DOSE RATE ASSESSMENT FOR THE TRANSPORT OF VITRIFIED RESIDUES ON BOARD PNTL SHIPS USING NEW FEATURES AVAILABLE IN THE MCBEND COMPUTER CODE

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ABSTRACT

Pacific Nuclear Transport Limited (PNTL) ships transport vitrified residues, produced at reprocessing plants in Europe, to the storage facility in Japan. The vitrified residues containers are transported in suitably designed shielded flasks (casks). This paper describes an improved radiation dose rate assessment methodology, which has been used for a maximum loading of these flasks on board one of the ships. The method is also applicable for the transport of spent fuel.

The MCBEND Monte Carlo computer code [1] has been used for determining both gamma and neutron dose rates. This represents an improved calculational route, compared to previous assessments, which used approximate point-kernel methods to assess ship loadings. The availability of novel routines in MCBEND9E enables Monte Carlo techniques to be used for the first time, for a ship fully loaded with flasks. Monte Carlo methods produce accurate values of dose rates.

The attenuation of radiation through the walls of the flasks is considerable, and to model the radiation source within up to 20 or more flasks on the ship is an extremely difficult calculation for Monte Carlo methods. The problem was surmounted by performing one MCBEND9E calculation for a single flask, with all of the information about particles leaving the flask being stored in an annular leakage file. This information was then used as the source data for each flask in a second MCBEND calculation for the whole ship, which included geometric models of all the flasks. The automated route, providing the ability to transpose source data submitted for a single flask in this way, has not been available until MCBEND9E was written.

Dose rates at points in the accommodation areas and regularly occupied working spaces have been calculated. The gamma and neutron contributions were summed to determine the worst case position on each deck. The most onerous dose rates for centre-line and off centre-line positions have been presented.

By using MCBEND Monte Carlo calculations, the analysis confirms that optimised loadings of vitrified residues flasks (and potentially also spent fuel flasks) can be carried on board PNTL Ships without exceeding the dose rate criteria, thus ensuring the safety of the crew and the public. The method demonstrates there is potential to carry more flasks, without exceeding the dose rate criteria. Using point-kernel techniques relied on experiment to theory comparisons to justify the method and needlessly restricted the number of flasks capable of being transported in a single shipment.

INTRODUCTION

Vitrified residues produced at the reprocessing plants in Europe is transported from European ports, on board PNTL ships, to the storage facility in Japan. Various flask types (casks) are used. This paper describes an assessment for a maximum loading of fourteen such flasks on board one of the PNTL ships, with Holds 1 to 3 filled to capacity (neglecting any limitations due to the thermal output of the flasks).

There is always a requirement to keep dose uptake to a minimum and to meet ALARP criteria. Restricting vitrified residues flasks to storage locations in Holds 1 to 3 minimises dose uptake to the crew, as accommodation is at the aft of the ships. Due to the nature of vitrified residues, these flasks have a consistently higher utilisation of their design radiological capacity than spent fuel flasks.

Peak dose rates in accommodation areas and regularly occupied working spaces, just aft of the housefront and the shielding tank, have been calculated. Dose rates were calculated at one metre intervals across the width of the ship (athwartships) on the same level as each of the dose rate measuring positions identified in Figure 1. The contributions from each of the Holds 1 to 3 were summed. The most onerous dose rates for centre-line and off centre-line positions have been determined on each deck, in order to ensure that the peak values are below the dose rate criteria.

In addition, dose rates can easily be calculated above the hatch covers and on the external surface of the ship's hull with the new features in the MCBEND code.

DOSE RATE CRITERIA

The shielding provided on the ships must be sufficient to satisfy three Articles of 'The Japanese Rules for The Carriage of Dangerous Goods in Ships':

Article 91-10	The total radiation dose rate at any point one metre 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.
Article 91-16-(2)	The Master of the ship shall limit the dose rates below 2 mSv/h at any point of shell plating, hold, compartment and deck 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 two metres from the external surface of the ship.

SHIP CALCULATIONAL MODEL

The profile of a typical PNTL ship is shown in Figure 1, with the most important dose point locations (DP1 to DP10) indicated, together with dose points HC1 and HC2 (hatch cover) and HL1 and HL2 (hull). Dose points are described in Tables 1 to 3. In the ship, the main radiation shields are the shielding tank and the concrete deck shields (not shown). The shielding tank contains a 750 mm 'thickness' of water (in a bow to stern direction) within 40 to 60 mm steel bulkheads. It extends from the tank top deck level 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. This protects accommodation below decks and the engine room and associated working areas.

All of the structure, materials and equipment on the ship provide radiation shielding to some degree but only the main structure of the ship was included in the calculational model. This included the main structural plating, hatch cover plating, flask support beams, the shielding tank and the concrete deck shields. Other items such as machinery, equipment, furnishings, fittings, most structural beams, non-structural partitions, insulation were neglected for pessimism and simplicity. The ship model used for the carriage of vitrified residues is similar to that used in previous studies [2].

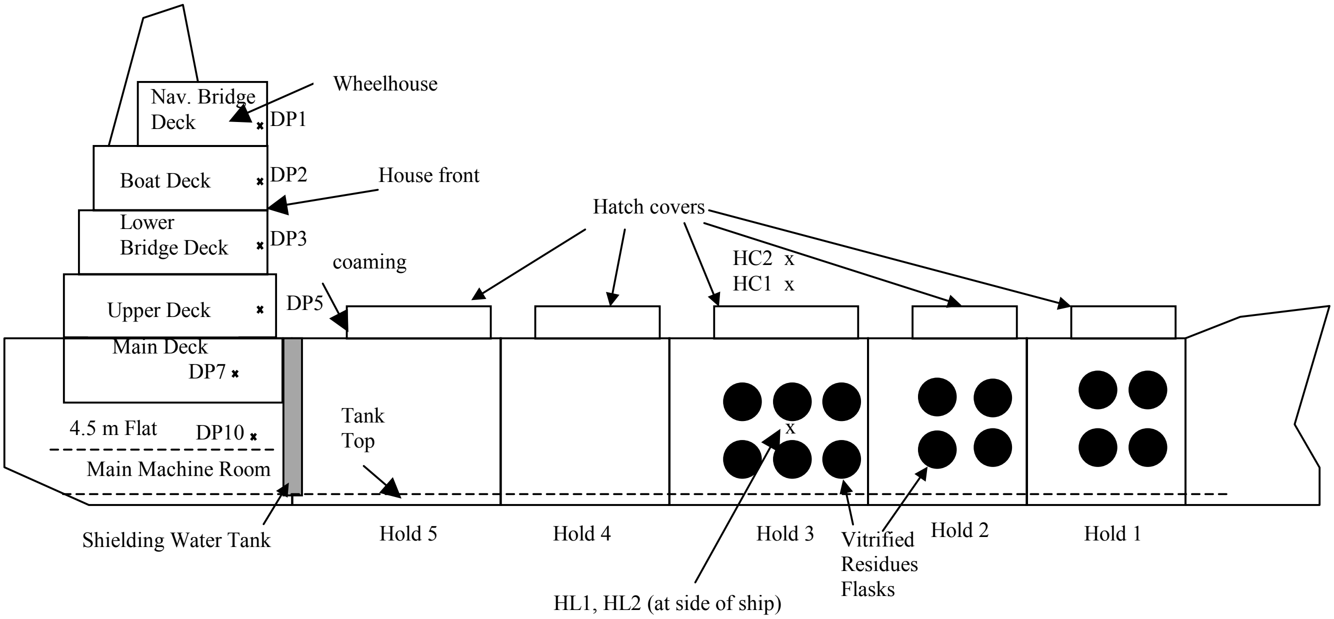

Figure 1. Profile of PNTL Ship Carrying 14 Vitrified Residues Flasks in Holds 1 to 3

PRESENT CALCULATIONAL METHOD

The MCBEND9E RU1 Monte Carlo computer code [1] has been used for determining both gamma and neutron dose rates. This calculational route is more accurate than the point-kernel RANKERN method used previously [2]. Dose rates were determined using the MCBEND code which treats neutron and gamma ray transport in sub-critical systems. The code models the transport of individual particles accurately, by using a very fine energy group representation of nuclear data and a flexible geometrical modelling package.

In order to achieve a reasonable accuracy with practical amounts of computing time, MCBEND is provided with acceleration techniques. These effectively cause more particles, or fractions of particles to be tracked in the directions of interest, compared to directions of less importance. An adjoint diffusion calculation is used to define an array of importance values for directions and energies.

The ship has been assessed for carrying up to fourteen vitrified residues flasks, in Holds 1, 2 and 3 (a customer requirement). The same typical design has been assumed for each flask. The attenuation through the walls of the flask is considerable. Thus, to model the source within the cavity of every flask in a single calculation is prohibited due to computer limitations. The problem was surmounted by initially performing one MCBEND calculation for a single flask. In this calculation, all of the information about particles leaving the flask and entering a thin annular region around the flask perimeter (Figure 2), was stored in a leakage file. This information was then used as the source data for a second stage MCBEND calculation for the whole ship, which included geometric models of the fourteen flasks within Holds 1 to 3. The source derived from the single flask calculations was input to all the flasks in individual holds, one hold at a time. This technique was carried out separately for neutrons and gamma rays. The dose rate contributions were then summed. The ability to transpose the source data submitted for a single flask in this way has not been available until MCBEND9E RU1 was written.

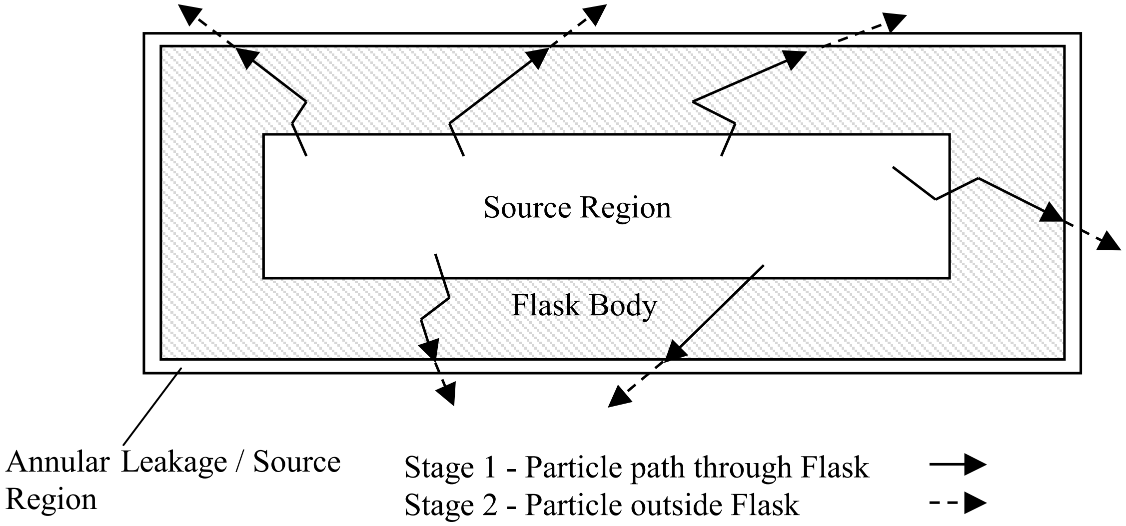

Figure 2. Schematic Diagram Demonstrating Two Stage Method

BENEFITS OF THE NEW METHOD

The present assessment has used the rigorous treatment in the MCBEND Monte Carlo code rather than the more approximate techniques of the point-kernel RANKERN code [3]. There are a number of benefits of using MCBEND.

The method used by RANKERN is to integrate over the source region for the direct line-of-sight contribution to the dose rate at the specified dose points. Three different techniques had to be used in RANKERN in order to take account of indirect radiation, scattered back towards the dose point when originally directed in a different direction. These were (i) the use of build-up factors for gamma rays, (ii) gamma ray volume scattering within hatch covers and air (sky-shine) and (iii) reflection of neutrons from albedo surfaces etc. The direct dose rate with build-up factors is carried out separately to the calculations for the indirect routes (ii) and (iii). Using MCBEND, additional calculations for sky-shine and hatch cover-scatter become superfluous, as these are an integral part of the calculation. Sky-shine is automatically taken into account, provided a large air volume is specified around the perimeter of the ship.

In addition, the neutron dose rates could only be assessed in RANKERN using neutron removal cross-sections, an approximate technique. The one-group neutron removal cross sections are generally derived from shielding experiments. This was the only practical method for neutrons until recent improvements in the efficiency of both Monte Carlo codes and computers and the development of the MCBEND source transposition described above.

As the use of RANKERN was an approximate method, the following approach was used. Two cases were considered; both obeying Article 91-10:

Case 1 The gamma component of the transport index = 0, the neutron component = 10.

Case 2 The neutron component of the transport index = 0, the gamma component = 10.

If the ship obeyed Article 91-18 for both Case 1 and Case 2, it would obey it for any combination of neutron and gamma components that obeyed Article 91-10. However, normalising each to 10 can needlessly restrict the number of flasks capable of being transported in a single shipment.

In reality, the total dose rate is due to a gamma ray component and a neutron component. Now that neutron dose rates can be determined accurately, this pessimistic approach is no longer essential. The peak gamma and neutron sources can be input to the first stage MCBEND calculation (after being normalised to give a total dose rate of 100 μSv/h at one metre). Then, the MCBEND leakage file, generated in the first stage and containing data about particles leaving the flask, can be input to the second stage MCBEND calculation.

Because of the approximate nature of point-kernel methods, experiment to theory comparisons, previously carried out on board PNTL ships for spent fuel, had to be used to justify the earlier RANKERN calculational techniques (in particular for neutrons). These showed that dose rates were over-estimated by the RANKERN technique. Monte Carlo methods are generally accepted worldwide as being definitive methods of calculation. MCBEND is supported by excellent comparisons with many experimental benchmarks.

FLASK MODEL AND SOURCE ACTIVITY

The flask was modelled in MCBEND as a series of cylinders (see Figure 3), with a cylindrical cavity containing the individual vitrified residues canisters. The vitrified residues material contained in the canisters was smeared together with the canister and basket material over the internal volume of the flask cavity. The main flask regions were modelled accurately, but for any regions approximated for simplicity, appropriate pessimistic assumptions were made. The shock absorbers were also modelled.

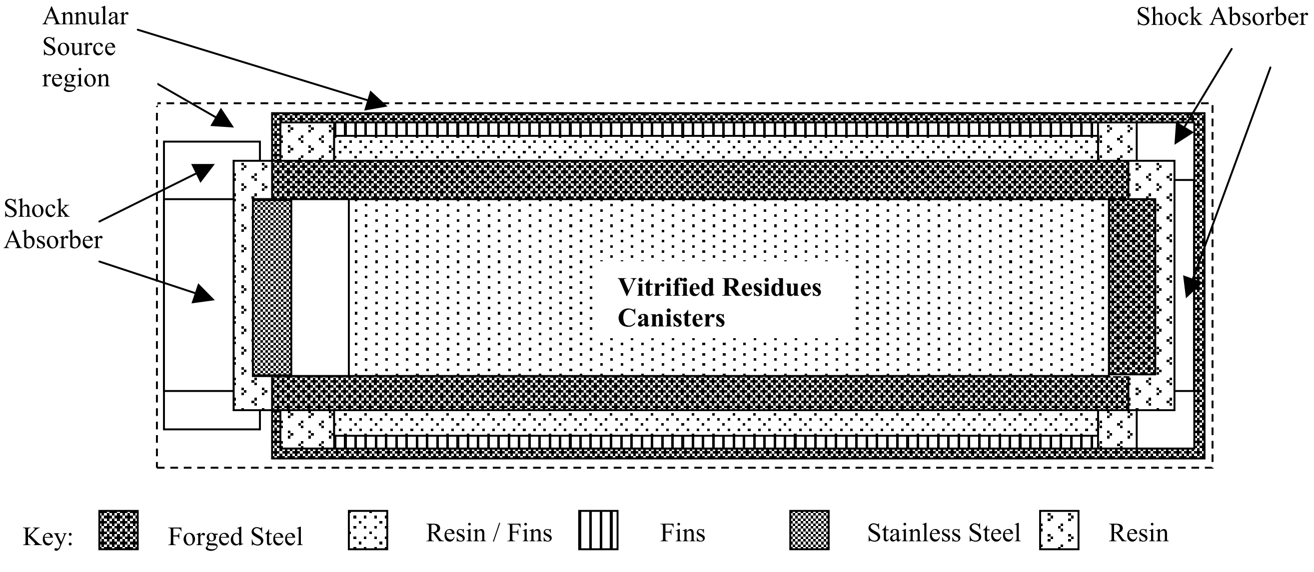

Figure 3. MCBEND Model of a Typical Vitrified Residues Flask

PRESENT SOURCE NORMALISATION

The source activity may vary in different reprocessing campaigns, due to the fuel parameters, burn-up and cooling. Bounding neutron and gamma activities for the vitrified residues to be transported in a particular flask type were used. The total spontaneous fission and (alpha, n) neutron activity in terms of neutrons per second per canister was used. The gamma source can be expressed as an inequality:

$$\Sigma_i(A(R_i)/Al_i) + \Sigma_j(M(T_j)/ Ml_j) < 1$$

Where $A(R_i)$ is the activity of the radionuclide and $M(T_j)$ is the mass of the transuranic nuclide and Al_i and Ml_j are maximum values for a range of isotopes. (The intensity of each nuclide is limited.) For gamma rays, it was assumed that all of the activity was due to Pr_{144} and Ce_{144}, for pessimism, as Pr_{144} produces the highest energy gamma rays. This produced a bounding gamma source activity.

Adopting the expected worst case vitrified residues to be transported, the total dose rate was calculated in the single flask MCBEND calculation. In order to normalise the source strengths, dose rates were calculated along the length of the flask and opposite the ends, at a distance of one metre (from readily accessible surfaces). The peak neutron and gamma dose rates at one metre occurred approximately opposite the axial centre of the smeared source region. The neutron dose rate was approximately 7% of the total dose rate. The sources were normalised to achieve a total radial dose rate of 100 µSv/h, at one metre, by uniformly scaling both the neutron and gamma ray source terms. This effectively maximises the activity within the flask, equating the transport index to a value of 10.

The ship dose rates were calculated for a range of dose point locations athwartships (across the breadth) of the house front. 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 adjacent to the ship's external hull. Various positions were investigated, to ensure that the worst case was identified.

RESULTS

Table 1 gives the peak dose rates in regularly occupied areas at any of the dose points shown in Figure 1. The peak total dose rate is determined to be 0.68 µSv/h for dose point 1 (off centre-line) on the Navigating Bridge Deck, inside the Wheelhouse. The peak dose rate on the centre-line of the ship is 0.60 µSv/h at dose point 2 on the Boat Deck, in the corners of two Officers' bedrooms. The dose rates in Table 1 are all well below the limiting criterion of 1.8 µSv/h. Dose rates at the other dose points (DP3 - DP10) in Figure 1 are much lower.

Table 1. Dose Rates at Dose Points shown on Figure 1

Dose Point	Location	Dose Rate (µSv/h)			
		Neutron	Gamma	Total	Target
DP1	Centre-line	0.15	0.42	0.56	1.8
	Off Centre-line	0.14	0.54	0.68	1.8
DP2	Centre-line	0.13	0.47	0.60	1.8
	Off Centre-line	0.13	0.49	0.62	1.8

Table 1 indicates that the peak neutron dose rate is 0.15 μSv/h on the ship centre-line for dose point 1 on the Navigating Bridge Deck. The peak gamma dose rate is 0.54 μSv/h off centre-line for dose point 1 on the Navigating Bridge Deck, at which the total dose rate also peaks at 0.68 μSv/h.

The source strengths used are considered to be bounding for the expected vitrified residues to be transported. However, the results in Table 1 indicate that neutron and gamma source strengths could uniformly increase by a factor of 2.5 without exceeding the dose rate criteria. Alternatively, the neutron source strength could increase by a factor of eight (if the gamma ray source strength remained constant). Similarly, the gamma source strength could increase by a factor of three (if the neutron source strength remained constant). This provides confidence that the dose rate criteria will not be exceeded and shows that there is scope for more active vitrified residues, without further modification.

These calculations show that no dose rate is likely to be greater than 0.68 μSv/h and that the dose rates are much less than previous analysis [2]. Thus, at least fourteen flasks may be carried, without compromising safety or ALARP and dose uptake will be kept to a minimum.

Table 2. Dose Rates Contributions from Each Hold for Dose Points 1 and 2

Dose Point	**Component**	**Percentage Contribution to Dose Rate**		
		6 Flasks in Hold 3	**4 Flasks in Hold 2**	**4 Flasks in Hold 1**
DP1 Centre-line	Neutron	67	22	11
	Gamma	51	44	5
DP2 Off Centre-line	Neutron	72	19	9
	Gamma	54	42	5

Table 2 shows typical contributions from each hold for the dose rates at dose point 1, on the centre-line and dose point 2, off centre-line. It can be seen that the percentage contributions do not vary dramatically for different dose points for either neutrons or gamma rays.

Table 3. Peak Dose Rates above the Hatch Covers and on the Hull Plating (on the C/L of Hold 3)

Dose Point	**Component**		**Dose Rate (μSv/h)**	**Dose Rate Target (μSv/h)**
	Neutron	Gamma	Total	
HC1, Surface of Hatch Cover 3	12.6	108.0	**121.0**	**2000**
HC2, 2 metres above Hatch Cover 3	7.3	60.7	**68.0**	**100**
HL1, Hull Surface opposite	1.3	17.5	**19.0**	**2000**
Centre of Hatch Cover 3				
HL2, 2 metres from Hull opposite	1.2	11.4	**13.0**	**100**
Centre of Hatch Cover 3				

Dose rates for points above the hatch covers and on the hull plating were also calculated (Table 3). These dose rates were based on the bounding source data described above. All were well within the limiting values of 2 mSv/h on the hull or deck plating, and 100 μSv/h at 2 metres from the external surface of the ship. The peak dose rates are all directly in line with the centre of Hatch Cover 3, as might be expected with 6 flasks loaded in Hold 3. The contribution from Hold 1 flasks was found to negligible in comparison to that from Hold 3 flasks. Hold 2 contributions were also negligible for the hull dose rates.

CONCLUSIONS

MCBEND Monte Carlo calculations demonstrate that up to 14 vitrified residues transport flasks can be carried on board PNTL ships without exceeding the dose rate criteria, based on currently foreseen maximum source activity. On average, source strengths would have to be increased by more than a factor of 2.5, representing a Transport Index exceeding 25 (i.e. a dose rate greater than 250 μSv/h at one metre) for any dose point in accommodation areas to exceed 1.8 μSv/h. Alternatively, because of the large margin between calculated dose rates and the dose rate criteria, it is clear that additional flasks could be carried, for example in Hold 4.

Peak dose rates, in accommodation areas and regularly occupied working spaces, are shown in Tables 1 and 2. These have been determined using expected bounding source strengths. Table 1 shows that dose rates are well within the required limit of 1.8 μSv/h. Dose rates are similar to those in previous studies [2] calculated using RANKERN. Dose rates on the ship's hull and hatch covers (Table 3) are also well within the appropriate limits.

It has been demonstrated that the new technique available in MCBEND provides an automated route for the analysis of ship loadings of vitrified residues. The single flask calculations for neutron and gamma rays are carried out and the source files generated are input into each flask in the calculations for the whole ship.

MCBEND is a rigorous analysis method for both neutrons and gamma rays. The use of a pessimistic approach that needlessly restricts the number of flasks is no longer necessary.

The use of MCBEND for the whole ship calculations avoids the need to perform separate gamma ray scatter and skyshine calculations required in point-kernel methods.

Similar studies have also shown its suitability for the ship transport of spent fuel but are beyond the scope of this paper. There are also opportunities for its use in flask storage arrangements.

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