Validation of KENO V.a and KENO-VI in SCALE 6.2.2 Using ENDF/B-VII.0 and ENDF/B-VII.1 Libraries

E. M. Saylor[1], W. J. Marshall[1], Z. J. Clifton[2], J. B. Clarity[1] and B. T. Rearden[1]

[1]*Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6170, USA, saylorem@ornl.gov*
[2]*University of Alabama-Huntsville, 301 Sparkman Dr., Huntsville, AL 35899, USA*

INTRODUCTION

ANSI/ANS-8.1 [1], *Nuclear Criticality Safety in Operations with Fissionable Materials outside Reactors*, and ANSI/ANS-8.24 [2], *Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations*, require validation of computer codes and associated data through calculation of benchmark evaluations based on physical experiments. Code and data performance are validated by comparing the calculated and benchmark results. The SCALE procedure to generate a verified, archived library of inputs and data (VALID) [3,4] provides a process for preparing, peer reviewing, and controlling models and data sets derived from benchmark definitions. The models and data can then be used with confidence that they were correctly generated with appropriate references, documented checks, and reviews. All models in the VALID library are based on evaluations documented in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook [5]. This paper summarizes the results contained in the SCALE 6.2.2 validation report to be published at Oak Ridge National Laboratory [6].

CODE AND DATA DESCRIPTIONS

The SCALE code system [7] contains two Monte Carlo transport codes used primarily for nuclear criticality safety analyses: KENO V.a and KENO-VI. Both codes solve the k-effective (k_{eff}) eigenvalue problem in three dimensions using the Monte Carlo method. The codes have been used for this purpose in the SCALE system for many years in criticality safety applications at sites around the world. KENO V.a allows a fairly simple description of complicated systems and is capable of using repeating Cartesian array structures and holes to facilitate system description. However, each geometry object must be oriented along a coordinate axis, and the objects are not allowed to intersect. KENO-VI has capabilities similar to KENO V.a, except it incorporates a generalized geometry package and is therefore able to represent significantly more complex systems. A predefined set of geometry objects is used to define regions in both codes, with a much large number of shapes available in KENO-VI. In addition, generalized quadratic surfaces can be supplied to define regions of space that are not well described by any of the predefined shapes in KENO-VI. KENO-VI also supports rotation and therefore allows bodies to be oriented in directions that are not parallel to the major coordinate axes. KENO-VI also supports arrays and holes. The range of arrays that can be used is expanded beyond that provided in KENO V.a to include triangular/hexagonal arrays, as well as dodecahedral arrays. Intersecting geometry definitions can be supplied for exact modeling of features such as pipe junctions.

Six libraries were tested in this validation effort, including two continuous-energy (CE) libraries and four multigroup (MG) libraries. CE and 238-group MG libraries based on ENDF/B-VII.0 are used to provide a direct comparison to results from SCALE 6.1 [8]. The second CE library and the remaining three MG libraries, with 56-, 200-, and 252-group structures, are based on ENDF/B-VII.1. The 252-group library is the primary multipurpose library for thermal system calculations; the 56-group library is a subset of this structure intended primarily for reactor physics depletion analyses. The 200-group library is coupled with 47-group photon data primarily for shielding calculations; KENO can be executed with the 200 neutron groups without consideration of the photon cross sections. This last library has a more detailed group structure in the fast energy range that provides lower biases for unmoderated systems.

VALID LIBRARY CONTENTS

The VALID library contains over 600 individual benchmark experiment configurations from 14 different ICSBEP experiment categories. Most of these cases use KENO V.a, but 57 cases use KENO-VI. No cases are currently archived in the VALID library using both codes, so each code is validated separately. The 14 categories represented in the library include the following systems:

- high-enriched uranium fast metal (HMF),
- high-enriched uranium thermal solution (HST),
- intermediate-enriched uranium fast metal (IMF),
- low-enriched uranium thermal compound (LCT),
- low-enriched uranium thermal solution (LST),
- mixed U/Pu fast compound (MCF),
- mixed U/Pu thermal compound (MCT),
- mixed U/Pu thermal solution (MST),
- plutonium fast metal (PMF),
- plutonium thermal solution (PST),
- ^{233}U thermal compound (UCT),
- ^{233}U fast metal (UMF),

- ^{233}U intermediate spectrum solution (USI), and
- ^{233}U thermal solution (UST).

KENO-VI cases come from only three categories: HMF, IMF, and MCT. A description of the evaluations used is provided in the complete validation report [6].

VALIDATION METHODS

This validation effort demonstrates the general performance of the KENO V.a and KENO-VI codes across a wide range of problems using a range of different data libraries included in SCALE 6.2 [7]. Code performance and data are reported in terms of the calculated-to-expected (C/E) ratio. The expected k_{eff} value for each benchmark model is provided in the ICSBEP Handbook evaluation [5]. An estimated uncertainty is also supplied for this expected value of k_{eff}. The C/E ratio and its uncertainty can be calculated from these two values in the evaluation, and the calculated k_{eff} and its uncertainty from KENO. The relative uncertainty in the C/E ratio is calculated as the square root of the sum of the squares of the relative calculation and evaluation uncertainties. The absolute uncertainty in the C/E ratio is thus simply the relative uncertainty multiplied by the C/E ratio. The uncertainty in the evaluated k_{eff} value is on the order of 10–50 times the KENO standard deviation, so the primary driver in the C/E uncertainty is the uncertainty from the evaluation. Most of the KENO results used in this validation have an uncertainty of approximately 0.01% Δk, but some Monte Carlo uncertainties are as high as about 0.05% Δk.

An average C/E value is determined for each category of experiment for each code. The average value reported is an arithmetic average of the individual C/E values. The uncertainty in the average C/E value is determined as the square root of the sum of the individual C/E variances for a given category of experiments divided by the number of experiments in that category. The results for each case are generated and reported for each library, allowing for the performance of the different libraries to be compared based on the same benchmark models.

RESULTS

The average C/E values for both CE cross section libraries for both KENO V.a and KENO-VI cases are provided in Table I. The results for the two multipurpose MG libraries are provided in Table II, and results for the two additional libraries based on ENDF/B-VII.1 in Table III. The results show that the average C/E values are near 1.0 for all libraries and all categories except for the USI case. The differences from an average C/E of unity are plotted for all six cross section libraries for KENO V.a in Figure 1 and for KENO-VI in Figure 2. The USI results are consistently poor for all libraries, as reported previously [9].

The results indicate that the CE libraries perform well for 13 of the 14 categories of experiments; the exception is the USI category. The bias difference between the libraries is less than 1-σ for 12 categories of experiments; the exceptions are the HMF and UMF experiments. The ENDF/B-VII.1 library is further from unity by 0.076% Δk (1.4σ) for the HMF experiments and by 0.111% Δk (1.5σ) for the UMF experiments.

The performance of the MG libraries is also generally good, again with the exception of the USI category for all libraries. The 56-group library does not perform well for fast metal systems, regardless of fissile isotope, and it also has larger magnitude biases for the HST, LST, and MST systems. Differences between the 56-group library and the other MG libraries are also apparent in the PMF and all ^{233}U systems. The 56-group library should not be treated as a general purpose library; its development is tailored for use in reactor physics calculations [7].

CONCLUSION

Overall, the KENO V.a and KENO-VI codes have been shown to provide consistent, low bias results across a range of systems commonly encountered in criticality safety applications. Large biases are encountered for USI systems [9], and it is not entirely clear if this is an issue with intermediate-spectrum systems generally or more specifically with ^{233}U systems. Work is currently in progress to investigate the cause of this bias.

ACKNOWLEDGMENT

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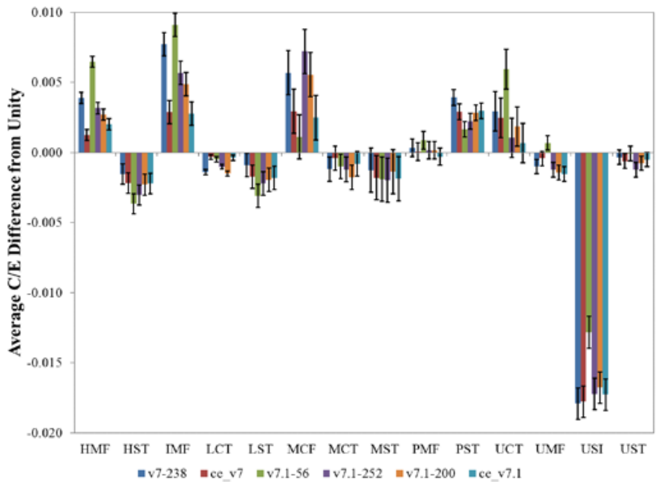

Figure 1. Difference from unity of average C/E value by category for KENO V.a (Δk_{eff}).

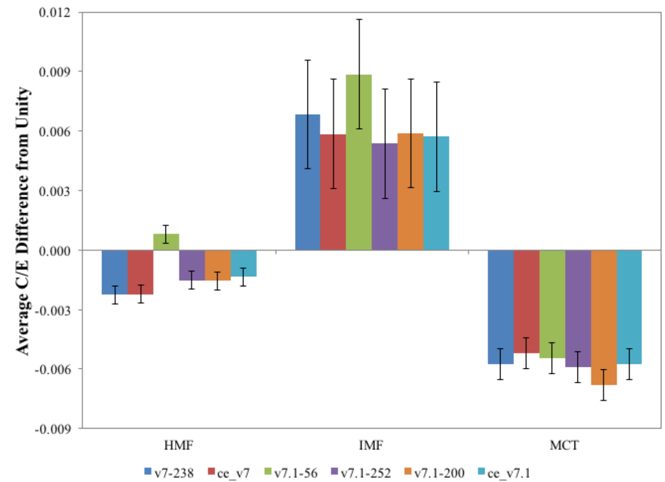

Figure 2. Difference from unity of average C/E value by category for KENO-VI (Δk_{eff}).

Table I. Results by Category for CE Libraries

Code	Category	ENDF/B-VII.0		ENDF/B-VII.1	
		Average C/E	Average C/E uncertainty	Average C/E	Average C/E uncertainty
KENO V.a	HEU-MET-FAST	1.00125	0.00039	1.00201	0.00039
	HEU-SOL-THERM	0.99783	0.00072	0.99779	0.00072
	IEU-MET-FAST	1.00288	0.00083	1.00276	0.00083
	LEU-COMP-THERM	0.99967	0.00018	0.99962	0.00018
	LEU-SOL-THERM	0.99826	0.00083	0.99819	0.00083
	MIX-COMP-FAST	1.00293	0.00158	1.00248	0.00158
	MIX-COMP-THERM	0.99959	0.00087	0.99919	0.00087
	MIX-SOL-THERM	0.99820	0.00158	0.99813	0.00158
	PU-MET-FAST	1.00005	0.00062	0.99970	0.00062
	PU-SOL-THERM	1.00289	0.00056	1.00296	0.00056
	^{233}U-COMP-THERM	1.00245	0.00141	1.00068	0.00141
	^{233}U-MET-FAST	0.99957	0.00051	0.99846	0.00051
	^{233}U-SOL-INTER	0.98223	0.00112	0.98273	0.00112
	^{233}U-SOL-THERM	0.99938	0.00052	0.99949	0.00052
KENO-VI	HEU-MET-FAST	0.99778	0.00044	0.99863	0.00044
	IEU-MET-FAST	1.00585	0.00275	1.00572	0.00275
	MIX-COMP-THERM	0.99480	0.00078	0.99422	0.00078

Table II. Results by Category for Multipurpose MG Libraries

Code	Category	238-Group ENDF/B-VII.0		252-Group ENDF/B-VII.1	
		Average C/E	Average C/E uncertainty	Average C/E	Average C/E uncertainty
KENO V.a	HEU-MET-FAST	1.00389	0.00039	1.00316	0.00039
	HEU-SOL-THERM	0.99847	0.00072	0.99696	0.00072
	IEU-MET-FAST	1.00772	0.00083	1.00567	0.00083
	LEU-COMP-THERM	0.99859	0.00018	0.99899	0.00018
	LEU-SOL-THERM	0.99911	0.00083	0.99777	0.00083
	MIX-COMP-FAST	1.00569	0.00158	1.00721	0.00158
	MIX-COMP-THERM	0.99879	0.00087	0.99878	0.00087
	MIX-SOL-THERM	0.99874	0.00158	0.99803	0.00158
	PU-MET-FAST	1.00032	0.00062	1.00015	0.00062
	PU-SOL-THERM	1.00392	0.00056	1.00222	0.00056
	^{233}U-COMP-THERM	1.00292	0.00141	1.00104	0.00141
	^{233}U-MET-FAST	0.99899	0.00051	0.99877	0.00051
	^{233}U-SOL-INTER	0.98209	0.00112	0.98278	0.00112
	^{233}U-SOL-THERM	0.99966	0.00052	0.99878	0.00052
KENO-VI	HEU-MET-FAST	0.99773	0.00044	0.99847	0.00044
	IEU-MET-FAST	1.00684	0.00275	1.00536	0.00275
	MIX-COMP-THERM	0.99426	0.00078	0.99408	0.00078

Table III. Results by Category for 56- and 200-Group ENDF/B-VII.1 MG Libraries

Code	Category	56-Group ENDF/B-VII.1		200-Group ENDF/B-VII.1	
		Average C/E	Average C/E uncertainty	Average C/E	Average C/E uncertainty
KENO V.a	HEU-MET-FAST	1.00647	0.00039	1.00270	0.00039
	HEU-SOL-THERM	0.99635	0.00072	0.99771	0.00074
	IEU-MET-FAST	1.00912	0.00083	1.00487	0.00083
	LEU-COMP-THERM	0.99950	0.00018	0.99850	0.00018
	LEU-SOL-THERM	0.99691	0.00083	0.99807	0.00083
	MIX-COMP-FAST	1.00110	0.00158	1.00555	0.00158
	MIX-COMP-THERM	0.99901	0.00087	0.99823	0.00087
	MIX-SOL-THERM	0.99810	0.00158	0.99864	0.00158
	PU-MET-FAST	1.00087	0.00063	1.00015	0.00062
	PU-SOL-THERM	1.00164	0.00056	1.00283	0.00056
	^{233}U-COMP-THERM	1.00594	0.00141	1.00184	0.00141
	^{233}U-MET-FAST	1.00068	0.00051	0.99857	0.00051
	^{233}U-SOL-INTER	0.98718	0.00113	0.98324	0.00112
	^{233}U-SOL-THERM	0.99992	0.00052	0.99923	0.00052
KENO-VI	HEU-MET-FAST	1.00080	0.00044	0.99844	0.00044
	IEU-MET-FAST	1.00885	0.00276	1.00587	0.00275
	MIX-COMP-THERM	0.99456	0.00078	0.99321	0.00078