COMPARISON OF RADIATION SHIELDING PROPERTIES OF MATERIALS FOR SPACE EXPLORATION INITIATIVE*

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ABSTRACT

Radiation transport calculations were performed using the Montecarlo Intranuclear Cascade Code LAHET in order to evaluate the shielding effectiveness of CH_4 and CH_2 materials compared with, Water, Aluminum, Iron and Lead. In addition, calculations were performed using the deterministic straight-ahead approximation code BRYNTRN for CH_4, CH_2, B, C, Al, Fe Ta, and Pb. The use of hydrogenous material is shown to be superior in its shielding properties of particle and energy spectra of SPE and for the GCR spectra.

INTRODUCTION

As the space program enters into an extended manned space operation, the shielding from Solar Particle Events (SPE) and from Galactic Cosmic Rays (GCR) becomes a problem of ever increasing importance. The most critical aspect of the space mission is the safety and health of the crew. The space ship and crew is bombarded with particles of varying energies and intensities. Three different types of radiation have to be considered for protecting the space ship crew from receiving harmful doses. These are: 1) Trapped electrons and protons in the Van Allen Belts, 2) Solar Flare Protons, 3) Galactic Cosmic Rays.

Outside the Earth's magnetic field the space ship will be exposed to the continuous bombardment of GCR flux, which delivers a steady dose. Proper shielding has to be provided for the duration of the space voyage. Very intense solar particle events are rare with one or two events per solar cycle. In the recent past the onset of cycle XII, with several intense events in the fall of 1989 (Fall 89) has raised new concerns for the safety of the space ship crew. A solar flare can deliver a very high dose in a short period of time if a space craft is not adequately shielded.

In the present investigation the effectiveness of various shielding materials against proton irradiation (SPE) and GCR radiation is investigated. In particular, the possible use of materials rich in Hydrogen content for shielding purposes is evaluated. Both the three dimensional Montecarlo Intranuclear Cascade (INC) and the deterministic straight-ahead approximation Transport Models are employed for calculating the energy deposited (or dose and dose equivalent) in a phantom (H_2O) with various shielding materials.

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TRANSPORT MODELS

Historically, two somewhat different approaches have been taken to simulate the transport of nucleons through bulk nuclear matter. Montecarlo and deterministic transport codes have been developed to study space radiation shielding problems.

At the fundamental level the interaction of high energy nucleon induced reaction may be described (according to Serber's formulation) in terms of essentially a two-step model.[1] At high energies (Eproj≥100MeV/nucleon) the reaction is assumed to proceed in two steps; 1) a fast process, and 2) a slow process based on the interaction time scale. In the first step, the incident nucleon interaction develops a series of binary nucleon-nucleon collision cascades with allowance for some particles to escape. At the end of the first step, the residual nucleus deexcites (after immediate equilibration) through the second step or statistical evaporation of other nucleons/light ions. In this second step, it is tacitly assumed that the residual nucleus is in statistical equilibrium prior to the commencement of the evaporation process. Serber's concept was employed in the works of Goldberger[2], Metropolis[3] and Bertini[4], who developed the intranuclear-cascade-evaporation model, which was subsequently incorporated in thick-target nucleon transport codes.

At sufficiently high energies, the initial phase of the reaction can be treated in terms of collisions of the incident particle with individual nucleons inside the nucleus. The struck nucleons can cause further collisions giving rise to a particle cascade inside the nucleus - the intranuclear cascade process. In thick targets such nuclear collisions produce further collisions with other nuclei, giving rise to internuclear cascade. After the intranuclear cascade, the nucleus is left in an excited state, and the subsequent deexcitation is determined by using an evaporation model, where the excitation energy is dissipated by the successive boiling off of low energy particles. Calculationally, the model is well suited to a statistical approach using Monte Carlo techniques. Allsmiller incorporated the Bertini's INC model in the thick-target nucleon transport code HETC.[5] The Monte Carlo technique has been used in all phases of the implementation of the model. The Los Alamos version of the HETC code is referred to as LAHET.[6] In LAHET an alternative INC model has been adapted from ISABEL code[7], which allows proton, helium ions and antiprotons as projectiles. In addition, few other reaction model options are included in LAHET.

The philosophy behind the HETC (and LAHET) code has been to treat all interactions by protons, pions and muons within HETC, but treat neutron interactions only above a cutoff energy, typically 20 MeV. Any neutron with energy less than 20 MeV has its kinematic parameters recorded on a neutron file for subsequent transport by a Monte Carlo code MCNP, which makes use of ENDF/B based neutron cross section libraries. For the preliminary energy deposition calculations reported here, the low energy neutron transport calculations were not performed due to the non-compatibility of the VAX/VMS generated neutron file with the IBM 3090 executable version of MCNP. Contribution from the transport of low energy neutrons to the total energy deposited in the medium is expected to be about 5-10%.

Both HETC and LAHET codes accept extremely complicated three dimensional target geometries, however, the predictions with low statistical uncertainties may require long computations and large computer storage facilities for complex geometry problems. In order to alleviate such problems and to develop a set of self contained codes for use in an engineering design environment, the NASA Langley group headed by Wilson and Townsend has developed the Baryon Transport Code BRYNTRN[8] and the high energy, high Z(HZE) transport code HZETRN[9] which incorporates the BRYNTRN code. Both of these codes are deterministic in nature and make use of the reasonable straight-ahead approximation for solving the fundamental Bollzman transport equation in one dimension:
where $\phi(X,E)$ is the flux of the particles of type j with energy E and at location X. A combined analytical-numerical technique is developed by Wilson

$$\left[\frac{\partial}{\partial X}-\frac{\partial}{\partial E}S_j(E)+\sigma_j(E)\right]\phi_j(X,E) = \sum_{k>j}\int_E^{\infty}\sigma_{jk}(E,E')\,\phi_k(X,E')\,dE' \quad (1)$$

and collaborators for solving the above given integrodifferential equation. The quantities $S_j(E)$, $\sigma_j(E)$ and $\sigma_{jk}(E,E')$ are the charged particle stopping power in various media, the macroscopic total and absorption cross section and the differential elastic and inelastic cross sections respectively. A detailed account of the methodologies employed in the development of BRYNTRN and HZETRN is presented in a recent NASA publication (NASA 1257, December 1991) by Wilson and collaborators.[10] Both of these codes are constantly under improvement both in physics and numerical computation and are targeted for analyzing the shielding requirement against the SPE flores and GCR radiation encountered in extended manned space missions.

Satisfactory agreement was found between the predictions of Monte Carlo INC code and NASA Langley code BRNTRN.[11]

MONTE CARLO INC TRANSPORT CODE PREDICTIONS

In the present study the Monte Carlo INC transport code LAHET described previously was employed to calculate the energy deposited in a spherical Phantom (H_2O) 15 cm in radius situated within a spherical 8 gm/cm^2 shielding materials Al, Fe, Pb, H_2O, CH_2 and CH_4 at 50 MeV, 100 MeV, 200 MeV, 500 MeV and 1000 MeV proton beam energies. The SPE spectrum ranges from very low energies to about 1000 MeV with the flux dropping by about several decades. Protons in the range of 50-200 MeV are responsible for most of the energy deposited in the nuclear medium. The low energy protons are readily absorbed in the shielding material while the high energy protons have lower proton flare flux, resulting in a lower energy deposited in the phantom.

The LAHET predicted results for the energy deposited per proton in the spherical phantom located within the spherical shielding material with 8gm/cm^2 thickness are listed in Table I. In order to convert the energy deposited in MeV to rads, the multiplication factor is 1.13 for the 15cm radius phantom (H_2O) for a proton intensity of 10^{12}. From the table it is obvious that for proton energies between 100 MeV to 1000 MeV the energy deposited in the Phantom is lower for CH_2 and CH_4 compared to the rest of the shielding materials considered in the present study. It should be pointed out that even though the LAHET calculated results presented in Table I are for the same shielding material thickness in gm/cm^2, however, the physical thicknesses are inversely proportional to the density of the shield. The thickness for Aluminum was arbitrarily taken to be 3 cm. Numbers in parantheses in Table I correspond to the predictions of LAHET code for the energy deposited in the phantom and in the shielding materials with 3 cm thickness for all the materials considered.

BRYNTRN AND HZETRN TRANSPORT CODE PREDICTIONS

The BRYNTRN code and the combined nucleon/heavy ion code HZETRN were used to evaluate the effectiveness of various shielding materials. The Fall 89 Solar Flare[13] and the GCR energy and flux distributions were used as input to the respective codes as the initial particle fluxes at the shielding material surface. The shielding material (thickness was arbitrarily chosen to be 9 gm/cm^2) and a 30 cm thick phantom (water) were taken to be infinite slabs. For the slab calculations with straight-ahead approximation, the dose at a specific depth of the shield with normal incident radiation is equivalent to the dose in the center of a spherical shield of the same thickness in a field with isotropic radiation as realized in space radiation environment.

In order to estimate the effective shielding properties of various materials including CH_2 and CH_4 (materials rich in hydrogen) against the SPE spectrum were considered for calculating the radiation doses with BRYNTRN in a phantom (water) by making use of the detailed body geometry of the computerized Anatomical Man (CAM) model[12] for the skin, outer lense, and blood-forming organs (BFO). This is accomplished by incorporating the appropriate CAM tissue thicknesses, which utilizes an evenly spaced distribution of 512 rays over a 4π solid angle for the 50 percentile U.S. Air Force male. The skin and BFO distributions are both average distributions of 33 locations in the human body, while the occuler lense distribution is for only one location. Generally, the skin and the BFO doses are approximated by slab doses at depths of 0 and 5 cm in tissue respectively.

The BRYNTRN predicted dose values (in the CAM model phantom) integrated over the Fall 89 Solar flare period for 9 gm/cm^2 shielding materials Boron, Carbon, Aluminum, Iron, Tantalum, Lead, CH_2 and CH_4 are listed in Table II. Dose estimates in units of Rem and Rad are given for BFO, Eyes and Skin components of the CAM model. From Table II it is evident that the radiation doses with CH_2 and CH_4 shields are lower in magnitude in comparison to the doses corresponding to the other shielding materials listed in Table II. Both Eye and Skin doses are similar in magnitude while the BFO dose is about 1/2 to 1/3 of the Eye (or Skin) dose for each shielding material.

HZETRN calculations were performed for 9 gm/cm^2 thick shielding materials (CH_2, Al, Fe, Ta and Pb) followed by 5 cm of water slab. The differential dose values in the final layer of water for the four shielding materials are listed in Table III as a function of LET. From an inspection of the table it is evident that the effect of the different shielding materials exposed to the GCR spectrum is somewhat dependent on the nature of the shielding material for the single thickness of the shielding material considered here. However, the doses for CH_2 at different LET values are consistently lower than those corresponding to Al, Fe, Ta and Pb shields.

LAHET AND BRYNTRN CALCULATED NEUTRON SPECTRA

One of the important predictions of the transport model is the secondary neutron energy spectrum generated by the incident proton or heavy ion beam. Figure 1 displays a comparison of the LAHET and BRYNTRN calculated neutron spectra generated in water for a proton beam of 200 MeV incident on an Aluminum shield of 3 cm thickness followed by 5 cm of H_2O. A slab geometry was used in both the set of calculations. It should be pointed out that the LAHET calculated neutron spectrum does not include contribution from the low energy (<20 MeV) neutron transport simulation. The agreement between the two sets of calculations is rather surprisingly good considering the difference in the methods of handling some of the physics problems encountered in the transport calculations.

In summary, the shielding materials rich in hydrogen provide superior shielding against the SPE proton fluxes and the GCR radiations. This conclusion is based on the energy/dose calculations performed with both the Monte Carlo INC Transport code LAHET and the deterministic code BRYNTRN. Since it was not possible to use the CAM model with LAHET code it is not possible to compare the results based on LAHET code and the BRYNTRN code on a one-to-one basis. As noted earlier, the comparison between the total dose calculations based on the Monte Carlo code and BRYNTRN were satisfactory, however, the complex geometry handling capability of LAHET has the advantage, in that localized regional dose calculations can be computed for a complex geometry target system.

TABLE I*

Energy Deposited (MeV) for 8 gm/cm^2 Shield - LAHET Predictions

Ep	50 MeV		100 MeV		200 MeV		500 MeV		1000 MeV	
Shield	H_2O	Shield	H_2O	Shield	H_2O	Shield	H_2O	Shield	H_2O	Shield
Al	0.02 (0.02)	49.3 (49.3)	36.0 (36.0)	60.7 (60.7)	153.7 (153.7)	33.0 (33.0)	111.5 (111.5)	50.7 (50.7)	137.1 (137.1)	59.9 (59.9)
Fe	0.0 (0.0)	49.4 (49.4)	46.5 (0.08)	50.9 (97.3)	156.8 (93.5)	29.5 (91.7)	114.8 (109.3)	44.1 (125.7)	138.1 (133.3)	53.0 (155.3)
Pb	0.0 (0.0)	49.3 (49.3)	65.3 (0.05)	31.7 (96.5)	166.2 (96.8)	19.8 (87.6)	114.3 (107.7)	31.1 (119.5)	136.1 (143.2)	36.5 (131.7)
H_2O	0.0 (0.0)	49.6 (49.3)	9.7 (72.4)	97.5 (25.2)	143.7 (172.8)	44.1 (15.5)	112.0 (114.6)	64.4 (24.0)	143.3 (137.0)	78.2 (27.5)
CH_2	0.0 (0.o)	49.6 (49.6)	0.3 (75.5)	96.9 (21.9)	141.6 (174.8)	46.2 (13.3)	111.9 (115.4)	68.7 (20.1)	135.1 (136.6)	85.0 (24.0)
CH_4	0.0 (21.9)	49.6 (27.7)	0.1 (84.2)	98.1 (13.6)	137.8 (180.2)	53.4 (8.2)	108.9 (115.5)	77.5 (12.6)	131.2 (136.2)	90.1 (14.2)

*The numbers in parantheses correspond to 3 cm thickness for the shield materials.

TABLE II

BRYNTRN Predictions for 9 gm/cm^2 Shield

Shielding Material	Rem			Rad		
	BFO	Eyes	Skin	BFO	Eyes	Skin
B	398	1090	1130	27.4	74.4	76.8
C	35.4	92.8	95.7	24.4	64.0	65.6
Al	42.6	122	130	29.3	82.7	86.3
Fe	50.0	156	172	34.0	103	110
Ta	73.9	286	355	48.8	177	201
Pb	77.8	309	389	51.2	191	219
CH_2	27.7	66.9	67.6	19.3	46.8	47.4
CH_4	23.4	53.5	53.5	16.4	37.8	38.0

TABLE III

HZETRN Predictions for 9 gm/cm^2 Shield

LET	CH_2		Al		Fe		Ta		Pb	
	Rad	Rem	Rad	Rem	Rad	Rem	Rad	Rem	Rad	Rem
1.08	14.0	56.8	14.2	59.2	14.3	60.1	14.5	62.0	14.6	62.3
5.03	8.96	51.7	9.0	54.0	9.18	54.8	9.12	56.6	9.14	56.9
23.5	5.84	48.6	5.9	50.8	5.91	51.7	5.96	53.4	5.98	53.7
109.	4.31	46.2	4.4	48.3	4.46	49.0	4.55	50.5	4.58	50.8
510.	1.94	33.0	1.9	33.7	1.93	33.7	1.87	33.3	1.86	33.2
2380	0.4	8.01	0.36	7.26	0.35	6.92	0.30	5.93	0.29	5.79
11100	0.05	0.95	0.42	0.82	0.38	0.76	0.03	0.59	0.03	0.57
51600	0.0006	0.009	0.0008	0.0008	0.0007	0.0007	0.0008	0.0007	0.001	0.0008

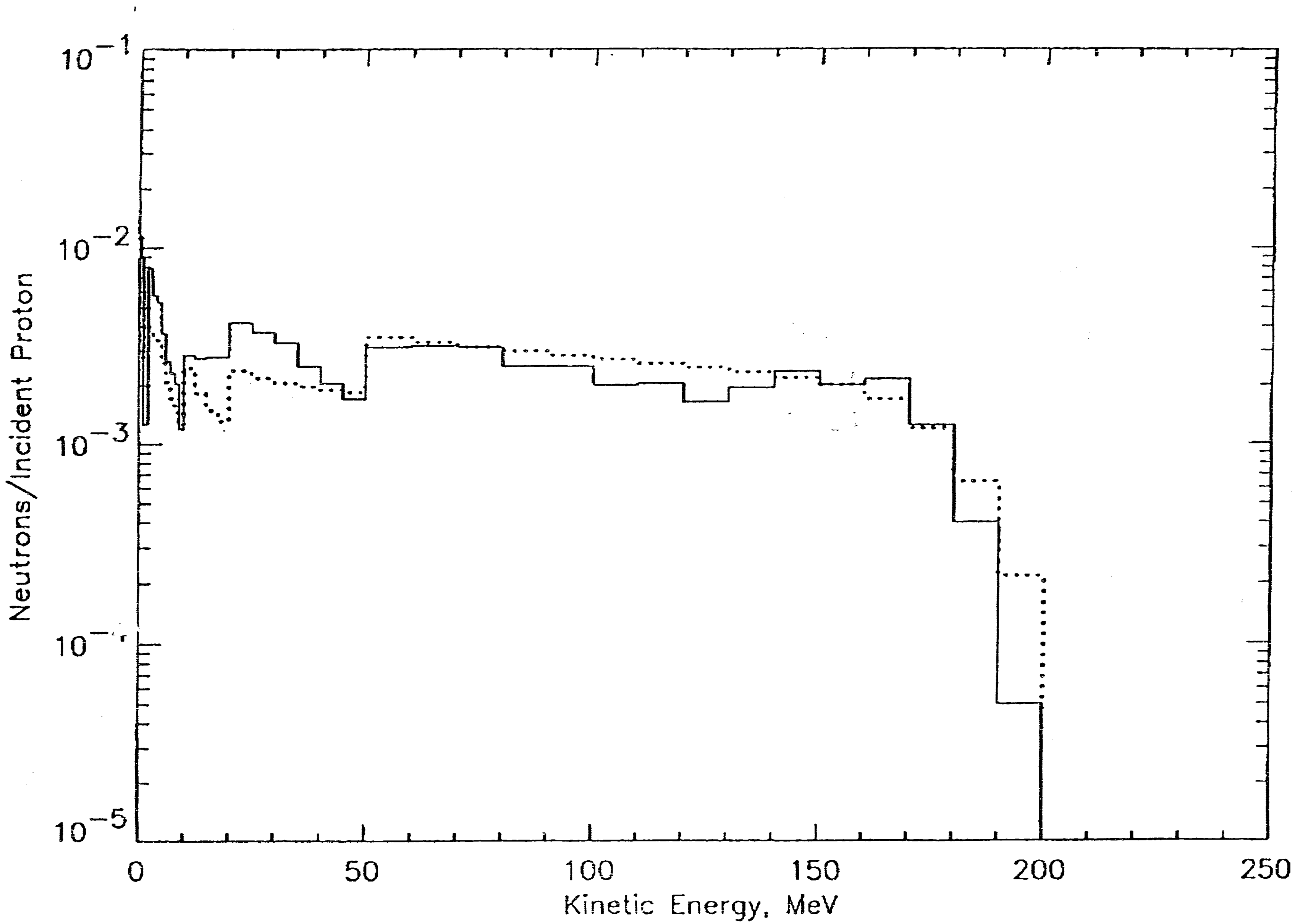

Fig. 1. Comparison of LAHET (Solid histogram) and BRYNTRN (dashed histrogram) predicted neutron Spectra for E_p = 200 MeV.

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