ON-BOARD EXPERIMENT AND ANALYSIS OF DOSE RATE DISTRIBUTIONS IN A SPENT FUEL SHIPPING VESSEL

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Abstract

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An on-board experiment was carried out in a spent fuel shipping vessel, the Pacific Swan, in which 13 casks of the TN-12A and Excellox 3 type were loaded in five holds, and neutron and gamma ray dose rates were measured on the hatch covers of the holds. Before shipping, dose rates were also measured on the cask surfaces one by one for the purpose of eliminating radiation from other casks. The Monte Carlo coupling technique was successfully employed to analyse the measured neutron dose rate distributions in the vessel. As a result of this study, the Monte Carlo coupling code system, MORSE-CG/CASK-VESSEL, on which the MORSE-CG was based, was established. The agreement between the measured and the calculated neutron dose rates on the TN-12A cask surface was satisfactory. The calculated neutron dose rates agreed with the measured values within a factor of 1.5 on the Hold 3 hatch cover but to within a factor of 2 on the Hold 5 cover in which a concrete shield was fixed.

1. INTRODUCTION

An on-board experiment was carried out in a spent fuel shipping vessel, the Pacific Swan, in which 13 casks were loaded in five holds; eight casks were of the TN-12A type and five were Excellox 3. Neutron and gamma ray dose rates were measured in detail on the hatch covers of the vessel. The dose rates on and at 1 m from the cask surfaces were also measured for each cask before shipping.

The first purpose of the on-board experiment was to provide good quality measured dose rates on the cask surfaces as well as in the spent fuel shipping vessel. These measured dose rates could serve as reference data for the calculational method proposed in this paper. In addition, the measured dose rates are useful in cask design and for providing information on the dose rate profile in the vessel.

In this study, we propose a Monte Carlo coupling code system – the MORSE-CG/CASK-VESSEL on which the MORSE-CG code [1] was based [2, 3] – as a reliable code system for the shielding analysis of a spent fuel shipping vessel. In the first step of the calculation in the MORSE-CG/CASK-VESSEL code system, the complex cask configurations were modelled in detail. Next, up to 10 casks and the large complex shielding system of the vessel were taken into account in the second step.

The calculated results from MORSE-CG/CASK-VESSEL were compared with the dose rates obtained from experiments. The calculated neutron dose rates on the TN-12A cask surface were in satisfactory agreement with the measured values. The calculated neutron dose rate was 1.6 mrem/h[1], which corresponds to 1.5 mrem/h for the averaged measured value on the middle surface of the TN-12A. The calculated value of 9.7 mrem/h on the lid side-surface of the TN-12A corresponds to a measured neutron dose rate of 10.0 mrem/h. The significant increase in the neutron dose rate around the lid side-surface is due to lack of any resin shield. The calculated neutron dose rates on the Hold 3 and Hold 5 hatch covers agreed with the measured values to within factors of 1.5 and 2, respectively. The calculational procedures needed to obtain the final results of interest, and the efficiency of the Monte Carlo coupling technique have already been discussed in previous works [2–4].

Gamma ray shielding calculations are rather easily performed by a point kernel code with build-up factor, such as the QAD code [5], even if the shielding system is complex or large. Accordingly, we applied the MORSE-CG/CASK-VESSEL code system to the neutron analysis. The application of the coupling code system to the gamma ray analysis is easily carried out with a minor modification of the code system. The point kernel RANKERN code [6] with neutron and gamma ray removal cross-sections has been applied successfully to analysing the measured neutron and gamma ray dose rates in the Pacific Crane [7]. The RANKERN code employed removal cross-sections, and the source intensity of neutrons and gamma rays was not obtained from an isotope generation and depletion code like ORIGEN-2 [8] but estimated from the dose rate on the cask surface using removal cross-sections. Accordingly, the RANKERN code could not be used to make a detailed general shielding analysis of casks and spent fuel shipping vessels.

2. DESCRIPTION OF VESSEL, CASK AND NEUTRON SOURCE

2.1. Vessel layout

The measurement of dose rates was carried out in the Pacific Swan, a spent fuel shipping vessel. It is 104 m long and operates at around 2950 tons dead weight. The vessel has five holds, each with an air cooling system for the loaded casks. Two types of shields are provided in the vessel. One is the 75 cm thick water tank sandwiched between iron slabs of 6.4 cm and located between Hold 5

[1] 1 rem = 10^{-2} Sv.

and the engine room; the other is concrete shields of 4 to 13.5 cm thick, fitted in the Hold 4 and 5 hatch covers.

The general layout of the Pacific Swan loaded with 13 casks is indicated in Fig. 1. The arrangement of the vessel structures and the loaded casks was taken into account in the second step calculation of the MORSE-CG/CASK-VESSEL code system, except for some miscellaneous structures with smaller shielding effect.

2.2. Casks

Two types of spent fuel shipping casks were loaded in the Pacific Swan; one was the dry type TN-12A and the other was the wet type Excellox 3. A TN-12A cask can contain 12 assemblies of PWR spent fuel or 30 BWR assemblies; on the other hand, an Excellox 3 cask carries 5 PWR assemblies or 12 BWR. For each cask, the maximum allowable total dose rate (neutrons plus gamma rays) is 200 mrem/h on the cask surface; meanwhile, in Japan the dose rate is limited to 10 mrem/h at any point 1 m from the cask surface.

In this study, the measurement of dose rates was carried out on the Hold 3 and 5 hatch covers. Some neutron and gamma ray contribution from the Excellox 3 casks loaded in Holds 1 and 2 to the dose rates observed on the Hold 3 and 5 hatch covers must be considered in a shielding calculation. However, as indicated in Fig. 1, the main part of the dose rates measured on the Hold 3 and 5 hatch covers could be due to the TN-12A casks loaded in Holds 3 and 5. Four TN-12A casks were in Hold 3 and four in Hold 5. There was no cask in Hold 4. We assumed the Excellox casks loaded in Holds 1 and 2 to be TN-12A casks.

Total, energy, and angular neutron fluxes were obtained on the TN-12A cask surface, and these fluxes were employed as the boundary source on the surface of all casks loaded in the vessel in the second step calculation of the MORSE-CG/CASK-VESSEL code system. The complex cask configurations were taken into account in detail in the first step calculation of the coupling code system to obtain precise flux distributions on the cask surface. However, miscellaneous structures such as shock absorbers, trunnion, and other items with smaller shielding effects were excluded from the calculation.

2.3. Neutron source

Neutrons are produced by the spontaneous fission of transplutonium nuclides and by (α,n) reactions of alpha particles emitted from decaying transplutonium nuclides primarily with ^{18}O nuclei in the spent fuel. The neutron source intensity was calculated by the ORIGEN-2/82 code and the effective multiplication factor was obtained from the Monte Carlo code KENO-IV [9] for the TN-12A cask. The

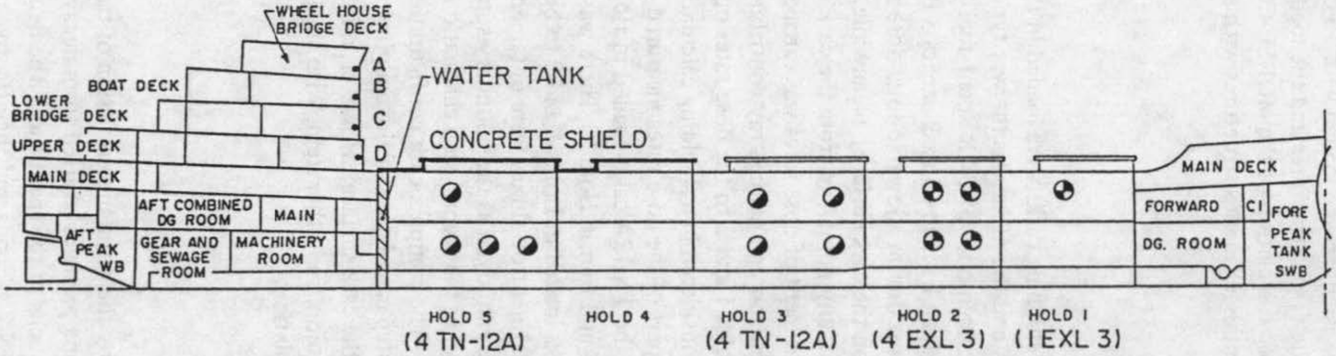

FIG. 1. Model for calculation of neutron dose rate distribution in the Pacific Swan loaded with 13 casks.

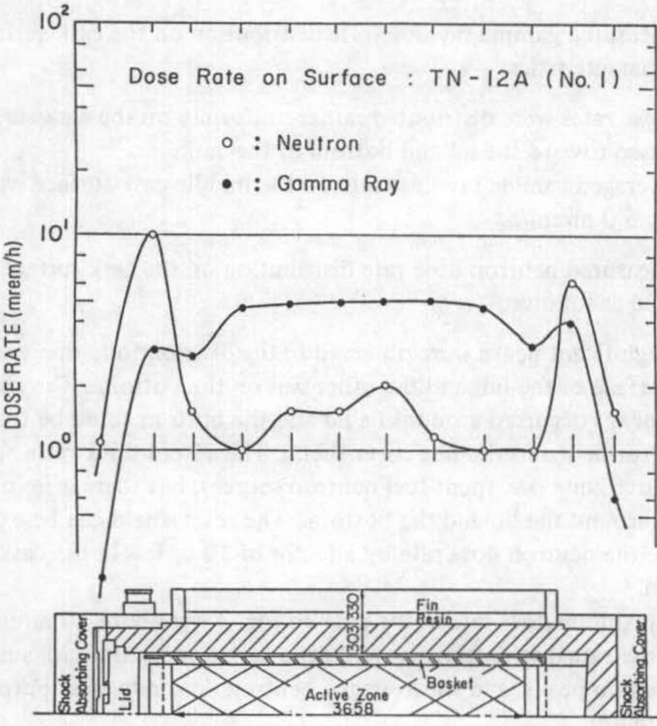

FIG. 2. Dose rate distribution on the surface of the TN-12A cask.

value was $k_{eff} = 0.3$ for the cask. The total neutron source intensity in a cask system S_n is estimated as follows

$$\hat{S}_n = \frac{S_n}{1 - k_{eff}}$$

where S_n is the neutron source intensity produced by spontaneous fission and by (α, n) reactions.

3. MEASUREMENT

3.1. Dose rates on the cask surface and at 1 m from the surface

The neutron and gamma ray dose rates were measured on each TN-12A cask surface and at 1 m from the cask surface for the purpose of eliminating radiation from other casks before the shipping. Typical measured neutron and gamma ray dose rate distributions on the TN-12A cask surface are summarized in Fig. 2.

The measured gamma ray dose rate distribution on the cask surface had the following characteristics:

(1) The dose rates were distributed rather uniformly on the cask surface and decreased toward the lid and bottom of the cask.
(2) The averaged gamma ray dose rate on the middle cask surface was approximately 5.0 mrem/h.

The measured neutron dose rate distribution on the cask surface was characterized as follows:

(a) Two significant peaks were observed in the distribution; one was on the side-surface of the lid, and the other was on the bottom. The reason why these peaks occurred around the lid and the bottom could be that the resin shield for neutrons did not cover them. The 10 cm thick resin shield covers the active zone (i.e. spent fuel neutron source), but there is no neutron shield around the lid and the bottom. The resin shield can be expected to reduce the neutron dose rate by a factor of 10 or less in the cask shielding system.
(b) The maximum dose rate at the peak in Fig. 2 was about 10 mrem/h.
(c) The dose rate distribution showed little variation on the cask surface except for the two peaks, and the averaged neutron dose rate was approximately 1.5 mrem/h.

3.2. Dose rate distributions on hatch covers

The neutron and gamma ray dose rates were measured in detail on the Hold 3 and 5 hatch covers.

The gamma ray dose rates on the Hold 3 hatch cover varied from 0.10 to 1.25 mR/h and from 0.06 to 0.37 mR/h on the Hold 5 hatch cover.[2] On the other hand, the neutron dose rates were from 0.25 to 0.79 mrem/h on the Hold 3 hatch cover and from 0.05 to 0.30 mrem/h on the Hold 5 hatch cover. The neutron dose rates were about 0.07 mrem/h for all the measuring points in the rooms indicated in Fig. 1 (as A, B, C and D).

On the centre line of the Hold 3 and Hold 5 hatch covers, the gamma ray dose rates were from 0.45 to 0.95 mR/h and from 0.13 to 0.36 mR/h, respectively. The neutron dose rates were observed to be from 0.41 to 0.79 mrem/h and from 0.10 to 0.19 mrem/h, respectively.

[2] 1 R = 258 μC/kg.

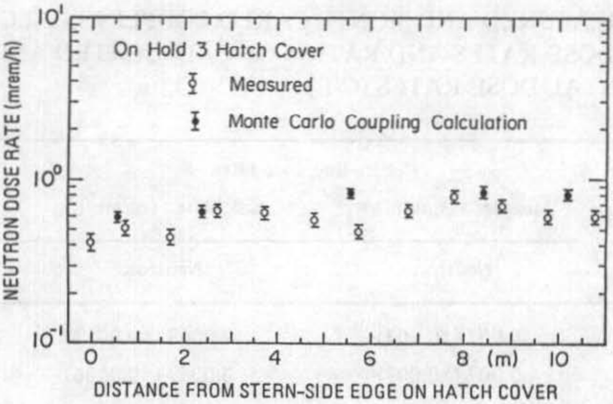

FIG. 3. Comparison between neutron dose rates on the Hold 3 hatch cover obtained by measurement and by Monte Carlo coupling calculation.

4. COMPARISON WITH EXPERIMENTS

4.1. On the Hold 3 hatch cover

The comparison of neutron dose rates between the measured values and those calculated by the MORSE-CG/CASK-VESSEL code system is summarized in Fig. 3. The distributions shown in Fig. 3 are all on the centre line of the Hold 3 hatch cover. In calculating the neutron dose rates on the Hold 3 hatch cover, we assumed 4 casks loaded in Hold 3 and also 4 in Hold 2 in the second step calculation of the coupling code system. The concrete shields were fixed in the Hold 4 and 5 hatch covers, but there was no concrete in the Hold 3 hatch cover. The neutron dose rate on the cask surfaces for all the casks included in the second step calculation was assumed to be 1.6 mrem/h. The angular fluxes on the cask surface were stored in the modified subroutine SOURCE.

As indicated in Fig. 3, the calculated dose rates on the Hold 3 hatch cover agreed with the measured values to within a factor of 1.5, and the FSDs (fractional standard deviation) of the calculated dose rates were within 0.08 in the second step calculation. The second step calculations were carried out for 15 000 source particles. The slight overestimate of the calculated dose rates compared with the measured values could be due to the fact that the calculation could not take into account many complex reinforcing structures such as ribs in the second step. However, the calculated results and FSDs agree quite satisfactorily from the shielding analysis point of view.

TABLE I. MEASURED AND MONTE CARLO COUPLING CALCULATED NEUTRON DOSE RATES AND RATIOS OF CALCULATED AND EXPERIMENTAL DOSE RATES (C/E)

Dose point	Centre line dose rates Measured (mrem/h)	Calculated (mrem/h)	C/E
	Neutron	Neutron	Neutron
A	0.007 (±0.003)	0.0063 (±0.0013)	0.90
B	0.007 (±0.003)	0.0057 (±0.0006)	0.81
C	0.007 (±0.003)	0.0070 (±0.0014)	1.00
D	0.007 (±0.003)	0.0087 (±0.0017)	1.24

4.2. On the Hold 5 hatch cover

In calculating the neutron dose rates on the Hold 5 hatch cover, we assumed 4 casks in Hold 5 and 4 in Hold 3. There was no cask in Hold 4, as shown in Fig. 1. The concrete shields were included in detail in the second step of the coupling code system. The total, energy, and angular fluxes on the cask surfaces had the same values as those in the calculation for the Hold 3 hatch cover.

Owing to the shielding effect of the concrete shields in the Hold 4 and 5 hatch covers, the neutron dose rates on the Hold 5 hatch cover were lower than those of the Hold 3 cover by a factor of 4. The shielding effect of the concrete was confirmed by a Monte Carlo coupling calculation.

The calculated dose rates agreed with the measured values to within a factor of 2 and the FSDs of the second step calculations were within 0.15. The measured values as well as the FSDs were a little lower than the values for the Hold 3 hatch cover. However, the results could be meaningful. The overestimate of the calculated dose rates may also be due to the fact that the calculation could not take into account miscellaneous structures such as the hatch cover ribs.

4.3. In the rooms

The neutron dose rates in the rooms shown in Fig. 1 at the dose points A, B, C, and D were also calculated by the MORSE-CG/CASK-VESSEL code system. Comparison between the measured and calculated neutron dose rates is summarized in Table I. The measured dose rates were very low (0.07 mrem/h) and there was no distinguishable difference between the points A, B, C and D. The maximum allowable dose rate in a room is 0.18 mrem/h in Japan.

The values of C/E (calculation/experiment) were between 0.81 and 1.24. The FSDs of the second step calculation were not so good (within 0.21). On the other hand, the measured count rates at the dose point were so few that the measured values have a large statistical error of about 40%. Accordingly, no significant comparison between the measured neutron dose rates and the calculated values could be made in Table I.

5. CONCLUSIONS

The Monte Carlo coupling technique has been used to analyse the measured neutron dose rate distributions in a spent fuel shipping vessel, the Pacific Swan, loaded with 13 casks, and the Monte Carlo code system, MORSE-CG/CASK-VESSEL, was produced through this study. In the first calculation step of the coupling code system, complex configurations of the cask were modelled in detail and the total, energy, and angular fluxes were calculated on the cask surface to serve as the boundary source conditions for the second calculation step. Up to 10 casks in the vessel as well as the large complex shielding system of the vessel could be taken into account in the second step calculation, to obtain realistic three dimensional neutron dose rate distributions in the vessel.

The agreement between the measured and calculated neutron dose rates on the TN-12A cask surface was quite satisfactory both on the middle side-surface and on the lid and the bottom side-surfaces.

The calculated neutron dose rates on the Hold 3 hatch cover in which there was no concrete shield agreed with the measured values to within a factor of 1.5; on the other hand, agreement was within a factor of 2 on the Hold 5 hatch cover in which concrete shields were fixed.

In its current state, the MORSE-CG/CASK-VESSEL code system can be used not only as an effective tool but also as an accurate method for analysing radiation shielding problems in a spent fuel shipping vessel. Furthermore, the code system proposed in this study can be applied immediately to a ship such as a radioactive waste shipping vessel.

The present measured data on the neutron and the gamma ray dose rates on the casks and on the hatch covers can serve directly as a reference for the shielding design of a cask as well as for planning radiation protection in a spent fuel shipping vessel.

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