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Validation of Monte-Carlo Methods for Generation Time and Delayed Neutron Fraction Predictions

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Abstract

The capability of Monte-Carlo codes to predict kinetic parameters of nuclear systems is validated against a series of experiments in zero-power reactors. Experimental data are issued from facilities operated by the CEA, SCK·CEN and PSI research institutes and analyzed in the framework of the Venus-Eole-Proteus international collaboration. Facilities were configured to study several reactor types (High Temperature Reactor, LWR, Material testing reactors, ADS demonstrator) and type of spectra (thermal, epithermal and fast). Monte-Carlo codes are used to predict the effective generation time and in some cases the effective delayed neutron fraction. The benchmarked codes are MCNP5 and MCNPX coupled to the LAMBDA scripts developed at SCK·CEN. Generation time predictions from the two codes agree within 2.5% for values larger than 1μs but have larger discrepancies (up to 7%) for faster systems. Discrepancies with the measured values depend largely on the selected experiment and can reach up until 9%. Delayed neutron predictions with MCNP5 compares well (3-4%) with all measurements.

Keywords: Generation time, Delayed neutron fraction, Monte-Carlo codes, Validation

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1. Introduction

Methods to estimate the effective generation time (Λ_{eff}) and the effective delayed neutron fraction (β_{eff}) of nuclear systems are standard in neutronics deterministic codes. The multigroup flux ϕ and adjoint flux ϕ^* are calculated and used to estimate the effective delayed neutron production $\langle \phi^*, F_d\,\phi \rangle$, effective fission neutron production $\langle \phi^*, F\,\phi \rangle$ and effective neutron density $\langle \phi^*, 1/v\,\phi \rangle$ and derive the effective parameters β_{eff} and Λ_{eff}. These methods were only recently adapted to Monte-Carlo codes due to the original difficulties to estimate effective parameters, or the adjoint flux, in continuous energy simulations. The main chosen technique today is the so-called "Iterated Fission Probability", which allows

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estimating the scalar products mentioned above using a set of latent generations. Several versions of this technique were recently implemented in Monte-Carlo codes used for neutronics studies, e.g. MCNP5 [1, 2], SERPENT2 [3] and TRIPOLI4 [4]. As such these methods need to be validated. This is often done on available benchmarked experiments such as that found in the International Handbook of Evaluated Criticality Safety Benchmark Experiments database [5]. In this paper we consider an alternate source of experimental data, which stems from a collaboration between the CEA, SCK·CEN and PSI institutes, to extend the validation process. In addition, we also compare effective generation time results obtained by the iterated fission probability technique in MCNP5 with that of the LAMBDA script, developed at SCK·CEN [6]. The script automatically launch several MCNP5/MCNPX calculations with different concentration of a fake absorber, having a 1/v cross sections, and tally the change in reactivity leading to the estimation the effective generation time.

Section 2 presents the experimental programs and the core configurations selected for the validation of the methods for kinetic parameters estimation. It also details the methods and code used in the validation. Sections 3 and 4 compares the experimental and calculation results for Λ_{eff} and β_{eff}, respectively, and discusses trends in light of other data in the open literature. We conclude the paper summarizing the findings and making recommendations as for the need for further validation work.

2. Materials and Methods

This section presents the experimental configurations and the Monte-Carlo codes selected for the validation of the methods to calculate kinetic parameters. A table synthesizing all measurements and calculations is given at the end of the section.

2.1. Experimental programs

Experimental programs selected for the validation originates from the Proteus , Venus, Masurca, Eole and Crocus zero-power reactors, which belong to PSI, SCK·CEN, and CEA research centers and to the EPFL university. All these reactors are test bed for reactor experiments targeting the validation of neutronics code. The experiments all have negligible thermal-hydraulic feedback because of the very low power. These machines are very flexible and several type of reactor concepts varying from Light Water Reactors to fast Accelerator Driven Systems, via High Temperature Reactors concepts can be studied, which provides in turn a wide range of spectral conditions to test the codes. The selected programs and configurations are presented below for the different reactors.

2.1.1. HTR- and LWR-Proteus programs

Proteus is a driven reactor containing an experimental central cavity surrounded by an annular section of graphite filled with UO_2 5% enriched fuel rods acting as driver and reflector region. The central cavity content is varied depending on the studied reactor concept, whereas the driver/reflector region remain practically unchanged [7]. For this paper we select the HTR-Proteus and LWR-Proteus programs.

The HTR-Proteus experiments were performed in the 1990s, in the framework of an IAEA coordinated research program, to validate design and safety related calculations for small-sized LEU-HTR. The central cavity of Proteus was loaded with different arrangements of fuel (graphite sphere containing coated LEU particles) and moderator (pure graphite) pebbles. In this paper, we focus on configurations 5 and 10 [8]. Configuration 5 is a reference configuration in which the fuel-to-moderator pebble ratio is 2-to-1, the packing arrangement is point-to-point and no additional moderator is present in the central cavity of Proteus. Configuration 10 simulates water ingress using polyethylene rods inserted between the pebbles. The pebbles are still arranged in a point-to-point layout but the fuel-to-moderator ratio is 1-to-1. During these experiments, a neutron generator was inserted below the core and the prompt decay constant $\alpha = (\beta_{eff} - \rho)/\Lambda_{eff}$ was measured by the pulse neutron source (PNS) [9] and neutron noise [10] techniques. Measurements were performed at different subcritical and power levels and the ratio $\alpha_0 = \beta_{eff}/\Lambda_{eff}$ was deduced. The results obtained by the PNS method were the reference values and are used in this paper. The generation time Λ_{eff} is estimated here using a β_{eff} value calculated with the Monte-Carlo code under scrutiny.

The LWR-Proteus experiments were performed in the 2000s in support to LWR physics. Phase II of the experiments was concerned with burnup credit, inserting spent fuel segments in a PWR mock-up. Phases I and III was dedicated to the neutronic characterization of modern fresh BWR assemblies. Phase III-2, selected for this paper, featured nine real SVEA-96 Optima-2 assemblies in the central cavity of Proteus [11]. No measurements of the kinetic parameters of the configuration were performed, but several codes were used to estimate the generation time.

2.1.2. CROCUS configuration

Crocus is a teaching reactor at the EPFL university in Switzerland [12, 13]. It is a pool type reactor with two lattices of UO_2 (0.95% enriched) and U_{metal} (1.8% enriched) fuel pins loaded in water. Several experiments are routinely performed for the Nuclear Engineering Master program common between EPFL and ETHZ. In 2013-14, a new neutron noise experiment was designed and is now part of the curriculum[14, 15]. This experiment allowed us to measure $\alpha = (\beta_{eff} - \rho)/\Lambda_{eff}$ but also β_{eff} and Λ_{eff} using the Power Spectral Density and Feynman-α techniques.

2.1.3. The AMMON program in EOLE

The AMMON experiments were performed in the Eole facility to study the Jules Horowitz Reactor (JHR) neutron and photon physics. JHR is the next European material testing reactor being build at CEA Cadarache [16]. It has several unique features such as the geometry and tolerances of its fuel assembly. During the AMMON experiments the experimental zone of Eole was loaded with six or seven JHR-type assemblies, each containing 24 U_3Si_2Al 27% enriched curved fuel plates, surrounded by a driver zone with enough standard pressurized water reactor (PWR) UO_2 fuel pins to reach criticality. The power profile distributions in the fuel plates, excess criticality, assembly power, spectral indices, effective delayed neutron and generation time and photon heating were measured. These results and their uncertainties were then transposed, thanks to data assimilation techniques applied to Monte-Carlo and deterministic neutronic codes, to the JHR design. This permit to quantify the required tolerance and reduce uncertainties on the reactor parameters of the JHR [17, 18]. Several core configurations were studied during the AMMON experiments. We focus here on the reference configuration in which the effective delayed neutron fraction and generation times were measured using the Cohn-α noise measurement technique [19].

2.1.4. The MUSE-4 program in MASURCA

The MUSE-4 experiments aimed at operating a fast subcritical core coupled to an external neutron source simulating the spallation source of an Accelerator Driven Systems without feedback. The experiments provided data to validate codes and allowed investigating measurement techniques to monitor sub-criticality levels. They were carried out in the Masurca fast zero-power reactor (<5 kW) located at CEA Cadarache from 2000 to 2004.

All core configurations were representative of a fast burner reactor. The core was loaded with MOX fuel and sodium rodlets and reflected with sodium and stainless steel regions. In its center a tritium target surrounded by lead buffer simulated the spallation target to be found in Accelerator Driven Systems. The external neutron source was provided by D-T reactions originating from the 250 keV deuteron beam provided by the Genepi accelerator manufactured by the CNRS. The accelerator worked in periodic pulsed condition. A reference critical and several subcritical configurations, with $\mathrm{k_{eff}}$ as low as 0.95, were investigated. The kinetic parameters β_{eff} and Λ_{eff} were measured in the reference configuration by different noise measurement techniques. We are focusing here on the measurement performed by Power Spectral Density with two large U-235 fission chambers ($\approx$ 5g U-235) located in the reflector and surrounded by polyethylene moderator [20].

2.1.5. The FREYA program in VENUS

The FREYA experiments (Fast Reactor Experiments for hYbrid Appplications) are designed to validate reactor monitoring in Accelerator Driven Systems [21]. The experiments are part of the 7th Euratom Framework Program and are carried out in the Venus reactor. The zero-power reactor Venus was converted in a fast reactor in 2011, Venus-F, and coupled with the Genepi-3c accelerator to study Accelerator Driven Systems with fast spectra at different subcritical levels ($\mathrm{k_{eff}}$ =0.85-0.99) and pave the way to the MYRRHA experiments. Venus-F is composed of highly enriched uranium fuel ($\approx$30%) mixed with solid lead rodlets. Genepi-3c is an evolution of the Genepi deuteron accelerator and can be operated in periodic, continuous or periodic beam interruption conditions. As such it allows investigating a larger range of reactivity measurement techniques, more representative of what is expected in a commercial Accelerator Driven Systems. For this work, we are interested in a set of measurements to determine the kinetics parameters that was performed by CNRS using the Rossi-α noise measurement technique. The measurements were performed in 2014 in the critical configuration with the accelerator turned off and both β_{eff} and Λ_{eff} were measured [22].

2.2. Codes and Libraries

Generation time (Λ_{eff}) and in some case delayed neutron fraction (β_{eff}) were estimated with MCNP5, LAMBDA and the modern nuclear libraries JEFF-3.1/3.1.1/3.1.2 and ENDF/B-VII.0/1. The following sections shortly presents the codes and their capabilities to calculate kinetic parameters.

2.2.1. MCNP5-1.6

MCNP5 was released in 2010 and is able to calculate $\alpha_0 = \beta_{eff}/\Lambda_{eff}$, Λ_{eff} and β_{eff} for any criticality calculation. In addition it computes the delayed neutron abundances (β_i) and average decay constants (λ_i) in a 6- or 8-group structure depending on the selected nuclear data library[1]. Effective parameters (β_{eff}, Λ_{eff}) requires estimating the adjoint flux. This is done in MCNP5 with the so-called iterated fission probability, which is calculated by estimating how much a neutron from an "original" generation (cycle in MCNP5) contributes to, for example, the neutron production by fission in a later "asymptotic" generation. In theory, to match the definition of the adjoint function, the number of generation between the original and the asymptotic generation should be infinite [23]. The number of these latent generations can be controlled in MCNP5 to reach a reasonable approximation of the adjoint quantities [24]. Ten latent generations has been proved to be a reasonable estimate for most problems and is the default implemented in MCNP5.

In this work we use 10 latent generation for each criticality calculation and a number of particle adequate to converge the source term, pass the statistical tests and yield sufficiently small uncertainties on the kinetic parameters.

2.2.2. LAMBDA

LAMBDA is a python script developed by SCK·CEN that is wrapped around any version of MCNP or MCNPX and allow calculating the effective generation time without using the capabilities of the latest version of MCNP detailed in the previous paragraph [6]. The method is based on the fact that the reactivity change between a reference state (0) and a perturbed state (c), in which an absorber having a macroscopic cross section $\Sigma(v) = c/v$ is added to all cells of the model, is:

$$\Delta\rho = \rho_c - \rho_0 = \frac{\langle \phi_0^*,\, \frac{c}{v}\,\phi_c \rangle}{\langle \phi_0^*,\, F_0\,\phi_c \rangle} \tag{1}$$

where F_0 is the production operator by fission in the reference state (0) and c is a constant. By definition, this reactivity change tends toward the generation time Λ_{eff} when c tends toward 0.

The LAMBDA wrapper modify the reference MCNP input file diluting the fictitious absorber in all cells of the problem and launch a series of perturbed calculations for several values of the constant c. The reactivity changes as compared to the reference state are

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[1] ENDF libraries still use the 6-group structure introduced by Keeping, whereas JEFF libraries switched to a more physical 8-group decomposition.

plotted as a function of c and the extrapolation to the value of c=0 gives the generation time. This approach works for small values of c for which the reactivity change is linear with c. The LAMBDA code only calculates the generation time and cannot be used for estimating the delayed neutron fraction, for example.

In this work, we select several c values to fully cover the linear domain of $\Delta\rho$ vs. c. This allows us to minimize the uncertainty on the generation time, which results from the intercept value of the weighted linear regression.

2.3. Measurements and Calculations Summary

Table 1 lists the kinetic parameters measured in the selected configurations and the measurement technique used. The nuclear data library of each calculation is given in the last two columns. MCNP5 calculations yield both Λ_{eff} and β_{eff}, whereas LAMBDA calculations only yield Λ_{eff}. The selected experiments are sorted by their approximate generation time to illustrate the range of conditions encountered in this validation suite. The generation time values vary by 4 order of magnitudes.

Table 1: Matrix of performed measurements and calculations

Config.	Λ_{eff}	Measured	MCNP5	LAMBDA
HTR-5	1850μs	β/Λ (PNS)	B-VII.0, J-3.1	J-3.1
HTR-10	1700μs	β/Λ (PNS)	B-VII.0, J-3.1	J-3.1
LWR-III.2	400μs	-	B-VII.0, J-3.1	J-3.1
CROCUS	47μs	Λ, β (CPSD)	B-VII.0/1, J-3.1	J-3.1
AMMON	30μs	Λ, β (Cohn-α)	B-VII.0, J-3.1	B-VII.0
MUSE-4	550ns	Λ, β (CPSD)	B-VII.0/1, J-3.1.2	B-VII.0/1, J-3.1.2
FREYA	410ns	Λ, β (Rossi-α)	B-VII.1, J-3.1.2	B-VII.1, J-3.1.2

3. Generation Time Results

This section presents the experimental and calculation results for the generation time. The effect of the nuclear data library is detailed before comparing predictions with experimental values.

3.1. Library Effect

Table 2 compares the generation time obtained with MCNP5 and different libraries. The selected configurations include thermal systems (HTR-Proteus, LWR-Proteus, Crocus and AMMON) and fast ones (MUSE-4 and FREYA). The uncertainties reported in Table 2 are the Monte-Carlo uncertainties given by MCNP5. These uncertainties are extremely low, less than 0.2% in most cases, and do not account for any uncertainty in the cross sections. Results obtained with different nuclear data libraries - especially between ENDF and JEFF - therefore do not always agree within 3σ. The agreement between the generation time predictions with the different tested libraries, however, is always better than 3%, that is about the target uncertainty on this value[2].

Table 2: Generation time predictions obtained with MCNP5 and different nuclear data libraries

Config.	B-VII.0	B-VII.1	J-3.1	J-3.1.2
HTR-5	1875.9±2.0μs	-	1871.5±2.0μs	-
HTR-10	1723.1±1.9μs	-	1716.4±1.9μs	-
LWR-III.2	392.1±0.4μs	-	389.7±0.5μs	-
CROCUS	47.70±0.05μs	47.68±0.05μs	47.82±0.05μs	-
AMMON	30.87±0.02μs	-	30.64±0.03μs	-
MUSE-4	546.7±0.9ns	538.7±0.9ns	-	533.8±0.9ns
FREYA	401.1±1.3ns	394.9±1.4ns	-	397.2±3.3ns

We also ran the LAMBDA with different nuclear libraries for the MUSE-4 and FREYA experiments. Results obtained with the different libraries agree within 1-2σ, that is within 2%. The uncertainty is naturally larger from that obtained with MCNP5 due to the method implementation [1].

3.2. Comparison of code and measurement results

Table 3 lists the measured generation times and their predictions with MCNP5, their comparisons, and the comparison of the values obtained with the MCNP5 and LAMBDA codes. As shown in the previous section, the impact of the nuclear data library on the predicted value of Λ_{eff} is generally within 1-2% (with the exception of that of the MUSE-4 program - within 3%). We therefore chose to present values from only one library in each case; when possible that obtained with the JEFF-3.1 or JEFF-3.1.2 library. The only exception is for the AMMON program, for which we used the ENDF/B-VII.0 library.

Table 3: Effective generation time predictions and measurements

Config.	Meas.	MCNP5	LAMB./MCNP-1	MCNP/Meas-1
HTR-5$^+$	1959.9±21.8μs	1871.5±2.0μs	-1.0±0.7%	-4.5±1.1%
HTR-10$^+$	1720.6±21.3μs	1716.4±1.9μs	0.0±0.7%	-0.2±1.2%
LWR-III.2	-	389.7±0.5μs	2.4±0.3%	-
CROCUS	49.0±1.5μs	47.82±0.05μs	-2.3±3.6%	-2.4±3.0%
AMMON*	28.8±0.8μs	30.87±0.02μs	1.1±2.0%	7.2±3.0%
MUSE-4	586±10ns	533.8±0.9ns	-6.8±2.0%	-8.9±1.6%
FREYA	407±35ns	397.2±1.6ns	-6.8±0.8%	-2.4±8.4%

$^+$Only β/Λ was measured; * ENDF/B-VII.0 is used instead of JEFF-3.1

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[2] As a side remark, a small increasing trend in the difference of Λ_{eff} predictions with JEFF and ENDF is seen when Λ_{eff} is reduced.

3.2.1. MCNP5 vs. LAMBDA

The agreement between the predictions of the two calculation methods is well within 1σ for all the systems having a generation time larger than 10μs, with the exception of the LWR-Proteus configuration. For all these systems the agreements remain, however, within 2.5%, i.e. in better agreement than the target uncertainty on the generation time. The fast systems, with a generation time lower than 1μs, exhibit, however, larger discrepancies ($\approx$4% and 7%) between the two methods.

Several other predictions were published in the open literature. Regarding the AMMON experiments, C. Vaglio-Gaudard et al. [19] reported, in addition to the experimental values listed in Table 3, an estimate for the generation time of $30.0\pm0.3\mu$s obtained with TRIPOLI4 and JEFF-3.1 while using the same method than that implemented in the LAMBDA code (see section 2.2.2). This prediction is in better agreement with the measured value than the prediction by the LAMBDA & ENDF/B-VII.0 ($31.22\pm0.62\mu$s), i.e. for the same method but different library, or than that by MCNP5 & JEFF-3.1 ($30.64\pm0.03\mu$s), i.e. for the different method but the same library. Assuming that the TRIPOLI4 and MCNP5 transport is the same, the difference suggests some small difference in the TRIPOLI4 and MCNP5 model, which could explain the large deviation with the measured value in Table 3.

3.2.2. MCNP5 vs. Measurements

The agreement of MCNP5 predictions with the measured values are harder to interpret. For the HTR-10, CROCUS and FREYA experiments, results agree well within 1σ and 2.5%. The other results disagree by more than 4.5% and by more than 2σ in each case.

In the HTR experiments, however, only the decay constant $\alpha_0 = \beta_{eff}/\Lambda_{eff}$ was measured. In Table 3 we used the delayed neutron fraction calculated with MCNP5 & JEFF-3.1 to scale the experimental results and be coherent with the calculations. To compare values for different libraries, we can compare directly the decay constants. The measured value for the HTR-5 experiment is $3.597\pm0.026\text{s}^{-1}$ and the predictions with JEFF-3.1 and ENDF/B-VII.0 differ by 4.7±1.2% and 3.8±1.2%, respectively. For this experiment, using ENDF/B-VII.0 instead of JEFF-3.1 slightly improve the results but the disagreement with measurement remains larger than 3σ. For the HTR-10 experiments the measured decay constant is $4.132\pm0.051\text{s}^{-1}$ and predictions with JEFF-3.1 and ENDF/B-B-VII.0 differ from the experimental value by 0.2±1.5% and -3.6±1.4%, respectively. Both libraries predictions agree with the measured value within 3σ but this time, predictions with JEFF-3.1 are in far better agreement. This contradicting results do not allow to favor one of the two libraries for HTR-type configurations.

Regarding the AMMON experiments, a similar disagreement is observed when using JEFF-3.1 instead of ENDF/B-VII.0 (as reported in Table 3), i.e. 6.4±3.0% instead of 7.2±3.0%. As for the HTR-Proteus experiments, we can compare directly the decay constant $\alpha_0 = \beta_{eff}/\Lambda_{eff}$, which is measured more easily and with better precision. Predictions with JEFF-3.1 and ENDF/B-VII.0 differs from the experimental value ($261.6\pm1.3\text{s}^{-1}$) by -1.8±0.8% and -5.0±0.6%, respectively. This points toward a large compensation effect between predicted values of Λ_{eff} and β_{eff} with JEFF-3.1 for this experiment (see section 4).

Regarding the MUSE-4 experiments, the disagreement with the experimental value remain similar when using ENDF/B-VII.0/1 (-6.7/8.1±1.6%) instead of JEFF-3.1.2 (-8.9±1.6%). Results obtained with the LAMBDA code and the different libraries are also in agreement within their uncertainty. However, the disagreement with the measured value becomes larger (from ≈-12% to -15%).

Generation time predictions were already performed for the MUSE-4 program and showed to agree with the experimental values [6]. In this comparison, the experimental values reported in [25] for the REF-1132 and REF-1115 configurations, which are 0.59±0.01μs and 0.55±0.02μs, were selected. In Ref. [6] Verboomen et al. chose to consider the two measurement as "identical" and to define a 2σ experimental domain of [0.51μs, 0.61μs], i.e. an experimental uncertainty of 0.05μs (≈ 9%). With such a high uncertainty, the validation of code methods becomes limited. In addition a 9% uncertainty is barely compatible with the uncertainty for the type of measurement performed. In this analysis, we chose to keep only the measurement by Power Spectral Density technique in the REF-1132 configuration, which was performed by one of the author [20], and for which the generation time obtained was 586±10ns, i.e. with an uncertainty 5 times lower and an improved validation power. On this ground, we selected this value for Table 3. In addition we specifically modeled the REF-1132 configuration with the two CFUK09 (5g U-235) fission chambers and their polyethylene cover that were used during the experiment [26] in the hope to improve the predictions. However, as reported above, the disagreement with the measurement still stands.

Finally, regarding the FREYA experiments, the agreement with the experimental value is satisfactory. The post-processing of the measured values are, however, preliminary and were only recently reported [22]. The uncertainty is high (≈8.5%) because of the low count rate of the available detectors. New measurements are already planned in the framework of the on-going FREYA program.

4. Delayed Neutron Fraction Results

Table 4 lists the measured delayed neutron fractions and the MCNP5 estimations obtained with different versions of the JEFF and ENDF/B-VII libraries. The MCNP5 results are presented in the form of deviation to the measurement value with the 1σ uncertainty. Fewer experiments are presented as the delayed neutron fraction was not measured in the HTR-Proteus and LWR-Proteus programs.

Table 4: Effective delayed neutron fraction predictions and measurements

Config.	Meas.	BVII.0/Meas-1	J31/Meas-1	BVII.0/J31-1
CROCUS	756±20pcm	-2.6±2.7%	0.4±2.8%	-3.0±1.3%
AMMON	754±19pcm	1.5±2.7%	4.1±2.8%	-2.5±0.7%
MUSE-4^{+}	334±6pcm	-6.0±1.8%	-3.3±1.8%	-2.8±0.9%
FREYA^{+}	730±11pcm	-0.3±1.6%	-1.0±1.6%	0.7±0.8%

$^{+}$JEFF-3.1.2 is used instead of JEFF-3.1

Predictions of β_{eff} are generally more sensitive to the employed nuclear data library, which contains the delayed neutron decay constants, λ_i, and abundances, β_i, than for Λ_{eff}. The last column of Table 4 shows an almost constant bias of 3% between β_{eff} values obtained with JEFF-3.1/3.1.2 and ENDF/B-VII.0; results for FREYA are the only exception. The same comparison was done for HTR-5 & 10 and for LWR-III.2 and resulted in differences in β_{eff} values of -0.6±1.2%, -3.4±1.2% and -3.4±0.7%, respectively. HTR-10 and LWR-III.2 shows a similar bias of -3% - whereas HTR-5 predictions agree. We also calculated β_{eff} values with ENDF/B-VII.1 for several configurations and obtained each time values agreeing with that obtained with ENDF/B-VII.0 within 1σ.

Hudelot et al. computed β_{eff} with MCNP and the NRG method [27] for the MISTRAL-1 and -2 experiments, which features UO_2 and MOX cores in the Eole facility, and observed the same -3.0% bias between JEFF-3.1.1 and ENDF/B-VII.0 [28]. Finally, Truchet et al. reported in Table 7 of [29] an extensive set of comparison for β_{eff} estimation with the iterated fission probability method implemented in TRIPOLI4. They selected the famous series of Los Alamos criticals including Godiva, Jezebel, the Flattops, and Bigten. Predicitons by ENDF/B-VII.0 and JEFF-3.1 are biased (by 2.5 to 3%) only in the Jezbel and Flattop-Pu cases, i.e. for a fissile part made of Pu-239, with and without U-238 reflector. β_{eff} predictions for experiments with high enriched uranium and uranium 233 agree well within 1σ. This observation concurred with the good agreement observed for the FREYA experiments, which contains high enriched uranium (≈30% enrichment) in a relatively fast spectra, and the 3% bias seen for the MUSE-4 experiments, whose fuel is loaded with solid sodium and contains 78% of U-238 and 21% of Pu-239.

Finally, predictions with both ENDF/B-VII.0 and JEFF-3.1/3.1.2 agree well within 1-2σ with the measured values (with the exception of the ENDF/B-VII.0 value for MUSE4). On average, the agreement is slightly better when using JEFF-3.1.

5. Conclusions

In this paper, we compared predictions of the effective generation time, Λ_{eff}, obtained with MCNP5 and the LAMBDA code developed at SCK·CEN with measurements performed in several zero-power reactor experiments. This validation suite is interesting as it comprises experiments modeling High Temperature Reactors, Light Water Reactors, material testing reactor, small reactor and fast UO_2 and MOX Accelerator Driven Systems, and has generation time spanning from about 0.41μs to 1850μs. Overall, we found that:

- Λ_{eff} predictions by MCNP5 and LAMBDA agree within 2.5% when larger than 1μs but disagree more when smaller (as illustrated by the MUSE-4 and FREYA experiments)
- Λ_{eff} predictions by MCNP5 and LAMBDA are rather insensitive (<3%) to the use of JEFF-3.1/3.1.2 or ENDF/B-VII.0/1.
- Λ_{eff} predictions by MCNP5 only agree in few cases with the measured values (HTR-10 and CROCUS experiments), and can differ by up to 9% (MUSE-4 experiments). The larger disagreement are suspected, however, to come from approximations in the modeled geometry.

- β_{eff} predictions by MCNP5 with ENDF/B-VII.0/1 and JEFF-3.1/3.1.2 agree in most cases within 1-2σ, i.e. 3-4%, with the measured values.

According to this list and to other findings available in the open literature, we conclude that the iterated fission probability method implemented in MCNP5 gives reliable estimates for β_{eff}, and predictions for Λ_{eff} that are compatible with that obtained with the "1/v" absorber dilution technique employed in LAMBDA. Agreement with the measured values of Λ_{eff} are, however, to be improved by refined model of the experimental conditions and more precise measurements, especially for fast systems.

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