Validation of KENO Delayed Neutron Fraction Capabilities*

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INTRODUCTION

The delayed neutron fraction, which is necessary for the safe operation of reactors, varies by fissionable material and neutron spectrum. A prompt fission neutron spectrum has been included in the SCALE 6.2 release to account for the removal of delayed neutrons from precursor materials from the neutron balance. This paper describes how experimental measurements from criticality safety benchmarks were used to validate the SCALE calculational procedure for the delayed neutron fraction. Additionally, the effect of nuclear data uncertainty on the KENO calculation of β_{eff} was examined with the SAMPLER sequence.

METHODOLOGY AND MODELING

SCALE 6.3.0-beta15 was used for all calculations to allow access to the nuclear data libraries based on Evaluated Nuclear Data File (ENDF)/B-VIII.0 and ENDF/B-VII.1 [1-3]. The k_{eff} calculations were performed with the CSAS5 sequence for all models, and KENO V.a was used for Monte Carlo (MC) neutron transport and calculation of k_{eff}. Models were constructed according to Section 3 of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook evaluation and are taken from the quality-controlled SCALE Verified, Archived Library of Inputs and Data [4,5].

β_{eff} was calculated by turning on the KENO "pnu=yes" parameter, utilizing only the prompt fission neutron spectrum. This produces a prompt k_{eff}, $k_{p,eff}$, which, along with a separately calculated full spectrum k_{eff}, results in an estimate of β_{eff} using the Bretscher approximation, as noted in Eq. (1) [6].

$$\beta_{eff} = 1 - \frac{k_{p,eff}}{k_{eff}} \quad (1)$$

Previous validation of the delayed neutron fraction was completed by Heinrichs et al. with Lawrence Livermore National Laboratory's COG and by Kodeli using Los Alamos National Laboratory's PARTISN and Monte Carlo N-Particle (MCNP) codes [6, 7].

RESULTS

The nominal SCALE-calculated k_{eff} values using SCALE 6.3.0-beta15 are provided in Table I. Cases were first run with the full spectrum, and then they were run again with only the prompt spectrum (denoted in Table I as "_p"). The resulting β_{eff} values, rounded to the nearest whole number in pcm, are given in Table II, along with reference experimental values and calculated values reported by Kodeli [6] and Heinrichs [7] when available. The stochastic uncertainty in the k_{eff} values is 0.002 %Δk in all SCALE cases, which propagates to 2.8 pcm uncertainty in β_{eff}. Cell shading in Table II indicates the agreement between the calculated and expected β_{eff}. No shading indicates a deviation within 1σ, light gray indicates a deviation between 1 and 2σ, and the darker gray indicates a deviation greater than 2σ. The maximum relative deviation is 2.19σ for all codes and 2.00σ for SCALE.

TABLE I. Nominal k_{eff} with and without Delayed Neutrons

Evaluation	Model run	k_{eff} (± 2 pcm)	
		ENDF/B-VII.1	ENDF/B-VIII.0
HMF-001	Godiva	0.999959	1.000158
	Godiva_p	0.993413	0.993630
	Shell	0.999961	1.000144
	Shell_p	0.993427	0.993650
PMF-001	Jezebel	1.000054	0.999806
	Jezebel_p	0.998185	0.997990
UMF-001	Skidoo	1.000218	0.999979
	Skidoo_p	0.997345	0.997024
HMF-028	Topsy	1.003238	1.001057
	Topsy_p	0.996321	0.994126
PMF-006	Popsy	1.001538	1.000040
	Popsy_p	0.998723	0.997270
UMF-006	Flattop23	0.999435	0.999178
	Flattop23_p	0.995757	0.995418
IMF-007	Big Ten	1.004787	1.004590
	Big Ten_p	0.997582	0.997319

Although the initial selection contains sparse benchmarks that are all fully in the fast spectrum due to the availability of relevant, constructed models in VALID, the chosen cases show good agreement with the reference measurements, and they also show a level of performance

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TABLE II. β_{eff} with Variable Transport Methods and Cross Section Libraries

Evaluation	Model run	Reference[6,7]	ENDF/B-VII.1 β_{eff}				ENDF/B-VIII.0 β_{eff}	
			MCNP[6]	PARTISN[6]	COG[7]	SCALE (± 3 pcm)	COG[7]	SCALE (± 3 pcm)
HMF-001	Godiva	659 ± 28	-	-	678	655	676	653
	Shell Model		-	-	678	653	676	649
PMF-001	Jezebel	195 ± 10	186	186	198	187	200	182
UMF-001	Skidoo	290 ± 10	-	297	303	287	312	296
HMF-028	Topsy	665 ± 13	-	690	657	689	660	692
PMF-006	Popsy	276 ± 7	284	278	268	281	271	277
UMF-006	Flattop23	360 ± 9	-	375	352	368	358	376
IMF-007	Big Ten	720 ± 7	-	734	726	717	729	724

Note: no shading < 1 σ; light gray 1 ≤ σ < 2; dark gray ≥ 2 σ

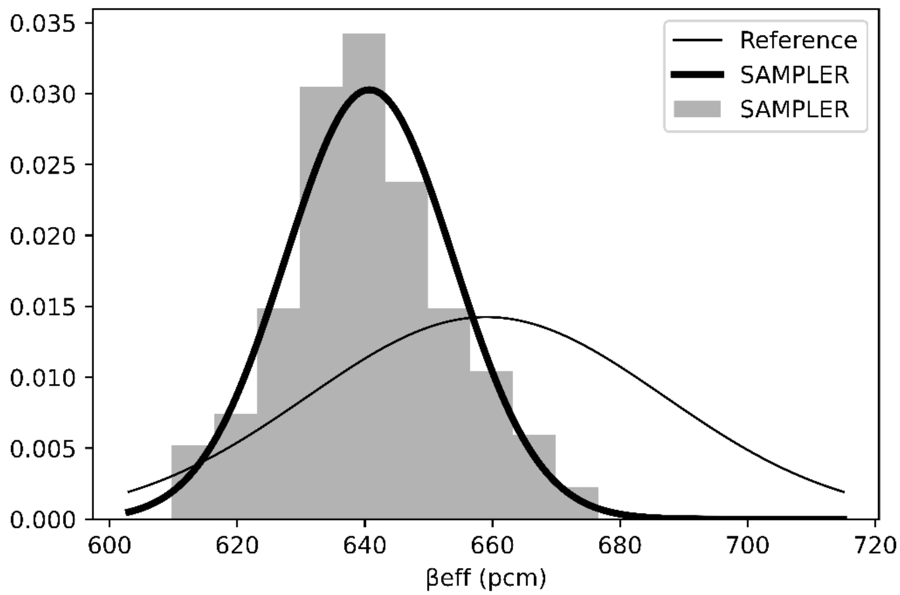

Figure 1. SAMPLER distribution relative to reference Godiva value.

similar to that of other major transport codes using both MC and deterministic methods. There is no consistent bias in β_{eff} results between SCALE and other codes (particularly COG with a comparable number of β_{eff} results); nor is there a bias between SCALE and reference values.

UNCERTAINTY QUANTIFICATION

The SCALE SAMPLER sequence was used to perturb cross sections according to their associated uncertainties [8]. A single MC calculation relies on the established cross section values, and although these values are the best estimate when using current methods, they are discrepant with the true values and are unable to be determined because of the uncertainties in measurement. Based on the sensitivities of the benchmark and the uncertainties in the data involved, a perturbation in the nuclear data within statistical limits could have a relatively significant impact on the calculated delayed neutron fraction. Therefore, the Godiva Shell Model was run using SAMPLER with 200 cross section perturbations defined by the uncertainties of the cross sections involved. With the prompt flag enabled, the same case was run again with 200 cases with the same cross section perturbations. β_{eff} was then calculated for each of the 200 perturbed data sets to produce a distribution of β_{eff} values. The average β_{eff} and uncertainty are 641 ± 13 pcm. This distribution is displayed in Fig. 1. The plot *x* axis is limited by the reference value ± 2σ, demonstrating that even the most dramatic cross section perturbations remained within 2σ of the reference value. Although 2σ agreement is maintained in all cases, it is notable that these perturbations within the established data uncertainty result in β_{eff} ranging from 610 to 677 pcm.

CONCLUSION

This study used the recent prompt fission neutron spectrum addition to SCALE to calculate the delayed neutron fraction. SCALE was used to analyze seven ICSBEP evaluations with delayed neutron measurements, and it was found that all calculated results fell within two standard deviations of the reference values, performing similarly to other MC and deterministic methods. Cross sections were perturbed according to their nuclear data uncertainties using SAMPLER, and a compilation of 200 data-perturbed calculations produced a β_{eff} comparable to a single calculation. Additionally, all 200 perturbations agreed within two standard deviations of the reference value.

Future work includes finding a more diverse selection of applicable experiments for validation of lower energy spectra and obtaining a broader selection of fissionable materials. Different fissionable materials have different cross sections and associated uncertainties, and the impact of fissionable material on β_{eff} uncertainty quantification should be further investigated with additional SAMPLER calculations. With different or larger uncertainties in relevant isotopes, perturbations may lead to less agreeable findings.

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