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Criticality Benchmark of UNIST Monte Carlo Code MCS for Light-Water-Reactor Fuel in Transportation and Storage Packages

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1. Introduction

MCS is a 3D neutron transport simulation code developed at the Computational Reactor physics and Experiment laboratory(CORE) of Ulsan National Institute of Science and Technology (UNIST) for nuclear reactor design and analysis. The code is a 3D continuous-energy computer code for particle transport based on the Monte Carlo (MC) method. Currently the code treats neutron and photon transport [1-4].The MC code is used to simulate the neutron transport in the reactor using a computerized method. Before using the MC code, Verification and Validation (V&V) should be performed to increase the reliability of the calculation results.

The NUREG/CR-6361 criticality benchmark guide provide specification of 173 models toward light water reactor(LWR) type transportation and storage packages [5]. In addition, the benchmark guide provides calculation results of KENO V.a in SCALE code [6] which is developed by Oak Ridge National Laboratory for all cases.

In this work, the MCS code was validated against 66 models of benchmark experiments provided in NUREG/CR-6361. Besides, the MCS results were compared with those of other MC codes such as McCARD and SCALE-6.2.1. McCARD is a MC particle transport simulation code developed at Seoul National University for nuclear reactor design [7]. The McCARD code was previously validated with NUREG/CR-6361 criticality benchmark problem [8]. All the code simulations were performed with ENDF-B VII.0 cross section library.

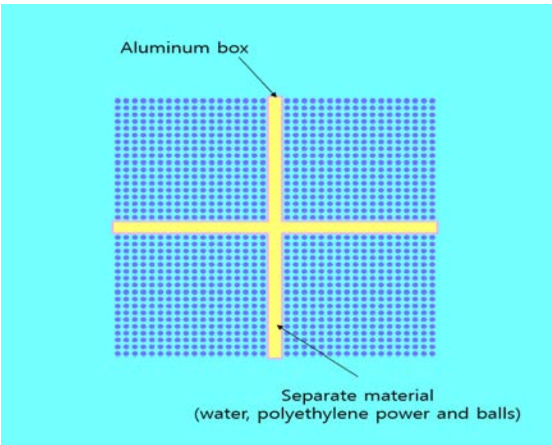
2. Validation of MCS code against NUREG/CR-6361 criticality benchmark problem

The NUREG/CR-6361 criticality benchmark guide contains a total of 173 LWR-type criticality benchmark problems. The models are classified as simple lattice problem, separator plates problem, reflecting walls problem, burnable absorber fuel rod problem, water holes problem, poison rod and borated moderator problem.

Section 2.1 describes the separator plate experiments from ANS transactions, one of the 66 models. Section 2.2 presents the numerical results of three codes for the 66 LWR type models.

2.1 Separator plate experiments from ANS Transactions

Table 1. shows critical data for separator plate experiments from ANS transactions. The ANS transaction consists of 2 x 2 arrays of fuel assemblies separated by aluminum boxes (four sides and a bottom) filled with water, polyethylene powder and balls, and expanded polystyrene. The enrichment of the fuel is 4.742 wt.% and the square lattices pitch is 1.35cm. The figure 1 shows configurations of ANS33EB1 experiment.



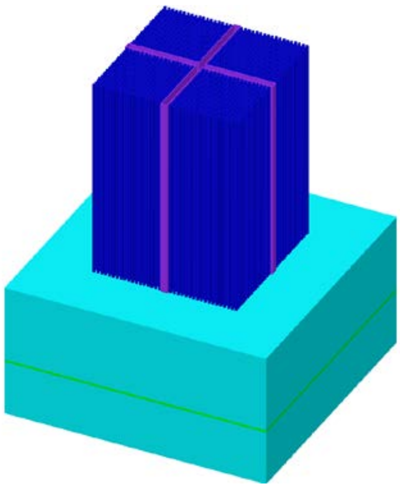


Fig. 1. Configurations of ANS33EB1 experiment

Table. 1. Critical data for separator plate experiments from ANS transaction

Experiment	Enrichment (wt%)	Pitch (cm)	Plate material	Plate thickness (cm)	Separation of assemblies (cm)	No. of assemblies-assembly size	Moderator height (cm)	Interstitial compound
ANS33AL1	4.742	1.35	aluminum	0.3	2.5	4-18x18	25.66	H_2O
ANS33AL2	4.742	1.35	aluminum	0.3	5.0	4-18x18	32.78	H_2O
ANS33AL3	4.742	1.35	aluminum	0.3	10.0	4-18x18	64.12	H_2O
ANS33EB1	4.742	1.35	aluminum	0.3	2.5	4-18x18	25.54	$(CH_2)_n$
ANS33EB2	4.742	1.35	aluminum	0.3	5.0	4-18x18	30.73	$(CH_2)_n$
ANS33EP1	4.742	1.35	aluminum	0.3	2.5	4-18x18	26.98	$(CH_2)_n$
ANS33EP2	4.742	1.35	aluminum	0.3	5.0	4-18x18	30.16	$(C_8H_8)_n$
ANS33STG	4.742	1.35	aluminum	0.3	2.5	4-18x18	28.61	$(C_8H_8)_n$

Table. 2. Multiplication factors of 66 whole core experiments

Case No.	Case name	McCARD			SCALE			MCS			Diff [pcm] (C-A)	Diff [pcm] (C-B)
		k_{eff} (A)	σ [pcm]	Error [pcm] (A-1.0)	k_{eff} (B)	σ [pcm]	Error [pcm] (B-1.0)	k_{eff} (C)	σ [pcm]	Error [pcm] (C-1.0)		
1	ANS33AL1	1.00961	22	+961	1.00900	21	+900	1.00973	27	+973	12	73
2	ANS33AL2	1.01609	22	+1609	1.01638	19	+1638	1.01572	23	+1572	-37	-66
3	ANS33AL3	1.00658	22	+658	1.00700	21	+700	1.00650	28	+650	-8	-50
4	ANS33EB1	1.00130	22	+130	1.00061	23	+61	1.00109	28	+109	-21	48
5	ANS33EB2	1.01239	19	+1239	1.01240	22	+1240	1.01181	26	+1181	-58	-59
6	ANS33EP1	1.00079	22	+79	1.00074	23	+74	1.00097	28	+97	18	23
7	ANS33EP2	1.00335	22	+335	1.00362	21	+362	1.00381	23	+381	46	19
8	ANS33SLG	1.00095	23	+95	1.00156	24	+156	1.00163	27	+163	68	7
9	ANS33STY	0.99562	21	-438	0.99546	23	-454	0.99576	30	-424	14	30
10	BW1810A	1.00231	18	+231	1.00187	21	+187	1.00257	18	+257	26	70
11	BW1810B	1.00165	19	+165	1.00138	21	+138	1.00186	19	+186	21	48
12	BW1810Cr	1.00245	17	+245	1.00206	24	+206	1.00209	16	+209	-36	3
13	BW1810D	1.00198	19	+198	1.00132	22	+132	1.00197	19	+197	-1	65
14	BW1810E	1.00198	19	+198	1.00147	20	+147	1.00149	19	+149	-49	2
15	BW1810F	1.00310	19	+310	1.00278	21	+278	1.00301	18	+301	-9	23
16	BW1810Gr	1.00239	16	+239	1.00167	20	+167	1.00248	18	+248	9	81
17	BW1810H	1.00264	20	+264	1.00199	20	+199	1.00232	19	+232	-32	33
18	BW1810I	1.00202	17	+202	1.00166	22	+166	1.00196	19	+196	-6	30
19	BW1810J	1.00181	18	+181	1.00211	20	+211	1.00207	18	+207	26	-4
20	P2615AL	1.00081	21	+81	1.00098	22	+98	1.00068	24	+68	-13	-30
21	P2615BA	1.00244	20	+244	1.00185	18	+185	1.00255	22	+255	11	70
22	P2615CD1	1.00200	19	+200	1.00199	24	+199	1.00223	19	+223	23	24
23	P2615CD2	1.00210	22	+210	1.00197	19	+197	1.00224	20	+224	14	27
24	P2615CU	1.00228	19	+228	1.00165	18	+165	1.00212	19	+212	-16	47
25	P2615SS	1.00226	18	+226	1.00166	22	+166	1.00257	21	+257	31	91
26	P2615ZR	1.00256	15	+256	1.00204	18	+204	1.00290	23	+290	34	86
27	P3602BB	1.00331	23	+331	1.00252	20	+252	1.00313	23	+313	-18	61
28	P3602BS1	1.00097	18	+97	1.00031	23	+31	1.00102	21	+102	5	71
29	P3602BS2	1.00410	23	+410	1.00421	22	+421	1.00484	24	+484	74	63
30	P3602CD1	1.00204	19	+204	1.00111	20	+111	1.00181	22	+181	-23	70
31	P3602CD2	1.00356	22	+356	1.00330	19	+330	1.00313	25	+313	-43	-17
32	P3602CU1	1.00244	16	+244	1.00184	20	+184	1.00250	20	+250	6	66
33	P3602CU2	1.00085	23	+85	1.00007	20	+7	1.00071	20	+71	-14	64
34	P3602CU3	1.00346	23	+346	1.00333	20	+333	1.00340	26	+340	-6	7
35	P3602CU4	1.00281	23	+281	1.00261	21	+261	1.00325	26	+325	44	64
36	P3602N11	1.00093	18	+93	1.00022	23	+22	1.00059	22	+59	-34	37
37	P3602N12	1.00014	22	+14	1.00087	23	+87	1.00001	22	+1	-13	-86
38	P3602N13	1.00192	18	+192	1.00105	23	+105	1.00193	20	+193	1	88

Case No.	Case name	McCARD (A)			SCALE (B)			MCS (C)			Diff [pcm] (C-A)	Diff [pcm] (C-B)
		k_{eff} (A)	σ [pcm]	Error [pcm] (A-1.0)	k_{eff} (B)	σ [pcm]	Error [pcm] (B-1.0)	k_{eff} (C)	σ [pcm]	Error [pcm] (C-1.0)		
39	P3602N14	1.00211	19	+211	1.00140	20	+140	1.00158	21	+158	-53	18
40	P3602N21	1.00186	18	+186	1.00097	20	+97	1.00224	20	+224	38	127
41	P3602N22	1.00139	18	+139	1.00060	21	+60	1.00221	17	+221	82	161
42	P3602N31	1.00509	18	+509	1.00493	23	+493	1.00513	27	+513	4	20
43	P3602N32	1.00569	19	+569	1.00515	18	+515	1.00605	24	+605	36	90
44	P3602N33	1.00682	18	+682	1.00614	20	+614	1.00688	28	+688	6	74
45	P3602N34	1.00588	18	+588	1.00509	23	+509	1.00623	26	+623	35	114
46	P3602N35	1.00572	20	+572	1.00540	23	+540	1.00633	27	+633	61	93
47	P3602N36	1.00567	18	+567	1.00495	19	+495	1.00566	25	+566	-1	71
48	P3602N41	1.00246	20	+246	1.00204	19	+204	1.00320	23	+320	74	116
49	P3602N42	1.00359	19	+359	1.00298	19	+298	1.00443	24	+443	84	145
50	P3602N43	1.00253	17	+253	1.00190	20	+190	1.00307	22	+307	54	117
51	P3602SS1	1.00144	20	+144	1.00097	20	+97	1.00182	24	+182	38	85
52	P3602SS2	1.00426	21	+426	1.00434	21	+434	1.00453	29	+453	27	19
53	P3926L1	1.00345	23	+345	1.00273	22	+273	1.00342	20	+342	-3	69
54	P3926L2	1.00281	23	+281	1.00338	22	+338	1.00258	20	+258	-23	-80
55	P3926L3	1.00204	17	+204	1.00130	18	+130	1.00193	19	+193	-11	63
56	P3926L4	1.00714	20	+714	1.00661	18	+661	1.00721	25	+721	7	60
57	P3926L5	1.00775	21	+775	1.00722	20	+722	1.00742	26	+742	-33	20
58	P3926L6	1.00695	24	+695	1.00623	20	+623	1.00695	24	+695	0	72
59	P3926SL1	1.00067	23	+67	1.00050	23	+50	1.00040	20	+40	-27	-10
60	P3926SL2	1.00414	18	+414	1.00410	24	+410	1.00445	24	+445	31	35
61	P3926U1	0.99939	22	-61	0.99863	24	-137	0.99945	23	-55	6	82
62	P3926U2	1.00195	24	+195	1.00136	22	+136	1.00177	22	+177	-18	41
63	P3926U3	1.00300	23	+300	1.00231	22	+231	1.00279	21	+279	-21	48
64	P3926U4	1.00348	24	+348	1.00265	22	+265	1.00338	23	+338	-10	73
65	P3926U5	1.00599	19	+599	1.00547	23	+547	1.00597	20	+597	-2	50
66	P3926U6	1.00551	20	+551	1.00541	24	+541	1.00615	24	+615	64	74

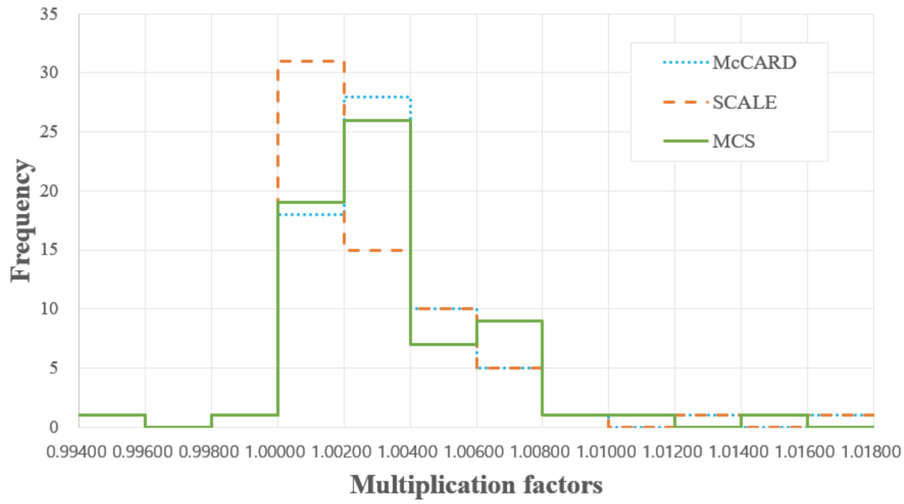


Fig 2. Frequency chart for calculated multiplication factors of 66 models.

Table. 3. Average of multiplication for 66 models

No.of exp.	McCARD		SCALE		MCS	
	Average k_{eff}	$\pm\sigma$ [pcm]	Average k_{eff}	$\pm\sigma$ [pcm]	Average k_{eff}	$\pm\sigma$ [pcm]
66	1.00332	293	1.00293	302	1.00339	291

2.2 The numerical results of 66 whole core experiments

Table 2 shows the numerical results of three codes for the 66 LWR type whole core critical experiments. All results include a statistical standard deviation related to the effective multiplication factor.

The range of MCS code errors is from -424 pcm to +1572 pcm. In the case of the multiplication factor, the maximum difference is +84pcm from the McCARD code, and the minimum difference is -58pcm. In addition, the difference from the SCALE code shows a maximum difference of +161pcm and a minimum difference of -86 pcm.

Figure 3 presents the frequency chart for the multiplication factors of 66 models. Table 3 shows the average multiplication factor with standard deviation. The results of figure 3 and table 3 present that the calculation result of the MCS code is over-estimated about 339 pcm. This similar trend can be found for the SCALE, McCARD code as well.

3. Conclusions

In this work, the MCS code was validated against 66 models of benchmark experiments provided in NUREG/CR-6361. Besides, the MCS results were compared with those of other MC codes such as McCARD and SCALE-6.2.1.

The range of MCS code errors is from -424 pcm to +1572 pcm. In the case of the multiplication factor, the maximum difference is +84pcm from the McCARD code, and the minimum difference is -58pcm. In addition, the difference from the SCALE code shows a maximum difference of +161pcm and a minimum difference of -86 pcm. The average of the multiplication factor is 1.00339. MCS code is overestimated about 339pcm which is considered a systematic bias. Similar trend can be found for the SCALE, McCARD code as well.

In this paper, only 66 models are compared for validation of the MCS code. This is much less than the 173 benchmark problems. In the future, validations will be performed on all models to obtain more accurate results.

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