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A comparison of Monte Carlo methods for neutron leakage at assembly level

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ABSTRACT

The treatment of neutron leakage at assembly level is an essential step in the generation of few-group cross section data for reactor calculations. This work compares methods used for the characterization of assembly leakage in the framework of Monte Carlo cross section generation, using nearly-critical colorset configurations in order to obtain approximate reference values. The B_1 fundamental mode approximation and the albedo-search method are compared in terms of eigenvalue, multi-group homogeneous scalar fluxes and maximum pin power differences for several cell types. The performance of a novel heterogeneous leakage method is also tested. Whereas B_1 corrections provide the best agreement in homogeneous fluxes, the new method furnishes the best consistence in terms of pin powers, whilst providing rich spectral information and reducing computational overheads associated with colorset calculations. Future investigations are suggested in order to test the performance of these methods in the calculation of few-group, leakage-corrected assembly cross sections and discontinuity factors.

1. Introduction

The adoption of Monte Carlo (MC) codes is becoming increasingly widespread in the field of reactor physics and nuclear reactor core design. The treatment of arbitrary geometries and the use of continuous-energy Cross Section (XS) data, in addition to detailed interaction physics models and efficient parallelization allow the calculation of reference solutions at core level, albeit the computation times and memory requirements can be excessive for many applications.

Monte Carlo techniques applied to homogenized XS generation are also spreading to the study of miscellaneous systems (Ilas and Rahnema, 2003; Fridman and Leppänen, 2011; Rachamin et al., 2013; Shen, 2012; Park et al., 2012) . The assumption of zero net neutron leakage at assembly level is severe and could be strongly violated in realistic reactor conditions. As a result, the effect of this boundary condition on calculated few-group constants needs to be accounted for and corrected. To that end, different leakage models at assembly level exist.

The premise of leakage models is to either characterize the inter-assembly neutron leakage directly or to represent the environment of the assembly of interest, so that the resulting flux resembles the fundamental mode associated with a critical system. Among others, we would like to mention buckling-search methods, albedo-search methods, and colorsets.

Within buckling-search, Yamamoto (2012) introduced the concept of complex neutron weights, although the most broadly adopted method is based on the homogeneous B_1 fundamental mode approximation (Stamm'ler and Abbate, 1983). Originally derived for deterministic calculations of multiplicative assemblies under the assumption of space-energy separability, it has been implemented in Monte Carlo codes such as McCARD (Shim et al., 2012) and SERPENT (Leppänen, 2007). Martin and Hébert (2011) developed an MC-specific adaptation of the B_1 leakage model which relies on homogeneous estimates of some group constants in order to solve the B_1 equations. A heterogeneous form of the B_1 fundamental mode approximation (Hébert, 2009) does not easily lend itself to Monte Carlo calculations, given the need for space-dependent estimates of several quantities.

The albedo-based leakage method (Yun and Cho, 2010) has the advantage that leakage is treated in a heterogeneous configuration. Nevertheless, a single albedo value for all neutron energies and all assembly boundaries is used. This limitation can be overcome by means of a Global–Local iteration scheme as proposed by Cho et al. (2009), although their results exhibit slow convergence.

Colorsets are extensions to the single-assembly concept: identical neighbors are explicitly represented in a symmetric configuration (generally, square or rectangular in Cartesian geometry, or concentric rings in hexagonal geometry) and cross sections are

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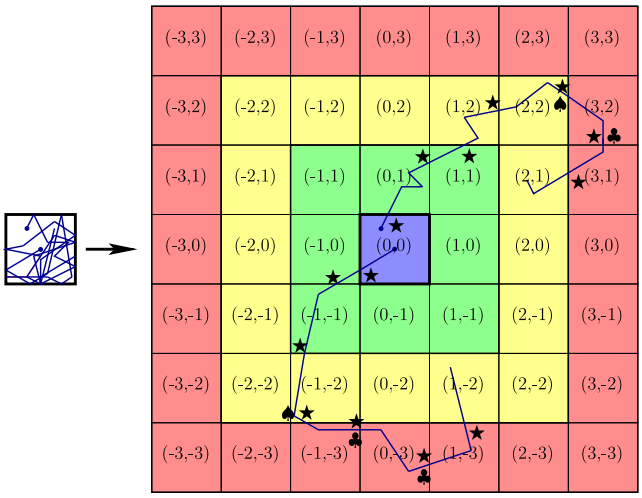
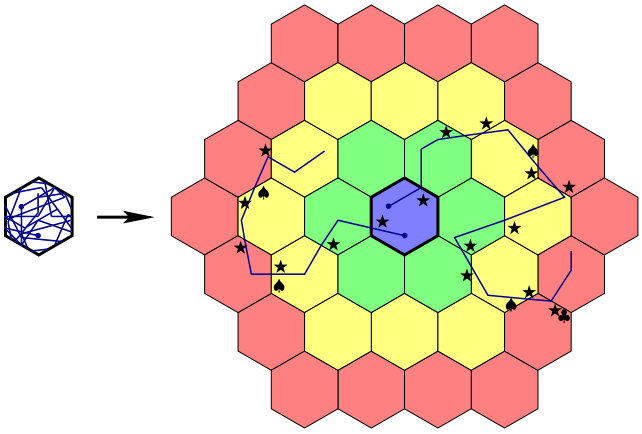


(a) Cartesian geometry with reflective boundary conditions



(b) Hexagonal geometry with periodic boundary conditions

Fig. 1. Single cell-based (left) and expanded (right) lattice systems used in trajectory unfolding. Every lattice element corresponds to a heterogeneous assembly.

generated in the central assembly only, thus using the others as a driver zone for an appropriate representation of the surrounding environment. Although nothing guarantees that the assembly under scrutiny will "see" that same environment in the actual reactor system, colorsets are versatile in the sense that leakage is treated heterogeneously, and that the surroundings can be associated with a *shape*.

Colorsets pose three main challenges:

(i) The number of elements needed to model a nearly-critical system is generally not known beforehand.
(ii) Memory requirements are increased.
(iii) The computational efficiency decreases considerably, because the multi-group constants generation process is restricted to the central element only.

In view of these observations, an assembly-level leakage model that can reproduce, although approximately, the environment seen by the central fuel assembly embedded in a nearly-critical colorset, without actually resorting to the calculation of the colorset itself, is highly desirable.

In this work, we compare some of the aforementioned leakage models against a critical reference obtained from colorsets. The

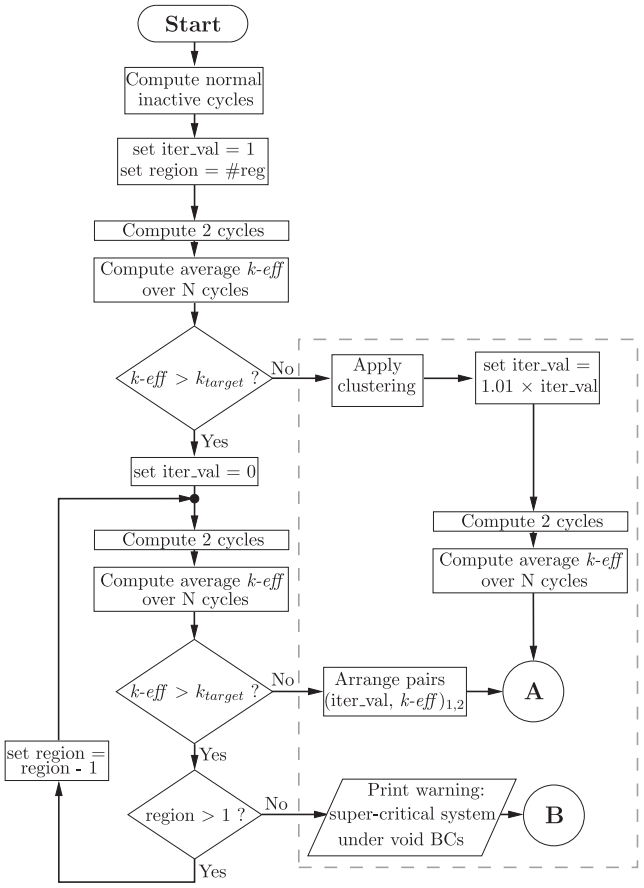


Fig. 2. Proposed algorithm for the determination of the iteration region index. The algorithm begins without clustering. When the algorithm reaches the dashed area, the value of the region is already known.

comparison will be conducted in terms of eigenvalue, maximum homogeneous assembly multi-group flux, and maximum pin power difference. The resulting XS data generated will not be further scrutinized.

Since not all leakage models are implemented in all Monte Carlo codes, our study will be focused on the methods available in the SERPENT 2 code only. In the interest of introducing a more tangible idea of periodicity, currently not present in the heterogeneous leakage methods available nowadays, a new leakage model proposed by the author will be described and tested.

The rest of the article is structured as follows: Section 2 describes the heterogeneous methods used in SERPENT 2 for criticality spectrum calculations, including the new proposal. The homogeneous B_1 fundamental mode flux approximation implemented in SERPENT is described in Fridman and Leppänen (2011). Different leakage models are tested and the results are discussed in Section 3. Lastly, Section 4 presents the main conclusions and future lines of work.

2. Materials and methods

2.1. Albedo iterations in Monte Carlo

The calculation of leakage-corrected critical spectra by Monte Carlo methods is presented in the work by Yun and Cho (2010). In their work, new updates of the albedo constant are based on the secant method using a pair of (`albedo`, *k-eff*) values. In SERPENT 2, however, an implicit estimator of the assembly leakage