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Dose Estimation**

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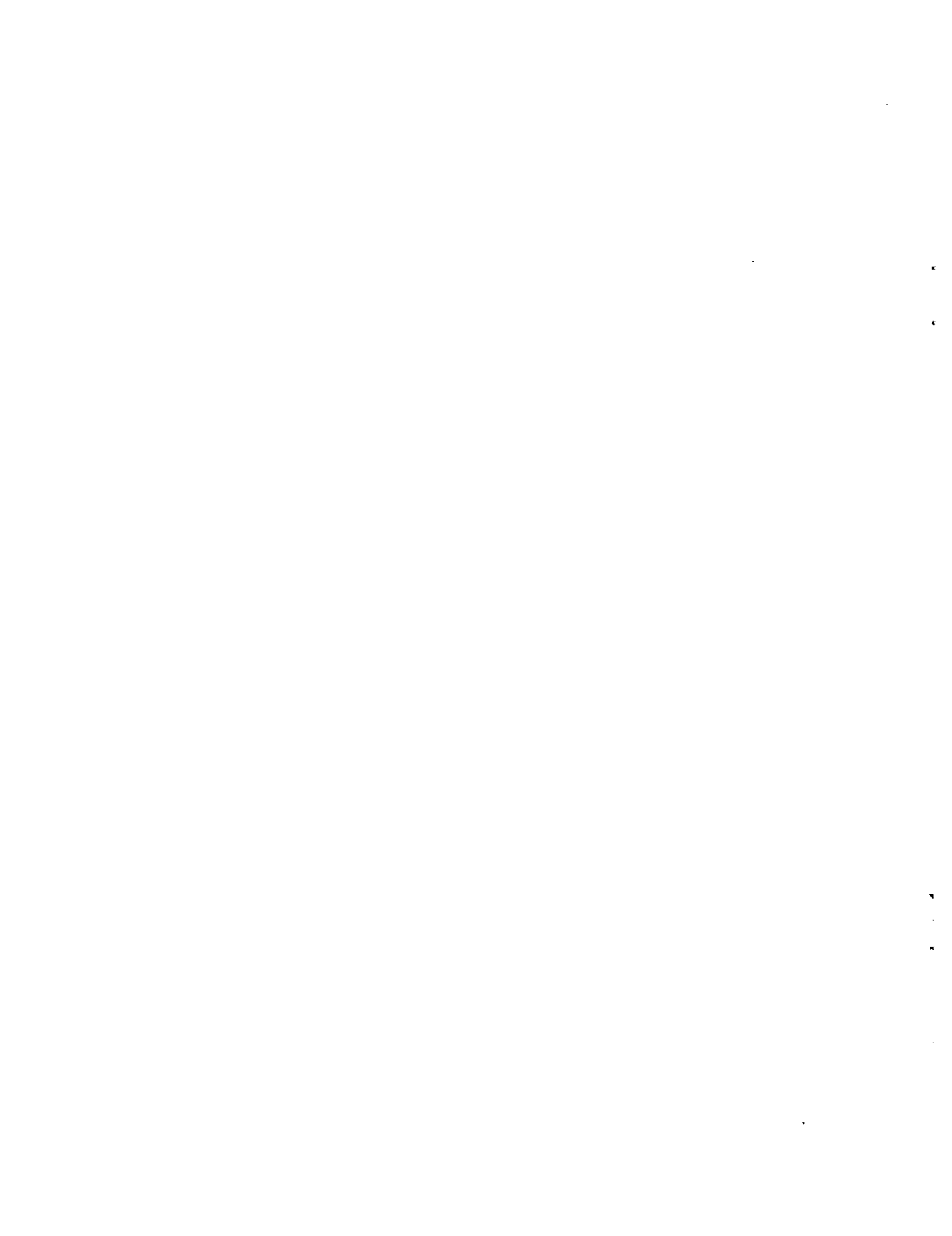
Reliability of Equivalent Sphere Model in Blood-Forming Organ Dose Estimation

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Abstract

The radiation dose equivalents to blood-forming organs (BFO's) of astronauts on the Martian surface due to major solar flare events are calculated using the detailed body geometry of Langley and Billings. The solar flare spectra of February 1956, November 1960, and August 1972 events are employed instead of the idealized Webber form. The detailed geometry results are compared with those based on the 5-cm sphere model, which has been used often in the past to approximate BFO dose and dose equivalent. Larger discrepancies are found for the later two events possibly due to the lower numbers of highly penetrating protons. It is concluded that the 5-cm sphere model is not suitable for quantitative use in connection with future NASA deep-space, long-duration mission shield design studies.

Introduction

One of the challenges for the future NASA space programs, which include lunar bases, a manned Mars mission, and Space Station Freedom, is to provide adequate radiation shielding to the astronauts. In the past, the missions were not as complex and long-durated. The radiation exposure to the astronaut was not critically high enough to warrant precise risk analysis. However, for the future missions, the astronauts not only will stay in space for extended durations, but will also be exposed to galactic cosmic rays (GCR's) and solar flare particles, for those missions beyond the lower Earth orbit, without the umbrella of the Earth's magnetic field.

The significance of improving the accuracy for predicting the dose and dose equivalent that astronauts will incur during future NASA missions has been demonstrated in several studies (refs. 1 and 2). For example, reference 1 indicates that an increase of 20 percent in predicted blood-forming organ (BFO) dose equivalent due to GCR's equates to a tripling of the required shield mass from 5 g/cm² to 16 g/cm² of water in order to satisfy the recommended (ref. 3) annual BFO limit of 50 rem. There are large uncertainties associated with the current state-of-the-art dose estimate analysis (refs. 1, 2, and 4), and every possible effort is needed to improve the accuracy in order to accomplish these missions in the most economical way without compromising the well-being of the astronauts.

One of the customary estimation practices that has been considered to be fairly reliable in the past is the use of the equivalent sphere model to obtain dose or dose equivalent to BFO's. Langley and Billings (ref. 5) examined the feasibility of using a set of dosimetry spheres to monitor real-time organ

doses received by astronauts under various space radiation and vehicle conditions. They made comparisons between the doses calculated for the spheres and the detailed body geometry under a range of solar proton energy spectrum characteristics and also under various vehicle radiation shielding thicknesses. The spectra were characterized by an assumed form due to Webber (ref. 6). The optimal radii of those spheres with the corresponding correlation constants that best represented the averaged organ doses under those assumed conditions were determined. Although a moderate error of 18 percent for the correlation was found (ref. 5), one might question if the accuracy will hold under less idealized particle spectral conditions.

The purpose of this study is to reexamine the accuracy of the equivalent sphere model in approximating the BFO doses for more realistic conditions. The calculation made in a separate study (ref. 7) for the radiation transport through the atmosphere of Mars for the three largest solar flares observed in the last half century is extended here to include detailed BFO geometry. Comparisons are made for the dose equivalent to the various distributed BFO's with the reported (ref. 7) values based on the equivalent sphere model.

Symbols

$D(\vec{X})$	dose or dose equivalent at the point \vec{X} , rad or rem
$D_x(t)$	dose or dose equivalent at depth t for normal proton incidence
E	incident proton energy, MeV
$f_x(t)$	areal density distribution function, $\frac{1}{\text{g/cm}^2}$
P_0	rigidity parameter, MV (megavolt)
$R(t, E)$	dose response at depth t for protons of energy E , $\frac{\text{rad or rem}}{\text{proton/cm}^2}$
t	depth from surface or areal density, g/cm ²
\vec{X}	vector locating point within the body, g/cm ²
$\phi(E)$	proton fluence spectrum, $\frac{\text{protons}}{\text{cm}^2\text{-MeV}}$

Calculational Methods

The Langley Research Center nucleon transport code BRYNTRN (ref. 4) was used in reference 7 to obtain dose and dose equivalent on the surface of Mars due to large solar flares. This transport

code was based on the "straightahead" approximation, which reduces consideration to one-dimensional transport; the merits of this approximation have been discussed elsewhere (refs. 8 and 9). An asymptotic expansion for the solution to the transport equation in two dimensions, subject to boundary conditions given for an arbitrary convex region, was derived (ref. 10). The first term of the expansion was found to be an accurate approximation of the dose (ref. 11), and for the case of an isotropic proton fluence spectrum is given by

$$D(\vec{X}) = 4\pi \int_0^\infty \phi(E) \int_0^\infty R(t,E) f_x(t) dt dE \quad (1)$$

with

$$\int_0^\infty f_x(t) dt = 1 \quad (2)$$

where $R(t, E)$ is the fluence-to-dose conversion factor at the depth t for normal incidence protons on a slab, and $f_x(t)$ is the areal density distribution function for the point \vec{X} . The quantity $f_x(t) dt$ is the fraction of the solid angle for which the distance to the surface from the point \vec{X} lies between t and $t + dt$.

To simplify the computational task (that is, without making any change to BRYNTRN code), equation (1) is rewritten as

$$D(\vec{X}) = 4\pi \int_0^\infty f_x(t) D_x(t) dt \quad (3)$$

with

$$D_x(t) = \int_0^\infty \phi(E) R(t,E) dE \quad (4)$$

where $D_x(t)$ is the dose (or dose equivalent) at depth t for normal incidence protons on a slab of tissue. With the areal density distribution function for BFO's given by the detailed geometry work described by Langley and Billings (ref. 12) and Billings and Yucker (ref. 13), equation (3) can be calculated.

Results

The three solar flare spectra used for this study are that of February 1956, November 1960, and August 1972 events, while Langley and Billings (ref. 5) used a Webber form (ref. 6) of integral spectra given by the inverse exponential of proton magnetic rigidity with a range of rigidity parameter P_0 from 50 to 200 MV. Figure 1 shows these three flare spectra and the best fit to the earlier two events with the Webber form. It can be seen that the actual spectra, especially the high-energy range of the February 1956 event, are very different from the analytical form of Webber.

The average dose equivalents at the surface of Mars due to these three solar flare events are shown in figure 2 as a function of slab (water) thickness for the low density Mars atmosphere model (16 g/cm² CO₂ vertically) used in reference 7. These average dose equivalent values are obtained by summing the directional (anisotropic) dose equivalent over the solid angle (ref. 7) and are used as $D_x(t)$ in this report. The calculated results from equation (3) are presented in table I for the five distributed organs. Also shown for comparison are the average BFO and 5-cm (water) depth dose equivalents.

It is customary (refs. 14 and 15) to represent the average BFO exposure (dose or dose equivalent) with the 5-cm depth exposure or exposure in a 5-cm sphere based on the recommendation of the Space Science Board (ref. 14). Conversely, the average BFO dose was found to be approximately half the 5-cm sphere dose in several analytical findings, such as the one from Langley and Billings (ref. 5). For the August 1972 event, the average BFO value for the detailed geometry (see table I) is fairly close (within 10 percent) to half of the value for a 5-cm sphere. However, the differences are larger for the other two flares, with 30 and 41 percent for November 1960 and February 1956 spectra, respectively. This wide discrepancy among these three events probably is due to the fact that there are more penetrating high-energy protons contained in the two earlier flares (see fig. 2) and that the actual spectra are not conforming to the simple analytical form as used by Langley and Billings. We further note that the 5-cm sphere dose is conservative for these three events.

Concluding Remarks

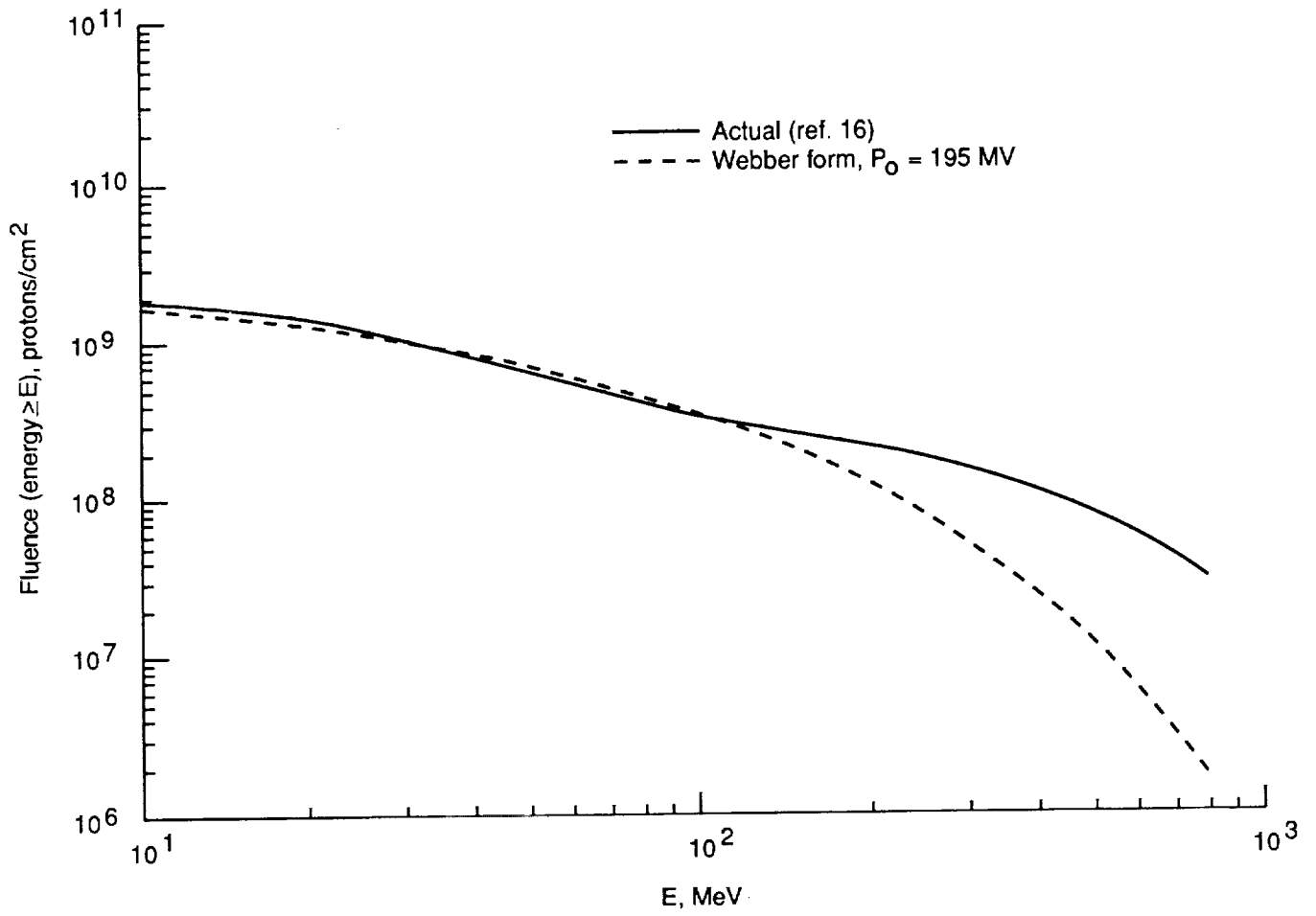
It has been found that the equivalent sphere model of Billings and Langley is not accurate enough for precise, quantitative estimates of body doses and vehicle shielding requirements in connection with future NASA mission studies. Furthermore, the 5-cm sphere dose recommended by the Space Science Board is always an overestimate and could lead to shielding penalties. This is based on the comparison made with the detailed body geometry calculation for BFO's (blood-forming organs) using actual solar flare spectra. The 5-cm equivalent sphere model of the BFO is shown to break down for more realistic spectra than the simple mathematical forms used in previous studies. It is recommended that future works involving actual exposure estimates or shield mass requirements be extended to include all the body geometries, including other critical organs, such as eyes, skin, and active BFO's.

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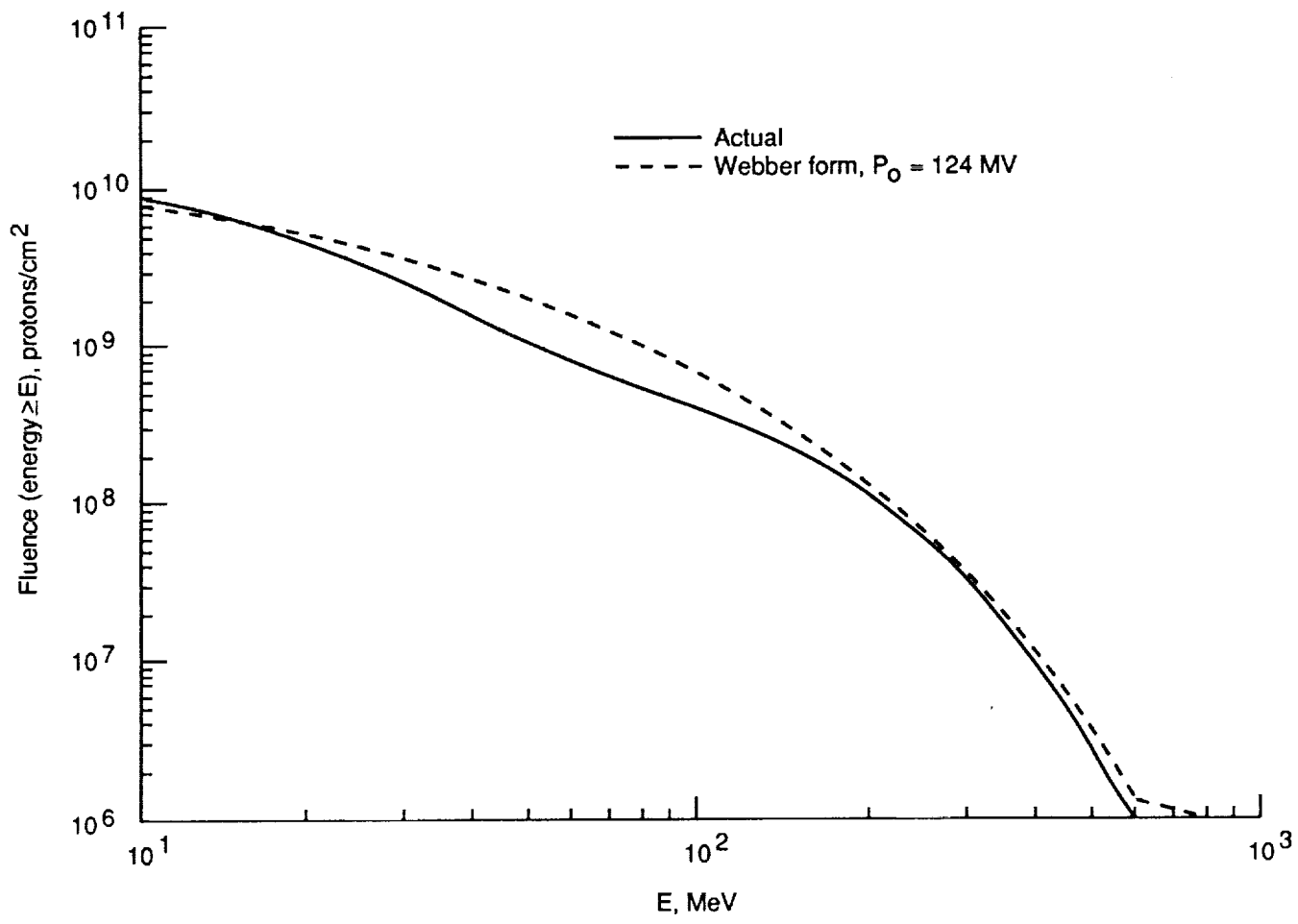
Table I. BFO Dose Equivalents on Mars Surface
 [Low density atmosphere model]

Solar flare event	Dose equivalent, rem, for—						
	Arms	Legs	High trunk	Low trunk	Skull	Average BFO value	5-cm sphere (ref. 7)
Feb. 1956	8.74	8.60	8.32	7.98	8.91	8.45	9.94
Nov. 1960	5.66	5.34	4.95	4.32	5.75	5.21	7.31
Aug. 1972	3.20	2.73	2.42	1.76	3.09	2.56	4.61



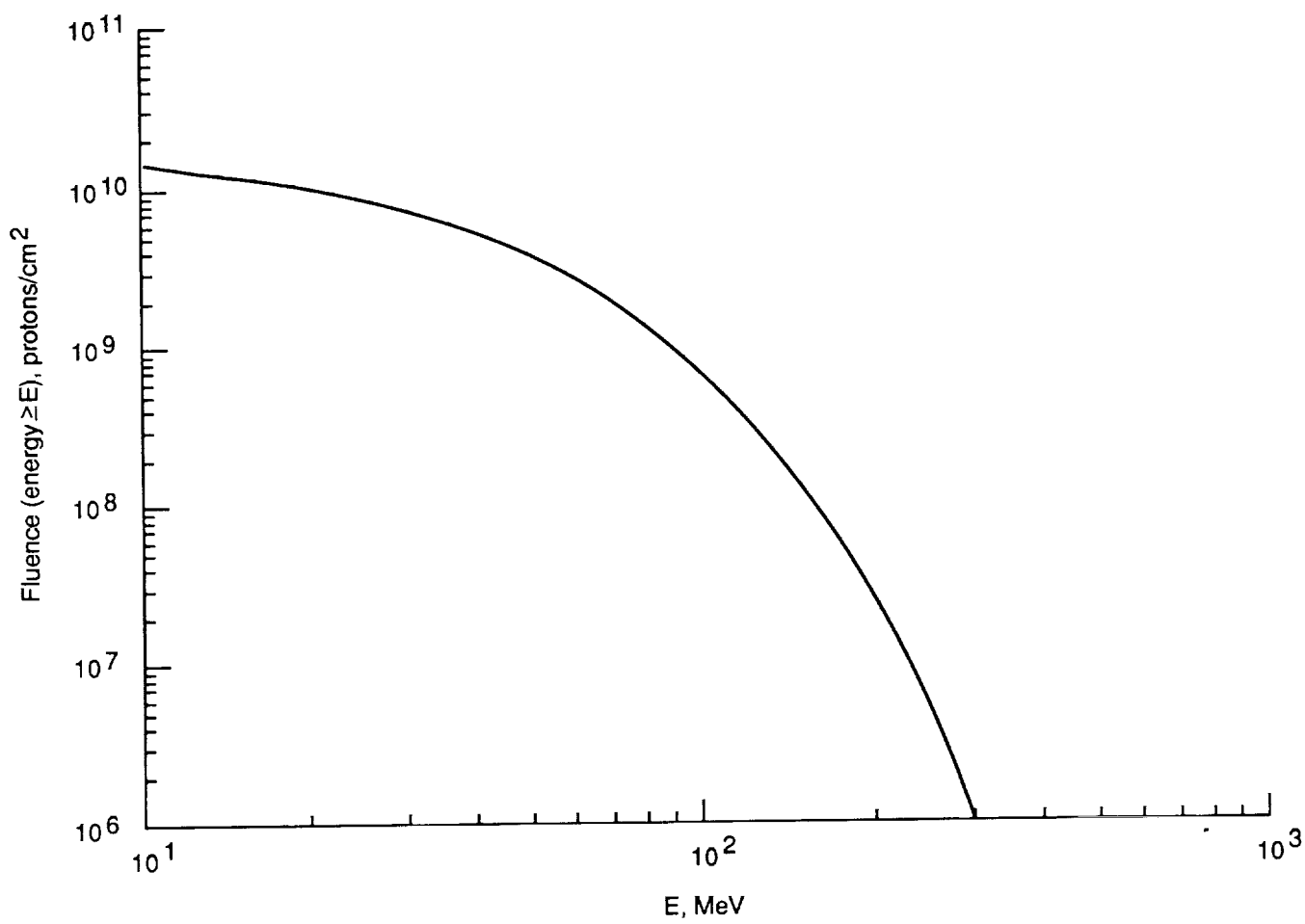
(a) February 1956 event.

Figure 1. Fluence spectra for three major solar particle events.



(b) November 1960 event.

Figure 1. Continued.



(c) August 1972 event.

Figure 1. Concluded.

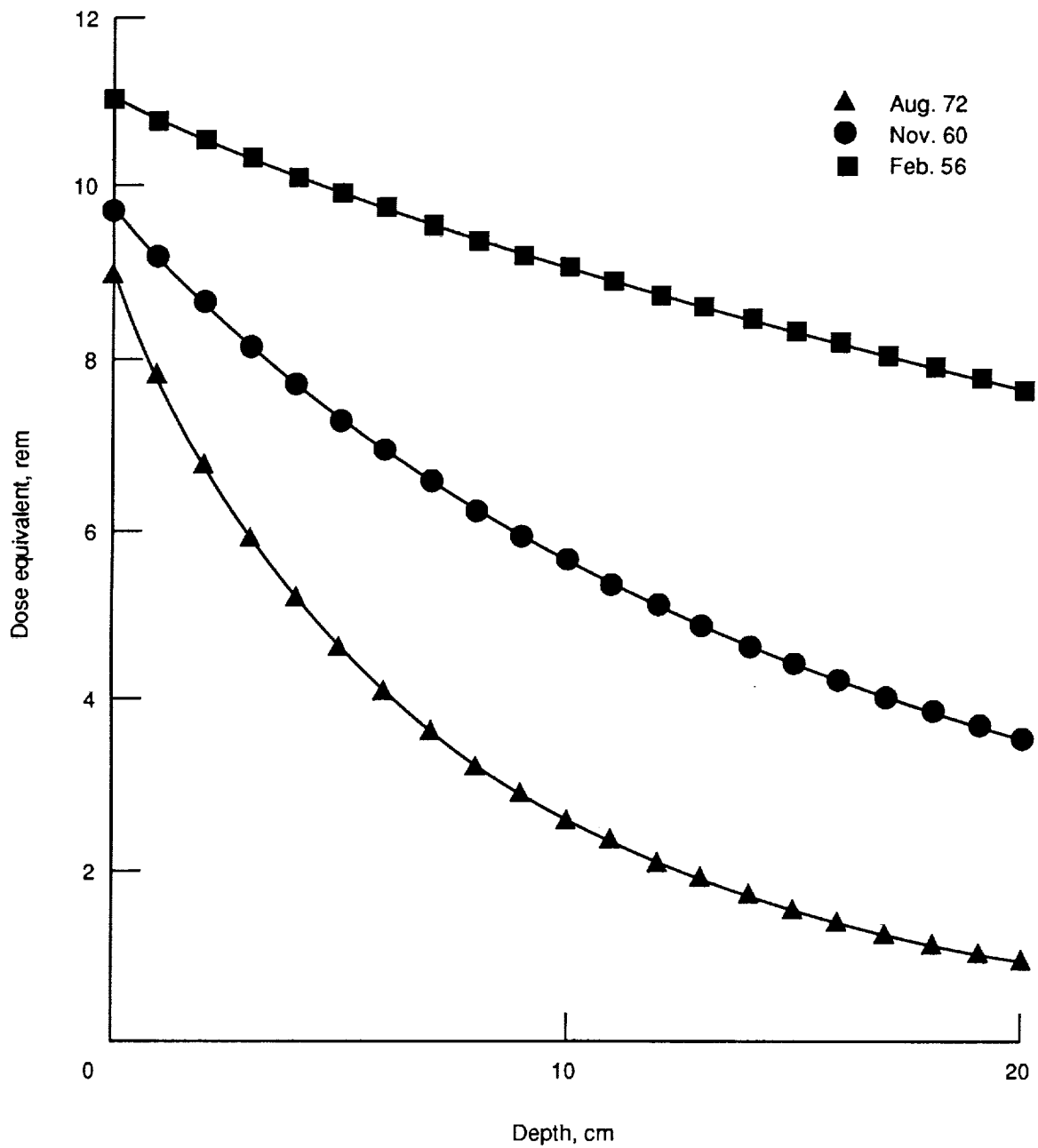


Figure 2. Dose equivalent as a function of slab (water) thickness on Mars surface. (Low density atmosphere model.)



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