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SHIELDING OF MANNED SPACE STATIONS AGAINST VAN ALLEN BELT PROTONS: A PRELIMINARY SCOPING STUDY

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ABSTRACT

Calculated results are presented to aid in the design of the shielding required to protect astronauts in a space station that is orbiting through the Van Allen proton belt. The geometry considered — a spherical shell shield with a spherical tissue phantom at its center — is only a very approximate representation of an actual space station, but this simple geometry makes it possible to consider a wide range of possible shield materials. Both homogeneous and laminated shields are considered. Also, an approximation procedure — the equivalent thickness approximation — that allows dose rates to be estimated for any shield material or materials from the dose rates for an aluminum shield is presented and discussed.

I. Introduction

The selection of shielding materials for use in manned space stations requires that the absorbed dose rate and dose equivalent rate received by the astronauts be determined as a function of the thickness and composition of candidate shield materials. The selection of the shield configuration is driven by several factors including the specified dose constraints to the spacecraft occupants and the shield weight limitations imposed by the lift capability of the launch vehicle. In this report, the performance of various candidate materials for protecting astronauts against Van Allen Belt protons are examined. The proton spectrum that is used is typical of the spectrum that will be incident on a space station in a low earth orbit that passes through the South Atlantic anomaly.

The absorbed dose and dose equivalent rates have been calculated under the assumptions that the attenuation of the incident protons due to nuclear collisions and all secondary particles produced by nuclear collisions in the shield and in tissue may be neglected. These assumptions were considered in detail in Refs. 1 and 2 and were shown to give reliable results for thin shields (≤ 20 g/cm^2) such as those considered in this report.

The absorbed dose and dose equivalent rates as a function of shield thickness have been estimated for both homogeneous and laminated shield geometries. The results obtained for the homogeneous shield configurations are intended to demonstrate the relative merits of the various candidate materials as a function of shield thickness while the data obtained for the laminated geometries reflect the merits of the shield assemblies with fixed dimensions and provide assessment of the shielding effectiveness versus weight.

The spacecraft-astronaut geometry, incident Van Allen Belt spectrum, and the methods of calculation are described in Sec. II. In Sec. III the results for both homogeneous and laminated shields are presented and discussed. In Sec. IV an approximation procedure is presented that enables dose rates to be estimated for any laminated shield configuration without significant additional computation. In Appendix A calculated dose rates similar to those presented in the body of the paper, but for a somewhat different proton spectrum are given. In Appendix B a typical example of the stopping power data used in the report is presented.

II. Geometry, Incident Spectrum, and Methods of Calculation

A schematic diagram of the geometry used to simulate a "spacecraft-astronaut" configuration is shown in Fig. 1. In the calculations reported here, the inside radius of the spherical shell was taken to be 150 cm so the shielded volume is the same for all cases considered. The dose rates are calculated at the center of tissue spheres having radii of 0.0, 1.0, and 15.0 g/cm^2 to estimate the dose rates to the skin, eyes, and midline of the body, respectively. The composition of the tissue is the same as that used in Ref. 1 and is given in Table 1.

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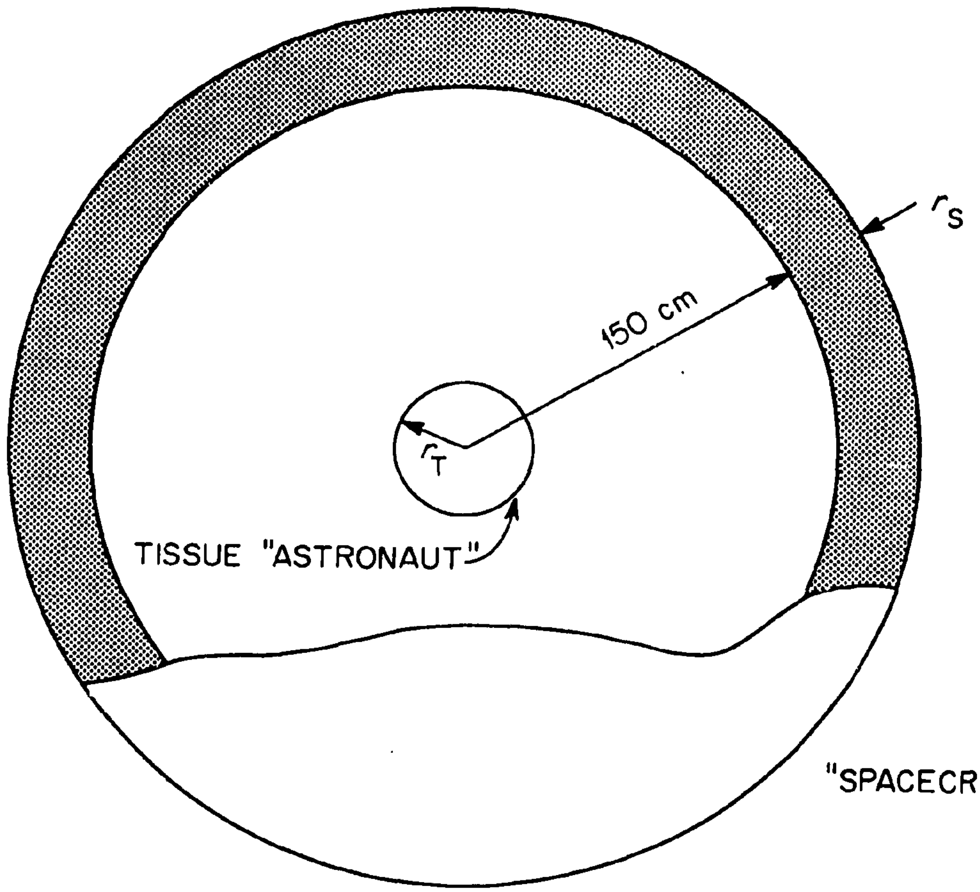

Fig. 1. A schematic diagram of the "spacecraft-astronaut" configuration. r_S is the shield thickness and r_T is the radius of the tissue sphere.

TABLE 1

Composition of Tissue
(Density = 1.0 g/cm^3)

Element	Number Density of Nuclei (No./cm^{-3})
H	$6.265 \cdot 10^{22}$
C	$9.398 \cdot 10^{21}$
N	$1.342 \cdot 10^{21}$
O	$2.551 \cdot 10^{22}$

Table 2 gives the compositions of the various shield materials that are studied.

The incident Van Allen Belt proton spectrum used was supplied by Martin Marietta Michoud Aerospace and is given in Table 3.[3] This spectrum corresponds to an orbit of 250 nautical miles at an inclination to the equatorial plane of 28.5°. The spectrum was obtained by processing trapped proton data provided by the National Space Science Data Center (AP8 proton distribution) over an orbital integration time of one day using a code designated as PD-202. The method of obtaining this spectrum is consistent with the recommendations of the minutes of the Space Station Radiation Panel Meeting of Experts[3,4] (see also Ref. 5).

The absorbed dose rates and dose equivalent rates as a function of shield thickness for homogeneous shields were calculated using the TRAPP[6] code. This code solves numerically the primary proton transport equation with attenuation due to nuclear collisions either included or neglected and calculates by numerical integration the absorbed-dose and dose-equivalent rates at the center of the tissue sphere shown in Fig. 1. In the work reported here, nuclear collisions are neglected and only the slowing down of the primary protons is considered since in Ref. 1 this was shown to give reliable results. The primary particles are assumed to travel in straight lines and undergo continuous slowing down. The effects of multiple Coulomb scattering and range straggling are neglected since these effects have been shown to be negligible in space-shielding calculations.[7] The stopping power data for TRAPP were calculated using the SPAR[8] code. The stopping powers calculated for the graphite/epoxy mixture (see Table 2) are given in Appendix B. These data are included for the purpose of showing a typical output generated by the SPAR code. The quality factor as a function of linear energy transfer used in TRAPP is that used in Ref. 1. In all of the TRAPP calculations the proton flux given in Table 2 was assumed to be isotropically incident on the shield.

The absorbed dose rates and the dose equivalent rates for the laminated shield configurations were calculated using the high-energy nucleon-meson, Monte Carlo code HETC.[9] This code has been described in detail elsewhere[1,9,10] and, therefore, will not be discussed here. HETC is primarily

TABLE 2
Composition of Shield Materials

Shield Material	Density (g/cm^{-3})	Element Density (No./cm^{-3})
Carbon	2.20	$1.10 \cdot 10^{23}$
Aluminum	2.70	$6.02 \cdot 10^{22}$
Iron	7.87	$8.48 \cdot 10^{22}$
Copper	8.92	$8.53 \cdot 10^{22}$
Polyethylene	0.92	
H		$7.98 \cdot 10^{22}$
C		$3.95 \cdot 10^{22}$
Graphite/Epoxy	1.60	
H		$1.83 \cdot 10^{22}$
C		$7.27 \cdot 10^{22}$
O		$2.50 \cdot 10^{21}$
N		$1.60 \cdot 10^{21}$
S		$3.00 \cdot 10^{20}$
Kevlar 49 Fiber	1.45	
H		$3.76 \cdot 10^{22}$
C		$5.09 \cdot 10^{22}$
O		$7.10 \cdot 10^{21}$
N		$7.30 \cdot 10^{21}$
S		$2.00 \cdot 10^{20}$
Na		$2.00 \cdot 10^{20}$
Kevlar 49/Epoxy	1.36	
H		$4.01 \cdot 10^{22}$
C		$4.27 \cdot 10^{22}$
O		$6.90 \cdot 10^{21}$
N		$6.20 \cdot 10^{21}$
S		$4.00 \cdot 10^{20}$
Na		$1.00 \cdot 10^{20}$
Glass/Epoxy	1.90	
H		$2.06 \cdot 10^{22}$
C		$1.79 \cdot 10^{22}$
O		$2.92 \cdot 10^{22}$
N		$1.90 \cdot 10^{21}$
S		$4.00 \cdot 10^{20}$
Si		$8.90 \cdot 10^{21}$
Fe		$1.00 \cdot 10^{20}$
Mg		$2.10 \cdot 10^{21}$
Na		$1.00 \cdot 10^{20}$
Al		$4.00 \cdot 10^{21}$
Spectra 900	0.97	
H		$8.53 \cdot 10^{22}$
C		$4.17 \cdot 10^{22}$
Spectra 900/Epoxy	1.10	
H		$7.16 \cdot 10^{22}$
C		$4.27 \cdot 10^{22}$
O		$2.70 \cdot 10^{21}$
N		$1.70 \cdot 10^{21}$
Si		$4.00 \cdot 10^{20}$

TABLE 3

Van Allen Belt Differential Proton Flux Used in the Calculations (Corresponds to an orbit of 250 nm at an inclination to the equatorial plane of 28.5° and a time average of 1 day.)

Proton Energy (MeV)	Differential Proton Flux (protons/cm²/d/MeV)
$1.00 \cdot 10^{-1}$	$2.79 \cdot 10^{5}$
$2.00 \cdot 10^{-1}$	$1.62 \cdot 10^{5}$
$3.00 \cdot 10^{-1}$	$1.62 \cdot 10^{5}$
$4.00 \cdot 10^{-1}$	$1.70 \cdot 10^{5}$
$5.00 \cdot 10^{-1}$	$1.59 \cdot 10^{5}$
$6.00 \cdot 10^{-1}$	$1.30 \cdot 10^{5}$
$7.00 \cdot 10^{-1}$	$1.27 \cdot 10^{5}$
$8.00 \cdot 10^{-1}$	$1.27 \cdot 10^{5}$
$9.00 \cdot 10^{-1}$	$1.26 \cdot 10^{5}$
$1.00 \cdot 10^{0}$	$3.77 \cdot 10^{4}$
$2.00 \cdot 10^{0}$	$2.53 \cdot 10^{4}$
$3.00 \cdot 10^{0}$	$2.55 \cdot 10^{4}$
$4.00 \cdot 10^{0}$	$2.53 \cdot 10^{4}$
$5.00 \cdot 10^{0}$	$2.49 \cdot 10^{4}$
$6.00 \cdot 10^{0}$	$2.79 \cdot 10^{4}$
$7.00 \cdot 10^{0}$	$2.72 \cdot 10^{4}$
$8.00 \cdot 10^{0}$	$2.71 \cdot 10^{4}$
$9.00 \cdot 10^{0}$	$2.67 \cdot 10^{4}$
$1.00 \cdot 10^{1}$	$1.99 \cdot 10^{4}$
$2.00 \cdot 10^{1}$	$1.52 \cdot 10^{4}$
$3.00 \cdot 10^{1}$	$1.53 \cdot 10^{4}$
$4.00 \cdot 10^{1}$	$1.54 \cdot 10^{4}$
$5.00 \cdot 10^{1}$	$1.58 \cdot 10^{4}$
$6.00 \cdot 10^{1}$	$1.42 \cdot 10^{4}$
$7.00 \cdot 10^{1}$	$1.28 \cdot 10^{4}$
$8.00 \cdot 10^{1}$	$1.16 \cdot 10^{4}$
$9.00 \cdot 10^{1}$	$1.05 \cdot 10^{4}$
$1.00 \cdot 10^{2}$	$1.14 \cdot 10^{4}$
$2.00 \cdot 10^{2}$	$4.03 \cdot 10^{3}$
$3.00 \cdot 10^{2}$	$1.39 \cdot 10^{3}$
$4.00 \cdot 10^{2}$	$4.72 \cdot 10^{3}$
$5.00 \cdot 10^{2}$	$1.60 \cdot 10^{2}$
$6.00 \cdot 10^{2}$	$5.04 \cdot 10^{1}$
$7.00 \cdot 10^{2}$	$6.42 \cdot 10^{0}$
$8.00 \cdot 10^{2}$	$4.84 \cdot 10^{-3}$
$9.00 \cdot 10^{2}$	0.00
$1.00 \cdot 10^{3}$	0.00

intended to carry out the transport of high-energy nucleons and mesons and the nuclear reaction products produced by nucleons and pions. To obtain the results reported here, HETC has been modified so that only unattenuated primary protons are considered. The point of using HETC is that it will treat laminated shields, while TRAPP cannot without modification treat such shields. The stopping power data, and the quality factors used in HETC are the same as those used in TRAPP. Because HETC uses Monte Carlo methods the dose rates calculated with HETC have a slightly different meaning from those calculated with TRAPP. In TRAPP the dose rates are calculated at the geometric center of the tissue phantom while in HETC the dose rates are averaged over the central, 1 cm radius, region of the tissue phantom. Also, since HETC utilizes Monte Carlo methods, the calculated results are subject to some statistical uncertainty, but in the case considered here the incident proton were biased in the direction of the central, 1 cm radius, region of the tissue phantom[1] and the statistical uncertainty on the results presented in Fig. 2 are smaller than the size of the plotted points. The good agreement between the TRAPP and HETC dose rates in Fig. 2 indicates the slight difference in meaning between the TRAPP and HETC dose rates does not lead to significant numerical difference.

In the HETC calculations as in the TRAPP calculations, the incident protons were taken to be isotropically incident on the outer surface of the shield. In Fig. 2 the dose rates as functions of aluminum shield thickness calculated with HETC and TRAPP are compared. The results of the two calculations are in excellent agreement as they should be.

III. Results and Discussion

A. Homogeneous Shields

In Tables 4-14 the absorbed-dose rates and the dose equivalent rates as functions of shield thicknesses for homogeneous shields are given. The shield material considered is specified in each of the tables. Results for each of the materials specified in Table 2 are given in one of the tables between 4 and 14. Shield thicknesses of 2 to 20 g/cm^2 have been considered. In each of the figures the dose rates are given at the center of spherical tissue phantoms (see Fig. 1) with radii of 0.0, 1.0, and 15.0 g/cm^2. The results of Tables 4-14 are for the incident proton spectrum shown in Table 2 isotropically incident on the shield.

The ratio of the dose equivalent rate to the absorbed dose rate for a given shield material and thickness and a given tissue radius is not large but does depend on material and thicknesses. This ratio varies between approximately 1.1 and 1.3 for the results shown in Tables 4 to 14. This variation is due to the fact that the dose equivalent rate is calculated using a quality factor that is a function of linear energy transfer.[1]

In Tables 4 to 14 the dose rates vary appreciably with shield and tissue thickness but do not vary strongly with shield material. This is because shield thicknesses in the tables have been specified in g/cm^2 and the shielding effectiveness of materials against high-energy protons is much more comparable on a g/cm^2 basis than on a cm basis.

B. Laminated Shields

The geometry considered in this subsection is that shown in Fig. 1, but the shield is composed of layers of different materials. The shield configuration is specified in Table 15. The aluminum and void regions are kept constant and the thickness of the region containing the "filler" material is held constant, but various filler materials are considered. All of the results are for the differential proton flux in Table 3 isotropically incident on the shield.

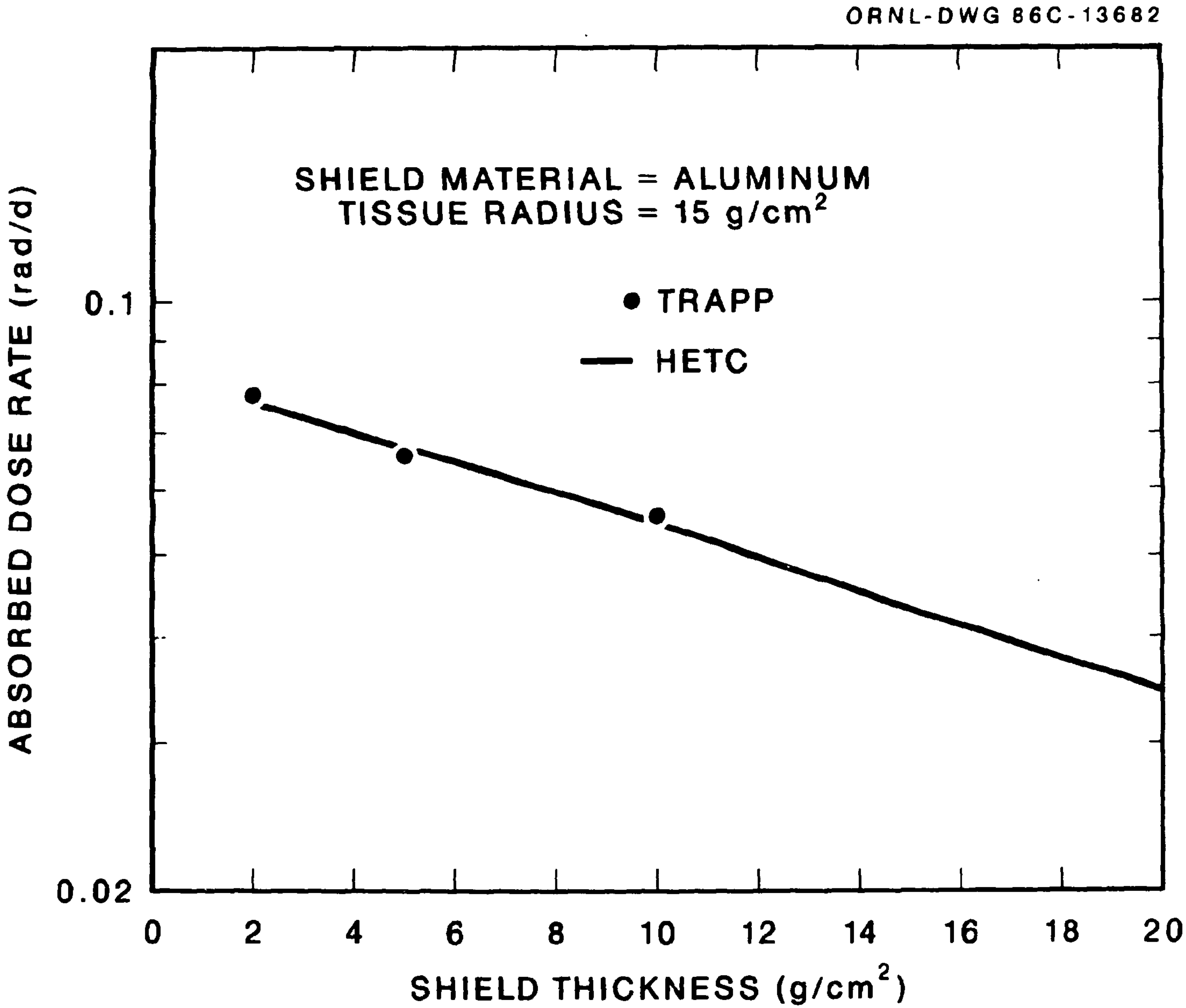

Fig. 2. Comparisons of absorbed dose rates obtained with TRAPP and HETC for aluminum shields.

TABLE 4

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as a Function of Shield Thickness

Shield Material = Carbon

Shield Thickness (g/cm²)	Tissue Radius (g/cm²) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.290	0.243	0.075	0.361	0.297	0.085
3.0		0.249	0.214	0.072	0.307	0.256	0.081
5.0		0.195	0.175	0.065	0.233	0.206	0.074
7.0		0.164	0.151	0.059	0.193	0.177	0.068
10.0		0.131	0.119	0.051	0.154	0.139	0.058
15.0		0.092	0.086	0.039	0.106	0.098	0.044
20.0		0.071	0.067	0.031	0.081	0.076	0.035

TABLE 5

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as a Function of Shield Thickness

Shield Material = Aluminum

Shield Thickness (g/cm²)	Tissue Radius (g/cm²) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.305	0.254	0.076	0.385	0.313	0.086
3.0		0.268	0.225	0.073	0.337	0.273	0.083
5.0		0.212	0.187	0.067	0.258	0.221	0.076
7.0		0.179	0.162	0.062	0.214	0.190	0.070
10.0		0.148	0.134	0.054	0.176	0.157	0.062
15.0		0.106	0.097	0.043	0.124	0.112	0.049
20.0		0.082	0.076	0.034	0.094	0.087	0.039

TABLE 6

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as a Function of Shield Thickness

Shield Material = Iron

Shield Thickness (g/cm²)	Tissue Radius (g/cm²) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.321	0.263	0.077	0.420	0.325	0.087
3.0		0.286	0.235	0.074	0.371	0.287	0.084
5.0		0.230	0.197	0.068	0.290	0.235	0.078
7.0		0.194	0.172	0.064	0.240	0.202	0.072
10.0		0.161	0.146	0.057	0.196	0.171	0.065
15.0		0.020	0.108	0.046	0.144	0.125	0.053
20.0		0.092	0.085	0.038	0.110	0.097	0.043

TABLE 7

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as a Function of Shield Thickness

Shield Material = Copper

Shield Thickness (g/cm²)	Tissue Radius (gm/cm²) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.325	0.265	0.077	0.428	0.328	0.087
3.0		0.290	0.238	0.074	0.379	0.290	0.084
5.0		0.234	0.200	0.069	0.298	0.238	0.078
7.0		0.198	0.174	0.064	0.246	0.205	0.073
10.0		0.164	0.148	0.058	0.200	0.174	0.066
15.0		0.123	0.110	0.047	0.150	0.128	0.054
20.0		0.095	0.087	0.038	0.114	0.100	0.044

TABLE 8

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as a Function of Shield Thickness

Shield Material = Polyethylene

Shield Thickness (g/cm²)	Tissue Radius (g/cm²) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.270	0.230	0.074	0.329	0.278	0.084
3.0		0.227	0.200	0.070	0.271	0.238	0.079
5.0		0.177	0.162	0.062	0.205	0.189	0.071
7.0		0.148	0.136	0.056	0.172	0.160	0.063
10.0		0.111	0.103	0.046	0.128	0.119	0.052
15.0		0.078	0.074	0.034	0.088	0.084	0.038
20.0		0.059	0.056	0.026	0.066	0.634	0.030

TABLE 9

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as a Function of Shield Thickness

Shield Material = Graphite/Epoxy

Shield Thickness (g/cm²)	Tissue Radius (g/cm²) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.287	0.242	0.075	0.356	0.295	0.085
3.0		0.246	0.212	0.072	0.301	0.254	0.081
5.0		0.193	0.174	0.065	0.229	0.204	0.074
7.0		0.162	0.150	0.059	0.190	0.176	0.067
10.0		0.129	0.117	0.050	0.151	0.136	0.057
15.0		0.090	0.085	0.038	0.104	0.096	0.043
20.0		0.069	0.066	0.030	0.079	0.075	0.034

TABLE 10

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as a Function of Shield Thickness

Shield Material = Kevlar 49

Shield Thickness	Tissue Radius	Absorbed Dose Rate (rad/d)			Dose Equivalent Rate (rem/d)		
(g/cm²)	(g/cm²) =	0.0	1.0	15.0	0.0	1.0	15.0
2.0		0.284	0.240	0.075	0.350	0.292	0.085
3.0		0.242	0.210	0.071	0.295	0.252	0.081
5.0		0.190	0.172	0.065	0.224	0.202	0.073
7.0		0.160	0.148	0.058	0.186	0.174	0.066
10.0		0.126	0.115	0.050	0.146	0.133	0.057
15.0		0.088	0.082	0.038	0.100	0.941	0.042
20.0		0.067	0.064	0.030	0.076	0.727	0.033

TABLE 11

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as a Function of Shield Thickness

Shield Material = Kevlar 49/Epoxy

Shield Thickness	Tissue Radius	Absorbed Dose Rate (rad/d)			Dose Equivalent Rate (rem/d)		
(g/cm²)	(g/cm²) =	0.0	1.0	15.0	0.0	1.0	15.0
2.0		0.284	0.239	0.075	0.349	0.292	0.085
3.0		0.242	0.210	0.071	0.294	0.251	0.081
5.0		0.189	0.171	0.064	0.223	0.201	0.073
7.0		0.160	0.148	0.058	0.186	0.173	0.066
10.0		0.125	0.114	0.049	0.146	0.133	0.056
15.0		0.088	0.082	0.037	0.100	0.094	0.042
20.0		0.067	0.064	0.030	0.076	0.072	0.033

TABLE 12

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as a Function of Shield Thickness

Shield Material = Glass/Epoxy

Shield Thickness (g/cm²)	Tissue Radius (g/cm²) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.292	0.246	0.075	0.363	0.300	0.086
3.0		0.252	0.216	0.072	0.310	0.259	0.081
5.0		0.198	0.177	0.066	0.236	0.208	0.074
7.0		0.166	0.153	0.060	0.195	0.179	0.068
10.0		0.134	0.122	0.052	0.157	0.142	0.058
15.0		0.094	0.088	0.039	0.108	0.100	0.045
20.0		0.072	0.068	0.031	0.082	0.078	0.035

TABLE 13

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as a Function of Shield Thickness

Shield Material = Spectra 900

Shield Thickness (g/cm²)	Tissue Radius (g/cm²) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.269	0.230	0.074	0.328	0.278	0.084
3.0		0.226	0.200	0.070	0.270	0.238	0.079
5.0		0.176	0.162	0.062	0.205	0.189	0.071
7.0		0.148	0.136	0.055	0.172	0.159	0.063
10.0		0.111	0.103	0.046	0.127	0.119	0.052
15.0		0.077	0.074	0.034	0.087	0.834	0.038
20.0		0.058	0.055	0.026	0.066	0.063	0.030

TABLE 14

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm^2 as a Function of Shield Thickness

Shield Material = Spectra 900/Epoxy

Shield Thickness (g/cm^2)	Tissue Radius (g/cm^2) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.275	0.233	0.074	0.336	0.283	0.084
3.0		0.232	0.204	0.070	0.279	0.243	0.080
5.0		0.181	0.165	0.063	0.212	0.193	0.072
7.0		0.153	0.140	0.057	0.177	0.165	0.064
10.0		0.116	0.107	0.047	0.134	0.124	0.054
15.0		0.081	0.077	0.035	0.092	0.087	0.040
20.0		0.062	0.059	0.028	0.070	0.067	0.031

TABLE 15

Laminated Shield Configuration

(The filler material in the table may be any of the materials in Table 2)

Region Outer Radius (cm)	Region Thickness (cm)	Material
150.3[a]	0.3	Aluminum
152.5	2.2	Void
158.9	6.4	Filler
161.2	2.3	Void
161.4	0.2	Aluminum

[a]The inner radius of this region is 150.0 cm.

In Table 16 the absorbed dose rates and the dose equivalent rates for tissue spheres of radii 1.0 and 15.0 g/cm^2 and for the various filler materials are given. The calculated results given in Table 16 were obtained using Monte Carlo methods and the dose rates are average dose rates over a tissue sphere of radius 1.0 g/cm^2 at the center of the configuration. This is in contrast to the dose rates given in Tables 4-14 where the calculated values are the dose rates at the geometric center of the tissue sphere (see discussion concerning Fig. 2). Since the results in Table 16 were obtained using Monte Carlo methods they are subject to statistical uncertainty. The statistical uncertainty, i.e., ± one standard deviation, expressed in percent is given in Table 16 for the absorbed dose rates. Similar errors are not shown for the dose equivalent rates, but they are of the same order of magnitude as those for the absorbed dose rates.

The ratio of the dose equivalent rate to the absorbed dose rate for a given shield and tissue configuration in Table 16 is of the order of 1.1 to 1.2 as in Tables 4-14, but there is more uncertainty in these ratios in Table 16 because of the statistical uncertainty in the dose rates.

C. Effect of Interchanging the Order of Materials in a Laminated Shield

In principle, even with thicknesses unchanged, the order in which the material occurs between the radiation source and the dose point will have an effect on the dose rates. That is, a shield of x cm of copper followed by y cm of aluminum does not give the same dose rate as a shield of y cm of aluminum followed by x cm of copper. To indicate the magnitude of this effect, calculated results for a specific example are given and discussed in this subsection.

TABLE 16

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms[a] of Radii 1.0 and 15.0 g/cm^2 for Laminated Shield Configurations[b]

Filler Material	Filler Material Thickness (g/cm^2)	Tissue Radius (g/cm^2) =	Absorbed Dose Rate (rad/d) 1.0	Absorbed Dose Rate (rad/d) 15.0	Dose Equivalent Rate (rem/d) 1.0	Dose Equivalent Rate (rem/d) 15.0
Graphite Epoxy	10.2		0.108±3.5%[c]	0.042±7.4%	0.120	0.046
Kevlar 49 Fiber	9.3		0.136±2.8%	0.052±5.9%	0.155	0.059
Kevlar 49 Epoxy	8.7		0.133±0.3%	0.052±1.7%	0.147	0.059
Glass Epoxy	12.2		0.102±7.8%	0.042±3.2%	0.118	0.046
Spectra 900	6.2		0.142±0.3%	0.055±9.5%	0.161	0.063
Spectra 900 Epoxy	7.0		0.130±0.6%	0.059±0.9%	0.147	0.066

[a]The dose rates in the table have been averaged over the central region central region (radius = 1 g/cm^2) of the tissue phantoms.
[b]See Table 15 for details of shield configuration.
[c]The percentages shown are the statistical uncertainty, ± one standard deviation, expressed in %.

The geometry is again that shown in Fig. 1 and the shield configurations are given at the bottom of Table 17. As indicated in the table, the configurations A and B have the same dimensions but the ordering of the materials is different. Calculations have been carried out for the differential proton flux given in Table 2 isotropically incident on both configurations and for a tissue sphere with radius of 15 g/cm^2. The absorbed dose rates and the dose equivalent rates are given at the top of Table 17. The dose rates for the two shield configurations are very similar and thus the interchange of the ordering of the materials has only a small effect. The results in Table 17 are for a specific but typical case, so in general, the ordering of materials in a shield can be expected to have only a negligible effect on the calculated dose rates.

IV. .. .alent Thickness Approximation

It is often convenient to obtain an estimate of the shielding thickness required for a laminated shield of various materials without performing detailed calculations. In Ref. 1 an approximate procedure, called the equivalent thickness approximation, for obtaining such estimates was presented and the validity of th procedure was tested by comparing the approximate dose rate results with detailed dose rate results obtained with TRAPP. In this section the approximate procedure is described and demonstrated.

Basically, the equivalent thickness approximation is a method for converting any material to an equivalent thickness of a comparison material so that dose rates for any laminated shield may be obtained from dose rate results for a shield of the comparison material. The geometry that will be considered is that used throughout this report a. d shown in Fig. 1.

The basic equations of the approximation are

$$r_c = \sum_{j=1}^{N} K_{cj}\, r_j \tag{1}$$

where

$$K_{cj} = \frac{S_j(E)}{S_c(E)}\bigg|_{E=E_c} \tag{2}$$

and

r_c = the equivalent thickness in g/cm^2 of the comparison material,

N = the number of materials that an incident proton passes through in going from the outside of the shield to the dose point,

r_j = the thickness of material j in g/cm^2,

$S_j(E)$ = the stopping power in $MeV/g/cm^2$ at energy E of a proton in material j,

$S_c(E)$ = the stopping power in $MeV/g/cm^2$ at energy E of a proton in the comparison material,

E_c = a fixed energy that must be chosen before the approximation can be used (see below).

TABLE 17

Absorbed Dose Rate and Dose Equivalent Rate at the Center of a Tissue Phantom of Radius 15.0 g/cm^2 for Two Laminated Shield Configurations

	Absorbed Dose Rate (rad/d)	Dose Equivalent Rate (rem/d)
Configuration A	0.045 ± 0.6%[a]	0.051
Configuration B	0.044 ± 0.6%	0.048

Region Outer Radius (cm)	Region Thickness (cm)	Material: Configuration A	Material: Configuration B
150.3	0.3	Aluminum	Polyethylene
150.6	0.3	Polyethylene	Aluminum
152.5	1.9	Void	Void
155.7	3.2	Graphite/Epoxy	Kevlar 49/Epoxy
158.9	3.2	Kevlar 49/Epoxy	Graphite/Epoxy
161.0	2.1	Void	Void
161.2	0.2	Polyethylene	Aluminum
161.4	0.2	Aluminum	Polyethylene

[a]The percentages shown are the statistical uncertainty, ± one standard deviation, expressed in %.

TABLE 18

Values of the K_{cj}'s defined in Eq. (2) for all of the materials considered in this report when the comparison material is chosen to be aluminum

Shield Material	K_{cj} When Comparison Material = Al E_c = 50 MeV
Carbon	1.16
Aluminum	1.00
Iron	.88
Copper	.76
Polyethylene	1.28
Graphite/Epoxy	1.18
Kevlar 49 Fiber	1.22
Kevlar 49/Epoxy	1.23
Glass/Epoxy	1.13
Spectra 900	1.40
Spectra 900/Epoxy	1.33
Tissue	1.29

There are several features of Eqs. (1) and (2) that should be noted. After the comparison material and the energy E_c are chosen, the quantities K_{cj} for each j is constant and for any sequence and thickness of materials r_c has a definite value. The statement is then that for any incident proton spectrum the dose rates at the center of a spherical shell shield of the comparison material of thickness r_c is the same as the dose rates at the center of laminated spherical shell shield specified by the r_j's. In calculating r_c for a set of r_j's, the sequence in which the r_j's occur does not enter so in this approximation interchanging materials in a laminated shield does not change the dose rates.

In principle, there is a wide range of choices for the comparison material and the energy E_c, but not all choices will lead to equally good approximations. In Ref. 1 it was found that using aluminum as the comparison material and an E_c of 50 MeV lead to good results for the type of proton spectra of interest in space shielding; these are the values used here. In Table 18 the values of K_{cj}'s for the material, including tissue, used in this report are given, and in Table 19 the absorbed dose and dose equivalent rates for an aluminum shield and no tissue are given. The values in Table 19 were obtained with TRAPP and correspond to the incident proton spectrum described previously.

As the first application of the approximation the dose rates for a shield of a specific material and a 15 g/cm^2 tissue sphere will be considered. Each of the materials in Table 18 will be considered to be the shield material. The results are shown in Table 20. The TRAPP results are those given previously and the equivalent thickness approximation results were obtained by linear interpolation in Table 19 using the r_c values obtained from Eqs. (1) and (2) and with the K_{cj} values of Table 18. The r_c values are also given in Table 20.

The results in Table 20 indicate the range of validity of the approximation for the materials considered in this report. In general, the approximation is valid to within a few percent, but errors of the order of 10% (note the comparisons in the case of copper) can occur. In general, the approximation becomes less valid as the shield thickness increases and is more valid for the absorbed dose rate than for the dose equivalent rate.

As a further application of this approximation the laminated shields considered in Sections 3.B and 3.C will be considered. In Table 21 the results given in Tables 16 and 17 are repeated along with the comparable results given by the approximation. The equivalent thickness r_c obtained by using the results in Table 18 is also given for each case in Table 21. The errors due to the approximation are, in general, larger in Table 21 than in Table 20, but they are for many practical purposes acceptable. It should also be remembered that there are statistical uncertainties associated with the HETC results and thus some of the errors shown in Table 21 may be due to these uncertainties and not to the use of the equivalent thickness approximation.

TABLE 19

Absorbed dose rate and dose equivalent rate from the Van Allen Proton spectrum incident on a spherical shell shield of aluminum (No tissue at the center of the shield is assumed.)

Shield Thickness g/cm^2	Absorbed Dose Rate rad/d	Dose Equivalent Rate rem/d
2.0	$3.05 \cdot 10^{-1}$	$3.85 \cdot 10^{-1}$
3.0	$2.68 \cdot 10^{-1}$	$3.37 \cdot 10^{-1}$
5.0	$2.12 \cdot 10^{-1}$	$2.58 \cdot 10^{-1}$
7.0	$1.79 \cdot 10^{-1}$	$2.14 \cdot 10^{-1}$
10.0	$1.48 \cdot 10^{-1}$	$1.75 \cdot 10^{-1}$
15.0	$1.06 \cdot 10^{-1}$	$1.24 \cdot 10^{-1}$
20.0	$8.16 \cdot 10^{-2}$	$9.42 \cdot 10^{-2}$
25.0	$6.61 \cdot 10^{-2}$	$7.60 \cdot 10^{-2}$
30.0	$5.34 \cdot 10^{-2}$	$6.18 \cdot 10^{-2}$
35.0	$4.22 \cdot 10^{-2}$	$4.85 \cdot 10^{-2}$
40.0	$3.40 \cdot 10^{-2}$	$3.88 \cdot 10^{-2}$
45.0	$2.82 \cdot 10^{-2}$	$3.21 \cdot 10^{-2}$
50.0	$2.36 \cdot 10^{-2}$	$2.68 \cdot 10^{-2}$
60.0	$1.68 \cdot 10^{-2}$	$1.89 \cdot 10^{-2}$
70.0	$1.22 \cdot 10^{-2}$	$1.37 \cdot 10^{-2}$
80.0	$8.92 \cdot 10^{-3}$	$1.00 \cdot 10^{-2}$
90.0	$6.63 \cdot 10^{-3}$	$7.44 \cdot 10^{-3}$
100	$4.99 \cdot 10^{-3}$	$5.57 \cdot 10^{-3}$

TABLE 20

Comparison of dose rates obtained with TRAPP with those given by the equivalent thickness approximation (The geometry is that shown in Fig. 1 with a tissue sphere of thickness of 15 g/cm².)

		Obtained with TRAPP			Obtained with Equivalent Thickness Approx.	
Shield Material	Shield Thickness	Absorbed Dose Rate	Dose Equivalent Rate	Equivalent Thickness of Al (r_e)	Absorbed Dose Rate	Dose Equivalent Rate
	g/cm²	rad/d	rem/d	g/cm²	rad/d	rem/d
Carbon	5.0	$6.53 \cdot 10^{-2}$	$7.41 \cdot 10^{-2}$	25.2	$6.56 \cdot 10^{-2}$ (0.4%)*	$7.54 \cdot 10^{-2}$ (1.8%)
Aluminum	10.0	$5.46 \cdot 10^{-2}$	$6.22 \cdot 10^{-2}$	29.4	$5.50 \cdot 10^{-2}$ (0.7%)	$6.35 \cdot 10^{-2}$ (2.1%)
Iron	5.0	$6.86 \cdot 10^{-2}$	$7.78 \cdot 10^{-2}$	23.8	$6.98 \cdot 10^{-2}$ (1.7%)	$8.03 \cdot 10^{-2}$ (3.2%)
Copper	10.0	$5.76 \cdot 10^{-2}$	$6.55 \cdot 10^{-2}$	27.0	$6.10 \cdot 10^{-2}$ (5.9%)	$7.03 \cdot 10^{-2}$ 11.4%)
Polyethylene	5.0	$6.25 \cdot 10^{-2}$	$7.10 \cdot 10^{-2}$	25.8	$6.41 \cdot 10^{-2}$ (2.6%)	$7.37 \cdot ^{-2}$ (3.8%)
Graphite/Epoxy	10.0	$5.04 \cdot 10^{-2}$	$5.75 \cdot 10^{-2}$	31.2	$5.07 \cdot 10^{-2}$ (0.6%)	$5.86 \cdot 10^{-2}$ (1.9%)
Kevlar 49 Fiber	5.0	$6.46 \cdot 10^{-2}$	$7.33 \cdot 10^{-2}$	25.4	$6.50 \cdot 10^{-2}$ (0.6%)	$7.48 \cdot 10^{-2}$ (2.0%)
Kevlar 49/Epoxy	10.0	$4.95 \cdot 10^{-2}$	$5.64 \cdot 10^{-2}$	31.6	$4.98 \cdot 10^{-2}$ (0.6%)	$5.75 \cdot 10^{-2}$ (2.0%)
Glass/Epoxy	5.0	$6.56 \cdot 10^{-2}$	$7.44 \cdot 10^{-2}$	25.0	$6.61 \cdot 10^{-2}$ (0.7%)	$7.60 \cdot 10^{-2}$ (2.0%)
Spectra 900	10.0	$4.57 \cdot 10^{-2}$	$5.21 \cdot 10^{-2}$	33.4	$4.58 \cdot 10^{-2}$ (0.2%)	$5.27 \cdot 10^{-2}$ (1.1%)
Spectra 900/Epoxy	5.0	$6.31 \cdot 10^{-2}$	$7.17 \cdot 10^{-2}$	26.0	$6.35 \cdot 10^{-2}$ (0.6%)	$7.32 \cdot 10^{-2}$ (2.0%)

*The values in parentheses under each approximate dose rate are the percentage difference between the approximate value and the TRAPP value.

TABLE 21

Comparison of dose rates obtained with HETC with those given by the equivalent thickness approximation (The geometry is that shown in Fig. 1 with tissue spheres of thickness 1 and 15 g/cm^2.)

	Obtained with HETC				Obtained with Equivalent Thickness Approx.	
Filler[a] Material	Tissue Thickness	Absorbed Dose Rate	Dose Equivalent Rate	Equivalent Thickness of Al (r_c)	Absorbed Dose Rate	Dose Equivalent Rate
	g/cm^2	rad/d	rem/d	g/cm^2	rad/d	rem/d
Graphite/Epoxy	1.0	0.108	0.120	14.7	0.108 (0.0%)	0.127 (5.8%)
Graphite/Epoxy	15.0	0.042	0.046	33.8	0.045 (7.1%)	0.52 (13.0%)
Kevlar 49 Fiber	1.0	0.136	0.155	14.0	0.114 (15.6%)	0.134 (13.5%)
Kevlar 49 Fiber	15.0	0.052	0.059	32.0	0.049 (5.8%)	0.56 (5.3%)
Kevlar 49/Epoxy	1.0	0.133	0.147	13.3	0.120 (9.1%)	0.141 (5.0%)
Kevlar 49/Epoxy	15.0	0.052	0.059	31.4	0.050 (3.8%)	0.58 (1.7%)
Glass/Epoxy	1.0	0.102	0.118	16.4	0.099 (2.9%)	0.115 (2.5%)
Glass/Epoxy	15.0	0.042	0.046	34.5	0.043 (2.3%)	0.050 8.7%)
Spectra 900	1.0	0.142	0.161	11.3	0.137 (2.8%)	1.61 (0.0%)
Spectra 900	15.0	0.055	0.063	29.4	0.055 (0.0%)	0.064 (1.6%)
Spectra 900/Epoxy	1.0	0.130	0.147	11.9	0.132 (2.9%)	1.55 (5.0%)
Spectra 900/Epoxy	15.0	0.059	0.066	30.0	0.053 (10.1%)	0.062 (6.1%)
Configuration A[b]	15.0	0.045	0.051	38.0	0.037 (17.8%)	0.043 (15.7%)
Configuration B[b]	15.0	0.044	0.048	38.0	0.037 (15.9%)	0.043 (10.4%)

[a]The laminated shield configuration is that shown in Table 15.
[b]See Table 17 for a description of the shielding configurations.

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APPENDIX A

In the body of the report a variety of results were presented for the incident Van Allen proton belt differential flux specified in Table 3. Before this spectrum became available, similar results had been obtained for the spectrum shown in Table A.1 and these results are presented in this Appendix. This spectrum was supplied by Martin Marietta Aerospace.[3] The spectrum shown in Table A.2 is higher, by approximately a factor of 2, than that used in the body of this report, and is generally believed[4,5] to be an overestimate of the one day differential proton flux spectrum for an orbit of 250 nautical miles at an inclination to the equatorial plane of 28.5°.

In Tables A.2 through A.12 the absorbed dose rates and dose equivalent rates for homogeneous shields of each of the materials specified in Table 2 are given. In Table A.13 the absorbed dose rates for the laminated shields considered in Section III.B are given. For these laminated shields, dose equivalent rates were not obtained and only results for a 1 cm radius tissue sphere were obtained.

TABLE A.1

Van Allen Belt Differential Proton Flux
Used to Obtain the Results Given in This Appendix

Proton Energy (MeV)	Differential Proton Flux ($protons/cm^2/d/MeV$)
$1.00 \cdot 10^0$	$6.21 \cdot 10^5$
$2.00 \cdot 10^0$	$3.34 \cdot 10^5$
$3.00 \cdot 10^0$	$3.33 \cdot 10^5$
$4.00 \cdot 10^0$	$3.30 \cdot 10^5$
$5.00 \cdot 10^0$	$3.28 \cdot 10^5$
$6.00 \cdot 10^0$	$2.64 \cdot 10^5$
$7.00 \cdot 10^0$	$2.63 \cdot 10^5$
$8.00 \cdot 10^0$	$2.62 \cdot 10^5$
$9.00 \cdot 10^0$	$2.61 \cdot 10^5$
$1.00 \cdot 10^1$	$8.76 \cdot 10^4$
$2.00 \cdot 10^1$	$7.33 \cdot 10^4$
$3.00 \cdot 10^1$	$7.23 \cdot 10^4$
$4.00 \cdot 10^1$	$7.13 \cdot 10^4$
$5.00 \cdot 10^1$	$7.04 \cdot 10^4$
$6.00 \cdot 10^1$	$7.81 \cdot 10^4$
$7.00 \cdot 10^1$	$7.69 \cdot 10^4$
$8.00 \cdot 10^1$	$7.57 \cdot 10^4$
$9.00 \cdot 10^1$	$7.46 \cdot 10^4$
$1.00 \cdot 10^2$	$5.85 \cdot 10^4$
$2.00 \cdot 10^2$	$4.12 \cdot 10^4$
$3.00 \cdot 10^2$	$3.90 \cdot 10^4$
$4.00 \cdot 10^2$	$3.54 \cdot 10^4$
$5.00 \cdot 10^2$	$3.81 \cdot 10^4$
$6.00 \cdot 10^2$	$3.43 \cdot 10^4$
$7.00 \cdot 10^2$	$3.09 \cdot 10^4$
$8.00 \cdot 10^2$	$2.79 \cdot 10^4$
$9.00 \cdot 10^2$	$2.52 \cdot 10^4$
$1.00 \cdot 10^3$	$2.58 \cdot 10^4$
$2.00 \cdot 10^3$	$8.91 \cdot 10^3$
$3.00 \cdot 10^3$	$3.17 \cdot 10^3$
$4.00 \cdot 10^3$	$1.15 \cdot 10^3$
$5.00 \cdot 10^3$	$4.24 \cdot 10^2$
$6.00 \cdot 10^3$	$1.56 \cdot 10^2$
$7.00 \cdot 10^3$	$5.22 \cdot 10^1$
$8.00 \cdot 10^3$	$6.73 \cdot 10^0$
$9.00 \cdot 10^3$	$1.06 \cdot 10^0$
$1.00 \cdot 10^4$	0.0

TABLE A.2

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as Functions of Shield Thicknesses

Shield Material = Carbon

Shield Thickness (g/cm²)	Tissue Radius (g/cm²) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.681	0.573	0.171	0.846	0.703	0.194
3.0		0.587	0.501	0.163	0.727	0.604	0.186
5.0		0.456	0.406	0.148	0.547	0.480	0.169
7.0		0.378	0.345	0.134	0.446	0.405	0.153
10.0		0.297	0.270	0.114	0.349	0.314	0.129
15.0		0.209	0.195	0.088	0.240	0.223	0.099
20.0		0.162	0.153	0.071	0.185	0.174	0.080

TABLE A.3

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm² as Functions of Shield Thicknesses

Shield Material = Aluminum

Shield Thickness (g/cm²)	Tissue Radius (g/cm²) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.714	0.600	0.174	0.899	0.742	0.197
3.0		0.633	0.529	0.166	0.799	0.643	0.189
5.0		0.497	0.435	0.153	0.608	0.518	0.174
7.0		0.414	0.372	0.140	0.498	0.438	0.160
10.0		0.335	0.302	0.122	0.400	0.355	0.139
15.0		0.239	0.220	0.096	0.279	0.253	0.109
20.0		0.185	0.174	0.079	0.214	0.198	0.088

TABLE A.4

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm^2 as Functions of Shield Thicknesses

Shield Material = Iron

Shield Thickness (g/cm^2)	Tissue Radius (g/cm^2) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.754	0.621	0.175	0.988	0.772	0.199
3.0		0.675	0.554	0.169	0.875	0.678	0.192
5.0		0.540	0.461	0.157	0.685	0.553	0.178
7.0		0.453	0.397	0.145	0.563	0.470	0.166
10.0		0.370	0.331	0.128	0.452	0.390	0.147
15.0		0.271	0.244	0.104	0.327	0.283	0.118
20.0		0.210	0.193	0.085	0.249	0.221	0.096

TABLE A.5

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm^2 as Functions of Shield Thicknesses

Shield Material = Copper

Shield Thickness (g/cm^2)	Tissue Radius (g/cm^2) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.762	0.626	0.175	1.009	0.778	0.199
3.0		0.684	0.559	0.169	0.891	0.686	0.192
5.0		0.550	0.466	0.157	0.704	0.560	0.179
7.0		0.462	0.402	0.146	0.578	0.477	0.166
10.0		0.377	0.336	0.130	0.463	0.397	0.148
15.0		0.278	0.249	0.105	0.338	0.289	0.119
20.0		0.215	0.198	0.087	0.257	0.226	0.098

TABLE A.6

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm^2 as Functions of Shield Thicknesses

Shield Material = Polyethylene

Shield Thickness	Tissue Radius	Absorbed Dose Rate (rad/d)			Dose Equivalent Rate (rem/d)		
(g/cm^2)	(g/cm^2) =	0.0	1.0	15.0	0.0	1.0	15.0
2.0		0.637	0.540	0.168	0.778	0.657	0.191
3.0		0.532	0.467	0.159	0.639	0.559	0.181
5.0		0.409	0.372	0.142	0.478	0.437	0.162
7.0		0.337	0.308	0.124	0.392	0.361	0.142
10.0		0.252	0.234	0.102	0.288	0.269	0.116
15.0		0.177	0.168	0.077	0.200	0.191	0.087
20.0		0.132	0.124	0.061	0.150	0.142	0.068

TABLE A.7

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm^2 as Functions of Shield Thicknesses

Shield Material = Graphite/Epoxy

Shield Thickness	Tissue Radius	Absorbed Dose Rate (rad/d)			Dose Equivalent Rate (rem/d)		
(g/cm^2)	(g/cm^2) =	0.0	1.0	15.0	0.0	1.0	15.0
2.0		0.675	0.569	0.171	0.835	0.698	0.194
3.0		0.580	0.497	0.163	0.713	0.599	0.185
5.0		0.450	0.402	0.148	0.537	0.474	0.168
7.0		0.373	0.341	0.133	0.438	0.401	0.152
10.0		0.291	0.265	0.112	0.340	0.308	0.128
15.0		0.205	0.192	0.086	0.234	0.219	0.097
20.0		0.158	0.150	0.070	0.180	0.170	0.078

TABLE A.8

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm^2 as Functions of Shield Thicknesses

Shield Material = Kevlar 49

Shield Thickness (g/cm^2)	Tissue Radius (g/cm^2) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.668	0.564	0.171	0.823	0.691	0.194
3.0		0.571	0.492	0.163	0.698	0.592	0.185
5.0		0.442	0.396	0.147	0.525	0.468	0.167
7.0		0.366	0.336	0.132	0.429	0.394	0.150
10.0		0.283	0.259	0.110	0.330	0.301	0.126
15.0		0.200	0.188	0.085	0.227	0.214	0.095
20.0		0.154	0.146	0.068	0.175	0.166	0.073

TABLE A.9

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm^2 as Functions of Shield Thicknesses

Shield Material = Kevlar 49/Epoxy

Shield Thickness (g/cm^2)	Tissue Radius (g/cm^2) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.667	0.563	0.171	0.821	0.690	0.194
3.0		0.569	0.491	0.162	0.695	0.591	0.185
5.0		0.441	0.396	0.147	0.523	0.466	0.167
7.0		0.365	0.334	0.131	0.427	0.393	0.150
10.0		0.282	0.258	0.110	0.328	0.299	0.125
15.0		0.199	0.187	0.084	0.226	0.213	0.095
20.0		0.153	0.145	0.068	0.174	0.165	0.076

TABLE A.10

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm^2 as Functions of Shield Thicknesses

Shield Material = Glass/Epoxy

Shield Thickness (g/cm^2)	Tissue Radius (g/cm^2) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.686	0.577	0.172	0.850	0.710	0.195
3.0		0.594	0.506	0.164	0.735	0.611	0.186
5.0		0.462	0.410	0.149	0.554	0.486	0.170
7.0		0.383	0.350	0.135	0.452	0.411	0.154
10.0		0.303	0.274	0.114	0.356	0.320	0.130
15.0		0.213	0.199	0.089	0.244	0.227	0.100
20.0		0.165	0.156	0.072	0.188	0.177	0.081

TABLE A.11

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm^2 as Functions of Shield Thicknesses

Shield Material = Spectra 900

Shield Thickness (g/cm^2)	Tissue Radius (g/cm^2) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.636	0.539	0.168	0.776	0.656	0.191
3.0		0.531	0.466	0.159	0.637	0.558	0.181
5.0		0.407	0.372	0.141	0.476	0.436	0.161
7.0		0.336	0.306	0.124	0.390	0.360	0.142
10.0		0.251	0.233	0.102	0.287	0.268	0.115
15.0		0.177	0.168	0.077	0.199	0.190	0.086
20.0		0.131	0.124	0.061	0.148	0.141	0.068

TABLE A.12

Absorbed Dose Rates and Dose Equivalent Rates at the Center of Tissue Phantoms of Radii 0.0, 1.0, and 15.0 g/cm^2 as Functions of Shield Thicknesses

Shield Material = Spectra 900/Epoxy

Shield Thickness (g/cm^2)	Tissue Radius (g/cm^2) =	Absorbed Dose Rate (rad/d) 0.0	1.0	15.0	Dose Equivalent Rate (rem/d) 0.0	1.0	15.0
2.0		0.648	0.548	0.169	0.794	0.669	0.192
3.0		0.545	0.476	0.160	0.658	0.570	0.182
5.0		0.420	0.381	0.144	0.494	0.447	0.164
7.0		0.347	0.318	0.127	0.404	0.374	0.145
10.0		0.262	0.242	0.105	0.302	0.280	0.119
15.0		0.185	0.175	0.080	0.209	0.199	0.090
20.0		0.140	0.132	0.063	0.159	0.151	0.071

TABLE A.13

Absorbed Dose Rates at the Center of a 1 cm Radius Tissue Sphere for Laminated Shield Configurations*

Filler** Material	Filler Material Thickness (g/cm^2)	Absorbed Dose Rate (rad/d)
Graphite/Epoxy	10.2	0.241
Kevlar 49/Fiber	9.3	0.303
Kevlar 49/Epoxy	8.7	0.298
Glass Epoxy	12.2	0.229
Spectra 900	6.2	0.319
Spectra 900/Epoxy	7.0	0.291

*The dose rates in this table have been averaged over the 1 cm radius tissue phantom.
**See Table 15 for the details of the shield configuration.

APPENDIX B

Output Data From SPAR

In this appendix an example of the data obtained from SPAR is presented. The particular material considered is graphite/epoxy (see Table 2). SPAR output is shown in Table B.1.

TABLE B.1

Output of SPAR for Protons in Graphite/Epoxy

INPUT FOR SUBROUTINE PREP

MXMAT = 1

THIS IS MEDIUM 1

NEL = 4 DENH = .1830000E-01 AVDEN = .1600000E+01

Z = 6.0	A = 12.0	DEN =	.7270000E-01
Z = 8.0	A = 16.0	DEN =	.2500000E-02
Z = 7.0	A = 14.0	DEN =	.1600000E-02
Z = 16.0	A = 32.0	DEN =	.3000000E-03

MEDIUM 1

PARTICLE TYPE = PROTONS

ENERGY (MEV/AMU)	ENERGY (MEV)	DEDX (MEV/CM)	DEDX/Z**2 (MEV*CM**2/MG)	RANGE (CM)	RANGE (MG/CM**2)
.11000000E+01	.11000000E+01	.35416960E+03	.22135600E+00	.24547890E-02	.39276620E+01
.11783590E+01	.11783590E+01	.33671310E+03	.21044570E+00	.26828410E-02	.42925460E+01
.12623000E+01	.12623000E+01	.31995210E+03	.19997010E+00	.29364620E-02	.46983400E+01
.13522200E+01	.13522200E+01	.30388110E+03	.18992570E+00	.32273140E-02	.51637030E+01
.14485460E+01	.14485460E+01	.28849000E+03	.18030620E+00	.35520810E-02	.56833300E+01
.15517340E+01	.15517340E+01	.27377130E+03	.17110700E+00	.39192940E-02	.62708700E+01
.16622730E+01	.16622730E+01	.25970950E+03	.16231850E+00	.43351600E-02	.69362570E+01
.17806850E+01	.17806850E+01	.24628970E+03	.15393110E+00	.48007040E-02	.76811270E+01
.19075330E+01	.19075330E+01	.23349490E+03	.14593430E+00	.53329210E-02	.85326730E+01
.20434170E+01	.20434170E+01	.22130700E+03	.13831690E+00	.59299450E-02	.94879110E+01
.21889810E+01	.21889810E+01	.20970700E+03	.13106690E+00	.66059980E-02	.10569600E+02
.23449140E+01	.23449140E+01	.19873360E+03	.12420850E+00	.73713370E-02	.11794140E+02
.25119550E+01	.25119550E+01	.18823140E+03	.11764460E+00	.82319670E-02	.13171150E+02
.26908950E+01	.26908950E+01	.17826150E+03	.11141340E+00	.92129490E-02	.14740720E+02
.28825820E+01	.28825820E+01	.16880160E+03	.10550100E+00	.10317120E-01	.16507400E+02

TABLE B.1 (Cont'd)

MEDIUM 1
PARTICLE TYPE = PROTONS

ENERGY (MEV/AMU)	ENERGY (MEV)	DEDX (MEV/CM)	DEDX/Z**2 (MEV*CM**2/MG)	RANGE (CM)	RANGE (MG/CM**2)
.30879240E+01	.30879240E+01	.15983010E+03	.99893800E-01	.11568120E-01	.18508980E+02
.33078930E+01	.33078930E+01	.15132550E+03	.94578440E-01	.12984250E-01	.20774800E+02
.35435330E+01	.35435330E+01	.14326690E+03	.89541810E-01	.14581720E-01	.23330760E+02
.37959570E+01	.37959570E+01	.13563390E+03	.84771190E-01	.16397130E-01	.26235400E+02
.40663640E+01	.40663640E+01	.12840660E+03	.80254090E-01	.18445340E-01	.29512550E+02
.43560330E+01	.43560330E+01	.12156550E+03	.75978420E-01	.20765380E-01	.33224610E+02
.46663370E+01	.46663370E+01	.11509190E+03	.71932410E-01	.23390790E-01	.37425270E+02
.49987450E+01	.49987450E+01	.10896750E+03	.68104690E-01	.26356920E-01	.42171070E+02
.53548330E+01	.53548330E+01	.10317480E+03	.64484230E-01	.29720360E-01	.47552580E+02
.57362870E+01	.57362870E+01	.97696710E+02	.61060440E-01	.33519640E-01	.53631420E+02
.61449140E+01	.61449140E+01	.92516910E+02	.57823070E-01	.37820370E-01	.60512580E+02
.65826500E+01	.65826500E+01	.87619640E+02	.54762270E-01	.42684850E-01	.68295770E+02
.70515670E+01	.70515670E+01	.82989760E+02	.51868600E-01	.48183460E-01	.77093540E+02
.75538880E+01	.75538880E+01	.78612820E+02	.49133010E-01	.54407970E-01	.87052750E+02
.80919930E+01	.80919930E+01	.79029010E+02	.49393130E-01	.61347190E-01	.98155500E+02
.86684280E+01	.86684280E+01	.74788090E+02	.46742560E-01	.68895270E-01	.11023240E+03
.92859280E+01	.92859280E+01	.70775640E+02	.44234780E-01	.77409710E-01	.12385550E+03
.99474140E+01	.99474140E+01	.66977020E+02	.41860640E-01	.87005050E-01	.13920810E+03
.10656020E+02	.10656020E+02	.63379420E+02	.39612140E-01	.97904960E-01	.15664790E+03
.11415110E+02	.11415110E+02	.59971470E+02	.37482170E-01	.11021090E+00	.17633740E+03
.12228270E+02	.12228270E+02	.56742930E+02	.35464330E-01	.12416370E+00	.19866200E+03
.13099360E+02	.13099360E+02	.53684370E+02	.33552730E-01	.13995650E+00	.22393050E+03
.14032490E+02	.14032490E+02	.50787120E+02	.31741950E-01	.15781870E+00	.25250990E+03
.15032100E+02	.15032100E+02	.48043050E+02	.30026900E-01	.17808450E+00	.28493520E+03
.16102920E+02	.16102920E+02	.45444520E+02	.28402820E-01	.20099790E+00	.32159660E+03
.17250020E+02	.17250020E+02	.42984330E+02	.26865200E-01	.22697340E+00	.36315740E+03
.18478830E+02	.18478830E+02	.40655620E+02	.25409760E-01	.25638380E+00	.41021410E+03
.19795180E+02	.19795180E+02	.38451890E+02	.24032430E-01	.28967500E+00	.46348000E+03
.21205300E+02	.21205300E+02	.36366910E+02	.22729320E-01	.32742150E+00	.52387450E+03

TABLE B.1 (Cont'd)

MEDIUM 1
PARTICLE TYPE = PROTONS

ENERGY (MEV/AMU)	ENERGY (MEV)	DEDX (MEV/CM)	DEDX/Z**2 (MEV*CM**2/MG)	RANGE (CM)	RANGE (MG/CM**2)
.22715860E+02	.22715860E+02	.34394790E+02	.21496750E-01	.37013530E+00	.59221650E+03
.24334040E+02	.24334040E+02	.32529860E+02	.20331160E-01	.41854520E+00	.66967240E+03
.26067490E+02	.26067490E+02	.30766700E+02	.19229190E-01	.47336360E+00	.75738180E+03
.27924420E+02	.27924420E+02	.29100170E+02	.18187600E-01	.53543620E+00	.85669790E+03
.29913620E+02	.29913620E+02	.27525340E+02	.17203330E-01	.60576930E+00	.96923080E+03
.32044530E+02	.32044530E+02	.26037500E+02	.16273440E-01	.68538470E+00	.10966150E+04
.34327240E+02	.34327240E+02	.24632170E+02	.15395110E-01	.77557060E+00	.12409130E+04
.36772560E+02	.36772560E+02	.23305080E+02	.14565670E-01	.87767240E+00	.14042760E+04
.39392060E+02	.39392060E+02	.22052130E+02	.13782580E-01	.99326650E+00	.15892260E+04
.42198170E+02	.42198170E+02	.20869460E+02	.13043410E-01	.11241290E+01	.17986070E+04
.45204170E+02	.45204170E+02	.19753340E+02	.12345840E-01	.12722410E+01	.20355860E+04
.48424310E+02	.48424310E+02	.18700270E+02	.11687670E-01	.14398570E+01	.23037710E+04
.51873840E+02	.51873840E+02	.17706900E+02	.11066810E-01	.16294960E+01	.26071940E+04
.55569100E+02	.55569100E+02	.16770040E+02	.10481270E-01	.18440460E+01	.29504730E+04
.59527580E+02	.59527580E+02	.15886660E+02	.99291640E-02	.20866210E+01	.33385930E+04
.63768060E+02	.63768060E+02	.15053900E+02	.94086860E-02	.23609840E+01	.37775740E+04
.68310590E+02	.68310590E+02	.14269020E+02	.89181370E-02	.26709910E+01	.42735850E+04
.73176750E+02	.73176750E+02	.13529430E+02	.84558940E-02	.30213380E+01	.48341410E+04
.78389500E+02	.78389500E+02	.12832680E+02	.80204280E-02	.34171870E+01	.54674990E+04
.83973640E+02	.83973640E+02	.12176440E+02	.76102750E-02	.38639050E+01	.61822490E+04
.89955510E+02	.89955510E+02	.11558500E+02	.72240650E-02	.43685210E+01	.69896330E+04
.96363510E+02	.96363510E+02	.10976780E+02	.68604850E-02	.49373980E+01	.78998370E+04
.10322800E+03	.10322800E+03	.10429270E+02	.65182960E-02	.55791810E+01	.89266890E+04
.11058150E+03	.11058150E+03	.99141240E+01	.61963280E-02	.63028270E+01	.10084520E+05
.11845890E+03	.11845890E+03	.94295490E+01	.58934680E-02	.71173460E+01	.11387750E+05
.12689730E+03	.12689730E+03	.89738720E+01	.56086700E-02	.80356450E+01	.12857030E+05
.13593690E+03	.13593690E+03	.85454990E+01	.53409370E-02	.90675440E+01	.14508070E+05
.14562040E+03	.14562040E+03	.81429320E+01	.50893320E-02	.10228790E+02	.16366060E+05
.15599380E+03	.15599380E+03	.77647450E+01	.48529650E-02	.11534270E+02	.18454830E+05
.16710600E+03	.16710600E+03	.74095980E+01	.46309990E-02	.12998530E+02	.20797650E+05

TABLE B.1 (Cont'd)

MEDIUM 1

PARTICLE TYPE = PROTONS

ENERGY (MEV/AMU)	ENERGY (MEV)	DEDX (MEV/CM)	DEDX/Z**2 (MEV*CM**2/MG)	RANGE (CM)	RANGE (MG/CM**2)
.17900980E+03	.17900980E+03	.70762220E+01	.44226390E-02	.14644790E+02	.23431670E+05
.19176170E+03	.19176170E+03	.67634150E+01	.42271340E-02	.16486560E+02	.26378500E+05
.20542190E+03	.20542190E+03	.64700490E+01	.40437810E-02	.18552330E+02	.29683730E+05
.22005530E+03	.22005530E+03	.61950520E+01	.38719070E-02	.20865310E+02	.33384490E+05
.23573100E+03	.23573100E+03	.59374190E+01	.37108870E-02	.23447860E+02	.37516570E+05
.25252350E+03	.25252350E+03	.56961940E+01	.35601210E-02	.26340690E+02	.42145110E+05
.27051200E+03	.27051200E+03	.54704830E+01	.34190520E-02	.29558670E+02	.47293870E+05
.28978200E+03	.28978200E+03	.52594370E+01	.32871480E-02	.33152830E+02	.53044530E+05
.31042480E+03	.31042480E+03	.50622540E+01	.31639090E-02	.37156020E+02	.59449640E+05
.33253800E+03	.33253800E+03	.48781860E+01	.30488660E-02	.41601020E+02	.66561630E+05
.35622660E+03	.35622660E+03	.47065190E+01	.29415740E-02	.46556740E+02	.74490780E+05
.38160240E+03	.38160240E+03	.45465850E+01	.28416150E-02	.52031000E+02	.83249600E+05
.40878620E+03	.40878620E+03	.43977490E+01	.27485930E-02	.58114030E+02	.92982450E+05
.43790610E+03	.43790610E+03	.42594200E+01	.26621380E-02	.64845750E+02	.10375320E+06
.46910040E+03	.46910040E+03	.41310340E+01	.25818960E-02	.72272220E+02	.11563560E+06
.50251720E+03	.50251720E+03	.40120610E+01	.25075380E-02	.90505480E+02	.12880880E+06
.53831400E+03	.53831400E+03	.39020020E+01	.24387510E-02	.89526820E+02	.14324290E+06
.57666130E+03	.57666130E+03	.38003840E+01	.23752400E-02	.99493080E+02	.15918890E+06
.61773980E+03	.61773980E+03	.37067630E+01	.23167270E-02	.11044140E+03	.17670620E+06
.66174490E+03	.66174490E+03	.36207160E+01	.22629480E-02	.12243480E+03	.19589570E+06
.70888450E+03	.70888450E+03	.35418480E+01	.22136550E-02	.13564660E+03	.21703450E+06
.75938240E+03	.75938240E+03	.34697810E+01	.21686130E-02	.14999880E+03	.23999810E+06
.81347710E+03	.81347710E+03	.34041600E+01	.21276000E-02	.16575580E+03	.26520930E+06
.87142530E+03	.87142530E+03	.33446450E+01	.20904030E-02	.18293060E+03	.29268900E+06
.93350190E+03	.93350190E+03	.32909170E+01	.20568230E-02	.20161170E+03	.32257870E+06
.10000000E+04	.10000000E+04	.32426730E+01	.20266710E-02	.22205440E+03	.35528700E+06

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