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SHIELDING ASSESSMENT OF A VARIETY OF TRANSPORT FLASKS CARRYING MIXED OXIDE FUEL OR VITRIFIED RESIDUE ON BOARD THE PACIFIC HERON SHIP

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ABSTRACT

A shielding and dose rate assessment has been conducted for a variety of transport flasks carrying Mixed Oxide fuels or Vitrified Residues on board a newly designed PNTL ship, Pacific Heron that will transport such flasks from Europe to Japan. The permanent shielding on board the ship was determined such that dose rates met Japanese Transport Regulations in terms of dose rate and dose uptake.

The MCBEND Monte-Carlo computer code has been used to optimise the shielding to be installed and to determine total neutron, primary and secondary gamma dose rates in key areas on board the ship with the final shielding layout. Furthermore, the work has been done using a high-performance 'Beowulf' cluster computer system for efficient distribution of multiple cases of the same input, thus when combined at job completion result in lower standard deviations (< 10%) in reasonable timescales (<1 day).

To demonstrate the applicability of MCBEND in the use of polythene shielding used on the ship, a validation/verification study was carried out against experiment and other codes such as MCNP *(calculations carried out both in UK and Japan)* and the more recent deterministic code Attila. Results from MCNP, MCBEND and Attila gave good agreement against experiment.

INTRODUCTION

A detailed shielding analysis has been conducted for a new ship called the Pacific Heron. It is intended to transport the following combination of fresh MOX fuels and vitrified residues in up to five types of transport flask namely; vitrified residues: TN28VT, BNFL 3320, fresh MOX: MX6, TN12/2 and EXCELLOX 4.

A previous study [i] utilised a leakage file as a new feature in MCBEND for radiation shielding assessment on board the Pacific Pintail. In this work further advantages in the use of leakage files were exploited such as tailoring the acceleration in the initial stage. In addition, a high-performance 'Beowulf' cluster computer system [ii], consisting of 82 2GHz standard computers, has been used to bring down the statistical error in a much shorter elapsed time period.

The main regulations of interest that set the dose rate and dose uptake criteria are the International Atomic Energy Agency Safety Standards [iii] and the Japanese Regulations for the transportation of dangerous goods [iv].

The Monte-Carlo computer code MCBEND [v] was chosen to determine neutron, primary gamma and secondary gamma dose rates in accordance with ICRP 51 for neutron and ICRP 60 for gamma [vi, vii]. One of the difficulties with the Monte-Carlo process is ensuring 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.

DOSE RATE CRITERIA

The shielding provided on the Pacific Heron has been judged against several Articles of The Japanese 'Regulations for Carriage and Storage of Dangerous Goods on Ship' [iv].

Article 89-1	The consignor shall control so that the maximum radiation dose rate does not exceed 2 mSv/h at the surface and 100 μSv/h at one metre from the surface of container or the overpack containing radioactive packages.
Article 103-1	The shipmaster shall limit the maximum dose rate to not over 1.8 μSv/h in the living quarters and the spaces normally occupied by persons aboard the ship.
Article 101	The shipmaster shall limit the maximum dose rates to below 2 mSv/h at the external surface of the shell plating, cargo hold, compartment and deck plating (except the cargo holds or compartments where radioactive packages are stowed and such a place where persons cannot easily approach) and 100 μSv/h at 2m from the external surface of the ship.
Article 103-2	The shipmaster shall limit the radiation dose that the persons aboard expose not over 1.0 mSv/year (up to 5.0 mSv/year in case the MLIT Minister admits it as appropriate).
Article 102-1	In case of the transport of radioactive materials and so forth, the shipmaster shall set up the controlled access areas around the places where the said radioactive materials and so forth are stowed, and limit the entry of any unauthorised persons into such areas, unless otherwise the exposure of the radioactive dose of the persons aboard the ship in such areas does not exceed 1.3 mSv in 3 months.

For the Pacific Heron, it was decided that the target dose rates in regularly occupied areas should be such that Article 102-1 should not be exceeded. Thus the target dose rate should be 1300 μSv / (24 hours * 91.25 days) = 0.6 μSv/h.

METHODOLOGY

Geometry

In this particular work a ship approximately 90 m x 17 m x 20 m was surrounded by a 40 cm thick layer of water up to the draft level and 500 m fore, aft, laterally and above of air, which would account for water scatter and skyshine. Radiation shielding surrounded the holds and consisted of over a 1.5 m thick water tank and ultimately up to 25 cm of polythene shielding. Figure 1 details a schematic of the radiation shielding layout (side shielding not shown).

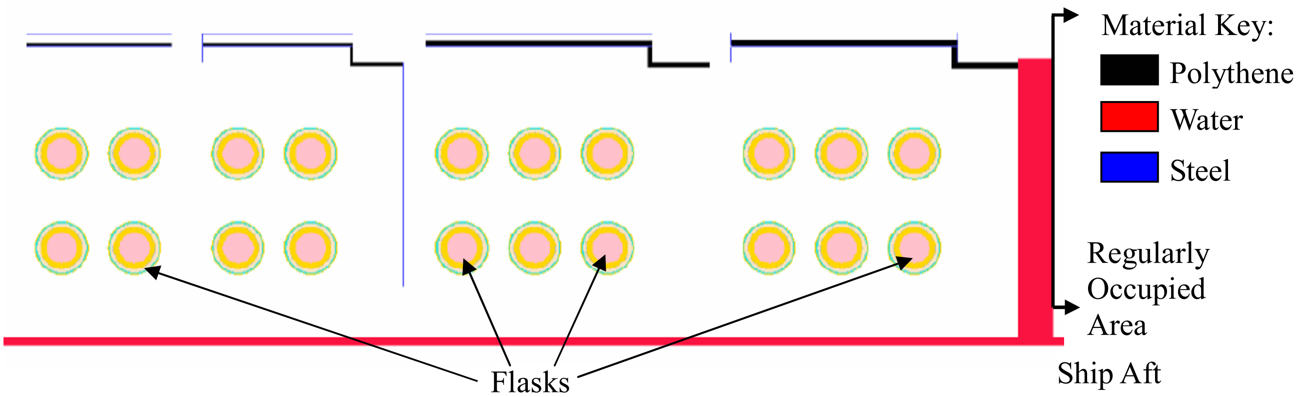


Figure 1. Longitudinal Cross section through Ship Centre-Line of the MCBEND model using the VISAGE [viii] graphics package.

Shielding Analysis

The ANSWERS Monte-Carlo computer code MCBEND [v] has been used as the primary method in this work. Using the leakage file capability within MCBEND permitted the calculation to be split into two stages with the boundary between the two stages being chosen to be at the flask surface. This permitted the use of two independent splitting mesh coordinate systems to be used for the purpose of variance reduction. A cylindrical splitting mesh coordinate system ideally suited the geometry of the flasks and in the second stage a Cartesian coordinate system was chosen to transport the radiation through the ship shielding. The first stage tracks particles to the flask surface and records particle characteristics such as, the particle's position, direction, energy and weight. However, to ensure calculated dose rates were bounding the initial flask stage was normalized to 100 μSv/h at 1m from the flask surface separately for both neutron and gamma. Since in reality the dose rate will be a mixture of neutron and gamma this approach will be pessimistic. Once normalised the leakage file was written and then tested to ensure 100 μSv/h. Figures 2a and 2b detail the neutron flux as a function of energy at 1 m from the flask surface with and without the use of a leakage file respectively, which provides confidence in the leakage file methodology.

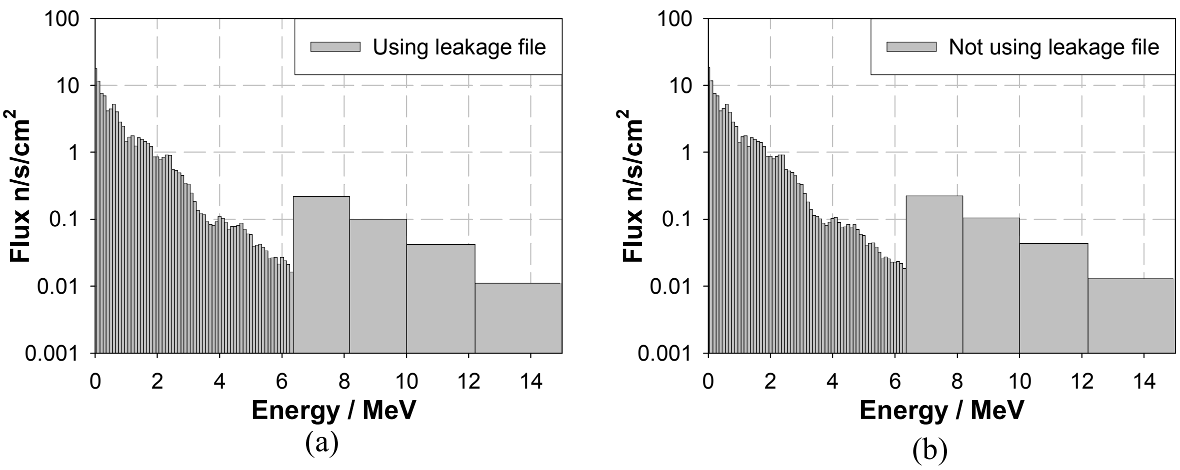
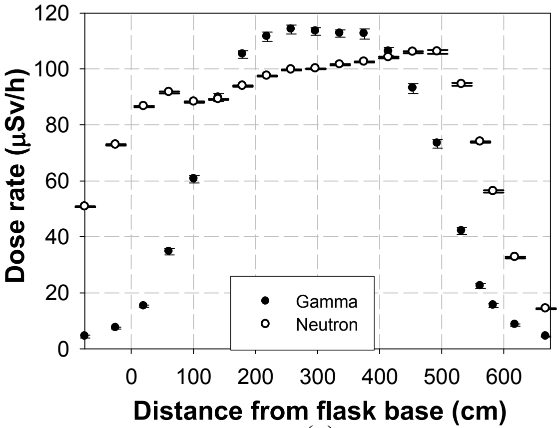
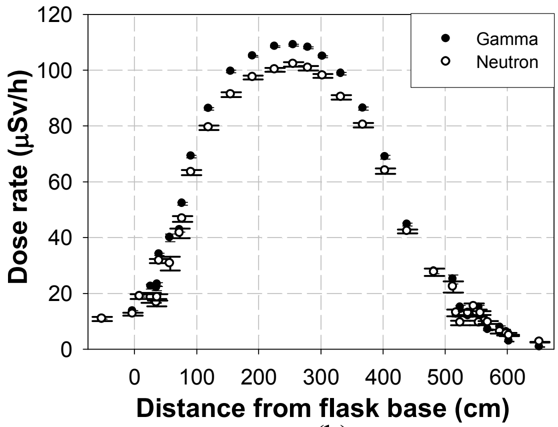


Figure 2. Neutron flux as a function of energy at 1m centrally in height from the TN28VT flask. (a) Details the neutron flux with energy using a leakage file around the flask surface as the starting source. (b) Shows the neutron flux with energy using the MCBEND source input module.

Figures 3a and 3b show typical neutron and gamma dose rate axial profiles of the BNFL 3320 VRT and the MX6 flasks.



(a)



(b)

Figure 3. Axial distribution of neutron and gamma dose rate at 1m from the side of the flask for (a) the BNFL 3320 VRT Flask and (b) the MX6 flask.

In the case of the BNFL 3320 VRT flask the neutron dose rate profile is more uniform due to several factors. Firstly, the trunnion areas in the BNFL 3320 VRT flask are nearer to the source, whereas the fuel in the MX6 is much further away. Secondly, realistic fuel geometry has been modelled in the case of the MX6 whereas a uniform smeared source over the entire basket has been assumed for the BNFL 3320 VRT flask. In the second (ship) stage of the shielding analysis the leakage file is read in and positioned over the flask surfaces of all flasks for each hold in turn, and thus this permits the contribution of each hold to specified detector locations to be determined. The detectors were located at positions within the stipulated regularly occupied areas on all decks. In essence the detectors are designated cells bounded by the splitting mesh in which the flux is tallied by a track length estimate. The appropriate ICRP response is applied to the flux within each energy group and summed to give an estimate of the dose rate in the detector location. Identical copies are made of the second stage input and each input is submitted to a processor on the Beowulf cluster. In general it took 13 CPU hours to create the first stage leakage file and then a further 200 CPU hours, which was normally split into 20 x 10 CPU hour cases for each of the 4 holds giving a total of 800 CPU hours.

Since the preliminary analysis indicated secondary gammas were negligible in the first (flask) stage a collision file was generated within the second stage which recorded all neutron collisions likely to produce a secondary gamma. In a separate case this file was read in to the same second stage geometry and the subsequent secondary gammas were tallied in the same manner as the neutrons and primary gamma.

Variance Reduction

Previous experience has shown that variance reduction would be necessary particularly in view of the size of the model (an allowance of 500 m fore, aft, lateral and above had been included to account for skyshine). The MCBEND computer code uses either a cylindrical or Cartesian coordinate meshing system superimposed over the geometry to provide an importance map. This allows particles to undergo splitting / Russian roulette according to the importance specified. In this present work the main focus of the variance reduction was applied to the first flask stage and the importance has been calculated using an optional MCBEND module called MAGIC [ix]. This module essentially performs an adjoint diffusion calculation which results in a mesh of importances that can be applied to the forward calculation, so long as the region of interest or detector is specified. One reason for using the MAGIC module on the first flask stage only is that large areas of low density material (e.g. air) were present in the second stage and thus presented difficulties on its use due to the application of an adjoint calculation on large areas of low density material. Figures 4a and 4b detail a VISAGE slice through the BNFL VRT MCBEND flask model longitudinally and as a cross section through the mid height of the flask.

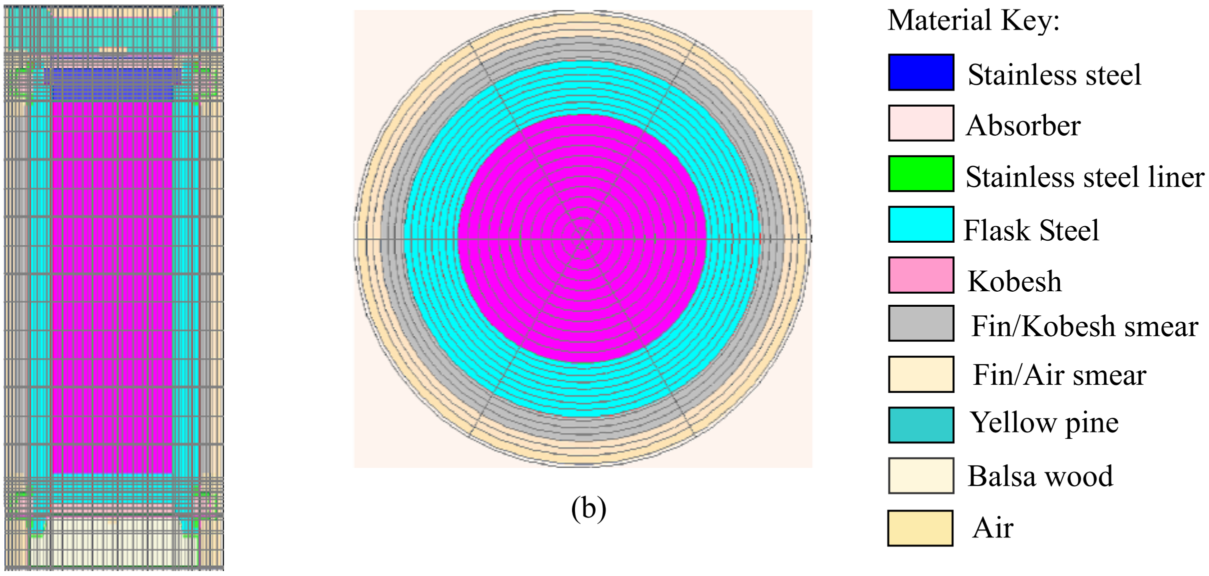


Figure 4. VISAGE cross sections of the BNFL 3320 VRT flask depicting splitting meshes for the neutron case. (a) Represents a longitudinal cross section through the flask centre-line. (b) Represents a cross section through the flask mid-height position.

Polythene Verification Study

To demonstrate the suitability of MCBEND for this ship which has large amounts of polythene as a neutron shield material a verification study was performed based on a previous benchmark experiment carried out in Japan [x]. In this analysis a ^{252}Cf source was placed inside a source collimator orientated towards a detector. Polythene slabs to give a variety of total thickness were placed between the detector and the source collimator. Figure 5 shows the MCBEND model representation of the experiment using Visage [viii]. In the MCBEND code the neutron energy spectrum for ^{252}Cf was simulated using IRDF 2002 data [xi]. However, this data gave a different spectrum to the Watt-fission spectrum using MCNP ^{252}Cf coefficients. Thus, to give confidence in this data a comparison was carried out against the Watt-fission spectrum formula using the ^{252}Cf coefficients from Shultis and Faw [xii]. Figure 6 shows the IRDF 2002 neutron energy spectrum used as a series of grouped energies. In addition, the Watt fission spectrum formula is plotted using Shultis and Faw and MCNP ^{252}Cf coefficient data.

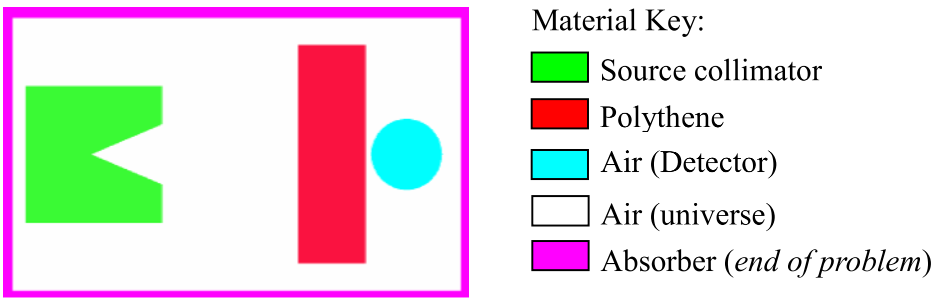


Figure 5. MCBEND Model of Polythene Verification study using VISAGE.

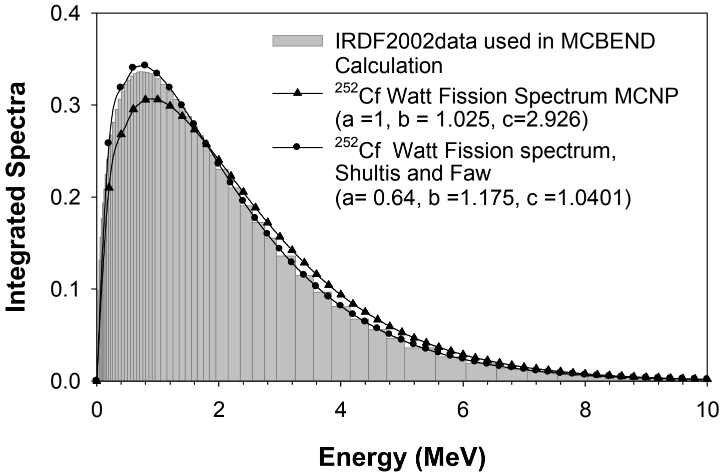


Figure 6. Neutron Energy Spectrum used within MCBEND for the polythene verification study (IRDF 2002 Data). Watt Fission Spectrum detailed using coefficients for ^{252}Cf from both Shultis and Faw and MCNP.

RESULTS

Dose rates at key regularly occupied areas for the TN28VT, BNFL 3320 VRT and MX6 flasks are shown in Tables 1 to 3.

Table 1. MCBEND and MCNP Comparison of Peak Neutron and Primary Gamma Dose Rates in Selected Accommodation Areas on the Centre Line of the Pacific Heron for the TN28VT Flask.

MCBEND									MCNP	
Radiation Type	Deck	Description	Dose rate (μSv/h)	St. Dev.	Hold Contributions in %				Dose rate (μSv/h)	St. Dev.
					H4	H3	H2	H1		
Neutron ICRP 74	8	Wheelhouse	2.91E-01	2.43%	16	21	21	42	2.62E-01	4.58%
	6	Crew Rooms	2.72E-01	2.71%	21	18	18	43	2.35E-01	2.98%
Primary Gamma*	8	Wheelhouse	3.93E-01*	1.64%	60	22	13	5	4.45E-01*	1.57%
	6	Crew Rooms	1.69E-01*	1.60%	59	28	7	6	2.53E-01*	4.74%

*MCBEND and MCNP gamma results are in accordance with ICRP 51 and ICRP 74 respectively.

Table 2. Peak Secondary Gamma Dose Rates in Selected Accommodation Areas on the Centre Line of the Pacific Heron for the BNFL 3320 VRT Flask.

Deck	Description	Dose rate (μSv/h)	St. Dev.
8	Wheelhouse	5.88E-02	1.37%
4	Clean Room	2.54E-02	1.97%

Table 3. Peak Neutron, and Primary Gamma Dose Rates in selected accommodation areas on the centre line of the Pacific Heron for the MX6 flask.

Radiation Type	Deck	Description	Dose rate (μSv/h)	St. Dev.	Hold Contributions in %			
					H4	H3	H2	H1
Neutron ICRP 60	8	Wheelhouse	1.50E-01	3.17%	17	19	25	40
	4	Clean Room	3.03E-02	4.42%	20	16	21	43
Primary Gamma ICRP51	8	Wheelhouse	2.40E-01	1.34%	60	23	10	8
	4	Clean Room	1.34E-02	3.54%	90	7	2	2

The peak neutron, secondary gamma and primary gamma dose rates occur for the TN28VT flask at the Wheelhouse location. This result is understood as the main radiation path to the higher decks is through the less attenuating hatch covers where as the lower decks are more protected by the shielding water tank. It is clear from Tables 1 to 3 that all total dose rates will be under the 0.6 μSv/h criterion determined. Furthermore, consistent standard deviations typically 3 % but less than 5 % have been achieved. Secondary gamma dose rates are shown to be typically less than 20 % of the neutron dose rate. The neutron dose rates between MCBEND and MCNP are within 3σ and thus demonstrate a good comparison. Although the MCBEND and MCNP gamma results use different response functions, a study has shown [xiii] ICRP 74 to be typically 0.6 % higher than ICRP 51, for a Co60 source. Comparison of the conversion factors has shown that the most they differ is ~ 33%, but for a narrow energy band around 0.06 MeV. In practise, a typical broad energy spectrum will experience difference between 0.6 % and 33 %. Thus, when taking this into account the gamma results also compare favourably.

Results of Polythene Verification Study

Figure 7 shows the neutron dose rate equivalent as a function of polythene thickness for experiment [x], MCBEND, MCNP4A [x] and a recently developed 3-D deterministic code Attila [xiv]. The 3-D deterministic code Attila utilises 3-D solid geometry computer-aided-design modelling as the basis for the geometry, onto which a user specified tetrahedral mesh is generated. The linearised Boltzmann transport equation is solved by the Attila program [xiv]. As part of a preliminary evaluation within Sellafield Ltd of this code, dose rates were calculated for this verification study. All dose rates have been evaluated according to ICRP 51 as this response was used in the original experiment [x]. As can be seen by Figure 7, a good comparison from MCNP, MCBEND and Attila is obtained with increased divergence from experiment by all codes at large polythene thickness. However, the discrepancies observed would in the majority of applications build pessimism into the analysis. i.e. the polythene attenuation is underestimated within MCNP, MCBEND and Attila. The MCBEND results consistently underestimate the MCNP results which may be due in part to the softer spectrum assumed in the MCBEND analysis.

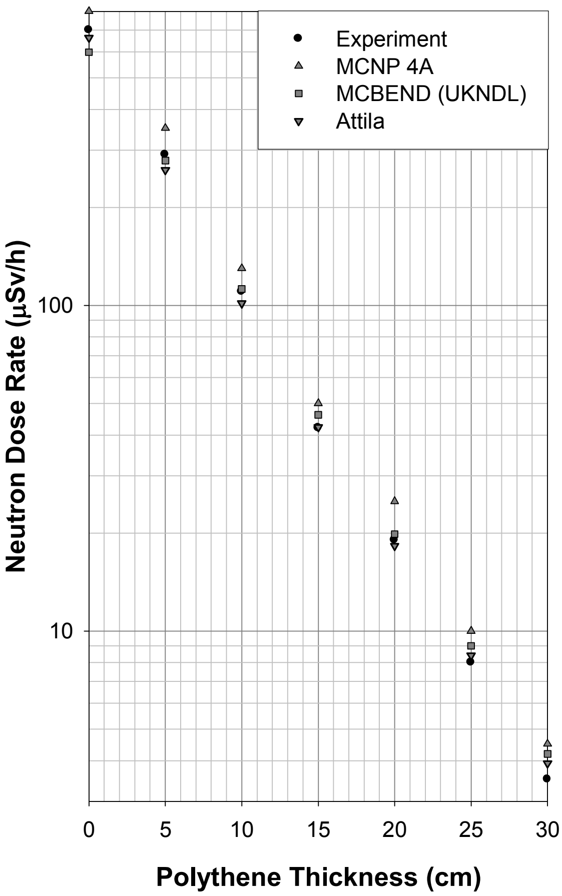


Figure 7. Experimental and MCNP 4A Neutron Dose Rate Equivalent Profile of Polythene obtained from reference x, MCBEND and Attila results.

CONCLUSIONS

Leakage files have been created for the TN28VT, BNFL 3320 VRT, MX6, TN12/2 and EXCELLOX 4 flasks for both neutron and gamma radiation. All leakage files have been tested and demonstrated to be normalised to approximately100 μSv/h at the flask side, although the TN12/2 gamma case was normalised at 1 m below the flask base. Furthermore, the methodology in using leakage files has been compared against using the alternative method of the MCBEND source input module by comparing the flux spectrum at 1 m from the side of a TN28VT flask centrally in height. Results

compare well against MCNP and this provides a high level of confidence in the use of leakage files within this project. The methodology employed together with the use of the Beowulf cluster has enabled dose rate with reasonable statistics < 10 % (standard deviation) to be determined in regularly occupied areas of the ship for a variety of flask types in a reasonable analysis time.
In the polythene verification study a favourable comparison between MCBEND and Attila against experiment has been obtained.

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