SHIELDING TESTS FOR A NEW SHIP FOR THE TRANSPORT OF SPENT NUCLEAR FUELS

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SUMMARY

A new ship for the transport of spent nuclear fuels which uses serpentine concrete as its major shielding material has been constructed. The shielding calculations are based on DOT3.5 code (CCC-276) and the DLC23 library (DLC-23). Experiments with Cf-252 and Co-60 sources were carried out to confirm the validity of this method of calculating the shielding effectiveness of serpentine concrete. In these experiments, neutron and gamma-ray dose equivalent rates were measured in various arrangements to simulate the shielding structures of the ship, the calculations for each arrangement were performed by this shielding calculation method. For both neutron and gamma-rays, the calculation results agreed with the experiments very well, confirming that this calculation method used in the ship's shielding design is valid.

Two kinds of on-board gamma-ray shielding tests were performed to confirm the ship's actual shielding effectiveness. In one kind of test, gamma-ray dose equivalent rates were measured for each shielding wall using Co-60 sources. In the other kind of test, gamma-ray dose equivalent rates in the ship's accommodation area were measured when a strong Co-60 source was placed in a loaded shipping cask's position. In both gamma-ray shielding tests all measured dose equivalent rates were less than the calculated values, confirming that the ship's actual shielding is sufficient to meet safety requirements.

INTRODUCTION

A new ship capable of carrying about 20 spent fuel shipping casks has been constructed. In designing the ship's shielding, conservative conditions that dose equivalent rate at 1m from each loaded cask surface was 100 [μ Sv/h] for both neutron and gamma-rays were required. So, serpentine concrete, which has better shielding characteristics for neutron than ordinary concrete, was employed as the ship's major shielding material to provide effective shielding form both neutron and gamma-rays.

The two-dimensional discrete ordinates transport code DOT3.5 and the DLC23 library (called the DOT/DLC method in this paper) are used as the method for calculating the ship's shielding design requirements. Although the DOT/DLC method has been used for calculating the shielding requirements for various shielding material, it has rarely been used for calculating serpentine concrete shielding requirements. Therefore, experiments were carried out to confirm the suitability of the DOT/DLC method for calculating the amount of serpentine concrete required to effectively shield for neutron and gamma-ray. On-board gamma-ray shielding tests were also performed to confirm the ship's actual shielding effectiveness.

SHIELDING EXPERIMENTS

The shielding experiments with a Cf-252 source of 4.94×10^7 [neutrons/sec](2.69×10^8 [photons/sec]) and a Co-60 source of 1.62×10^9 [photons/sec] respectively, were carried out at the Ship Research Institute. The experiment arrangements are shown in Fig.1～3. In the experiments shown in Fig.1and 2, several serpentine concrete plates (80cm $\times$ 88cm $\times$ 5cm) and steel plates (80cm $\times$ 88cm $\times$ 1cm) were combined to simulate the ship shielding walls of various thicknesses. The experiments shown in Fig.3 simulated the various combinations of two shielding walls (total concrete thickness : 40cm) by changing the position of the inside steel plates. Neutron dose equivalent rates were measured by a moderation-type survey meter (ALOKA TPS-451S), and gamma-ray dose equivalent rates were measured by an ionization-type survey meter (ALOKA ICS-315) and a NaI scintillation type survey meter (ALOKA TCS-161). The chemical composition of the materials used in the experiments is shown in Table 1. The composition of the serpentine concrete in Table 1 is based on a chemical assay of the concrete plate used in the shielding experiments.

The DOT/DLC method was used to calculate the dose equivalent rate for each shielding experiment. The utility program GRTUNCLE for the DOT code was used to avoid the 'ray-effect' caused by a small volume source. The energy spectrums of the Cf-252 source and the Co-60 source, which are converted to the energy structure of the DLC23 library, are shown in Table 2 (Compendium). A comparison of the experiment results and calculations is shown in Table 3～5 and Fig. 4,5. The errors in the experiment results mean a statistical error for neutron measurement and a 10% detector accuracy for gamma-ray. In Table 5, primary gamma-ray means gamma-rays from the Cf-252 directly and secondary gamma-ray means gamma-rays generated in the serpentine concrete by neutron from the Cf-252.

Table 3 and 4 show that the calculation results in values slightly higher than those achieved in the experiments and that the discrepancies get bigger with concrete thickness. However, these discrepancies are less than 20%, even in the case involving the thick concrete (about 40cm). Accordingly, it has been confirmed that the DOT/DLC method is valid for calculating the effectiveness of serpentine concrete for shielding against both neutron and gamma-rays. On the other hand, Table 5 shows that the calculation results are greater than the experiment results by over 70%. In particular, even if the primary gamma-ray calculation result is ignored, the secondary gamma-ray calculation alone is greater than the experiment result, confirming that the DOT/DLC method is conservative in calculating the shielding effectiveness of serpentine concrete for the secondary gamma-ray.

ON-BOARD GAMMA-RAY SHIELDING TEST

An overview of the ship's shielding structure is shown in Fig.6. This shows that the ship's major shielding structure is the cargo hold hatch-covers, the cross-deck and the transverse bulkheads (PATRAM'98). Two kinds of on-board gamma-ray shielding tests were performed in Mitsui Engineering and Shipbuilding Co. Ltd.'s Tamano Works to confirm the actual effectiveness of each shielding wall and the validity of the ship's shielding design.

・TEST-1

Serpentine concrete was used to fill up the space in the steel structure of the ship's shielding wall, and then shielding tests for each shielding wall were carried out to confirm its shielding effectiveness (called TEST-1 in this paper). General arrangements of TEST-1 are shown in

Fig.7. In TEST-1, a Co-60 source was fixed at 15cm from the surface of the shielding wall and the gamma-rays penetrating the wall were measured at 15cm from the other surface. The gamma-ray dose equivalent rates were measured at about 80 locations by an ionization-type survey meter (ALOKA ICS-311). A weak Co-60 source (7.26×10^7 [photons/sec]) and a strong one (1.82×10^9 [photons/sec]) were used for thin and thick walls respectively.

· TEST-2

Whenever possible, a shielding test should use actual shipping casks containing spent fuel as the radiation source. However, it is impossible to use the casks in the works, so the shielding tests used a very strong Co-60 source (3.04×10^{11} [photons/sec]) to confirm the validity of the ship's shielding design (called TEST-2 in this paper). A general arrangement of TEST-2 is shown in Fig.8. In TEST-2, a Co-60 source was fixed at the center of a loaded shipping cask in the cargo hold and the gamma-ray dose equivalent rates were measured at about 50 locations of the ship's accommodation area. The gamma-ray dose equivalent rates were measured by the same ionization-type survey meter.

The comparison of the experiments results and calculations are shown in Table 6 and 7. In these calculation, the DOT/DLC method was used and the density of the serpentine concrete was employed the conservative value used in the ship's shielding design.

· TEST-1

Table 6 shows that all experiment results are smaller than the calculations, and that the discrepancies between the experiment results and calculations increase with shielding wall thickness. This means that the serpentine concrete used in the shielding wall provides sufficient shielding. It's confirmed that the density and thickness of the actual serpentine concrete walls in the ship have sufficient safety margin.

· TEST-2

Table 7 shows that all experiment results are much smaller than the calculations. This means that the ship's shielding design is sufficiently conservative for practical use. It is considered that the discrepancies between the experiment results and calculations are caused by the shielding effects of the equipment in the cargo hold, which were not taken into account in the shielding design, and the slanting penetration effects of the shielding wall in addition to the actual serpentine concrete wall's safety margin as stated above.

CONCLUSION

The following remarks were obtained from this study.

- The effectiveness of serpentine concrete for shielding for neutron and gamma-rays (Cf-252 and Co-60) was confirmed by shielding experiments in the Ship Research Institute.
- The results of the shielding experiments show that the DOT/DLC method used for the ship's shielding design is valid for calculating the effectiveness of serpentine concrete shielding.
- The results of the on-board shielding test (TEST-1) show that the actual serpentine concrete walls in the ship provide sufficient shielding and safety margin.
- The on-board shielding test (TEST-2) confirmed that the results of the ship's shielding design is sufficiently conservative to meet safety requirements.

REFERENCES

DOT3.5 - Two-dimensional Discrete Ordinates Radiation Transport Code, CCC-276, Oct. 1976

ORNL-RSIC CASK-40 Group Coupled Neutrons and Gamma-ray Cross-section Data, DLC-23, Sep. 1973

PATRAM'98, H.Akiyama et al. Construction of an Exclusive Ship for Transport of Spent Nuclear Fuels (II) - Technical feature-, May 1998

R.G.Jaegoer, et.al., ed. Engineering Compendium on Radiation Shielding, Vol.1 (1968)

Table 1 Chemical composition of the material

Material		Serpentine Concrete*	Steel	Paraffin
Density [g/cm³]		2.275	7.85	0.86
Element [%]	H	1.916	0.0	14.4
	C	0.0	0.600	85.6
	O	50.415	0.0	0.0
	Na	0.062	0.0	0.0
	Mg	16.9	0.0	0.0
	Al	1.28	0.0	0.0
	Si	15.5	0.325	0.0
	P	0.0	0.030	0.0
	S	0.016	0.035	0.0
	K	0.077	0.0	0.0
	Ca	6.95	0.0	0.0
	Ti	0.005	0.0	0.0
	Mn	0.79	0.750	0.0
	Fe	6.80	98.260	0.0
Total		100.0	100.0	100.0

* : made and assayed by Fijita Co.Ltd.

Table.2 Energy spectrum of Cf-252 and Co-60 source

Gr.*	Neutron		Gamma-ray		
	Upper energy* [eV]	Cf-252 spectrum**	Upper energy* [eV]	Cf-252 spectrum***	Co-60 Spectrum
1	1.492×10^{7}	7.00×10^{-4}	1.000×10^{7}	0.0	0.0
2	1.220×10^{7}	2.85×10^{-3}	8.000×10^{6}	0.0	0.0
3	1.000×10^{7}	8.56×10^{-3}	6.500×10^{6}	4.61×10^{-4}	0.0
4	8.180×10^{6}	2.69×10^{-2}	5.000×10^{6}	1.51×10^{-3}	0.0
5	6.360×10^{6}	5.31×10^{-2}	4.000×10^{6}	5.15×10^{-3}	0.0
6	4.960×10^{6}	6.43×10^{-2}	3.000×10^{6}	6.59×10^{-3}	0.0
7	4.060×10^{6}	1.25×10^{-1}	2.500×10^{6}	1.32×10^{-2}	0.0
8	3.010×10^{6}	9.51×10^{-2}	2.000×10^{6}	2.86×10^{-2}	0.0
9	2.460×10^{6}	2.19×10^{-2}	1.660×10^{6}	4.57×10^{-2}	0.25
10	2.350×10^{6}	1.17×10^{-1}	1.330×10^{6}	7.66×10^{-2}	0.75
11	1.830×10^{6}	1.97×10^{-1}	1.000×10^{6}	9.16×10^{-2}	0.0
12	1.110×10^{6}	1.67×10^{-1}	8.000×10^{5}	2.13×10^{-1}	0.0
13	5.500×10^{5}	1.07×10^{-1}	6.000×10^{5}	1.57×10^{-1}	0.0
14	1.110×10^{5}	1.25×10^{-2}	4.000×10^{5}	4.22×10^{-2}	0.0
15	3.350×10^{3}	6.32×10^{-5}	3.000×10^{5}	8.32×10^{-2}	0.0
16	5.830×10^{2}	4.59×10^{-6}	2.000×10^{5}	2.37×10^{-1}	0.0
17	1.010×10^{2}	3.02×10^{-7}	1.000×10^{5}	0.0	0.0
18	2.900×10^{1}	4.36×10^{-8}	5.000×10^{4}	0.0	0.0
19	1.070×10^{1}	9.41×10^{-9}	-	-	-
20	3.060×10^{0}	1.46×10^{-9}	-	-	-
21	1.120×10^{0}	3.23×10^{-10}	-	-	-
22	4.140×10^{-1}	9.33×10^{-11}	-	-	-
Total	-	1.0	-	1.0	1.0

* : Energy structure of DLC-23 library

** : Cf-252 neutron energy spectrum is based on the following equation (Compendium).

$N(E) = 0.373\ \mathrm{EXP}(-0.883E)\ \sinh(2.0E)^{1/2}$

E : neutron energy [MeV]

*** : This Cf-252 gamma-ray energy spectrum is converted to the energy structure of DLC-23 library .

Table.3 Comparison of the experiments and calculation (neutron)
(Experiment arrangement : Fig.1)

Concrete thickness [cm]	Experiment [μSv/h]	Calculation [μSv/h]	C/E (cal./exp.)
1 5	$(9.71\pm0.05)\times10^{1}$	1.01×10^{2}	1.04
2 5	$(3.13\pm0.03)\times10^{1}$	3.34×10^{1}	1.07
3 5	$(9.48\pm0.16)\times10^{0}$	1.12×10^{1}	1.18
4 5	$(3.21\pm0.09)\times10^{0}$	3.77×10^{0}	1.17

Table.4 Comparison of the experiments and calculation(gamma-ray)
(Experiment arrangement : Fig.2)

Concrete thickness [cm]	Experiment [μSv/h]	Calculation [μSv/h]	C/E (cal./exp.)
1 0	$(7.87\pm0.79)\times10^{1}$	7.37×10^{1}	0.94
2 0	$(2.90\pm0.29)\times10^{1}$	3.03×10^{1}	1.05
3 0	$(1.00\pm0.10)\times10^{1}$	1.14×10^{1}	1.14
4 0	$(3.75\pm0.38)\times10^{0}$	4.08×10^{0}	1.09
5 0	$(1.00\pm0.10)\times10^{0}$	1.47×10^{0}	1.47

Table.5 Comparison of the experiments and calculation(secondary gamma-ray)
(Experiment arrangement : Fig.3)

Concrete thickness**** [cm]	Experiment [μSv/h]	Calculation [μSv/h] (C/E)		
		Primary gamma-ray*	Secondary gamma-ray**	total
1 0 + 3 0	$(1.06\pm0.11)\times10^{0}$	0.23	1.64	1.87 (1.76)***
2 0 + 2 0	$(1.00\pm0.10)\times10^{0}$	0.22	1.51	1.73 (1.73)***
3 0 + 1 0	$(8.90\pm0.89)\times10^{-1}$	0.22	1.38	1.60 (1.80)***

* : Primary gamma-ray from the Cf-252 source

** : Secondary gamma-ray generated in the concrete by neutron from the Cf-252 source

*** : C(Calculation)/E(Experiment)

****: (Concrete thickness of the Cf-252 source side) + (Concrete thickness of the detector side)

Table. 6 Results of the on-Board Gamma-ray Shielding Test-1

Position	No.	Co-60 strength* [Bq]	Calculation [μSv/h]	Experiment [μSv/h]	C／E**
Stern Transverse bulkhead (Wheel house)	A5P3	7.26×10^7	2.3×10^1	1.42×10^1	1.62
	A5P2		2.3×10^1	1.92×10^1	1.20
	A5P1		2.3×10^1	1.73×10^1	1.33
	A5S1		2.3×10^1	1.58×10^1	1.46
	A5S2		2.3×10^1	1.55×10^1	1.48
Stern Transverse bulkhead (Captain room)	A4P3	7.26×10^7	1.1×10^1	6.2×10^0	1.77
	A4P2		1.1×10^1	6.7×10^0	1.64
	A4P1		1.1×10^1	5.8×10^0	1.90
	A4S1		1.1×10^1	6.3×10^0	1.75
	A4S2		1.1×10^1	6.9×10^0	1.59
Stern Transverse bulkhead (Engine room)	5H1P1	1.82×10^9	6.0×10^0	2.2×10^0	2.73
	5H1S1		6.0×10^0	2.1×10^0	2.86
	5H1S2		6.0×10^0	2.1×10^0	2.86
Stem Transverse bulkhead	1H1P2	1.82×10^9	3.2×10^0	1.2×10^0	2.50
	1H1P1		3.2×10^0	1.2×10^0	2.50
	1H1S1		3.2×10^0	1.1×10^0	2.73

* : Co-60 source was used following
7.26×10^7 [Bq] for thin wall (≦30 cm)
1.82×10^9 [Bq] for thick wall (>30 cm)
**: C(Calculation) / E(Experiment)

Table.7 Results of the on-Board Gamma-ray Shielding Test-2

Position	No.	Co-60 strength [Bq]	Calculation [μSv/h]	Experiment [μSv/h]	C／E*
Stern Transverse bulkhead (Wheel house)	A5P3	3.04×10^{11}	5.2×10^0	$<1.0\times10^{-1}$ **	-***
	A5P2		5.7×10^0	$<1.0\times10^{-1}$ **	-***
	A5P1		6.2×10^0	$<1.0\times10^{-1}$ **	-***
	A5S1		5.7×10^0	$<1.0\times10^{-1}$ **	-***
	A5S2		5.2×10^0	$<1.0\times10^{-1}$ **	-***
Stern Transverse bulkhead (Engine room)	5H3P2	3.04×10^{11}	2.0×10^1	9.0×10^{-1}	22.2
	5H3P1		2.9×10^1	3.3×10^0	8.78
	5H3S1		1.9×10^1	1.8×10^0	10.6
Stem Transverse bulkhead	1H1P2	3.04×10^{11}	2.4×10^1	8.0×10^{-1}	30.0
	1H1P1		3.5×10^1	4.5×10^0	7.80
	1H1S1		2.4×10^1	9.0×10^{-1}	26.7

* : C(Calculation) / E(Experiment)
** : under the detection limit (0.1 [μSv/h]).
*** : can't calculate the C/E because Experiment results is under the detector limit.

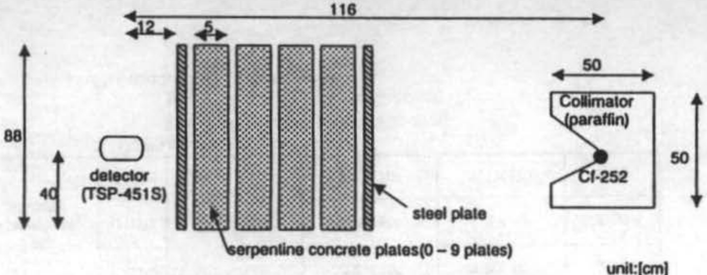

Fig. 1 Experiment arrangement for neutron(Cf-252)

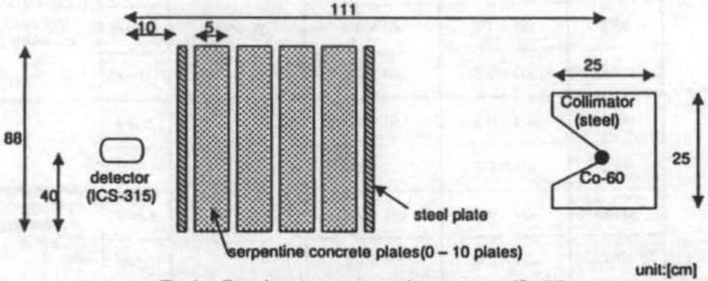

Fig. 2 Experiment arrangement for gamma-ray(Co-60)

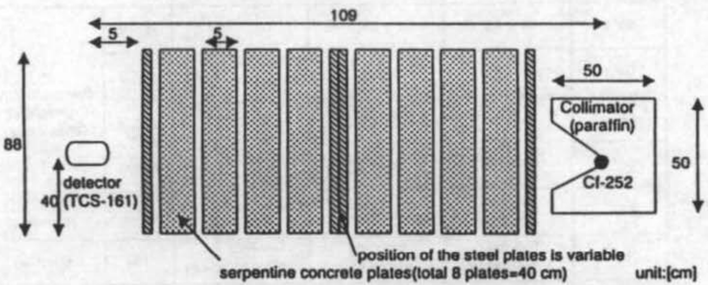

Fig. 3 Experiment arrangement for secondary gamma-ray(Cf-252)

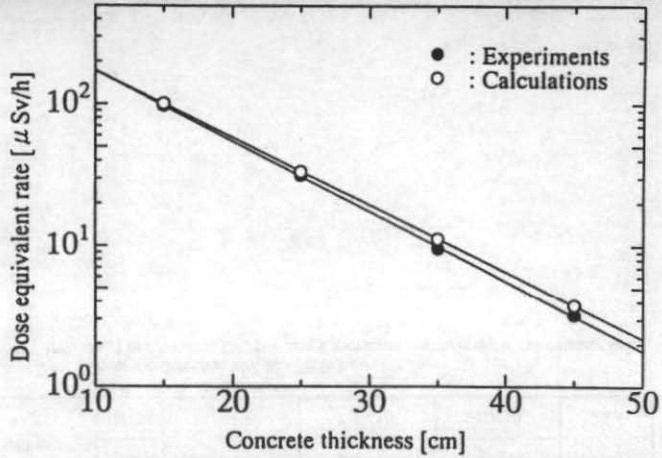

Fig.4 Comparison of the experiments and calculations (neutron dose equivalent rates)

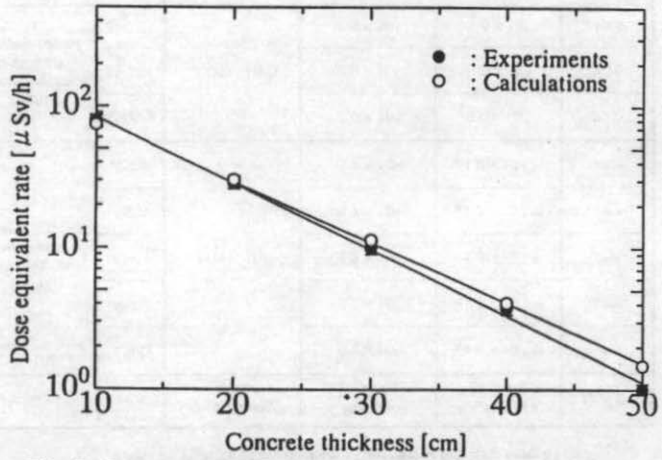

Fig.5 Comparison of the experiments and calculations (gamma-ray dose equivalent rates)

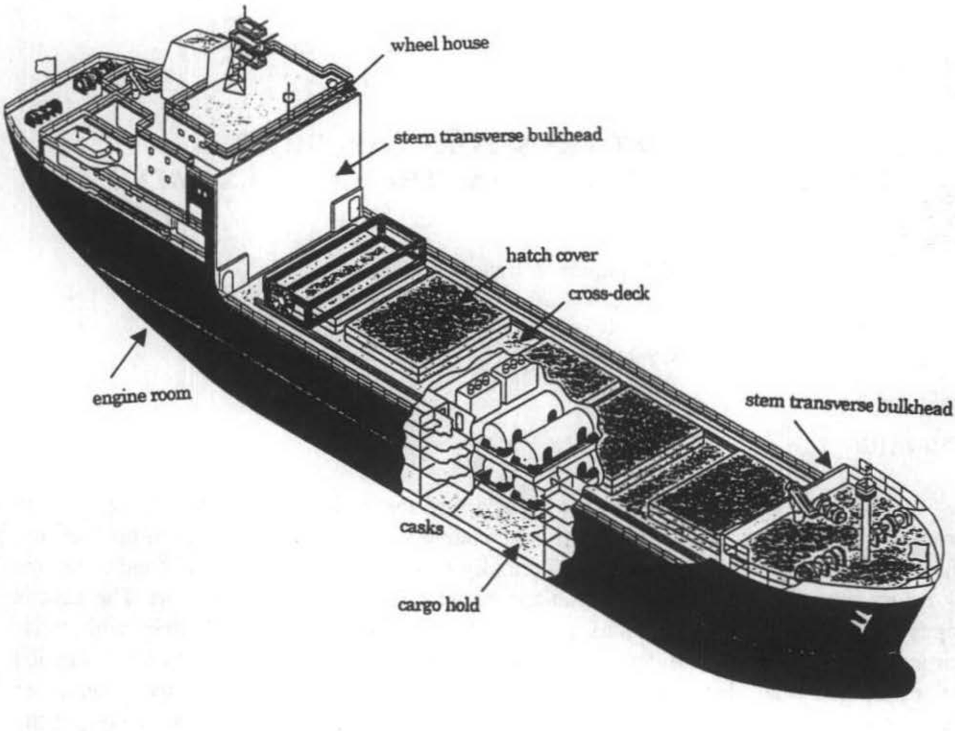

Fig.6 Overview of the ship's shielding structure

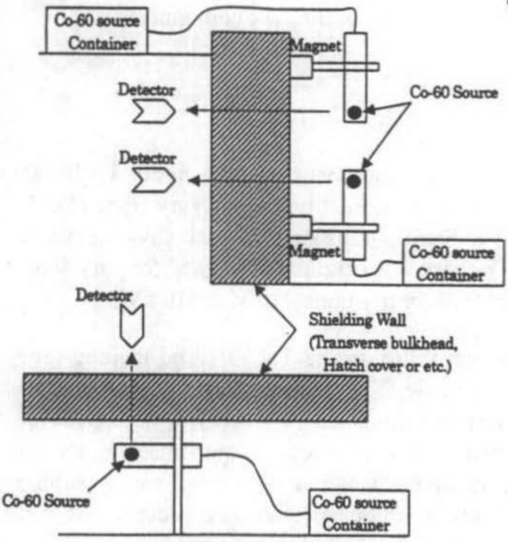

Fig. 7 General arrangement of the Shielding Test-1
($Co-60 : 7.26\times10^7, 1.82\times10^9$ [Bq])

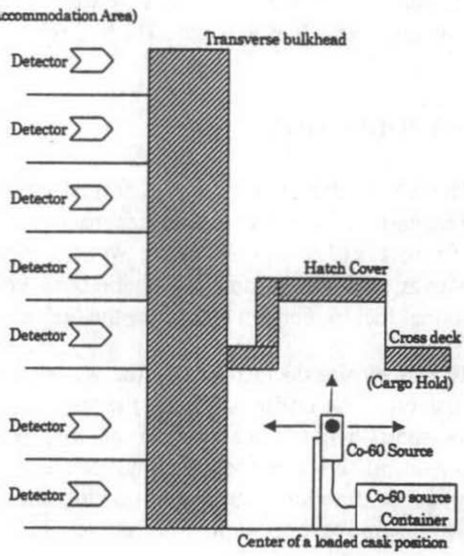

Fig. 8 General arrangement of the Shielding Test-2
($Co-60 : 3.04\times10^{11}$ [Bq])