Neutron and Gamma Shielding Test and Its Analysis of Ductile Cast Packaging

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INTRODUCTION

Most of transport packagings for spent fuels have neutron shielding, made of water, resin, etc., which are arranged in a uniform layer in circumference of packagings. These structures can be easily made into shielding analytical model with high fidelity and these analytical models are supported by many shielding data and analyses. However, it is scarcely reported neutron shielding test data of transport packagings with more complicated structure of neutron shielding.
In this study the "Zigzag" neutron shielding structure with a ductile cast packaging body is chosen as the complicated shielding structure. Measurements and calculations of the "Zigzag" neutron shielding structure are performed and compared with the simplified model of this structure so as to discuss the differences between the actual complicated structure and the simplified model structure.

NEUTRON AND GAMMA SHIELDING TEST

Ductile cast packaging model

(1) Configulation

Fig. 1 shows the ductile cast packaging model used for the test.
The dimension of the model is 1400mm in outer diameter × 1700mm in height × 400 mm in thickness. The model is divided into three regions having different kinds of shielding structures as shown in Fig. 1.
The shielding structures of the three regions are as follows.

Region (Ⅰ) : Polyethylene bars, the neutron shielding material, are arranged in the "Zigzag" manner. The number of polyethylene bars is selected so that the diameter of the polyethelene bars and the thickness of the polyethelene plate in region (Ⅱ) will be the same thickness.

Region (Ⅱ) : Polyethylene plates are arranged instead of polyethylene bars in region (Ⅰ). The total volume of polyethylene plates is equal to the polyethylene bars in region (Ⅰ) and the positions of the polyethylene bars and plates are shown in Fig. 2.

Region (Ⅲ) : No polyethylene

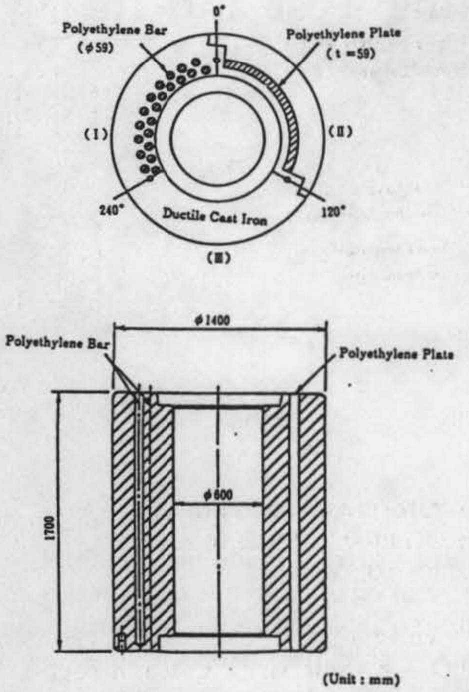


Fig. 1 Configulation of Ductile Cast Packaging Model

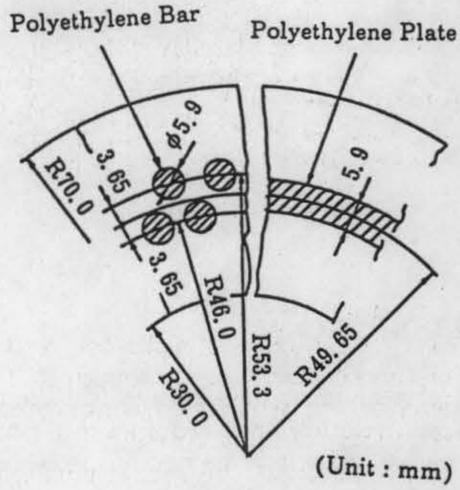


Fig. 2 Relation of Polyethylene Bars and Plates

(2) Materials of model
The gamma shielding material is a ductile cast iron which is the main body material of the model. The neutron shielding material is polyethylene. The densities and chemical compositions of these materials are shown in Table 1.

Shielding Test Facility

Measurements are carried out using CRIEPI's shielding test facility. The shielding test facility consists of a shielding test room, radiation measurement equipment, and radiation sources. The concrete wall thickness of the shielding test room is 40 cm. The room includes a turning bed for the model packaging, a detector driving mechanism, a driving system for radiation sources and a monitoring camera. All driving systems necessary for measurements are remote controled from a control room. The bird's-eye view of the shielding test facility is shown in Fig. 3.

(1) Sources
The neutron source is Cf−252, and the gamma suurce is Co−60. Both sources are considered as cylindrical surface sources because about one hundred small sources are distributed on the surface of the cylinder which is 500mm in diameter ×500mm in height as shown in Fig. 4.
The source intensity of Cf−252 is about 265 μg and Co−60 is about 126Ci.
The measurement results are normalized to 1mg of Cf−252 and 200Ci of Co−60.

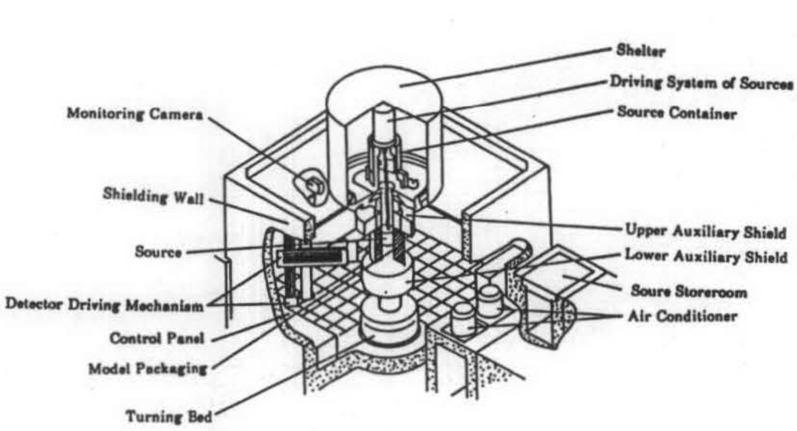


Fig. 3 Bird's−eye View of Shielding Test Facility

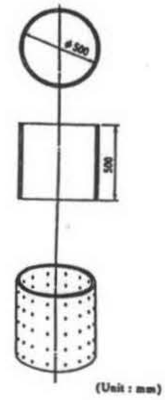


Fig. 4 Configulation of Sources (Cf−252 or Co−60)

(2) Detectors
A Rem−counter is used for neutron dose rate measurements and an ionization chamber survey meter and a Na I (T ℓ) scintillator (3inch in diameter ×3inch in length) are used for gamma dose rate measurements.

(3) Geometry of measurement
The location of the model packaging is shown in Fig. 5. The results of the preliminary gamma dose rate measurements are shown in Fig. 6 and Fig. 7.
Fig. 6 shows that the axial position of 4100mm from the floor is the best position because the influence of scattering components from the upper and lower auxiliary shield is the smallest in this position. With respect to the circumference, the measurement point is the center of each of the 3 regions.

Results of Measurements

The maximum dose rates for each region are shown in Table 2.

(1) Neutron dose rate
The surface neutron dose rates of region (I) and (II) are about 1 / 7 to 1 / 8 of that of region (III). In addition, the neutron dose rates 1 m from the surface of region (I) and (II) are 1 / 5 to 1 / 6 of that of region (III).
According to this comparison the dose rate of the complicated structure is about 13 % larger than that of the simplified structure.

(2) Secondary gamma dose rate
The secondary gamma dose rates are 3 to 5% of the neutron dose rate for region (I) and (II) and about 1% for region (III). The large ratio of secondary gamma dose rates in region (I) and (II) is due to the effect of the thermal neutron capture reactions of hydrogen or carbon in polyethylene.

(3) Gamma dose rate
The gamma dose rates of region (I) and (II) are 5 to 8 times larger than that of region (III). According to this comparison, the dose rate of the complicated structure is 30 to 50% larger than that of the simplified structure.

(4) Circumference distribution of dose rate
As shown in Fig. 7, the circumference gamma dose rate distribution within region (I) is virtually flat without any special peak caused by the complicated structure. The shape of this distribution is almost the same as region (II). The same applies to the neutron dose rate distribution.

Table 1 Composition of Materials

Material	Density	Chemical Composition (wt%)			
Ductile Cast Iron	7.0 g/cm³	C Si Mn P	3.3～3.8 1.3～2.6 ≦0.6 ≦0.03	S Mg Ni Cu	≦0.01 0.035～0.09 ≦1.3 ≦0.15
Polythylene	0.934 g/cm³	C H	85.6 14.4		

Table 2 Maximum Does Rate of Each Region (Length of source:50cm)

	Location	Surface			1m from Surface		
	Region	(I) Bar	(II) Plate	(III) Casting	(I) Bar	(II) Plate	(III) Casting
Neutron*1 (mrem/hr)	Rem-Counter	128	113	908	41.0	35.9	207
Secondary Gamma*1 (mR/hr)	NaI(Tℓ) Scintillator	4.3	3.26	10.6	2.2	1.72	4.31
	Ionization Chamber Survey Meter	3.4	3.01	7.4	1.5	1.39	2.6
Gamma*2 (mR/hr)	NaI(Tℓ) Scintillator	4.04	3.12	0.61	0.96	0.68	0.13
	Ionization Chamber Survey Meter	4.85	3.3	0.6	1.0	0.7	0.17

*1 Source Intrnsity is Normalized to 1 mg = 0.53Ci ^{252}Cf

*2 Source Intensity is Normalized to 200Ci ^{60}Co

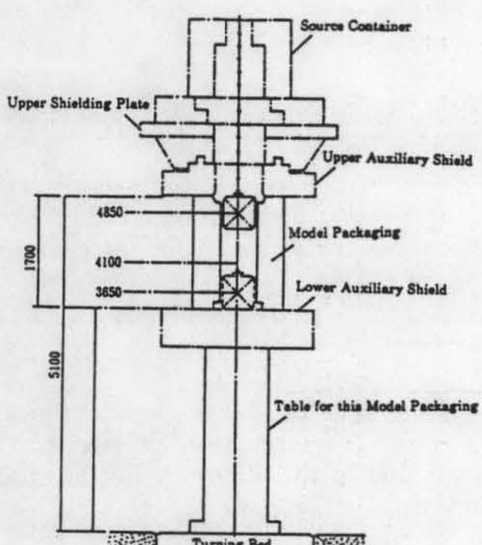


Fig. 5 Geometry of Measurement

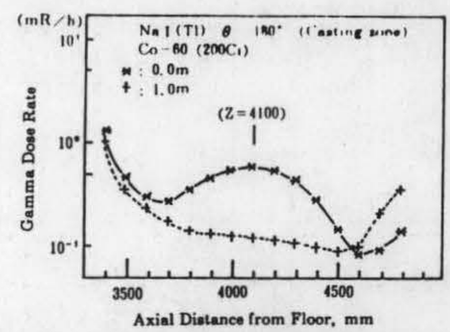


Fig. 6 Axial Gamma Dose Rate Distribution [NaI (Tl), Region (III)]

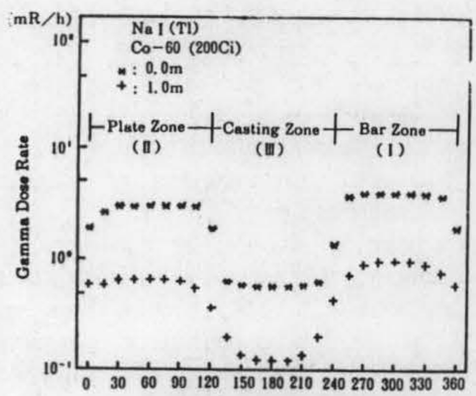


Fig. 7 Circumference Gamma Dose Rate Distribution [NaI (Tl)]

ANALYSIS

Calculational Method

Analysis is performed by using the two-dimensional discrete ordinate code DOT3. 5.

(1) Cross section library

The energy group structures, dose rate conversion factors and source spectra used for neutron shielding calculation are shown in Table 3 and 4. The original energy group structure of this library is 36 neutron groups and 18 gamma groups. This library is collapsed to the library with 9 neutron groups and 6 gamma groups for the DOT3. 5 calculations.

The data for gamma shielding calculation is also shown in Table 5. The details of these data are described in *Experiment and Analysis of CASTOR Type Model Cask for Verification of Radiation Shielding*, S. Hattori and K. UEKI1988.

(2) Source condition

The shape of the source used in measurements for both neutron and gamma is a cylinder 500mm in diameter and 500 mm in height as shown in Fig. 4. The source is set to the upper, middle and lower position in the cavity of the model package for one measurement. In other words, the source is 500mm in diameter and 1500 mm in height. This height is considered in the calculation.

① Neutron source

The fission neutron source spectra of Cf−252 used in the calculation is shown in Table 3. The number of neutrons emitted from 1mg Cf−252 is 2.4×10^{9} n/sec.

② Gamma source

The gamma source, Co−60 emits two gamma rays with the energy of 1. 33 MeV and 1. 17MeV. These gamma rays correspond respectively to group 1 and 2 of the library shown in Table 5. The number of gamma rays emitted from 200Ci Co−60 is 7.4×10^{12} ph/sec for both groups of energy.

Table 3 Cross section libray date for neutron shielding calculation (Neutron group)

Energy group	Collapsed group	Upper Energy (eV)	Does rate conversion factor (mrem/hr)(ph/sec/cm²)		^{252}Cf Neutron spectra	
1 2 3 4 5 6	1	1. 733E +7 1. 221E +7 1. 000E +7 8. 187E +6 6. 703E +6 4. 493E +6	1. 508E −1 1. 483E −1 1. 459E −1 1. 432E −1 1. 409E −1 1. 389E −1	1. 414E −1	6. 928E −4 2. 860E −3 8. 508E −2 1. 938E −2 0. 025E −2 7. 301E −2	1. 947E −1
7 8 9	2	3. 679E +6 3. 012E +6 2. 466E +6	1. 389E −1 1. 389E −1 1. 389E −1	1. 389E −1	8. 690E −2 9. 433E −2 9. 507E −2	2. 763E −1
10 11 12	3	2. 019E +6 1. 653E +6 1. 353E +6	1. 389E −1 1. 355E −1 1. 291E −1	1. 316E −1	9. 027E −2 8. 171E −2 7. 118E −2	2. 432E −1
13 14 15	4	1. 108E +6 9. 972E +5 7. 427E +5	1. 230E −1 1. 035E −1 8. 723E −2	9. 243E −2	6. 011E −2 4. 952E −2 3. 999E −2	1. 496E −1
16 17 18 19 20	5	6. 081E +5 4. 979E +5 4. 076E +5 2. 732E +5 1. 832E +5	7. 352E −2 6. 284E −2 5. 446E −2 4. 091E −2 3. 075E −2	4. 802E −2	3. 177E −2 2. 491E −2 3. 420E −2 1. 999E −2 1. 144E −2	1. 223E −1
21 22 23 24 25	6	1. 228E +5 8. 652E +4 5. 247E +4 3. 183E +4 1. 503E +4	2. 310E −2 1. 917E −2 1. 525E −2 1. 212E −2 8. 596E −3	1. 687E −2	5. 840E −3 5. 549E −3 2. 182E −3 1. 333E −3 0. 0	1. 390E −2
26 27 28 29 30	7	7. 102E +3 2. 613E +3 9. 611E +2 4. 540E +2 1. 670E +2	6. 095E −3 4. 304E −3 4. 236E −3 4. 186E −3 4. 120E −3	5. 237E −3	0. 0 0. 0 0. 0 0. 0 0. 0	0. 0
31 32 33 34 35	8	6. 144E +1 2. 260E +1 8. 315E +0 3. 059E +0 1. 125E +0	4. 058E −3 3. 997E −3 3. 932E −3 3. 872E −3 3. 810E −3	3. 981E −3	0. 0 0. 0 0. 0 0. 0 0. 0	0. 0
36	9	4. 140E −1 1. 000E −5	3. 731E −3	3. 731E −3	0. 0	0. 0
Total					1. 0	1. 0

Table 4　　Cross section library date for neutron shielding calculation (Gamma gruop)

Energy group	Collapsed group	Upper Energy (eV)	Dose rate conversion factor (mrem/hr)/(ph/sec/cm²)	
1	1	1.400E+7	9.792E−3	7.313E−3
2		8.000E+6	8.280E−3	
3		6.500E+6	6.840E−3	
4		5.000E+6	5.760E−3	
5	2	4.000E+6	4.752E−3	3.552E−3
6		3.000E+6	3.960E−3	
7		2.500E+6	3.492E−3	
8	3	2.000E+6	2.988E−3	2.207E−3
9		1.660E+6	2.413E−3	
10		1.330E+6	1.908E−3	
11	4	1.000E+6	1.602E−3	1.404E−3
12		8.000E+5	1.260E−3	
13	5	6.000E+5	9.216E−4	8.125E−4
14		4.000E+5	6.372E−4	
15	6	3.000E+5	4.392E−4	3.615E−4
16		2.000E+5	2.376E−4	
17		1.000E+5	1.404E−4	
18		4.500E+4	3.024E−4	
		1.000E+4		

Table 5　　Cross section library date for gamma shielding calculation

Energy group	Upper Energy (MeV)	Dose rate conversion factor (mrem/hr)/(ph/sec/cm²)
1	1.4	2.423E−3
2	1.2	2.214E−3
3	1.1	2.049E−3
4	1.0	1.834E−3
5	0.8	1.524E−3
6	0.6	1.271E−3
7	0.5	1.077E−3
8	0.4	8.780E−4
9	0.3	6.310E−4
10	0.2	3.793E−4
11	0.1	2.697E−4
12	0.08	2.577E−4
13	0.06	2.904E−4
14	0.04	5.821E−4
15	0.02	1.952E−3
	0.01	

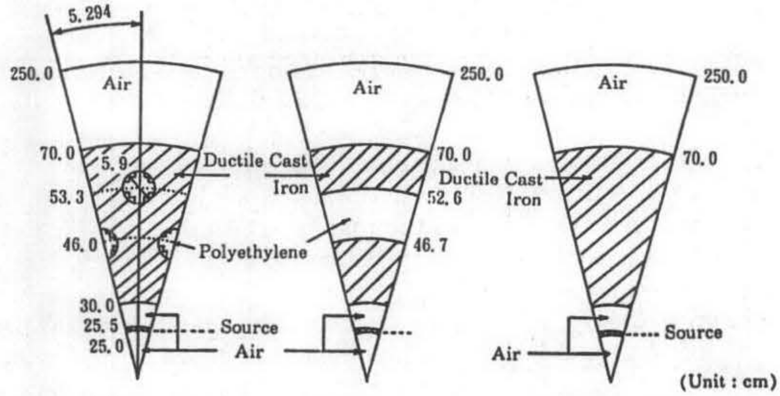
(3) Calculational model

The DOT3.5 code with an R−θ coordinate is used for the calculation. The number of Legendre (Pℓ) of the cross section library is P_3 for neutron and P5 for gamma. The number of discrete scattering angles (Sn) is S96 for both the neutron and gamma calculations.

The calculational models are shown in Fig. 8. As it is impossible for the R−θ coordinate to express the polyethylene bars exactly, the bars are transformed as shown in Fig. 8 (a) assuming that the transformed shape and the polyethylene have equal volumes.

As the DOT3.5calculation with an R−θ coordinate assumes that the axial length is infinite, it overestimates the dose rates, especially at 1 m from the model packaging. Because of this effect, a modification factor is introduced. The ratio of the results of the DOT3.5 calculation with R−Z coordinate and R−θ coordinate for region (Ⅱ) is used for the modification factor. The difference of both calculations is whether the axial length is infinite or finite.

Table 7 shows the results after modificated.



(a) Region (Ⅰ) (b) Region (Ⅱ) (c) Region (Ⅲ)

Fig. 8 Model for Shieding Calculation

Table 6 Comparison of Measurement and calculation

		Measurement (Length of source:150cm)						Calculation					
	Location	Surface			1m from surface			Surface			1m from surface		
	Region	(Ⅰ) Bar	(Ⅱ) Plate	(Ⅲ) Casting	(Ⅰ) Bar	(Ⅱ) Plate	(Ⅲ) Casting	(Ⅰ) Bar	(Ⅱ) Plate	(Ⅲ) Casting	(Ⅰ) Bar	(Ⅱ) Plate	(Ⅲ) Casting
Neutron (mrem/hr)	Rem-counter	254	219	1881	119	107	553	205	197	2095	51.4	49.2	520
Secondary gamma (mR/hr)	NaI(Tℓ) Scintillator	11.1	8.3	27.0	6.7	5.3	12.8	5.5	6.0	9.3	1.93	1.55	2.24
	Ionization chambor survery meter	7.8	7.4	17.5	4.6	4.0	7.6						
Gamma (mR/hr)	NaI(Tℓ) Scintillator	5.7	4.5	0.85	2.5	1.8	0.38	7.03	5.07	0.86	3.18	2.42	0.41
	Ionization chambor survery meter	6.5	4.4	0.83	2.5	1.8	0.41						

Results of Calculation

The calculated dose rates are shown in Table 6 along with the measured ones.

(1) Neutron dose rate

The neutron dose rates of region (Ⅰ) and (Ⅱ) are about 1 / 10th of region (Ⅲ) both on the surface and at 1 m from the surface of the model packaging. Comparatively the neutron dose rate of the complicated structure is about 4% larger than that of the simplified structure.

(2) Secondary gamma dose rate

The secondary gamma dose rates are 3 to 4% of the neutron dose rates for regions (Ⅰ) and (Ⅱ) and about 0.4% for region (Ⅲ).

(3) Gamma dose rate

The gamma dose rates of regions with polyethylene are 6 to 8 times larger than that of region without polyethylene. The gamma dose rate of the complicated structure is 30 to 40% larger than that of the simplified structure.

DISCUSSION

A comparison of measurements and calculations as well as a comparison of the complicated structure containing polyethylene bars and the simplified structure containing polyethylene plate are discussed in the following.

① Influence of room scattering components in shielding test room
With respect to the neutron dose rate, the calculated values on the surface of each region are not much different than the measured ones. The calculated values at 1 m from the surface of each region−except region (Ⅲ) −is less than 1 / 2 of the measured ones.
This difference seems to be caused by the room scattering components from the concrete wall of the shielding test room because there is no concrete wall in the calculation. The influence of room scattering components appears in the relatively lower dose rate position, such as the position 1 m from the surface of region (Ⅰ) and (Ⅱ). Therefore the comparison of the measured neutron dose rate of region (Ⅰ) and that of region (Ⅱ) will be performed using the values on the surface.
The secondary gamma dose rates are more sensitive to room scattering components than neutron dose rates. The calculated secondary gamma dose rates of all positions are lower than the measured ones.
On the other hand, the calculated gamma dose rates of each ragion agree with the measured ones. In other words, the room scattering components do not affect gamma rays.

② Shielding ability of complicated structures with polyethylene bars.
The comparison of the neutron dose rates of regions (Ⅰ) and (Ⅱ) shows that the effect of modeling the complicated structures with polyethylene bars on the simplified structure with a uniform layer where the volume of the neutron shield is the same for the two structures will be to underestimate the dose rates. The rate of underestimation is about 16% of the measured values on the surface and about 4 % of the calculated values both on the surface and 1 m from the surface.
Since the measurement seems to include some back ground radiation from the room scattering components, this modeling method will be usefull for the neutron shielding calculation. Nevertheless, this method will overestimate to some extent the shielding ability.
This modeling method also overestimates the gamma shielding ability by about 40 % for both measurement and calculation. This value is so large that it is necessary for the gamma shielding calculation to modify the modeling method.

CONCLUSION

The simplified model is valid for the neutron shielding calculation but is not valid for gamma shielding calculation because the simplified model will overestimate the gamma shielding ability of the actual complicated structure.

REFERENCE

S. Hattori and K. UEKI, *Experiment and Analysis of CASTOR Type Model Cask for Verification of Radiation Shielding*, CRIEPI Abiko Laboratory Report No.U87065, Central Research Institute of Electric Power Industry (1988).