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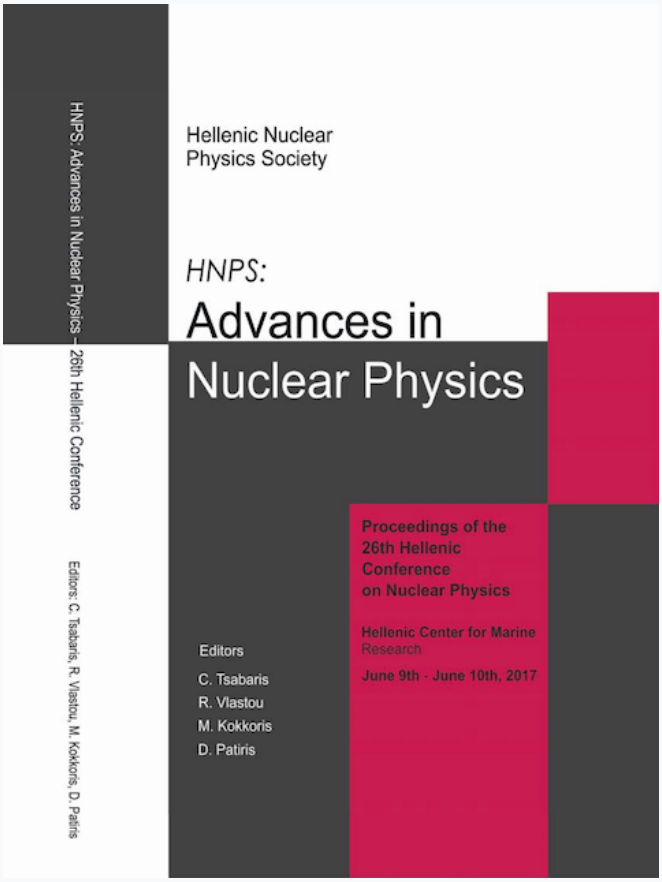

Developing a Monte-Carlo solver for the simulation of the reactor core dynamics

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Developing a Monte-Carlo Solver for the Simulation of the Reactor Core Dynamics

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Abstract Reactor core dynamics is usually analyzed by deterministic algorithms. However, deterministic algorithms utilize various approximations mainly in the treatment of geometry and energy of neutrons. These approximations are associated with induced inaccuracy. On the other hand the Monte-Carlo methodology, which generally does not require significant approximations, is currently very extensively used in the analysis of reactor statics but not in dynamics. Since nowadays the available computational resources are continuously increasing, the potential use of the Monte-Carlo methodology in the field of reactor dynamics seems quite attractive. This work presents the development of a Monte-Carlo dynamic solver and its testing to the analysis of two problems. The presented results are encouraging giving motivation for further investigation and development.

Keywords nuclear reactor, Monte-Carlo, neutronics, dynamics, solver, simulation

INTRODUCTION

The computational nuclear reactor analysis is moving continuously towards a detailed analysis of the reactor core system in a multi-physics context. In this framework, the Monte-Carlo method is extensively employed standalone and/or coupled with other tools since it can analyze the neutronic model of the nuclear reactor core thoroughly. At this point a scientific "gap" arises. While reactor dynamics is of great interest, the Monte-Carlo method that could analyze it without making use of significant approximations is not extensively employed in this domain. Usually, reactor dynamics is analyzed with deterministic methods which make use of various approximations and they are strongly problem-dependent. On the other hand Monte-Carlo is only involved in hybrid kinetics analysis. This has been achieved by coupling the Monte-Carlo method with Point-Kinetics (PK) schemes. The almost inexistence of pure Monte-Carlo dynamic tools reveals the presence of an "open" research field of great interest. Recently, a method that analyses in a pure Monte-Carlo way the physical phenomena that are involved in the transient behavior of a reactor core has been published in [1] and constitutes the starting point for this work. Of course, the primary constraint of performing large-scale Monte-Carlo simulations is the prohibitive computational cost. This argument is stronger when time-dependent problems are considered. However, literature results show that the Monte-Carlo simulation is moving towards finer and finer resolution within a more and more

realistic computational cost.

BRIEF DESCRIPTION OF THE DEVELOPED MODULE

The described module has been developed on the Monte-Carlo code OpenMC [2]. 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. Also it is written in modern Fortran making use of “type” structures and other advanced 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 presented in Fig. 1. The blue underline indicates some of the new capabilities added in the fixed-source algorithm of OpenMC to achieve dynamic analysis.

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 into 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 [3] 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 to continue its simulation in the next step.

RESULTS AND DISCUSSION

In this work the analysis of a control-rod induced transient in a 17x17 UO2 Fuel Assembly (FA) is presented. The FA model has reflective boundary conditions in the periphery. At the axial edges of the water reflectors, vacuum boundaries have been implemented. This FA model is captured from the whole-core Monte-Carlo benchmark presented in [4]. The main difference is that here, partially inserted control rods are located in the water-filled guide tubes. Also, the material compositions have been modified.

Initially the critical height of the inserted control rods is specified. Afterwards two different scenarios are analyzed. In both of them the configuration remains critical for the first 0.3 s. Subsequently two different transients occur.

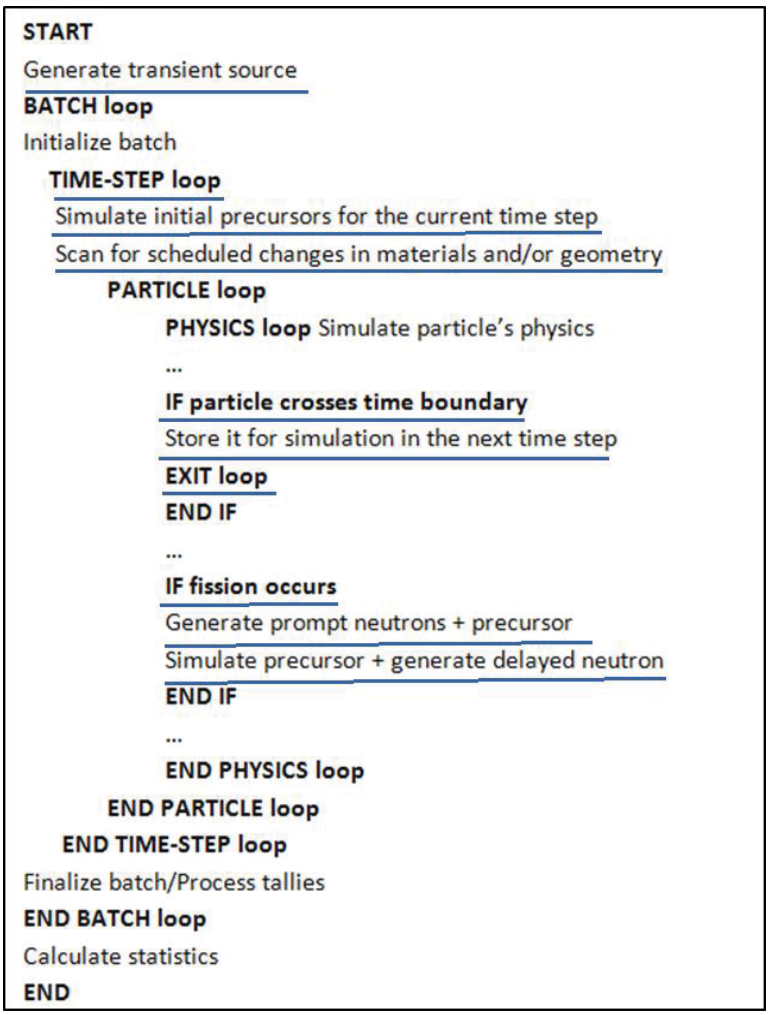
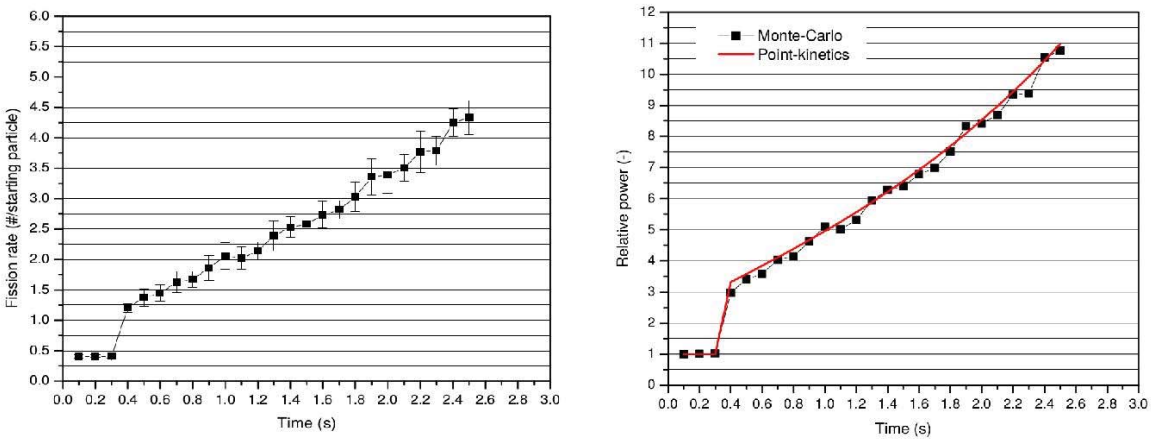


Fig. 1. A simplified-general overview of the developed module.

In the first case, at t = 0.3 s, the control rods are extracted in one step to a new level. The inserted reactivity at that level has been calculated ~477 pcm. The evolution of the power is monitored for a time interval of 2.5 s. This dynamic calculation has been performed using 60 batches and 106 initial neutrons per batch. The calculated temporal evolution of the total fission-rate (power) along with the standard deviation is illustrated in Fig. (3a). The

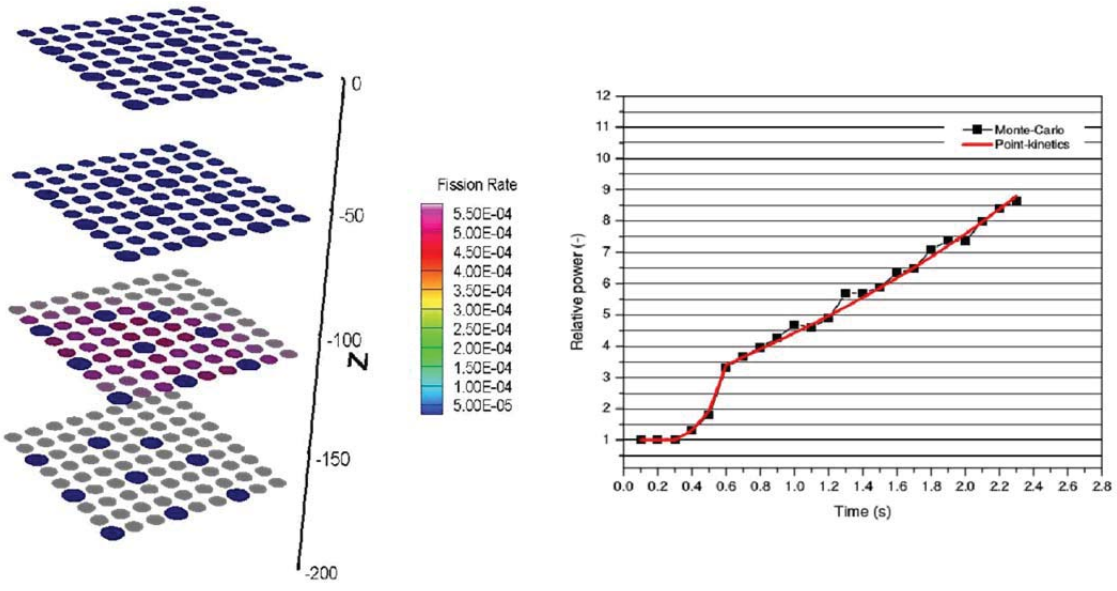
maximum statistical error is 3.45 %. Then the Monte-Carlo solution is compared with PK; Fig. (3b) shows a satisfactory agreement. Fig. (2a) shows the power distribution at t = 1.9 s and confirms the high-resolution analysis of reactor dynamics hat can be performed by Monte-Carlo.



(a) (b)

Fig. 2. Monte-Carlo solution vs PK for the first scenario.

In the second case the movement of the control rods is implemented progressively; between t=0.3 s - 0.5 s. The evolution of the power is monitored for a time-interval of 2.3 s. This dynamic calculation has been performed using 20 batches and 106 initial neutrons per batch. The maximum statistical error is 5.67 %. This significant increase of the statistical error compared with the first case is attributed to the smaller number of used batches, i.e. 20 instead of 60. A comparison with PK shows a satisfactory agreement (Fig. (3b)).



(a) (b)

Fig. 3. Fission-rate (power) distribution (a.u.) for t=1.9 s (1st scenario) (a). Monte-Carlo solution vs PK for the second scenario (b).

CONCLUSIONS

In this work a pure Monte-Carlo tool for dynamic analysis that is under development in NCSR “Demokritos” is tested in two FA transients induced by control-rod movement. The results are encouraging showing very good agreement with Point-Kinetics. Therefore the ability of this tool to analyze control-rod induced transients is proved.

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