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

A. Zoia, C. Jouanne, P. Sireta, P. Leconte, G. Braoudakis, L. Wong

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

Andrea Zoia[a,*], Cédric Jouanne[a], Patricia Siréta[b], Pierre Leconte[c], George Braoudakis[d], Lindee Wong[d]

[a] *Den-Service d'études des réacteurs et de mathématiques appliquées (SERMA), CEA, Université Paris-Saclay, F-91191, Gif-sur-Yvette, France*
[b] *CEA/Cadarache, DEN/CAD/DER/SRJH/CCAP, F-13108, Saint Paul Lez Durance, France*
[c] *CEA/Cadarache, DEN/CAD/DER/SPRC/LEPh, F-13108, Saint Paul Lez Durance, France*
[d] *Nuclear Section Analysis, Australian Nuclear Science and Technology Organization (ANSTO), Australia*

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 in-hour equation. When reference experimental 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.

Keywords: Reactivity, Nuclear data, IFP, IPEN, SPERT, TRIPOLI-4®, MCNP6

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 (Feghni et al., 2007, 2008; Nauchi and Kameyama, 2010; Kiedrowski, 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, 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 (Leppanen, 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), 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 $\alpha_{\text{Rossi}} = -\beta_{\text{eff}}/\Lambda_{\text{eff}}$.

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 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

*Corresponding author. Tel. +33 (0)1 6908 9544
Email address: andrea.zoia@cea.fr (Andrea Zoia)

[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).

[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)

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 infer the so-called dynamic reactivity ρ_d of the core by the in-hour equation (Keepin, 1965). Then, the dynamic reactivity thus estimated can be contrasted to measurements of the core reactivity $\rho_e(T)$ 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; Leppanen, 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 and relative abundances a_i of each precursor family). 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 the reactivity $\rho_e(T)$ has 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 the experimental in-hour curve 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 measured and computed reactivity allow 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 distributions of delayed neutron families as reported in the nuclear data libraries, which might then hinder the accurate simulation of non-stationary reactor cores.

This work is organized as follows. In Sec. 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 Sec. 3 we will analyze the case of the IPEN/MB-01 core. In Secs. 4 and 5 we will then consider the SPERT III E-core and the SPERT IV D-12/25 core, respectively. Conclusions will be finally drawn in Sec. 6.

2. Methodology

Our analysis will be based on the following procedure. We will select some reactor configurations where the reactivity ρ_e has been determined as a function of the asymptotic reactor period T, so that an in-hour curve $\rho_e = \rho_e(T)$ 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 fission-weighted decay constants λ_i. Then, based on these quantities, we will estimate the so-called dynamic reactivity ρ_d (expressed in dollars \$) via the in-hour equation as

$$\rho_d[\$] = \frac{\Lambda^*_{\text{eff}}}{T} + \sum_i \frac{a_i}{\lambda_i T + 1}, \tag{1}$$

where $\Lambda^*_{\text{eff}} = \Lambda_{\text{eff}}/\beta_{\text{eff}}$ 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.

The dynamic reactivity ρ_d can be evaluated for each T, and thus contrasted to the experimental reactivity ρ_e. Systematic differences between the experimental measurements 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 time Λ^*_{eff}, of the relative fractions a_i, and of the decay constants λ_i to the observed discrepancies.

We will first address the case of the IPEN/MB-01 core, for which an analogous analysis has been recently carried out based on the `MCNP` Monte Carlo code (dos Santos and Diniz, 2014). Comparison with published results will allow establishing the proposed procedure on firm grounds. Then, we will present the case of the SPERT III E-core and the SPERT IV D-12/25 core, where measured and computed in-hour curves have never been compared before, to the authors' best knowledge.

Several nuclear data libraries will be considered to this aim: `JEFF3.1.1` (Santamarina et al., 2009), `ENDF/B-VII.r0` (Chadwick et al., 2006), and `JENDL-4.0` (Shibata et al., 2011). We remind that, following the OECD/NEA working group WPEC6 (WPEC6, 2002), a eight-group structure was adopted for the time dependence of delayed neutron in `JEFF3.1.1`, with fixed decay constants λ_i for any fissioning isotope. The other two libraries have kept the historical six-group structure, mostly due to neutron transport code limitations in reading the eight-group format.

2.1. Monte Carlo simulations

All Monte Carlo simulations described in the following have been carried out by resorting to Tripoli-4®, the general-purpose Monte Carlo radiation transport code developed at CEA and devoted to shielding, reactor physics with depletion, criticality safety and nuclear instrumentation (Brun et al., 2015). Tripoli-4® is the reference Monte Carlo code for CEA (including laboratories and reactor facilities) and the French utility company EDF. It is also the reference code of the CRISTAL Criticality Safety package (Gomit et al., 2011) developed with IRSN, EDF and AREVA. The code offers both fixed-source and criticality simulation modes. Neutrons are simulated in the energy range from 20 MeV to 10^{-5} eV. Particle transport is performed in continuous-energy, and the necessary nuclear data (i.e., point-wise cross-sections, scattering kernels, secondary energy-angle distributions, secondary particle yields, fission spectra, and so on) are read by the code from any evaluation written in ENDF-6 format (McLane, 2004). The code can directly access files in ENDF and PENDF format. For the unresolved resonance range, probability tables (when present and requested) are generated for Tripoli-4® by using the CALENDF code (Sublet et al., 2011).

Concerning kinetics parameters calculations, the method based on the expected number of fission neutrons in the next generation was already available in Tripoli-4®, as discussed, for instance, in (Lee and Hugot, 2011; Hugot and Lee, 2011). Starting from version `4.10`, un-weighted kinetics parameters and IFP-based adjoint-weighted delayed neutron fraction and mean generation time are now available (Truchet et al., 2015). For IFP, a superposed-cycles implementation has been chosen, with an arbitrary number of latent generations M; here we have taken $M = 20$ latent generations, based on previous experiences on similar cores. In the development version of the code

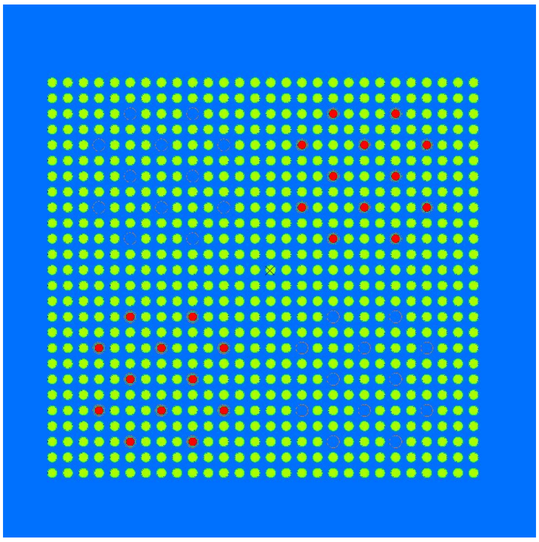

Figure 1: (Color online) Radial view of the Tripoli-4® model of the IPEN/MB-01 core.

that was used for the simulations reported in the following sections, further capabilities allowing for partial delayed neutron fractions and precursor decay constants (per family) have been added.

Nuclear data libraries have been processed at CEA at the closest temperature compatible with the benchmark specifications. Thermal data for bound hydrogen in water have been included. Doppler broadening of elastic scattering differential cross sections has been enforced by using the standard SVT model. The DBRC model for resonant nuclides, although available (Zoia et al., 2012), has not been used, since it is not expected to have any significant impact on kinetics parameters at room temperature.

3. The IPEN/MB-01 reactor facility at Sao Paulo

The IPEN/MB-01 reactor is a zero power critical facility specially designed for measurement of a wide variety of reactor physics parameters. It has been thus adopted to produce benchmark-quality experimental data for checking the computational methodologies used to design a nuclear reactor and the related nuclear data libraries. The facility consists of a 28×26 rectangular array of UO_2 fuel rods 4.3% enriched and clad by stainless steel (SS-304) inside a light water tank (see Fig. 1). The control banks are composed by 12 Ag-In-Cd rods and the safety banks by 12 B_4C rods. The pitch of the IPEN/MB-01 reactor was chosen to be close to the optimum moderator ratio. The specifications for the IPEN/MB-01 configuration used for kinetics parameters measurements are provided in (dos Santos et al., 2013) and references therein.

For the Tripoli-4® criticality simulations, we have run 10^2 inactive cycles and $4{\times}10^3$ active cycles, with 10^5 neutrons per cycle. The attained convergence on k_{eff} is less than 6 pcm for all tested libraries.

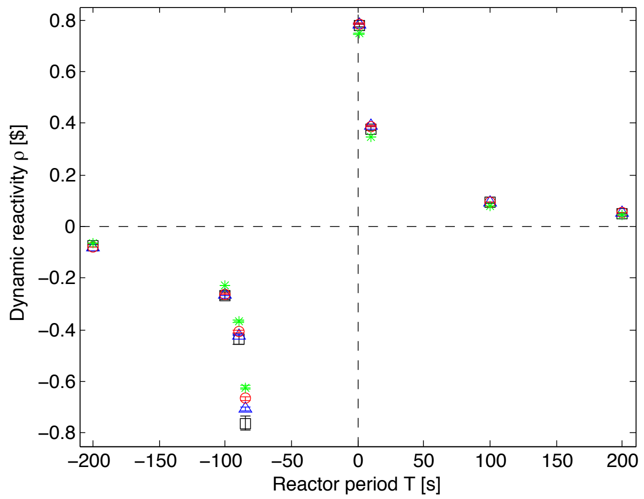

Figure 2: (Color online) Comparison between reference and computed dynamic reactivity of the IPEN/MB-01 core. Black squares represent reference data from (dos Santos et al., 2013; dos Santos and Diniz, 2014). The other symbols correspond to TRIPOLI-4® calculations with different nuclear data libraries: blue triangles for `JEFF3.1.1`; green stars for `ENDF/B-VII.r0`; and red circles for `JENDL-4.0`.

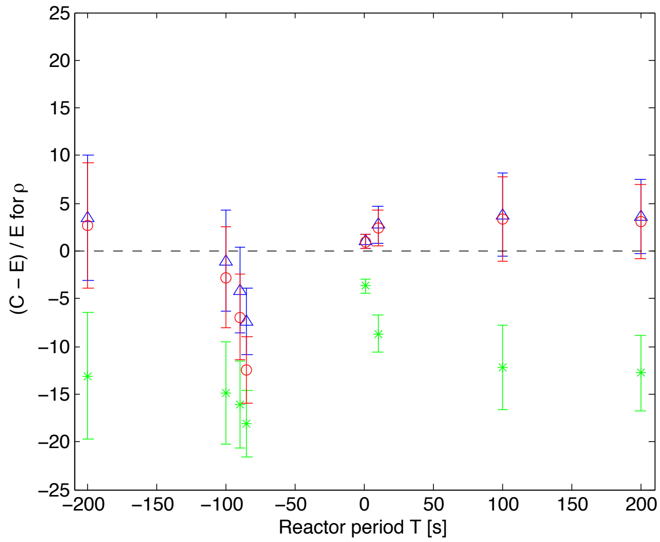

Figure 3: (Color online) Relative errors $(C - E)/E$ between reference and computed dynamic reactivity of the IPEN/MB-01 core. Reference data (E) are taken from (dos Santos et al., 2013; dos Santos and Diniz, 2014). Symbols correspond to TRIPOLI-4® calculations (C) with different nuclear data libraries: blue triangles for `JEFF3.1.1`; green stars for `ENDF/B-VII.r0`; and red circles for `JENDL-4.0`. Errors $(C - E)/E$ are expressed in percent.

3.1. The kinetics parameters β_{eff}, Λ_{eff}, and α_{Rossi}

The effective delayed neutron fraction β_{eff} and the effective generation time Λ_{eff} of the IPEN/MB-01 reactor have been carefully determined and transformed into benchmark-quality values with associated experimental uncertainties (dos Santos et al., 2013) in a series of so-called microscopic noise experiments (dos Santos and Diniz, 2014). The TRIPOLI-4® calculation results for the effective delayed neutron fraction and for the effective mean generation time are shown in Tab. 2. The `MCNP` estimates reported in (dos Santos and Diniz, 2014) are also provided in the same Table. The Rossi alpha parameter $\alpha_{\text{Rossi}} = -\beta_{\text{eff}}/\Lambda_{\text{eff}}$ has been separately measured in the microscopic noise experiments (dos Santos and Diniz, 2014), and it has been compared to TRIPOLI-4® simulation results in Tab. 2. The `MCNP` estimates reported in (dos Santos and Diniz, 2014) are also provided in the same Table. The global agreement between the simulation results computed by TRIPOLI-4® and the reference benchmark values is good. Code-code comparison with `MCNP` is also satisfactory for all tested libraries. Computed values for β_{eff} appear to be in better agreement with the benchmark value for `ENDF/B-VII.r0` and `JENDL-4.0` than for `JEFF3.1.1`. This is due to the lower value for the total delayed neutron yield of ^{235}U, which is 1.585% in the `ENDF/B-VII.r0` and `JENDL-4.0` libraries, compared with 1.62% in `JEFF3.1.1`. The mean neutron generation time Λ_{eff} does not appear to be significantly affected by the choice of the nuclear data library, as its value is mostly related to neutron transport issues (see, e.g., the discussion in (Zoia et al., 2016)).

3.2. Partial kinetics parameters

In a series of so-called macroscopic noise experiments, measurements for the partial kinetics parameters per precursor family have been determined for the IPEN/MB-01 reactor, together with the associated uncertainties (dos Santos and Diniz, 2014). The approach consists in a least-squares fitting procedure where the decay constants are initially kept fixed at the value suggested in the `ENDF/B-VI.r8` nuclear data library, and the relative abundances $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ are fitted. Then the decay constants are fitted with the relative abundances kept fixed and the process is repeated until no further changes occur in the fitted data. The respective numerical values for $\beta_{\text{eff,i}}/\beta_{\text{eff}}$ and λ_i are reported in Tab. 3 and Tab. 4. Precursors have been regrouped into six groups. A new processing of the raw macroscopic noise from (dos Santos and Diniz, 2014) was recently performed at CEA, in order to fit the relative abundances in the eight-group structure, with the same fixed decay constants than in `JEFF3.1.1`: the resulting benchmark values are reported in Tab. 5.

We have computed the partial kinetics parameters $\beta_{\text{eff,i}}$ and λ_i with TRIPOLI-4®: simulation results are given in Tab. 5 for `JEFF3.1.1`, and in Tabs. 3 and 4 for `JENDL-4.0` and `ENDF/B-VII.r0`. They are respectively compared to the eight-group and six-group results from the fit of macroscopic noise measurements. These findings are illustrated in Figs. 12 and Fig 13 for the relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ and in Fig. 14 for the decay constants λ_i.

T [s]	T4 JEFF-3.1.1	MCNP JEFF-3.1.1	T4 ENDF/B-VII.r0	MCNP ENDF/B-VII.r0	T4 JENDL-4.0	MCNP JENDL-4.0
1	1.0 ± 0.7	1.2 ± 0.7	-3.7 ± 0.7	-3.8 ± 0.8	0.9 ± 0.7	1.6 ± 0.7
10	2.8 ± 1.9	3.1 ± 2.0	-8.7 ± 1.9	-9.0 ± 1.8	2.4 ± 1.9	2.9 ± 1.9
100	3.8 ± 4.4	4.3 ± 4.7	-12.2 ± 4.4	-12.8 ± 4.3	3.3 ± 4.4	2.7 ± 4.6
200	3.6 ± 3.9	4.2 ± 4.2	-12.8 ± 3.9	-13.2 ± 4.6	3.1 ± 3.9	2.4 ± 4.1
-200	3.5 ± 6.6	2.7 ± 6.9	-13.1 ± 6.7	-14.5 ± 6.0	2.7 ± 6.6	0.03 ± 6.7
-100	-1.1 ± 5.3	-2.9 ± 5.5	-14.9 ± 5.3	-16.4 ± 4.8	-2.8 ± 5.3	-6.1 ± 5.3
-90	-4.1 ± 4.5	-6.9 ± 4.7	-16.1 ± 4.5	-17.8 ± 4.3	-6.9 ± 4.5	-9.9 ± 4.6
-85	-7.3 ± 3.5	-11.2 ± 4.1	-18.1 ± 3.5	-20.0 ± 3.8	-12.5 ± 3.5	-16.8 ± 4.0

Table 1: Relative errors $(C - E)/E$ (in percent) for the dynamic reactivity of the IPEN/MB-01 core as a function of the asymptotic period T. Simulation results (C) are obtained with Tripoli-4® from the in-hour equation with various nuclear data libraries. Reference values (E) are taken from (dos Santos and Diniz, 2014). For MCNP, relative errors are those reported in (dos Santos and Diniz, 2014).

3.3. The dynamic reactivity

Once the kinetics parameters $\beta_{\text{eff}}/\Lambda_{\text{eff}}$, $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$, and λ_i have been estimated as described above, the dynamic reactivity ρ_d can be finally inferred based on the in-hour equation 1. Benchmark-quality values for the reactivity of the IPEN/MB-01 core corresponding to several reactor periods are given in (dos Santos and Diniz, 2014). The reactivity results obtained by Tripoli-4® are displayed in Fig. 2 for the three libraries JEFF3.1.1, ENDF/B-VII.r0 and JENDL-4.0, where they are contrasted to the reference data. The relative discrepancies between calculations and benchmark data are provided in Fig. 3.

The reactivity curve had been previously estimated in the framework of the MCNP model of IPEN/MB-01 (dos Santos and Diniz, 2014), based on kinetics parameters computed by an independently developed IFP method. In order to discriminate between the impact of nuclear data and that of the Monte Carlo methods adopted for the calculations (in particular the IFP algorithm), it is instructive to compare the in-hour curve obtained by Tripoli-4® to that of MCNP: results are reported in Tab. 1.

The Tripoli-4® results for the dynamic reactivity are in very close agreement with MCNP results reported in (dos Santos and Diniz, 2014), especially for positive periods and large negative periods. A few percent differences appear for negative reactor periods close to 85s, which may be due to convergence issues in the first family group (where the dynamic reactivity depends almost entirely on the the decay of ^{87}Br). Indeed, the MCNP results have a statistical uncertainty almost one order of magnitude higher than those of Tripoli-4®.

The C/E agreement is quite satisfactory for JEFF3.1.1 and JENDL-4.0, while the ENDF/B-VII.r0 results are systematically underestimating the benchmark values. This trend was already mentioned in (Leconte et al., 2016) as a result of the mean delayed neutron lifetime τ: in fact, τ is in close agreement with the benchmark value in JEFF3.1.1 (2.6% agreement) while it is strongly underestimated in ENDF/B-VII.r0 (-13.6%). This finding is a consequence of the too large decay constants in ENDF/B-VII.r0 for the fifth and the sixth family groups, as observed in Fig. 14. For negative reactivity close to $-1\$$, JEFF3.1.1 results appear slightly better than those of JENDL-4.0, thanks to a better estimate of the relative abundances in the first and second group. Moreover, it is now recognized that the decay constants used in the six-group structure do not accurately reproduce the asymptotic die-away time constants associated with the three longest-lived dominant precursors (WPEC6, 2002).

4. The SPERT III E-core

The Special Power Excursion Reactor Test III (SPERT-III) is a small pressurized-water research reactor built and operated in the United States in the 1960s (Heffner and Wilson, 1961; Houghtaling et al., 1965; McCardell et al., 1969). The main goal of SPERT-III was to analyze the kinetic behavior of nuclear reactors with the purpose of assessing the safety of the installation and the thermal-mechanical stress of the structural materials. Several core configurations have been successively tested within the SPERT-III reactor: the E-core type consisted of a pressurized light-water-moderated core with 4.8%-enriched UO_2 fuel pellets arranged in a regular lattice of cylindrical pins (see Fig. 4), with (volumetric) moderator to non-moderator ratio equal to 0.971 (Heffner and Wilson, 1961; Houghtaling et al., 1965; McCardell et al., 1969). The E-core has attracted a considerable amount of interest in view of the possibility of validating reactor physics and thermal-hydraulics codes in both steady-state and transient conditions. Concerning reactor physics, most of the previous analyses have been carried out by means of deterministic codes, which can be easily coupled with thermal-hydraulics codes, but suffer from various approximations (Kosaka et al., 1988; Ikeda and Takeda, 2001; Yamaji et al., 2014; Grandi and Moberg, 2012; Grandi, 2014; Aoki et al., 2009; Wang et al., 2013). In particular, the modelling of the complex and highly heterogeneous geometry of SPERT-III has been often dealt with by resorting to spatial homogenization methods, which may induce some discrepancies in the estimation of the physical parameters (see for instance the discussion in (Cao et al., 2015)). More recently, Monte Carlo models for MCNP (X-5 Monte Carlo Team, 2003) and KENO (Bowman, 2011) have been also proposed (Olson, 2013a,b; Cao et al., 2015), and intensive efforts have been made in order to distil the available technical information on the E-core specifications so as to propose an international benchmark for reactor physics

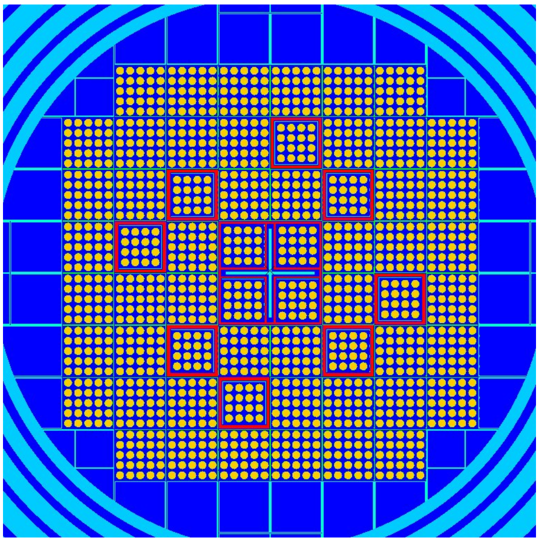

Figure 4: (Color online) Radial view of the TRIPOLI-4® model of the SPERT III E-core.

analysis at IAEA (Olson, 2013c; IAEA, 2015).

A new Monte Carlo model of the E-core has been developed for TRIPOLI-4®, and has been reported in (Zoia and Brun, 2016): several reactor physics parameters have been satisfactorily tested, including reactivity, control rod worths, Doppler and void coefficients. For the present work, we have run TRIPOLI-4® criticality simulations with 5×10^2 inactive cycles and 2.5×10^3 active cycles, and 4×10^4 neutrons per cycle. The attained convergence on k_{eff} is less than 10 pcm for all tested libraries.

Several core loading specifications are available (Olson, 2013c; IAEA, 2015): for our calculations, we have selected the fully loaded operational configuration including 60 elements, with all reactor components at 70 °F and atmospheric pressure (corresponding to cold zero power condition). The critical rod height to achieve criticality for this configuration is 14.6 *in* [3] from the bottom of the active fuel height (Potenza et al., 1966; Taxelius and Potenza, 1967; Taxelius, 1967; McCardell et al., 1969).

4.1. The kinetics parameters β_{eff}, Λ_{eff}, and $\Lambda^\dagger$

The reduced mean generation time $\Lambda^\dagger = \Lambda_{eff}/\beta_{eff}$ has been measured by neutron noise analysis (the power spectral density technique), and reads $\Lambda^\dagger = 2.15 \pm 0.008$ ms (Taxelius and Potenza, 1967). Previous calculations based on perturbation theory had given $\Lambda^\dagger = 1.91$ ms (Taxelius and Potenza, 1967). Even though the uncertainty of the set of measurements is of the order of 1%, for conservatism (because of the observed discrepancy with respect to the perturbation calculation) the uncertainty attributed to the reduced mean generation time has been evaluated at 12% (Taxelius, 1967). The kinetics parameters for this configuration had been separately computed by resorting to the deterministic codes DOPP-3C and CORA [4], and read $\beta_{eff} = 718$ pcm and $\Lambda_{eff} = 15.55\ \mu$s (McCardell et al., 1969). The estimated uncertainty for the delayed neutron fraction and of the mean generation time is of the order of $7 - 15\%$ (assuming independence between β_{eff} and $\Lambda^\dagger$) (McCardell et al., 1969; Olson, 2013a). These data are recalled in Tab. 6.

The kinetics parameters obtained for TRIPOLI-4® model with `JEFF3.1.1`, `ENDF/B-VII.r0` and `JENDL-4.0` are reported in Tab. 6. These numerical findings are compatible with the measured and computed kinetics parameters reported above: the discrepancies with respect to the computed kinetics parameters are most probably due to the approximations of the deterministic codes (simplified geometry and energy group meshes) and to the evolution of nuclear data libraries since the late 1960s. The kinetics parameters at 70 °F have been previously computed for the `MCNP` model of the SPERT-III E-core by resorting to the IFP method with the `ENDF/B-VII.r0` nuclear data library (Olson, 2013a,b): these results are also reported in Tab. 6 for comparison.

4.2. Partial kinetics parameters

In (Taxelius, 1967), the partial kinetics parameters $\beta_{\text{eff,i}}$ and λ_i are also quoted. These values have been computed by resorting to the arguments and numerical estimates reported in (Keepin, 1965), and have been used in order to infer the in-hour equation for the calibration of the system reactivity during rod drop and period doubling experiments. Uncertainties have been also evaluated. As such, while they do not represent experimental data (partial kinetics parameters of the SPERT III E-core have not been measured, to the authors' best knowledge), they can be used as reference values in order to probe the appropriateness of the nuclear data libraries used to produce the Monte Carlo estimates. The data reported in (Taxelius, 1967) are regrouped into 6 precursor families and read as given in Tab. 8 and 9. This allows separately evaluating the impact of nuclear data libraries for the calculation of $\beta_{\text{eff,i}}$ and λ_i, at least limitedly to `ENDF/B-VII.r0` and `JENDL-4.0`.

We have computed the partial kinetics parameters $\beta_{\text{eff,i}}$ and λ_i with TRIPOLI-4®: simulation results are given in Tab. 7 for `JEFF3.1.1`, and in Tabs. 8 and 9 for `JENDL-4.0` and `ENDF/B-VII.r0`. For `ENDF/B-VII.r0` and `JENDL-4.0`, we have also computed the relative errors with respect to literature data (see Tabs. 8 and 9). These findings are illustrated in Fig. 15 for the relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ and in Fig. 16 for the decay constants λ_i.

4.3. The dynamic reactivity

In (McCardell et al., 1969), a series of experimental measurements of the asymptotic reactor period T following rapid reactivity insertions were reported, in the context of a vast program aimed at assessing the dynamic behaviour of the E-core.

[3] Here and in the following, the critical height refers to the four control rod pairs together. In (Potenza et al., 1966), the critical control rod height at cold zero power was reported to be 14.55 *in*, then 14.6 *in* in all the following reports.

[4] Four energy groups were used for the calculations reported here and below, namely, [10 MeV - 0.82 MeV], [0.82 MeV - 5.5 keV], [5.5 keV - 0.532 eV], and [0.532 eV - 0 eV] (McCardell et al., 1969).

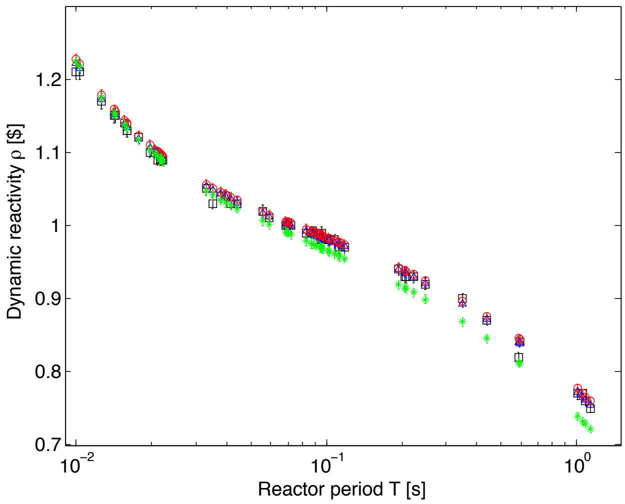

Figure 5: (Color online) Comparison between reference and computed dynamic reactivity of the SPERT III E-core. Black squares represent reference data from (McCardell et al., 1969; Olson, 2013a,b). The other symbols correspond to Tripoli-4® calculations with different nuclear data libraries: blue triangles for `JEFF3.1.1`; green stars for `ENDF/B-VII.r0`; and red circles for `JENDL-4.0`.

These data can be easily reprocessed in order to provide the in-hour curve $\rho_e = \rho_e(T)$, expressing the reactivity ρ_e (in dollars) as a function of the measured asymptotic reactor period T.

Once the kinetics parameters $\beta_{\text{eff}}/\Lambda_{\text{eff}}$, $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$, and λ_i have been estimated as described above, the dynamic reactivity ρ_d can be finally inferred based on the in-hour equation 1. The results of the Tripoli-4® simulations for the E-core corresponding to `JEFF3.1.1`, `ENDF/B-VII.r0` and `JENDL-4.0` are displayed in Fig. 5, where they are contrasted to the measured data. The relative discrepancies between calculations and experimental data are provided in Fig. 6.

The IFP adjoint-weighted kinetics parameters and the precursor decay constants have been independently estimated in the framework of the `MCNP` model of the E-core (Olson, 2013a,b), by resorting to the `ENDF/B-VII.r0` library. In order to discriminate between the impact of nuclear data and that of the Monte Carlo methods, it is instructive to compare the in-hour curve obtained by Tripoli-4® to that of `MCNP` for the `ENDF/B-VII.r0`: results are displayed in Fig. 7 and show that Tripoli-4® and `MCNP` are in excellent agreement with each other.

Both `JEFF3.1.1` and `JENDL-4.0` results are in good agreement with reference values, over the 0.75$ to 1.2$ reactivity range, which allows extending the validation range above prompt criticality with respect to the IPEN/MB-01 benchmark. The `ENDF/B-VII.r0` results are working fine for very short reactor periods, mostly because of the predominance of the mean generation time Λ_{eff} in the in-hour equation. For longer reactor periods, simulations performed with `ENDF/B-VII.r0` display a systematic underestimation of about 4%, which is similar to the one observed in the IPEN/MB-01 benchmark for $T = 1$ s.

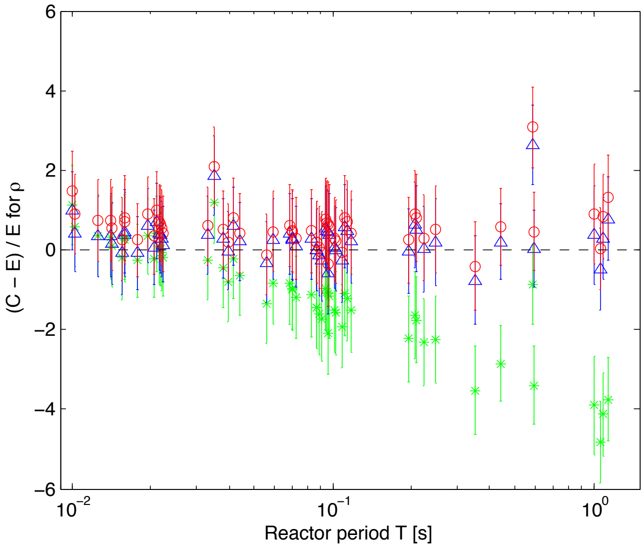

Figure 6: Relative errors $(C - E)/E$ between reference and computed dynamic reactivity of the SPERT III E-core. Reference data (E) are taken from (McCardell et al., 1969; Olson, 2013a,b). Symbols correspond to Tripoli-4® calculations (C) with different nuclear data libraries: blue triangles for `JEFF3.1.1`; green stars for `ENDF/B-VII.r0`; and red circles for `JENDL-4.0`. Errors $(C - E)/E$ are expressed in percent.

5. The SPERT-IV reactor facility at Idaho Falls

The SPERT-IV reactor facility (Phillips Petroleum Company, Atomic Energy Division) was specifically designed to perform a program of self-limiting power excursions tests (Crocker and Stephan, 1964). The main goal of these tests was to establish the response of the reactor core to a series of step insertions of reactivity, with the core being in critical or slightly subcritical conditions at a power of a few watts or less at atmospheric pressure and ambient temperature. The configuration chosen for the experiments was the SPERT-IV D-12/25, a highly enriched, water-moderated, plate type core (see Fig. 8). A full reactor description can be retrieved from (Day, 2011b,a), where the original data have been collected and formatted into specifications for an international IAEA benchmark in the field of reactor physics.

A detailed and thorough analysis of the SPERT-IV core has been previously carried out at CEA/Cadarache: a Monte Carlo model has been developed for Tripoli-4®, and the key core features have been then computed and successfully compared to the experimental values, including reactivity, control rod worth and kinetics parameters (Siréta and Bouret, 2014).

For this work, we have used the model described in (Siréta and Bouret, 2014). We have simulated 10^2 inactive cycles and 10^3 active cycles, with 5×10^4 neutrons per cycle. The attained convergence on k_{eff} is less than 15 pcm for all tested libraries.

A Monte Carlo model of SPERT IV had been independently developed at ANSTO (Australian Nuclear Science and Technology Organization) by using `MCNP` in the framework of the IAEA benchmark (Day, 2011b,a). At that time, exact

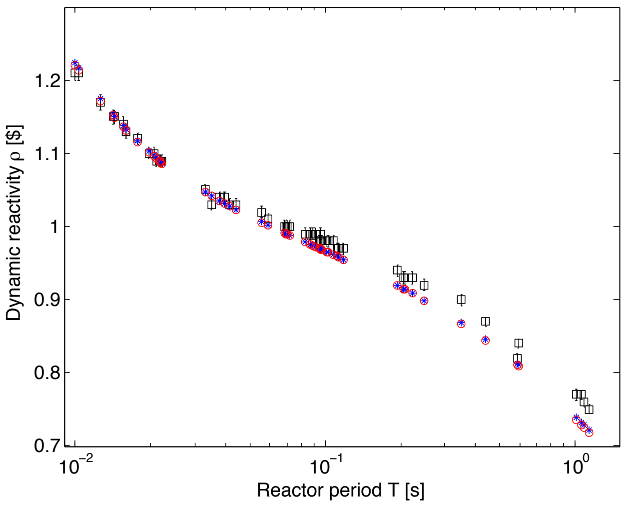

Figure 7: (Color online) Comparison between reference and computed dynamic reactivity of the SPERT III E-core. Black squares represent reference data from (McCardell et al., 1969; Olson, 2013a,b). Blue stars correspond to Tripoli-4® calculations with `ENDF/B-VII.r0`; red circles to `MCNP` calculations with `ENDF/B-VII.r0`, from (Olson, 2013a,b).

adjoint-weighted scores were not available, and kinetics parameters had been computed by resorting to the method proposed in (Bretscher, 1997). For this work, ANSTO has revised and re-run the SPERT IV model using `MCNP6`, which includes IFP capabilities, with the `ENDF/B-VII.r0` nuclear data library. The simulation parameters are the following: 4×10^3 cycles with 2×10^5 neutrons per cycle, and $M = 20$ latent generations.

5.1. The kinetics parameters β_{eff}, Λ_{eff}, $\Lambda^\dagger$, and $\ell^\dagger$

To the authors' best knowledge, the only experimentally measured kinetics parameters for the SPERT-IV D-12/25 core were the reduced neutron generation time $\Lambda^\dagger = \Lambda_{\text{eff}}/\beta_{\text{eff}}$ and the reduced prompt neutron lifetime $\ell^\dagger = k_{\text{eff}}\Lambda_{\text{eff}}/\beta_{\text{eff}}$. Several independent tests have been carried out for $\Lambda^\dagger$, based on different experimental techniques, leading to the following values: $\Lambda^\dagger = 7.94 \pm 0.26$ ms from transient analysis during excursion tests with various reactivity insertions (Crocker and Stephan, 1964; Huffman et al., 1963), $\Lambda^\dagger = 7.93 \pm 0.12$ ms from super-prompt critical excursions tests (Johnson, 1963), and $\Lambda^\dagger = 8.07 \pm 0.17$ ms from statistical analysis of reactor noise (Johnson, 1963). For the experiments devoted to $\ell^\dagger$, the reported measurements are $\ell^\dagger = 8.1 \pm 0.09$ ms (Huffman et al., 1963) and $\ell^\dagger = 8.06 \pm 0.26$ ms (Crocker and Stephan, 1964) from two series of transient test analysis.

For conservatism, we will retain $\Lambda^\dagger = 7.94 \pm 0.26$ ms for the reduced neutron generation time and $\ell^\dagger = 8.06 \pm 0.26$ ms for the reduced prompt neutron lifetime. Kinetics parameters have been originally computed in (Siréta and Bouret, 2014) by resorting to the only method available in Tripoli-4® at that time, i.e., weighting by the expected number of fission neutrons in the next generation (Lee and Hugot, 2011; Hugot and Lee, 2011). Since this method can be basically seen as a particular case of the IFP when $M = 1$, it is also called IFP_1 (Truchet et al., 2015). For the reduced prompt neutron lifetime, the value previously computed in (Siréta and Bouret, 2014) by using the IFP_1 method and the `JEFF3.1.1` library was $\ell^\dagger = 8.3 \pm 0.13$ ms.

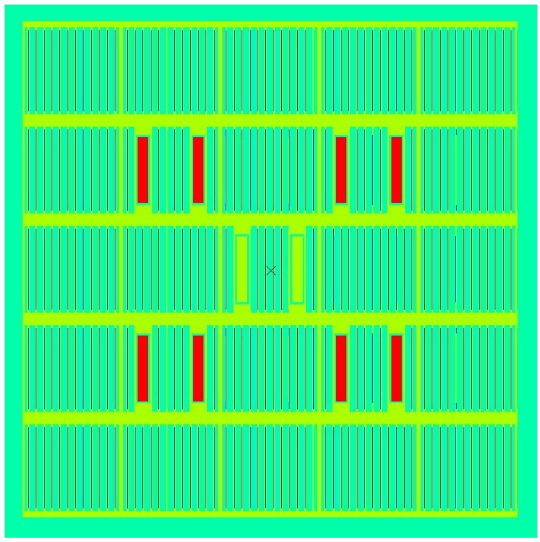

Figure 8: (Color online) Radial view of the Tripoli-4® model of the SPERT IV D-12/25 core.

For this work, we have run new Monte Carlo simulations with the development version of Tripoli-4®, and computed the kinetics parameters of the SPERT-IV D-12/25 core by resorting to the IFP method and the three nuclear data libraries. The kinetics parameters obtained for Tripoli-4® model with `JEFF3.1.1`, `ENDF/B-VII.r0` and `JENDL-4.0` are reported in Tab. 10. These numerical findings are compatible with the measured kinetics parameters reported above. Simulation results obtained with the `MCNP6` model for SPERT IV using `ENDF/B-VII.r0` are reported in Tab. 10 for comparison: a good agreement is found with respect to Tripoli-4®.

5.2. Partial kinetics parameters

In (Johnson, 1963), the partial kinetics parameters $\beta_{\text{eff,i}}$ and λ_i for the SPERT IV 12/25-D core are also reported. Similarly as for the case of the SPERT III E-core, these values have been computed by resorting to the arguments and numerical estimates reported in (Keepin, 1965), and have been used in order to infer the in-hour equation for the calibration of the system reactivity during rod drop and period doubling experiments. Uncertainties have been also evaluated. Thus, these data can again be used as reference values in order to probe the appropriateness of the nuclear data libraries used to produce the Monte Carlo estimates. The partial kinetics parameters provided in (Johnson, 1963) are regrouped into 6 precursor families and read as given in Tab. 12 and 13. This allows separately evaluating the impact of nuclear data libraries for the calculation of $\beta_{\text{eff,i}}$ and λ_i, at least limitedly to `ENDF/B-VII.r0` and `JENDL-4.0`.

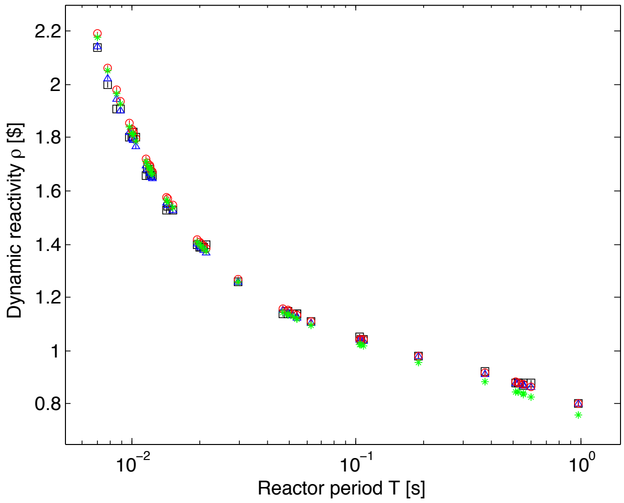

Figure 9: (Color online) Comparison between reference and computed dynamic reactivity of the SPERT IV 12/25-D core. Black squares represent reference data from (Crocker and Stephan, 1964). The other symbols correspond to Tripoli-4® calculations with different nuclear data libraries: blue triangles for `JEFF3.1.1`; green stars for `ENDF/B-VII.r0`; and red circles for `JENDL-4.0`.

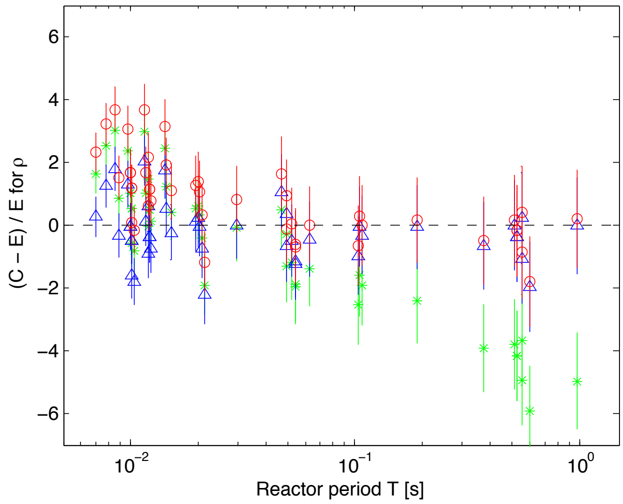

Figure 10: (Color online) Relative errors $(C-E)/E$ between reference and computed dynamic reactivity of the SPERT IV 12/25-D core. Reference data (E) are taken from (Crocker and Stephan, 1964). Symbols correspond to Tripoli-4® calculations (C) with different nuclear data libraries: blue triangles for `JEFF3.1.1`; green stars for `ENDF/B-VII.r0`; and red circles for `JENDL-4.0`. Errors $(C-E)/E$ are expressed in percent.

We have computed the partial kinetics parameters $\beta_{\text{eff,i}}$ and λ_i with Tripoli-4®: simulation results are given in Tab. 11 for `JEFF3.1.1`, and in Tabs. 12 and 13 for `JENDL-4.0` and `ENDF/B-VII.r0`. For `ENDF/B-VII.r0` and `JENDL-4.0`, we have also computed the relative errors with respect to literature data (see Tabs. 12 and 13). These findings are illustrated in Fig. 17 for the relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ and in Fig. 18 for the decay constants λ_i. Simulation results for a_i and λ_i obtained with the `MCNP6` model for SPERT IV are also reported in Tabs. 12 and 13 for comparison: an excellent agreement is found with respect to Tripoli-4®.

5.3. *The dynamic reactivity*

Analogously as for the SPERT III E-core, a series of reactor excursion experiments was also performed on the SPERT IV 12/25-D core. In the context of this program, the asymptotic reactor period T following rapid reactivity insertions was experimentally determined (Crocker and Stephan, 1964). These data allow determining the in-hour curve $\rho_e = \rho_e(T)$, expressing the reactivity ρ_e (in dollars) as a function of the measured asymptotic reactor period T.

The dynamic reactivity ρ_d can be inferred based on the in-hour equation 1 based on the kinetics parameters $\beta_{\text{eff}}/\Lambda_{\text{eff}}$, $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$, and λ_i estimated as described above. The results of the Tripoli-4® simulations for the SPERT IV 12/25-D core corresponding to `JEFF3.1.1`, `ENDF/B-VII.r0` and `JENDL-4.0` are displayed in Fig. 9, where they are contrasted to the measured data. The relative discrepancies between calculations and experimental data are provided in Fig. 10.

Both `JEFF3.1.1` and `JENDL-4.0` results are in good agreement with reference data, over the 0.75$ to 1.2$ range, analogously as for the SPERT III E-core results. Results obtained with `ENDF/B-VII.r0` show the same decreasing trend with a 4-5% underestimation for reactor period close to 1 s.

Based on the kinetics parameters for the `MCNP6` model, we have computed the dynamic reactivity resulting from the `ENDF/B-VII.r0` library, and compared it to the values obtained with Tripoli-4®. This allows singling out the impact of the model with respect to that of the nuclear data. Results are illustrated in Fig. 11: it is apparent that `MCNP6` and Tripoli-4® are in excellent agreement with respect to each other (largely within one sigma), and both show a systematic bias with respect to the reference experimental data, which mirrors the effects of the nuclear data library.

6. Conclusions

A new capability for the calculation of the partial kinetics parameters β_i (delayed neutron fractions per precursor family i, as obtained by the IFP method) and λ_i (precursor decay constants per precursor family i) has been recently implemented into the development version of the Monte Carlo code Tripoli-4®. Once the partial kinetics parameters have been determined, the dynamic reactivity of a core can be computed based on the in-hour equation. In this work, we have investigated the behaviour of the dynamic reactivity for three reactor configurations, namely, IPEN/MB-01, SPERT III E-core and SPERT IV 12/25-D core. For these three reactors, the in-hour curve has been estimated as a function of the asymptotic reactor pe-

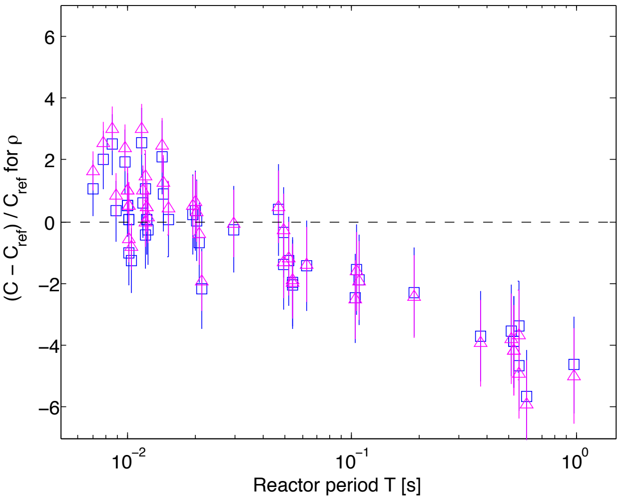

Figure 11: (Color online) Relative errors $(C - E)/E$ between reference and computed dynamic reactivity of the SPERT IV 12/25-D core. Reference data (E) are taken from (Crocker and Stephan, 1964). Symbols correspond to calculations (C) with `ENDF/B-VII.r0` data library and independent Monte Carlo models for geometry and compositions. Blue squares: Tripoli-4®; magenta triangles: `MCNP6`. Errors $(C - E)/E$ are expressed in percent.

riod and made available in the literature. We have therefore compared the computed dynamic reactivity curve to the known data, with a two-fold aim. On one hand, we have validated the newly developed calculation routines for the partial kinetics parameters. On the the other hand, we have been able to probe the impact of nuclear data on the obtained results. The comparison between the Monte Carlo estimates and the values reported in the literature is overall satisfactory. However, by contrasting the measured reactivity curves with those computed by resorting to `JEFF3.1.1`, `ENDF/B-VII.r0` and `JENDL-4.0`, we have singled out some possible inconsistencies in the nuclear data libraries used for the Monte Carlo simulation. While the computed values of the delayed neutron fraction β_{eff} and of the mean generation time Λ_{eff} are in good agreement with reference data (within statistical uncertainties), the repartition of $\beta_{\text{eff,i}}$ and λ_i as a function of the precursor families seems more problematic and might lead to systematic discrepancies in the dynamic reactivity. This is especially true for the case of `ENDF/B-VII.r0`, where the mean delayed neutron lifetime τ, as computed from the time constants λ_i and relative abundances a_i, has been shown to be systematically underestimated in the current benchmarks. The results obtained in this work call thus for future investigation aimed at improving delayed neutron distributions in nuclear libraries, since the quality and the accuracy of these data are of utmost importance especially for the simulation of the transient behaviour of reactor cores.

Acknowledgements

TRIPOLI® and TRIPOLI-4® are registered trademarks of CEA. A. Zoia and C. Jouanne wish to thank Électricité de France (EDF) for partial financial support. A. Zoia expresses his gratitude to Dr. dos Santos of the IPEN-MB/01 facility for providing unpublished data.

References

Aoki, S., Suemura, T., Ogawa, J., Takeda, T., 2009. J. Nucl. Sci. Techn. **46**, 239-251.

Bowman, S.M., 2011. Nucl. Technol. **174**, 126-148.

Bretscher, M.M.,1997. Evaluation of reactor kinetic parameters without the need for perturbation codes. Presented at the *1997 International Meeting on Reduced Enrichment for Research and Test Reactors*, Jackson Hole, Wyoming USA.

Brun, E., et al., 2015. Tripoli-4®*, CEA, EDF and AREVA reference Monte Carlo code*, Ann. Nucl. Energy **82**, 151-160.

Cao, L., Gerlach, A., Xu, Y., Downar, T., Lee, J. C., 2015. Ann. Nucl. Energy **80**, 207-218.

Chadwick, M.B., et al. (2006). Nuc. Data Sheets **107**, 2931-3060.

Chadwick, M.B., et al. (2011). Nuc. Data Sheets **112**, 2887-2996.

Crocker, J. G., Stephan, L. A., 1964. Reactor power excursion tests in the SPERT IV facility. IDO-17000.

Day, S. E., 2011a. SPERT IV D-12/25 Reactor Specification - Revision 03 - IAEA CRP Innovative Methods for Research Reactors.

Day, S. E., 2011b. SPERT IV D-12 /25 Benchmark Specification - Revision 2 - IAEA CRP Innovative Methods for Research Reactors.

Dugone, J. (1965). SPERT-III reactor facility: E-CORE revision, IDO-17036.

Feghhi, S. A. H., Shahriari, M., Afarideh, H., 2007. Ann. Nucl. Energy **34**, 514.

Feghhi, S. A. H., Shahriari, M., Afarideh, H., 2008. Ann. Nucl. Energy **35**, 1397.

Gomit, J.M., et al., 2011. In *Proceedings of the ICNC 2011 conference*, Edinburgh, Scotland.

Grandi, G., 2014. In Proceedings of the PHYSOR2014 conference, Kyoto, Japan.

Grandi, G., Moberg, L., 2012. In Proceedings of the PHYSOR2012 conference, Knoxville, Tennessee, USA.

Heffner, R. E., Wilson, T. R., 1961. SPERT-III reactor facility, IDO-16721.

Houghtaling, J. E., Norberg, J. A., Haire J. C., Addendum to the SPERT-III hazards summary report. Low-enrichment oxide core, IDO-17003.

Huffman, J. R., Nyer, W. E., Schroeder, F., 1963. Quarterly technical report, SPERT project. IDO-16893.

Hugot, F.-X., Lee, Y.-K., (2011). Progr. Nuc. Sci. Techn. **2**, 851-854.

Johnson, R. L., 1963. A statistical determination of the reduced prompt neutron generation time in the SPERT IV reactor, IDO-16903.

Keepin, G. R., 1965. Physics of Nuclear Kinetics, Addison-Wesley, Reading, UK.

Kiedrowski, B. C., 2011a. *Adjoint Weighting for Continuous-Energy Monte Carlo Radiation Transport*, PhD thesis, Michigan University.

Kiedrowski, B. C., Brown, F. B., Wilson, P. P. H., 2011b. Nucl. Sci. Eng. **68**, 226.

Kosaka, I., Kawata, N., Wakabayashi, T., 1988. PNC SN 9410 88-057.

IAEA, 2015. IAEA Technical Reports Series **480**, Research Reactor Benchmarking Database: Facility Specification and Experimental Data, Vienna.

Ikeda, H., Takeda, T., 2001. J. Nucl. Sci. Techn. **38**, 492-502.

Leconte, P., Truchet, G., Vidal, J-F., Santamarina, A., Blaise, P., 2016. In *Proceedings of the PHYSOR 2016 Conference*, Sun Valley, Idaho, USA.

Lee, Y. K., Hugot, F. X., 2011. In *Proceedings of the M&C 2011 Conference*, Rio de Janeiro, Brazil.

Leppänen, J., 2008. In *Proceedings of the IYNC2008 conference*, Interlaken, Switzerland.

Leppänen, J., et al., 2014. Ann. Nucl. Energy **65**, 272.

McCardell, R. K., Herborn, D. I., Houghtaling, J. E., 1969. Reactivity accident test results and analyses for the SPERT-III E-CORE - A small oxide-fueled, pressurized-water reactor, IDO-17281.

McLane, V., 2004. Brookhaven National Laboratory report BNL-NCS-44945-01/04-REV KB0301042.

Meulekamp, R. K., van der Marck, S. C., 2006. Nucl. Sci. Eng. **152**, 142.

Nauchi, Y., Kameyama, T., 2005. J. Nucl. Sci. Technol. **42**, 503.

Nauchi, Y., Kameyama, T., 2008. In *Proceedings of the PHYSOR2008 conference*, Interlaken, Switzerland.

Nauchi, Y., Kameyama, T., 2009. In *Preprints of the 2009 annual meeting of Atomic Energy Society of Japan*, Tokyo, Japan, March 23-25 K41 [in Japanese].

Nauchi, Y., Kameyama, T., 2010. J. Nucl. Sci. Technol. **47**, 977.

Nauchi, Y., 2014. In *Proceedings of the SNA+MC 2013 conference*, Paris, France.

OECD/NEA, 2007. Benchmark on the kinetics parameters of the CROCUS reactor, in Plutonium recycling, volume IX, NEA 4440.

Olson, A. P., 2013a. Neutronics calculations for SPERT-III, E-Core, ANL/GTRI/TM-13/10.

Olson, A. P., 2013b. Consolidator's report for the SPERT-III benchmark, ANL/GTRI/TM-13/9.

Olson, A. P., 2013c. SPERT III E-CORE: Facility specifications, Argonne National Laboratory (ANL).

Paratte, J.M., Früh, R., Kasemeyer, U., Kalugin, M.A., Timm, W., Chawla, R., 2006. Ann. Nucl. Energy **33**, 739.

Perfetti, C. M., 2012. *Advanced Monte Carlo methods for eigenvalue sensitivity coefficient calculations*, PhD thesis, Michigan University.

Potenza, R. M., Haire, J. C., Nyer, W. E., 1966. Quarterly technical report SPERT project, IDO-17206.

Santamarina, A., et al., (2009). The JEFF-3.1.1 Nuclear Data Library, JEFF Report 22, OECD-NEA Data Bank.

dos Santos, A., et al. (2013) LEU-COMP-THERM-077: Critical loading configurations of the IPEN/MB-01 reactor, In *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC (95)03/I, J. B. briggs Ed., Nuclear Energy Agency.

dos Santos, A., Diniz, R., 2014. Nucl. Sci. Eng. **178**, 459.

Shibata, K., Iwamoto, O., Nakagawa, T., Iwamoto, N., Ichihara, A., Kunieda, S., Chiba, S., Furutaka, K., Otuka, N., Ohsawa, T., Murata, T., Matsunobu, H., Zukeran, A., Kamada, S., Katakura, J., 2011. J. Nucl. Sci. Technol. **48**, 1-30.

Shim, H. J., Kim, C. H., Kim, Y., 2011. J. Nucl. Sci. Technol. **48**, 1453.

Siréta, P., Bouret, C., 2014. Interpretation of the static neutronics measurements carried out in the SPERT IV reactor. Note technique DEN/CAD/DER/SRJH 2014 DO 313.

Sjenitzer, B.L., Hoogenboom, J.E., 2013. Nucl. Sci. Engng. **175**, 94-107.

Soon, S. (1995). NEA/NSC/DOC/(95)03/II.

Sublet, J.C., et al., 2011. CALENDF-2010: User Manual, Rapport CEA-R-6277.

Taxelius, T. G., Potenza, R. M., 1967. Quarterly technical report SPERT project, IDO-17207.

Taxelius, T. G., 1967. Quarterly technical report SPERT project, IDO-17228.

Taxelius, T. G., Haire, J. C., Forbes, S. G., 1967. Quarterly technical report SPERT project, IDO-17245.

Truchet, G., Leconte, P., Santamarina, A., Damian, F., Zoia, A., 2015. Ann. Nucl. Energy **81**, 17-26.

Tripoli-4 Project Team, 2012. Tripoli-4 User guide, Rapport CEA-R-6316.

Vollaire, J., Plaschy, M., Jatuff, F., Chawla, R., 2006. In *Proceedings of the PHYSOR2006 conference*, Vancouver, Canada.

Wang, R. C., Xu, Y., Hudson, N., Downar, T. J., 2013. Nucl. Techn. **183**, 504.

WPEC6, 2002. *Delayed neutron data for the major actinides*, NEA/WPEC-6 report, OECD/NEA.

X-5 Monte Carlo Team, 2003. MCNP - A general Monte Carlo N-particle transport code, Version 5, Volume I: Overview and theory. LA-UR-03-1987, Los Alamos National Laboratory.

Yamaji, H., Takemoto, Y., Kirimura, K., et al., 2014. In Proceedings of the PHYSOR2014 conference, Kyoto, Japan.

Zoia, A., Brun, E., Jouanne, C., Malvagi, F., 2012. Ann. Nucl. Energy **54**, 218-226.

Zoia, A., Brun, E., Malvagi, F., 2014. Ann. Nucl. Energy **63**, 276.

Zoia, A., Brun, E., Damian, F., Malvagi, F., 2015. Ann. Nucl. Energy **75**, 627.

Zoia A., Brun, E., 2016. Annals of Nuclear Energy **90**, 71-82.

Zoia, A., Nauchi, Y., Brun, E., Jouanne, C., 2016. Annals of Nuclear Energy **96**, 377-388.

	β_{eff} [pcm]	(C-E)/E	Λ_{eff} [μs]	(C-E)/E	$\beta_{\text{eff}}/\Lambda_{\text{eff}}$ [s^{-1}]	(C-E)/E
Benchmark	750 ± 5		31.96 ± 1.06		234.66 ± 7.92	
`T4 JEFF-3.1.1`	772.5 ± 2	3.0 ± 0.72	30.48 ± 0.011	-4.63 ± 3.32	253.6 ± 0.7	8.0 ± 3.4
`T4 ENDF/B-VII.r0`	753.5 ± 2.1	0.47 ± 0.72	30.52 ± 0.011	-4.51 ± 3.32	247.0 ± 0.7	5.3 ± 3.4
`T4 JENDL-4.0`	759.2 ± 2	1.2 ± 0.72	30.53 ± 0.011	-4.47 ± 3.32	249.0 ± 0.7	6.1 ± 3.4
`MCNP JEFF-3.1.1`	766.0 ± 3.6	2.13 ± 0.95	30.68 ± 0.035	-4.0 ± 4.6	249.7 ± 2.4	6.42 ± 4.93
`MCNP ENDF/B-VII.r0`	750.0 ± 3.6	0 ± 0.82	30.72 ± 0.037	-3.89 ± 3.19	244.3 ± 2.4	4.11 ± 3.54
`MCNP JENDL-4.0`	745.0 ± 7.0	-0.67 ± 0.94	30.76 ± 0.035	-3.76 ± 4.60	242.3 ± 2.38	-3.76 ± 4.6

Table 2: Effective delayed neutron fraction β_{eff}, effective mean neutron generation time Λ_{eff} and the ratio $\beta_{\text{eff}}/\Lambda_{\text{eff}}$ for the IPEN/MB-01 core. Benchmark values (E) are taken from (dos Santos and Diniz, 2014). Simulation results (C) are obtained with Tripoli-4® with various nuclear data libraries. Relative errors $(C - E)/E$ are expressed in percent. For `MCNP`, relative errors are those reported in (dos Santos and Diniz, 2014).

family	Benchmark	`ENDF/B-VII.r0`	(C-E)/E	`JENDL-4.0`	(C-E)/E
1	$0.0357 \pm 8\times10^{-5}$	$0.03021 \pm 5\times10^{-4}$	-15.4 ± 1.6	$0.03194 \pm 5\times10^{-4}$	-11.5 ± 1.7
2	$0.1951 \pm 1.3\times10^{-2}$	$0.16235 \pm 1.1\times10^{-3}$	-16.8 ± 4.8	$0.21120 \pm 1.3\times10^{-3}$	7.8 ± 4.8
3	$0.1787 \pm 2.3\times10^{-2}$	$0.15999 \pm 1.2\times10^{-3}$	-10.4 ± 9.8	$0.19511 \pm 1.3\times10^{-3}$	9.0 ± 9.8
4	$0.4133 \pm 4.1\times10^{-2}$	$0.45759 \pm 1.9\times10^{-3}$	10.7 ± 3.3	$0.39153 \pm 1.8\times10^{-3}$	-5.2 ± 3.3
5	$0.1108 \pm 6.8\times10^{-3}$	$0.14182 \pm 1\times10^{-3}$	28.0 ± 7.8	$0.12614 \pm 1\times10^{-3}$	14.6 ± 7.6
6	$0.0665 \pm 1.7\times10^{-3}$	$0.04805 \pm 6.3\times10^{-4}$	-27.8 ± 5.7	$0.04407 \pm 6\times10^{-4}$	-33.1 ± 5.8

Table 3: Effective relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ for the IPEN/MB-01 core: benchmark values from (dos Santos and Diniz, 2014) and simulation results obtained with Tripoli-4® by using `ENDF/B-VII.r0` and `JENDL-4.0` nuclear data libraries. Relative errors are expressed in percent.

family	Benchmark	`ENDF/B-VII.r0`	(C-E)/E	`JENDL-4.0`	(C-E)/E
1	0.012456	0.012491	0.2 ± 0.0	0.0125145	0.4 ± 0.0
2	$0.0317 \pm 1.1\times10^{-3}$	0.03168	-0.6 ± 10	0.030686	-3.8 ± 10
3	$0.1085 \pm 5.4\times10^{-3}$	0.10996	1.4 ± 5.0	0.11397	5.0 ± 5.0
4	$0.3054 \pm 5.5\times10^{-3}$	0.319188	4.5 ± 1.8	0.30684	0.5 ± 1.8
5	1.085 ± 0.044	1.350806	2.4 ± 4.2	1.16232	7.1 ± 4.1
6	3.14 ± 0.11	8.7570	179 ± 7.2	3.1099	-1.0 ± 3.5

Table 4: Precursor decay constants λ_i [s^{-1}] for the IPEN/MB-01 core: benchmark values from (dos Santos and Diniz, 2014) and simulation results obtained with Tripoli-4® by using `ENDF/B-VII.r0` and `JENDL-4.0` nuclear data libraries. Error bars on λ_i are smaller than 10^{-4} for all families. Relative errors are expressed in percent.

family	Benchmark	`JEFF3.1.1`	(C-E)/E
1	$0.0357 \pm 3.1\times10^{-4}$	$0.0318 \pm 1.2\times10^{-4}$	-11.0 ± 0.9
2	$0.1418 \pm 5.0\times10^{-3}$	$0.1452 \pm 5.7\times10^{-5}$	2.4 ± 3.5
3	$0.0760 \pm 7.7\times10^{-3}$	$0.0892 \pm 7.3\times10^{-5}$	17.4 ± 10.2
4	$0.1813 \pm 1.3\times10^{-2}$	$0.1939 \pm 5.1\times10^{-5}$	6.9 ± 7.4
5	$0.3444 \pm 9.7\times10^{-3}$	$0.3263 \pm 3.9\times10^{-5}$	-5.2 ± 2.8
6	$0.1017 \pm 8.0\times10^{-3}$	$0.0993 \pm 7.0\times10^{-5}$	-2.4 ± 7.9
7	$0.0862 \pm 3.2\times10^{-3}$	$0.0849 \pm 7.7\times10^{-5}$	-1.5 ± 3.8
8	$0.0329 \pm 7.0\times10^{-3}$	$0.0294 \pm 1.3\times10^{-4}$	-10.7 ± 21.2

Table 5: Effective relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ for the IPEN/MB-01 core: benchmark values from a new analysis of macroscopic noise measurements (with eight families) and simulation results obtained with Tripoli-4® by using `JEFF3.1.1` nuclear data library.

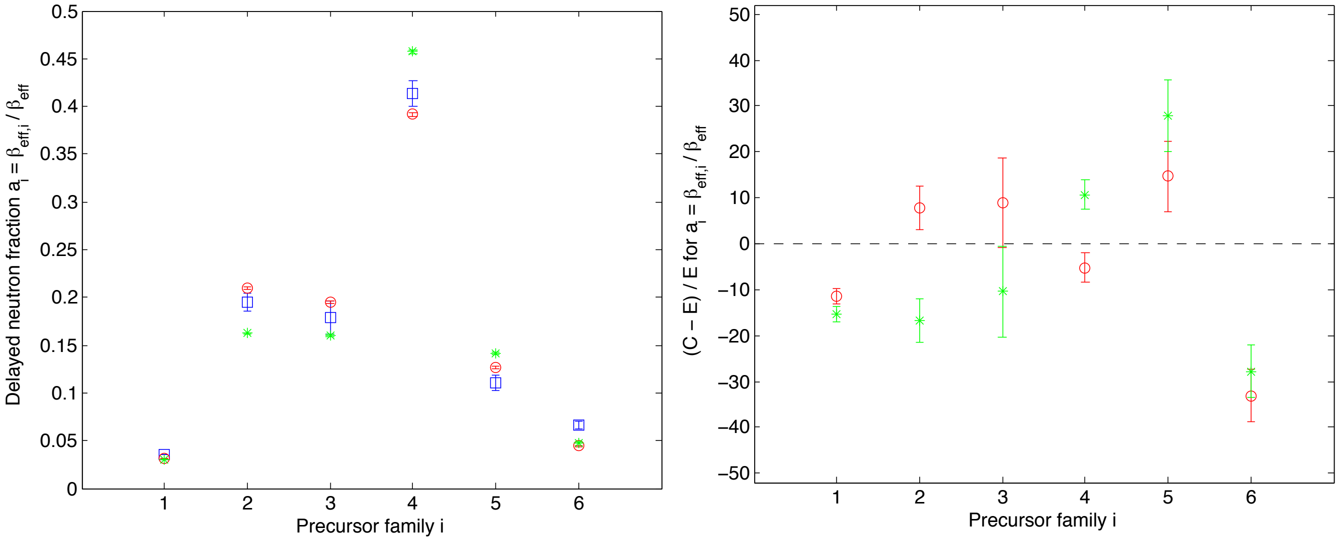

Figure 12: (Color online) Effective relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ for the IPEN/MB-01 core. Left. Blue squares represent reference values (E) taken from (dos Santos and Diniz, 2014). The other symbols represent Tripoli-4 ® calculations (C): green stars for `ENDF/B-VII.r0` and red circles for `JENDL-4.0`. Right. Relative errors $(C - E)/E$, in percent.

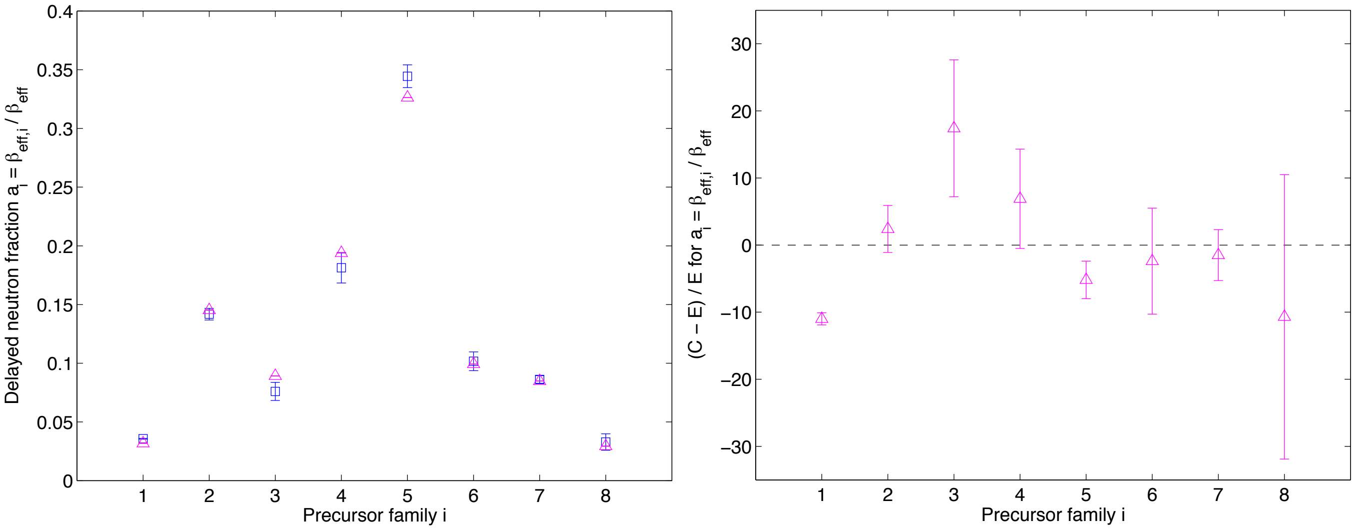

Figure 13: (Color online) Effective relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ for the IPEN/MB-01 core, from a new analysis of macroscopic noise measurements with eight families. Left. Blue squares represent reference values (E) taken from (dos Santos and Diniz, 2014). Magenta triangles represent Tripoli-4 ® calculations (C) for `JEFF-3.1.1`. Right. Relative errors $(C - E)/E$, in percent.

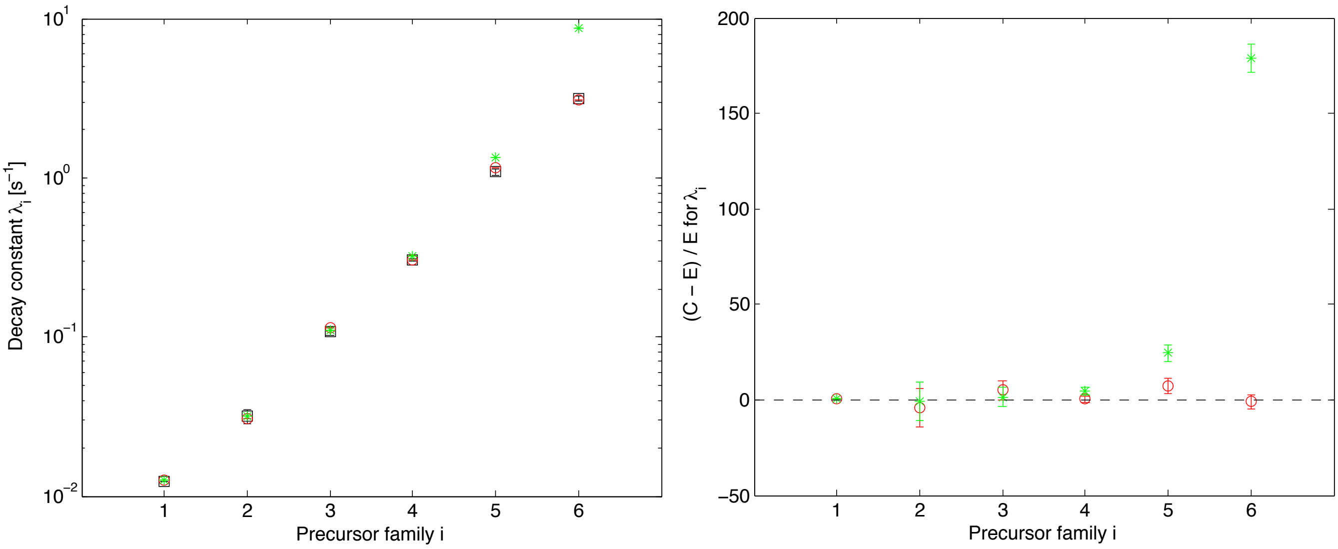

Figure 14: (Color online) Precursor decay constants λ_i for the IPEN/MB-01 core. Left. Blue squares represent reference values (E) taken from (dos Santos and Diniz, 2014). The other symbols represent Tripoli-4® calculations (C): green stars for `ENDF/B-VII.r0` and red circles for `JENDL-4.0`. Right. Relative errors $(C - E)/E$, in percent.

	Reference	T4 JEFF3.1.1	T4 ENDF/B-VII.r0	T4 JENDL-4.0	MCNP ENDF/B-VII.r0
β_{eff} [pcm]	718 (7 – 15%)	764.0 ± 4.6	748.2 ± 4.4	745.2 ± 4.4	778 ± 21
Λ_{eff} [μs]	15.55 (7 – 15%)	17.3 ± 0.01	17.3 ± 0.01	17.3 ± 0.01	17.72 ± 0.06
$\Lambda^{\dagger}$ [ms]	2.15 (1 – 12%)	2.27 ± 0.02	2.31 ± 0.02	2.32 ± 0.03	2.28

Table 6: Kinetics parameters of the SPERT III E-core. Reference values are taken from (McCardell et al., 1969; Taxelius and Potenza, 1967). Simulation results are obtained with Tripoli-4® with several nuclear data libraries. For comparison, results obtained in (Olson, 2013a,b) by using a MCNP Monte Carlo model with ENDF/B-VII.r0 are also reported.

family	$\beta_{\text{eff,i}}/\beta_{\text{eff}}$	λ_i
1	0.0284 ± 2.7×10^{-4}	0.012467
2	0.1426 ± 1.5×10^{-4}	0.028292
3	0.0856 ± 7.9×10^{-5}	0.042524
4	0.1937 ± 1.4×10^{-4}	0.133042
5	0.3184 ± 1.5×10^{-4}	0.292467
6	0.1066 ± 2.3×10^{-4}	0.666488
7	0.0890 ± 3.0×10^{-4}	1.634781
8	0.0352 ± 2.3×10^{-4}	3.5546

Table 7: Effective relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ and precursor decay constants λ_i [s^{-1}] for the SPERT III E-core: simulation results obtained with Tripoli-4® by using JEFF3.1.1 nuclear data library.

family	Reference	ENDF/B-VII.r0	$(C - C_{ref})/C_{ref}$	JENDL-4.0	$(C - C_{ref})/C_{ref}$	MCNP ENDF/B-VII.r0
1	0.0355 ± 5×10^{-3}	0.02808 ± 1×10^{-3}	-20.9 ± 14.7	0.03112 ± 1×10^{-3}	-12.3 ± 14.5	0.0228
2	0.2015 ± 1.1×10^{-2}	0.16206 ± 2.4×10^{-3}	-19.6 ±5.7	0.21107 ± 2.7×10^{-3}	4.7 ± 5.63	0.1568
3	0.1863 ± 1.78×10^{-2}	0.15353 ± 2.3×10^{-3}	-17.6 ±10.0	0.19411 ± 2.6×10^{-3}	4.2 ± 10.0	0.1452
4	0.4 ± 8.2×10^{-3}	0.45896 ± 4.1×10^{-3}	14.7 ± 2.3	0.38694 ± 3.6×10^{-3}	-3.3 ± 2.2	0.4756
5	0.1435 ± 1.51×10^{-2}	0.14931 ± 2.3×10^{-3}	4.1 ± 10.7	0.13109 ± 2.1×10^{-3}	-8.6 ± 10.7	0.1555
6	0.0328 ± 7.4×10^{-3}	0.04806 ± 1.3×10^{-3}	46.5 ± 25.2	0.04567 ± 1.2×10^{-3}	39.2 ± 24.5	0.0450

Table 8: Effective relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ for the SPERT III E-core: reference values (C_{ref}) from (Taxelius, 1967) and simulation results (C) obtained with Tripoli-4® by using ENDF/B-VII.r0 and JENDL-4.0 nuclear data libraries. Relative errors $(C - C_{ref})/C_{ref}$ are expressed in percent. For comparison, results obtained in (Olson, 2013a,b) by using a MCNP Monte Carlo model with ENDF/B-VII.r0 are also reported.

family	Reference	ENDF/B-VII.r0	$(C - C_{ref})/C_{ref}$	JENDL-4.0	$(C - C_{ref})/C_{ref}$	MCNP ENDF/B-VII.r0
1	0.0127 ± 3×10^{-4}	0.01249	-1.6 ± 2.4	0.012558	-1.1 ± 2.4	0.01249
2	0.0317 ± 1.1×10^{-3}	0.0316	-0.3 ± 3.5	0.03077	-2.9 ± 3.5	0.0316
3	0.1167 ± 4.2×10^{-3}	0.11031	-5.5 ± 3.6	0.11546	-1.1 ± 3.6	0.11012
4	0.3142 ± 1.2×10^{-2}	0.32048	2.0 ± 3.8	0.31001	-1.3 ± 3.8	0.32041
5	1.4 ± 0.11	1.348945	-3.6 ± 7.9	1.17762	-15.9 ± 8.0	1.34624
6	3.8803 ± 0.51	8.8278	127.5 ± 21.3	3.1656	-18.4 ± 13.3	8.8746

Table 9: Precursor decay constants λ_i for the SPERT III E-core: reference values (C_{ref}) from (Taxelius, 1967) and simulation results (C) obtained with Tripoli-4® by using ENDF/B-VII.r0 and JENDL-4.0 nuclear data libraries. Relative errors (C-C_{ref})/C_{ref} are expressed in percent. For comparison, results obtained in (Olson, 2013a,b) by using a MCNP Monte Carlo model with ENDF/B-VII.r0 are also reported.

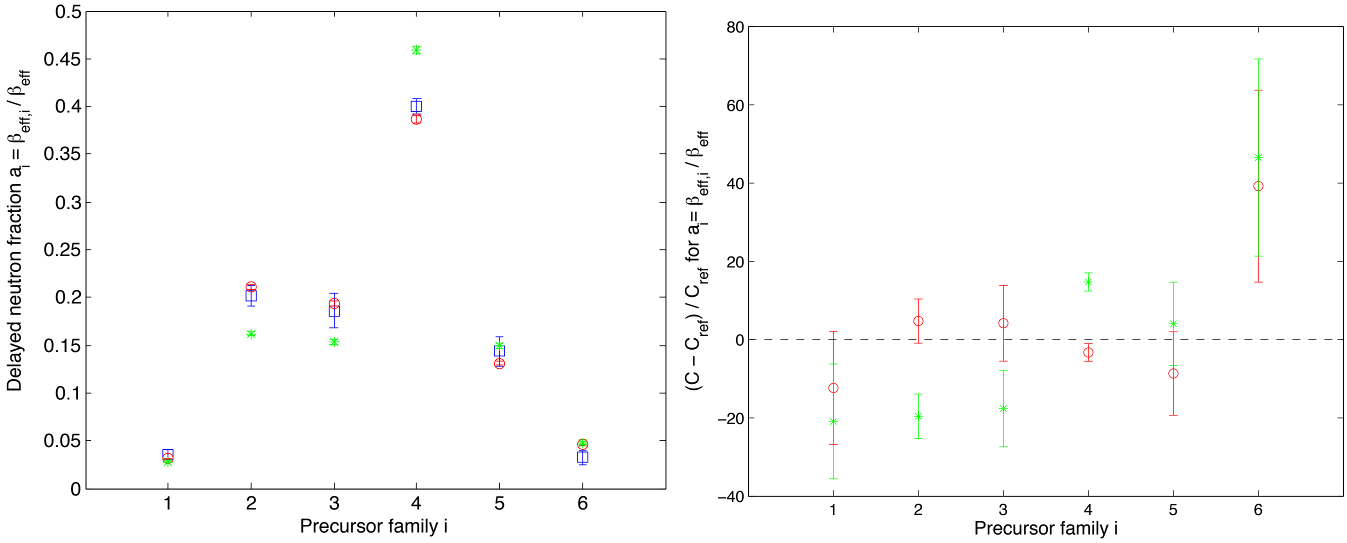

Figure 15: (Color online) Effective relative delayed neutron fractions $a_i = \beta_{\mathrm{eff,i}}/\beta_{\mathrm{eff}}$ for the SPERT III E-core. Left. Blue squares represent reference values (C_{ref}) taken from (Taxelius, 1967). The other symbols represent Tripoli-4® calculations (C): green stars for `ENDF/B-VII.r0` and red circles for `JENDL-4.0`. Right. Relative errors $(C - C_{ref})/C_{ref}$, in percent.

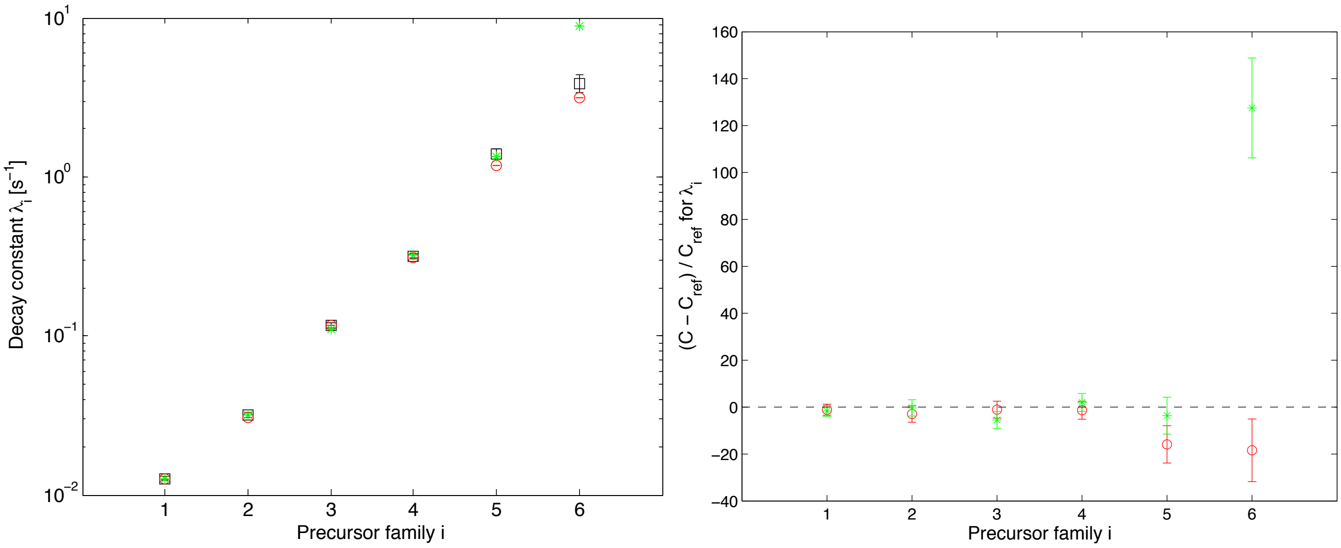

Figure 16: (Color online) Precursor decay constants λ_i [s^{-1}] for the SPERT III E-core. Left. Black squares represent reference values (C_{ref}) taken from (Taxelius, 1967). The other symbols represent Tripoli-4® calculations (C): green stars for `ENDF/B-VII.r0` and red circles for `JENDL-4.0`. Right. Relative errors $(C - C_{ref})/C_{ref}$, in percent.

	Reference	T4 `JEFF3.1.1`	T4 `ENDF/B-VII.r0`	T4 `JENDL-4.0`	`MCNP6` `ENDF/B-VII.r0`
β_{eff} [pcm]		769.7 ± 6.3	749.7 ± 5.8	742.7 ± 6.0	755 ± 6
Λ_{eff} [μs]		61.86 ± 0.056	61.91 ± 0.052	61.97 ± 0.056	61.67 ± 0.05
$\Lambda^{\dagger}$ [ms]	7.94 ± 0.26	8.03 ± 0.06	8.25 ± 0.07	8.27 ± 0.07	8.17 ± 0.07
$\ell^{\dagger}$ [ms]	8.06 ± 0.26	8.04 ± 0.06	8.27 ± 0.07	8.36 ± 0.07	8.16 ± 0.07

Table 10: Kinetics parameters of the SPERT IV 12/25-D core. Reference values are taken from (Crocker and Stephan, 1964; Huffman et al., 1963; Johnson, 1963). Simulation results are obtained with Tripoli-4® with several nuclear data libraries. Simulation results obtained with `MCNP6` by using `ENDF/B-VII.r0` are also reported.

family	$\beta_{\text{eff,i}}/\beta_{\text{eff}}$	λ_i
1	0.0330 ± 3.3×10^{-4}	0.012467
2	0.1548 ± 1.5×10^{-4}	0.028292
3	0.0948 ± 2.0×10^{-5}	0.042524
4	0.1961 ± 1.4×10^{-4}	0.133042
5	0.3238 ± 1.1×10^{-4}	0.292467
6	0.0921 ± 2.0×10^{-4}	0.666488
7	0.0818 ± 2.1×10^{-4}	1.634781
8	0.0236 ± 3.7×10^{-4}	3.5546

Table 11: Effective relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ and precursor decay constants λ_i [s^{-1}] for the SPERT IV 12/25-D core: simulation results obtained with Tripoli-4® by using `JEFF3.1.1` nuclear data library.

family	Reference	`ENDF/B-VII.r0`	$(C - C_{ref})/C_{ref}$	`JENDL-4.0`	$(C - C_{ref})/C_{ref}$	`MCNP6` `ENDF/B-VII.r0`
1	0.038 ± 3×10^{-3}	0.03193 ± 1.5×10^{-3}	-16.0 ± 8.9	0.03424 ± 1.4×10^{-3}	-9.7 ± 8.8	0.0318 ± 1.4×10^{-3}
2	0.213 ± 5×10^{-3}	0.16953 ± 3.2×10^{-3}	-20.4 ± 2.8	0.22425 ± 3.8×10^{-3}	5.2 ± 3.0	0.172 ± 4×10^{-3}
3	0.188 ± 1.6×10^{-2}	0.15908 ± 3.1×10^{-3}	-15.43 ± 8.8	0.19929 ± 3.5×10^{-3}	5.6 ± 8.7	0.162 ± 4×10^{-3}
4	0.407 ± 7×10^{-3}	0.45828 ± 5.5×10^{-3}	12.6 ± 2.2	0.38439 ± 4.9×10^{-3}	-5.4 ± 2.1	0.456 ± 6×10^{-3}
5	0.128 ± 8×10^{-3}	0.13397 ± 2.8×10^{-3}	4.7 ± 6.6	0.11483 ± 2.7×10^{-3}	-9.3 ± 6.6	0.134 ± 3×10^{-3}
6	0.026 ± 3×10^{-3}	0.04721 ± 1.6×10^{-3}	81.6 ± 16.2	0.04299 ± 1.7×10^{-3}	62.2 ± 15.0	0.0438 ± 14×10^{-3}

Table 12: Effective relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ for the SPERT IV D-12/25 core: reference values (C_{ref}) from (Johnson, 1963) and simulation results (C) obtained with Tripoli-4® by using `ENDF/B-VII.r0` and `JENDL-4.0` nuclear data libraries. Relative errors $(C-C_{ref})/C_{ref}$ are expressed in percent. Simulation results obtained with `MCNP6` by using `ENDF/B-VII.r0` are also reported.

family	Reference	`ENDF/B-VII.r0`	$(C - C_{ref})/C_{ref}$	`JENDL-4.0`	$(C - C_{ref})/C_{ref}$	`MCNP6` `ENDF/B-VII.r0`
1	0.0127 ± 2×10^{-4}	0.01249	-1.7 ± 1.6	0.01244	-2.1 ± 1.6	0.01249
2	0.0317 ± 8×10^{-4}	0.0318	0.4 ± 2.5	0.03054	-3.7 ± 2.5	0.03182
3	0.115 ± 3×10^{-3}	0.1094	-4.9 ± 2.6	0.1114	-3.1 ± 2.6	0.10938
4	0.311 ± 8×10^{-3}	0.31699	1.9 ± 2.6	0.3014	-3.1 ± 2.6	0.31699
5	1.40 ± 0.081	1.35398	-3.3 ± 5.8	1.1360	-18.9 ± 5.9	1.35384
6	3.87 ± 0.369	8.6366	123.2 ± 15.13	3.0141	-22.1 ± 9.8	8.63415

Table 13: Precursor decay constants λ_i for the SPERT IV D-12/25 core: reference values (C_{ref}) from (Johnson, 1963) and simulation results (C) obtained with Tripoli-4® by using `ENDF/B-VII.r0` and `JENDL-4.0` nuclear data libraries. Error bars on λ_i are smaller than 10^{-4} for all families. Relative errors $(C-C_{ref})/C_{ref}$ are expressed in percent. Simulation results obtained with `MCNP6` by using `ENDF/B-VII.r0` are also reported.

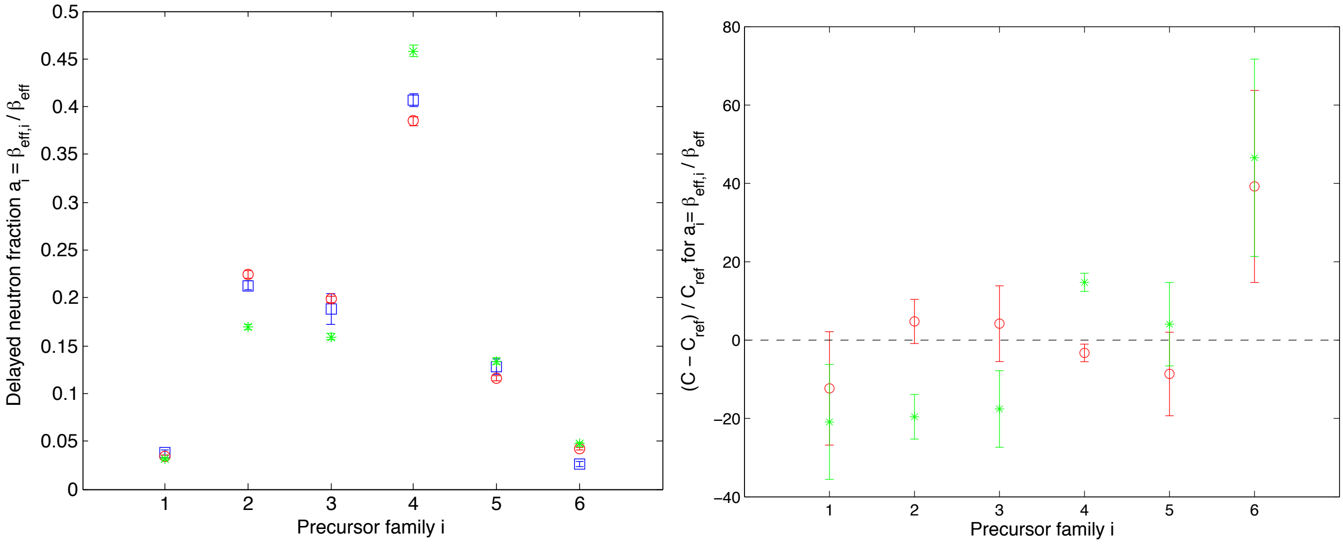

Figure 17: (Color online) Effective relative delayed neutron fractions $a_i = \beta_{\text{eff,i}}/\beta_{\text{eff}}$ for the SPERT IV 12/2-D core. Left. Blue squares represent reference values (C_{ref}) taken from (Johnson, 1963). The other symbols represent Tripoli-4® calculations (C): green stars for `ENDF/B-VII.r0` and red circles for `JENDL-4.0`. Right. Relative errors $(C - C_{ref})/C_{ref}$, in percent.

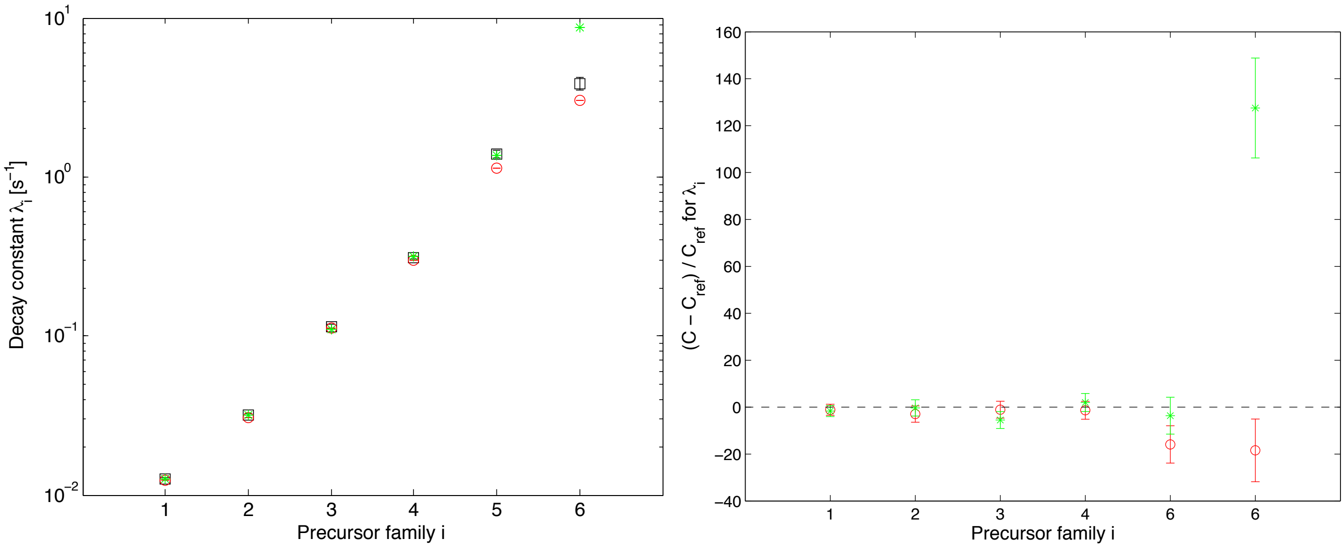

Figure 18: (Color online) Precursor decay constants λ_i for the SPERT IV 12/2-D core. Left. Black squares represent reference values (C_{ref}) taken from (Johnson, 1963). The other symbols represent Tripoli-4® calculations (C): green stars for `ENDF/B-VII.r0` and red circles for `JENDL-4.0`. Right. Relative errors $(C - C_{ref})/C_{ref}$, in percent.