Benchmark Results for Delayed Neutron Data

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Abstract. We have calculated the effective delayed neutron fraction $\beta_{\text{eff}}$ for 32 benchmark configurations for which measurements have been reported. We use these results to test the delayed neutron data of JEFF-3.0, ENDF/B-VI.8, and JENDL-3.3.

INTRODUCTION

The proof of nuclear data quality is in the validation. For each purpose for which nuclear data are used, such as criticality safety, shielding, or transient calculations, these data have to be validated. This can be done by comparing the results of calculations based on these nuclear data with experimental results. For criticality safety, many such experimental results have been evaluated, resulting in thousands of benchmark specifications [1]. Similarly, for shielding there is e.g., the NEA project Sinbad [2], or the IAEA collection of fusion-shielding benchmarks [3]. For delayed neutron data, the number of systems that may serve as a benchmark is considerably smaller.

Recently, experiments have been performed in fast systems to measure the effective delayed neutron fraction $\beta_{\text{eff}}$ [4]. For thermal systems, a re-evaluation of an older measurement of $\beta_{\text{eff}}$ is reported [5], and a recent measurement in a research reactor was published [6]. To extend this work, we present in this article a list of systems for which measurements of $\beta_{\text{eff}}$ or $\alpha$ (see below) are reported. For the validation of the JEF-2.2 nuclear data library, many of these systems were also analysed [7]. We have also performed calculations of $\beta_{\text{eff}}$ and $\alpha$ using a recently developed Monte Carlo method [8], and using nuclear data from JEFF-3.0, ENDF/B-VI.8, and JENDL-3.3.

BENCHMARK SYSTEMS

We have searched in the literature for measurements of the effective delayed neutron fraction, the result of which is listed below. We will use these experiments as benchmarks for our calculation of $\beta_{\text{eff}}$. For some systems we have found experimental values for the parameter $\alpha$, which is linked to $\beta_{\text{eff}}$ through $\alpha = [k(1-\beta_{\text{eff}})]/l$, where $l$ is the prompt neutron life-time. All systems described below are at delayed criticality, so that the parameter we can compare with is the value $\alpha_{\text{dc}} = \alpha(k = 1) = -\beta_{\text{eff}}/l$.

When not stated explicitly, the MCNP [9] model for the experiment was taken, without modifications, from the ICSBEP data [1]. Where possible, the ICSBEP identification is given in brackets after the benchmark name.

- **Godiva** (heu-met-fast-001)
  A bare sphere of highly enriched (94 wt%) uranium.

- **Jezebel** (pu-met-fast-001)
  A bare sphere of plutonium (95 at% Pu-239).

- **Skidoo** (u233-met-fast-001)
  A bare sphere of uranium, of which 98 at% U-233.

- **Topsy** (Flattop 25, heu-met-fast-028)
  A highly enriched (93 wt%) uranium sphere surrounded by a thick reflector of normal uranium. Experimental results are given in [10].

- **Popsy** (Flattop-Pu, pu-met-fast-006)
  A plutonium (94 wt% Pu-239) sphere surrounded by a thick reflector of normal uranium. Experimental results are given in [10].

- **Flattop 23** (u233-met-fast-006)
  A uranium (98 at% U-233) sphere surrounded by a thick reflector of normal uranium. Experimental results are given in [10].

- **Big Ten** (ieu-met-fast-007)
  A large, mixed-uranium-metal cylindrical core with 10% average U-235 enrichment, surrounded by a thick reflector of depleted uranium [12].

- **ZPR** (heu-met-inter-001, ieu-met-fast-010, mix-met-fast-011 case 1, pu-met-inter-002)
  Four cores in the Zero Power Reactor at ANL. The first one is a highly enriched uranium/iron...
benchmarks, reflected by steel. The second is a heterogeneous cylindrical core of uranium (average enrichment 9%). The third has plutonium/uranium/zirconium fuel, reflected by graphite. The last core had heterogeneous plutonium metal fuel with carbon/stainless-steel dilutions, and a steel reflector. Measured values for $\beta_{\text{eff}}$ are given in e.g., [7].

- **SNEAK** (cores 7A, 7B, 9C1, and 9C2)
  Measurements of $\beta_{\text{eff}}$ in four unmoderated PuO$_2$-UO$_2$ cores, surrounded by a depleted uranium reflector [13]. One core, 9C1, had only uranium as fuel. The 9C2 core was diluted with sodium. MCNP models were built based on the R-Z model descriptions in [13].

- **Masurca** (cores R2 and ZONA2)
  Measurements of $\beta_{\text{eff}}$ by several international groups in two unmoderated cores, viz. R2 and ZONA2 [4]. Core R2 had of ~ 30% enriched uranium as fuel, whereas ZONA2 had both plutonium and depleted uranium. Both cores were surrounded by a 50-50 UO$_2$-Na mixture blanket, and by steel shielding. MCNP models were built based on the R-Z model descriptions in [4].

- **FCA** (cores XIX-1, XIX-2, and XIX-3)
  Measurements of $\beta_{\text{eff}}$ by several international groups in three unmoderated cores in the Fast Critical Assembly [4]. One core had highly enriched uranium, one had plutonium and natural uranium, and the third one had plutonium as fuel. The cores were surrounded by two blanket regions, one with depleted uranium oxide and sodium, and another one with only depleted uranium metal. MCNP models were built based on the R-Z model descriptions in [4].

- **TCA** (related to leu-comp-therm-006)
  A light water-moderated low-enriched UO$_2$ core in the Tank-type Critical Assembly. From the description of this experiment in [5] it is clear that this experiment is closely related to benchmark leu-comp-therm-006 [1]. We have taken the MCNP input decks given in [1], and changed the loading pattern, water height, and lattice pitch.

- **IPEN/MB-01** (related to leu-comp-therm-077)
  Measurement of $\beta_{\text{eff}}$ in the research reactor IPEN/MB-01, with a core consisting of 28 $\times$ 26 UO$_2$ (4.3% enriched) fuel rods inside a light-water-filled tank [6]. An MCNP input deck was made available by the authors of [6].

- **Winco slab tanks** (related to heu-sol-therm-038 case 5)
  Measurement of $\alpha$ in the Westinghouse Idaho Nuclear Company Slab Tank Assembly. The experiment consisted of two thin coaxial slab tanks with 93% enriched uranyl nitrate solution. From the description of this experiment in [14] it is clear that this experiment is closely related to heu-sol-therm-038, case 5 [1]. We have taken the MCNP input deck given in [1], and removed the stainless-steel absorber between the two slab tanks.

- **Stacy** (leu-sol-therm-004, -007, -016, -021)
  Measurements of $\beta_{\text{eff}}/l$ in uranyl nitrate solution (10% enrichment) in several cores in the STACY facility. From the description of these experiments in [15], one can identify several experiments that have been included in the criticality benchmark collection [1].

- **Sheba** (core II)
  Measurement of $\beta_{\text{eff}}/l$ in a critical assembly vessel, filled with 5% enriched uranyl fluoride, UO$_2$F$_2$, the Solution High-Energy Burst Assembly [16]. The vessel had a cylindrical shape, and there was no reflector. An MCNP model was built from scratch.

- **SHE-8**
  Measurement of $\beta_{\text{eff}}/l$ in a split table-type critical assembly called Semi-Homogeneous Assembly [17]. The core was shaped in a hexagonal prism, with graphite matrix tubes and graphite rods. There was no axial reflector. The central region in core 8 consisted of 73 fuel rods with 2.9% enriched UO$_2$ dispersed in graphite. An MCNP model was built from scratch.

- **Proteus** (core 5)
  Measurement of $\beta_{\text{eff}}/l$ in a graphite-reflected pebble-bed reactor, containing uranium-carbon fuel pebbles (16.7% enrichment) and graphite moderator pebbles. As the reactor was operated below 1 kW, no coolant was needed. Since one of the present authors (AH) was a contributor to [18], an MCNP model was readily available.

For Godiva, Jezebel, and Skidoo, both Keepin [11] and Paxton [10] give experimental values for $\beta_{\text{eff}}$. Although these values are not identical, the differences are small and have no significant impact on the conclusions drawn in this paper. Therefore we will use the numbers given by Keepin, because this is the commonly used reference.

For Big Ten, an experimental value $\alpha = -(1.17 \pm 0.01) \times 10^5$ s$^{-1}$ is given by Paxton [10]. Based on a calculation of $\beta_{\text{eff}} = 720$ pcm, he estimates the prompt neutron life-time to be $6.15 \times 10^{-8}$ s, which is consistent with our calculation of $6.15 \times 10^{-8}$ s within a fraction of a percent. Therefore we feel it is justified in this case to compare with the value of $\beta_{\text{eff}} = 720$ pcm as if it were determined by experiment.

For the Stacy, Winco, SHE-8, Sheba-II, and Proteus experiments, we will compare with the $\alpha$ values given
in the respective references, because that is the measured quantity. Also, for the Winco experiment, there is some uncertainty in deriving a value for $\beta_{\text{eff}}$ from the measured $\alpha$. The comparison in the next section is done by dividing the calculated $\beta_{\text{eff}}$ by the prompt neutron fission life-time. This life-time is calculated by MCNP by default, and is given in the output as the ‘fission lifespan’ (see the discussion of life-time estimation in section 2.VIII.B of the manual [9]).

Results and Discussion

We have calculated $\beta_{\text{eff}}$ for all experiments described in the previous section, based on three different nuclear data evaluations, viz. JEFF-3.0 [19], ENDF-B/VI.8 [20], and JENDL-3.3 [21]. The results for the Sheba-II, SHE-8, TCA, and Winco experiments should be viewed with some caution, since the preparation of the MCNP models for these experiments involved interpretation on our part, based on the references given earlier. However, since the computational results for these cases are close to the experimental values, we judge the models to be appropriate for calculating $\beta_{\text{eff}}$ and $\alpha$.

Concerning the Winco slab-tank experiment, another remark is in order. Our calculation of $\beta_{\text{eff}}$ yields a value of $822\pm 10$ pcm, contradicting the value $1500\pm 120$ calculated in [14], based on the experimental $\alpha$-value and other experimental information, not involving the prompt neutron fission life-time. However, in [14] it is noted that its calculated value is higher than the expected value of roughly 900 pcm, the reason for which was not well understood. Our value for $\alpha$ is close to the experimental value.

For the IPEN/MB-01 results, we can also compare with the calculational results quoted in [6]: 792 pcm using ENDF/B-VI.8 and 756 pcm using JENDL-3.3 data. These values were obtained by using a NJOY/AMPX-II/TORT code system. Our results are $782\pm 4$ and $756\pm 4$ pcm, respectively. (The experimental value is $742\pm 7$ pcm.)

From the results presented in Fig. 1, we conclude the following:

- Almost all results are within 6% of the experimental value. Only in a limited number of cases, the results lie outside the combined experimental and statistical uncertainty margin.
- Judging by the results for TCA, IPEN/MB-01, Stacy, Winco, and Proteus, the JENDL-3.3 nuclear data library gives the best $\alpha$ and $\beta_{\text{eff}}$ results for LWR and HTR type applications.
- JEFF-3.0, ENDF/B-VI.8 lead to a ~4% overprediction of $\beta_{\text{eff}}$ for LWR- and HTR-type applications.
- For fast systems the three libraries used here perform roughly equally well, when judged on the basis of the results for Masurca and FCA.

One can also look at $\beta_{\text{eff}}$ the fundamental delayed neutron fraction, and $\beta_{\text{eff}}$ per time group. For instance, to investigate why the results for the Winco slab tanks are so different between ENDF-B/VI.8 and JENDL-3.3, we have plotted the ratio of $\beta_{\text{eff}}$ for ENDF-B/VI.8 divided by the results based on JENDL-3.3 in Fig. 2. In the same figure we have plotted the ratio for $\beta_{\text{eff}}$.

From the plot it is evident that there are large deviations between these two data libraries when looking at specific time groups. Because the ratio for $\beta_{\text{eff}}$ is roughly the same as for $\beta_{\text{eff}}$, for each time group, we can conclude that the differences are not due to differences in the energy spectrum of the delayed neutrons. Therefore the differences have to be the result of differences in delayed neutron yields per time group.

This method of comparing $\beta_0$ and $\beta_{\text{eff}}$ per time group can be used to gather information on which part of the nuclear data is responsible for discrepancies between calculations based on different evaluations. Unfortunately, in JEFF-3.0 the delayed neutron data for $^{238}\text{U}$ and $^{239}\text{Pu}$ are given in eight time groups, but for all other isotopes in six. An investigation to upgrade JEFF-3.0 to include an 8-group representation for all isotopes is in progress [22].

References

2. www.nea.fr/html/science/shielding
3. www-nds.iaea.or.at/fend/PF/fen-bench.htm
FIGURE 1. C/E for $\beta_{\text{eff}}$ (or $\beta_{\text{eff}}/l$, see text) for many benchmark systems. The systems are roughly ordered with respect to the average energy at which fission takes place, from low energy (left) to high (right).

FIGURE 2. The ratio of $\beta_{0,i}$ results based on ENDF-B/VI.8 and those based on JENDL-3.3. Similarly, the ratio for $\beta_{\text{eff},i}$ is plotted.


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