Dose Rate Calculations for Transport of Vitrified Residues by Sea*

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INTRODUCTION

It is planned that vitrified residues (high level waste, (HLW)) from fuel reprocessing operations in Europe will be transported in purpose-designed vitrified residues flasks by sea to Japan. This paper describes gamma and neutron radiation dose rate calculations which were performed to allow the carriage of a maximum of 14 flasks on board typical Irradiated Nuclear Fuel vessels. These flasks may be carried in Holds 1, 2, and 3 of each ship, with a number of empty oxide flasks in other locations in Holds 4 and 5. As the exact loading plan of the empty oxide flasks will vary from voyage to voyage, for pessimism, no empty flasks were included in the geometric models of the ship (as these would provide extra shielding).

Dose rates at off-center-line points in the accommodation areas and regularly occupied working spaces, athwartships of points immediately aft of the center-line of the house front, and those just aft of the shielding tank have been assessed. In addition, dose rates have been calculated above the hatchcovers and on the external surface of the ships' hulls.

RADIATION LIMITS

The shielding provided on the ships is determined by two Articles of the Japanese Rules for the Carriage of Dangerous Goods in Ships (JMOT 1991): Article 91 - 10, the total radiation dose rate at any point one meter from the actual external surface of a flask shall not exceed 100 μSv/h, i.e., the transport index of a flask must not exceed 10. Article 91-18, the total radiation dose rate at any point in the regularly occupied areas of the ship shall not exceed 1.8 μSv/h.

Two cases are considered in the radiation assessment. Case 1 has the gamma component of the transport index = 0, the neutron component = 10; case 2 has the neutron component of the transport index = 0, the gamma component = 10. If the ship obeys Article 91-18 for both cases, it will also obey it for any combination of neutron and gamma components that obeys Article 91 - 10.

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In addition, the regulation for external ship dose rates which is given in Article 91-16-(2) also applies. The master of the ship shall limit the dose rates below 2 mSv/h at any point of shell plating (except in the hold or compartment where radioactive packages are stowed and such a place where persons cannot approach easily) and 100 μSv/h at 2 metres from the external surface of the ship.

CALCULATIONAL METHODS

The general profile of a typical HLW carrier is shown in Figure 1. The main radiation shields are the shielding tank and the concrete deck shields. The latter are also listed in Table 1. The shielding tank is situated between the house front and Hold 5 and contains 750 mm of water contained within 40 mm steel bulkheads. It extends from the tank top to the upper deck in height and laterally for 4.5 metres from the centre-line of the ship, in both port and starboard directions.

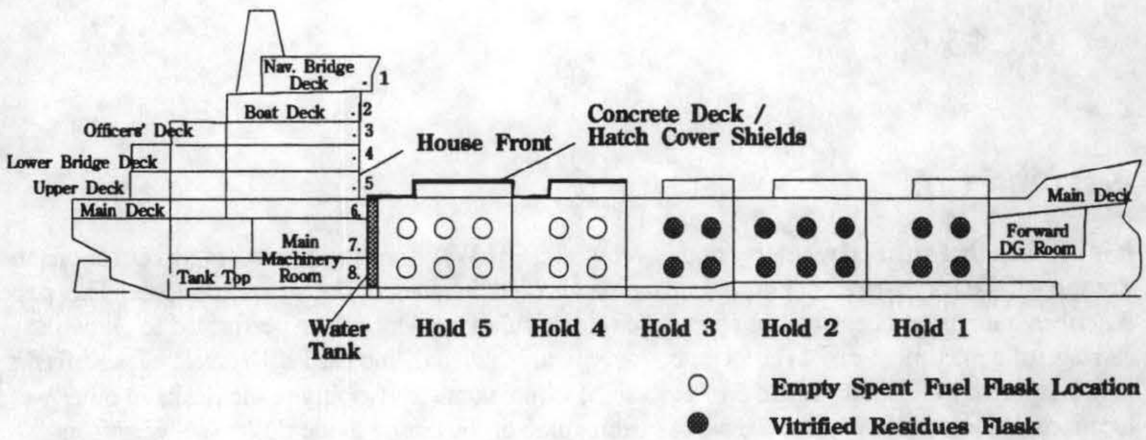

Figure 1. Sketch of Profile of a Typical HLW Carrier With Location of Dose Points.

All of the structure, materials, and equipment on the ship provide radiation shielding, but only the main structure of the ship was included in the calculational models. The items which were included are the shielding tank, concrete deck shielding, main structural plating, hatch cover plating, hatch cover beams, and flask support beams. Other items such as machinery, equipment, furnishings, fittings, most structural beams, nonstructural partitions and bulkheads, and insulation were neglected for pessimism and simplicity. (The ship calculational models used for the carriage of vitrified residues were originally used in the assessment of the carriage of spent oxide fuel and are similar to the model used for Pacific Crane, for which an experiment to theory comparison was described, in order to validate the calculational methods (Dean 1985).)

The vessel was assessed with 14 vitrified residues flasks on board (stored with their axes horizontal), using the RANKERN point kernel computer code (Dean 1994). RANKERN has many features, including the geometry package, in common with the Monte Carlo code MCBEND (Chucas 1994) and is also compatible with the MONK criticality code (Smith 1995). The ship models were 3-D models described in combinatorial geometry. The main structural plating and shielding were specified as given in architectural drawings of the ships. The 14 vitrified residues flasks were located in Holds 1, 2, and 3, at which locations they will be carried in practice.

The RANKERN computer model of the flask is shown in Figure 2. Each flask will contain 21 canisters of vitrified residues. Each of the 14 flasks was modeled using a series of cylinders with a cylindrical cavity containing the vitrified residues, smeared with the intersource region material to fill the internal dimensions of the basket (apart from the void regions above and below). The flask was modeled accurately, although some regions were approximated for simplicity. Overall, the model was a pessimistic representation of the actual flask, with the shock absorbers being excluded.

Table 1. Description and Location of Concrete Deck Shields.

Shield No.	Location	Concrete Thickness (mm) at density of 2200 kg/m³	Width (meters)
1	Between the aft end of shielding tank and Hatch 5 coaming	214	9
2	Up the aft coaming of Hatch 5	214	9
3a	Under the aft cover of Hatch 5, inboard of 3 metres port and starboard	171	6
3b	Under the aft cover of Hatch 5, outboard of 3 metres port and starboard	54	1.5 (each)
4	Under the forward cover of Hatch 5	171	6
5	Up the forward coaming of Hatch 5	107	6
6	Between Hatch 5 and Hatch 4	107	6
7	Up the aft coaming of Hatch 4	107	6
8	Under the aft cover of Hatch 4	107	6
9	Under the forward cover of Hatch 4	43	6

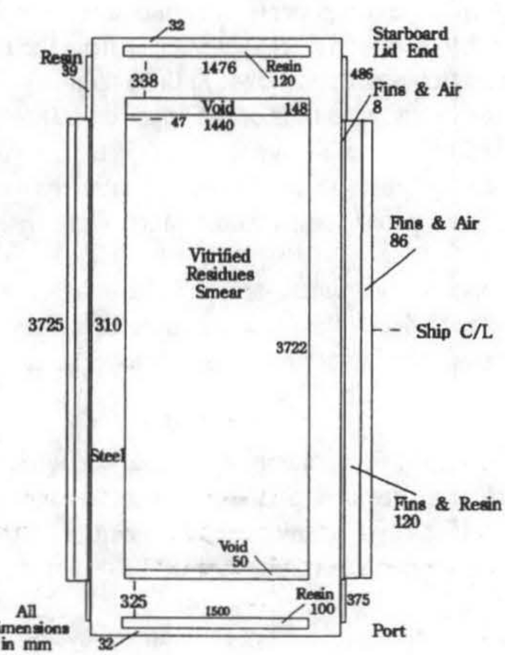

Figure 2. RANKERN Model of Flask.

The flask was also modeled as a series of cylinders in a number of ANISN (Engle 1967) calculations, from which neutron removal cross sections for use in RANKERN were obtained for the flask materials. For gamma rays, cross sections (and build up factors and flux to dose conversion factors) were obtained explicitly from the RANKERN libraries. Flux to dose conversion factors for both neutrons and gamma rays were based on ICRP 21 (ICRP 1973). Because of the way in which the source strengths are normalised to give a transport index of 10, the use of other flux to dose conversion factors would have no effect on the results.

The neutron source strength specified for the solid vitrified residues was such that, when smeared over the dimensions of the basket, it equated to 1067.0 neutrons per second per cubic cm. The gamma rays were treated by a pessimistic approach by assuming that all the activity was due to Pr144 (as this decays with the release of 2.2 MeV gamma rays which are more difficult to attenuate than lower energy ones released by other radionuclides). In reality, the vitrified residues in the whole basket (21 containers) may contain a maximum of 91.56 TBq of Pr144. The source strengths obtained in this way were then normalized to give 100 μSv/h at one meter from the external flask surface, for neutrons and gamma rays separately. In the case of neutrons, source strengths had to be scaled by a factor greater than 40 in order to achieve this and hence the neutron dose rates are grossly pessimistic. The source strengths used in the initial RANKERN calculations derived as above are tabulated in Table 2, for convenience, together with the final normalized source strengths.

Table 2. Source Strengths.

Source Strength	Neutrons /s/cc	Gamma Rays /s/cc
Before Normalization	1067	1.71×10^8
After Normalization	45929	1.55×10^8

For the gamma ray calculations, three components of radiation were considered in order to assess the dose rates for dose points 1 to 5: (i) the direct component from the source to the detector (with buildup factors allowing for scattered radiation close to the path along the line-of-sight), (ii) the radiation scattered in hatch covers and materials of the upper deck (not close to the line-of-sight), and (iii) skyshine radiation, scattered from the air above the hatch covers and decks back to the above dose points. In (ii) and (iii), buildup was allowed on both legs of the trajectory. For dose points 6 to 8 and the external dose points, only component (i) was considered.

For the neutrons, a direct component was calculated, and also scattering from the steel bulkheads was included, using surface albedo data. The latter was only significant for Hold 3. As neutron source strengths had to be scaled by a factor of 40, no additional scattering contributions were considered necessary.

The vitrified residues were assumed to have a uniform source strength throughout the smeared volume, such that for the peak axial position, and with no external shielding, the dose rate at one meter from the flask would be 100 μSv/h at any azimuthal position (with the assumed cylindrical model). All angles of emission are considered in RANKERN.

The direct gamma ray calculations were carried out for gamma rays of energy 2.2 MeV, but the scatter calculations included an extra 10 lower energy groups, to allow for subsequential reduction in energy on scattering.

The component (ii) was calculated for gamma rays emitted from flasks in Hold 3 scattering from Hatch Cover 3, those from flasks in Hold 2 scattering from Hatch Cover 2, and those from flasks in Hold 1 scattering from Hatch Cover 1. It was found that contributions scattering from the port and starboard walkways were small in comparison and the contributions from the deck area lying between the hatch cover coamings were already covered in path (i).

The skyshine components (iii) were calculated for the flasks in Holds 1, 2, and 3, integrating scattering events taking place in air for up to 300 meters above the deck (and for up to 200 meters to the sides of the ship). Total gamma ray dose rates were calculated from the sum of the components (i), (ii), and (iii).

The whole process of gamma rays being emitted from the vitrified residues flasks and subsequently being scattered by either the hatch covers or the air above (skyshine) etc is carried out within the RANKERN code. This type of trajectory is treated by the collision option in RANKERN. The flux at the dose point r due to an isotropic source in volume V which results from scattering of particles in volume Vs is determined from the following:

$$\phi(r)=\int_{V_s}\int_{V}\frac{S(r_0)B(\tau_0)e^{-\tau_0}}{4\pi D_0^2}\frac{\sigma_s(r_s)B(\tau_s)e^{-\tau_s}}{D_s^2}dv\,dv_s \qquad (1)$$

where $S(r_0)$ is the source per unit volume at r_0, $\sigma_s(r_s)$ is the differential scattering cross section for the deflection at the point r_s, D_0 is the penetration distance from the source point to the scatter point, D_s is the penetration distance between the scatter point and the dose point, and B is the buildup factor.

Each source and scatter body is subdivided. The RANKERN code includes an optimization to identify the most probable penetration paths with respect to the individual scattering sub-bodies. Source points for gamma rays are randomly selected within the source sub-bodies, and trajectories to points randomly selected within each scattering sub-body are investigated. Contributions to the dose rate at the dose point are determined, and, as the calculation proceeds, the importance of each sub-body is modified to optimize the sampling probabilities of transmissions between source and scatter bodies and dose points.

The scattering cross sections for the materials are based on the Klein-Nishina equation (Klein and Nishina 1929), and the magnitude of the cross sections are derived using the mean electron density values for the materials from RANKERN internal libraries. The angular distribution for scatter is assumed to be as for Compton scattering.

A multigroup calculation is performed with correlated tracking for the groups. Thus the energy spectrum at the point of scatter will be based on the spectra at the source point adjusted for the attenuation in the flask and other intermediate shielding materials. For the scattering problem, the energies of the incident groups are equated to the mean group values, and the energies of the radiation scattered towards the dose point are determined using the Compton expression. The scattered radiation is allotted to the appropriate energy group and its magnitude adjusted to conserve energy, assuming all gamma rays to be at the mean energy of the group.

CALCULATIONS

Dose rates were calculated at various points at one meter from the side of the flask for normalization purposes. As the peak dose rate at one meter from the flask is towards the lid and radially opposite the top of the cylindrical vitrified residues not 'covered' by the fins, the source was normalized to give 100 μSv/h at this position. The ship dose rates were therefore calculated on the starboard side (the flask lids lie to the starboard side), for pessimism, at the most important off-center-line dose point locations on the HLW Carrier. (Dose rates on the ship center-line were found to be lower, due to the substantial shielding provided by the water tank and concrete deck shields). It was necessary to show that none of the dose rates in accommodation areas and regularly occupied working spaces exceeded 1.8 μSv/h. Dose rates were also calculated above the hatch covers and on the ship external surface. This particular HLW Carrier represents the worst case for hatch cover dose rates, with 6 flasks in Hold 2, and 4 flasks located forward and aft in Holds 1 and 3. Dose rates for other vessels, where 6 flasks are carried in Hold 3, and 4 flasks in Holds 1 and 2 were lower. Dose rates on the hull were calculated for both port and starboard in order to determine the maximum values.

RESULTS AND CONCLUSIONS

Selected results of the calculations showing total dose rates are given in Tables 3 and 4. Dose rates are given for the standard dose points in both accommodation areas and in regularly occupied working spaces and also above Hold 2 hatch cover and on the external surface (hull) of the ship. Points with the largest dose rates were selected.

It can be seen from these tables that none of the dose rates exceeds the appropriate limits. The locations of the dose points are shown in Figures 1 and 3. It can be seen that the highest dose rate in the accommodation or regularly occupied working spaces is 0.60 μSv/h at dose point 2. This is a gamma dose rate and is well within the allowable limit of 1.8 μSv/h.

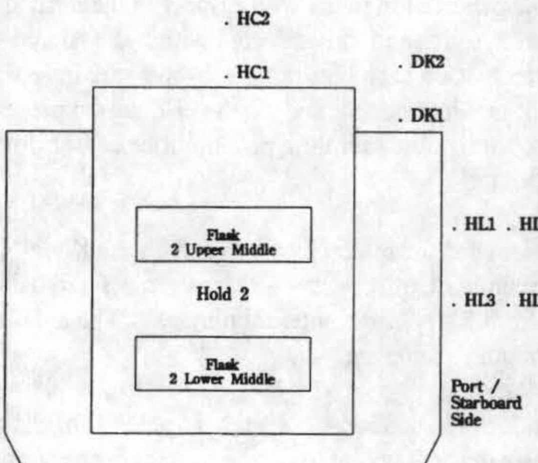

Figure 3. HLW Carrier, Midship Section.

Dose rates above the Hold 2 hatch cover were found to be the highest external dose rates. The dose rates at 2 meters above the hatch cover were found to be 27.9 μSv/h (neutron) and 57.5 μSv/h (gamma), these still being well below the appropriate limit.

Table 3. Dose Rates in Accommodation and Regularly Occupied Working Spaces.

	Dose Rates (μSv/h)				
Dose Point	Hold 3	Hold 2	Hold 1	Total	Limit
2 Captain's Bathroom					1.8
Neutron	2.52×10^{-1}	1.14×10^{-1}	3.20×10^{-2}	3.97×10^{-1}	
Direct Gamma (i)	2.36×10^{-1}	2.35×10^{-1}	8.82×10^{-2}	5.59×10^{-1}	
Scattered Gamma (ii)	5.34×10^{-3}	1.36×10^{-2}	1.28×10^{-3}	2.02×10^{-2}	
Skyshine Gamma (iii)	4.84×10^{-3}	6.25×10^{-3}	4.26×10^{-3}	1.53×10^{-2}	
Total Gamma	2.47×10^{-1}	2.54×10^{-1}	9.37×10^{-2}	5.95×10^{-1}	
1 Starboard Bridge Wing					1.8
Neutron	3.13×10^{-1}	9.43×10^{-2}	2.62×10^{-2}	4.34×10^{-1}	
Total Gamma	3.46×10^{-1}	1.33×10^{-1}	4.56×10^{-2}	5.25×10^{-1}	
3 Chief Officer's Dayroom					1.8
Neutron	2.62×10^{-1}	2.57×10^{-2}	4.90×10^{-3}	2.93×10^{-1}	
Total Gamma	3.34×10^{-1}	2.60×10^{-2}	6.15×10^{-3}	3.66×10^{-1}	
4 Officers' Lounge					1.8
Neutron	1.09×10^{-1}	2.79×10^{-2}	3.40×10^{-3}	1.40×10^{-1}	
Total Gamma	4.96×10^{-2}	5.01×10^{-2}	4.29×10^{-3}	1.04×10^{-1}	
5 Deck Office					1.8
Neutron	5.20×10^{-2}	4.70×10^{-3}	3.00×10^{-5}	5.67×10^{-2}	
Total Gamma	6.24×10^{-2}	7.00×10^{-3}	2.01×10^{-3}	7.15×10^{-2}	
6 Store					1.8
Neutron	2.07×10^{-1}	3.83×10^{-2}	4.30×10^{-3}	2.50×10^{-1}	
Direct Gamma	1.06×10^{-1}	1.61×10^{-2}	1.00×10^{-3}	1.23×10^{-1}	
7 Engine Room					1.8
Neutron	9.00×10^{-6}	2.00×10^{-7}	0.00×10^{-0}	9.00×10^{-6}	
Direct Gamma	3.10×10^{-3}	3.00×10^{-6}	0.00×10^{-0}	3.10×10^{-3}	
8 Machinery Room					1.8
Neutron	5.00×10^{-6}	6.00×10^{-9}	0.00×10^{-0}	5.00×10^{-6}	
Direct Gamma	1.40×10^{-3}	1.00×10^{-8}	0.00×10^{-0}	1.40×10^{-3}	

Table 4. Selected External Dose Rates From Vitrified Residues Flasks.

External Dose Rates (μSv/h)				
Dose Point	Hold 1	Hold 2	Total*	Limit
HC1				
Neutron	39.3	1.1	41.6	2000
Direct Gamma	82.8	1.7	86.1	
HC2				
Neutron	24.3	1.8	27.9	100
Direct Gamma	51.0	3.2	57.5	
DK2				
Neutron	18.8	1.7	22.3	100
Direct Gamma	0.4	0.8	2.1	
HL3				
Neutron	25.4	2.2	29.8	2000
Direct Gamma	8.1	0.3	8.8	

* Total = Hold 2 +2(Hold 1), as Hold 3 and Hold 1 contributions are very similar

Because the neutron and gamma ray dose rates were separately normalized to 100 μSv/h at a meter from the flask, the total dose rates will lie between the calculated values for neutrons and gamma rays. However, as indicated earlier, there is a considerable degree of pessimism in the neutron calculations due to this normalization procedure. Even so, the radiation dose rates from the 14 flasks are well within JMOT rules, and, hence, such voyages are clearly acceptable.

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