Verification of KENO V.a and KENO-VI Using Analytical Benchmarks

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VERIFICATION OF KENO V.a AND KENO-VI USING ANALYTICAL BENCHMARKS

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Abstract

To verify that the multigroup Monte Carlo codes KENO V.a and KENO-VI of the SCALE (Standardized Computer Analyses for Licensing Evaluation) code system properly calculate the effective or infinite multiplication factor of a system, numerous analytically solved criticality benchmark problems with simple geometries and explicitly defined macroscopic cross sections have been modeled. It has been demonstrated that the KENO V.a and KENO-VI codes calculate expected multiplication factors very accurately.

Introduction

SCALE[1] is a computer code system that is widely used and accepted around the world for criticality safety analyses. It is a modular code system that utilizes individual programs for performing one or more of the required calculations for a desired analysis result. The Monte Carlo codes KENO V.a and KENO-VI are used to calculate the multiplication factor of fissile systems as well as the flux distributions throughout the system. KENO V.a and KENO-VI differ in their treatment of the geometric modeling of the problem; KENO-VI is not the next version of KENO V.a. Rather, it is a somewhat different code with different geometric modeling capabilities. As such, both codes are maintained and improved continuously. KENO V.a contains simpler geometric modeling capabilities and therefore runs much faster while still allowing very complex geometries to be modeled using simple geometric shapes. KENO-VI allows more complex geometric modeling and runs longer than KENO V.a. Current versions of both of these codes employ a multigroup scheme to treat the energy dependence of the transport equation, although continuous-energy versions will be available with the next release of SCALE.

Because the KENO V.a and KENO-VI codes are continually modified, improved, and updated, they must be verified to demonstrate that they provide accurate answers. Generally, these codes are tested using hundreds of validation benchmark cases taken from various sources to compare the accuracy of the calculations against actual experiments. Recently, a new set of problems have been identified and modeled to verify the accuracy of these codes. These so-called analytical benchmarks, which are summarized in Reference 2, allow for verification that transport algorithms and computer codes correctly calculate k_{eff} or k_{inf}. By keeping the nuclear data (i.e., cross sections, nu and chi) the same as in the analytical benchmarks, an attempt has been made to verify the correctness of the geometry and the mathematical modeling and criticality calculations in KENO V.a and KENO-VI.

Analytical Benchmark Problems

A total of 75 analytical benchmark problems have been collected from various sources and documented in Reference 2. Of these 75 cases, 43 problems use one-energy group, 30 of which assume isotropic scattering and 13 of which have anisotropic scattering. Of the 30 two-energy group problems, 26 assume isotropic scattering and 4 have linearly anisotropic scattering. Three-group and six-group isotropic problems are also considered. The geometries in these problems included infinite slabs, infinite cylinders, infinite homogeneous

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media, and spheres. Except for the cases involving infinite homogeneous mediums, all k_{eff} eigenvalues are unity to at least five decimal points.

The problems in the test set use cross sections representative of plutonium, uranium, U-D_2O, and research reactor fuels. Twenty of the seventy-five cases are reflected with either water or iron, and one is externally moderated by sodium. While the cross sections used in these problems are reasonable representations of nuclear material, they are not actual cross sections and were used solely to achieve a k_{eff} of unity.

A subset of these 75 problems was selected for use as verification cases for KENO V.a and KENO-VI. The problem definitions for these cases are given in Table I. Except for cases 31-a and 31-b, all cases assume isotropic scattering. Cross sections are determined such that they yield k_{eff} of 1 for finite or semi-infinite systems.

Calculations and Results

After creating a cross-section library for the materials used in these problems based on the analytically solved benchmark problems, 45 cases were run using both KENO V.a and KENO-VI. To obtain the necessary precision of 5 decimal places, approximately 20,000 generations with 434,000 particles per generation were run. The calculated k_{eff} or k_{inf} values are listed in Table II. In almost all cases, standard deviations less than 0.00001 were obtained. The calculated results are all within three standard deviations of the analytical solutions. In addition, Table III shows the percent difference between the calculated k_{eff} or k_{inf} values and the analytical values. The comparisons indicate that calculated values for all cases are within 0.003% of the analytical results.

Conclusions and Future Work

Based on the accuracy of the results given in Table II, it can be concluded that mathematical and geometric modeling in KENO V.a and KENO-VI Monte Carlo codes of the SCALE code system are accurate as indicated by the calculated eigenvalues and the corresponding standard deviations.

Because of time limitations, most of the anisotropic cases were not modeled and therefore could not be included in this study. In the future, all 75 cases will be modeled and used to verify the mathematical and geometric accuracy of the KENO V.a and KENO-VI codes.

Table I. Problem definitions for modeled cases

Case	Neutron Groups	Geometry	Fuel	Reflector	Multiplication Factor
1	1	Infinite	Pu-239	--	2.612903
2	1	Slab	Pu-239	--	1
3	1	Slab	Pu-239	H_2O	1
4	1	Slab	Pu-239	H_2O	1
5	1	Infinite	Pu-239	--	2.290323
6	1	Slab	Pu-239	--	1
7	1	Cylinder	Pu-239	--	1
8	1	Sphere	Pu-239	--	1
9	1	Cylinder	Pu-239	H_2O	1
10	1	Cylinder	Pu-239	H_2O	1
11	1	Infinite	U-235	--	2.25
12	1	Slab	U-235	--	1
13	1	Cylinder	U-235	--	1
14	1	Sphere	U-235	--	1
15	1	Infinite	U-235	--	2.330917
16	1	Sphere	U-235	H_2O	1
17	1	Infinite	U-235	--	2.256083
18	1	Sphere	U-235	H_2O	1
19	1	Infinite	U-235	--	2.232667
20	1	Sphere	U-235	H_2O	1
21	1	Infinite	U-D_2O	--	1.133333
22	1	Slab	U-D_2O	--	1
23	1	Cylinder	U-D_2O	--	1
24	1	Sphere	U-D_2O	--	1
25	1	Slab	U-D_2O	H_2O	1
26	1	Slab	U-D_2O	H_2O	1
27	1	Cylinder	U-D_2O	H_2O	1
28	1	Cylinder	U-D_2O	H_2O	1
29	1	Infinite	U-235	--	2.180667
30**	1	Slab	U-235	Fe	1
31-a*	1	Infinite	Pu-239	--	2.5
31-b*	1	Infinite	Pu-239	--	2.5
44	2	Infinite	Pu-239	--	2.683767
45	2	Slab	Pu-239	--	1
46	2	Sphere	Pu-239	--	1
47	2	Infinite	U-235	--	2.216349
48	2	Slab	U-235	--	1
49	2	Sphere	U-235	--	1
50	2	Infinite	U-Al	--	2.661745
53	2	Infinite	U	--	1.631452
55	2	Sphere	U-H_2O	H_2O	1
62	2	Infinite	U-H_2O	--	1.03497
65	2	Inf. slab	U-H_2O	H_2O	1
66	2	Inf. slab	U-H_2O	H_2O	1
74	3	Infinite	U	--	1.6

* Anisotropic scattering.

** Externally moderated by sodium.

Table II. Calculated values

		KENO V.a			KENO-VI		
Case	Analytical	k_{eff} or k_{inf}	σ	Number of σ's	k_{eff} or k_{inf}	σ	Number of σ's
1	2.612903	2.612903	8.E-06	0.0	2.612910	8.E-06	0.9
2	1	1.000007	9.E-06	0.8	0.999996	9.E-06	0.5
3	1	0.999979	9.E-06	2.3	0.999976	9.E-06	2.6
4	1	0.999979	9.E-06	2.3	0.999978	9.E-06	2.4
5	2.290323	2.290322	7.E-06	0.1	2.290318	7.E-06	0.8
6	1	0.999989	9.E-06	1.3	0.999988	9.E-06	1.3
7	1	0.999999	9.E-06	0.1	1.000002	9.E-06	0.2
8	1	1.000005	9.E-06	0.5	0.999999	9.E-06	0.2
9	1	1.000007	8.E-06	0.9	1.000003	8.E-06	0.3
10	1	1.000003	8.E-06	0.4	1.000004	8.E-06	0.5
11	2.25	2.249998	6.E-06	0.3	2.249995	6.E-06	0.8
12	1	1.000005	8.E-06	0.6	0.999993	8.E-06	0.9
13	1	1.000010	9.E-06	1.2	0.999998	9.E-06	0.2
14	1	0.999995	9.E-06	0.6	0.999992	9.E-06	0.9
15	2.330917	2.330915	7.E-06	0.3	2.330914	7.E-06	0.4
16	1	0.999985	8.E-06	1.8	1.000001	9.E-06	0.2
17	2.256083	2.256088	6.E-06	0.8	2.256082	6.E-06	0.1
18	1	1.000001	8.E-06	0.1	0.999994	8.E-06	0.7
19	2.232667	2.232663	6.E-06	0.6	2.232669	6.E-06	0.4
20	1	1.000001	8.E-06	0.1	1.000003	8.E-06	0.4
21	1.133333	1.133332	3.E-06	0.2	1.133329	3.E-06	1.2
22	1	0.999989	5.E-06	2.4	0.999994	5.E-06	1.3
23	1	0.999993	6.E-06	1.4	1.000007	6.E-06	1.2
24	1	0.999989	6.E-06	1.8	0.999992	6.E-06	1.3
25	1	0.999999	4.E-06	0.2	1.000003	5.E-06	0.8
26	1	0.999997	4.E-06	0.8	0.999995	4.E-06	1.2
27	1	1.000007	4.E-06	1.6	0.999997	5.E-06	0.7
28	1	1.000003	5.E-06	0.6	1.000008	5.E-06	1.6
29	2.180667	2.180667	6.E-06	0.1	2.180660	6.E-06	1.0
30	1	1.000008	8.E-06	1.1	1.000004	8.E-06	0.5
31-a	2.5	2.499999	7.E-06	0.1	2.499999	7.E-06	0.1
31-b	2.5	2.499999	7.E-06	0.1	2.499999	7.E-06	0.1
44	2.683767	2.683771	7.E-06	0.6	2.683775	7.E-06	1.2
45	1	1.000011	7.E-06	1.6	0.999994	7.E-06	0.9
46	1	0.999991	1.E-05	0.9	1.000019	8.E-06	2.4
47	2.216349	2.216349	6.E-06	0.1	2.216348	6.E-06	0.2
48	1	0.999998	9.E-06	0.2	1.000000	9.E-06	0.0
49	1	0.999998	9.E-06	0.2	1.000003	1.E-05	0.3
50	2.661745	2.661745	8.E-06	0.0	2.661733	8.E-06	1.5
53	1.631452	1.631457	5.E-06	1.0	1.631448	5.E-06	0.8
55	1	1.000007	1.E-05	0.7	0.999998	1.E-05	0.2
62	1.03497	1.034966	3.E-06	1.2	1.034970	3.E-06	0.1
65	1	0.999998	3.E-06	0.6	1.000001	3.E-06	0.3
66	1	0.999995	3.E-06	1.6	0.999999	3.E-06	0.3
74	1.6	1.599997	5.E-06	0.7	1.599993	5.E-06	1.5

Table III. Percent difference against benchmark values

Case	KENO V.a	KENO-VI	Case	KENO V.a	KENO-VI
1	-8.E-06	2.7E-04	24	-1.E-03	-8.E-04
2	7.E-04	-4.3E-04	25	-1.E-04	3.E-04
3	-2.E-03	-2.4E-03	26	-4.E-04	-5.E-04
4	-2.E-03	-2.2E-03	27	7.E-04	-3.E-04
5	-4.E-05	-2.3E-04	28	3.E-04	8.E-04
6	-1.E-03	-1.2E-03	29	3.E-05	-3.E-04
7	-1.E-04	2.2E-04	30	8.E-04	4.E-04
8	5.E-04	-1.5E-04	31-a	-4.E-05	-4.E-05
9	7.E-04	2.6E-04	31-b	-4.E-05	-4.E-05
10	3.E-04	3.8E-04	44	2.E-04	3.E-04
11	-9.E-05	-2.1E-04	45	1.E-03	-6.E-04
12	5.E-04	-7.2E-04	46	-9.E-04	2.E-03
13	1.E-03	-2.1E-04	47	2.E-05	-5.E-05
14	-5.E-04	-8.5E-04	48	-2.E-04	2.E-05
15	-8.E-05	-1.1E-04	49	-2.E-04	3.E-04
16	-2.E-03	1.3E-04	50	4.E-06	-5.E-04
17	2.E-04	-3.5E-05	53	3.E-04	-3.E-04
18	7.E-05	-6.1E-04	55	7.E-04	-2.E-04
19	-2.E-04	1.0E-04	62	-4.E-04	-2.E-05
20	6.E-05	3.2E-04	65	-2.E-04	7.E-05
21	-5.E-05	-3.4E-04	66	-5.E-04	-1.E-04
22	-1.E-03	-6.1E-04	74	-2.E-04	-4.E-04
23	-8.E-04	6.7E-04			

References

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