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Application of practical FSD reduction technique for MCNP code in the spent fuel cask shielding analysis

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Abstract

In order to apply the MCNP code to shielding analysis of spent fuel casks, the reduction of Fractional Standard Deviation (FSD) is an important issue of the practical use, especially in the calculation for Fission Products (FP) gamma rays. Among the FSD reduction techniques, Energy Group Division Method using Weight Window Generator (WWG) built-in MCNP code is an effective method that can be applied to the calculation for FP gamma rays. In the result of applying the Energy Group Division Method to some casks in actual, some effectiveness against the FSD reduction is obtained. Here, we present an example of using the Energy Group Division Method for FP gamma rays shielding analysis of a transport/storage cask for spent fuel.

Introduction

Monte Carlo method has been utilized in shielding analysis of spent fuel transport packages (casks) recently, because it can model complicated and detailed geometry in three dimensions. However, Monte Carlo calculation takes long time for calculation even by today’s advanced computer performance. In particular, on the deep penetration problem in radiation shielding fields, particles which reach detector position are much less than total particles generated at source in many cases. Then it is difficult to obtain a well reliable solution (i.e., solution with low FSD).

The MCNP code 1) has some basic variance reduction techniques. Weight Window (WW) method is one of the typical variance reduction techniques. As using WW method, WW values depending on space and energy are set for each region (cell) of calculation geometry, and Russian roulette/splitting is carried out depending on the weight value of the particle at the region. WWG provided in MCNP can generate WW value semi-automatically.

Generally, gamma ray shielding calculation with wide energy spectrum takes longer time. In particular, in the thick gamma ray shielding geometry like cask, it is difficult to obtain the valid solution with low FSD even if using WW method. Therefore, we propose Energy Group Division Method (EGDM) 2), which could reduce the variance effectively on FP gamma ray shielding calculation, and validate the variance reduction effect in cask system which has thicker shield.

1. The Outline of Energy Group Division Method

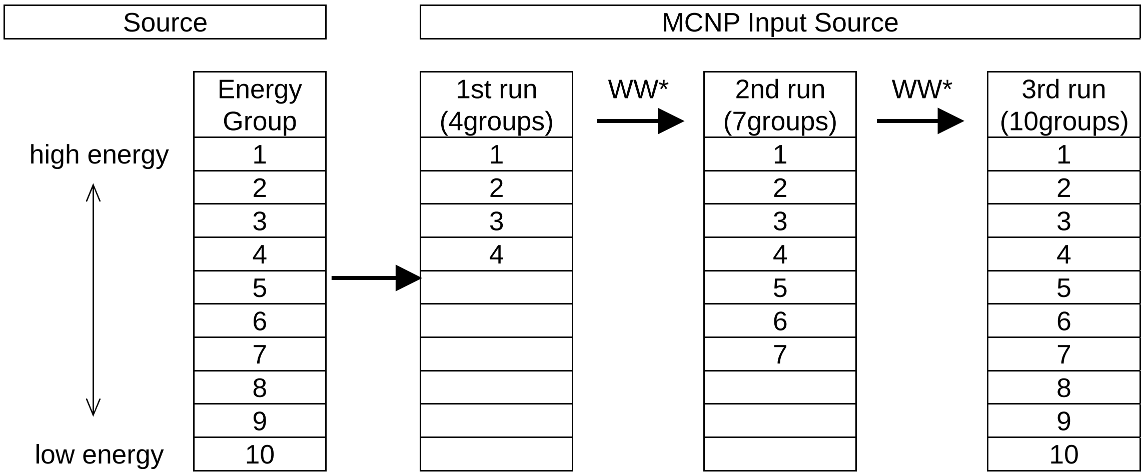
1.1 Problem of the FP Gamma ray Shielding Analysis on Cask Geometry

Low energy gamma rays account for a large fraction in the FP gamma ray energy spectrum from spent fuel. On the other hand, high energy FP gamma rays account for only a small fraction of the spectrum, but its penetration through the shield is high, and the penetration gets lower with decreasing gamma ray energy. While, in the case of thick shield for gamma rays, low energy FP gamma rays cannot reach the detector position. Thus, gamma ray shielding calculation by Monte Carlo method on cask system with thick gamma ray shield takes a large fraction of time for calculation of low energy FP gamma rays that has very small probability of reaching the detector, and results in the degradation of calculation efficiency.

In the case of using WW method, it is difficult to configure WW value for the complicated geometry manually. Therefore, we usually configure WW value semi-automatically by using WWG. However, even by using WWG, unless a sufficient number of particles reach the region in which we would like to generate WW (in many cases, cells between the source and detector position), valid WW are not generated easily. Thus, in spent fuel gamma ray shielding calculation of which low energy gamma rays account for a large fraction, it takes long time to generate valid WW.

1.2 Energy Group Division Method

EGDM proposed in this paper, at first calculation we use source with only high energy particles having high penetration and easily reaching at important region (cell) to generate WW. Then, we can generate WW at important region (cell) effectively compared to using source including lower energy particles. However, this WW is generated by high energy particles only, then, by increasing sequentially the number of energy groups from higher energy groups to lower energy groups, it is possible to generate valid WW for calculation using original energy spectrum effectively. Calculation procedure of EGDM is shown in Figure 1.1.



* WW created by WWG in the previous calculation

Figure 1.1 Calculation Procedure of Energy Group Division Method

2. Validation Calculation

2.1 Calculation Model

We apply EGDM to the shielding calculation of cask with MCNP, and we validate its variance reduction effect. We adopt the design example of transport and storage cask (OCL-2521 type cask) which loads 21 PWR fuel assemblies as the calculation geometry. OCL-2521 type cask is multilayer cylindrical type cask.

In this calculation, we model real cask geometry into almost realistic three dimensional model. Moreover, fuel region is homogenized in each fuel assembly.

OCL-2521 type cask calculation model and detector positions are shown in Figure 2.1. In validation calculation, we select fuel center height and lower trunnion height of cask side, at cask surface and at 1 meter from cask surface as detector positions, in order to validate EGDM at some detector positions with different convergence behavior. Summary of detector positions is shown in Table 2.1.

Table 2.1 Detector positions

Position No.	Axial Position	Distance from Cask
(1)	Fuel Center Height	At 1m
(2)	Bottom Trunnion	At 1m
(3)	Fuel Center Height	Surface
(4)	Bottom Trunnion	Surface

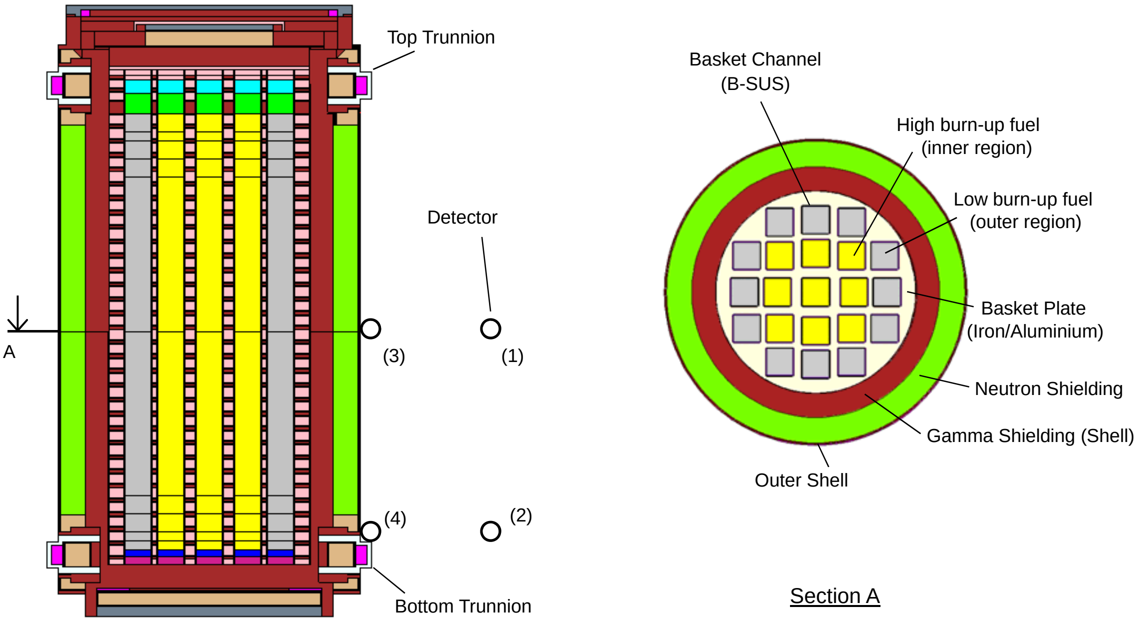


Figure 2.1 OCL-2521 Cask model and Detectors

2.2 Conditions of Validation Calculation

We calculate FP gamma ray source intensity by ORIGEN-2 [3]. Though FP gamma ray spectrum obtained from ORIGEN-2 code consist of 18 energy groups, we use 10 energy groups FP gamma ray spectrum that excluded lower energy groups empirically known that there is little contribution for calculation result (dose, etc.).

In this paper, we use 3 steps EGDM. The number of energy groups used in each runs is gradually increased from higher energy groups of source spectrum, 4 groups for 1st run, 7 groups for 2nd run and 10 groups for 3rd run. For comparison purpose, we carry out the calculation without EGDM too.

And also we compare two WW energy group structure cases, one is 6 energy groups and the other is 1 group (not divide). Summary of calculation cases is shown in Table 2.2.

Table 2.2(a) Summary of calculation cases

Calculation Case	EGDM	WW energy group division
Case (a)	not use	6 groups
Case (b)	use	6 groups
Case (c)	not use	1 group
Case (d)	use	1 group

Table 2.2(b) Energy structure of source and Weight Window

ORIGEN2 Source (FP gamma ray)			MCNP Source				WW energy structure	
			Case(b)(d)			Case(a)(c)		
Energy Group	Upper Energy (MeV)	Normalized Spectrum	1st run (4groups)	2nd run (7groups)	3rd run (10groups)	1st-3rd run (10groups)	Case(c)(d)	Case(a)(b)
1	1.10E+01	4.377E-11	1	1	1	1	1st (no energy division)	1st*
2	8.00E+00	3.810E-10	2	2	2	2		
3	6.00E+00	3.304E-09	3	3	3	3		2nd
4	4.00E+00	1.083E-08	4	4	4	4		
5	3.00E+00	1.187E-07	-	5	5	5		3rd
6	2.50E+00	2.502E-07	-	6	6	6		
7	2.00E+00	4.024E-04	-	7	7	7		4th
8	1.50E+00	1.308E-02	-	-	8	8		5th
9	1.00E+00	1.957E-02	-	-	9	9		
10	7.00E-01	4.440E-01	-	-	10	10		6th
11	4.50E-01	1.052E-02	Ignored					
12	3.00E-01	2.459E-02						
13	1.50E-01	2.789E-02						
14	1.00E-01	2.952E-02						
15	7.00E-02	5.257E-02						
16	4.50E-02	6.676E-02						
17	3.00E-02	5.234E-02						
18	2.00E-02	2.587E-01						

* Upper energy of the highest WW group is 15 MeV

3. Comparisons of Calculation Results

3.1 Calculation time

We carry out the validation calculation of 3 steps EGDM with condition shown in previous chapter. For each runs, we set the same calculation time for 1st and 2nd run, and longer calculation time than previous runs for 3rd run. We set the same calculation time for the same detector position, but we do not unify the calculation time among detector positions. Calculation times for each detector position are shown in Table 3.1.

Table 3.1 Calculation time (min)

Detector positon	1st run	2nd run	3rd run
(1)	720	720	1440
(2)	1440	1440	2880
(3)	4320	4320	10080
(4)	5760	5760	7200
Remarks: Computer specs are not same among detector positions.			

3.2 Behavior of Statistical Indicators

In this validation, we compare calculation results with focusing FSD and variance of the variance (VOV) values which are typical statistical indicators of MCNP. In the case of using Point Detector (F5 tally), convergence criteria are <0.05 for FSD and <0.1 for VOV. The behavior of mean (dose rate), FSD and VOV against calculation time at each detector position are shown in Figure 3.1 - Figure 3.4.

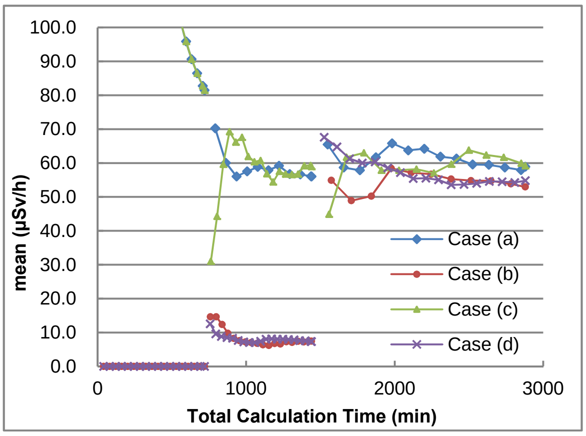
Because detector position (1) and (2) are the position of at 1m from the cask surface where calculation is easy to converge, dose rate is almost converged in comparatively short calculation time. About the behavior of FSD and VOV, case (d) which applied EGDM with WW of no energy division has the best convergence behavior. Moreover, it is found that VOV of case (b) varies discontinuously. There is little difference of convergence behavior among the other cases.

About the result of cask surface detector position (3) and (4) where calculation is not easy to converge, they do not satisfy the convergence criterion although calculation time is longer than detector position (1) and (2).

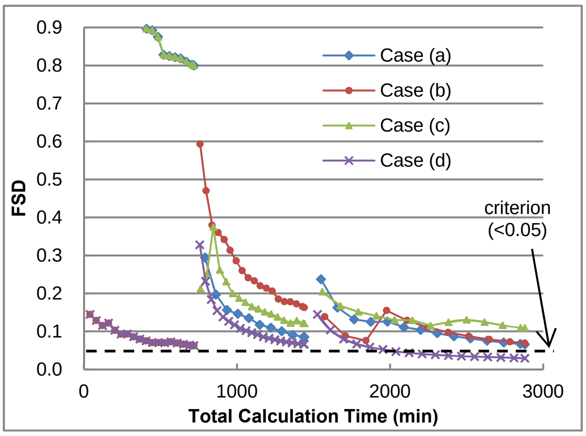
It is found that convergence tendency of case (d) at detector positon (3) is comparatively good similarly to detector position (1) and (2). However, the convergence at detector position (4) with EGDM is inferior to without EGDM and bad even in the 2nd run.

Detector position (4) is located at the height of near the lower edge of source region, thus the shielding thickness of shell between the source region and detector positon varies largely by the axial position of the source. Owing to generating WW with higher energy FP gamma rays in EGDM, the FP gamma rays emitted away from the detector position in the axial direction and penetrating long distance of the shell can contribute to generating WW. However, the WW of the shell are averaged in the axial direction because the number of axial cell divisions of the shell in this calculation model is very small. Thus, there is a possibility that the WW of the shell is inappropriate for lower energy FP gamma rays. In such a case, it is considered that we should devise the energy group division of EGDM and the axial cell division of the calculation model.

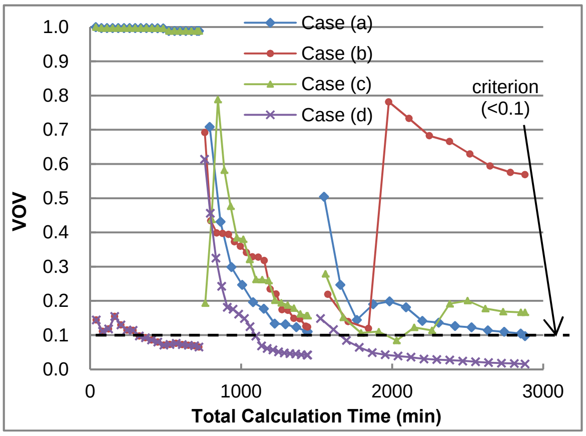
Based on the above convergence tendency, good variance reduction effect is obtained by using EGDM. However, degradation of variance reduction effect is observed with energy divided WW.



Behavior of mean

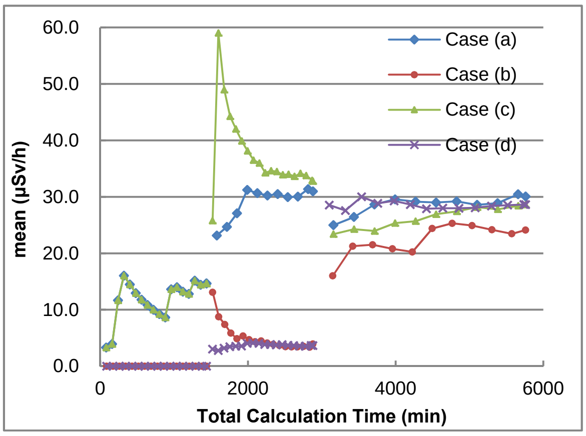


Behavior of FSD

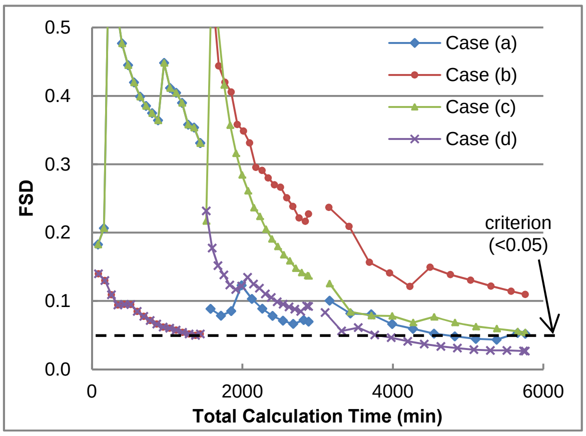


Behavior of VOV

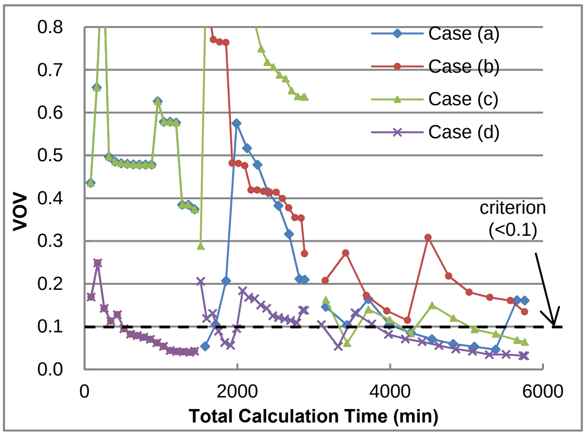
Figure 3.1 Behavior of statistical indicators (Detector position (1))



Behavior of mean

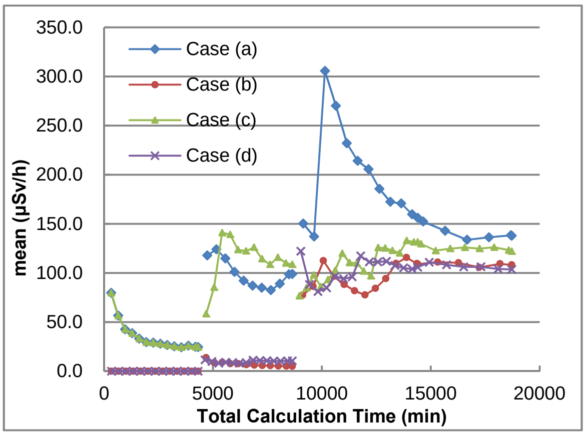


Behavior of FSD

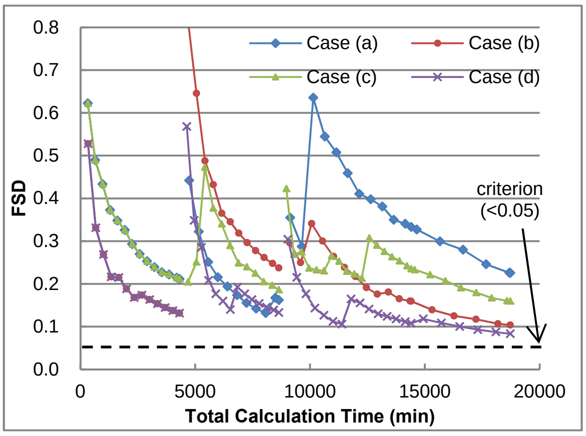


Behavior of VOV

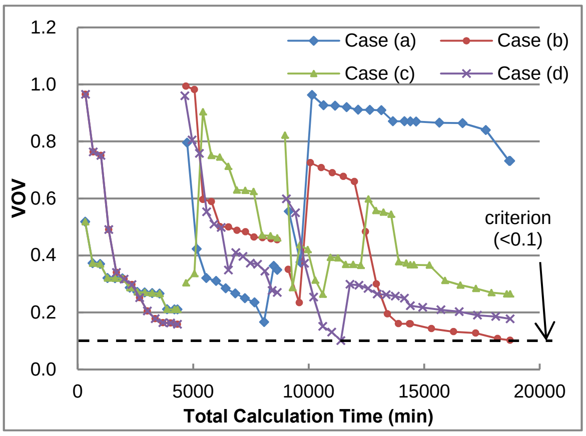
Figure 3.2 Behavior of statistical indicators (Detector position (2))



Behavior of mean

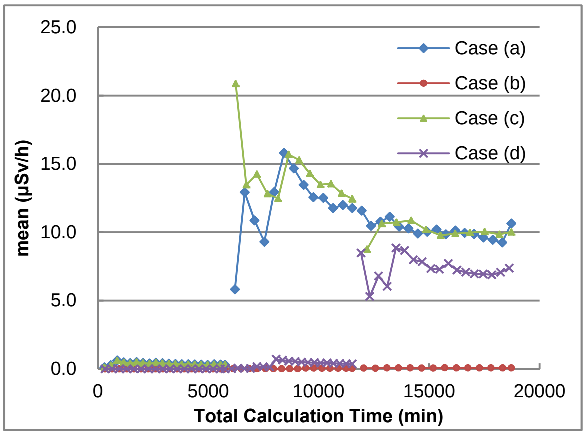


Behavior of FSD

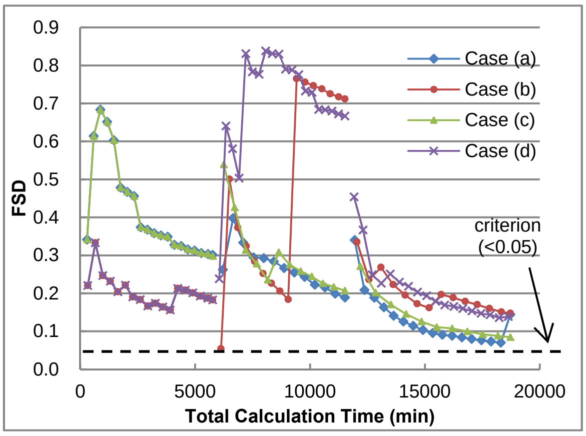


Behavior of VOV

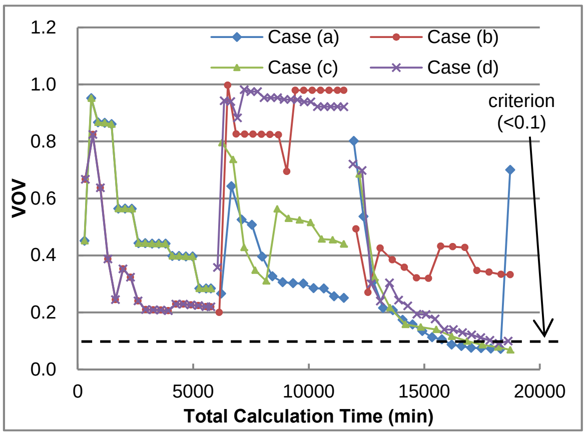
Figure 3.3 Behavior of statistical indicators (Detector position (3))



Behavior of mean



Behavior of FSD



Behavior of VOV

Figure 3.4 Behavior of statistical indicators (Detector position (4))

3.3 Effect of Energy Group Division on WW

Degradation of variance reduction effect is confirmed when EGDM with energy divided WW is applied. Therefore, we compare the WW of detector position (1) as a representation, and search for the cause of degradation of variance reduction effect.

Almost all FP gamma rays which would contribute to detector position (1) go through gamma shielding and neutron shielding. Therefore, WW of those regions would have the largest effect on calculation result. Then, we comprise the WW value of those regions which are generated at 2nd run, and used at 3rd run. Comparison of lower energy 2 group WW which account for a large fraction of spectrum and have a large effect on variance reduction is shown in Figure 3.5.

As for the WW of lowest energy group, it is found that WW value with EGDM varies discontinuously. The cause of discontinuity is estimated that there are no lower energy group of source in 2nd run and sufficient number of lower energy particles cannot reach corresponding region. Thus, in the case of using EGDM with energy divided WW, it is considered that some energy groups of WW generated by previous calculation is inappropriate, and using this WW at subsequent run result in degradation of variance reduction effect.

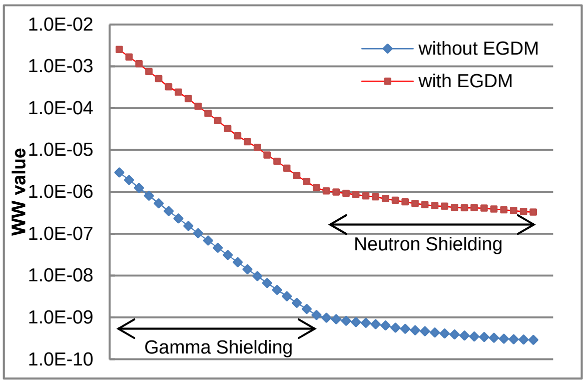


Figure 3.5(a) Comparison of WW (Energy range : 1.5 - 0.7 MeV)

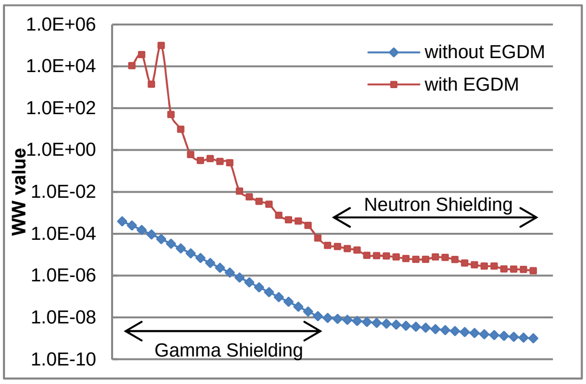


Figure 3.5(b) Comparison of WW (Energy range : 0.7 - 0.0 MeV)

Conclusions

It is confirmed that variance reduction effect can be obtained by applying EGDM for the shielding calculation on the condition of which gamma ray shielding is thick and FP gamma rays are difficult to reach the detector position. However, when applying the EGDM with energy divided WW, degradation of convergence is observed, whereas a variance reduction effect is obtained for EGDM without energy divided WW. The application of EGDM with energy divided WW is a future challenge.

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