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Analysis of dynamic reactivity by Monte Carlo methods: The impact of nuclear data

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ABSTRACT

We compute the dynamic reactivity of several reactor configurations by resorting to Monte Carlo simulation. The adjoint-weighted kinetics parameters are first determined by the Iterated Fission Probability (IFP) method, together with precursor decay constants, and the reactivity is then estimated by the inhour equation. When literature values are available for the reactivity as a function of the asymptotic reactor period, comparison with the Monte Carlo simulation findings allows validating the IFP algorithm and at the same time probing the accuracy of the nuclear data libraries used in numerical simulations. For our calculations we resort to the TRIPOLI-4® Monte Carlo code, developed at CEA, where IFP methods have been recently implemented. We perform a detailed analysis of the IPEN/MB-01 core, the SPERT III E-core, and the SPERT IV D-12/25 core, for which benchmark-quality reactor specifications have been published. We single out some systematic discrepancies between computed and measured core reactivity that might mirror possible inconsistencies in nuclear data libraries.

1. Introduction

The Iterated Fission Probability (IFP) algorithm has provided a major breakthrough in Monte Carlo methods as applied to criticality calculations, enabling adjoint-weighted physical observables to be estimated (Feghhi et al., 2007; Feghhi et al., 2008; Nauchi and Kameyama, 2010; Kiedrowski et al., 2011b). Exact calculation of adjoint-weighted quantities by the IFP method thus establishes Monte Carlo simulation as a reference tool for the analysis of effective kinetics parameters, which are key to nuclear reactor safety during transient operation and accidental excursions (Nauchi and Kameyama, 2010; Kiedrowski et al., 2011b; Shim et al., 2011; Nauchi and Kameyama, 2009). A number of Monte Carlo production codes have integrated or are planning to integrate IFP capabilities: a non-exhaustive list includes MCNP[1] (Kiedrowski, 2011a), SCALE (Perfetti, 2012), SERPENT (Leppänen et al., 2014), and TRIPOLI-4® (Truchet et al., 2015).

In a series of recent papers, we have reported the IFP algorithm as implemented in the TRIPOLI-4® Monte Carlo code (Brun et al., 2015; Truchet et al., 2015; Terranova and Zoia, 2017), and we have described the results of the validation tests performed against several reactor configurations, including the Rossi alpha suite and research reactors operated at CEA (Truchet et al., 2015), the SPERT III E-core (Zoia and Brun, 2016), and the CROCUS benchmark (Zoia et al., 2016). So far, the IFP method has been used in TRIPOLI-4® to compute the effective delayed neutron fraction β_{eff}, the effective neutron generation time Λ_{eff}, and the so-called Rossi alpha parameter $\alpha_{\text{Rossi}} = -\beta_{\text{eff}}/\Lambda_{\text{eff}}$ (corresponding to the neutron decay constant at delayed criticality).

In the development version of TRIPOLI-4®, based on release 4.10, we have added a new capability allowing the components $\beta_{\text{eff},i}$ of the delayed neutron fractions due to each precursor family i to be computed (Zoia et al., 2016). Such components are estimated by resorting to the existing IFP method, and by recording each event contributing to β_{eff} on the basis of its label i, i.e., the sampled precursor family. In the development version of TRIPOLI-4® the decay constants λ_i of the precursor families are also estimated. Contrary to the effective delayed neutron fraction $\beta_{\text{eff},i}$, the quantities λ_i

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[1] The IFP method has been implemented in the official release of MCNP in 2010. However, on August 20th, 2014, Dr. Kiedrowski of LANL has reported a bug concerning the IFP algorithm in MCNP5-1.60, MCNP6.1, and MCNP6.1.1 (see https://mcnp.lanl.gov/BUGS/BUGS.shtml). Prior to them, Dr. Nauchi has independently implemented his own version of the IFP method for the enhanced MCNP5 version developed at CRIEPI in 2009 (Nauchi and Kameyama, 2009).

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according to their definitions in standard point reactor kinetics need not to be adjoint-weighted (Keepin, 1965), and are thus computed at each fission event by simply recording the decay constant value pertaining to the sampled delayed neutron event.

A fairly large number of experimental data based on reactor noise techniques exist for β_{eff} and α_{Rossi}, [2] which allows extensively validating the IFP method. Very limited knowledge is instead available for the partial $\beta_{\text{eff,i}}$ and λ_i per precursor family, so that the validation of the Monte Carlo methods for these quantities is more problematic (see, e.g., WPEC6, 2002). For instance, in Zoia et al. (2016) we have resorted to code-code comparison between the development version of TRIPOLI-4® and the enhanced version of MCNP5 developed by Dr. Y. Nauchi at CRIEPI, based on MCNP5.1.30.

Intensive research efforts are being made so as to produce benchmark-quality experimental results for the kinetics parameters of light water reactors, such as in the case of the IPEN/MB-01 reactor (dos Santos and Diniz, 2014), including partial kinetics parameters and their associated uncertainties. Progress is however hindered by the complexity of the experimental techniques for singling out the family contributions (dos Santos and Diniz, 2014).

In parallel to comparison with direct experimental measurements of $\beta_{\text{eff,i}}$ and λ_i (typically by reactor noise techniques), the validation of Monte Carlo calculations of the partial kinetics parameters by the IFP method can be carried out by resorting to the indirect approach proposed for instance for the CROCUS (OECD/NEA, 2007; Paratte et al., 2006) or IPEN/MB-01 (dos Santos and Diniz, 2014) benchmarks. The partial kinetics parameters $\beta_{\text{eff,i}}$ and λ_i can be used in combination with β_{eff} and Λ_{eff} so as to estimate the so-called dynamic reactivity ρ_d of the core by the inhour equation (Keepin, 1965) (for a precise definition, see Eq. (1) in the next section). Then, the dynamic reactivity thus computed can be contrasted to the core reactivity $\rho_r(T)$ as a function of the asymptotic reactor period T, when available from rod-drop or reactivity insertion experiments, or to the so-called direct reactivity ρ_k, which is obtained by calculation as the difference of the fundamental k_{eff} eigenvalues between a critical and a perturbed configuration.

In the CROCUS benchmark, for instance, it is proposed to compute the dynamic reactivity ρ_d of several core configurations and to compare it to the direct reactivity ρ_k (OECD/NEA, 2007; Paratte et al., 2006). When the results of the CROCUS benchmark were originally published in 2006, relatively large discrepancies were reported for some of the participants, and possible lack of accuracy in the simulation methods and/or in the nuclear data chosen by some of the participants was pointed out as a possible reason (OECD/NEA, 2007; Paratte et al., 2006). The CROCUS benchmark has been later considered by several authors with different Monte Carlo codes, methods and libraries (Vollaire et al., 2006; Leppänen, 2008; Meulekamp and van der Marck, 2006; Nauchi and Kameyama, 2008). In Zoia et al. (2016), we have systematically revisited the CROCUS benchmark by resorting to the exact IFP method, and we have thus been able to single out the impact of nuclear data libraries on the discrepancies between direct and dynamic reactivity. In other words, based on the observation that the IFP method is largely successful in reproducing experimental observations for β_{eff}, the decomposition of the delayed neutron fraction into the precursor family contributions does not hide any algorithmic or conceptual difficulty. The disagreement between dynamic and direct reactivity should then be attributed to the quality of the delayed neutron parameters in the nuclear data libraries (in terms of total multiplicity, energy spectra, decay constants λ_i, relative abundances a_i of each precursor family, and the ratio of the number of fission neutrons between different fissile isotopes). The two related integral quantities are β_{eff}, i.e., the amount of delayed neutron emission, and $\tau = \sum_i a_i/\lambda_i$, i.e., the average lifetime of delayed neutron emission. Analogous observations are reported for instance for the IPEN/MB-01 benchmark (dos Santos and Diniz, 2014).

In this paper, we extend the analysis that we have previously carried out for the CROCUS benchmark by considering a few benchmark-quality reactor configurations where values of reactivity $\rho_r(T)$ have been accurately determined, namely the IPEN/MB-01 facility (dos Santos and Diniz, 2014), the SPERT III E-core (Heffner and Wilson, 1961), and the SPERT IV D-12/25 core (Crocker and Stephan, 1964). In doing so, we pursue two intimately related goals: on one hand, we resort to available inhour curves in order to validate the new TRIPOLI-4® routines enabling the calculation of partial kinetics parameters by the IFP method; on the other hand, investigation of the discrepancies between reported and computed reactivity allows assessing the impact of nuclear data on these calculations, and possibly pointing out inconsistencies in the values of the decay constants and/or of the average delayed neutron number. Errors in the partial kinetics parameters actually mirror underlying incoherences in the values of delayed neutron family fractions as reported in the nuclear data libraries, which might then hinder the accurate simulation of non-stationary reactor cores (Nauchi, 2014; Sjenitzer and Hoogenboom, 2013; Zoia et al., 2014; Zoia et al., 2015).

This work is organized as follows. In Section 2, we detail the methodology that we will adopt for our investigation, and briefly describe the nuclear data libraries that will be tested. In the same section we will also describe the TRIPOLI-4® Monte Carlo code and provide the simulation details. In Section 3 we will analyze the case of the IPEN/MB-01 core. In Sections 4 and 5 we will then consider the SPERT III E-core and the SPERT IV D-12/25 core, respectively. Finally, conclusions will be drawn in Section 6.

2. Methodology

Our analysis will be based on the following procedure. We will select some reactor configurations where the core reactivity has been determined as a function of the asymptotic reactor period T, so that the inhour curve $\rho_r = \rho_r(T)$ is available. By resorting to TRIPOLI-4®, we will perform criticality calculations on the Monte Carlo models corresponding to these configurations, and compute the adjoint-weighted kinetics parameters $\beta_{\text{eff,i}}$, $\beta_{\text{eff}} = \sum_i \beta_{\text{eff,i}}$ and Λ_{eff} by the IFP method, and the precursor decay constants λ_i. Then, based on these quantities, we will estimate the so-called dynamic reactivity ρ_d (expressed in dollars \$) via the inhour equation as

$$\rho_d[\$] = \frac{\Lambda^\dagger}{T} + \sum_i \frac{a_i}{\lambda_i T + 1}, \tag{1}$$

where $\Lambda^\dagger = \Lambda_{\text{eff}}/\beta_{\text{eff}}$ is the reduced generation time (carrying units of time), $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ are the relative fractions of the delayed neutron families, and the sum is extended over all families. It will be assumed that the kinetics parameters are only weakly dependent on reactivity, so that the values of a_i, $\Lambda^\dagger$ and λ_i needed in Eq. (1) can be computed once, for the configuration corresponding to the critical core.

The dynamic reactivity ρ_d can be evaluated for each T, and thus contrasted to the available reactivity ρ_r. Systematic differences between the literature and the computed values can be therefore used to probe the impact of the nuclear data libraries on the calculation of the kinetics parameters. In particular, we will separately determine the distinct contributions of the reduced generation

[2] Sometimes, independent measurements are provided also for Λ_{eff}. Most often, however, the effective mean generation time is estimated by taking the ratio between the experimental values of β_{eff} and α_{Rossi}. See, for instance, the discussion in Truchet et al. (2015).