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Abstract

Results of continuing efforts toward validating the buildup-factor method and the baryon transport code (BRYNTRN), which use the deterministic approach to solving radiation transport problems and are the candidate engineering tools in space radiation shielding analyses, are presented. A simplified theory of proton-buildup factors assuming no neutron coupling has been derived to verify a previously chosen form for parameterizing the dose-conversion factor that includes the secondary-particle buildup effect. Estimates of dose in tissue made by the two deterministic approaches and the Monte Carlo method are compared for cases with various thicknesses of shields and various types of proton spectra. The results are in reasonable agreement but there is some overestimation by the buildup-factor method when the effect of neutron production in the shield is significant. Future improvement, including neutron coupling in the buildup-factor theory, is suggested to alleviate this shortcoming. Impressive agreement for individual components of doses, such as those from the secondaries and heavy-particle recoils, is obtained between BRYNTRN and Monte Carlo results.

Introduction

As NASA continues to develop a vigorous space program, tools for the analysis of optimum shielding against space radiation are a continuing requirement. The tools must ultimately account for the complex mixtures of radiations in the space environment and be complete in the description of the physical processes involved to minimize engineering-design error. Still, a complete model must be computationally efficient and numerically accurate to be a useful tool for design work. For the model to be used with confidence, efforts toward model validation must be made.

Monte Carlo computer codes have been written that meet many of the above requirements (ref. 1). However, the enormous computational time and storage requirements have impeded their usefulness in the space program. Other alternatives, such as BRYNTRN, a nucleon (baryon) transport code (ref. 2), and a galactic cosmic ray (GCR) transport code (refs. 3 and 4), both developed at Langley, use the deterministic approach, which imposes fewer computational requirements. In reference 2, comparisons were made between BRYNTRN and Monte Carlo calculated doses in bare (no shielding) tissue exposed to incident monoenergetic protons, and the results were in reasonable agreement.

Current efforts at Langley include (but are not limited to) pursuing further improvement and validation of the transport codes and developing a simple, easy-to-use, application-oriented code for estimating doses that result from incident space protons (refs. 5 and 6). The latter effort makes use of the buildup factors, which compress the detailed computation of secondary-particle buildup into the dose-conversion factor. The buildup-factor method is clearly the most computationally efficient method if one is only interested in doses as the end result, but it is limited to materials for which buildup factors are known.

The purpose of this study is to continue the comparison effort made in reference 2, to include dose estimation in tissue behind shielding materials, and to extend the comparison to the newly developed buildup-factor code, BRYNTRN, and the Monte Carlo method. Dose calculations are made for protons with either continuous or discrete spectra where low-energy Monte Carlo or experimental data are available. Doses calculated for the penetrating solar flare of the February 1956 event by the buildup-factor method and BRYNTRN are also compared to ensure that the parameters used in the buildup factors are valid for the high-energy region. A detailed discussion of a simplified buildup-factor theory is given.

Symbols

a_i	parametric constants
B	buildup factor or ratio of total dose to primary proton dose
B_Δ	buildup-factor correction
b	slope parameter in secondary proton production cross section, $\mathrm{cm}^4/\mathrm{g}^2$
$D(x, E)$	total dose (or dose equivalent) at depth x in exposed medium to incident proton of energy E, rad (or rem)
D_i	ith order of dose (or dose equivalent) contribution, rad (or rem)
$D_s(t_s, x, E)$	total dose (or dose equivalent) at depth x in exposed medium behind a shield of thickness t_s to incident proton of energy E, rad (or rem)
E	proton energy, MeV
E_r	$= \epsilon\,(r_0 - x)$, residual proton energy after penetrating a distance x, MeV
E_s	$= \epsilon\,(r_0 - t_s)$, MeV
$f(E, E')$	production cross section for secondary proton of energy E by primary proton of energy E', cm^2/g-MeV
$\bar{f}(r, r')$	$= S(E) f(E, E')$, $\mathrm{cm}^4/\mathrm{g}^2$
HZE	high-energy heavy ion
m	average number of secondary protons produced per nuclear event
P	$\exp(-\tau)$
Q	quality factor
$r(E)$	range of proton with energy E, $\mathrm{g/cm}^2$
$S(E)$	stopping power of proton with energy E, MeV-cm^2/g
$\bar{S}_i$	ith order spectral average of stopping power, MeV-$\mathrm{g/cm}^2$
t_s	equivalent thickness of shield relative to tissue such that stopping powers of shield and tissue are equal, $\mathrm{g/cm}^2$
x, z	distance or range, $\mathrm{g/cm}^2$
β	parameter in secondary proton production cross section, cm^2/g
$\epsilon(r)$	energy of proton with a range r, MeV
σ	macroscopic interaction cross section, cm^2/g
τ	optical thickness for proton
$\phi(x, E)$	proton fluence spectrum at distance x, protons/cm^2-MeV
$\psi(x, r)$	$= S(E)\phi(x, E)$, g^{-1}

Subscripts:

0	initial value
p	proton
s	shield material

where m is the average number of protons produced per nuclear event. Although m and σ are in reality functions of E', our current interest is in monoenergetic boundary conditions as

$$\phi(0,E) = \delta(E - E_0) \tag{8}$$

When m and σ are evaluated at the beam energy E_0, the corresponding boundary condition on ψ is

$$\psi(0,r) = \delta(r - r_0) \tag{9}$$

The high-energy production cross section is an exponential function of $E' - E$ and is used to approximate equation (4) as

$$\bar{f}(r,r') \cong b\exp[-\beta(r' - r)] \tag{10}$$

The normalization in equation (7) requires

$$b = \frac{m\sigma\beta}{1 - \exp(-\beta r_0)} \tag{11}$$

and $\beta \cong 0.01$ cm^2/g. Equation (5) may be solved by perturbation theory (ref. 2) to obtain

$$\psi(x,r) = \sum_{i=0}^{\infty} \psi_i(x,r) \tag{12}$$

where

$$\psi_0(x,r) = \exp(-\sigma x)\delta(r + x - r_0) \tag{13}$$

$$\psi_1(x,r) = \exp(-\sigma x)\int_0^x \bar{f}(r + z, r_0 - x + z)dz \tag{14}$$

$$\psi_{n+1}(x,r) = \int_0^x dz\exp(-\sigma z)\int_{r+z}^{\infty} dr'\bar{f}(r + z, r')\psi_n(x - z, r') \tag{15}$$

Equation (12) may be reduced using equation (10). For example,

$$\psi_1(x,r) = x\exp(-\sigma x)\bar{f}(r, r_0 - x) \tag{16}$$

$$\psi_2(x,r) = \frac{1}{2}x^2\exp(-\sigma x)b \cdot (r_0 - x - r) \cdot \bar{f}(r, r_0 - x) \tag{17}$$

The successive contributions to dose may now be calculated as follows:

$$D_0(x) = \int_0^{\infty} \exp(-\sigma x)\delta(r + x - r_0)dE = S[\epsilon(r_0 - x)]\exp(-\sigma x) \tag{18}$$

$$D_1(x) = \overline{S}_1[\epsilon(r_0 - x)]m\sigma x\exp(-\sigma x) \tag{19}$$

$$D_2(x) = \overline{S}_2[\epsilon(r_0 - x)]m^2\frac{\sigma^2 x^2}{2}\exp(-\sigma x) \tag{20}$$

where $\overline{S}_1$ and $\overline{S}_2$ are spectral averages of stopping power in which $\overline{S}_1(\epsilon) = O(\epsilon^2)$ and $\overline{S}_2(\epsilon) = O(\epsilon^3)$ for small values of ϵ. The total dose is then

$$D(x) = S[\epsilon(r_0 - x)]\exp(-\sigma x) + \sum_{i=1}^{\infty}\frac{1}{i!}(m\sigma x)^i\exp(-\sigma x)\overline{S}_i[\epsilon(r_0 - x)] \tag{21}$$

Simplified Theory of Proton-Buildup Factors

In passing through material or tissue, energetic protons interact mostly through ionization of atomic constituents by the transfer of small amounts of momentum to orbital electrons. Although the nuclear reactions are far less numerous, their effects are magnified because of the large momentum transferred to the nuclear particles and the struck nucleus itself. Many of the secondary particles of nuclear reactions are sufficiently energetic to promote similar nuclear reactions and to cause a buildup of secondary radiations. The description of such processes requires solution of either the integral or integrodifferential form of the Boltzmann equation as is done, for example, in the Monte Carlo method or BRYNTRN. To bypass such extensive calculation for the physical processes, the effect of secondary-particle buildup was folded into dose-conversion factors that relate the primary monoenergetic proton fluence to dose or dose equivalent as a function of distance in a slab of tissue or material (refs. 5, 7, and 8).

A parameterization of the conversion factors, including the secondary-particle buildup in a slab of tissue, was first introduced by Wilson and Khandelwal (ref. 7). Their method allows reliable interpolation and extrapolation of known values obtained from Monte Carlo results. A refinement to the parameterized form of Wilson and Khandelwal was subsequently made (ref. 8). The work has also been extended to the tissue behind an aluminum shield, and an aluminum-buildup factor relative to tissue has been introduced (ref. 8). To elucidate and verify how these parameterized forms were obtained, a simplified theory that assumes no neutron coupling from aluminum is presented in the following sections and serves as a basis for future development.

Buildup in Exposed Medium

The Boltzmann equation for proton transport in the straight ahead approximation is given as

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E}S(E) + \sigma\right]\phi(x,E) = \int_E^\infty f(E,E')\phi(x,E')dE' \tag{1}$$

where $S(E)$ is the proton stopping power, σ is the macroscopic interaction cross section, which we presently take as energy independent, and $f(E,E')$ is the production cross section for secondary protons (ref. 2). Using the definitions

$$r = \int_0^E dE'/S(E') \tag{2}$$

$$\psi(x,r) = S(E)\phi(x,E) \tag{3}$$

and

$$\bar{f}(r,r') = S(E)f(E,E') \tag{4}$$

allows equation (1) to be rewritten (ref. 2) as

$$\psi(x,r) = e^{-\sigma x}\psi(0,x+r) + \int_0^x dz\,\exp(-\sigma z)\int_{r+z}^\infty dr'\bar{f}(r+z,r')\psi(x-z,r') \tag{5}$$

where the boundary condition is

$$\psi(0,r) = S(E)\phi(0,E) \tag{6}$$

The secondary-particle production cross section is normalized as

$$\int_0^{E'} f(E,E')dE = m\sigma \tag{7}$$

The dose buildup factor defined as the ratio of the total dose to the primary proton dose is then

$$B(x, E_0) = 1 + \frac{\sum_{i=1}^{\infty} \frac{1}{i!}(m_T x)^i \overline{S}_i[\epsilon(r_0 - x)]}{S[\epsilon(r_0 - x)]} \tag{22}$$

with the property that

$$\lim_{x \to r_0} B(x, E_0) = 1 \tag{23}$$

which follows here from the neglect of the coupling between the proton and neutron fields.

Wilson and Khandelwal (ref. 8) assumed that the buildup factor had the form

$$B(x, E_0) = (a_1 + a_2 x + a_3 x^2) \exp(-a_4 x) \tag{24}$$

where a_4 was chosen to satisfy equation (23). The choice of a_4 is not to be governed by the nuclear cross section, but rather by the result that $\overline{S}_i(\epsilon) \sim O(\epsilon^{i+1})$ for small values of ϵ. This conclusion is modified because of the presence of neutron production in the medium.

The buildup-factor parameters are shown in table 1 and are to be used in the following form:

$$D(x, E_0) = B(x, E_0) Q[S(E_r)] P(E_0) S(E_r)/P(E_r) \tag{25}$$

where E_r is the residual energy at $r(E_0) - x, Q(S)$ is the quality factor as a function of the stopping power, and

$$P(E) = \exp[-\tau(E)] \tag{26}$$

with

$$\tau(E) = \int_0^E \sigma(E') dE' / S(E') \tag{27}$$

Equation (27) expresses the full energy dependence of the nuclear cross sections. The optical thickness $\tau(E)$ is given in table 2. Note that $Q(S)$ is set to unity when expressing absorbed dose.

Buildup in an External Shield

The effect of buildup in an external shield on the exposed medium (tissue) doses is now considered. If it is assumed that an equivalent distance in the shield can be defined such that the stopping power in equivalent distance units of the shield and exposed medium (tissue) are equal, then the Boltzmann equations of the two media differ only in their nuclear cross sections as

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E} S(E) + \sigma_s\right] \phi(x, E) = \int_E^\infty f_s(E, E') \phi(x, E') dE' \tag{28}$$

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E} S(E) + \sigma\right] \phi(x, E) = \int_E^\infty f(E, E') \phi(x, E') dE' \tag{29}$$

For a monoenergetic beam on the boundary of the shield, the solution is given as

$$\psi_0(x, r) = \exp(-\sigma_s x) \delta(r_0 - x - r) \tag{30}$$

$$\psi_1(x, r) = x \exp(-\sigma_s x) \bar{f}_s(r, r_0 - x) \tag{31}$$

The particles appearing at the media interface provide the boundary condition of the exposed medium; thus,

$$\psi_0(0, r) = \exp(-\sigma_s t_s) \delta(r_0 - t_s - r) + t_s \exp(-\sigma_s t_s) \bar{f}_s(r, r_0 - t_s) + \ldots \tag{32}$$

where t_s is the equivalent thickness of the shield. To evaluate the proton field in the exposed media, we may use equation (5) and the boundary value in equation (32) to obtain

$$\psi(x,r) = \exp(-\sigma x)\exp(-\sigma_s t_s)\delta(r_0 - t_s - x - r) + \exp(-\sigma x) t_s \exp(-\sigma_s t_s)\bar{f}_s(r + x, r_0 - t_s)$$
$$+ \exp(-\sigma_s t_s) x \exp(-\sigma x)\bar{f}(r, r_0 - t_s - x) + \ldots \tag{33}$$

Utilizing equation (10), equation (33) may be rewritten as

$$\psi(x,r) = \exp(-\sigma_s t_s - \sigma x)\delta(r_0 - t_s - x - r)$$
$$+ [t_s \bar{f}_s(r, r_0 - t_s - x) + x\bar{f}(r, r_0 - t_s - x)]\exp(-\sigma_s t_s - \sigma x) + \ldots \tag{34}$$

Similar to equation (21), we can write the total dose at depth x in an exposed medium behind a shield of equivalent thickness t_s as

$$D_s(t_s, x, E_0) = \exp(-\sigma_s t_s - \sigma x) S[\epsilon(r_0 - t_s - x)] + \{m_s \sigma_s t_s \overline{S}_{s1}[\epsilon(r_0 - t_s - x)]$$
$$+ m\sigma x \overline{S}_1 [\epsilon(r_0 - t_s - x)]\}\exp(-\sigma_x t_s - \sigma x) + \ldots \tag{35}$$

Equation (35) may be written as

$$\begin{aligned} D_s(t_s, x, E_0) &= D(t_s + x, E_0) + [\exp(-\sigma_s t_s) - \exp(-\sigma t_s)]\, D(x, E_s) \\ &+ t_s \exp(-\sigma x)\{m_s \sigma_s \overline{S}_{s1}[\epsilon(r_0 - t_s - x)]\exp(-\sigma_s t_s) \\ &- m\sigma \overline{S}_1 [\epsilon(r_0 - t_s - x)]\exp(-\sigma t_s)\} + \ldots \\ &\approx D(t_s + x, E_0) + t_s\{(\sigma - \sigma_s) D(x, E_s) + \exp(-\sigma x)(m_s\sigma_s - m\sigma) \\ &\times \overline{S}_1[\epsilon(r_0 - t_s - x)]\} + \ldots \end{aligned} \tag{36}$$

where $E_s = \epsilon(r_0 - t_s)$. The shield buildup factor can be defined relative to the exposed medium as

$$\begin{aligned} B_\Delta(t_s, x, E_0) &= D_s(t_s, x, E_0)/D(t_s + x, E_0) \\ &= 1 + t_s[(\sigma - \sigma_s)D(x, E_s) + \exp(-\sigma x)(m_s\sigma_s - m\sigma)\overline{S}_1]/D(t_s + x, E_0) + \ldots \end{aligned} \tag{37}$$

Clearly, the coefficient of t_s in equation (37) is reduced if $\sigma \cong \sigma_s$ and reduces to a smaller contribution as $m \to m_s$. This reduction results because the spectral distribution functions have $\beta_s \cong \beta$ for all materials, where β is largely determined from the proton-proton scattering amplitude.

For the present work, the buildup-factor forms from reference 5, which possess the same quality as equation (37), are used and are given as

$$B_\Delta(t_s, x, E_0) = 1 + \frac{0.02 E t_s}{1 + E}\exp(-0.022 t_s) \tag{38}$$

for the dose equivalent and

$$B_\Delta(t_s, x, E_0) = 1 + \frac{0.02 E t_s}{6(1 + E)}\exp(-0.01 t_s) \tag{39}$$

for the absorbed dose, where E is in MeV and t_s in gm/cm^2. Equations (38) and (39) are used in the expression

$$D_s(t_s, x, E_0) = B_\Delta(t_s, x, E_0) B(t_s + x, E_0) Q[S(E_r)] P(E) S(E_r)/P(E_r) \tag{40}$$

for the dose in the tissue behind an aluminum shield where Q is set to unity for the absorbed dose. Equations (38) and (39) are in agreement qualitatively with the derived form (eq. (37)) in that values of $B_\Delta(t_s, x, E)$ are linear in t_s for small values of t_s and linear in E for small values of E. Also, these equations are chosen to fit existing data that exhibit plateaus for large values of E or t_s. Although the derived form (eq. (37)) has resulted from the assumption of no neutron coupling, the chosen form with the constants as given in equations (38) and (39) is obtained based on data that include neutron coupling.

Results and Discussion

Since the buildup factors are functions of both energy and thickness, the first step in verifying such a method is to compare the results at various fixed (discrete) energies. In reference 2, comparisons were made between BRYNTRN and Monte Carlo results for monoenergetic protons at various energies, and they were in reasonable agreement considering the numerical difficulty involved in discrete energy calculations (ref. 2) with BRYNTRN. For the buildup-factor method, comparisons made between Monte Carlo and experimental data are shown in figures 1 to 3.

The dose and dose equivalent calculated as functions of depth in tissue with and without an aluminum shield are shown in figures 1 and 2 for normal incident protons at discrete energies of 400, 660, 730, 1500, and 3000 MeV. The limited Monte Carlo results with 0 g/cm^2 shielding are obtained from reference 9. The calculated values with the buildup-factor method are in reasonable agreement despite the crudeness in the buildup parameters chosen. Although there are no Monte Carlo data available with shielding at discrete energy, the doses calculated with 30 g/cm^2 of aluminum shield by the buildup-factor method are also presented in the figures for qualitative comparison. In general, the dose is increased because of the presence of the shield. The increase in dose over those with no shielding results from neutrons produced in aluminum, especially in the first few centimeters of the tissue. For protons at the lowest energy (400 MeV), the Bragg peak appears at 55 cm in depth as the protons approach their limiting range while traveling through the shield and tissue.

Figure 3 shows the comparison of the experimental data (fig. 4 of ref. 7), the buildup-factor calculation, and the interpolated Monte Carlo results (refs. 9, 10, and 11) for the absorbed dose in tissue that is exposed to a proton beam of 592 MeV. Also shown are the earlier (ref. 7) buildup-factor calculations for uncollided primary and total absorbed dose. The dose from the buildup, which is the difference between the total and uncollided primary, is substantial. The usual Bragg peak is also obvious for both the analytical and experimental results. The buildup-factor calculations are in general within the uncertainties of interpolated Monte Carlo values and are in reasonable agreement with the experimental data.

To verify both BRYNTRN and the buildup-factor method in case of a continuous energy spectrum of incident protons, dose calculations were made (figs. 4 and 5) for a shielded tissue exposed to a typical solar-flare spectrum for which Monte Carlo results were available (refs. 12 and 13). The flare spectrum taken from references 12 and 13 of the Webber form (ref. 14) is exponential in rigidity with characteristic rigidity P_0 = 100 MV and is normalized to 10^9 protons/cm^2 with energy greater than 30 MeV. Only the portion of the spectrum between 50 and 400 MeV was considered for the Monte Carlo calculation (refs. 12 and 13). Nevertheless, for the current calculations, the high-energy cutoff at 400 MeV was ignored; very small differences of a few percent were found (figs. 4(a) and 5(a)), because the spectrum contains very few highly penetrating energetic protons, which may become significant only at depths beyond current interest. The aluminum shields (fig. 4) and the iron shields (fig. 5) for the tissue were 20 g/cm^2

in thickness. The buildup-factor results presented for iron, however, were obtained with the same values of buildup parameters chosen for aluminum, because the nuclear-reaction cross sections are roughly the same for both materials at the energies of interest (below 400 MeV). The total doses by the buildup-factor method are in good agreement with both Monte Carlo and BRYNTRN results (see figs. 4(a), 5(a), and 5(b)) except at the first few centimeters in tissue depth, where the effect of neutron production in the shield is significant. Therefore, future improvement is needed in the buildup-factor method for treating neutron coupling explicitly.

Detailed dose comparisons are also given between BRYNTRN and Monte Carlo results in figures 4(b), 4(c), and 5(c) to 5(f) for the aforementioned low-energy spectrum. The primary doses are in good agreement where, for the worst case, the discrepancies came partly from the intrinsic nature of the Monte Carlo fluctuations. This fluctuating phenomenon is even more severe for the total secondary dose (figs. 4(c), 5(e), and 5(f)). (The total secondary dose is the sum of the secondary-proton and secondary-neutron doses, as they are termed in references 12 and 13.) The heavy-ion-recoils dose and dose equivalent of BRYNTRN show that the actual physical dose from heavy recoils may not be important, but that the dose equivalent can be significant because of the large quality factor.

Dose calculations are also made for a continuous spectrum that contains more high-energy protons. Since there are no Monte Carlo results available in the high-energy range, the February 1956 solar-flare event is chosen for comparison between BRYNTRN and the buildup-factor method. The solar-flare spectrum given as the integral fluence form in protons/cm^2 is

$$\phi_p(>E) = 1.5 \times 10^9 \exp\left(-\frac{E-10}{25}\right) + 3 \times 10^8 \exp\left(-\frac{E-100}{320}\right) \tag{41}$$

where E is the energy in MeV. The results shown in figures 6(a) and 6(b) are for the dose and dose equivalent in tissue with 0, 10, and 30 g/cm^2 of aluminum shield. The agreement between these two deterministic methods is reasonably good. With the future improvement to include neutron coupling, the buildup-factor method, which is gaining in computational efficiency for flare-dose analysis, would probably be favored in parametric studies of spacecraft shield design.

Concluding Remarks

Comparisons between the buildup-factor method, the baryon transport code (BRYNTRN), and the Monte Carlo method are made for the calculated doses in tissue behind various thicknesses of shielding with exposure to various proton spectra. The results are in reasonable agreement, but there is some overestimation by the buildup factors when the effect of neutron production in the shield is significant. Future improvement, including neutron coupling in the buildup-factor theory, should alleviate the shortcoming. Impressive agreement for various components of doses is obtained between BRYNTRN and the Monte Carlo results.

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Table 1. Buildup-Factor Parameters for Tissue

E, GeV	Dose equivalent				Dose			
	a_1	a_2	a_3	a_4	a_1	a_2	a_3	a_4
*0.03	1.00	0	0	0	1.00	0	0	0
*.06	1.20	0		.0130	1.07	.010		.0100
.10	1.40	.020		.0300	1.10	.040		.0260
*.15	1.45	.065		.0385	1.12	.060		.0310
.20	1.50	.080		.0400	1.15	.062		.0320
.30	1.60	.100		.0330	1.20	.068		.0260
.40	1.80	.120	↓	.0228	1.24	.071	↓	.0228
.73	3.00	.140	.00031	.0160	1.40	.090	.00010	.0150
*1.20	3.90	.150	.00130	.0150	1.67	.094	.00080	.0122
1.50	4.10	.155	.00225	.0140	1.80	.095	.00150	.0120
3.00	4.70	.160	.00270	.0130	2.00	.100	.00200	.0100
10.00	5.60	.250	.00329	.0120	2.30	.111	.00205	.0100

*Interpolated values.

Table 2. Total Tissue Optical Thickness for Protons

E, GeV	$\tau(E)$	E, GeV	$\tau(E)$
0	0	1.300	6.57
.010	.0033	1.500	8.03
.025	.0171	1.700	9.52
.050	.0510	2.000	11.76
.100	.1350	2.200	13.27
.150	.2390	2.400	14.78
.200	.3620	2.600	16.29
.250	.5010	2.800	17.79
.300	.6550	3.000	19.29
.350	.8220	4.000	26.62
.400	1.0040	5.000	33.81
.500	1.4290	6.000	40.84
.700	2.4710	7.000	47.75
.900	3.7430	8.500	57.91
1.100	5.1430	10.000	67.85

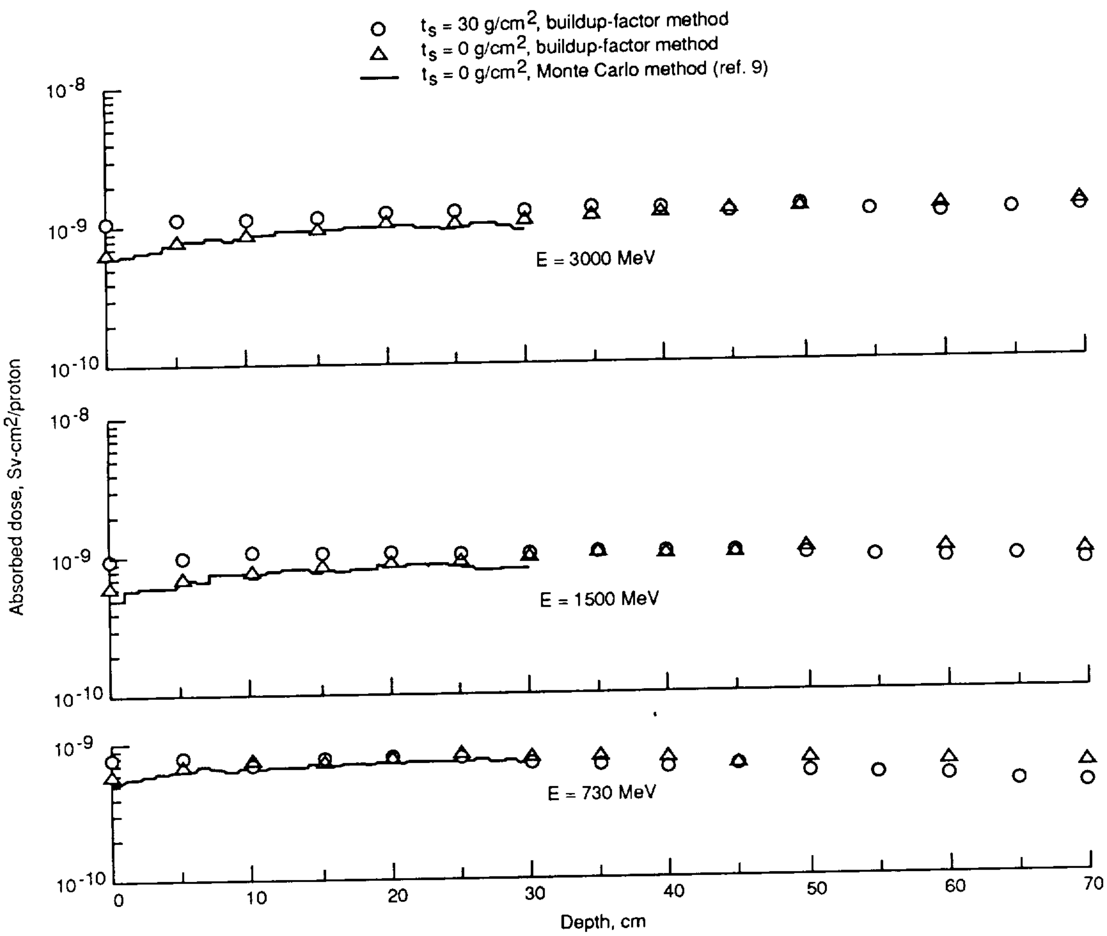


Figure 1. Dose in tissue (with or without aluminum shield) exposed to normal incident protons at various discrete energies.

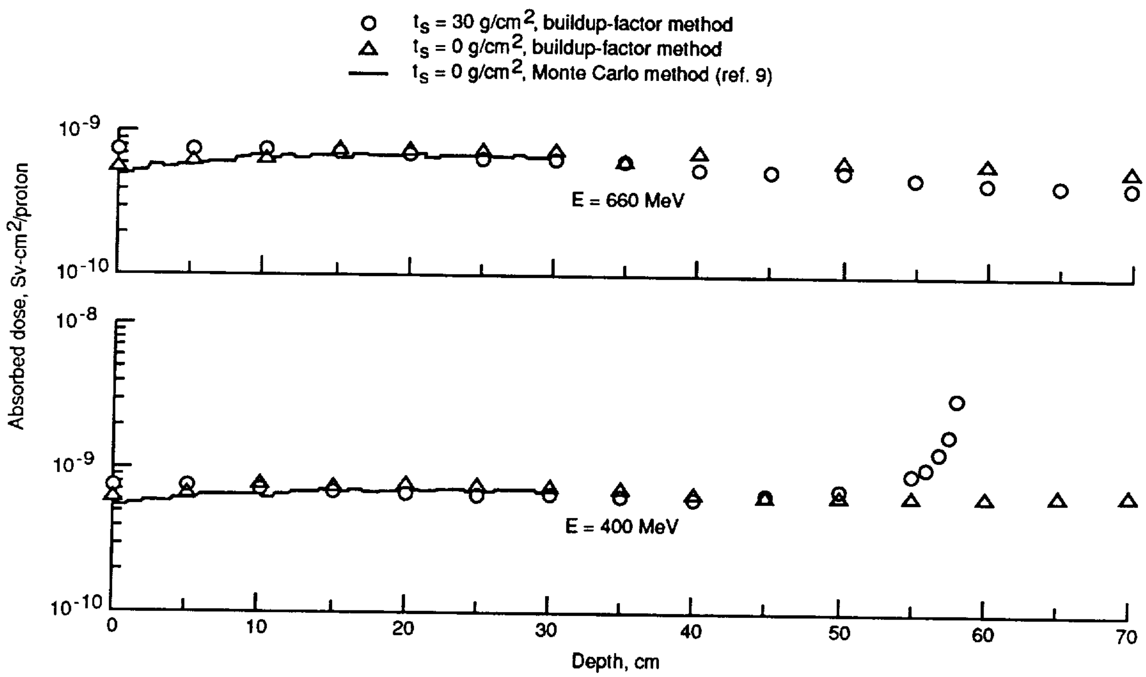


Figure 1. Concluded.

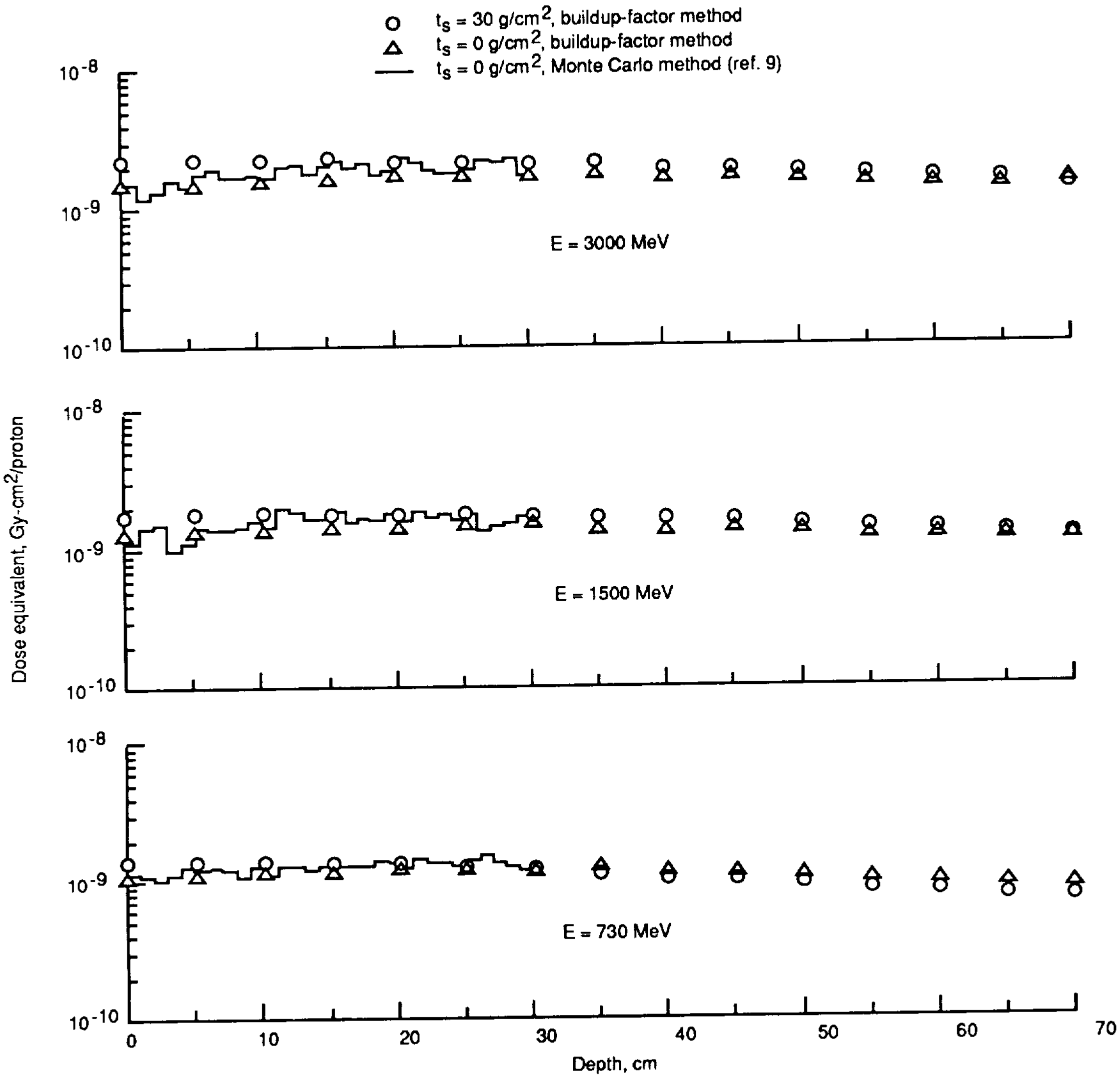


Figure 2. Dose equivalent in tissue (with or without aluminum shield) exposed to normal incident protons at various discrete energies.

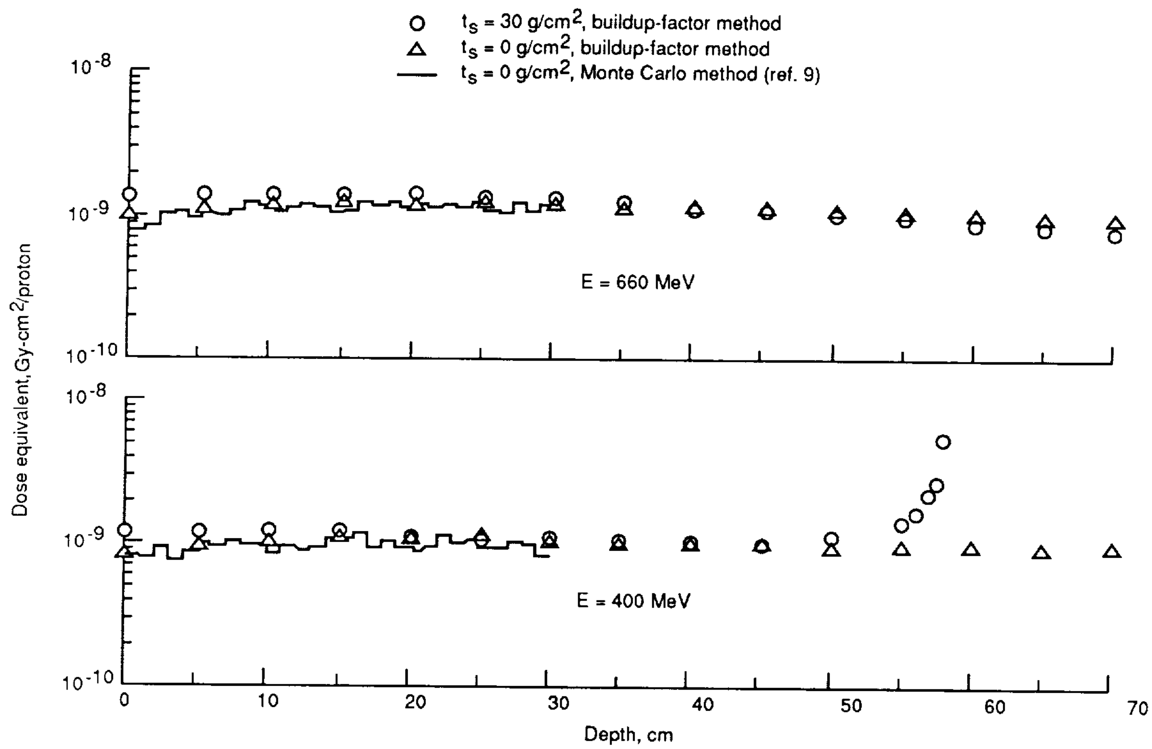


Figure 2. Concluded.

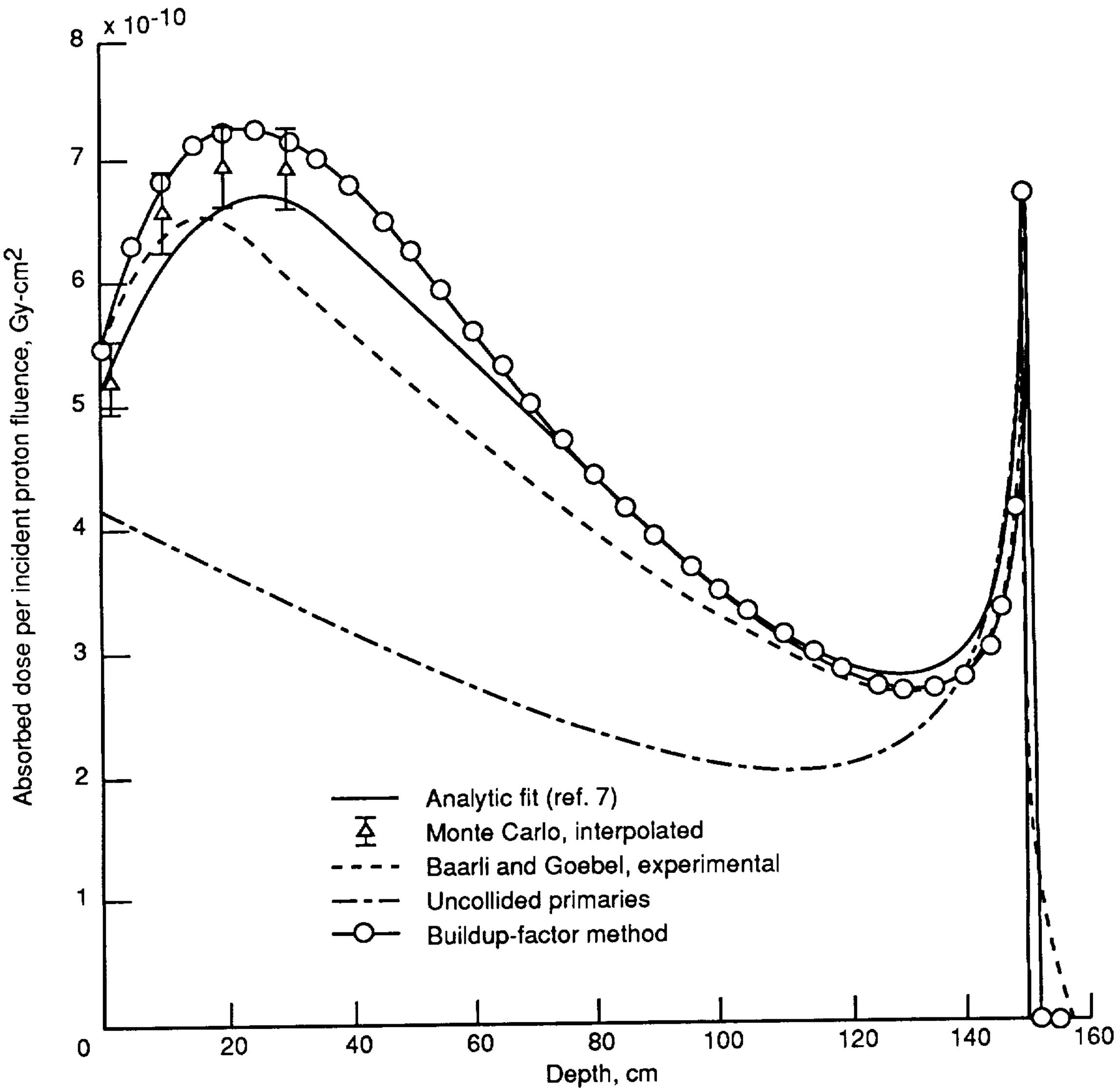
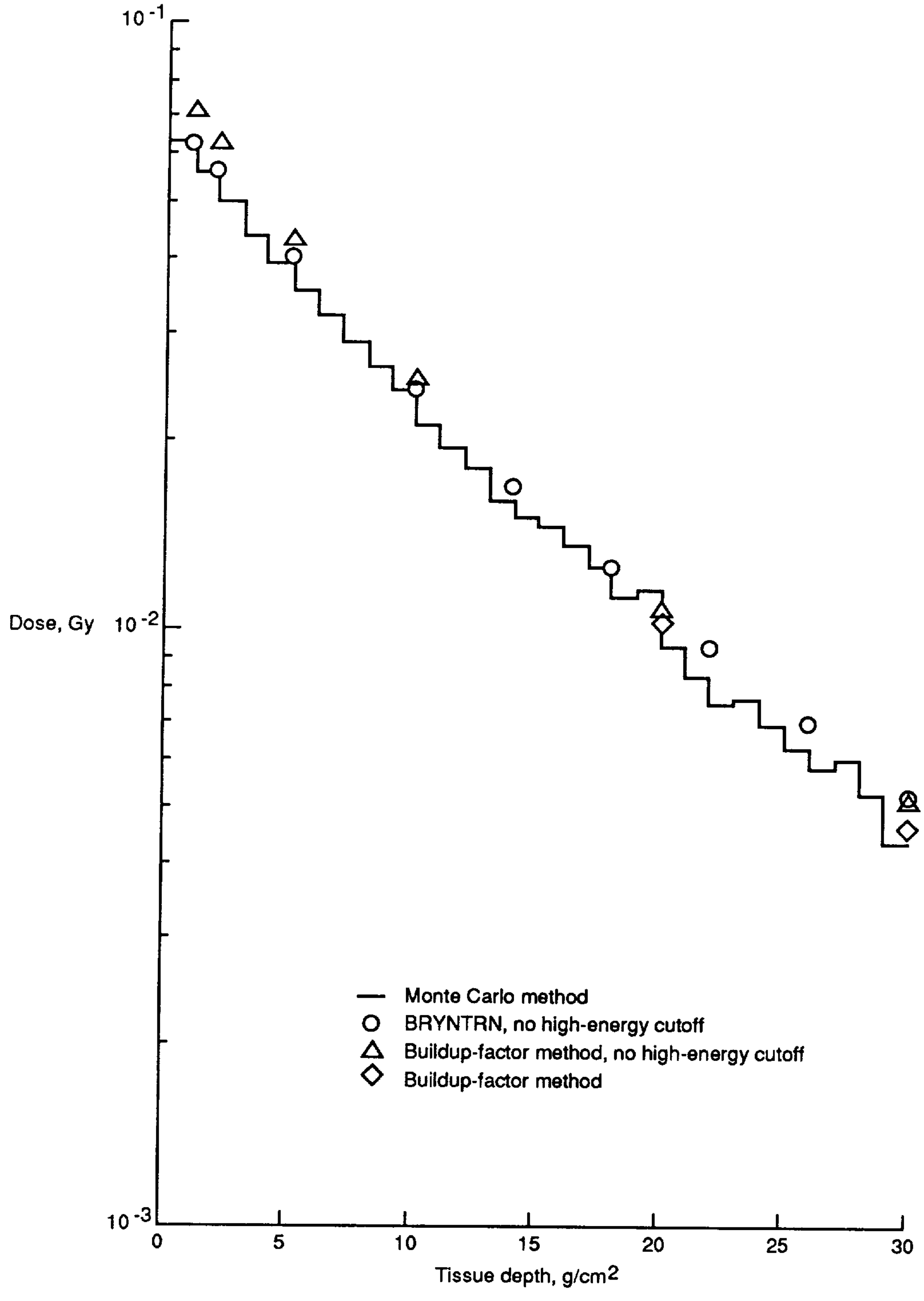
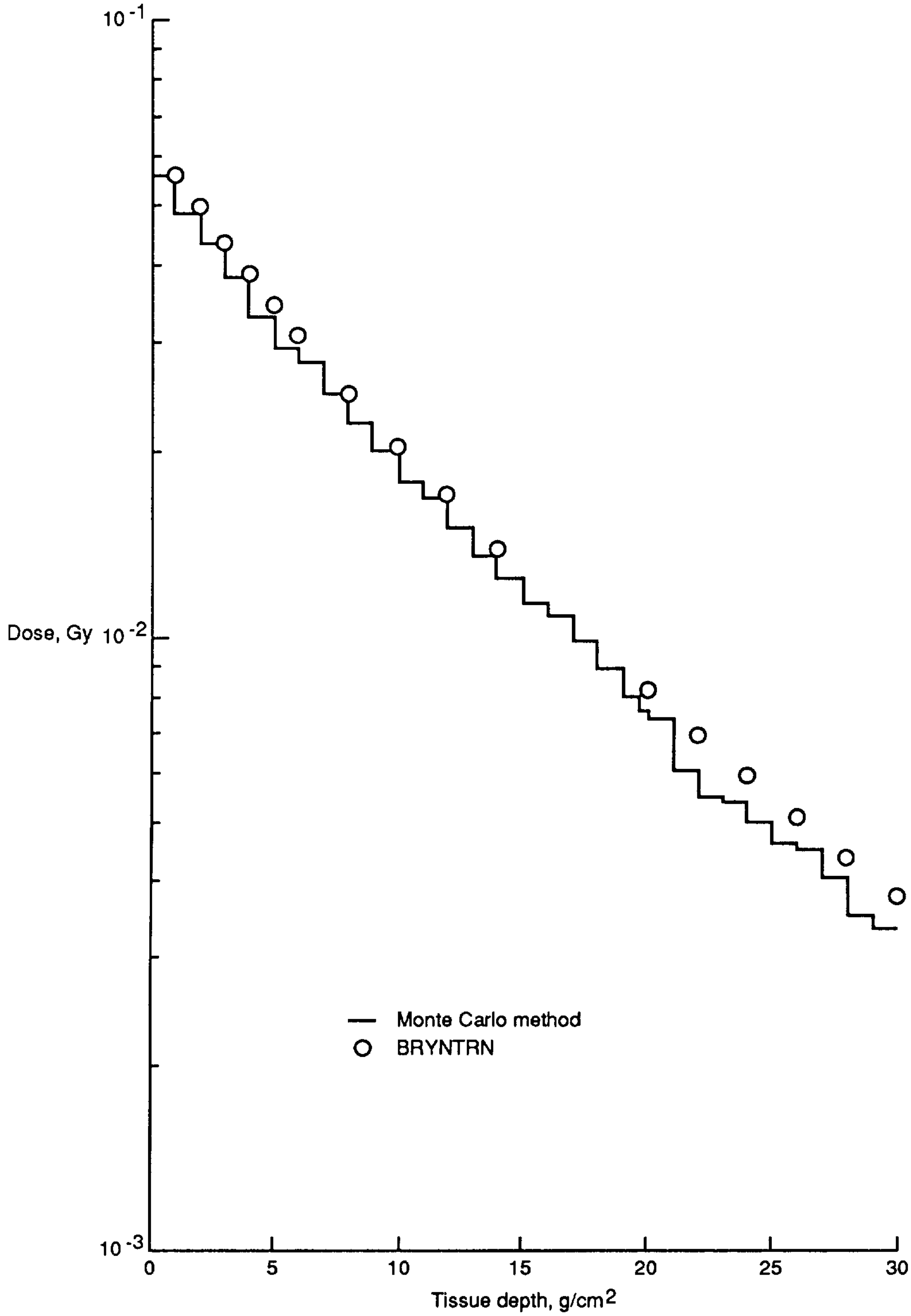


Figure 3. Comparison of predicted dose in tissue with experimental data for normal incident protons at 592 MeV.



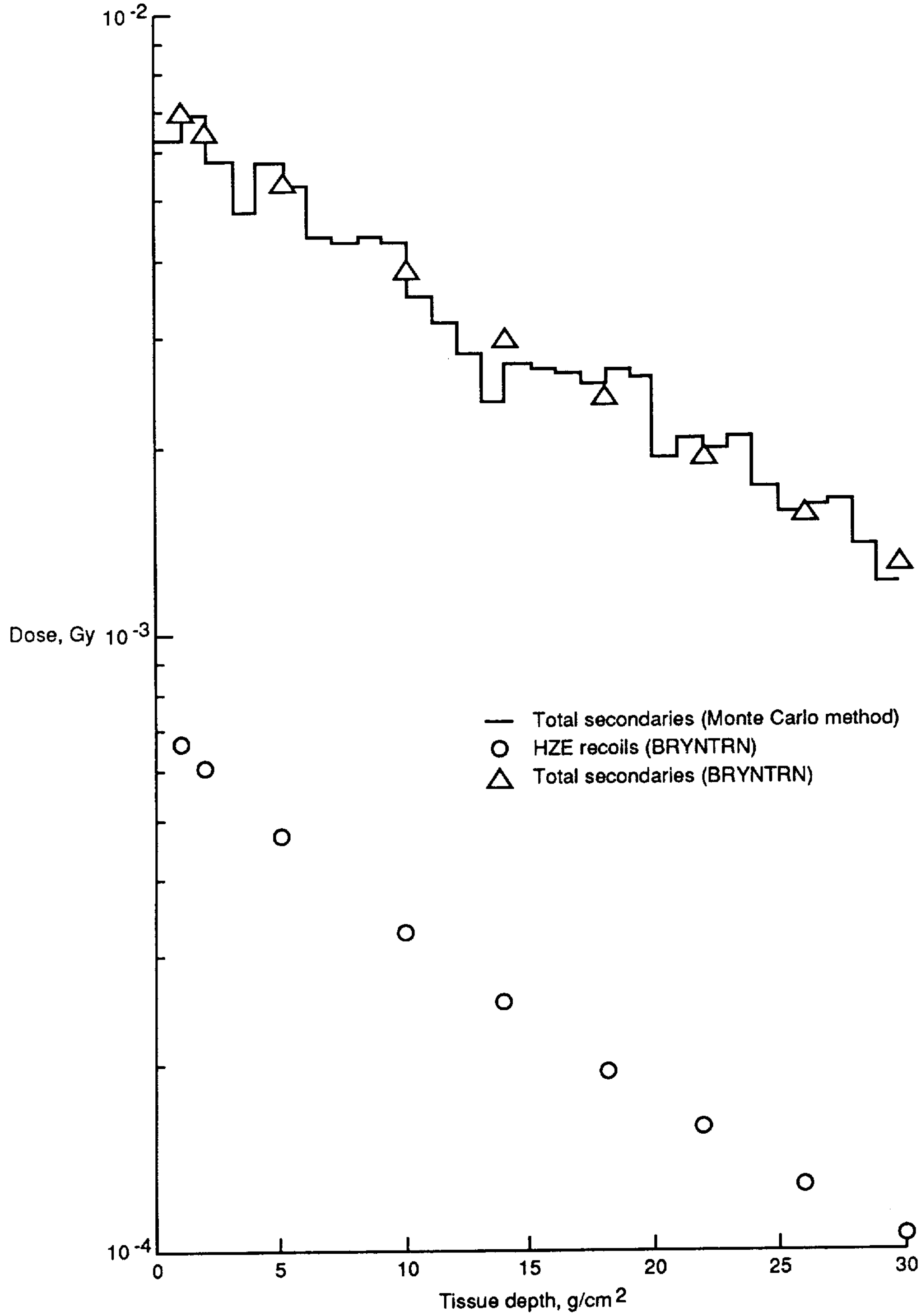
(a) Total dose.

Figure 4. Doses in tissue behind 20 g/cm^2 of aluminum shield to normal incidence of a Webber solar-flare proton spectrum. 100-MV rigidity.



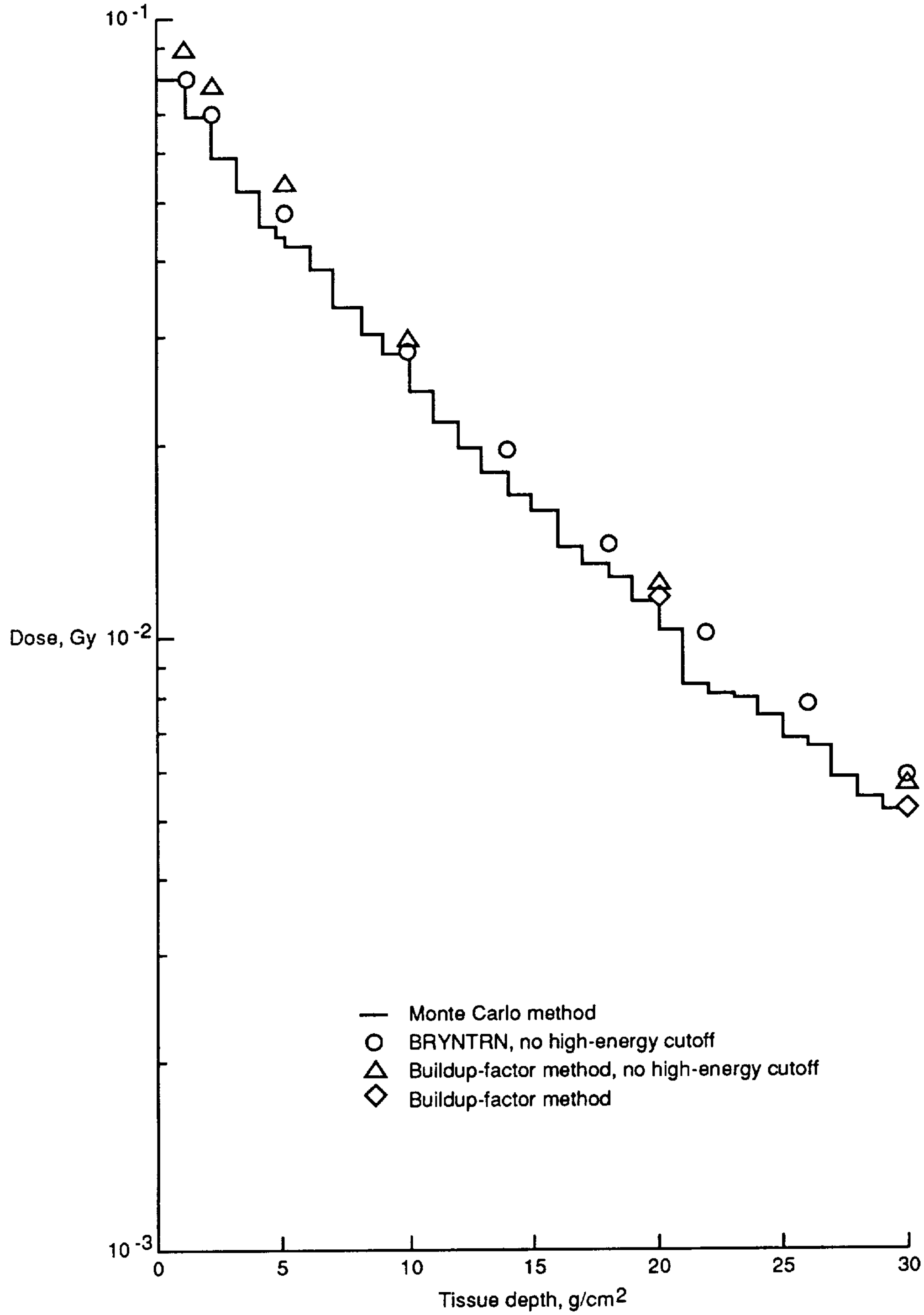
(b) Primary proton dose.

Figure 4. Continued.



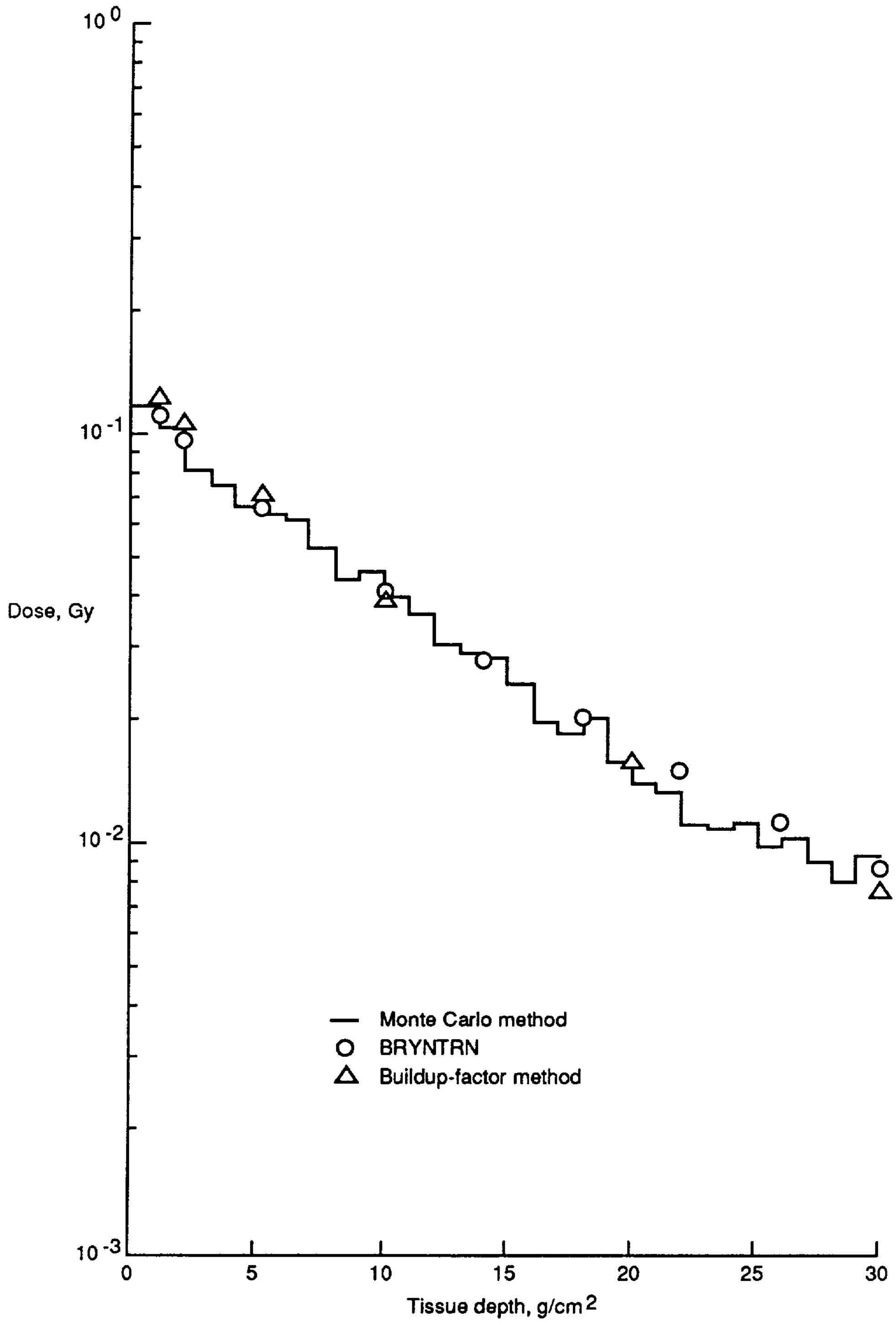
(c) Total secondary and heavy-ion recoil dose.

Figure 4. Concluded.



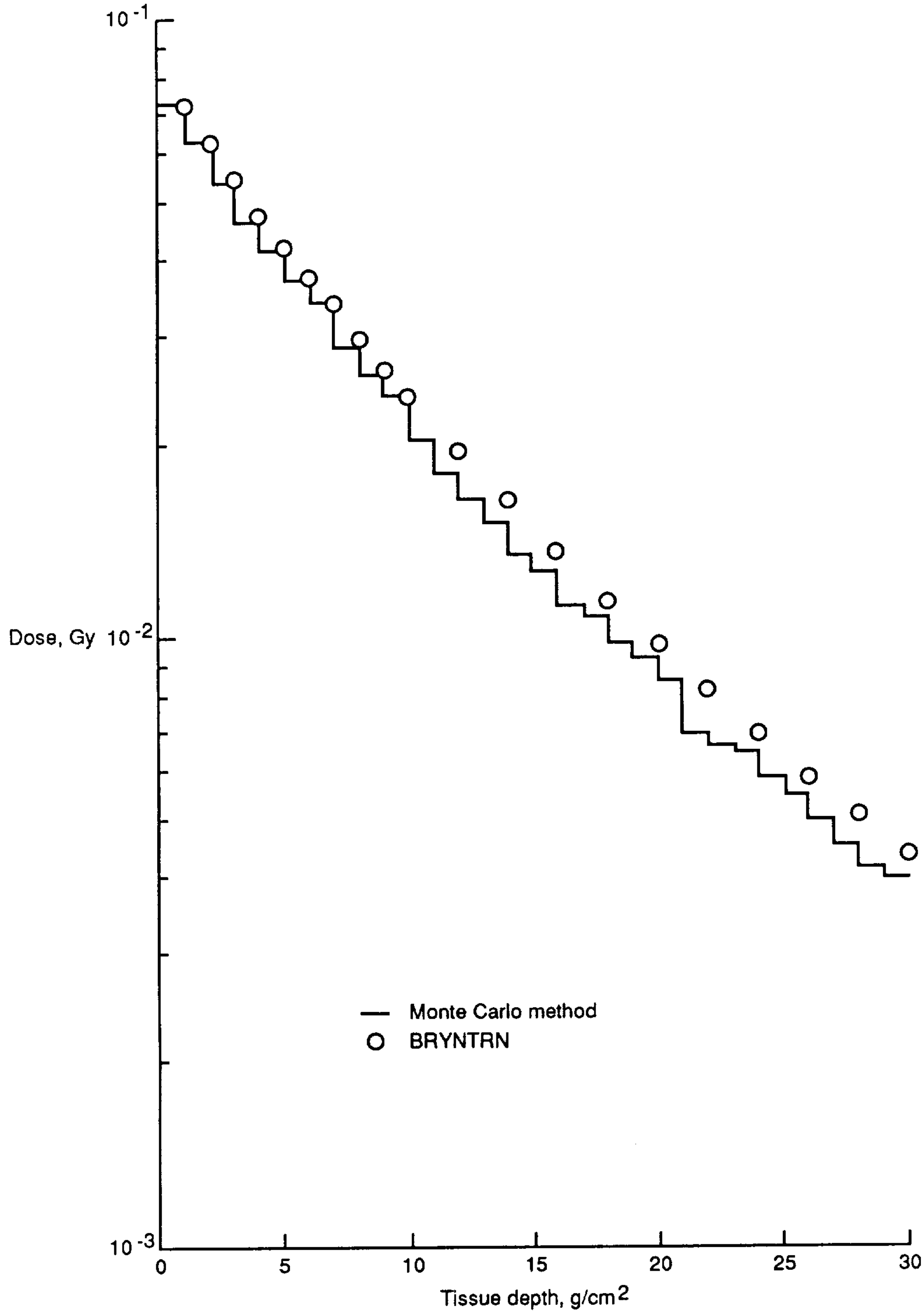
(a) Total dose.

Figure 5. Doses in tissue behind 20 g/cm^2 of iron shield to normal incidence of a Webber solar-flare proton spectrum. 100-MV rigidity.



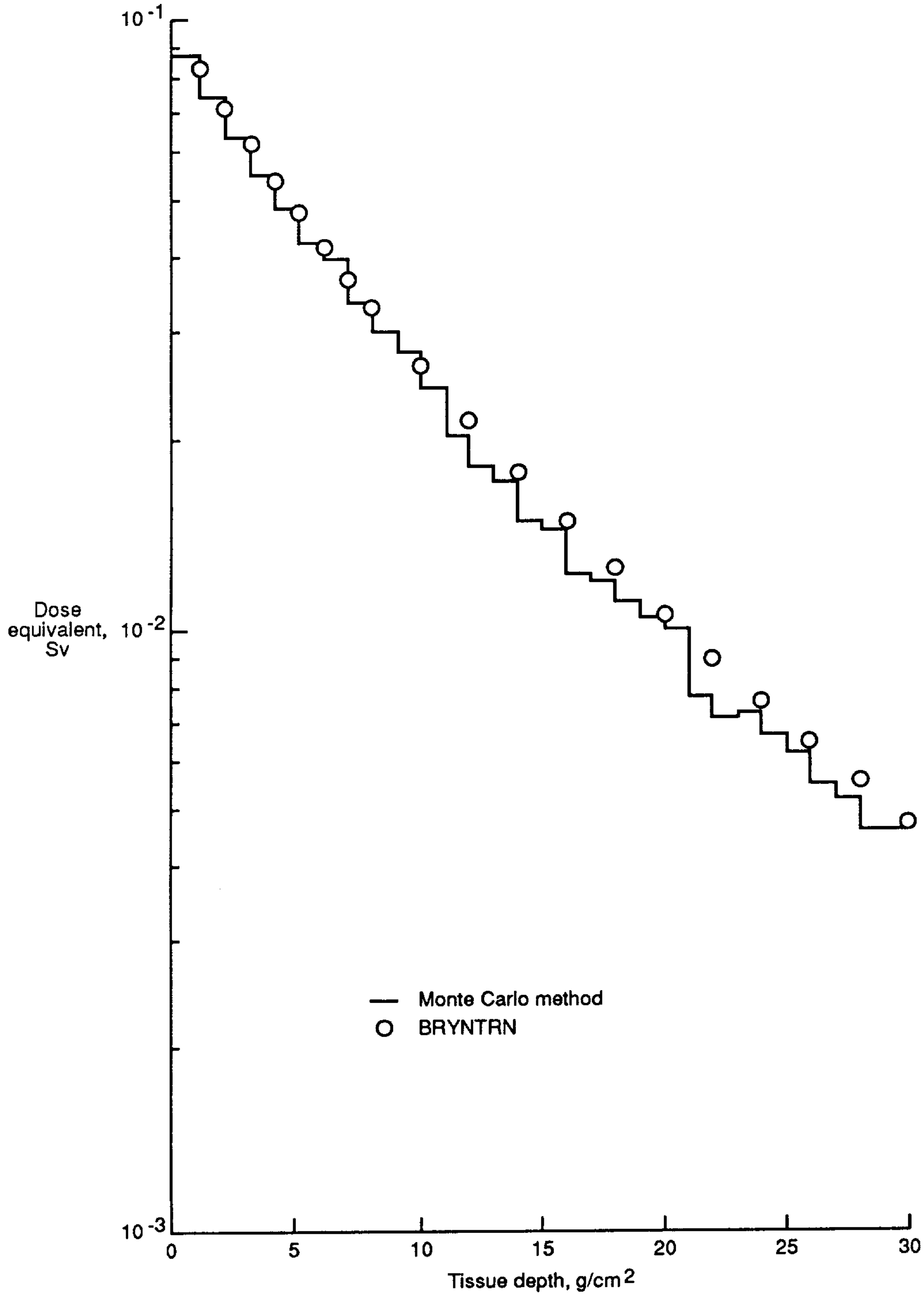
(b) Total dose equivalent.

Figure 5. Continued.



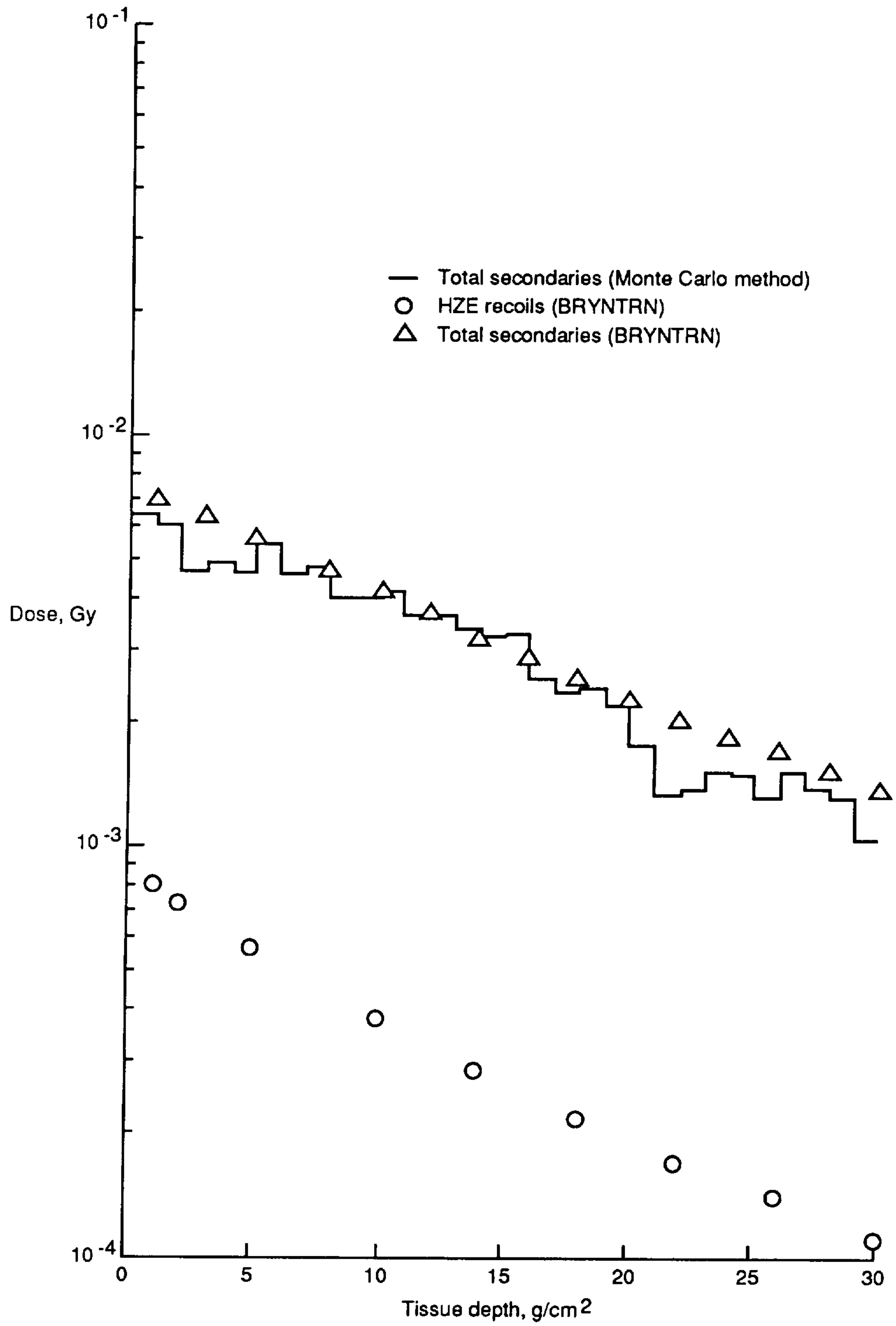
(c) Primary dose.

Figure 5. Continued.



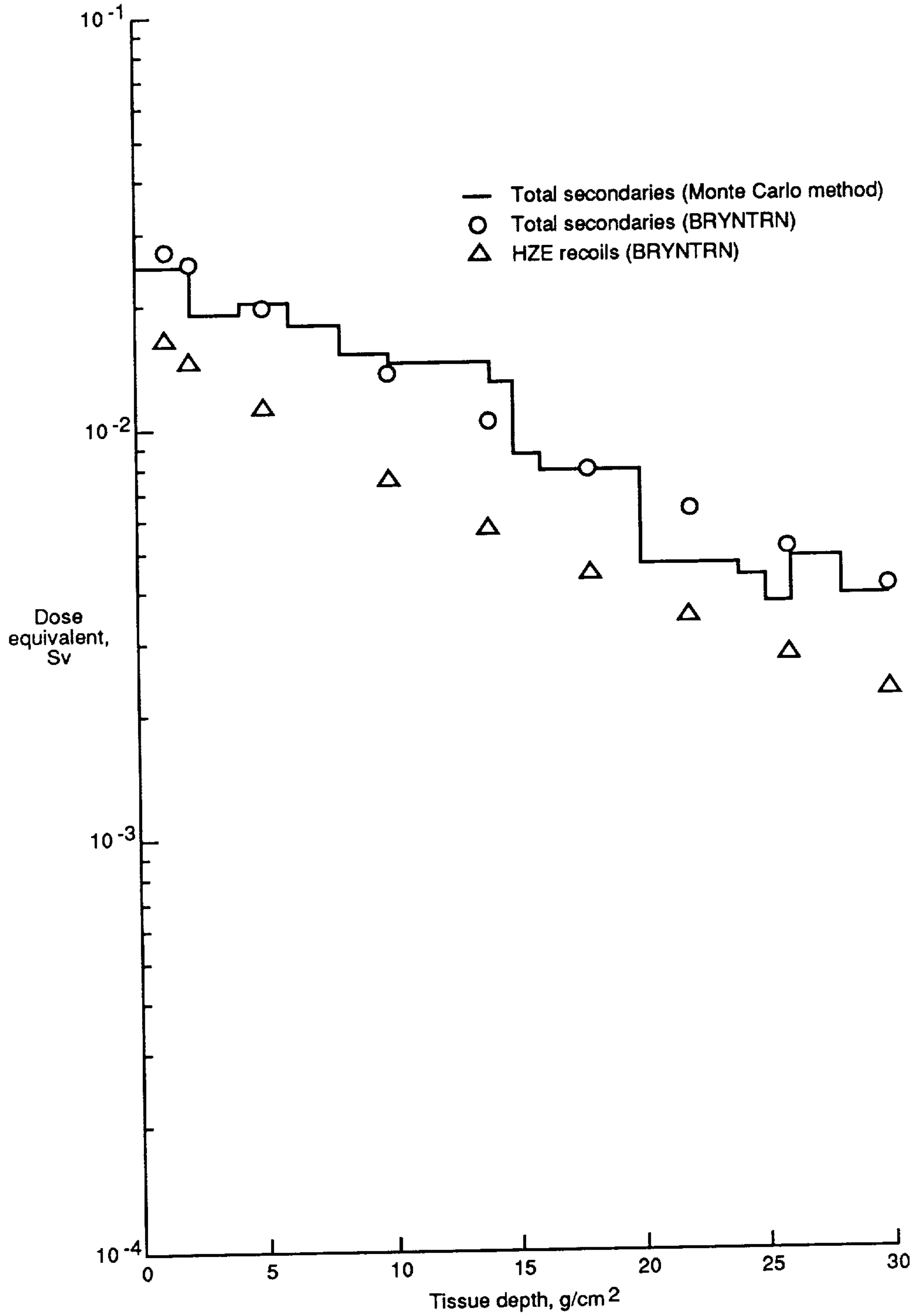
(d) Primary dose equivalent.

Figure 5. Continued.



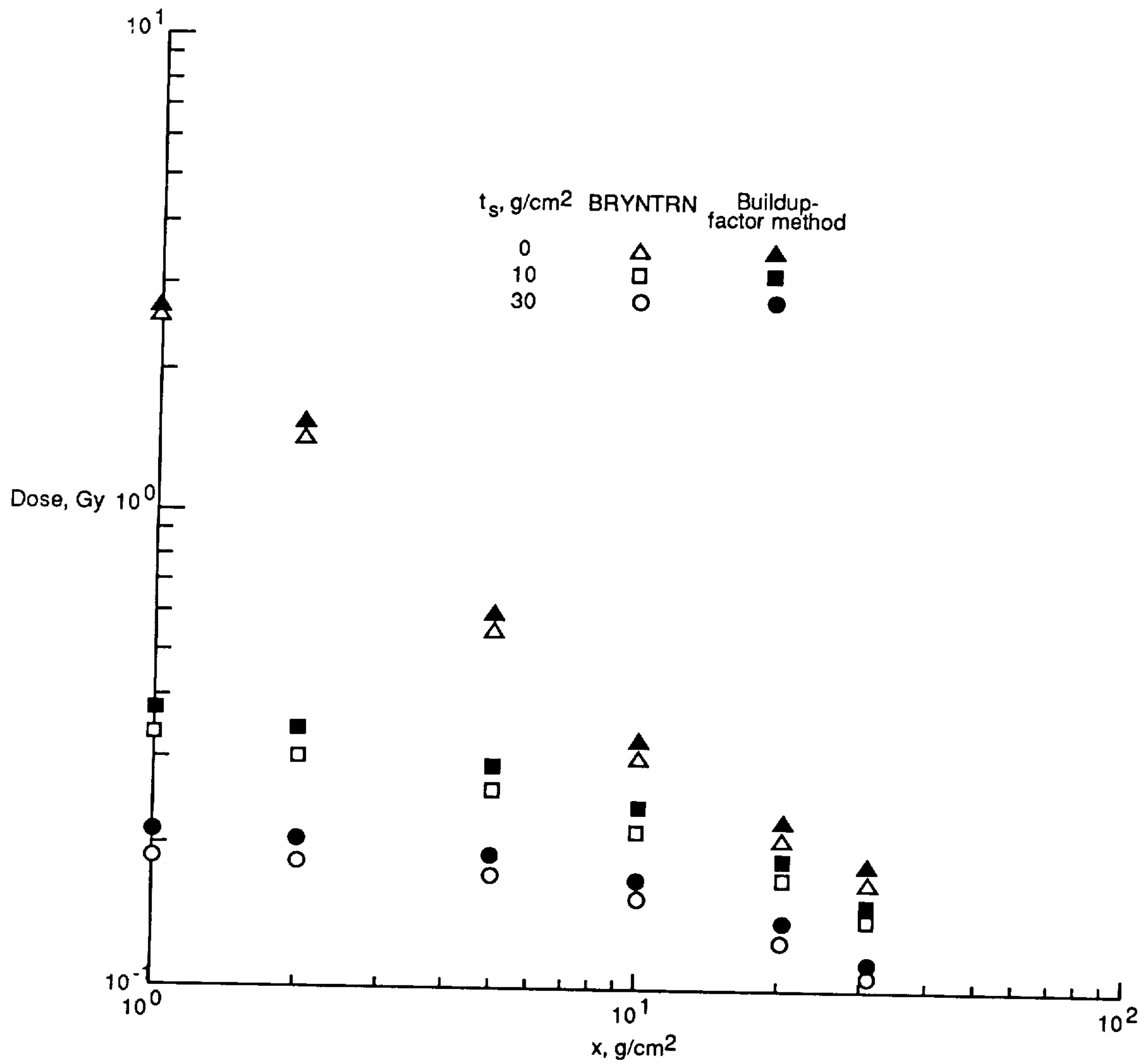
(e) Total secondary and heavy-ion-recoil dose.

Figure 5. Continued.



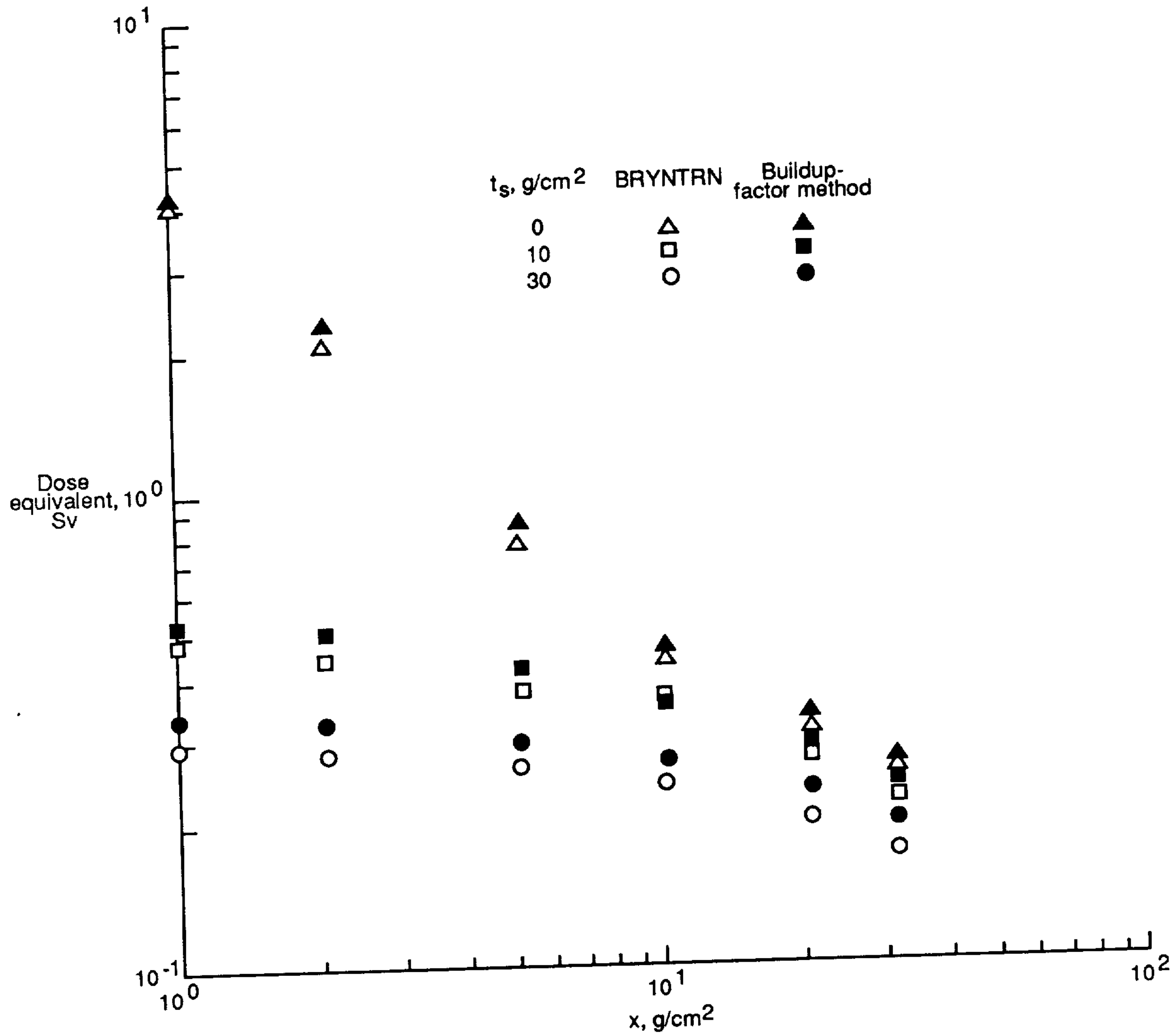
(f) Total secondary and heavy-ion-recoil dose equivalent.

Figure 5. Concluded.



(a) Dose.

Figure 6. Dose in tissue behind various thicknesses of aluminum shield to normal incidence of February 1956 solar-flare event.



(b) Dose equivalent.

Figure 6. Concluded.

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15. Supplementary Notes

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16. Abstract

Results of continuing efforts toward validating the buildup-factor method and the baryon transport code (BRYNTRN), which use the deterministic approach to solving radiation transport problems and are the candidate engineering tools in space radiation shielding analyses, are presented. A simplified theory of proton-buildup factors assuming no neutron coupling has been derived to verify a previously chosen form for parameterizing the dose-conversion factor that includes the secondary-particle buildup effect. Estimates of dose in tissue made by the two deterministic approaches and the Monte Carlo method are compared for cases with various thicknesses of shields and various types of proton spectra. The results are in reasonable agreement but there is some overestimation by the buildup-factor method when the effect of neutron production in the shield is significant. Future improvement, including neutron coupling in the buildup-factor theory, is suggested to alleviate this shortcoming. Impressive agreement for individual components of doses, such as those from the secondaries and heavy-particle recoils, is obtained between BRYNTRN and Monte Carlo results.

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