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Benchmark Analysis of NCA Tungsten Critical Experiment

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1. Introduction

Critical experiments using tungsten gray rods and polystyrene were performed at the Toshiba Nuclear Critical Assembly (NCA) critical facility. This tungsten contained gray rod is very important because AP1000 uses this tungsten gray rod during their operation for reactivity control. This paper presents an analysis of these experiments using comparisons between the stochastic codes and deterministic codes, i.e., between MCNP and MCS, and between CASMO4E and STREAM. This analysis of a series of critical experiments demonstrates the accuracy in-house reactor core analysis codes; STREAM and MCS codes. Recently, new analysis codes have been developed at Ulsan National Institute of Science and Technology (UNIST), a Monte Carlo code MCS and an MOC code STREAM. There are a Ref. [3] about MCS and a Ref. [4] about STREAM.

2. Description of NCA Experiment

In the experiments, the tungsten rods are used for cores 1, 2, and 3. Cores 3, 4, and 5 are moderated with the polystyrene blocks in some areas while cores 1 and 2 are moderated by water in the whole area. Polystyrene containing boron is used for cores 3 and 4, but polystyrene without boron is used for core 5. Core 4 contains borated water in the water holes. Cores 1, 2, and 5 do not use boron.

The water in the core tank is exposed to the atmospheric condition and is at room temperature. In the core, the region is divided into 2 regions: one region is filled with fuel rods with 2w/o enrichment and another region is a main region at the center area which is filled according to the cores' experiments needs. These experiments are designed as a series of five core configurations according to various reactor core conditions.

An important point is that in these experiments the modeling of the tungsten rod is required. Recently, the tungsten cross section has been improved in the ENDF library. There is a big difference between the tungsten cross section of ENDF/B-VI.8[7] and that of ENDF/B-VII.0[6], and there is also a difference between the tungsten cross section of ENDF/B-VII.0[6] and that of ENDF/B-VII.1[5].

Cores 1 and 5 are composed of 27×27 square pitches of length 1.52 cm. Cores 2, 3, and 4 are composed of 31×31 square pitches of the same size. All of the fuel pellets have a radius of 0.50 cm. The cladding, which is made of aluminum, has an outer radius of 0.59 cm and a thickness of 0.08 cm. The UO_2 fuel density is 10.4 g/cm^3 except for poisoned pellets. The density of fuel pellets with gadolinium is 10.1 g/cm^3. The polystyrene density is 1.04g/cm^3. The temperature at the time of the experiments is room temperature. However, the moderator hydrogen atom density used in cores 3 through 5 is adjusted to the hot full power condition of PWR. More details of each core follow.

2.1 Core 1 configuration

As shown in Fig. 1(a), core 1 contains various enrichments of fuel from 2 w/o to 4.9 w/o. It has 25 tungsten gray rods and 12 poisoned fuel rods. 12 poisoned fuel rods are 2 w/o uranium enrichments fuel pins with 5 w/o gadolinium burnable absorber. Core 1 simulates the real commercial core. The purpose of this experiment is the measurements of the reactivity and the fission rates.

2.2 Core 2 configuration

Core 2 has a relatively less complex configuration than Core 1. All the fuel rods used in this experiment are 2w/o and it has 12 tungsten rods. The purpose of this experiment is to measure the tungsten reactivity worth and pin power distribution in the presence of the tungsten rod.

2.3 Core 3 configuration

Core 3 has 2 w/o and 4.9 w/o fuel rods and total four tungsten gray rods. This core has a polystyrene block containing 1000 ppm of boron. Four stainless steel rods support this polystyrene block sheet and have a radius of 0.60 cm. This core simulates the hot full power condition of commercial core.

2.4 Core 4 configuration

As shown in Fig. 1, core 4 has a similar configuration with core 1. In core 4, there are water holes in 25 guide tubes containing boric acid water rather than tungsten. The polystyrene block used in core 3 is also present in core 4. Stainless steel rods support the polystyrene block. This core simulates the beginning of cycle of commercial cores.

2.5 Core 5 configuration

Core 5 simulates the end of cycle of commercial cores. For this reason, the fuel enrichment and concentration of absorber are lower than those of core 4. The polystyrene contains no boron. Stainless steel rods are used to support the polystyrene block sheet. Actually, there is no burnable absorber like gadolinium or boron in core 5.

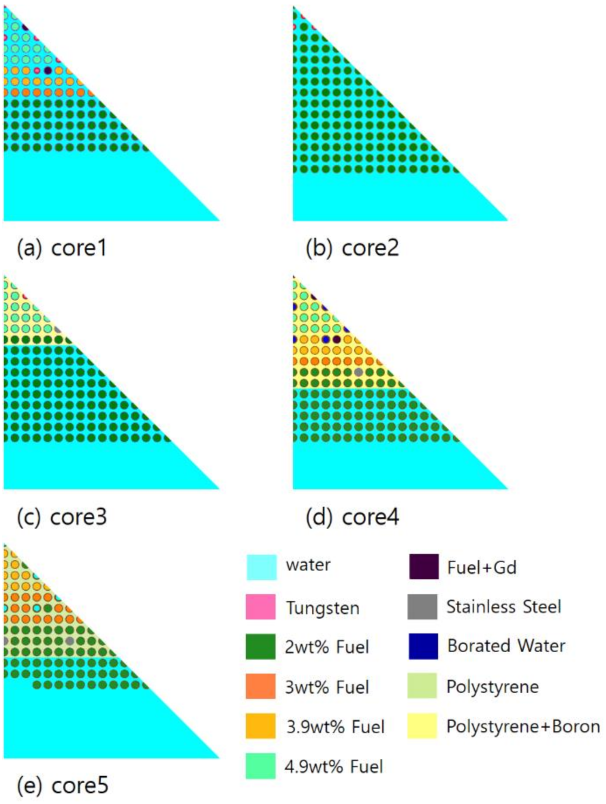


Fig. 1. Core configurations.

3. Simulation Codes

3.1 Stochastic codes

Both MCS and MCNP are stochastic codes. The Monte Carlo code MCS was developed at UNIST. Two acceleration techniques, (1) MOC-MC hybrid method and (2) modified power iteration method, were implemented in the MCS code to reduce computational time

3.2 Deterministic codes

Both STREAM and CASMO4E are deterministic codes. The MOC code STREAM was also developed at UNIST. STREAM adopted several newly developed resonance self-shielding methods. These new methodologies encompass (1) extension of the energy range of resonance treatment, (2) the optimum rational approximation, and (3) the resonance treatment for isotopes in the cladding region. These methods improve the accuracy of the STREAM code.

4. Benchmark Results

4.1 Monte Carlo results

In the Monte Carlo codes, MCS and MCNP6, 2-dimensional models were carried out with 50,000 neutron histories in 2,000 active cycles so that statistical error is less than 10pcm for eigenvalues. Tables I and II show the comparisons of MCNP6 eigenvalue results with other codes. MCNP6$^{(1)}$ represents k-effective results from Westinghouse Electric Co., MCNP6$^{(2)}$ from Studsvik Scandpower Inc., and MCNP6$^{(3)}$ represents UNIST calculations. All reference MCNP6 data use ENDF/B-VII.1[5]. Table I shows the stochastic code eigenvalues for the five core configurations and Table II shows comparisons of k values between MCNP6 and MCS.

Table I. Stochastic Code Eigenvalues for the Five Core Configurations

Core #	MCNP6$^{(1)}$	MCNP6$^{(2)}$	MCNP6$^{(3)}$
1	1.00890	1.00222	1.00701
2	1.03581	1.02727	1.03193
3	1.03878	1.03688	1.03920
4	0.97749	0.97040	0.97126
5	0.99725	0.99752	1.00018

(1) From reference [1]
(2) From reference [2]
(3) UNIST calculation

Table II. Comparison of MCNP6 and MCS Core Reactivity

Core #	k_{eff}(MCNP6)	k_{eff}(MCS)	k_{eff}(MCNP6)-k_{eff}(MCS) (pcm)
1	1.00701 ±0.00007	1.01742 ±0.00008	-1041
2	1.03193 ±0.00007	1.03479 ±0.00007	-286
3	1.03920 ±0.00007	1.04117 ±0.00008	-197
4	0.97126 ±0.00008	0.97824 ±0.00008	-698
5	1.00018 ±0.00008	1.00134 ±0.00008	-116

k_{eff} results of MCNP6 calculated in UNIST are well agree with reference values. As shown in Table I, those k_{eff} results are between two MCNP6 reference results except for core 5.

Tables II shows k_{eff} results calculated in UNIST using MCNP6 and MCS. Comparing k-results of MCNP6 and MCS, k- are bigger than those of MCNP6.

4.2 Deterministic code results

Tables III and IV show comparisons of the eigenvalue results of deterministic codes. CASMO5$^{(2)}$ represents the k_{eff} results from Studsvik Scandpower Inc. CASMO4E and STREAM represent UNIST calculations. Table IV shows the differences between these k-values. The CASMO5 code eigenvalue is denoted as k_{ref}.

Table III. Deterministic Code Eigenvalues
for the Five Core Configurations

Core #	CASMO5$^{(2)}$	CASMO4E	STREAM
1	1.00254	0.98174	0.99551
2	1.02727	1.01613	1.02608
3	1.03663	1.02753	1.03804
4	0.97028	0.97804	0.97692
5	0.99770	0.99027	0.99640

(2) From reference [2]

Table IV. Deterministic Code Eigenvalues
for the Five Core Configurations

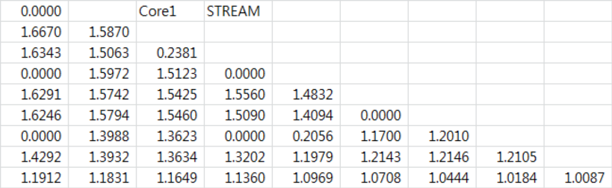
Core #	CASMO5$^{(2)}$	CASMO4E	STREAM(pcm)
	k_{ref}	δ=k-k_{ref}(pcm)	δ=k-k_{ref}(pcm)
1	1.00254	-2080	-703
2	1.02727	-1114	-119
3	1.03663	-910	141
4	0.97028	776	-336
5	0.99770	-743	-130

CASMO4E has big differences in k values from the reference because of a difference in the ENDF library. CAMSO5 uses ENDF/B-VII.1, but CASMO4E uses ENDF/B-VI.8. We can see that δ of cores 1, 2, and 3 between CASMO5 and CASMO4E is bigger than δ of other cores 4 and 5. Because core 1, 2, and 3 use tungsten grey rods, but the tungsten cross section library has different values between ENDF/B-VI.8 and ENDF/B-VII.1. Otherwise, STREAM shows a smaller δ value than that of CASMO4E. The STREAM code uses ENDF/B-VII.0. STREAM has relatively higher accuracy than CASMO4E because of the recent ENDF library when it is compared with the CASMO5 reference values.

Table V. Benchmark Analysis Code Eigenvalues
for the Five Core Configurations

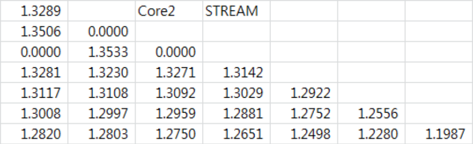
Core #	MCNP6	MCS	CASMO4E	STREAM
1	1.00701	1.01742	0.98174	0.99551
2	1.03193	1.03479	1.01613	1.02608
3	1.03920	1.04117	1.02753	1.03804
4	0.97126	0.97824	0.97804	0.97692
5	1.00018	1.00134	0.99027	0.99640

The fission rate distributions of STREAM for cores at vital middle parts are in the tables below.



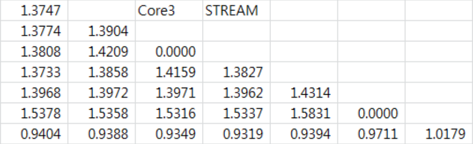
0.0000		Core1	STREAM					
1.6670	1.5870							
1.6343	1.5063	0.2381						
0.0000	1.5972	1.5123	0.0000					
1.6291	1.5742	1.5425	1.5560	1.4832				
1.6246	1.5794	1.5460	1.5090	1.4094	0.0000			
0.0000	1.3988	1.3623	0.0000	0.2056	1.1700	1.2010		
1.4292	1.3932	1.3634	1.3202	1.1979	1.2143	1.2146	1.2105	
1.1912	1.1831	1.1649	1.1360	1.0969	1.0708	1.0444	1.0184	1.0087

(a) Core 1



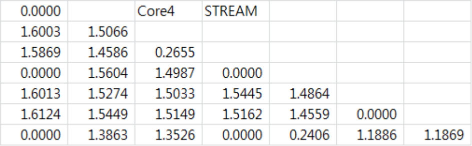
1.3289		Core2	STREAM			
1.3506	0.0000					
0.0000	1.3533	0.0000				
1.3281	1.3230	1.3271	1.3142			
1.3117	1.3108	1.3092	1.3029	1.2922		
1.3008	1.2997	1.2959	1.2881	1.2752	1.2556	
1.2820	1.2803	1.2750	1.2651	1.2498	1.2280	1.1987

(b) Core 2



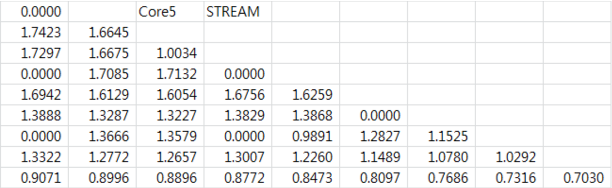
1.3747		Core3	STREAM			
1.3774	1.3904					
1.3808	1.4209	0.0000				
1.3733	1.3858	1.4159	1.3827			
1.3968	1.3972	1.3971	1.3962	1.4314		
1.5378	1.5358	1.5316	1.5337	1.5831	0.0000	
0.9404	0.9388	0.9349	0.9319	0.9394	0.9711	1.0179

(c) Core 3



0.0000		Core4	STREAM			
1.6003	1.5066					
1.5869	1.4586	0.2655				
0.0000	1.5604	1.4987	0.0000			
1.6013	1.5274	1.5033	1.5445	1.4864		
1.6124	1.5449	1.5149	1.5162	1.4559	0.0000	
0.0000	1.3863	1.3526	0.0000	0.2406	1.1886	1.1869

(d) Core 4

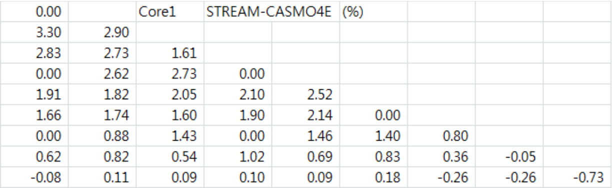


0.0000		Core5	STREAM					
1.7423	1.6645							
1.7297	1.6675	1.0034						
0.0000	1.7085	1.7132	0.0000					
1.6942	1.6129	1.6054	1.6756	1.6259				
1.3888	1.3287	1.3227	1.3829	1.3868	0.0000			
0.0000	1.3666	1.3579	0.0000	0.9891	1.2827	1.1525		
1.3322	1.2772	1.2657	1.3007	1.2260	1.1489	1.0780	1.0292	
0.9071	0.8996	0.8896	0.8772	0.8473	0.8097	0.7686	0.7316	0.7030

(e) Core 5

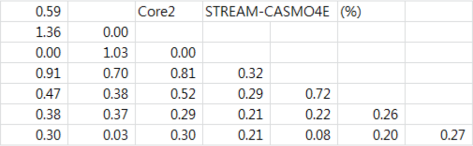
Fig. 2. Fission rate distribution of STREAM

The fission rate distribution comparison between STREAM and CASMO4E is in the table below.



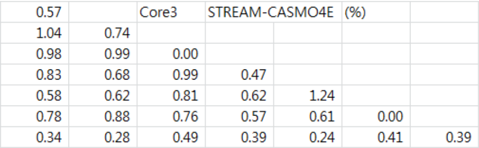
0.00		Core1	STREAM-CASMO4E		(%)			
3.30	2.90							
2.83	2.73	1.61						
0.00	2.62	2.73	0.00					
1.91	1.82	2.05	2.10	2.52				
1.66	1.74	1.60	1.90	2.14	0.00			
0.00	0.88	1.43	0.00	1.46	1.40	0.80		
0.62	0.82	0.54	1.02	0.69	0.83	0.36	-0.05	
-0.08	0.11	0.09	0.10	0.09	0.18	-0.26	-0.26	-0.73

(a) Core 1



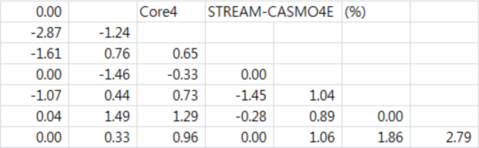
0.59		Core2	STREAM-CASMO4E		(%)	
1.36	0.00					
0.00	1.03	0.00				
0.91	0.70	0.81	0.32			
0.47	0.38	0.52	0.29	0.72		
0.38	0.37	0.29	0.21	0.22	0.26	
0.30	0.03	0.30	0.21	0.08	0.20	0.27

(b) Core 2



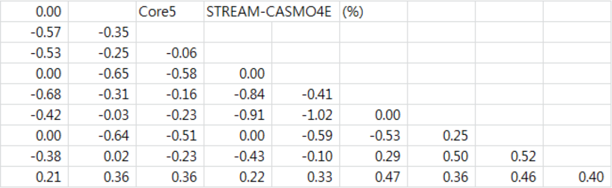
0.57		Core3	STREAM-CASMO4E		(%)	
1.04	0.74					
0.98	0.99	0.00				
0.83	0.68	0.99	0.47			
0.58	0.62	0.81	0.62	1.24		
0.78	0.88	0.76	0.57	0.61	0.00	
0.34	0.28	0.49	0.39	0.24	0.41	0.39

(c) Core 3



0.00		Core4	STREAM-CASMO4E		(%)	
-2.87	-1.24					
-1.61	0.76	0.65				
0.00	-1.46	-0.33	0.00			
-1.07	0.44	0.73	-1.45	1.04		
0.04	1.49	1.29	-0.28	0.89	0.00	
0.00	0.33	0.96	0.00	1.06	1.86	2.79

(d) Core 4



0.00		Core5	STREAM-CASMO4E		(%)			
-0.57	-0.35							
-0.53	-0.25	-0.06						
0.00	-0.65	-0.58	0.00					
-0.68	-0.31	-0.16	-0.84	-0.41				
-0.42	-0.03	-0.23	-0.91	-1.02	0.00			
0.00	-0.64	-0.51	0.00	-0.59	-0.53	0.25		
-0.38	0.02	-0.23	-0.43	-0.10	0.29	0.50	0.52	
0.21	0.36	0.36	0.22	0.33	0.47	0.36	0.46	0.40

(e) Core 5

Fig. 3. Fission rate distribution comparison of STREAM and CASMO4E.

5. Conclusions

This paper presents the benchmark analyses of a series of five NCA tungsten critical experiments with four codes. These experiments were designed to simulate the full power conditions of PWRs, and various data, such as neutron multiplication factor and fission rate distribution, were calculated with the analysis codes MCNP6, MCS, CASMO4E, and STREAM.

These analyses were focused on validating the high accuracy of newly developed in-house codes. The comparisons of k values were performed with other references and good agreements were observed for both the reactivity and fission reaction rates except for CASMO4E. The differences of STREAM fission rate distribution from that of CASMO4E were relatively bigger for the cores 1, 2, and 3, which can be attributed to the difference of the tungsten cross section found in different versions of the ENDF files. ENDF/B-VII.0 was used for Monte Carlo calculations. The comparison of the two MCNP6 results revealed that UNIST MCNP6 results agree well with the experiment data. The k-eigenvalue of MCS is noted to be bigger than the others.

The solutions of the deterministic codes showed small differences from those of MCNP6 and MCS, but overall the STREAM solutions showed reasonably accurate results compared to the results of CASMO4E.

Acknowledgements

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