Statistical Sampling Improvement in Tiny Regions of Critical Systems

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Abstract. A time saving methodology to tally tiny regions of a critical system is presented. It comprises of a 2 step procedure. The first step consists in charactering the system so as to create a source file while the second step utilizes this file to effectively tally the region of interest. Time saving strategies and related limitations are also discussed.

INTRODUCTION

MCNP[1] is a Monte Carlo radiation transport code which lays one of its main advantages on the possibility to geometrically describe very complex problems in a detailed way . It has been used by the staff of the department of reactor physics of CEN-IPEN/CNEN for some years as a supporting tool in the design of nuclear experiments as well as in the evaluation of their results.

However, as the study of critical systems consists in one of the main activities of this group, to better characterize the critical environment, the employment of MCNP demands more time than it does when it is dealing with a fixed source simulating configuration. MCNP becomes even an eager time consumer if the tally region is only a small amount of the simulated one. To overcome this time consuming hurdle, present at the calculation of some reaction rates in activation foils, a two step geometric sampling upgrade technique has been applied. It relies in a resource available in MCNP through the SSW and SSR cards. The first step consists in a short run of the entire system, thereby to well characterize the neutron population all over the system and principally recording this neutron population in the vicinity of the region of interest. The following step consists in running MCNP restricting the simulated region to coincide with the reduced one defined in the previous run. As the neutron population was characterized through the neutron recorded histories of the first run these histories are used to permit running this step in a geometric reduced fixed source simulating configuration, which runs faster even for a larger number of initial neutron histories than it does in the original way. Therefore, it is feasible to improve the precision of the calculated results through the continuous use of the fixed source with different pseudo-random sequences.

In this work the above methodology is implemented to evaluate an experiment performed in the IPEN/MB-01 research reactor aiming to determine reactor physics parameters, known as the spectral indices $^{28}\rho$ and $^{25}\delta$, respectively defined as the ratio of epicadimium to subcadmium radioative captures in ^{238}U and the ratio of epicadimium to subcadmium fission in ^{235}U. It is accomplished by determining the capture reaction rate induced in two Uranium foils placed in two distinct positions of the same dismountable fuel rod. In one of them the fuel rod is encircled by a Cadmium sleeve. These positions are chosen so to have the same neutron flux density in the absence of the Cadmium sleeve. Besides, each of these foils are placed between two Aluminum foils. More details about this experiment can be found in Bitelli et al. [2] and Santos et al. [3]

The adequacy of this methodology is discussed by comparing the calculated results obtained by both the present and the traditional method. It is shown a study of the play of of the reduce region size in the improvement of the simulation performance (such time and memory demands) as well as in the tallied results. A sensibility analysis of the calculated results on reduced universe size representation is presented. The role played by the number of particles history registered in recorded file is the also included in this study.

SIMULATIONS

Simulation starts by describing the entire universe of interest, i.e. The IPEN/MB-01 reactor core in its critical experimental configuration. Therefore, everything from the tiny activation foils up to the water tank which envelops the reactor core must be represented.

To simulate a critical system, MCNP provides a source information card known as KCODE which allows to represent a sustained chain reaction induced by fission neutrons. Successive neutron generations are represented by simulation cycles in which each neutron distribution source is characterized by the previous cycle, i.e. source distribution changes from cycle to cycle.

As the first generation source distribution is a user provided one, KCODE also allows the system to be stabilized before tally begins.

It also controls how long simulation shall last. The higher the precision aimed the larger the number of particles histories to be followed. As the tallied volumes (approximately 5.7 mm^3) are very small compared to the size of the represented universe (approximately 2.6 m^3) a demand for a great number of histories is even more critical. For that reason allied to the need of waiting the stabilization of the system turn simulations to last long.

A typical simulation is made up of some tens of thousands cycles with 25.000 particle histories per cycle, skipping the first hundreds of cicles. A 2.4 Ghz Pentium 4 CPU with 512 MB RAM executes around 2 thousands cycles a day.

To overcome this time consuming procedure MCNP allows to adopt a 2 step procedure through SSW and SSR cards. The first step generates a file which shall be used as a source in the second step.

The first step records all particle histories which have crossed any choosen set of surfaces or have been created in the specific volume. SSW card is included in a regular run (where a source is described by the KCODE card) specifying all the selected surfaces and volumes whose related histories must be recorded. The second step uses the recorded file as a source specification for the particles hereafter generated. SSR card is used instead of the KCODE card.

The simulation so approached turns the description of the system from a dynamical behavior, with particle histories of one cycle depending on the particle histories of the previous cycle (source description by KCODE card), to a static behavior, with all source information registered in a file (fixed source description). Therefore, there is no need to describe the whole system to tally a specific region since the particle population is already well characterized in recorded file. Modelling a reduced universe of interest, embracing the tallied volume, samples a larger number of particle histories in a shorter time because time is not spent following unimportant particle histories, i.e. Particles which do not play any role in the tally.

It is shown in this work how do the size of the modelled represented universe interferes with simulations performance and tallied results.

Reduced Universe

No matter how small the reduced universe is the source file is only created along a run of the whole universe representation. Figure 1a depicts the the water tank surrounding the reactor core. Figures 1b – d show in each of them, the reactor core and the volume selected to be the reduced universe in the sequence

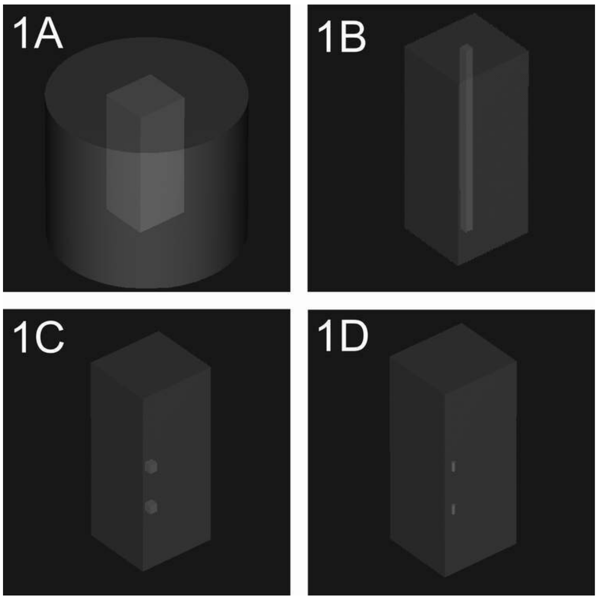

FIGURE 1. A. Schematic view of the entire universe depicting the water tank (cilinder) embracing the reactor core (parallelepiped). **B – D.** Schematic view of the reactor core (parallelepiped) depicting reduced universes of diminishing sizes in brighter shapes.

run. The reduced universe of figure 1b consists of the 9 innermost fuel rods and the water of the related pitches. The reduced universe of figure 1c is formed by two slices of the previous reduced universe. Each slice is 5 cm hight and their middle plane are made to coincide with the middle plane of the activation foils. The reduced universe of figure 1d is a reduction of the former. Each slice is restricted to a cilinder centered along the dismountable rod.

All reduced universes include the tallied regions (the activation foils). The source file records all particle histories which have either entered into the reduced universe or have been originated in it. The larger the size of the reduced universe the larger the source file created for a fixed number of original histories (number of cycles x number of histories per cycle). Table 1 shows the size of each source file created for 25.000 histories per cycle and the values obtained for $^{28}\rho$ and $^{25}\delta$.

TABLE 1. Source file characteristics and associated spectral indices.

Reduced Universe	Number of Cycles	Source File Size	$^{28}\rho$	$^{25}\delta$
9 rods – full lenght	2,000	716 MB	1.6 (11)	0.159 (13)
9 rods – 2 slices	10,000	895 MB	2.4 (12)	0.1370 (52)
1 rod – 2 slices	10,000	238 MB	2.7 (13)	0.1225 (43)

The values obtained for the spectral indices are well dispersed but still compatible due to their large uncertainties. The uncertainties related to $^{25}\delta$ stresses better the N^{-2} (N is the number of particle histories) behaviour of the statistical error than does $^{28}\rho$ As the uncertainties related to both spectral indices are proportional to the square of their values, the N^{-2} behaviour is not so clear for $^{28}\rho$ because their values are larger and sparcer than those from $^{25}\delta$.

As soon as the source files were created simulations of the reduced universe were run. Each run consisted of 2.1 billion particle histories. Although the number of histories were 42 times larger for 9 rods – full length representation its processing time consumes only one third of the time required to run 2,000 cycles (50,000 histories) in the full universe representation. The smaller the reduced universe, the faster its run. 2.1 billion particle histories in the 1 rod – 2 slices configuration takes shorter than half an hour.

Table 2 shows the time required to run 2.1 billion histories in each one of the reduced universes and the mean values obtained for the spectral indices among the 84 simulations.

TABLE 2. Spectral indices obtained from 3 different reduced universe representation.

Reduced Universe	Time spent	$^{28}\rho$	$^{25}\delta$
9 rods – full lenght	~ 8 hours	2,83 (6)	0,12863 (19)
9 rods – 2 slices	~ 2 hours	2.98 (6)	0.12962 (21)
1 rod – 2 slices	>0.5 hour	3.39 (7)	0.12890 (17)

The uncertainties of the spectral indices presented in this table are much smaller than the respective values in the table 1 due to the increase of statistical sampling. However the values obtained for 28ρ are no longer statistically compatible

Number of Cycles

Aiming to test the convergence of the tallied results, 2 other source files were created by extending the number of cycles from 10,000 to 19,800 and further to 39,800. The 1 rod – 2 slice reduced universe configuration was selected in order to create shorter source files. Eighty four runs of 2.1 billion histories were conducted in a procedure similar to the one described above in a way to get more precise results. Table 3 shows the spectral indices mean values obtained from 3 different source sizes.

TABLE 3. Spectral indices obtained from 3 different source sizes of the same reduced universe representation

Number of Cycles	Source File Size	$^{28}\rho$	$^{25}\delta$
10,000	238 MB	3.39 (7)	0.12890 (17)
19,800	496 MB	2.98 (6)	0.12921 (18)
39,800	949 MB	3.03 (7)	0.12947 (18)

As the mean values were obtained for the same number of histories their uncertainties are quite the same. The dependence on the average value responds for the tiny differences observed in the uncertainties.

Although the values obtained for the spectral indices by different source sizes (number of cycles) are all statistically compatible, it can not be stated that their values have converged.. Simulations using an even larger source file should be performed to certify this.

It must also be noted that the values obtained for the spectral indices by the use of the largest source file are compatible to the values presented in table 2 for the other 2 different source size specification.

Primary Source

The study was further extended to verify the dependence of the tallied results with the source file. Therefore four source files were created with 10,000 cycles for the same 1 rod – 2 slice reduced universe configuration. These sources differ in their primary source specification for the whole universe run. Except for the first source which had around 25,000 original source points (SRCTP file) they had 5 distinct source points (KSRC card). All of them started recording particle histories to create the related source files after 200 cycles were done. Table 4 shows the average values obtained for the spectral indices following the procedure described above. Mean values were however obtained for a set of 21 runs and therefore the uncertainties are larger.

TABLE 4. Spectral indices obtained from 4 different file sources of the same reduced universe representation with distinct primary source points.

$^{28}\rho$	$^{25}\delta$
3.54 (17)	0.12835 (31)
2.40 (10)	0.12642 (40)
2.80 (10)	0.12837 (35)
3.31 (16)	0.13112 (32)

The values of the spectral indices presented in table 4 are statistically incompatible, although their uncertainties do behave as expected.

Probably the same remarks done in the analysis of table 3 may respond for the differences in the mean values observed here, Therefore source files with extended number of cycles should be used to evaluate if it plays any role in the tallied final values. Source mischaracterization could also derive from recording particle histories from early cycles, where the system might not be well stabilized as thefirst cycles of a complete run have a multiplication factor larger than the last ones. However a further study must check the number of cycles that must be skipped before histories start to be recorded

CONCLUSIONS

The proposed methodology to increase statistical sampling in tiny regions of a critical system is a very promising one, mainly due to its high capability of time saving but some open questions regarding convergence criteria must still be answered.

Although a reasonable time has to be spent at the beginning of the simulation to create the source files and to certify that the related uncertainties do reflect the real one,They may become very important for further studies where the same source files can be used.

ACKNOWLEDGMENTS

The authors of this paper would like to thanks FAPESP for supporting this work

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