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NUCLEON-MESON CASCADE CALCULATIONS:

SHIELDING AGAINST AN 800-Mev

PROTON BEAM

R. G. Alsmiller, Jr.
J. E. Murphy

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

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NEUTRON PHYSICS DIVISION

NUCLEON-MESON CASCADE CALCULATIONS: SHIELDING
AGAINST AN 800-Mev PROTON BEAM

R. G. Alsmiller, Jr.
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Date Issued
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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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Abstract

Nucleon-meson cascade calculations have been carried out and the dose as a function of depth has been obtained for an 800-Mev proton beam incident on a shield. The physical properties used for the shielding medium are only a rough approximation to the properties of any particular medium.

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I. Introduction

In a series of previous reports^{1,2,3} (hereinafter referred to as 1, 2, and 3, respectively) nucleon-meson cascade calculations have been presented. In this report similar calculations are presented for an 800-Mev proton beam incident on a shield.

The equations and method of calculation are the same as in 1. The physical data used to represent the shielding medium is the same as described in 1 and 2, except that the density has been changed to 2.3 g/cm². This density is a rough average of the density of the shielding materials usually used -- earth, heavy concrete, etc. Of course, the other physical properties of the medium are only a rough approximation to the properties of any particular medium.

The various particle fluxes are converted to dose by the method described in 1. In particular, an estimate of the dose from low-energy neutrons obtained from the measured cosmic-ray neutron spectrum is included. The results of the calculation are given in Section II. In Appendix I some numerical results associated with the dose calculation are given.

II. Results

The IBM code which was used to solve the cascade equations numerically is written in such a manner that only a source with a continuous energy distribution can be used. Therefore, the 800-Mev proton source was approximated by a suitable continuum for the purposes of computation.

1. R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy, Nucleon-Meson Cascade Calculations: Transverse Shielding for a 45-Gev Electron Accelerator (Part I), ORNL-3289 (1962).
2. R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy, Nucleon-Meson Cascade Calculations: Transverse Shielding for a 45-Gev Electron Accelerator (Part II), ORNL-3365 (1962).
3. R. G. Alsmiller, Jr. and J. E. Murphy, Space Vehicle Shielding Studies: Calculation of the Attenuation of a Model Solar Flare and Monoenergetic Proton Beams by Aluminum Slab Shields, ORNL-3317 (1962).

The method of approximation is described in detail in 3, and the actual energy distribution used for the source is shown in Fig. 1.*

The primary proton, secondary proton, neutron, pion, and muon fluxes are given as a function of energy and distance into the shield in Tables 1 through 9. For the first few collision lengths the primary proton beam is slowing down and the secondary particles are building up. After approximately four collision lengths the primary beam has been stopped and all secondary fluxes are decaying nearly exponentially with distance. For a given particle specie the decay length is energy dependent but the dependence is quite weak.

The neutron dose, d_N , proton dose, d_P , pion dose, d_π , muon dose, d_μ , and total dose, d , are shown in Fig. 2. The doses were obtained from the particle fluxes by the methods described in 1 and 3. In particular, the neutron dose contains an estimate of the dose from low-energy neutrons obtained from the measured cosmic-ray neutron spectrum as explained in 1, and the charged particle doses contain an estimate of the dose from low-energy charged particles obtained by the extrapolation procedure discussed in 3. Since the methods used to obtain the low-energy dose are not entirely satisfactory, the results with and without the estimated contribution are given in Appendix 1 for purposes of comparison.

As may be seen from Fig. 2, all of the doses decrease very nearly exponentially, and the total dose is due almost entirely to neutrons. It is to be noted that the decay length is slightly different for the different particle species.

*This source strength and the results from it are, strictly speaking, for the case of an infinitely broad beam incident normally on a slab shield. The results, however, apply equally well to the case of a narrow beam if it is understood that an integration over a plane transverse to the beam axis has been performed. That is, if the source strength of Fig. 1 is taken to be the number of protons per second striking the shield, the fluxes which are calculated may be interpreted as the total number of particles per second leaving the shield per unit energy at a distance z from the slab face.

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Fig. 1. Incident Proton Flux vs Energy.

Table 1. Primary Proton Flux
 x in collision lengths (1 collision length = 1.34 ft)

E (Mev)	Primary Proton Flux, $P_i(E,x)$ [(protons/Mev.cm ² .sec)/(proton/cm ² .sec)]			
	$x = 0$	$x = 0.992$	$x = 2.08$	$x = 3.02$
834	0			
800	2.981×10^{-2}			
767	0			
676		0		
649		2.999×10^{-3}		
622		1.126×10^{-2}		
596		3.307×10^{-3}		
572		0		
445			0	
426			1.469×10^{-3}	
409			2.910×10^{-3}	
392			2.846×10^{-3}	
376			1.526×10^{-3}	
361			2.503×10^{-4}	
346			0	
218				0
209				1.084×10^{-5}
201				1.453×10^{-4}
192				2.667×10^{-4}
184				3.757×10^{-4}
177				4.731×10^{-4}
170				5.595×10^{-4}
163				6.355×10^{-4}
156				7.019×10^{-4}
150				7.593×10^{-4}
143				8.085×10^{-4}
137				8.500×10^{-4}
131				7.721×10^{-4}
126				7.007×10^{-4}

Table 1. (cont.)

E (Mev)	Primary Proton Flux, $P_1(E,x)$ [(protons/Mev.cm ² .sec)/(proton/cm ² .sec)]			
	x = 0	x = 0.992	x = 2.08	x = 3.02
121				6.356×10^{-4}
116				5.761×10^{-4}
112				5.219×10^{-4}
107				4.726×10^{-4}
102				4.276×10^{-4}
98.3				3.868×10^{-4}
94.3				3.498×10^{-4}
90.4				3.161×10^{-4}
86.7				2.856×10^{-4}
83.1				2.580×10^{-4}
79.7				2.330×10^{-4}
76.5				2.103×10^{-4}
73.3				1.899×10^{-4}
70.3				1.714×10^{-4}
67.4				1.546×10^{-4}
64.6				1.396×10^{-4}
62.0				1.259×10^{-4}
59.4				1.136×10^{-4}
57.0				1.026×10^{-4}
54.7				9.256×10^{-5}
52.4				8.355×10^{-5}
50.3				7.543×10^{-5}
48.2				6.811×10^{-5}
46.2				6.151×10^{-5}
44.3				5.557×10^{-5}
42.5				5.022×10^{-5}
40.8				4.540×10^{-5}
39.1				4.105×10^{-5}
37.5				3.714×10^{-5}
36.0				3.362×10^{-5}

Table 1. (cont.)

E (Mev)	Primary Proton Flux, $P_i(E,x)$ [(protons/Mev.cm ² .sec)/(proton/cm ² .sec)]			
	x = 0	x = 0.992	x = 2.08	x = 3.02
34.5				3.044×10^{-5}
33.1				2.759×10^{-5}
31.7				2.501×10^{-5}
30.4				2.269×10^{-5}

Table 2. Secondary Proton Flux
x in collision lengths (1 collision length = 1.34 ft)

E (Mev)	Secondary Proton Flux, $P_s(E, x)$ [(protons/Mev.cm ² .sec)/(proton/cm ² .sec)]							
	x = 0.010	x = 0.530	x = 0.992	x = 2.08	x = 3.03	x = 4.05	x = 5.02	x = 6.01
30.4	4.192×10^{-4}	5.807×10^{-4}	4.998×10^{-4}	2.256×10^{-4}	8.551×10^{-5}	2.792×10^{-5}	1.398×10^{-5}	6.933×10^{-6}
50.3	4.067×10^{-4}	6.476×10^{-4}	5.709×10^{-4}	2.649×10^{-4}	9.772×10^{-5}	3.018×10^{-5}	1.506×10^{-5}	7.443×10^{-6}
107	3.080×10^{-4}	6.415×10^{-4}	6.062×10^{-4}	2.974×10^{-4}	9.412×10^{-5}	2.714×10^{-5}	1.332×10^{-5}	6.514×10^{-6}
209	1.763×10^{-4}	4.910×10^{-4}	5.008×10^{-4}	2.563×10^{-4}	4.349×10^{-5}	1.550×10^{-5}	7.430×10^{-6}	3.561×10^{-6}
318	1.163×10^{-4}	3.565×10^{-4}	3.731×10^{-4}	1.773×10^{-4}	1.742×10^{-5}	7.002×10^{-6}	3.341×10^{-6}	1.573×10^{-6}
409	8.636×10^{-5}	2.686×10^{-4}	2.826×10^{-4}	6.813×10^{-5}	7.270×10^{-6}	3.081×10^{-6}	1.483×10^{-6}	6.894×10^{-7}
526	6.064×10^{-5}	1.895×10^{-4}	1.896×10^{-4}	7.142×10^{-5}	1.832×10^{-6}	7.942×10^{-7}	3.930×10^{-7}	1.798×10^{-7}
622	4.623×10^{-5}	1.372×10^{-4}	7.701×10^{-5}	1.046×10^{-5}	3.996×10^{-7}	1.749×10^{-7}	9.216×10^{-8}	4.172×10^{-8}
800	6.959×10^{-6}	6.316×10^{-7}	3.539×10^{-8}	1.766×10^{-9}	8.212×10^{-10}	5.504×10^{-7}	6.084×10^{-10}	2.780×10^{-10}

Table 3. Secondary Proton Flux (cont.)
 x in collision lengths (1 collision length = 1.34 ft)

E (Mev)	Secondary Proton Flux, $P_s(E,x)$ [(protons/Mev.cm ² .sec)/(proton/cm ² .sec)]						
	$x = 8.02$	$x = 10.03$	$x = 12.01$	$x = 14.02$	$x = 16.01$	$x = 18.01$	$x = 20.00$
30.4	1.637×10^{-6}	3.817×10^{-7}	8.976×10^{-8}	2.054×10^{-8}	4.753×10^{-9}	1.072×10^{-9}	2.448×10^{-10}
50.3	1.745×10^{-6}	4.047×10^{-7}	9.467×10^{-8}	2.156×10^{-8}	4.968×10^{-9}	1.116×10^{-9}	2.540×10^{-10}
107	1.494×10^{-6}	3.400×10^{-7}	7.806×10^{-8}	1.749×10^{-8}	3.969×10^{-9}	8.794×10^{-10}	1.976×10^{-10}
209	7.830×10^{-7}	1.711×10^{-7}	3.793×10^{-8}	8.212×10^{-9}	1.805×10^{-9}	3.879×10^{-10}	8.468×10^{-11}
318	3.325×10^{-7}	6.999×10^{-8}	1.498×10^{-8}	3.136×10^{-9}	6.677×10^{-10}	1.391×10^{-10}	2.949×10^{-11}
409	1.416×10^{-7}	2.899×10^{-8}	6.044×10^{-9}	1.233×10^{-9}	2.564×10^{-10}	5.216×10^{-11}	1.081×10^{-11}
526	3.566×10^{-8}	7.059×10^{-9}	1.425×10^{-9}	2.817×10^{-10}	5.679×10^{-11}	1.121×10^{-11}	2.257×10^{-12}
622	8.072×10^{-9}	1.560×10^{-9}	3.078×10^{-10}	5.945×10^{-11}	1.172×10^{-11}	2.263×10^{-12}	4.460×10^{-13}
800	5.287×10^{-11}	1.004×10^{-11}	1.946×10^{-12}	3.694×10^{-13}	7.161×10^{-14}	1.360×10^{-14}	2.636×10^{-15}

Table 4. Neutron Flux
 x in collision lengths (1 collision length = 1.34 ft)

E (Mev)	Neutron Flux, $N(E,x)$ [(neutrons/Mev.cm ² .sec)/(proton/cm ² sec)]							
	$x = 0.010$	$x = 0.530$	$x = 0.992$	$x = 2.08$	$x = 3.03$	$x = 4.05$	$x = 5.02$	$x = 6.01$
30.4	1.762×10^{-3}	6.600×10^{-3}	8.271×10^{-3}	6.296×10^{-3}	3.399×10^{-3}	1.461×10^{-3}	6.867×10^{-4}	3.570×10^{-4}
50.3	1.015×10^{-3}	4.055×10^{-3}	5.410×10^{-3}	4.726×10^{-3}	2.872×10^{-3}	1.404×10^{-3}	7.064×10^{-4}	3.544×10^{-4}
107	4.351×10^{-4}	1.778×10^{-3}	2.433×10^{-3}	2.260×10^{-3}	1.530×10^{-3}	7.508×10^{-4}	4.032×10^{-4}	2.108×10^{-4}
209	2.123×10^{-4}	8.092×10^{-4}	1.088×10^{-3}	1.036×10^{-3}	6.044×10^{-4}	3.372×10^{-4}	1.594×10^{-4}	8.181×10^{-5}
318	1.248×10^{-4}	4.839×10^{-4}	6.326×10^{-4}	5.375×10^{-4}	3.005×10^{-4}	1.458×10^{-4}	7.276×10^{-5}	3.602×10^{-5}
409	9.151×10^{-5}	3.466×10^{-4}	4.432×10^{-4}	3.543×10^{-4}	1.792×10^{-4}	8.406×10^{-5}	4.072×10^{-5}	1.960×10^{-5}
526	6.338×10^{-5}	2.337×10^{-4}	2.909×10^{-4}	1.783×10^{-4}	8.641×10^{-5}	3.900×10^{-5}	1.824×10^{-5}	8.491×10^{-6}
622	4.839×10^{-5}	1.749×10^{-4}	2.053×10^{-4}	8.789×10^{-5}	4.146×10^{-5}	1.819×10^{-5}	8.288×10^{-6}	3.762×10^{-6}
800	9.738×10^{-5}	8.786×10^{-5}	5.983×10^{-6}	2.412×10^{-6}	1.108×10^{-6}	4.725×10^{-7}	2.105×10^{-7}	9.343×10^{-8}

Table 5. Neutron Flux (cont.)
x in collision lengths (1 collision length = 1.34 ft)

E (Mev)	Neutron Flux, N(E,x) [(neutrons/Mev.cm ² .sec)/(proton/cm ² .sec)]						
	x = 8.02	x = 10.03	x = 12.01	x = 14.02	x = 16.01	x = 18.01	x = 20.00
30.4	7.786 x 10 ⁻⁵	1.845 x 10 ⁻⁵	4.425 x 10 ⁻⁶	1.032 x 10 ⁻⁶	2.428 x 10 ⁻⁷	5.562 x 10 ⁻⁸	1.288 x 10 ⁻⁸
50.3	8.605 x 10 ⁻⁵	2.069 x 10 ⁻⁵	5.011 x 10 ⁻⁶	1.179 x 10 ⁻⁶	2.797 x 10 ⁻⁷	6.455 x 10 ⁻⁸	1.505 x 10 ⁻⁸
107	5.444 x 10 ⁻⁵	1.367 x 10 ⁻⁵	3.418 x 10 ⁻⁶	8.251 x 10 ⁻⁷	1.999 x 10 ⁻⁷	4.698 x 10 ⁻⁸	1.113 x 10 ⁻⁸
209	2.045 x 10 ⁻⁵	4.905 x 10 ⁻⁶	1.218 x 10 ⁻⁶	2.877 x 10 ⁻⁷	6.832 x 10 ⁻⁸	1.576 x 10 ⁻⁸	3.671 x 10 ⁻⁹
318	8.431 x 10 ⁻⁶	1.944 x 10 ⁻⁶	4.510 x 10 ⁻⁷	1.016 x 10 ⁻⁷	2.313 x 10 ⁻⁸	5.128 x 10 ⁻⁹	1.151 x 10 ⁻⁹
409	4.359 x 10 ⁻⁶	9.600 x 10 ⁻⁷	2.138 x 10 ⁻⁷	4.638 x 10 ⁻⁸	1.109 x 10 ⁻⁸	2.187 x 10 ⁻⁹	4.759 x 10 ⁻¹⁰
526	1.772 x 10 ⁻⁶	3.681 x 10 ⁻⁷	7.773 x 10 ⁻⁸	1.604 x 10 ⁻⁸	3.365 x 10 ⁻⁹	6.903 x 10 ⁻¹⁰	1.441 x 10 ⁻¹⁰
622	7.469 x 10 ⁻⁷	1.481 x 10 ⁻⁷	2.993 x 10 ⁻⁸	5.922 x 10 ⁻⁹	1.194 x 10 ⁻⁹	2.358 x 10 ⁻¹⁰	4.746 x 10 ⁻¹¹
800	1.774 x 10 ⁻⁸	3.368 x 10 ⁻⁹	6.528 x 10 ⁻¹⁰	1.240 x 10 ⁻¹⁰	2.403 x 10 ⁻¹¹	4.562 x 10 ⁻¹²	8.843 x 10 ⁻¹³

Table 6. Pion Flux
x in collision lengths (1 collision length = 1.34 ft)

E (Mev)	Pion Flux, $\pi(E,x)$ [(pion/Mev.cm ² .sec)/(proton/cm ² .sec)]							
	x = 0.010	x = 0.530	x = 0.992	x = 2.08	x = 3.03	x = 4.05	x = 5.02	x = 6.01
30.4	5.994×10^{-5}	1.266×10^{-4}	1.077×10^{-4}	3.909×10^{-5}	1.415×10^{-5}	4.610×10^{-6}	1.871×10^{-6}	8.846×10^{-7}
50.3	5.877×10^{-5}	1.368×10^{-4}	1.1967×10^{-4}	4.500×10^{-5}	1.467×10^{-5}	5.220×10^{-6}	2.078×10^{-6}	9.815×10^{-7}
107	4.422×10^{-5}	1.154×10^{-4}	1.083×10^{-4}	4.415×10^{-5}	1.651×10^{-5}	4.621×10^{-6}	1.774×10^{-6}	8.384×10^{-7}
209	2.800×10^{-5}	8.213×10^{-5}	8.280×10^{-5}	3.795×10^{-5}	1.276×10^{-5}	2.609×10^{-6}	1.036×10^{-6}	4.879×10^{-7}
318	1.948×10^{-5}	6.127×10^{-5}	6.446×10^{-5}	3.034×10^{-5}	5.603×10^{-6}	1.158×10^{-6}	5.104×10^{-7}	2.389×10^{-7}
409	1.514×10^{-5}	4.857×10^{-5}	5.157×10^{-5}	1.863×10^{-5}	1.901×10^{-6}	5.406×10^{-7}	2.521×10^{-7}	1.173×10^{-7}
526	1.150×10^{-5}	3.695×10^{-5}	3.835×10^{-5}	3.078×10^{-6}	4.029×10^{-7}	1.587×10^{-7}	7.737×10^{-8}	3.561×10^{-8}
622	9.474×10^{-6}	2.961×10^{-5}	1.956×10^{-5}	3.712×10^{-7}	9.461×10^{-8}	4.052×10^{-8}	2.090×10^{-8}	9.527×10^{-9}
800	1.879×10^{-6}	2.141×10^{-7}	1.493×10^{-8}	5.284×10^{-10}	2.404×10^{-10}	1.554×10^{-10}	1.752×10^{-10}	8.094×10^{-11}

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Table 7. Pion Flux (cont.)
x in collision lengths (1 collision length = 1.34 ft)

E (Mev)	Pion Flux, $\pi(E,x)$ [(Pions/Mev.cm ² .sec)/(proton/cm ² .sec)]						
	x = 8.02	x = 10.03	x = 12.01	x = 14.02	x = 16.01	x = 18.01	x = 20.00
30.4	2.010×10^{-7}	4.537×10^{-8}	1.036×10^{-8}	2.310×10^{-9}	5.219×10^{-10}	1.152×10^{-10}	2.578×10^{-11}
50.3	2.226×10^{-7}	5.016×10^{-8}	1.144×10^{-8}	2.546×10^{-9}	5.744×10^{-10}	1.266×10^{-10}	2.830×10^{-11}
107	1.886×10^{-7}	4.212×10^{-8}	9.534×10^{-9}	2.107×10^{-9}	4.723×10^{-10}	1.035×10^{-10}	2.301×10^{-11}
209	1.061×10^{-7}	2.292×10^{-8}	5.028×10^{-9}	1.079×10^{-9}	2.352×10^{-10}	5.015×10^{-11}	1.088×10^{-11}
318	5.005×10^{-8}	1.042×10^{-8}	2.208×10^{-9}	4.577×10^{-10}	9.661×10^{-11}	1.996×10^{-11}	4.199×10^{-12}
409	2.396×10^{-8}	4.870×10^{-9}	1.008×10^{-9}	2.044×10^{-10}	4.221×10^{-11}	8.536×10^{-12}	1.759×10^{-12}
526	7.046×10^{-9}	1.389×10^{-9}	2.793×10^{-10}	5.500×10^{-11}	1.105×10^{-11}	2.174×10^{-12}	4.361×10^{-13}
622	1.844×10^{-9}	3.561×10^{-10}	7.016×10^{-11}	1.354×10^{-11}	2.667×10^{-12}	5.145×10^{-13}	1.013×10^{-13}
800	1.541×10^{-11}	2.926×10^{-12}	5.673×10^{-13}	1.077×10^{-13}	2.088×10^{-14}	3.964×10^{-15}	7.684×10^{-16}

Table 8. Muon Flux
x in Collision lengths (1 collision length = 1.34 ft)

E (Mev)	Muon Flux, $\mu(E,x)$ [(muons/Mev.cm ² .sec)/(proton/cm ² .sec)]							
	x = 0.010	x = 0.530	x = 0.992	x = 2.08	x = 3.03	x = 4.05	x = 5.02	x = 6.01
30.4	2.245×10^{-7}	1.788×10^{-6}	2.555×10^{-6}	2.156×10^{-6}	1.350×10^{-6}	4.601×10^{-7}	9.432×10^{-8}	3.457×10^{-8}
50.3	1.724×10^{-7}	1.660×10^{-6}	2.562×10^{-6}	2.375×10^{-6}	1.526×10^{-6}	4.810×10^{-7}	9.484×10^{-8}	3.499×10^{-8}
107	8.165×10^{-8}	1.028×10^{-6}	1.912×10^{-6}	2.111×10^{-6}	1.331×10^{-6}	3.005×10^{-7}	5.830×10^{-8}	2.290×10^{-8}
209	3.168×10^{-8}	4.837×10^{-7}	9.888×10^{-7}	1.233×10^{-6}	4.954×10^{-7}	5.954×10^{-8}	1.594×10^{-8}	7.158×10^{-9}
318	1.548×10^{-8}	2.714×10^{-7}	5.790×10^{-7}	4.814×10^{-7}	6.215×10^{-8}	7.830×10^{-9}	3.328×10^{-9}	1.602×10^{-9}
409	9.657×10^{-9}	1.610×10^{-7}	3.317×10^{-7}	8.107×10^{-8}	5.792×10^{-9}	1.322×10^{-9}	7.075×10^{-10}	3.477×10^{-10}
526	5.855×10^{-9}	7.729×10^{-8}	5.505×10^{-8}	1.404×10^{-9}	1.625×10^{-10}	6.698×10^{-11}	4.906×10^{-11}	2.447×10^{-11}
622	1.604×10^{-9}	2.608×10^{-9}	4.386×10^{-10}	5.385×10^{-12}	1.432×10^{-12}	8.265×10^{-13}	1.467×10^{-12} *	7.824×10^{-13}

*The muon flux at the higher energies show slight irregularities in the vicinity of x = 5 because the grid size in the finite difference calculation was changed at this point.

Table 9. Muon Flux (cont.)
x in collision lengths (1 collision length = 1.34 ft)

E (Mev)	Muon Flux, $\mu_s(E, x)$ [(muons/Mev.cm ² .sec)/(proton/cm ² .sec)]						
	x = 8.02	x = 10.03	x = 12.01	x = 14.02	x = 16.01	x = 18.01	x = 20.00
30.4	7.476×10^{-9}	1.632×10^{-9}	3.609×10^{-10}	7.807×10^{-11}	1.717×10^{-11}	3.695×10^{-12}	8.085×10^{-13}
50.3	7.548×10^{-9}	1.638×10^{-9}	3.602×10^{-10}	7.752×10^{-11}	1.696×10^{-11}	3.633×10^{-12}	7.916×10^{-13}
107	4.916×10^{-9}	1.046×10^{-9}	2.261×10^{-10}	4.780×10^{-11}	1.029×10^{-11}	2.168×10^{-12}	4.652×10^{-13}
209	1.514×10^{-9}	3.116×10^{-10}	6.518×10^{-11}	1.335×10^{-11}	2.787×10^{-12}	5.6989×10^{-13}	1.187×10^{-13}
318	3.306×10^{-10}	6.610×10^{-11}	1.346×10^{-11}	2.684×10^{-12}	5.460×10^{-13}	1.033×10^{-13}	2.210×10^{-14}
409	6.999×10^{-11}	1.369×10^{-11}	2.731×10^{-12}	5.335×10^{-13}	1.063×10^{-13}	2.076×10^{-14}	4.136×10^{-15}
526	4.799×10^{-12}	9.185×10^{-13}	1.793×10^{-13}	3.430×10^{-14}	6.696×10^{-15}	1.281×10^{-15}	2.500×10^{-16}
622	1.536×10^{-13}	2.918×10^{-14}	5.658×10^{-15}	7.716×10^{-15}	2.083×10^{-16}	2.355×10^{-17}	7.669×10^{-18}

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Fig. 2. Dose vs Distance.

Appendix I

Since the method used to estimate the low-energy dose is not entirely satisfactory, we shall in this appendix give the dose results with and without this estimated contribution.

In general, the dose from any particle specie may be written

$$d_i(\Gamma, x) = C \int_{\Gamma}^{E_{\max}} F_i(E, x) S_i(E) dE,$$

where

$d_i(\Gamma, x)$ = dose from particles of type i with energy greater than Γ ,

$F_i(E, x)$ = flux of particles of type i ,

S_i = energy loss per unit distance of particles of type i in tissue,

C = constant which converts energy per unit volume into rads,

$E_{\max}$ = maximum energy of particles being considered.

In Table A-1 the neutron dose is given for various values of Γ . The first column, $\Gamma = 109$ Mev, is the neutron dose calculated from those neutrons with energy greater than 109 Mev. The second column is the dose from neutrons with energy less than 109 Mev estimated by fitting the measured cosmic-ray neutron spectrum to our calculated flux at 109 Mev (see 1).^{*} It is the sum of these two columns that is shown as d_n in Fig. 2. Column 3 contains the neutron dose for $\Gamma = 32$ Mev. Since only particles with energy greater than 32 Mev are considered in the cascade calculation, $\Gamma = 32$ Mev is the smallest value of Γ for which the dose can be obtained directly from our calculations. Column 4, $\Gamma = 0$, is the neutron dose obtained by extrapolation. The extrapolation procedure is

^{*}An energy of 109 Mev is used since this is the energy at which the calculated flux and the cosmic-ray spectrum have approximately the same slope.

to calculate $d_i(\Gamma, x)$ for several values of Γ , fit the resulting points by linear least squares, and extrapolate the resulting curve to zero.

By comparing columns 3 and 4 it can be seen that the extrapolation indicates that the neutrons below 32 Mev do not contribute appreciably to the dose. On the other hand the dose estimate using the cosmic-ray spectrum, the sum of columns 1 and 2, is somewhat larger than the dose estimate obtained by extrapolation, column 4.

In Tables A-2, A-3, and A-4, the proton, pion, and muon doses for $\Gamma = 0$ and $\Gamma = 32$ Mev are given. The tables indicate that the low-energy charged particles do not contribute appreciably to the total charged particle dose.

Table A-1. Neutron Dose

x (Collision Lengths)	Neutron Dose, d_N [(rads/hr)/(protons/cm ² .sec)]			
	$\Gamma = 109$ Mev	Estimated From Cosmic- Ray Spectrum*	$\Gamma = 32$ Mev	$\Gamma = 0$ Mev
9.926	1.036×10^{-7}	4.916×10^{-7}	1.552×10^{-7}	1.796×10^{-7}
11.94	2.411×10^{-8}	1.207×10^{-7}	3.656×10^{-8}	4.226×10^{-8}
13.94	5.556×10^{-9}	2.913×10^{-8}	8.520×10^{-9}	9.839×10^{-9}
15.96	1.269×10^{-9}	6.928×10^{-9}	1.899×10^{-9}	2.269×10^{-9}
17.96	2.877×10^{-10}	1.628×10^{-9}	4.498×10^{-10}	5.190×10^{-10}
19.97	6.479×10^{-11}	3.784×10^{-10}	1.021×10^{-10}	1.178×10^{-10}

*The dose, d_N , shown in Fig. 2 is the sum of columns 1 and 2.

Table A-2. Proton Dose

x (Collision Lengths)	Proton Dose, d_p [(rads/hr)/(protons/cm ² ·sec)]	
	$\Gamma = 32$ Mev	$\Gamma = 0$
9.926	3.517×10^{-8}	4.906×10^{-8}
11.94	7.882×10^{-9}	1.109×10^{-8}
13.94	1.757×10^{-9}	2.490×10^{-9}
15.96	3.506×10^{-10}	5.560×10^{-10}
17.96	8.593×10^{-11}	1.235×10^{-10}
19.97	1.888×10^{-11}	2.729×10^{-11}

Table A-3. Pion Dose

x (Collision Lengths)	Pion Dose, d_π [(rads/hr)/(protons/cm ² ·sec)]	
	$\Gamma = 32$ Mev	$\Gamma = 0$
9.926	1.905×10^{-9}	2.344×10^{-9}
11.94	4.144×10^{-10}	5.129×10^{-10}
13.94	8.985×10^{-11}	1.118×10^{-10}
15.96	1.830×10^{-11}	2.431×10^{-11}
17.96	4.188×10^{-12}	5.265×10^{-11}
19.97	9.005×10^{-13}	1.137×10^{-12}

Table A-4. Muon Dose

x (collision lengths)	Muon Dose, d_{μ} [(rads/hr)/(protons/cm ² .sec)]	
	$\Gamma = 32$ Mev	$\Gamma = 0$
9.926	2.938×10^{-11}	4.196×10^{-11}
11.94	6.227×10^{-12}	8.956×10^{-12}
13.94	1.318×10^{-12}	1.908×10^{-12}
15.96	2.785×10^{-13}	4.056×10^{-13}
17.96	5.876×10^{-14}	8.610×10^{-14}
19.97	1.238×10^{-14}	1.824×10^{-13}

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