Monte Carlo Simulations of the SLOWPOKE-2 Reactor

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Summary

The goal of this project is to study the transient behaviour of the SLOWPOKE-2 reactor using Monte-Carlo simulations. By validating the Monte-Carlo methods in G4-STORK with experimental measurements we hope to extend our understanding of reactor transients as well as further develop our methods to model the transients of the next generation reactor designs. A SLOWPOKE-2 reactor such as the one at RMC is modelled using simulation tools from GEANT4 and data taken from open literature. Simulations in G4-STORK find a neutron flux of order 10^{12} n cm^{-2} s^{-1} and a control rod worth of (4.9 ± 2.0) mk compared to the experimentally measured worth of 5.45 mk.

1. Introduction

The study of reactor transients is of major importance to the nuclear community. Reactivity insertion/removal, loss-of-coolant accidents, delayed neutrons, and xenon buildup are examples of such transients which can lead to significant variations in reactor properties and the overall controllability.

G4-STORK (STOchastic Reactor Kinetics) is a toolkit developed in C++ for nuclear reactor physics applications. It is derived from the GEANT4 (GEometry ANd Tracking 4) toolkit developed at CERN laboratories. Originally developed for modelling detector-particle interactions GEANT4 has been applied in several projects in the field of medical physics. G4-STORK provides additional flexibility in that the user is required to input the simulation world, particles and their interactions. Features such as the ability to follow neutron populations in time, on-the-fly Doppler broadening, dynamic geometry changes and the implementation of user-derived models allow for an attractive platform for transient simulations.[2]

The SLOWPOKE-2 (Safe LOW POwer Kritical Experiment) reactor is a low-power, in-pool type, research reactor and features a light-water moderated low enriched uranium core which runs at a nominal power of 20 kW. The core measures 22.1 cm in diameter and 22.7 cm in depth.[1] The small size and high neutron flux on the order of 10^{12} n cm^{-2} s^{-1} means the SLOWPOKE is tightly coupled neutronically[1] and is a sensible candidate for computer simulation.

2. Methodology

2.1 Population Renormalization

In G4-STORK neutron populations are simulated in real time, thus for any non-critical reactor state the population size can exponentially increase or decrease. To keep the computational expense reasonable the population must be renormalized at regular intervals. These intervals which we call a “run” can be altered by the user to simulate a chosen number of neutrons over a chosen length of time. Before the start of each run the remaining neutrons from the previous run deemed "survivors" are randomly duplicated or deleted depending if the population has grown or shrunk. The renormalized neutron population serves as the primaries for the next run.[2]

To provide a measure of convergence from run to run, G4-STORK calculates the Shannon entropy of the fission sites and the surviving neutron positions. Shannon entropy is a concept taken from information theory which quantifies the amount of information gained for each event measured.

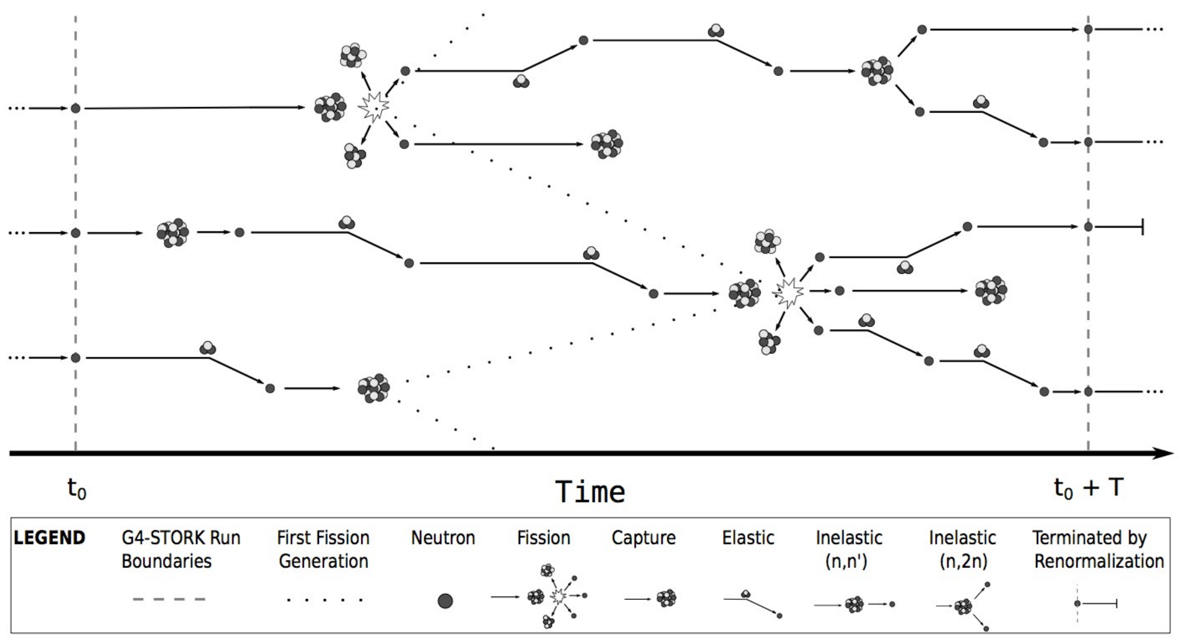

Figure 1 The renormalization process in G4-STORK.

2.2 The k-multiplication Factor

G4-STORK provides two measures of criticality. The first is called k-run and measures the change in neutron population over the run. It is defined as:

$$k_{\text{run}} = \frac{\text{Neutron population of current run}}{\text{Neutron population of previous run}} \quad (1)$$

The other measure of criticality is the effective multiplication factor k-eff which characterizes the instantaneous rate of change.

$$k_{\text{eff}} = \frac{\text{Rate of Production}}{\text{Rate of Loss}} \tag{2}$$

Both k factors are calculated at the end of each run.

2.3 Delayed Neutrons

For the proper treatment of delayed neutrons, G4-STORK tracks the size of six precursor groups. The removal and addition of precursors occurs between runs and is dictated by the following equations:

$$\frac{dC_i}{dt} = -\lambda_i C_i + \gamma_i R(x,t) \tag{3}$$

where C_i is our precursor population of group i, λ_i the decay constants, γ_i fission yield and R is the volumetric fission rate of U-235 in units of fissions/s/cm^3.

To generate an initial population we assume a steady-state condition, then we integrate over time and space. This means using the total number of fissions and the time duration of a previous simulation.

$$C_i = \frac{\gamma_i}{\lambda_i T} n_f \tag{4}$$

where T is the time duration and n_f the number of fissions. During a simulation the number of precursors added is simply the product of the number of fissions in the run with the fission yield:

$$C_i \mathrel{+}= \gamma_i n_f^{\text{run}} \tag{5}$$

Russian roulette is used to remove precursors:

$$T_{decay} = \frac{-\ln(r)}{\lambda} \tag{6}$$

where r is a random number in the interval [0,1]. The roulette is run for every precursor and if the decay time is less than the upcoming run duration a delayed neutron is added to the survivor list and a precursor is removed.

2.4 Neutron Flux

Since G4-STORK provides us with the positions and momenta of neutrons at the end of each run the simulated flux can be calculated as:

$$\phi_{R,E}^{sim} = \frac{\sum_i v_i}{\text{Volume of R}} \tag{7}$$

where v_i are the velocities of neutrons in energy range E and region R. To provide an actual neutron flux in the reactor we use a scaling factor which is simply the ratio of the actual reactor power and the simulated reactor power.

$$\text{Scaling factor} = \frac{P_{actual}}{P_{sim}} \tag{8}$$

where the actual power is user inputted and the simulated power is given as:

$$P_{sim} = \frac{n_f^{\text{run}} \times 198 \text{ [MeV]} \times (1.602 \times 10^{-13}) \text{ [J/MeV]}}{T \text{ [s]}} \tag{9}$$

The actual neutron flux can now be calculated as the product:

$$\phi_{R,E}^{actual} = \text{Scaling factor} \times \phi_{R,E}^{sim} \tag{10}$$

3. Results

To calculate the reactivity worth of the central control rod of the SLOWPOKE two simulations were run with the same input but different control rod placements. An initial point source was used, placed in the center of the reactor core using a Gaussian distribution of energies centred around 2.0 MeV. The simulations each underwent a single run of 2 ms with 20000 neutrons initially produced. The control rod was moved out by 20.66 cm and the effective multiplication factor was used to calculate reactivity.

$$\text{Control Rod Worth} = (4.9 \pm 2.0) \text{ mk}$$

The neutron fluxes are plotted in Figure 2 at 20kW of power and for the thermal neutron spectrum (0.00 - 0.04 eV) as well as the cadmium absorbing spectrum (0.00 - 0.40 eV).[4] It should be noted that the actual flux for the rod-in case is zero since the reactor is not at power.

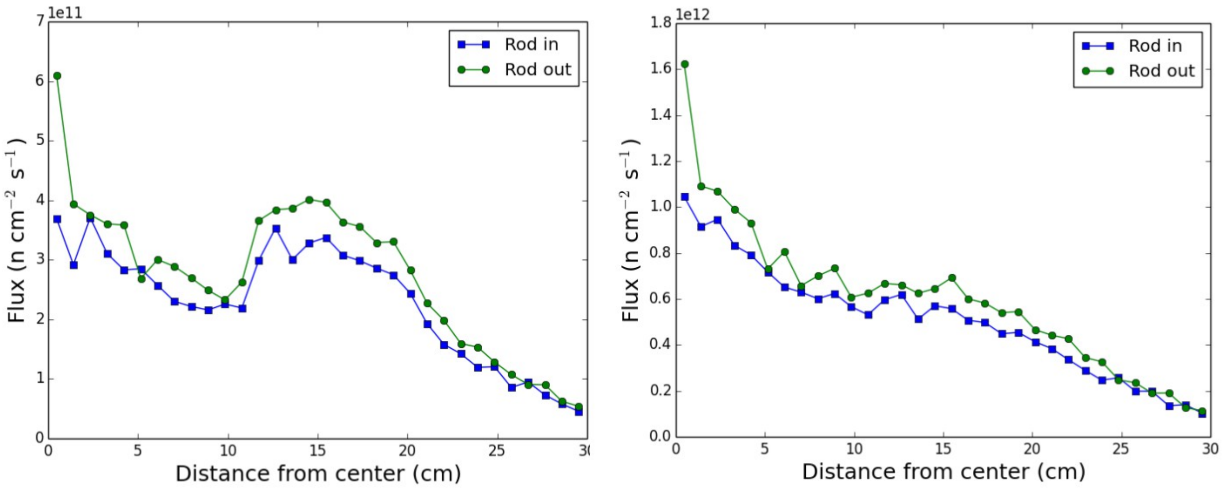

Figure 2 Neutron flux as a function of radial distance. Thermal energy region *(left)* and cadmium absorbing region *(right)*.

4. Discussion

The rod worth of the SLOWPOKE-2 at RMC was measured to be 5.45 mk. The same reactor geometry was modelled in MCNP-4A and it was found that the control rod was worth 7.85 mk from rod in to rod out.[3] Replicating this same reactor G4-STORK found a control rod worth of (4.9 ± 2.0) mk. This result shows that the methods employed in G4-STORK can model reactivity changes accurately. The discrepancy between the experiment and simulated worth can be attributed to several factors. The first is that there are differences between the simulated reactor geometry and the real reactor geometry, an example being the cadmium sheath lining in the control rod which may be $\pm$ 1 cm from the simulated location. Another example are the exact compositions of the material and the impurities that are present in the reactor. Finally there is of course the statistical uncertainty in that the control rod region may not be sufficiently sampled.[3]

The SLOWPOKE reactor has been measured to provide a relatively high neutron flux on the order of 10^{12} n cm^{-2} s^{-1}. From Figure 2, the calculated fluxes are on the same order of magnitude. As we expect the amplitude of the flux is reduced when the control rod is fully inserted with the flux shape remaining relatively intact. This means that our perturbation mainly affects the overall reactivity of the system and supports the use of the SLOWPOKE reactor as a favourable reactor for simulation.

The fuel rods of the SLOWPOKE extend out to a radius of roughly 10 cm and this is demonstrated in the flux of the thermal energy region as it increases at quickly after 10cm before dropping off in the outer regions of the reactor.

5. Conclusion and Future Work

G4-STORK is a stochastic reactor code currently being developed for transient simulations of next generation reactor designs. It is evident from the simulated control rod worth of (4.9 $\pm$ 2.0) mk compared to the experimental measured worth of 5.45 mk and the agreement of neutron flux magnitude on the order of 10^{12} n cm^{-2} s^{-1} that the Monte Carlo methods applied in G4-STORK provide an acceptable representation of the SLOWPOKE-2 reactor. Additional simulated experiments are set to be performed. Specifically during a rod movement in the SLOWPOKE a temperature feedback effect is experimentally observed.[3] Further work involves developing and testing methods to allow the code to simulate this transient response.

5. References

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[4] Carron, N.J. (2007). An Introduction to the Passage of Energetic Particles Through Matter. p. 308.