325

APR 7 1964

MASTER

ORNL-3583
UC-34 - Physics
TID-4500 (27th ed.)

A NOTE ON IMPORTANCE FUNCTIONS FOR THE
SHIELDING OF MANNED SPACE VEHICLES

R. G. Alsmiller, Jr.

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in USA. Price: \$0.75 Available from the
Office of Technical Services
U. S. Department of Commerce
Washington 25, D.C.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Contract No. W-7405-eng-26

Neutron Physics Division

A NOTE ON IMPORTANCE FUNCTIONS FOR THE SHIELDING
OF MANNED SPACE VEHICLES*

R. G. Alsmiller, Jr.

MARCH 1964

*Work performed under NASA Order Nos. T-7632 and R-104.

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE NUCLEAR COMPANY
for the
U.S. ATOMIC ENERGY COMMISSION

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

Abstract

The tissue dose calculations of Kinney and Zerby have been used to calculate several importance functions which are of interest in the shielding of manned space vehicles. The functions considered are concerned with the dose from primary and secondary particles in the tissue which arise from a solar-flare proton spectrum that has penetrated an aluminum shield. The secondary particles which are produced in the aluminum are not considered.

Table of Contents

	<u>Page No.</u>
Abstract -----	iii
I. Introduction -----	1
II. Definition of Importance Functions -----	1
III. Results and Discussion -----	7
Appendix -----	21
Acknowledgment -----	22

I. Introduction

In a previous report¹ (hereinafter referred to as 1) results were given for two "importance functions" which are of interest in the shielding of manned-space vehicles. An importance function as that term was used in 1, measures the importance of each energy region in a given proton flare spectrum in producing some definite physical effect. Thus, a large variety of importance functions may be defined.

In this note results are given for several more importance functions. While the functions discussed in 1 were concerned with the surface dose from primary and secondary particles which emerge from an aluminum shield, the functions discussed here are concerned with the dose from primary and secondary particles in tissue which arise from a primary proton beam that has penetrated an aluminum shield.

The calculations presented in this note are based on the tissue dose calculations of W. E. Kinney et al.² The results refer specifically to primary proton beams which are normally incident on slab shields and yield little if any information about the more general case of isotropic incidence.

In Section II the various importance functions are defined and their meanings discussed. In Section III calculated values of the importance functions are given and conclusions drawn. In the appendix the relation between the importance functions given in 1 and the more general functions discussed in this note is considered.

II. Definition of Importance Functions

To understand the significance of the term importance function and the various functions which may be defined consider Fig. 1.

-
1. R. G. Alsmiller, Jr. and J. E. Murphy, Space Vehicle Shielding Studies: Calculations of the Attenuation of a Model Solar Flare and Monoenergetic Proton Beams by Aluminum Shields, ORNL-3317 (1963).
 2. W. E. Kinney and C. D. Zerby, private communication. (A brief description of this work may be found in ORNL-3499, Vol. II, p 56.) I would like to thank Mr. Kinney and Dr. Zerby for allowing me to use their results prior to their publication.

UNCLASSIFIED
ORNL-DWG 64 745

Fig. 1.

Let $P(E_0, \omega_0)$ be an infinite monoenergetic, monodirectional proton flux of energy E_0 and direction ω_0 and let this flux be incident normally on an infinite slab of aluminum of thickness r . That is, we consider an incident proton flux of the form

$$P(E_0, \omega_0) = P_0 \delta(E - E_0) \frac{\delta(\omega - \omega_0)}{2\pi},$$

where

P_0 = normalizing constant,

$\omega = \cos\theta$,

$\omega_0 = \cos\theta_0$,

(all angles are measured with respect to a z axis which is normal to the slab), and we take the very special case

$$\omega_0 = 1.$$

We may distinguish two fluxes leaving the aluminum slab:

$P_{iA}(E_0, \omega_0=1, E, r, \vec{\Omega})$ = angular flux of primary protons per unit energy range, i.e., those protons which did not undergo nuclear reaction in the aluminum;

$O_{sA}(E_0, \omega_0=1, E, r, \vec{\Omega})$ = angular flux of all secondary particles per unit energy range, including protons, neutrons, heavy nuclei, etc.

In these functions the notation $\omega_0 = 1$ has been used to emphasize that only normal incidence is considered. Of course, the same definitions could be used with an arbitrary ω_0 .

Consider next the geometry shown in Fig. 2. The situation is the same as in Fig. 1 except that an infinite slab of tissue, of thickness 30 cm, now follows the aluminum. At any depth x in the tissue four fluxes may be distinguished:

Fig. 2.

$P_{iAiT}(E_0, \omega_0=1, E, r, x, \vec{\Omega})$ = angular flux per unit energy range of primary protons in the tissue which arise from the flux P_{iA} ,

$P_{iAsT}(E_0, \omega_0=1, E, r, x, \vec{\Omega})$ = angular flux per unit energy range of secondary particles in the tissue which arise from the flux P_{iA} ,

$O_{sAiT}(E_0, \omega_0=1, E, r, x, \vec{\Omega})$ = angular flux per unit energy range of "primary" particles in the tissue which arise from the flux O_{sA} ,

$O_{sAsT}(E_0, \omega_0=1, E, r, x, \vec{\Omega})$ = angular flux per unit energy range of secondary particles in the tissue which arise from the flux O_{sA} .

It is important to note that in the above definitions P_{iA} and O_{sA} are the fluxes which are calculated in the absence of the tissue. To emphasize this, we note that between the fluxes of Fig. 1 and Fig. 2 the following relations exist:

$$P_{iA}(E_0, \omega_0=1, E, r, \vec{\Omega}) = P_{iAiT}(E_0, \omega_0=1, E, r, x, \vec{\Omega}) \Big|_{x=0},$$

$$O_{sA}(E_0, \omega_0=1, E, r, \vec{\Omega}) = O_{sAiT}(E_0, \omega_0=1, E, r, x, \vec{\Omega}) \Big|_{x=0},$$

and

$$P_{iAsT}(E_0, \omega_0=1, E, r, x, \vec{\Omega}) \Big|_{x=0} \neq 0,$$

$$O_{sAsT}(E_0, \omega_0=1, E, r, x, \vec{\Omega}) \Big|_{x=0} \neq 0.$$

At the depth x in the tissue each of these fluxes will be depositing energy, and thus a dose may be associated with each of them. We shall use the notation

$D_{PiAiT}(E_o, \omega_o=1, r, x)$ = dose rate per unit incident flux from the flux P_{iAiT} ,

$D_{PiAiT+PiAsT}(E_o, \omega_o=1, r, x)$ = dose rate per unit incident flux from the fluxes P_{iAiT} and P_{iAsT} , etc.

Let $F(E_o)$ be a time-integrated isotropic proton flare spectrum (protons/MeV cm² ster.). A generic importance function, I , is defined by the equation

$$I_P(E_o, \omega_o=1, r, x) = F(E_o) D_P(E_o, \omega_o=1, r, x) ,$$

where P may be any flux one wishes to consider. From the definition of D_P it follows that the integral of I over E_o gives the dose at x due to the flux P when the flare spectrum is incident normally on the aluminum.*

The largest contribution to the integral will, of course, come from those values of E_o for which I is largest. Thus the magnitude of I is a measure of the importance per MeV of a particular energy region in the incident spectrum in producing the specific dose under consideration.

In addition to the value of the functions at a specific x we shall in some cases be interested in the functions averaged over all x . For future reference we define $\bar{I}_P$ by

$$\bar{I}_P(E_o, \omega_o=1, r) = F(E_o) \frac{1}{30} \int_0^{30} D_P(E_o, \omega_o=1, r, x) dx .$$

*Importance functions as they are defined here will have units of rem/MeV steradians. When something other than normal incidence is to be considered one would consider I to be a function of ω_o and define an energy importance function, I' , as

$$I'_P(E_o, r, x) = 2\pi \int_{-1}^1 I_P(E_o, \omega_o, r, x) d\omega_o .$$

In addition to the importance functions defined above there is another closely related class of functions which are of interest. A primary proton of energy E_0 will lose energy on traversing the aluminum and will arrive at the aluminum-tissue interface with an energy E_{OT} . These energies are related through the equation

$$\int_{E_{OT}}^{E_0} \frac{dE}{S(E')} = r ;$$

i.e.,

$$E_0 = E_0(E_{OT}, r) ,$$

where $S(E')$ = stopping power of aluminum. Using this relation, the importance functions can be considered to be a function of E_{OT} . To retain the integral property of the functions, it is appropriate to introduce a Jacobian and define the new class of functions, J_P , through the equation

$$J_P(E_{OT}, \omega_0=1, r, x) = I_P \left[E_0(E_{OT}, r), \omega_0=1, r, x \right] \frac{S(E_0)}{S(E_{OT})} .$$

The integral of J_P over E_{OT} now has the same value and meaning as the integral of I_P over E_0 ; however, J_P may now be considered to measure the importance of a given energy region at the aluminum-tissue interface while I_P measures the importance of a given energy region in the incident spectrum. One also has, of course

$$\bar{J}_P(E_{OT}, \omega_0=1, r, x) = \bar{I}_P \left[E_0(E_{OT}, r), \omega_0=1, r, x \right] \frac{S(E_0)}{S(E_{OT})} .$$

III. Results and Discussion

In this section numerical results for the functions I_{PiAiT} , I_{PiAsT} , J_{PiAiT} , and J_{PiAsT} will be given. Throughout this section the function I_{PiAsT} will be broken into two parts: a contribution from secondary protons and a contribution from heavy nuclei. The function itself is,

of course, to be obtained by adding the two contributions. It is important to note that all results are given in rems; i.e., an RBE has been included.²

For purposes of comparison three quite different flare spectra have been considered. The time-integrated differential energy spectra used are shown in Fig. 3.³ Also a spectrum representative of the protons in the Van Allen belt has been considered.⁴ This spectrum is shown in Fig. 4.*

In Fig. 5 the importance functions I_{PiAiT} and I_{PiAsT} are plotted against E_0 for the case of the Bailey model flare incident with

$$r = 9.38 \text{ g/cm}^2$$

and

$$x = 5 \text{ cm.}$$

The lowest energy for which the curves are given correspond to a proton of energy 100 MeV incident on the tissue. This is the lowest energy for which the calculations of Kinney are available. It should be noted that at an energy such that a primary proton cannot penetrate 9.38 g/cm² of aluminum (~ 97 MeV) all of the functions necessarily go to zero.

All of the curves fall off very rapidly with increasing energy so most of the area under the curves comes at the lowest energies. In general the figure indicates that the most important energy in the incident spectrum for producing a dose from primary protons and from secondary particles in the tissue is an energy just slightly larger than the energy which a primary proton must have to get through the aluminum shield. The secondary particles will contribute approximately 20% of the total dose. The contribution to the secondary dose from the heavy nuclei is roughly comparable to the contribution from the secondary protons.**

3. The time-integrated integral energy spectra from which these differential spectra were obtained were supplied by W. L. Gill, private communication.

4. S. C. Freden and R. S. White, "Particle Fluxes in the Inner Radiation Belt," J. Geophys. Res. 65, 1377-1383 (1960).

*Since the Freden-White spectrum is not integrated over time, the importance functions from this spectrum will have units of rem/MeV.ster.sec.

**In considering this last statement it must be remembered that the comparison is being made in rems and a large RBE (20) has been used for the heavy nuclei.²

UNCLASSIFIED
ORNL-DWG 63-4091

Fig. 3. Time-Integrated Differential Energy Spectra.

UNCLASSIFIED
ORNL-DWG 64-747

Fig. 4. Freden White Spectrum of Protons in Lower Radiation Belt.

UNCLASSIFIED
ORNL-DWG 64-748

Fig. 5. Bailey's Model Flare.

In Fig. 6 the functions J_{PiAiT} and J_{PiAsT} are plotted against E_{OT} for the case of the Bailey flare incident with

$$r = 9.38 \text{ g/cm}^2$$

and

$$x = 5 \text{ cm.}$$

These curves are similar to the curves of Fig. 5 but contain slightly different information. If experimental measurements are to be made using monoenergetic proton beams in tissue, it is the curves of Fig. 6 which indicate the most appropriate energy for these beams since E_{OT} is the energy of protons incident on the tissue.

Since we have no information about the shape of the curves for energies of less than 100 MeV, it is not possible to decide exactly what energy would be best for experimental measurement; however, it is clear that proton energies of the order of 100 MeV or less are of the most interest.

Numerical values of these importance functions are given for a variety of cases in Tables 1 through 6. In all cases considered with $x = 5 \text{ cm}$ the curves have the same general shape as those in Figs. 5 and 6 and lead to conclusions similar to those stated above.

When one considers the average whole-body dose rather than the 5-cm dose the situation changes. For the Bailey flare at the larger r values (see Table 5) and for the Freden-White spectrum at all r values (see Table 6 and Fig. 7) the secondary curves (whose sum gives $\bar{I}_{PiAsT}$) do not continue to rise as the energy decreases but rather they exhibit a broad maximum in the vicinity of 200 MeV. The secondary contribution to the total dose is somewhat less in this case than in the previous cases. Insofar as the total dose is concerned, the low-energy region is still of most importance but if one is interested in the dose from secondaries only, the higher energy regions become important.*

*Since the dose from primary particles is readily calculable, experimental measurements are usually concerned with measuring secondary particles.

UNCLASSIFIED
ORNL-DWG 64-749

Fig. 6. Bailey's Model Flare.

Table 1. Bailey Flare, $\omega_0 = 1$, $x = 5$ cm

Importance Function (rem/MeV.ster)							
E_{oT} (MeV)	E_o (MeV)	I_{PiAiT}	I_{PiAsT}		J_{PiAiT}	J_{PiAsT}	
			Secondary Protons	Heavy Nuclei		Secondary Protons	Heavy Nuclei
r = 0							
					$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$
100					115	13.6	12.8
200					1.72	.415	.648
300					.160	.0507	.0866
400					.0306	.00105	.0194
r = 9.38 g/cm ²							
		$\times 10^{-4}$	$\times 10^{-4}$	$\times 10^{-4}$	$\times 10^{-4}$	$\times 10^{-4}$	$\times 10^{-4}$
100	146	172	20.3	19.2	131	15.6	14.7
200	231	7.27	1.75	2.73	6.66	1.60	2.50
300	325	.951	.302	.516	.911	.289	.494
400	422	.211	.0723	.133	.206	.0707	.130
r = 30.5 g/cm ²							
		$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$
100	224	153	18.1	17.1	88.7	10.5	9.92
200	294	17.1	4.12	6.44	13.6	3.28	5.13
300	379	3.53	1.12	1.91	3.13	.994	1.70
400	470	.993	.341	.627	.918	.315	5.80
r = 49.2 g/cm ²							
		$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
100	281	400	47.3	44.7	203	24.0	22.7
200	344	64.0	15.4	24.1	46.9	11.3	17.6
300	423	16.6	5.28	9.02	14.0	4.45	7.60
400	511	5.32	1.83	3.36	4.79	1.64	3.02

Table 2. Sept. 28, 1961 Flare, $\omega_0 = 1$, $x = 5$ cm

Importance Function (rem/MeV.ster)							
E_{OT} (MeV)	E_O (MeV)	I_{PiAiT}	I_{PiAsT}		J_{PiAiT}	J_{PiAsT}	
			Secondary Protons	Heavy Nuclei		Secondary Protons	Heavy Nuclei
r = 0							
					$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
100					436	51.6	48.8
200					54.8	13.2	20.6
300					20.6	6.55	11.2
400					10.2	3.50	6.44
r = 9.38 g/cm ²							
		$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
100	146	197	23.3	22.0	151	17.8	16.9
200	231	38.7	9.33	14.6	35.5	8.54	13.3
300	325	16.4	5.21	8.90	15.7	4.99	8.53
400	422	8.33	2.86	5.26	8.14	2.80	5.14
r = 30.5 g/cm ²							
		$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
100	224	74.4	8.82	8.36	43.1	5.10	4.82
200	294	21.4	5.16	8.06	17.1	4.11	6.42
300	379	11.0	3.22	5.50	8.99	2.86	4.88
400	470	5.46	1.88	3.45	5.05	1.73	3.19
r = 49.2 g/cm ²							
		$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
100	281	43.0	5.09	4.81	21.8	2.58	2.44
200	344	13.7	3.30	5.16	10.0	2.42	3.78
300	423	6.77	2.15	3.68	5.71	1.81	3.10
400	511	3.78	1.30	2.38	3.40	1.17	2.14

Table 3. Feb. 23, 1956 Flare,* $\omega_0 = 1$, $x = 5$ cm

Importance Function (rem/MeV.ster)							
E _{oT} (MeV)	E _o (MeV)	I _{PiAiT}	I _{PiAsT}		J _{PiAiT}	J _{PiAsT}	
			Secondary Protons	Heavy Nuclei		Secondary Protons	Heavy Nuclei
r = 0							
					x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴
100					431	51.1	48.3
200					103	24.8	38.7
291*					55.4	17.2	30.2
300					41.4	13.2	22.5
400					4.35	1.49	2.74
r = 9.38 g/cm ²							
		x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴
100	146	278	33.0	31.1	213	25.2	23.8
200	231	82.4	19.8	31.0	75.4	18.2	28.4
264*	291	57.0	18.9	26.8	54.0	17.9	25.4
300	325	22.6	7.20	12.3	21.7	6.90	11.8
400	422	2.59	.888	1.63	2.53	.868	1.60
r = 30.5 g/cm ²							
		x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴
100	224	155	18.3	17.3	89.5	10.6	10.0
185*	291	68.4	14.2	20.6	52.1	10.8	15.7
200	294	48.1	11.6	18.1	38.2	9.22	14.4
300	379	5.61	1.78	3.04	4.97	1.60	27.0
400	470	.916	.314	.578	8.46	.291	.535
r = 49.2 g/cm ²							
		x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴	x 10 ⁻⁴
100	281	106	12.6	11.9	53.8	6.37	6.02
118*	291	93.1	12.0	12.6	52.2	6.74	7.07
200	344	12.8	3.08	4.80	9.35	2.25	3.52
300	423	1.97	.626	1.07	1.66	.528	.902
400	511	.394	.135	.249	.355	.122	.224

*Since the flare spectrum in this case has a discontinuous derivative at E_o equal to 280 MeV, the importance functions will also have a discontinuous derivative. To aid in drawing the curves an estimate of the value of the functions at the point where the discontinuity occurs is given.

Table 4. Freden-White Spectrum, $\omega_0 = 1$, $x = 5$ cm

Importance Function (rem/MeV.ster)							
E _{OT} (MeV)	E _O (MeV)	I _{PiAiT}	I _{PiAsT}		J _{PiAiT}	J _{PiAsT}	
			Secondary Protons	Heavy Nuclei		Secondary Protons	Heavy Nuclei
r = 0							
					x 10 ⁻⁹	x 10 ⁻⁹	x 10 ⁻⁹
100					57.5	6.81	6.43
200					9.54	2.30	3.59
300					3.64	1.16	1.98
400					1.81	.623	1.15
r = 9.38 g/cm ²							
		x 10 ⁻⁹	x 10 ⁻⁹	x 10 ⁻⁹	x 10 ⁻⁹	x 10 ⁻⁹	x 10 ⁻⁹
100	146	30.3	3.59	3.39	23.2	2.75	2.60
200	231	6.65	1.60	2.50	6.09	1.47	2.29
300	325	2.89	.917	1.57	2.76	.878	1.50
400	422	1.51	.518	9.53	1.47	.506	.931
r = 28.1 g/cm ²							
		x 10 ⁻⁹	x 10 ⁻⁹	x 10 ⁻⁹	x 10 ⁻⁹	x 10 ⁻⁹	x 10 ⁻⁹
100	216	13.8	1.63	1.54	8.14	.965	.911
200	288	3.97	.955	1.49	3.20	.770	1.20
300	373	1.87	.595	1.02	1.67	.531	.908
400	465	1.03	.353	.650	.963	.331	.608
r = 46.9 g/cm ²							
		x 10 ⁻⁹		x 10 ⁻⁹	x 10 ⁻⁹	x 10 ⁻⁹	x 10 ⁻⁹
100	273	8.03	.953	.900	4.12	.488	.461
200	339	2.56	.616	.961	1.89	.454	.709
300	418	1.29	.411	.703	1.10	.348	.595
400	506	.724	.248	.457	.654	.224	.413

Table 5. Bailey Model, $\omega_0 = 1$

		Importance Function (rem/MeV.ster)					
E_{OT} (MeV)	E_0 (MeV)	$\bar{I}_{PiAsT}$			$\bar{J}_{PiAsT}$		
		$\bar{I}_{PiAiT}$	Secondary Protons	Heavy Nucleai	$\bar{J}_{PiAiT}$	Secondary Protons	Heavy Nuclei
$r = 0$							
					$\times 10^{-4}$	$\times 10^{-4}$	$\times 10^{-4}$
100					393	19.7	41.4
200					21.7	3.56	5.52
300					1.59	.638	.684
400					.285	.165	.152
$r = 9.38 \text{ g/cm}^2$							
		$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$
100	146	588	29.5	61.9	450	22.6	47.4
200	231	91.7	15.0	23.3	84.0	13.8	21.3
300	325	9.49	3.80	4.07	9.09	3.64	3.90
400	422	1.96	1.14	1.05	1.92	1.11	1.02
$r = 30.5 \text{ g/cm}^2$							
		$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
100	224	524	26.4	55.3	303	15.2	32.0
200	294	216	35.4	54.8	172	28.2	43.6
300	379	35.2	14.1	15.1	31.2	12.5	13.4
400	470	9.24	5.35	4.93	8.54	4.95	4.56
$r = 49.2 \text{ g/cm}^2$							
		$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
100	281	137	6.87	14.4	69.3	3.48	7.31
200	344	80.8	13.2	2.05	59.1	9.69	15.0
300	423	16.6	6.65	7.12	14.0	5.60	6.00
400	511	4.96	2.87	2.64	4.46	2.58	2.38

Table 6. Freden-White Spectrum, $\omega_0 = 1$

		Importance Function (rem/MeV.ster)					
E_{OT} (MeV)	E_O (MeV)	$\bar{I}_{PiAsT}$			$\bar{J}_{PiAsT}$		
		$\bar{I}_{PiAiT}$	Secondary Protons	Heavy Nuclei	$\bar{J}_{PiAiT}$	Secondary Protons	Heavy Nuclei
r = 0							
					$\times 10^{-9}$	$\times 10^{-9}$	$\times 10^{-9}$
100					19.7	.989	2.07
200					12.0	1.97	3.05
300					3.64	1.46	1.56
400					1.69	.979	.902
r = 9.38 g/cm ²							
		$\times 10^{-9}$	$\times 10^{-9}$	$\times 10^{-9}$	$\times 10^{-9}$	$\times 10^{-9}$	$\times 10^{-9}$
100	146	10.4	.522	1.09	7.94	.399	.837
200	231	8.39	1.38	2.13	7.68	1.26	1.95
300	325	2.88	1.15	1.24	2.76	1.10	1.18
400	422	1.40	.813	.749	1.37	.795	.733
r = 28.1 g/cm ²							
		$\times 10^{-9}$	$\times 10^{-9}$	$\times 10^{-9}$	$\times 10^{-9}$	$\times 10^{-9}$	$\times 10^{-9}$
100	216	4.71	.236	.496	2.79	.140	.294
200	288	5.00	.820	1.27	4.03	.660	1.02
300	373	1.87	.749	.802	1.67	.669	.716
400	465	.957	.550	.512	.896	.519	.479
r = 46.9 g/cm ²							
		$\times 10^{-10}$	$\times 10^{-10}$	$\times 10^{-10}$	$\times 10^{-10}$	$\times 10^{-10}$	$\times 10^{-10}$
100	275	27.5	1.38	2.90	14.1	.709	1.49
200	339	32.2	5.28	8.18	23.8	3.90	6.04
300	418	12.91	5.18	5.55	10.9	4.38	4.70
400	506	6.74	3.90	3.60	6.09	3.52	3.26

Fig. 7. Freden White Spectrum.

Appendix

The importance functions calculated in 1 constitute special cases of the more general functions discussed in Section II.

In the notation of Section II the functions I_1 and I_2 in 1 may be written

$$I_1 = I_{PiAiT+PiAsT+OiAiT+OiAsT}(E_o, \omega_o=1, r, x) \Big|_{\substack{\text{vicinity} \\ \text{of} \\ x=0}}, \quad (A1)$$

$$I_2 = I_{OiAiT+OiAsT}(E_o, \omega_o=1, r, x) \Big|_{\substack{\text{vicinity} \\ \text{of} \\ x=0}} \quad (A2)$$

It is indicated that the functions are to be evaluated in the vicinity of $x = 0$ rather than at $x = 0$ to emphasize that the crudeness of the method of calculation used in 1 does not allow an explicit determination on this point. It is probably best to think of the results for I_1 and I_2 in 1 as representing the functions of Eqs. A1 and A2 averaged over a small (not very well defined) region in the vicinity of $x = 0$.

It is very important in considering the results given in 1 to note that the primary dose is always defined by

$$\text{Primary Dose} = D_{PiAiT+PiAsT}(E_o, \omega_o=1, r, x) \Big|_{\substack{\text{vicinity} \\ \text{of} \\ x=0}} ;$$

i.e., when primary protons enter the tissue and produce secondaries which deposit energy, this energy deposition is included as part of the primary dose. Thus no information about the importance function I_{PiAsT} is given in 1.

It is to be noted that even if one neglects any difference between aluminum and tissue, so that the importance functions become functions of $r + x$, the function $I_{O_iA_iT+O_iAsT}$ evaluated at $r + x$ contains different information from the function I_{p_iAsT} evaluated at the same $r + x$.

Acknowledgment

I would like to thank W. E. Kinney for many helpful discussions concerning his dose calculations.

ORNL-3583
UC-34 - Physics
TID-4500 (27th ed.)

INTERNAL DISTRIBUTION

1. Biology Library	76. C. E. Larson
2-4. Central Research Library	77. F. C. Maienschein
5. Reactor Division Library	78. R. W. Peelle
6-7. ORNL - Y-12 Technical Library	79. J. J. Pinajian
Document Reference Section	80. R. T. Santoro
8-57. Laboratory Records Department	81. M. J. Skinner
58. Laboratory Records, ORNL R.C.	82. J. A. Swartout
59-68. R. G. Alsmiller	83. A. M. Weinberg
69. J. A. Auxier	84. H. A. Wright
70. R. D. Birkhoff	85. R. A. Charpie (consultant)
71. E. P. Blizard	86. P. F. Gast (consultant)
72. R. D. Bundy	87. M. L. Goldberger (consultant)
73. W. A. Gibson	88. R. F. Taschek (consultant)
74. W. H. Jordan	89. T. J. Thompson (consultant)
75. L. Jung	

EXTERNAL DISTRIBUTION

90. J. E. Duberg, NASA, Langley Field, Virginia
91. Trutz Foelsche, NASA, Langley Research Center, Hampton, Virginia
92. W. C. Hulten, NASA - IRD, Langley Research Center, Hampton, Virginia
93. L. F. Vosteen, NASA, Langley Research Center, Hampton, Virginia
94. W. L. Gill, NASA, Manned Spacecraft Center, Houston, Texas
95. R. H. Steele, NASA, Manned Spacecraft Center, Houston, Texas
96. Evalyn Repplinger, Crew Systems Division, Houston, Texas
97. W. N. Hess, NASA, Goddard Space Flight Center, Greenbelt, Maryland
98. H. E. Stern (M-RP-N), NASA, George C. Marshall Space Flight Center, Huntsville, Alabama
99. Frank Voorhis, USAF(MC), OART/RBH, NASA, Washington, D.C.
100. J. W. Keller, NASA Headquarters, Washington, D.C.
101. Jerry Modisette, Manned Spacecraft Center, Houston, Texas
102. Jim Johnson, LTV Research Center, Dallas, Texas
103. Lt. Duane Adams, Air Force Weapons Laboratory, WLRB-1, Kirtland Air Force Base, New Mexico
104. Lt. Col. Edward Harney, Air Force Space Systems Division, SSTA, Air Force Unit Post Office, Los Angeles, California
- 105-107. Aerospace Corporation, 2400 El Segundo Blvd., El Segundo, California (1 copy each to F. L. Keller, Stan Freden, and Robert Pruett)
108. George Joanou, General Atomic, San Diego, California
109. G. F. Pieper, NASA Headquarters, Washington, D.C.
110. Arthur Reetz, NASA Headquarters, Washington, D.C.
111. R. C. Good, Jr., General Electric Company, Philadelphia, Pennsylvania

- 112. R. T. Siegel, College of William and Mary, Williamsburg, Virginia
- 113. K. Ziock, University of Virginia, Charlottesville, Virginia
- 114. Jerry Speakman, 6570 AMRL (MRBBR), Wright-Patterson Air Force Base, Ohio
- 115. T. J. McGuire, ASD(ASRSSV-e), Shielding Research Reports, Wright-Patterson Air Force Base, Ohio
- 116. Loren Pittman, 6570 AMRL (MRBBR), Wright-Patterson Air Force Base, Ohio
- 117. Capt. R. F. Cooper, ASRPE-20, Wright-Patterson Air Force Base, Ohio
- 118. C. A. Dempsey, 6570 AMRL, Wright-Patterson Air Force Base, Ohio
- 119. R. E. Fortney, Northrop Space Laboratories, Hawthorne, California
- 120. M. C. Chapman, Northrop Space Laboratories, Hawthorne, California
- 121. S. H. Levine, Northrop Space Laboratories, Hawthorne, California
- 122. L. W. McCleary, North American Aviation, Inc., Downey, California
- 123. G. E. Laubaugh, North American Aviation, Inc., Downey, California
- 124. Frederick Raymes, North American Aviation, Inc., Downey, California
- 125. M. R. Kinsler, North American Aviation, Inc., Downey, California
- 126. E. R. Beever, North American Aviation, Inc., Downey, California
- 127. T. J. Rock, General Dynamics, Fort Worth, Texas
- 128. C. F. Johnson, General Dynamics, Fort Worth, Texas
- 129. T. R. Strayhorn, General Dynamics, Fort Worth, Texas
- 130. G. T. Western, General Dynamics, Fort Worth, Texas
- 131. R. A. Miller, General Dynamics, Fort Worth, Texas
- 132. T. W. De Vries, General Dynamics, Fort Worth, Texas
- 133. E. C. Kidd, General Dynamics, Fort Worth, Texas
- 134. D. H. Robey, General Dynamics/Astronautics, San Diego, California
- 135. Sidney Russak, The Martin Company, Baltimore, Maryland
- 136. Ed Divita, 1504 Doxbury Road, Towson, Maryland
- 137. I. M. Karp, Lewis Research Center, Cleveland, Ohio
- 138. R. V. Meghreblian, Jet Propulsion Laboratory, Pasadena, California
- 139. R. I. Hildebrand, Lewis Research Center, Cleveland, Ohio
- 140. R. J. Mackin, Jr., Jet Propulsion Laboratory, Pasadena, California
- 141. F. Felberg, Jet Propulsion Laboratory, Pasadena, California
- 142. D. F. Spencer, Jet Propulsion Laboratory, Pasadena, California
- 143. D. L. Dye, Boeing Aircraft Company, Seattle, Washington
- 144. Maurice Wilkinson, Boeing Aircraft Company, Seattle, Washington
- 145. J. C. Noyes, Boeing Scientific Research Laboratories, Seattle, Washington
- 146. J. F. Kenney, Boeing Scientific Research Laboratories, Seattle, Washington
- 147. Maynard Pearson, Boeing Aircraft Company, Seattle, Washington
- 148. Brian Mar, Boeing Aircraft Company, Seattle, Washington
- 149. Lt. Col. R. G. Allen, Jr., USAF Aerospace Medical Center, Brooks Air Force Base, Texas
- 150. Col. J. E. Pickering, USAF Aerospace Medical Center, Brooks Air Force Base, Texas
- 151. W. M. Schofield, Advanced Research Corporation, Atlanta, Georgia
- 152. E. C. Smith, Advanced Research Corporation, Atlanta, Georgia

153. Wade Patterson, University of California, Lawrence Radiation Laboratory, Berkeley, California
154. Cornelius Tobias, University of California, Lawrence Radiation Laboratory, Berkeley, California
155. M. J. Berger, National Bureau of Standards, Washington, D.C.
156. H. J. Schulte, Bellcomm, Inc., Washington, D.C.
157. Phil Mittleman, United Nuclear Corporation, White Plains, New York
158. Sol Krasner, Office of Naval Research, Washington, D.C.
159. W. H. Langham, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
160. M. A. Van Dilla, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
161. G. A. Whan, University of New Mexico, Albuquerque, New Mexico
162. D. W. Drawbaugh, Westinghouse Electric Company, Pittsburgh, Pennsylvania
163. E. M. Finkelman, Grumman Aircraft, Bethpage, New York
164. R. V. Glowzowski, McDonnell Aircraft, St. Louis, Missouri
165. R. A. Glass, Lockheed Missiles and Space Company, Palo Alto, California
166. S. P. Shen, New York University, New York, New York
167. J. P. Neissel, General Electric Company, Schenectady, New York
168. R. L. Harvey, General Electric Company, San Jose, California
169. David Langford, Pratt and Whitney Aircraft, East Hartford, Connecticut
170. C. W. Hill, Lockheed-Georgia Company, Marietta, Georgia
171. C. K. Bauer, Lockheed-Georgia Company, Marietta, Georgia
172. K. D. George, Picatinny Arsenal, Dover, New Jersey
173. R. B. Curtis, University of Indiana, Bloomington, Indiana
174. H. J. Schaefer, U.S. Naval School of Aviation Medicine, Pensacola, Florida
175. William Steigelmann, Kuljian Corporation, Philadelphia, Pennsylvania
176. G. P. Wachtell, Franklin Institute, Philadelphia, Pennsylvania
177. Keith Morc, Bendix Systems Division, Ann Arbor, Michigan
178. L. R. Lewis, Bendix Systems Division, Ann Arbor, Michigan
179. T. H. Colvin, Bendix Systems Division, Ann Arbor, Michigan
180. Borje Larsson, The Gustaf Werner Institute, University of Uppsala, Uppsala, Sweden
181. Martin Leimdorfer, Research Institute of National Defense, FOA4, Stockholm 80, Sweden
182. Richard Madey, Republic Aviation Corporation, Farmingdale, Long Island, New York
183. F. E. Schwamb, Applied Physics Research, Republic Aviation Corporation, Farmingdale, Long Island, New York
184. C. D. Zerby, Union Carbide Research Institute, Tarrytown, New York
185. Fred Casal, NASA Headquarters, Washington, D.C.
186. V. B. Bhanot, Physics Department, Panjab University, Chandigarh-3, India

- 187. Jacobo Rapaport, University of Chile, Box 2777, Institute of Science, Santiago, Chile
- 188. Research and Development Division, AEC, ORO
- 189-823. Given distribution as shown in TID-4500 (27th ed.) under Physics Category (75 copies - OTS)