UTILISATION OF THE MONTE-CARLO CODE 'MCBEND' AND THE DETERMINISTIC CODE 'ATTILA' TO ASSIST WITH THE SHIELDING AND DOSE ANALYSIS FOR THE LAND AND MARINE TRANSPORTATION OF AN INTERNATIONAL TRANSPORT FLASK

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ABSTRACT

A shielding and dose uptake assessment is required for the transportation of nuclear fuel to overseas customers. The fuel is contained within transport packages that when transported individually meet the IAEA transport criteria. In addition to dose rate criteria around a transport flask, dose uptake to ship personnel must not exceed the criteria set by the International Atomic Energy Agency (IAEA) of 1milli-Sievert per year for the general public.

Methods of driving down the dose were employed in accordance with the 'As Low As Reasonably Achievable (ALARA) principle. Ship personnel living onboard the vessel are subject to radiation for the full duration of each day during the voyage. Consequently dose rates in occupied areas are required to be low in order to comply with the stipulated criteria. Methods to drive down dose are applied in line with the ALARA principle to restrict dose uptake.

The Monte-Carlo computer code MCBEND has been used to optimise the shielding to be installed and to determine total neutron, primary and secondary gamma dose rates at key locations around the road vehicle. The use of Monte-Carlo methods in large models such as ships can present potential problems. With ship personnel able to occupy many locations around the ship, dose rates are required in various locations that may require individual acceleration methods in MCBEND. The three-dimensional deterministic code Attila solves the transport equation using a tetrahedral mesh system over all model space, assessing potential problem areas that could be overlooked when selecting dose rate regions. The post-processing tool TecPlot can be used to present two-dimensional or three-dimensional dose rate contours. This can be useful for assessing potential weaknesses around the transport flask and as a visualisation tool for the project.

It was demonstrated that calculated dose rates surrounding the vehicle and dose uptake on board the ship were within the criteria stipulated by the IAEA. With the aid of MCBEND and Attila, dose uptake estimates can be provided with a degree of confidence in addition to two-dimensional contour plots on the vessel.

INTRODUCTION

A shielding and dose uptake assessment has been conducted for the land and marine transportation of flasks containing fresh fuel to European destinations. This paper describes an assessment to determine the dose uptake to personnel during a single voyage. An initial loading plan has been specified and assessments will be carried out based on this plan. The Monte-Carlo computer code MCBEND was used to determine neutron and gamma dose using flux to dose conversion factors from ICRP 51 [5] and ICRP 60 [6] at key locations on the ship. One of the difficulties with the Monte-Carlo process is ensuring that the problem has been sampled sufficiently in all areas of interest, including important scatter regions. This is exacerbated in the case of large models where significant amounts of air are present and shielding is located in vastly different locations, as is the case with a ship. In addition to the Monte-Carlo simulations, the three-dimensional deterministic code Attila has been used to verify MCBEND dose rates. The Attila post-processing tool TecPlot has been utilized to present two-dimensional dose rate contours that can be used as a visual aid tool, displaying radiation propagation and scatter.

Dose rates at points in the living quarters and regularly occupied working spaces have been calculated. The living quarters are located towards the forward end of the ship. Another area of high occupancy is the engine room, located towards the rear of the ship. Devising a suitable loading plan and occupancy schedule may be required, to minimize dose rates to the highly occupied areas and manage dose efficiently.

The flasks will be transported to the ship in a secure vehicle. Early assessments indicated that dose rates around the flask are low enough to ensure that shielding on the vehicle requires no consideration in the shielding and dose calculations.

DISCUSSION

The Monte-Carlo Code ‘MCBEND’ and the deterministic code ‘Attila’

The *Monte-Carlo* program MCBEND has been used to calculate dose rates surrounding the flask and on board the vessel. An advantage of using a Monte-Carlo code is the timeframe and processing power required to perform complex calculations with respect to deterministic methods. MCBEND also has the ability to model complex geometries. The main disadvantage with Monte-Carlo methods used in shielding calculations is that to ascertain accurate dose rates with a low standard deviation, a large number of particles must be sampled in the region of interest. With the purpose of shielding being to reduce the number of particles in the region of interest, an obvious conflict of interests will arise. This can be counteracted by the utilization of acceleration methods. Simple methods of acceleration, including the utilization of reflection boundaries where symmetries exist within the model (and consequently a reduction in particle tracking) and source subdivisions and weighting to sample the source efficiently are employed in the model.

Deterministic methods aim to solve the Transport Equation by breaking the problem down into discrete components of space (computational meshes), angle (angular components of flux) and energy (multigroup energy data). The code then solves the radiation transport equation for the angular and energy dependent flux for each of the spatial elements throughout the computational mesh. A solution is obtained everywhere in the domain meaning that there is no requirement to accelerate to regions of interest, and all areas of the problem are assessed. The post processing tool TecPlot is a visualisation tool that has the ability to plot three-dimensional and two-dimensional contour maps allowing the user to assess radiation propagation, scatter and shielding weaknesses in order to gain a real understanding of the problem.

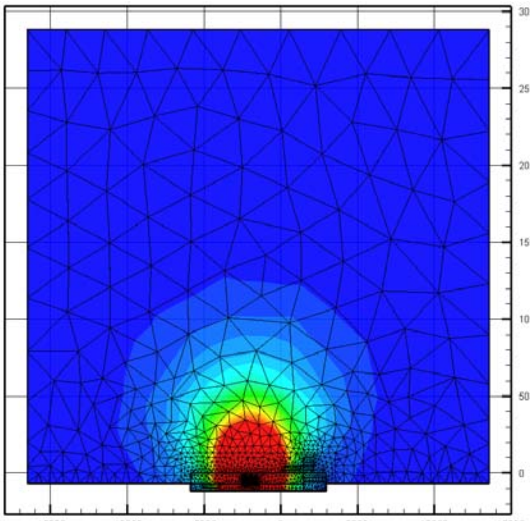


Figure 1: Mesh system generated by Attila using Tetrahedral Cells of pre-determined size

Large models with relatively heavy shielding and containing multiple radiation paths are often difficult to assess using Monte-Carlo methods. In some instances, more advanced acceleration methods are required. The main methods of acceleration used in these calculations are Splitting and Russian Rouletting using the MAGIC module [7], with the requirement for the user to specify local regions of importance where particles are accelerated towards. This method has the facility to 'kill' particles that are travelling away from regions of importance, and accelerate those that are travelling towards it. Some particles travelling away from the detector are forced back to the region of importance (with a reduced weight) to take into consideration any back scatter, and accelerating particles to important scatter regions can be difficult without a thorough understanding of the problem. Consequently, this could lead to an underestimation of the calculated dose rates. In the deterministic code Attila, the spatial and angular discretisation is often difficult to manage in order to avoid negative flux calculations and ray-effects, especially in large models were these parameters are the driver behind the calculation run time.

When calculating dose rates for transport projects, with realistic source terms used to calculate dose rates that must remain within the transport criteria, and detailed (often large) geometries are constructed, both calculation methods can be used simultaneously to calculate dose rates that after appropriate refinements, converge on the same answer.

CRITERIA

The main requirements relating to transport under exclusive use by road [1] state that the radiation level shall not exceed:

a) 10mSv/h at any point on the external surface of any package or overpack, and may only exceed 2mSv/h provided that the vehicle is enclosed preventing unauthorized access, the package remains in a fixed position during transport and there is no loading/unloading during shipment.

b) 2mSv/h at the outer surfaces of vehicle.

c) 0.1mSv/h at any point 2m from the vertical planes represented by the outer lateral surfaces of the vehicle.

For occupational exposures arising from transport activities, where it is assessed that the effective dose:

a) is likely to be between 1 and 6mSv in a year, a dose assessment program via work place monitoring or individual monitoring shall be conducted;
b) is likely to exceed 6mSv in a year, individual monitoring shall be conducted.

In addition to this, it must be shown that dose uptake is 'As Low As Reasonably Achievable'.

CALCULATION ANALYSIS

MCBEND Rate Calculations around a Transport Flask

The flask transports fresh mixed oxide fuel, and consequently dose rates are expected to be relatively low. The flask has been designed to meet the IAEA Transport Regulations. However, calculations have been undertaken to calculate dose rates around the flask with the required fuel specification. These will also serve as a cross check to dose rates calculated when the flask is on board the ship.

A MCBEND case was submitted with a detailed flask model suspended in air and realistic source terms generated using the product inventory code FISPIN [8]. Dose rates were calculated in close proximity to the flask to check the calculations against the transport criteria, and at distances up to 50m away from the flask to assist with the dose uptake cross checks. It was anticipated that Attila calculations would require a flask containing a smeared source and as such, a secondary MCBEND flask was created with individual fuel pins smeared over the assembly. This would be used in conjunction with the unsmeared case to verify that the two source geometries calculate the same dose rates. A smeared source will have the effect of increasing dose rates within close proximity to the flask, where distance falloff changes at the greatest rate. It should be expected however, that dose rate further from the flask will not be affected, as shown in Table 1. Finally, a leakage file was created to calculate radiation fluxes at the flask surface. This allows independent acceleration methods to be used in the primary flask run, recording a well sampled 'leakage source' around the flask body that can be inserted into the ship geometry. Secondary acceleration methods can then be used on the ship to accelerate towards regions of interest, if required. Table 1 shows the neutron and gamma dose rates at key locations around the flask for the unsmeared source, smeared source and the leakage file.

Table 1: Dose Rates around a flask calculated in MCBEND using an unsmeared, smeared and leakage source

	Neutron Dose Rates (µSv/h)			Gamma Dose Rates (µSv/h)			Total Dose Rates (µSv/h)		
	Unsmeared	Smeared	Leakage	Unsmeared	Smeared	Leakage	Unsmeared	Smeared	Leakage
Contact	129.0	137.0	143.8	29.6	32.9	30.6	158.6	169.9	174.4
0.3m	73.6	75.1	77.1	17.4	19.4	17.6	91.0	94.5	81.8
1m	35.0	37.5	39.9	8.9	9.5	8.9	43.9	47.0	42.3
5m	4.7	4.9	5.5	1.2	1.3	1.2	5.9	6.2	5.8
10m	1.4	1.5	1.7	0.35	0.38	0.36	1.8	1.9	1.8
20m	0.37	0.38	0.43	0.09	0.10	0.09	0.46	0.48	0.45
50m	0.05	0.05	0.06	0.01	0.01	0.01	0.06	0.07	0.06

Attila Rate Calculations around a Transport Flask

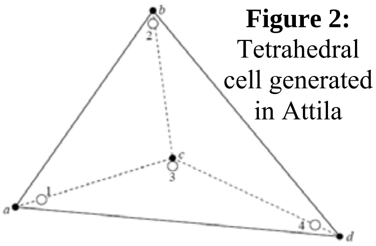


Figure 2: Tetrahedral cell generated in Attila

Attila has the ability to input detailed geometries from pre-processing CAD packages such as SolidWorks [9]. The solid geometry is imported into Attila in a parasolid format, before an internal meshing tool transforms the solid model into a meshed geometry. Each mesh length is predetermined, with each edge typically set to one mean free path. The meshing tool will construct a meshed geometry with cell boundaries forced at the same position as the solid body boundaries. With large models it is important to accurately mesh the system and avoid oversized/undersized cells. The internal meshing tool will make a smooth transition between bodies of differing mesh sizes. For example, as the steel exterior of the flask is relatively thin with respect to the surrounding air body (~100m), the mesh lengths in the air will be forced by the thickness of the steel. The mesh length required in the surrounding air body is much higher, due to the large mean free path in

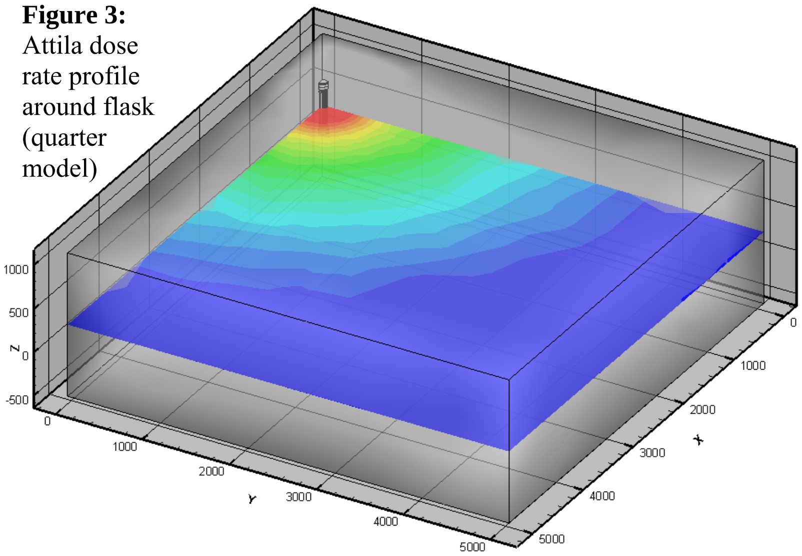


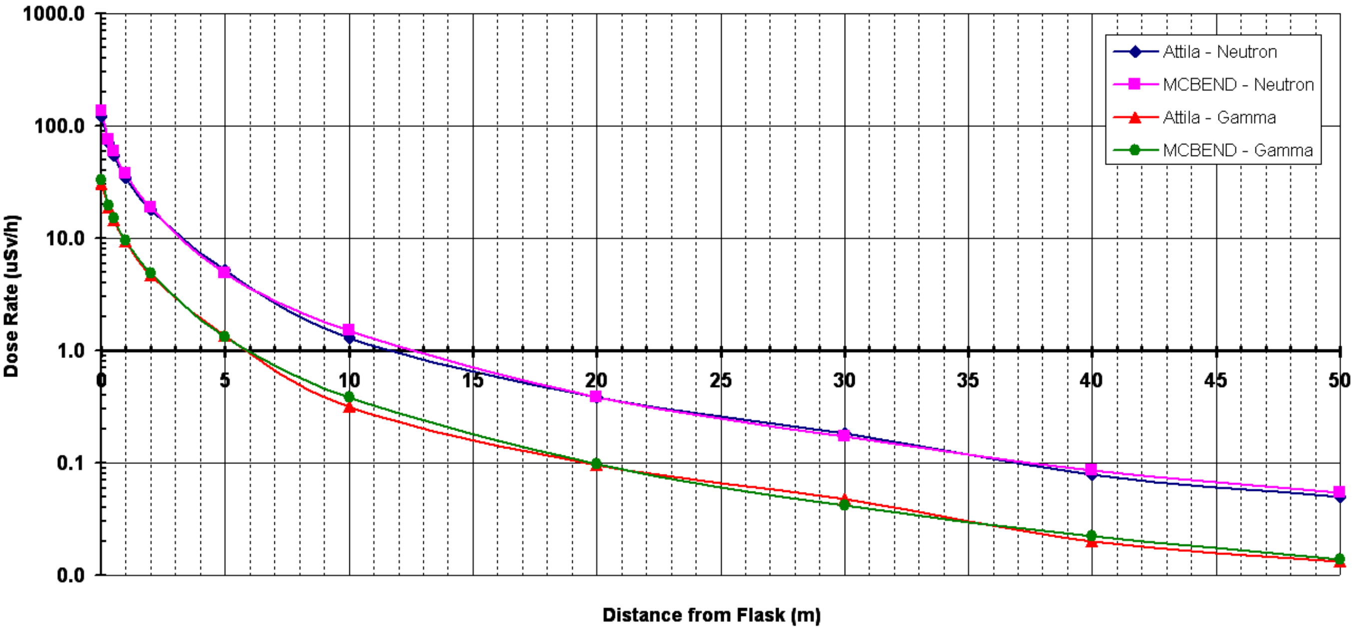
Figure 3: Attila dose rate profile around flask (quarter model)

air. The mesh size will transition smoothly to avoid any flux discontinuities whilst optimising the cell count (see Figure 1). With the side of a tetrahedral cell being straight (Figure 2), it is important to select a small enough mesh size to simulate a cylindrical surface. Using a coarse mesh length could result in an overestimation or underestimation of cylindrical / spherical source or shielding material.

There are over 200 cylindrical rods in each fuel assembly with diameters of <1cm per rod. The mesh size required to simulate a cylindrical geometry for individual rods would drive up the cell count (and therefore run time) for each flask to in excess of 1 million cells. MCBEND calculations from Table 1 suggest that smearing the source will have a negligible impact on dose rates around the flask, and as such fuel rods were smeared over the assembly which in turn reduced the cell count in the system. Utilising the symmetry of the geometry, the flask was reduced into a quarter model with reflection boundaries positioned at X=0 and Y=0, further reducing the cell count by a factor of 4.

Figure 1 shows the neutron and gamma dose rates calculated around the flask in Attila and MCBEND, with the neutron component contributing ~80% in each case.

Figure 4: Neutron and Gamma falloff dose rates calculated in MCBEND and Attila up to a distance of 50m showing a neutron contribution of ~80% of the total dose rate around a flask suspended in air



MCBEND and Attila Dose Rate Calculations on board the Vessel

Even with a high quality leakage file (containing over 1E+06 samples) created around the flask, acceleration methods were still required on the ship. Each leakage body was overlaid in the ship geometry with suitably placed scoring bodies located in areas of high occupancy. A falloff sub-divided scoring body was placed in the centreline of the weather deck (spanning from the rear of the ship to the weather deck cabin) to compare dose rates with those calculated in Attila (Figure 5).

When considering the marine transportation of radioactive fuel, there are two additional scatter sources to consider. Skyshine (the scatter of neutron and gamma radiation from a large body of air) has been considered by surrounding the ship by a 100m x 100m x 500m volume of air. Sea water layers (up to 3 mean free paths in thickness, to avoid any unnecessary particle tracking) surrounded the ship to take into account any back scatter from the sea.

Figure 5 displays the dose rate profile along the weather deck calculated in Attila and MCBEND, with the peak dose rate of 10μSv/h calculated by Attila directly above the flasks. Figure 6 displays a dose rate contour slice across the ship, through the flasks. The passageway links the highly occupied engine room to the living quarters, and a transient dose rate of up to 12μSv/h can be expected in this location.

Figure 5: MCBEND and Attila dose rate profile on weather deck

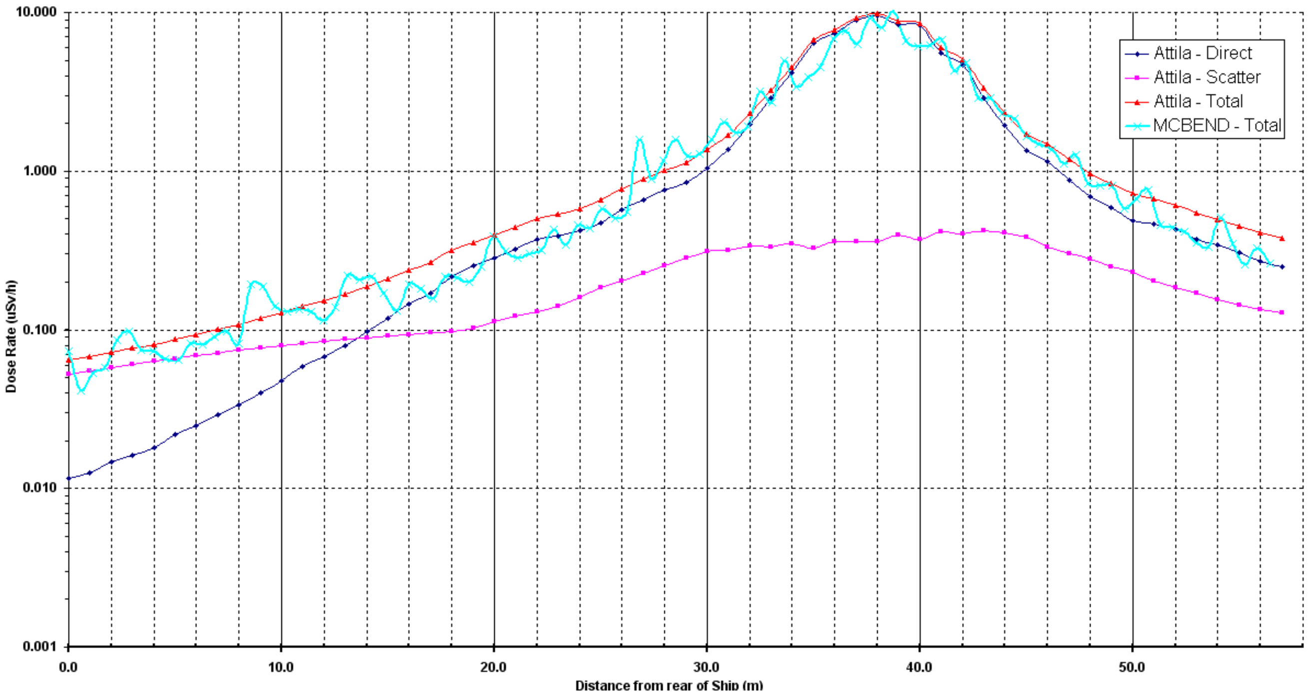
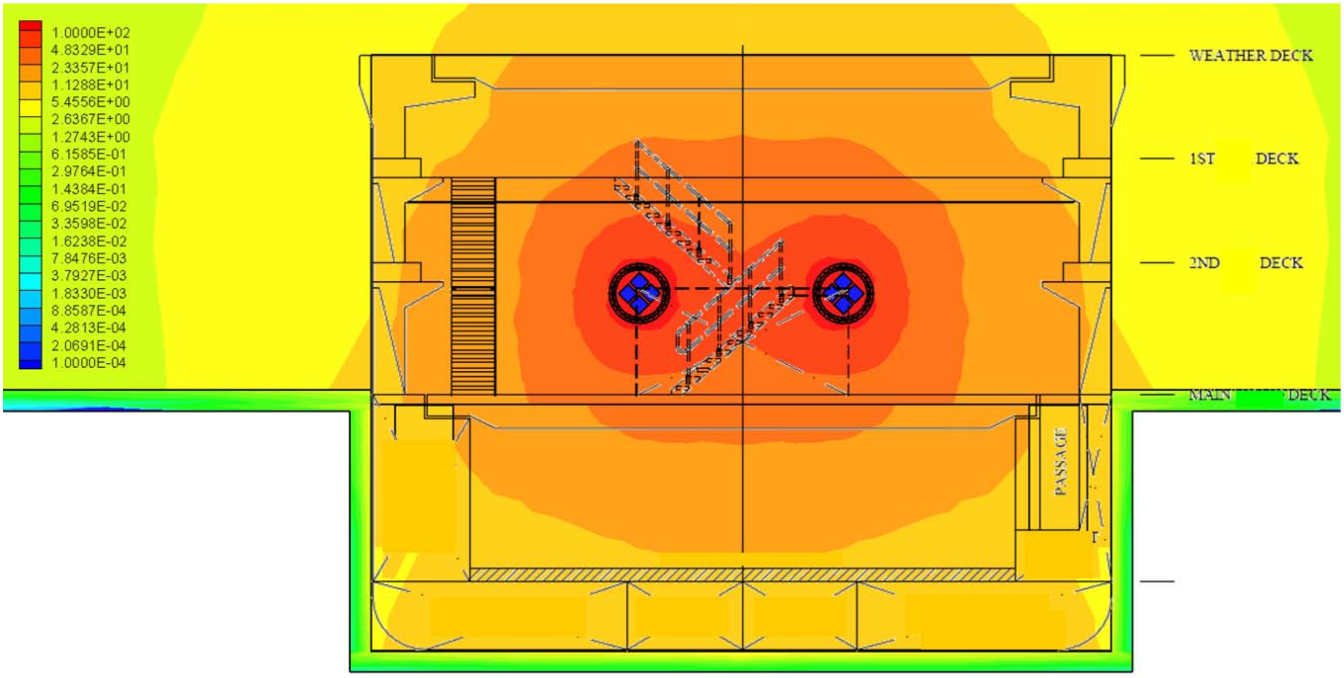


Figure 6: Attila dose rate profile across the transport flasks



RESULTS

Dose rates around a single transport flask calculated in MCBEND are consistent for both smeared and unsmeared sources (Table 1), giving confidence in the use of a smeared source in Attila. Secondary stage dose rate calculations around the flask with the primary stage leakage source are also consistent with the single calculations.

Figure 1 displays the neutron and gamma fall off dose rate around the transport flask calculated in MCBEND and Attila. They are consistent in each case as would be expected for simple falloff dose rates around a flask suspended in air.

Calculated dose rates are well within the IAEA transport criteria. The contact dose rate calculated in Attila is 152µSv/h with the transport criteria stipulated as 2mSv/h. The dose rate at 1m from the package is 44µSv/h, which suggests that even for the most pessimistic transport case, with a flask in contact with the vehicle lateral surface and no shielding present, dose rates at contact with the surface of the transport vehicle and at 2m from a lateral surface will meet the criteria.

Dose rates have been calculated at key locations on the ship using Attila. Table 2 displays dose rates calculated at key locations on the ship. In the weather deck accommodation areas, the peak dose rate is 0.22µSv/h and is dominated by neutron radiation (98%). With steel deck plating and the bulk head between the flasks and the accommodation areas, the low energy gamma radiation from the fresh fuel is easily shielded. Figure 10 shows the dose rate profile in the weather deck accommodation areas. The peak dose rate on Deck X is 0.27µSv/h in the outside recreation space. Within the cabins, dose rates peak at 0.23µSv/h in the lounge. Figure 13 displays the dose rate profile. Dose rates in decks Y and Z peak at 0.07µSv/h. Dose rate profiles are displayed in Figures 11 and 12. Figure 7 shows that dose points within the living quarters lie either fully or partially within the shadow cast by the bulk head. This, along with the deck plating and cabin structure, reduces the gamma radiation to almost insignificant levels in comparison to the 20% gamma contributions around the unshielded flask.

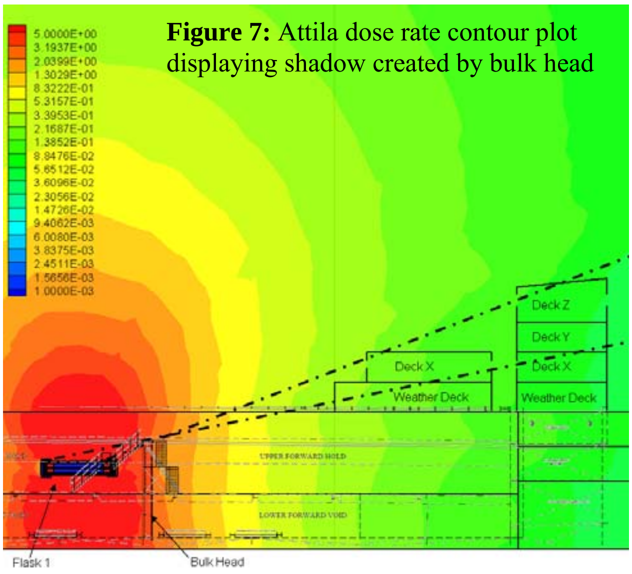


Figure 7: Attila dose rate contour plot displaying shadow created by bulk head

Table 2: Dose Rates on the ship

		Neutron Dose Rates (µSv/h)			Gamma Dose Rates (µSv/h)	Total Dose Rates (µSv/h)		
	Dose Point	Direct Component	Direct + Scatter	Scatter Contribution	Direct + Scatter	Direct + Scatter	Neutron Contribution	Gamma Contribution
Weather Deck	DP 1	0.02	0.07	67%	5.56E-04	0.07	99%	1%
	DP 2	0.02	0.06	69%	4.31E-04	0.06	99%	1%
	DP 3	0.09	0.21	56%	4.32E-03	0.22	98%	2%
	DP 4	0.08	0.17	55%	2.85E-03	0.17	98%	2%
	DP 5	0.06	0.14	55%	2.12E-03	0.14	98%	2%
	DP 6	0.05	0.11	58%	1.51E-03	0.11	99%	1%
	DP 7	0.03	0.07	64%	6.64E-04	0.07	99%	1%
	DP 8	0.02	0.06	65%	5.08E-04	0.06	99%	1%
Deck A	DP 9	0.14	0.26	46%	1.03E-02	0.27	96%	4%
	DP 15	0.09	0.22	60%	6.83E-03	0.23	97%	3%
	DP 16	0.06	0.16	63%	2.64E-03	0.16	98%	2%
	DP 17	0.05	0.13	62%	1.87E-03	0.13	99%	1%
	DP 19	0.03	0.07	65%	6.65E-04	0.07	99%	1%
	DP 20	0.02	0.06	69%	4.67E-04	0.06	99%	1%
Deck B	DP 23	0.02	0.07	68%	8.68E-04	0.07	99%	1%
	DP 24	0.01	0.05	75%	4.52E-04	0.05	99%	1%
	DP 25	0.02	0.07	73%	8.11E-04	0.07	99%	1%
	DP 26	0.01	0.05	77%	4.58E-04	0.05	99%	1%
Deck C	DP 27	0.02	0.07	76%	1.56E-03	0.07	98%	2%
	DP 28	0.01	0.05	84%	7.73E-04	0.05	99%	1%
Engine Room	DP 31	0.12	0.23	46%	5.63E-03	0.23	98%	2%

Dose rates calculated across the weather deck in Attila and MCBEND are displayed in Figure 5. The dose rate profile extends from the rear of the ship up to the living quarters on the weather deck. Dose rates calculated above the flask are dominated by the direct component of radiation. As the distance from the flask increases, the scattered component of the radiation (from skyshine and sea scatter) begins to dominate the dose rate. The scattered component of the total dose rate at the rear of the ship is around 85% (Table 2 shows that the scattered component of radiation is also dominant in the living quarters). Due to the Monte-Carlo nature of MCBEND calculations, there are some discrepancies between Attila and MCBEND dose rates. As computational run time is increased, the standard deviation of MCBEND dose rates will be reduced, producing a smooth curve similar to the Attila profile.

Attila and MCBEND can be used simultaneously to provide an accurate and completely independent neutron dose rate cross check. With a comprehensive understanding of the radiation propagation gained from the TecPlot contours, the acceleration techniques required in MCBEND can be used efficiently in order to gain accurate dose rates with a low statistical uncertainty.

Figure 8: Attila neutron dose rate contours

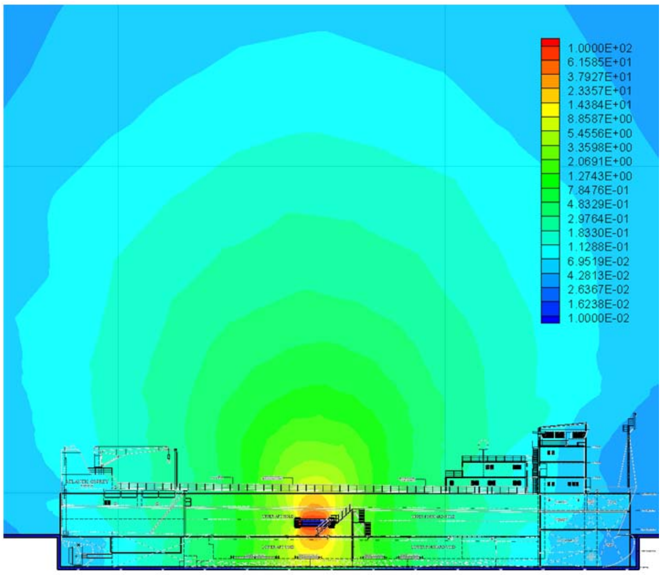
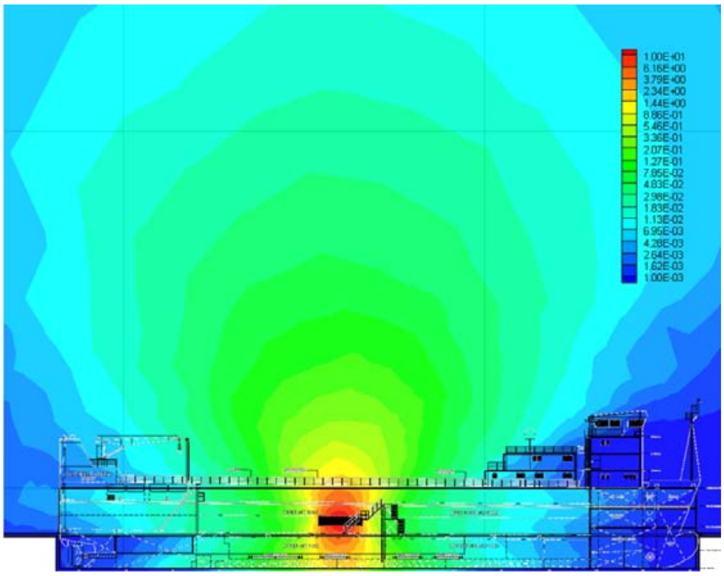


Figure 9: Attila gamma dose rate contours



CONCLUSIONS

Tables 1 and 3 show that dose rates calculated at key locations around the flask and the dose uptake received by ship personnel are within the criteria stipulated by the IAEA. There is no requirement for additional shielding on the ship or to revise the loading plan. The crew will be able to undertake multiple voyages with similar radiation sources before there is any requirement for individual monitoring.

Table 3: Dose uptake to crew

Worker Group	Committed Man-hours	Voyage man-hours (h)	Remaining man-hours	Individual Dose Uptake (mSv)
M	54.00	96	42.00	0.006
C/O	58.5	96	37.5	0.041
2/O	61.5	96	34.5	0.043
3/O	58.5	96	37.5	0.043
CPO	57	96	39	0.009
R	252.6	288	35.4	0.008
C/E	60	96	36	0.034
2/E	60	96	36	0.014
ETO	60	96	36	0.011
S	721.5	768	46.5	0.042
C	60	96	36	0.038
Totals	**1279**	**1920**	**737**	

Dose rates have been calculated in Attila and MCBEND, both around the flask and on the ship. At certain locations on the ship, the scattered component of radiation dominates the dose and it is essential that key scatter paths are accounted for in the calculations, in order to avoid underestimations in the calculated dose uptake. When both tools are used simultaneously, dose rates can be generated that agree to within just a few percent providing an accurate and independent method of neutron calculation.

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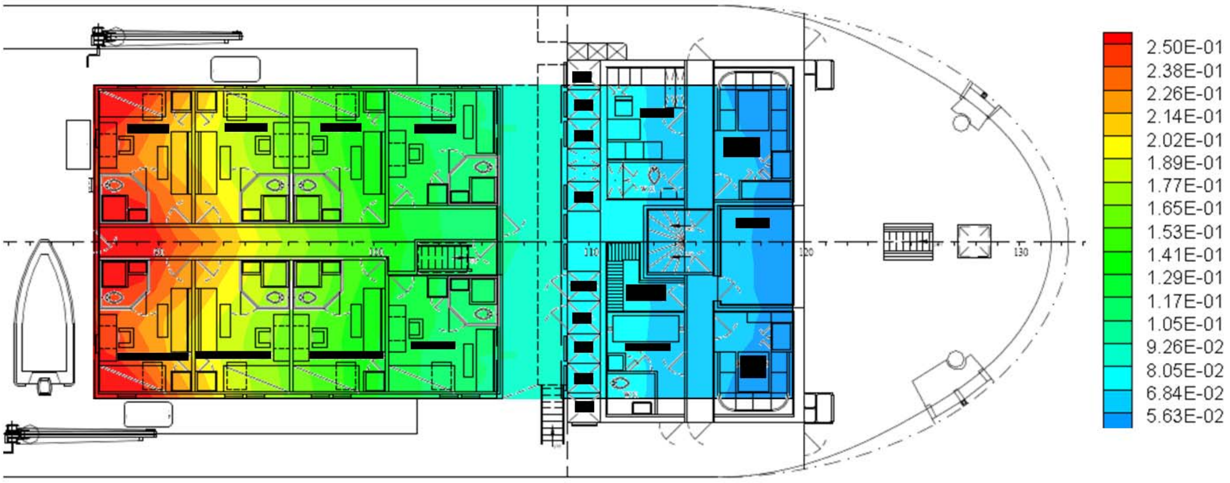
Figure 10: Attila dose rate profile in Weather Deck Cabins



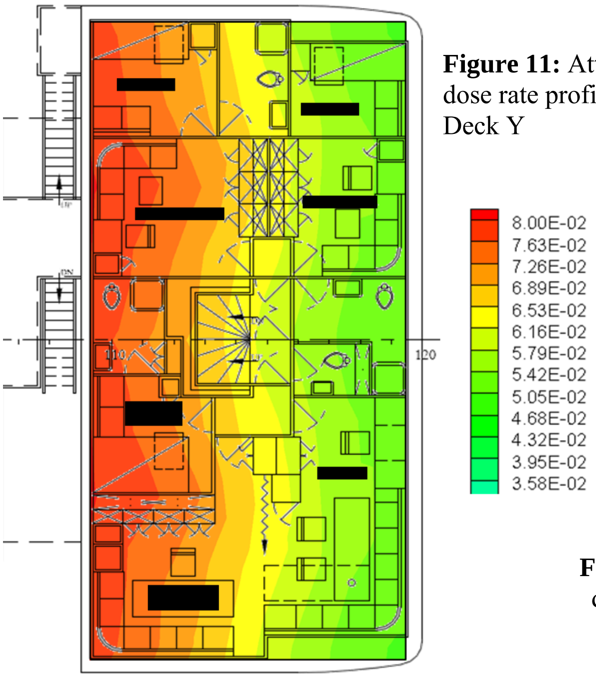


Figure 11: Attila dose rate profile on Deck Y

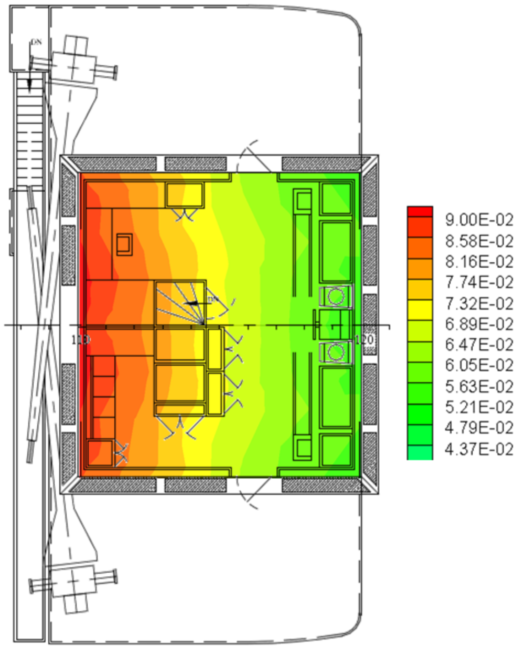
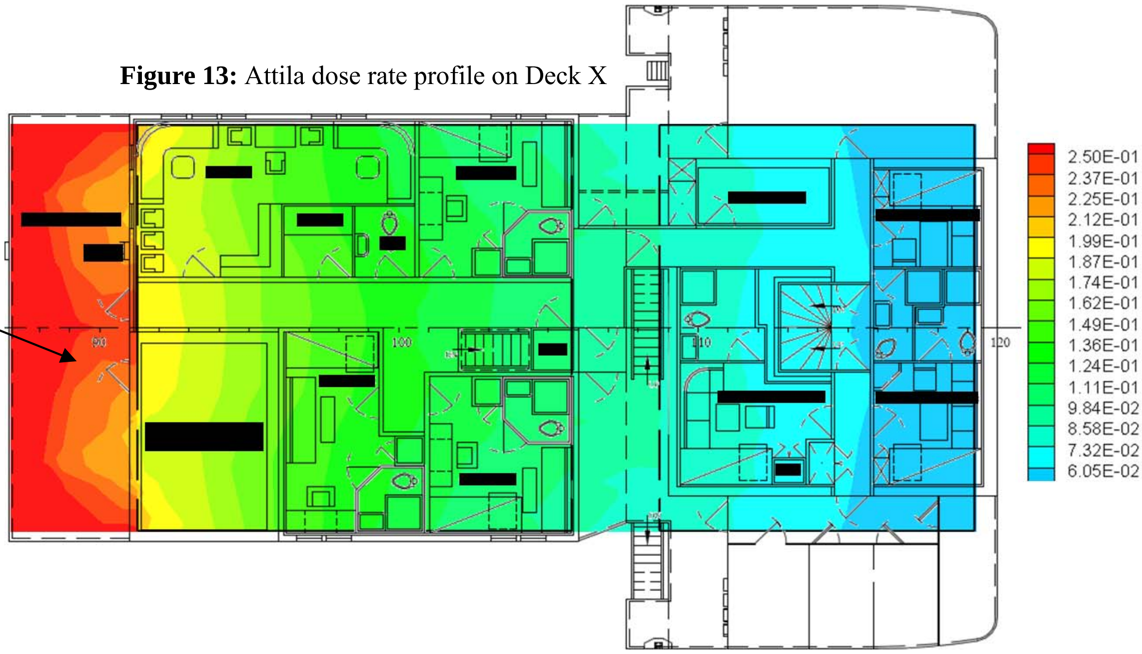


Figure 12: Attila dose rate profile on Deck Z

Figure 13: Attila dose rate profile on Deck X



Outside Recreation Space