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Comparative Analysis of VERA Depletion Problems

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1. Introduction

When verifying the depletion calculation module of reactor analysis codes, the code-to-code comparisons of depletion benchmark calculation results can be one of the viable methods. A depletion benchmark suite has been developed based on "The VERA core physics benchmark progression problems [1]". The detail design data and guidelines are provided in this benchmark problem suite [2].

Each code has its own solver for depletion, which can produce different depletion calculation results. In order to produce reference solutions for depletion calculation comparison, sensitivity studies should be preceded for each depletion solver. The sensitivity tests for burnup interval, number of depletion zones, and recoverable energy per fission (Q-value) were performed in this paper.

For the comparison of depletion calculation results, usually the multiplication factors are compared as a function of burnup. In this study, new comparison methods have been introduced by using the number density of isotope or element, and a cumulative flux instead of burnup.

2. VERA depletion benchmark

The VERA depletion benchmark problems include 10 single fuel pins and 16 fuel assembly problems with various fuel temperatures, enrichments of ^{235}U, control rods and burnable poisons. Among 26 problems, problems of 3.1wt. % UO_2 pin with fuel temperature of 900K (1C), and 5% gadolinia rod (1I) with 40W/gU as power density were selected for the sensitivity tests.

In the sensitivity study, SERPENT2, MCNP6, and STREAM codes were used for the depletion calculation. SERPENT2 is a Monte Carlo code with Chebyshev Rational Approximation Method (CRAM) depletion solver [3]. MCNP6 is also a Monte Carlo code and its depletion calculation is performed with CINDER90 using Matrix Exponential Method (MEM) [4]. STREAM is a lattice code using Method Of Characteristic (MOC) method developed by UNIST [5]. Its depletion calculation was performed with CRAM depletion solver. Table 1 represents the burnup intervals for depletion calculation.

3. Sensitivity study

The sensitivity tests of burnup intervals, depletion intra-zones, and Q-values were performed for depletion calculation. The neutronics calculation was performed with ENDF-B/VII.0 continuous energy neutron cross section library. The Monte Carlo simulation parameters are 20,000 histories per cycle, 20 inactive cycles, and 80 active cycles to achieve the standard deviations of multiplication factors below 20 pcm.

Table I: The burnup points for depletion calculation

Step	MWD / kgU	Step	MWD / kgU	Step	MWD / kgU	Step	MWD / kgU
1	0.00	11	7.00	21	17.00	31	37.50
2	0.01	12	8.00	22	18.00	32	40.00
3	0.25	13	9.00	23	19.00	33	42.50
4	0.50	14	10.00	24	20.00	34	45.00
5	1.00	15	11.00	25	22.50	35	47.50
6	2.00	16	12.00	26	25.00	36	50.00
7	3.00	17	13.00	27	27.50	37	52.50
8	4.00	18	14.00	28	30.00	38	55.00
9	5.00	19	15.00	29	32.50	39	57.50
10	6.00	20	16.00	30	35.00	40	60.00

3.1. Burnup interval sensitivity

The burnup interval sensitivity test was performed with SERPENT2, MCODE, and MCNP6. From the given 40 burnup steps, the intervals were split by 1/2, 1/4, and 1/8 to make 79, 157, and 313 burnup steps.

Figures 1 and 2 show the differences of multiplication factor of 40, 79 and 157 burnup steps from that of 313 steps by using SERPENT2 and MCNP6 for the pin problem 1C. In Figure 1, there is no noticeable trend of the differences of multiplication factor. It means that the 40 burnup steps is sufficient to produce converged solutions using SERPENT2. However, MCNP6 can produce the converged solutions by using 157 burnup steps. It is caused by the difference of depletion solver, in other words, CRAM depletion solver can treat better for larger burnup intervals then MEM.

This kind of burnup interval sensitivity was intensified in the gadolinia pin problem. Figures 3 and 4 show the differences of multiplication factor of 40, 79 and 157 burnup steps from that of 313 steps by using SERPENT2 and MCNP6 for the pin problem 1I. As shown in Figures 3 and 4, even if the CRAM depletion solver was used, 157 burnup steps are required to converge the solutions. Also, 157 burnup steps are insufficient to converge the solutions using MCNP6.

In summary, if CRAM depletion solver is used, 40 and 157 burnup steps are required to converge the solutions for the normal UO_2 and the gadolinia pin problems, respectively. In contrast with CRAM, if MEM depletion solver is used, 157 burnup steps are needed to produce the converged solutions for the normal UO_2 pin problem.

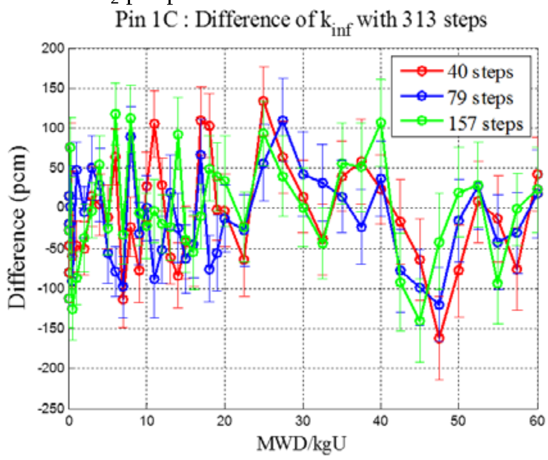

Fig. 1. Difference of multiplication factor from 313 steps using SERPENT2 for problem 1C.

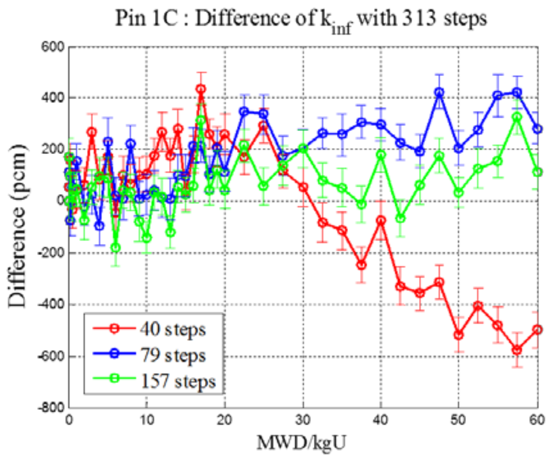

Fig. 2. Difference of multiplication factor from 313 steps using MCNP6 for problem 1C.

3.2. Depletion intra-zone sensitivity

The depletion intra-zone sensitivity test was performed by using SERPENT2 for problems 1C and 1I. The depletion calculation was performed with 1, 3, 5, and 10 equi-volumetric zones for the normal UO_2 pin and 1, 5, 10, and 15 zones for the gadolinia rod. In order to exclude the effects of burnup intervals, 157 burnup steps are used for the converged solutions in terms of burnup intervals.

Figure 5 shows the difference of multiplication factor of 1, 3, and 5 depletion intra-zone from that of 10 zones by using SERPENT2 for the pin problem 1C. And, Figure 6 shows the difference of multiplication factor of 1, 5 and 10 depletion intra-zone from that of 15 zones for the pin problem 1I. As shown in Figure 5, there is no trend of the differences of multiplication factor between 1 and 10 depletion zones. In other words, the division of UO_2 fuel rod is not required to get the converged solution in terms of depletion intra-zone. Unlikely, at least 10 depletion intra-zones are required to produce the reference solution for the gadolinia rod.

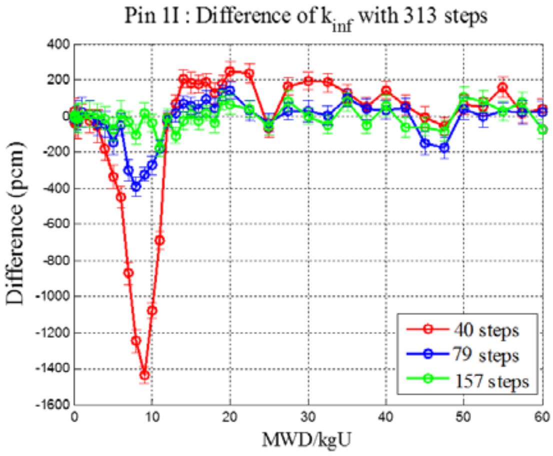

Fig. 3. Difference of multiplication factor from 313 steps using SERPENT2 for problem 1I.

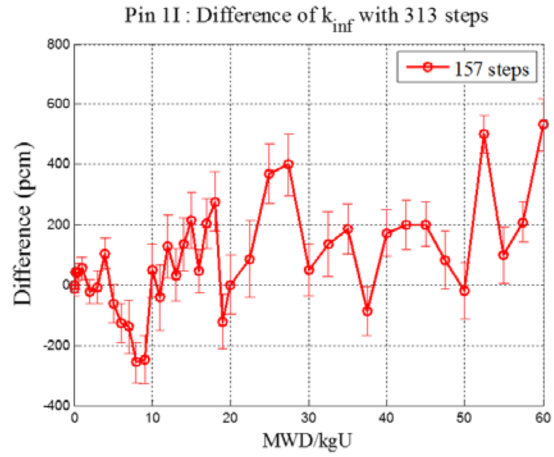

Fig. 4. Difference of multiplication factor from 313 steps using MCNP6 for problem 1I.

In summary, the depletion intra-zone sensitivity is independent on depletion solver, but, only dependent on the pin type. Also, 1 and 10 depletion intra-zones are sufficient for the normal UO_2 pin and the gadolinia rod, respectively, to produce the converged solutions.

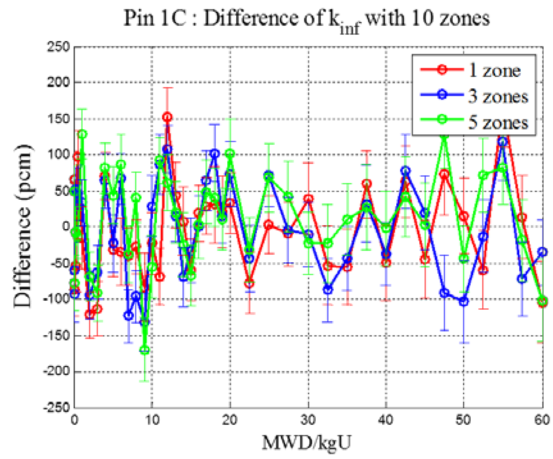

Fig. 5. Difference of multiplication factor from 10 depletion intra-zone using SERPENT2 for problem 1C.

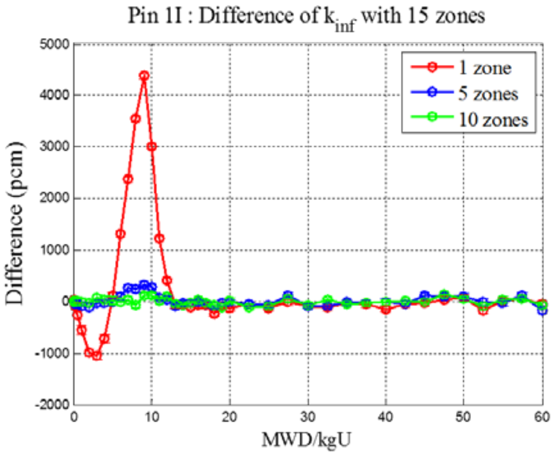

Fig. 6. Difference of multiplication factor from 15 depletion intra-zone using SERPENT2 for problem 1I.

3.3. Q-value sensitivity

The sensitivity test of Q-value was performed by STREAM for the problems 1C and 1I. It was noticed that he difference of Q-value can cause different solutions during the depletion calculations. Table II represents the various Q-values from VERA depletion benchmark suite, ORIGEN2.2, and SERPENT2. The VERA Q-values of main fissionable nuclides are larger than those of ORIGEN2.2, and SERPENT2 libraries.

Figures 7 and 8 show the differences of multiplication factor for various Q-values by STREAM for the problems 1C and 1I. Because the VERA Q-values are larger than the others, the flux level can be lower and the fuel will burn out slowly. Therefore, as shown in Figure 7, the multiplication factor with the VERA Q-values is largest among them.

Table II: The various Q-value of main fissionable nuclides

Isotope	Q-value (MeV)		
	VERA	ORIGEN2.2	SERPENT2
^{235}U	202.3400	202.3375	202.2700
^{238}U	212.6004	212.6030	206.7723
^{239}Np	213.8699	213.8674	198.3858
^{236}Pu	205.9501	205.9511	203.6065
^{237}Pu	206.0499	-	-
^{238}Pu	210.1799	210.1779	-
^{239}Pu	214.2768	211.1087	207.6202
^{240}Pu	214.1801	214.1822	-
^{241}Pu	216.8446	213.6371	210.8946
^{242}Pu	216.9800	216.9789	210.4769
^{243}Pu	-	-	208.8272
^{244}Pu	212.9998	-	-
^{241}Am	217.4200	217.4198	210.8737
^{242}Am	215.3834	213.8606	208.8272
^{242}Am	222.2877	215.8425	208.8272

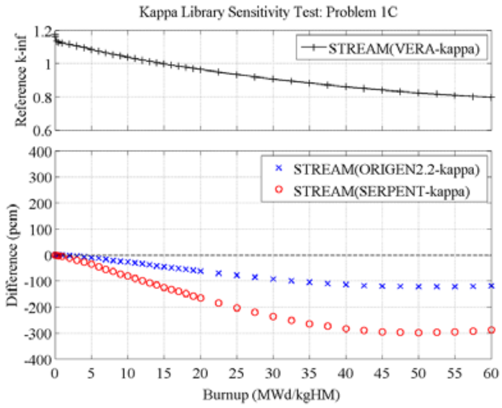

Fig. 7. Difference of multiplication factor of various Q-value using STREAM for problem 1C.

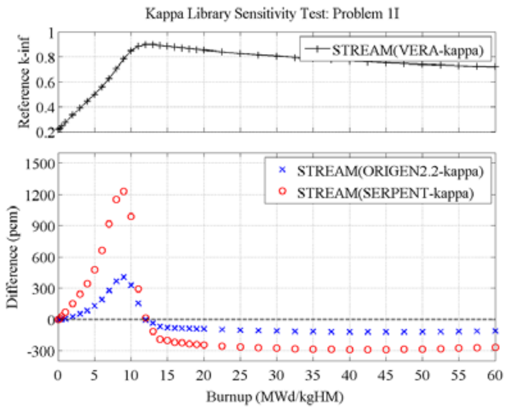

Fig. 8. Difference of multiplication factor of various Q-value using STREAM for problem 1I.

4. Comparison methods

In the previous section, the depletion calculation options to produce the converged solutions were determined, and the main cause of solution differences in the code-to-code comparisons is the difference of kappa values. In order to overcome this issue, new comparison methods have been developed.

When comparing the results of depletion calculation, the difference is represented using the burnup as x-axis. Figures 9-12 show the difference of multiplication factor using various Q-values for the problem 1C comparing with burnup, number density of ^{148}Nd, that of erbium element, and cumulative flux as x-axis. As shown in Figure 9, the maximum difference of multiplication factor of various Q-values is around -180 ~ 120pcm.

When the number density of ^{148}Nd is used as x-axis instead of burnup for comparison, the difference of multiplication factor are reduced from -180 ~ 120 to -7 ~ 6 pcm. Also, when the number density of erbium element is used, the difference are reduced to -5 ~ 15 pcm. These isotope and element are selected from the tests for all fission products generated during depletion calculation.

Lastly, the accumulated flux in fuel rod is used instead of burnup for comparisons. As shown in Figure 12, the difference of multiplication factor are reduced to -3 ~ 12pcm. When the number density of isotope and element, and cumulative flux are used as x-axis instead of burnup in code-to-code comparison, the difference of multiplication factor of various Q-values are significantly reduced.

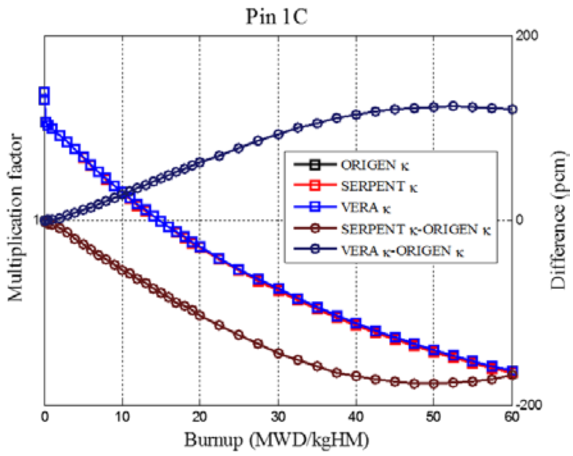

Fig. 9. Difference of multiplication factor of various Q-values comparing with burnup as x-axis.

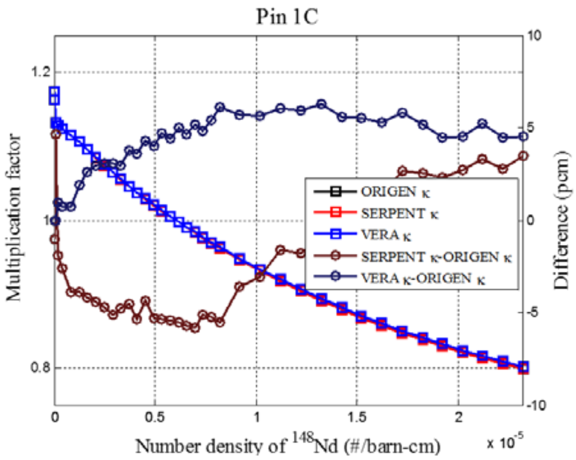

Fig. 10. Difference of multiplication factor of various Q-values comparing with number density of ^{148}Nd as x-axis.

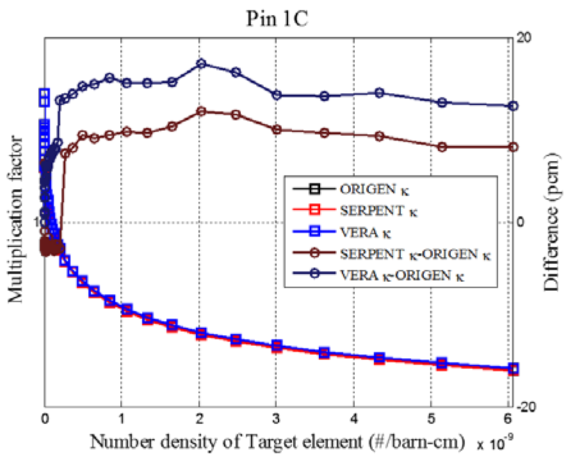

Fig. 11. Difference of multiplication factor of various Q-values comparing with erbium (Er) element as x-axis.

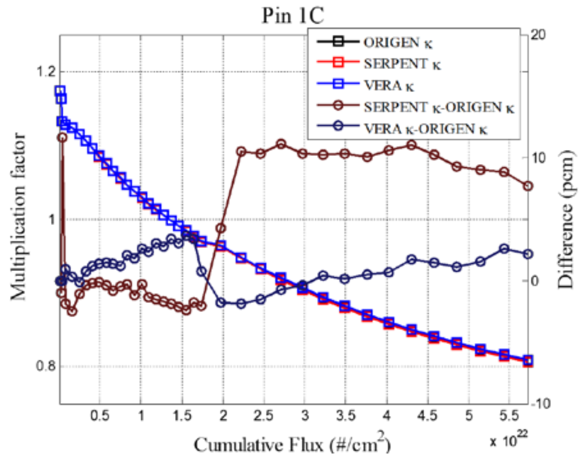

Fig. 12. Difference of multiplication factor of various Q-values comparing with cumulative flux as x-axis.

5. Conclusions

In this paper, optimum depletion calculation options are determined through the sensitivity study of the burnup intervals and the number of depletion intra-zones. Because the depletion using CRAM solver performs well for large burnup intervals, smaller number of burnup steps can be used to produce converged solutions. It was noted that the depletion intra-zone sensitivity is only pin-type dependent. The 1 and 10 depletion intra-zones for the normal UO_2 pin and gadolinia rod, respectively, are required to obtain the reference solutions. When the optimized depletion calculation options are used, the differences of Q-values are found to be a main cause of the differences of solutions.

In this paper, new comparison methods were introduced for consistent code-to-code comparisons even when different kappa libraries were used in the depletion calculations. The ^{148}Nd and erbium element are selected isotope and element for the x-axis in code-to-code comparison. The accumulated flux in the fuel rod is also used as x-axis. When these are used as x-axis instead of burnup, the difference of multiplication factor is significantly reduced in the code-to-code comparison.

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