, at the beginning of each time-step the decay process of the existing (i.e. banked) precursors is simulated. Within each time-step each precursor is forced to produce a delayed neutron without dying after the decay. This aims to artificially increase the delayed neutron generation rate for statistical reasons. It should be mentioned that so far only one group of precursors is used for developing purposes. At each time step the total neutron population (i.e. the ones coming from the previous step and the ones generated by the precursor decay at the beginning of the current time-step and within that) is simulated. The simulation is done in a

generation-by-generation context. As regards the treatment of fission, a fission event may generate prompt and/or delayed neutrons. When a delayed neutron is going to be produced, a precursor is firstly generated and saved in the proper bank and then its decay process is simulated. This results in a forced birth of a delayed neutron within the remaining time interval of the current time step. If a neutron crosses the time boundary of the current time-step it is stored in order to continue its simulation in the next step.

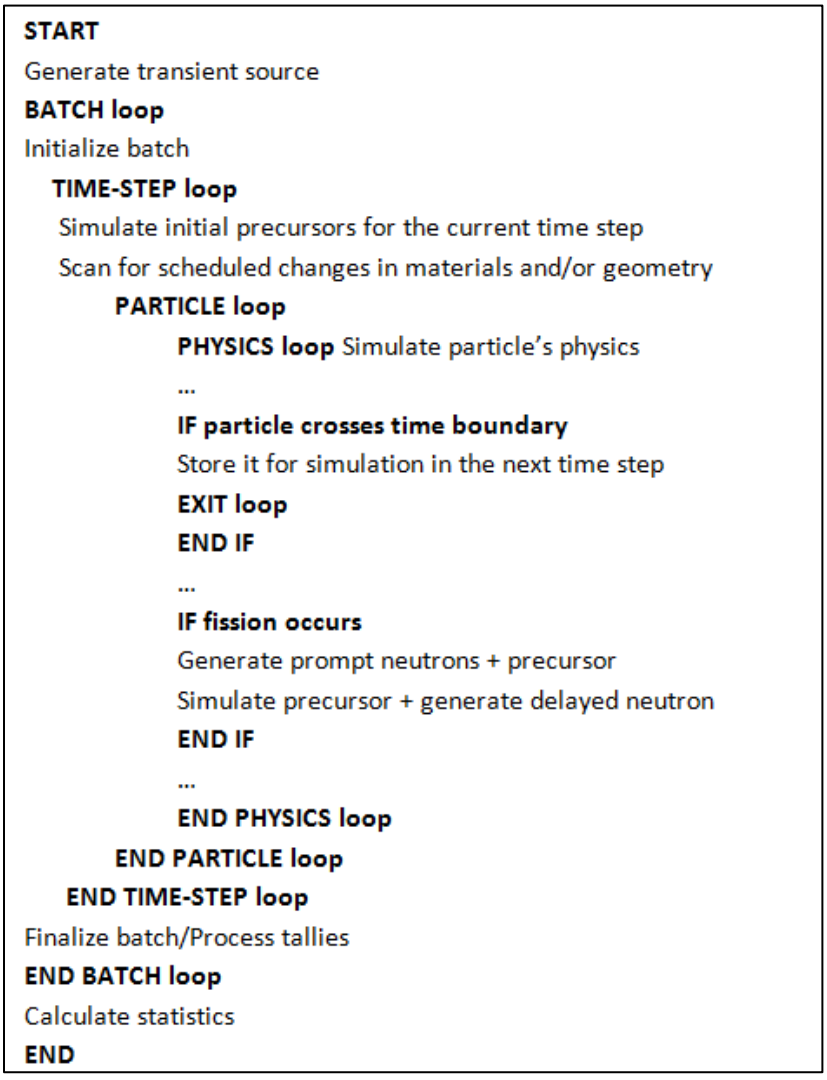

Fig.1: Simplified flowchart of the developed module

3. Numerical experiments - Results

In [3], an example with insertion of reactivity has been analyzed providing satisfying results. Here two small-scale problems of subcritical nature are analyzed in order to demonstrate the applicability of this tool in this kind of problems. More specifically, an originally subcritical problem and a critical one that is afterwards made subcritical with insertion of negative reactivity are analyzed. The results are compared with Point-kinetic ones.

3.1 First Test-Case

The first test-case consists of a simplified energy-dependent homogeneous parallelepiped which is composed of pure U-235. The density and dimensions are suitably selected in order to achieve a subcritical state. The dimensions are $10cm \times 20cm \times 24cm$ and the initial density has a value of $0.044809\ \frac{atoms}{barn-cm}$. This configuration, after performing a *k*-eigenvalue calculation with 1000 batches, 300 skipped and 1.5E6 neutrons per batch, gives $k_{eff} = 0.99745 \pm 0.00002$; the configuration is indeed subcritical. The evolution of the fission rate is monitored for a time interval of 30s. The time step is $\Delta t = 0.1s$ and the precursor decay constant is equal to $\lambda = 0.0748s^{-1}$.

Fig.2 illustrates the temporal evolution of the fission rate during the transient phenomenon associated with the Monte-Carlo statistical uncertainty. Fig. 3 shows a comparison of the Monte-Carlo calculated relative fission rate with the point-kinetic calculated one, where a very satisfying agreement between them is noticed.

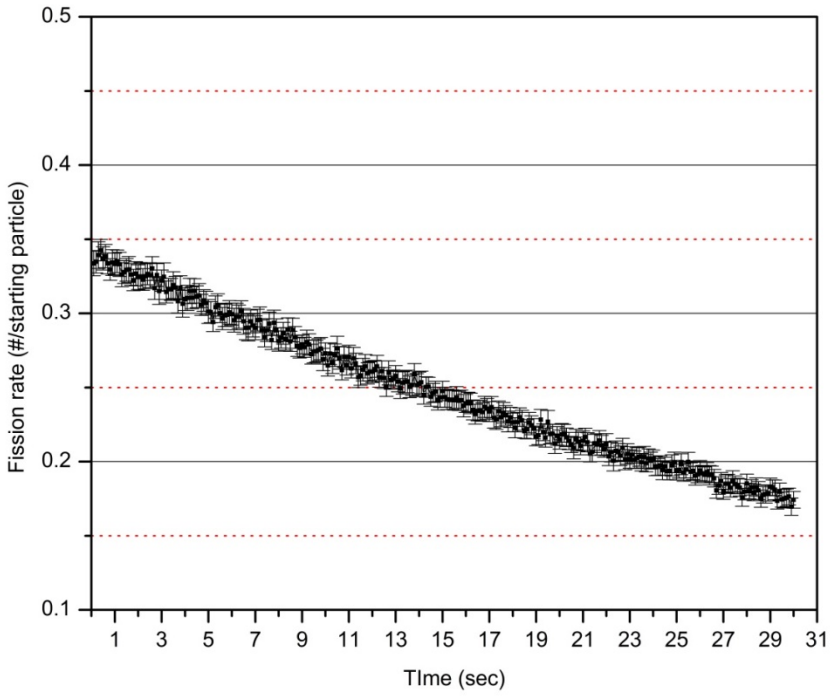

Fig.2: Temporal evolution of the total fission rate [$\frac{fission}{starting\ particle}$] with statistical error.

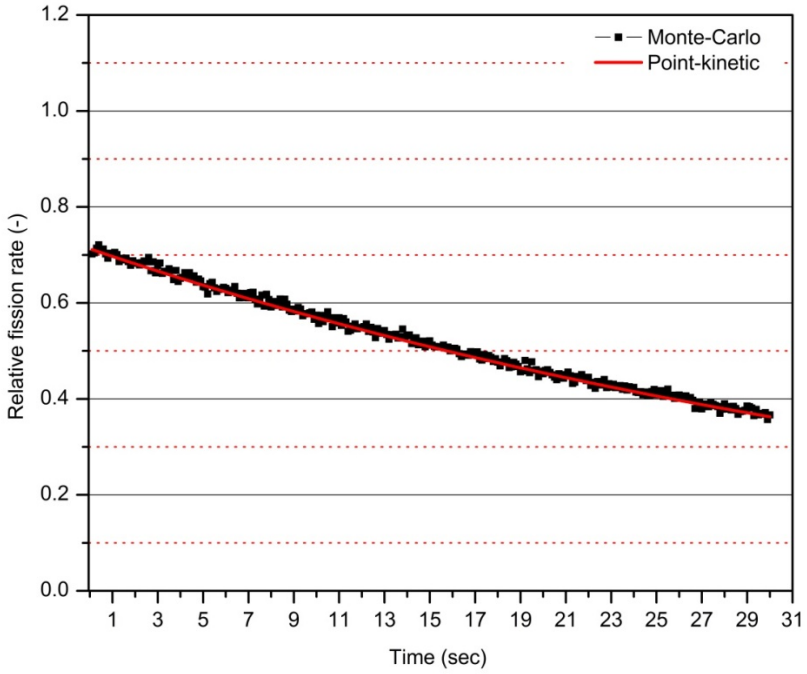

Fig. 3: Comparison between Monte-Carlo and Point-Kinetics

3.2 Second test-case

The second test-case concerns the same geometric configuration as in the previous one. The density and dimensions are suitably selected in order to achieve a critical state; the dimensions are $10cm \times 20cm \times 24cm$ and the initial density has a value of $0.0449495\ \frac{atoms}{barn-cm}$. This configuration, after performing a *k*-eigenvalue calculation with 1000 batches, 300 skipped and 1.5E6 neutrons per batch, gives $k_{eff} = 0.99998 \pm 0:00001$; the configuration is almost critical. During the first 2.9s of the analyzed phenomenon the model is in a steady-state. For t = 2.9s the density decreases to $0.04509\ \frac{atoms}{barn-cm}$ inducing a negative reactivity of $\sim 246pcm$. The configuration remains in this subcritical state until $t = 9.9s$. For $t = 9.9s$ the inserted negative reactivity is removed by re-adjusting the density of the material and the model returns in a critical state again. The time step and the precursor decay constant are equal to those of the first test-case.

Fig. 4 illustrates the temporal evolution of the fission rate during the transient phenomenon associated with the Monte-Carlo statistical uncertainty. Fig. 5 shows a comparison of the Monte-Carlo calculated relative fission rate with the point-kinetic calculated one, where a very satisfying agreement between them is noticed. Both the prompt-jump as well as the afterwards behavior is well-predicted. Fig. 6 shows some frames of the temporal evolution of the fission rate spatial distribution. The first two frames (Figs.6a and 6b) are taken from the time interval of the initial steady-state before the insertion of reactivity. The next two (Figs.6c and 6d) concern the subcritical state after the insertion of reactivity and the last one (Fig.6e) corresponds to the new critical state after the re-adjustment of density. As it can be seen, the second critical state ($t = 9.9 - 15s$) corresponds to a lower power level than the initial one, which is an expected

result. The simulation was performed on a computer cluster consisted of computational nodes, each one with 4 physical Intel Xeon cores (2 threads per core) clocked at 3.5GHz. Utilizing 48 threads (=24 physical cores) the total wall-clock time was ~3.57 h. It should be mentioned that the total wall-clock in this case is significantly lower than the one of supercritical problems. This is due to the fact that in subcritical cases the number of the simulated particles decreases continuously with time.

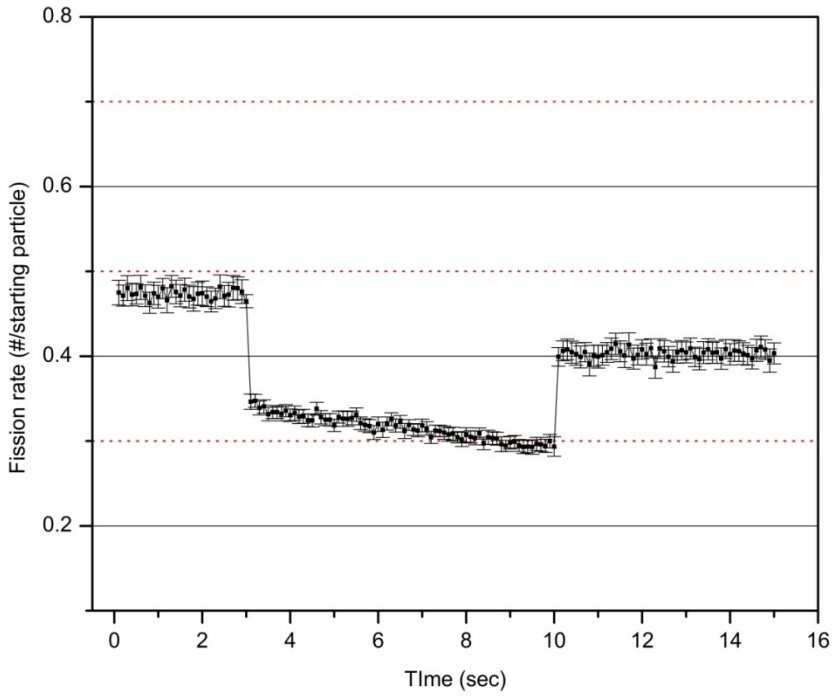

Fig.4: Temporal evolution of the total fission rate [$\frac{fission}{starting\ particle}$] with statistical error.

Conclusion and perspectives

In this work a pure Monte-Carlo tool for dynamic analysis that is under development in NCSR "Demokritos" is tested in two small-scale test-cases of subcritical nature. The results are encouraging showing very good agreement with Point-kinetics and proving the applicability of this tool to the analysis of subcritical transient problems. The computational time is significantly lower than in problems of supercritical nature as expected.

Main perspectives are the implementation of multi-group precursor treatment, the verification of this tool in problems of larger scale and finally the investigation of ways that could reduce the required computational time.

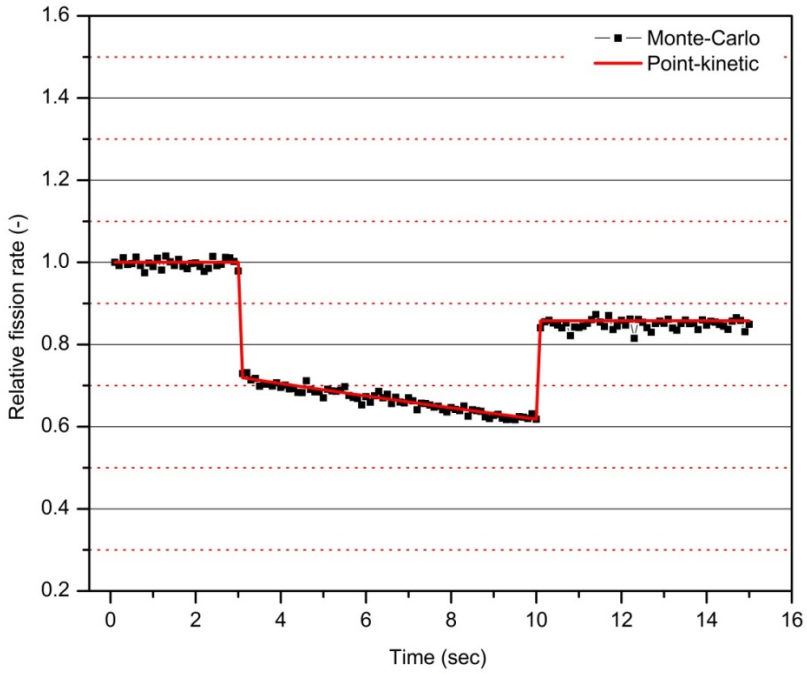

Fig. 5: Comparison between Monte-Carlo and Point-Kinetics

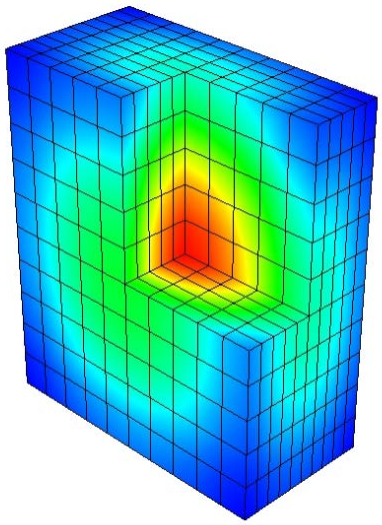

Fig.6a: $t = 0.1s$

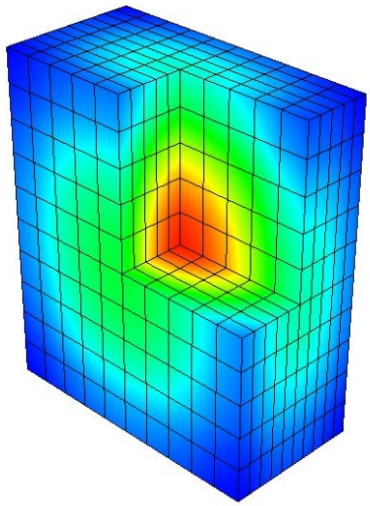

Fig.6b: $t = 2.9s$

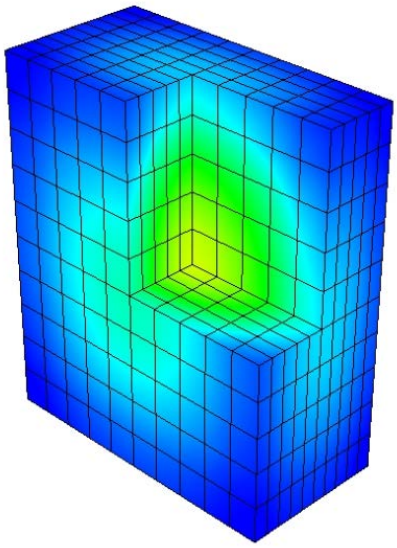

Fig.6c: $t = 3.0s$

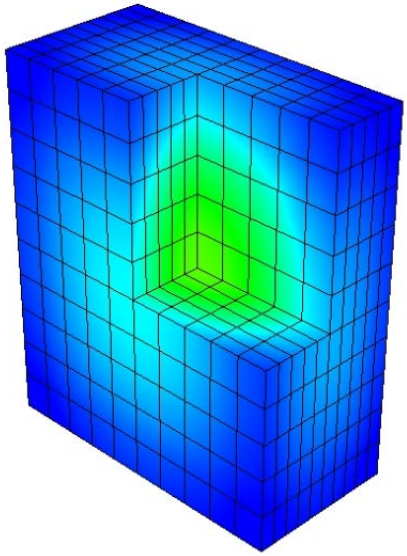

Fig.6d: $t = 9.9s$

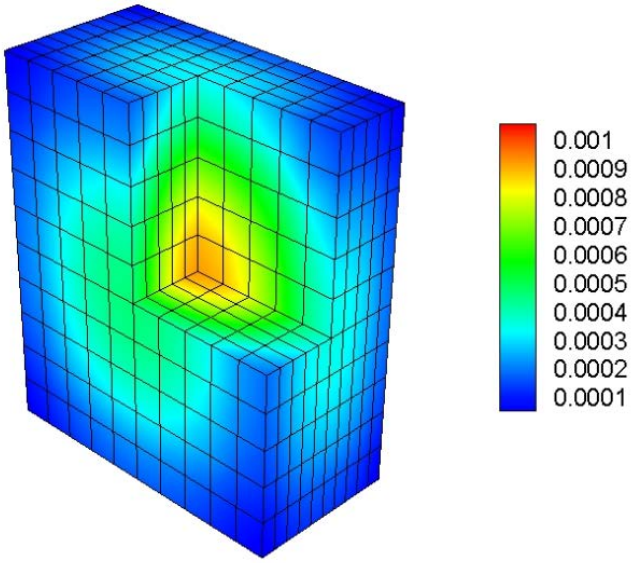

Fig.6e: $t = 15.0s$

Fig.6: Temporal evolution of the fission rate $[\frac{fission}{starting\ particle}]$ spatial distribution.

References

[1] I. Lux, L. Koblinger, Monte Carlo Particle Methods: Neutron and Photon Calculations, CRC Press, 1991.

[2] D.C. Kontogeorgakos, H.M. Connaway, D.D. Papadias, A.E.Wright, "Neutronics and Transient Calculations for the Conversion of the Transient Reactor Test Facility (TREAT)", Proceedings of the 36th International Meeting On Reduced Enrichment For Research And Test Reactors (RERTR 2015), The Plaza Hotel Seoul, South Korea, October 11-14, 2015.

[3] A.G. Mylonakis, M. Varvayanni, N. Catrsaros, "On-the-fly towards Pure Monte-Carlo Transient Reactor Core Analysis", Proceedings of the 25th International Conference Nuclear Energy for New Europe (NENE2015), Portoroz, Slovenia, September 5-8, 2016.

[4] B.L. Sjenitzer, "The Dynamic Monte Carlo Method for Transient Analysis of Nuclear Reactors, Ph.D thesis, Delft University of Technology, Delft, The Netherlands, 2013.

[5] B.L. Sjenitzer, J.E. Hoogenboom, A Monte-Carlo method for calculation of the dynamic behaviour of nuclear reactors, Prog. Nucl. Sci. Technol. 2, pp. 716721, 2011.

[6] P. K. Romano, B. Forget, The OpenMC Monte Carlo particle transport code, Nucl. Technol., 51, pp. 274-81, 2013.