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Abstract

For extended manned space missions, the radiation shielding design requires efficient and accurate cosmic-ray transport codes that can handle the physics processes in detail. The Langley Research Center galactic cosmic-ray transport code (HZETRN) is currently under development for such design use. The cross sections for the production of secondary nucleons in the existing HZETRN code are energy dependent only for nucleon collisions. The approximation of energy-independent, heavy-ion fragmentation cross section is now removed by implementing a mathematically simplified energy-dependent stepping formalism for heavy ions. The cross section at each computational grid is obtained by linear interpolation from a few tabulated data to minimize computing time. Test runs were made for galactic cosmic-ray transport through a liquid hydrogen shield and a water shield at solar minimum. The results show no appreciable change in total fluxes or computing time compared with energy-independent calculations. Differences in high LET (linear energy transfer) spectra are noted, however, because of the large variation in cross sections at the low-energy region. The high LET components are significantly higher in the new code and have important implications on biological risk estimates for heavy-ion exposure.

Introduction

As the space program proceeds into an era of extended manned space operations, the shielding from galactic heavy ions becomes a problem of ever-increasing importance (ref. 1). The high-energy heavy ions that originate in deep space undergo energy degradation and nuclear fragmentation as they interact with the target nuclei. The nuclear fragmentation results in the production of secondary and subsequent-generation reaction products that alter the elemental and isotropic composition of the transported radiation fields. Accurate knowledge of nuclear fragmentation cross section is needed to better estimate the altered flux and biological quantities for shielding design. (See refs. 2 and 3.) It is also required that the transport calculation be efficient and handle the physics processes in detail, such as energy-dependent cross sections.

A newly developed Langley Research Center galactic cosmic-ray transport code (HZETRN, ref. 4) is a unique, deterministic code that can be used as an engineering tool for shielding design. It is currently under constant improvement and refinement. Recently, the efficiency of the code has been increased tenfold (ref. 5), but some other shortcomings listed in reference 2 remain to be corrected. The major shortcomings of the codes are:

1. All secondary particles from HZE (high-energy heavy-ion) interactions are assumed to be produced with a velocity equal to that of the incident particle; for neutrons produced in HZE particle fragmentation, this assumption is conservative.

2. Meson contributions to the propagating radiation fields are neglected; the light-ion contributions will be implemented in the immediate future.

3. Nucleus-nucleus cross sections are not fully energy dependent (but nucleon-nucleus cross sections are already energy dependent).

4. Backward scattering, a first-order contribution in a three-dimensional effect, is not yet included.

Item 3, with the assumption of energy-independent fragmentation cross sections for the heavy ions, is removed in the current study.

In the following sections, the development of a galactic cosmic-ray transport method that allows all the transport parameters to be fully energy dependent is presented. The secondary production cross section for baryons has already been treated as energy dependent in the BRYNTRN (ref. 6) portion of the HZETRN code (refs. 5 and 4); nonetheless, a formalism is derived for energy-dependent heavy-ion fragmentation cross sections. This formalism will be implemented into the existing HZETRN code. These results are presented in the context of comparing the fully energy-dependent calculation and the previously assumed energy-independent fragmentation cross sections.

Galactic Cosmic-Ray Transport Method

When moving through extended matter, heavy ions lose energy as a result of interaction with atomic electrons along their trajectories. They occasionally interact violently with nuclei of the matter and produce ion fragments that move forward and low-energy fragments of the struck target nucleus. The transport equations for the short-range target fragments can be solved in closed form in terms of collision density (ref. 7). Hence, the projectile fragment transport is the interesting problem. In reference 8, the projectile ion fragments were treated as if they all went straight ahead. The straight-ahead approximation is quite accurate for the near-isotropic, cosmic-ray fluence (ref. 7).

With the straight-ahead approximation and the target secondary fragments neglected (refs. 7 and 8), the transport equation may be written as

$$\left[\frac{\partial}{\partial x} - \nu_j \frac{\partial}{\partial E} S(E) + \sigma_j(E)\right] \phi_j(x,E) = \sum_k \int_E^\infty f_{jk}(E,E')\, \phi_k(x,E')\; dE' \tag{1}$$

where $\phi_j(x,E)$ is the flux of ions of type j with atomic mass A_j and charge Z_j at x moving along the x-axis at energy E in units of MeV/amu, σ_j is the corresponding macroscopic nuclear absorption cross section, $S(E)$ is the stopping power of the protons, $f_{jk}(E,E')$ is a differential energy cross section for production of ion j in collision by ion k, and ν_j is the range scaling parameter that is defined as

$$\nu_j = Z_j^2/Aj \tag{2}$$

Utilizing the definitions

$$r = \int_0^E dE'/S(E') \tag{3}$$

$$\psi_j(x,r) = S(E)\, \phi_j(x,E) \tag{4}$$

and

$$\bar{f}_{jk}(r,r') = S(E)\, f_{jk}(E,E') \tag{5}$$

allows equation (1) to be rewritten as

$$\left[\frac{\partial}{\partial x} - \nu_j \frac{\partial}{\partial r} + \sigma_j(r)\right] \psi_j(x,r) = \sum_k \int_r^\infty \bar{f}_{jk}(r,r')\, \psi_k(x,r')\; dr' \tag{6}$$

which may be rewritten (refs. 9 and 10) as

$$\psi_j(x,r) = \exp\left[-\zeta_j(r,x)\right]\psi_j\left(0,r+\nu_j x\right) + \sum_k \int_0^x \int_r^\infty \exp\left[-\zeta_j(r,z)\right]\bar{f}_{jk}\left(r+\nu_j z,r'\right)\psi_k\left(x-z,r'\right)\,dr'\,dz \tag{7}$$

where the exponential is the integrating factor with

$$\zeta_j(r,t) = \int_0^t \sigma_j\left(r+\nu_j t'\right)\,dt' \tag{8}$$

Simple numerical procedures follow from equation (7). The first-order nature of equation (1) allows $\psi_j(x,r)$ to be taken as a boundary condition for propagation to larger values of x, so equation (7) may be approximated as

$$\psi_j(x+h,r) = \exp\left[-\zeta_j(r,h)\right]\psi_j\left(x,r+\nu_j h\right) + \sum_k \int_0^h \int_r^\infty \exp\left[-\zeta_j(r,z)\right]\bar{f}_{jk}\left(r+\nu_j z,r'\right)\psi_k\left(x+h-z,r'\right)\,dz\,dr' \tag{9}$$

If h is sufficiently small that

$$\sigma_j\left(r'\right)h \ll 1 \tag{10}$$

then, according to perturbation theory (ref. 9),

$$\psi_k\left(x+h-z,r'\right) \approx \exp\left[-\zeta_k\left(r',h-z\right)\right]\psi_k\left[x,r'+\nu_k(h-z)\right] \tag{11}$$

Equation (11) may be used to reduce the integral of equation (9), yielding

$$\begin{aligned}\psi_j(x+h,r) \approx{}& \exp\left[-\zeta_j(r,h)\right]\psi_j\left(x,r+\nu_j h\right)\\ &+\sum_k \int_0^h \int_r^\infty \exp\left[-\zeta_j(r,z)-\zeta_k\left(r',h-z\right)\right]\bar{f}_{jk}\left(r+\nu_j z,r'\right)\\ &\times \psi_k\left[x,r'+\nu_k(h-z)\right]dr'\,dz\end{aligned} \tag{12}$$

Currently, it is assumed that secondary ions j are produced in collision by ion k with the velocity equal to that of the incident ion k for $k > j$ and $k \geq {}^4$He. In the near future, elastic and nonelastic collision spectra that were treated for baryons in detail in reference 6 will be extended to α-particles and light isotopes, so that the following approximation may be applied only for $j \geq {}^6$Li. However, in the present text, the assumption is continued for $Z_j > 1$ and $k > j$ that

$$\bar{f}_{jk}\left(r,r'\right) = \sigma_{jk}\left(r'\right)\,\delta\left(r-r'\right) \tag{13}$$

Using equation (13), equation (12) now becomes

$$\psi_j(x+h,r) \approx \exp\left[-\zeta_j(r,h)\right]\psi_j\left(x,r+\nu_j h\right) + \sum_k \int_0^h dz \exp\left[-\zeta_j(r,z)-\zeta_k\left(r',h-z\right)\right]\sigma_{jk}\left(r'\right)\psi_k\left[x,r'+\nu_k(h-z)\right] \tag{14}$$

where $r' = r + \nu_j z$. Equation (14) is further approximated as

$$\begin{aligned}
\psi_j(x+h,r) &\approx \exp\left[-\zeta_j(r,h)\right]\psi_j(x,r+\nu_j h) \\
&\quad + \sum_k \int_0^h dz \exp\left[-\zeta_j(r,z) - \zeta_k(r,h-z)\right] \sigma_{jk}(r)\ \psi_k\left[x, r+\nu_j\ z + \nu_k(h-z)\right] \\
&\approx \exp\left[-\sigma_j(r)\,h\right]\ \psi_j(x,r+\nu_j h) \\
&\quad + \sum_k \sigma_{jk}(r)\left\{\frac{\exp\left[-\sigma_j(r)\,h\right] - \exp\left[-\sigma_k(r)\,h\right]}{\sigma_k(r) - \sigma_j(r)}\right\}\ \psi_k(x,r+\nu_j h) \\
&\quad + O\left[(\nu_k - \nu_j)\,h\right]
\end{aligned} \tag{15}$$

Equation (15) is the stepping formalism with energy-dependent cross sections for $k >\ ^4$He. The corresponding stepping formalism for nucleons has been discussed in detail in reference 6.

Results and Discussion

As an initial checkout in the implementation of equation (15) to the existing HZETRN code, calculations have been made with water and liquid hydrogen as the target materials. These two materials were chosen because there is more experimental fragmentation data with proton beams at various energies than with any other ion. Hence, the energy dependence of nuclear fragmentation from hydrogen targets is relatively well-known. Moreover, heavy-ion fragmentation cross sections with hydrogen targets tend to show a large variation over the energy range being considered. In the present work, Rudstam's semiempirical formula (ref. 11) of heavy-ion fragmentation cross sections for a hydrogen target is used for convenience. Figures 1 and 2 display a few typical fragmentation cross sections with the hydrogen target (σ_{jk} in cm^2/g) as functions of energy for nickel and iron beams, respectively, with some extrapolation made in the low energy. (1 cm^2/g = 1.67 barn for the hydrogen target.) In the near future, modifications to Rudstam's formalism by Silberberg, Tsao, and Shapiro (ref. 12) will be incorporated into the data base. As for the oxygen target (or any target other than hydrogen), the cross sections are generated by the NUCFRAG code (ref. 13).

To reduce computational time for obtaining energy-dependent fragmentation cross sections, a table of $\sigma_{jk}(E)$ values was generated for use in each calculational step. The table is made up of seven discrete energy points (E = 25, 75, 150, 300, 600, 1200, and 2400 MeV) and covers all the possible j and k ions for $j < k$. The cross section at each range (energy) grid is then obtained by linear interpolation (or extrapolation) from these discrete points. Since Rudstam's formula gives incorrect results at low-energy values for some heavier ions, $\sigma_{jk}(E)$ for $E < 150$ MeV is assumed to be equal to σ_{jk} (150 MeV) for all values of $j < k$ and k = 20 to 28. These results are reflected in figures 1 and 2. The overall computational time for radiation transport is then about the same as for the previous calculation when the energy-independent version of HZETRN (ref. 5) was used.

In the past, GCR (galactic cosmic rays) transport calculations assuming energy-independent cross sections were made by using the asymptotic value of fragmentation cross section at high energies. For comparison purposes, the energy-independent calculations presented herein are obtained by using the newly implemented energy-dependent code with constant cross sections set at the value corresponding to 1 GeV/amu. Results of the GCR transport at the solar minimum using the CREME environment through various thicknesses of liquid hydrogen and water are obtained for energy-dependent and energy-independent calculations. Although the total doses and fluxes do not differ appreciably between these two separate calculations, the differences in energy or LET (linear energy transfer) spectra might alter some biological endpoints significantly. Some detailed spectra are examined in this section.

Individual energy spectra of ion flux ψ for $Z = 27$, 25, and 19 are shown, respectively, in figures 3 to 5 at various depths of liquid hydrogen. Production of cobalt mainly came from fragmentation of nickel, since the latter is more abundant than the former. The larger cross section at lower energy for $j = 27$ and $k = 28$ (fig. 1) explains the increase of flux ψ with depth (for energy-dependent calculation) below 1 GeV/amu over the energy-independent calculation and the slight decrease above 1 GeV/amu, as seen in figure 3. Figure 4 shows a similar trend for manganese from the combined effect of nickel and iron cross sections (figs. 1 and 2 for $j = 25$). The decrease in cross section for $j = 19$ and $k = 26$ at lower energy (fig. 2) explains the reverse trend shown in figure 5. When water is used as the target material, the results are similar but not as pronounced (fig. 6) as for liquid hydrogen. This will be generally true, but the energy dependence of HZE fragmentation on nuclear targets is poorly known and may not be represented well by NUCFRAG.

Action cross sections of several biological endpoints increase at least three orders of magnitude from the lowest LET to 10^3 keV/μm and above (e.g., the action cross section of the Chinese hamster cell survival curve shown in fig. 3 of ref. 14 and the action cross section of *Caenorhabditis elegans* mutation in fig. 5 of ref. 15). This severe increase, however, may not be necessarily neutralized by the lower flux in the high LET region. Thus, differences in LET spectra calculated with energy-dependent and energy-independent cross sections must be considered. Figure 7 reveals the importance of energy-dependent calculation; the ratio of doses and fluxes between the two calculations increases sharply at 10^2 keV/μm and above. At 5 g/cm^2 of liquid hydrogen, the curve indicates a difference of more than 40 percent at 10^3 keV/μm.

Concluding Remarks

A fully energy-dependent version of galactic cosmic-ray transport code is developed by implementing to the existing code a newly derived stepping formalism for heavy ions. Test runs made for a liquid hydrogen shield and a water shield indicate no appreciable change in total fluxes, total doses, or computing time from runs that would have been made with the existing code. Differences in high LET (linear energy transfer) spectra are noted, however, because of the large variation in cross sections at the low-energy region. The LET components above 100 keV/μm are increased substantially and may increase the biological risk for the heavy ions in the galactic cosmic-ray environment.

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October 5, 1992

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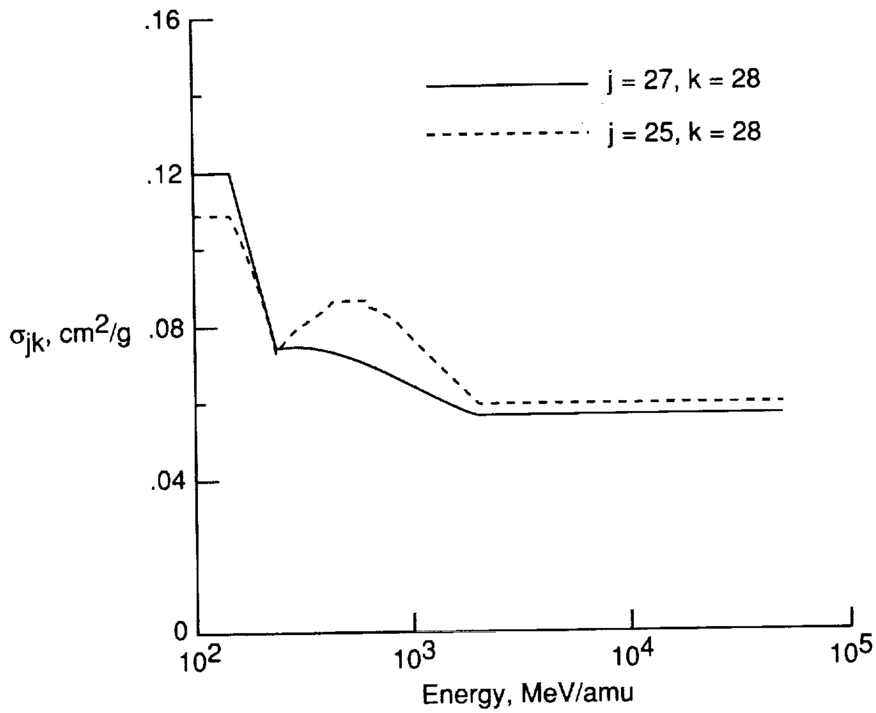


Figure 1. Energy-dependent fragmentation cross section σ_{jk} (production of ion j in collision by ion k) of nickel on hydrogen target in producing cobalt and manganese.

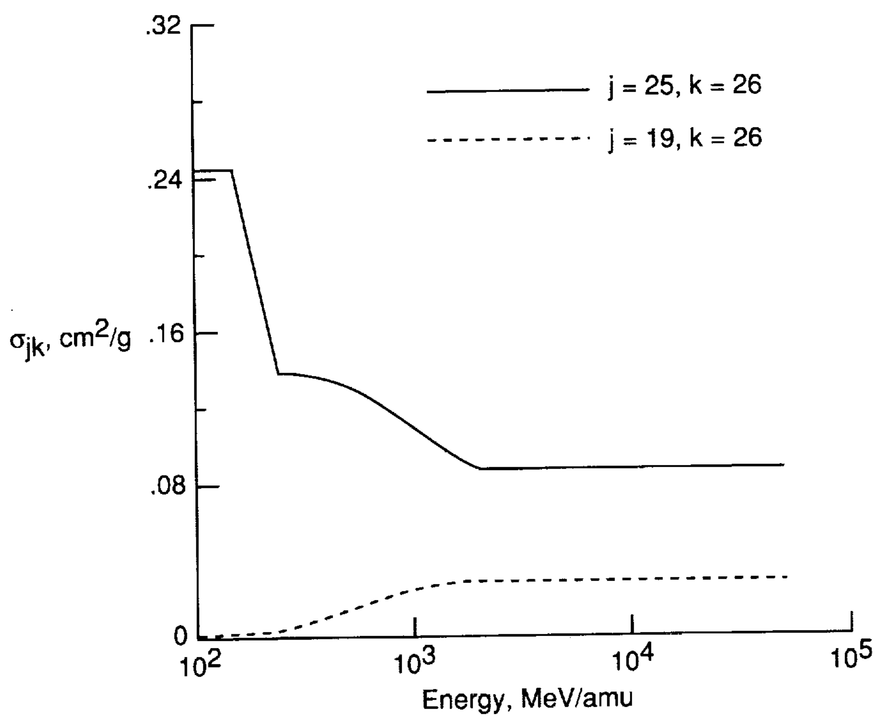
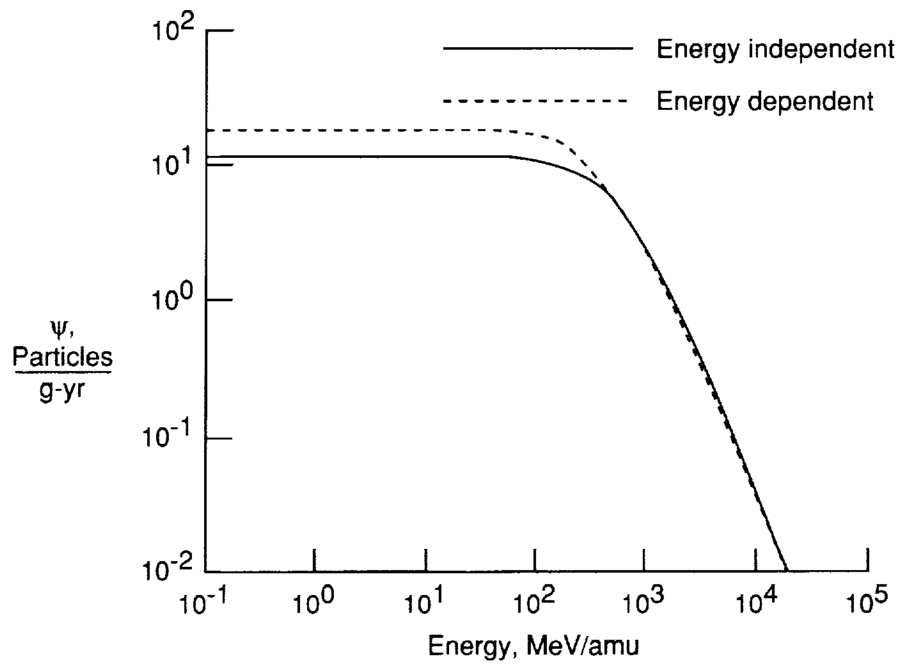
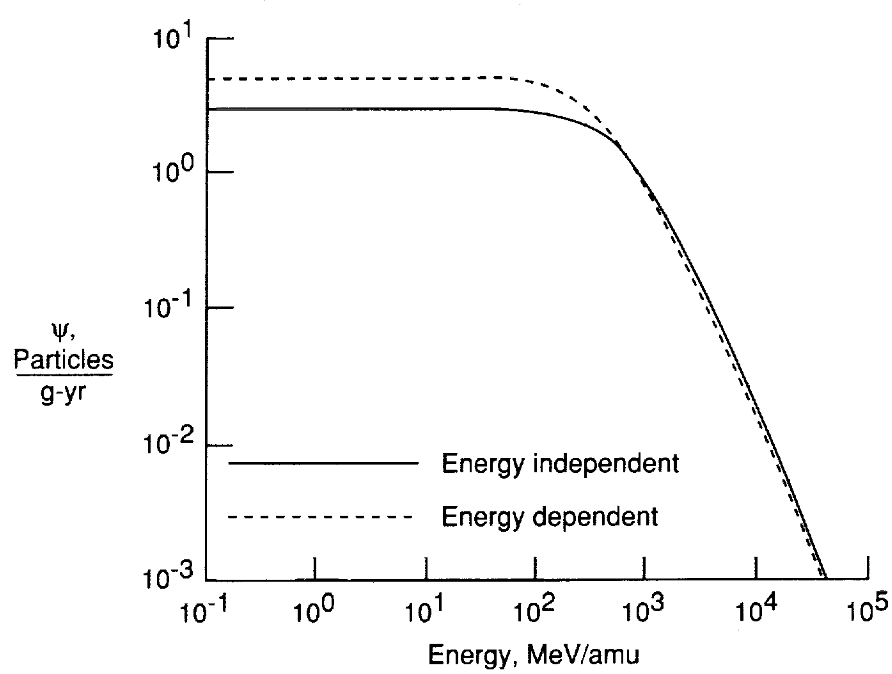


Figure 2. Energy-dependent fragmentation cross section σ_{jk} (production of ion j in collision by ion k) of iron on hydrogen target in producing manganese and potassium.

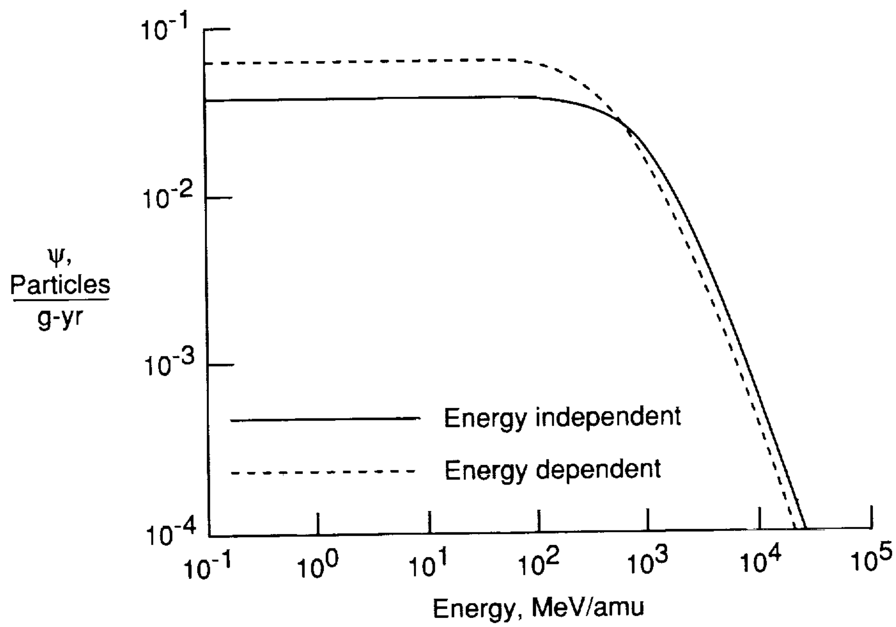


(a) 1 g/cm^2.



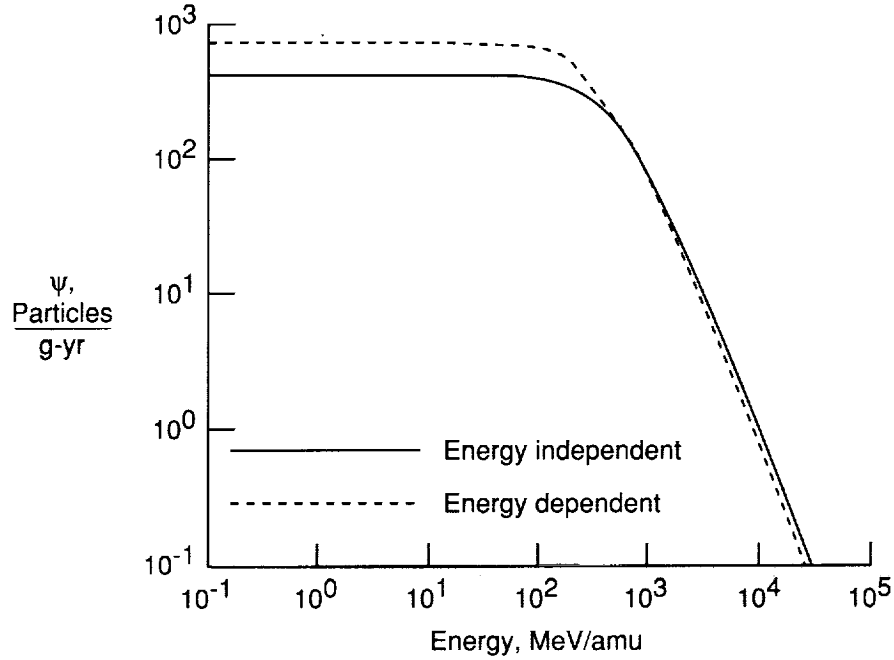
(b) 5 g/cm^2.

Figure 3. Comparison of differential flux (in transformed coordinates) ψ of cobalt (Z = 27) between energy-dependent and energy-independent calculations at various depths of liquid hydrogen shield exposed to galactic cosmic rays at solar minimum per year.

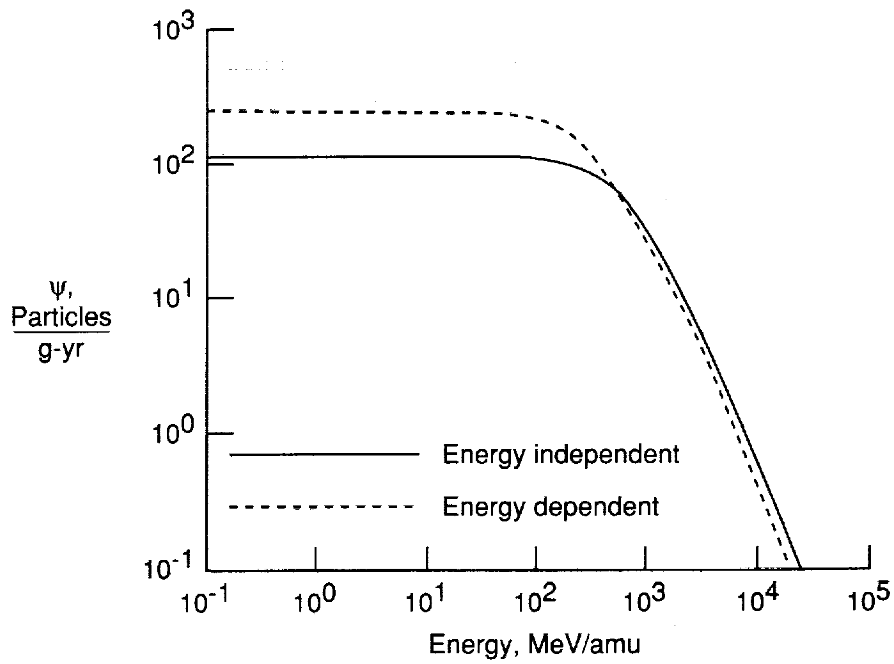


(c) 15 g/cm^2.

Figure 3. Concluded.

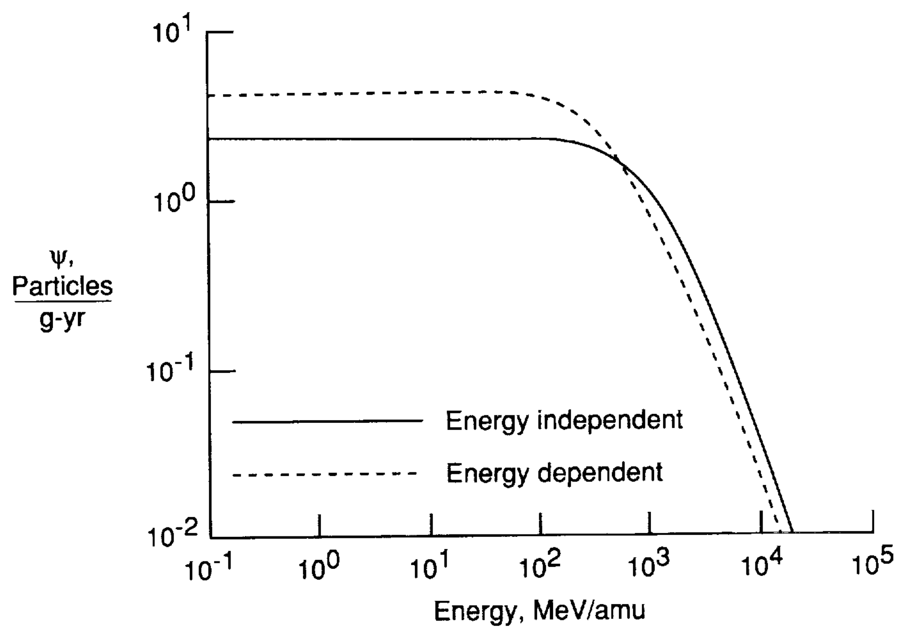


(a) 1 g/cm^2.



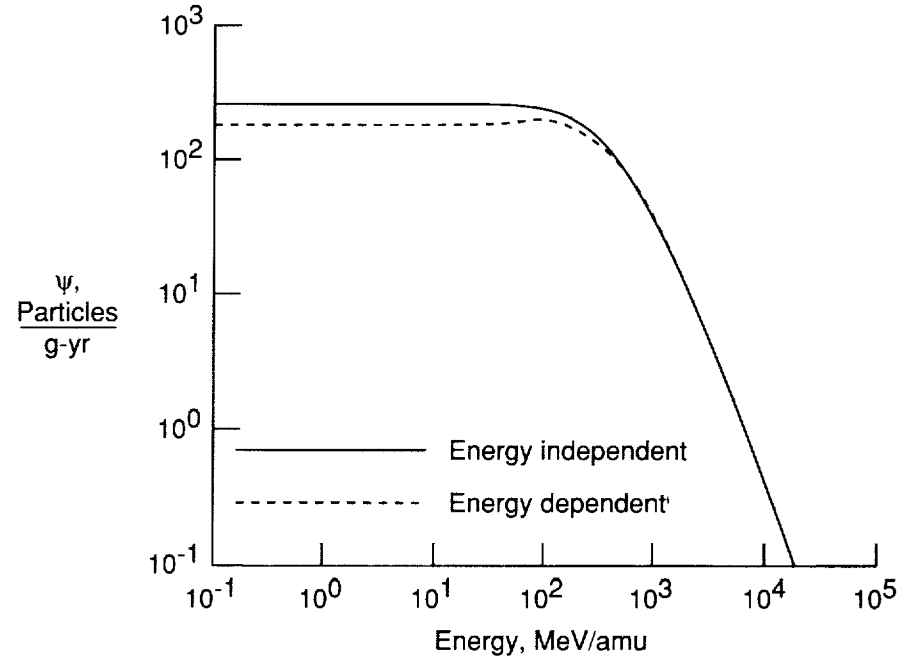
(b) 5 g/cm^2.

Figure 4. Comparison of differential flux (in transformed coordinates) ψ of manganese ($Z = 25$) between energy-dependent and energy-independent calculations at various depths of liquid hydrogen shield exposed to galactic cosmic rays at solar minimum per year.

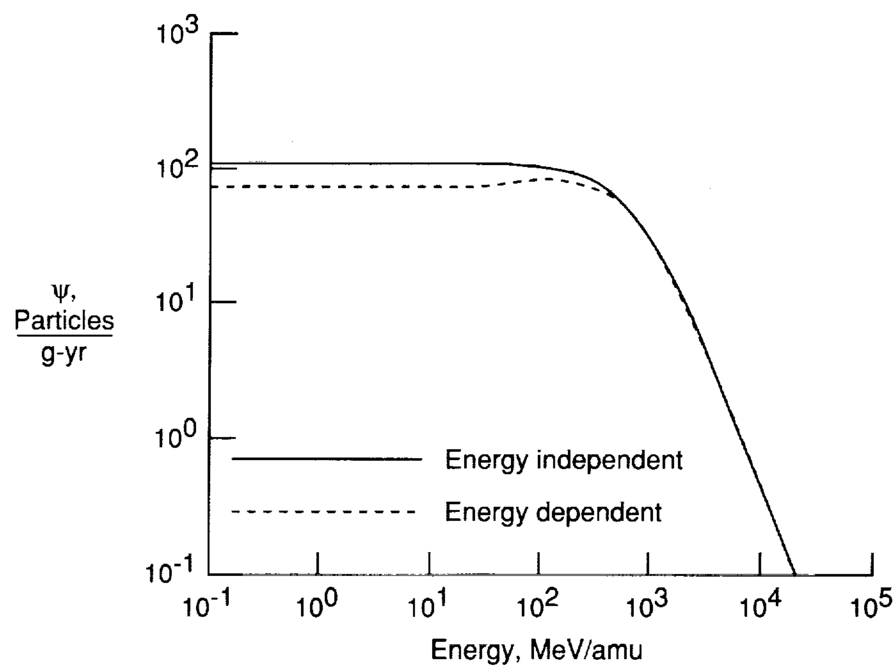


(c) 15 g/cm^2.

Figure 4. Concluded.

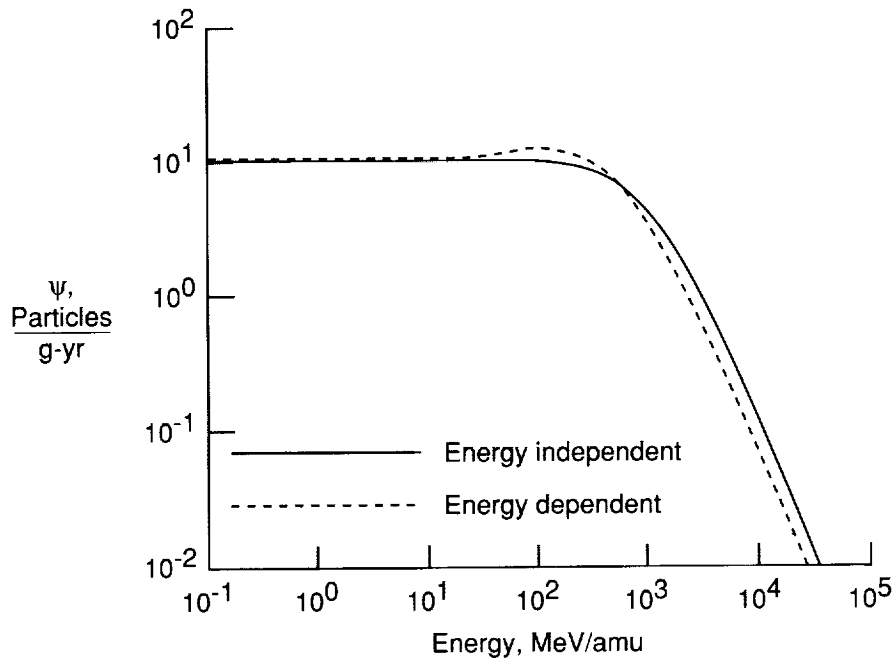


(a) 1 g/cm^2.



(b) 5 g/cm^2.

Figure 5. Comparison of differential flux (in transformed coordinates) ψ of potassium ($Z = 19$) between energy-dependent and energy-independent calculations at various depths of liquid hydrogen shield exposed to galactic cosmic rays at solar minimum per year.



(c) 15 g/cm^2.

Figure 5. Concluded.

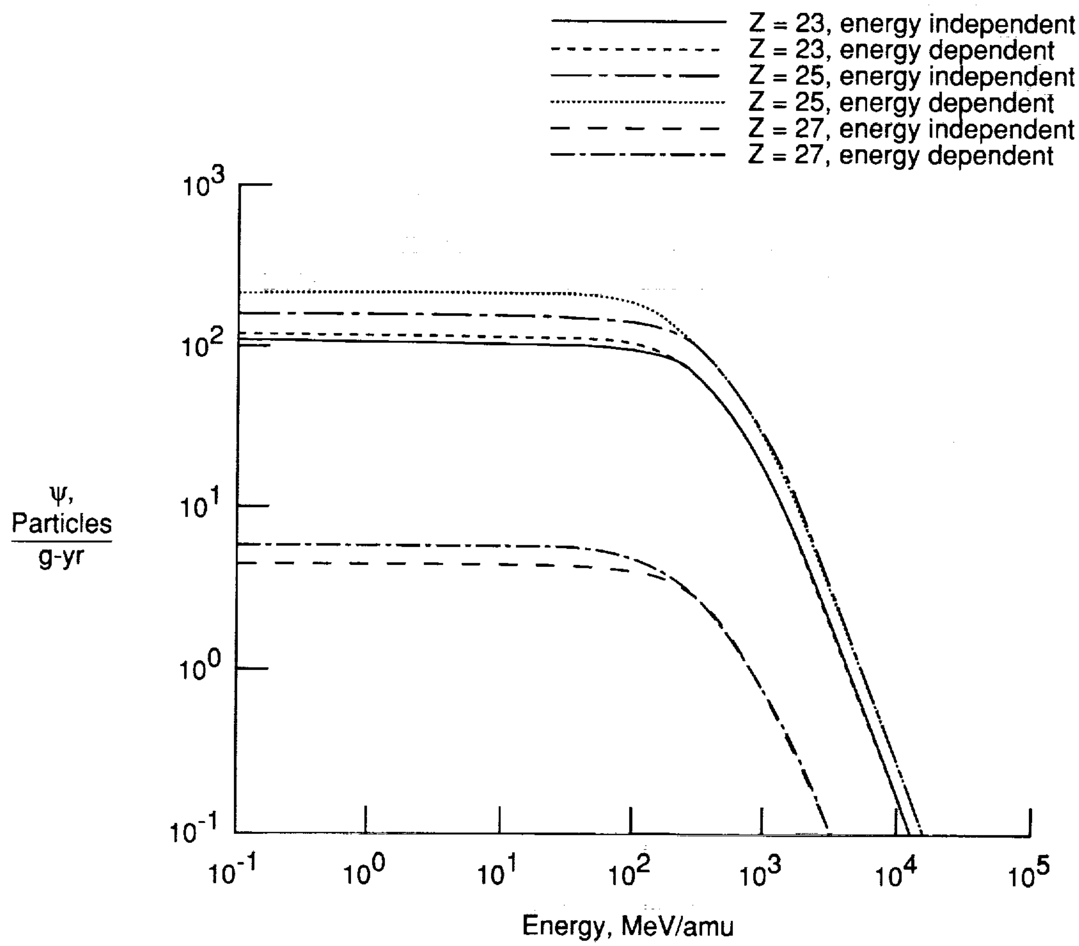
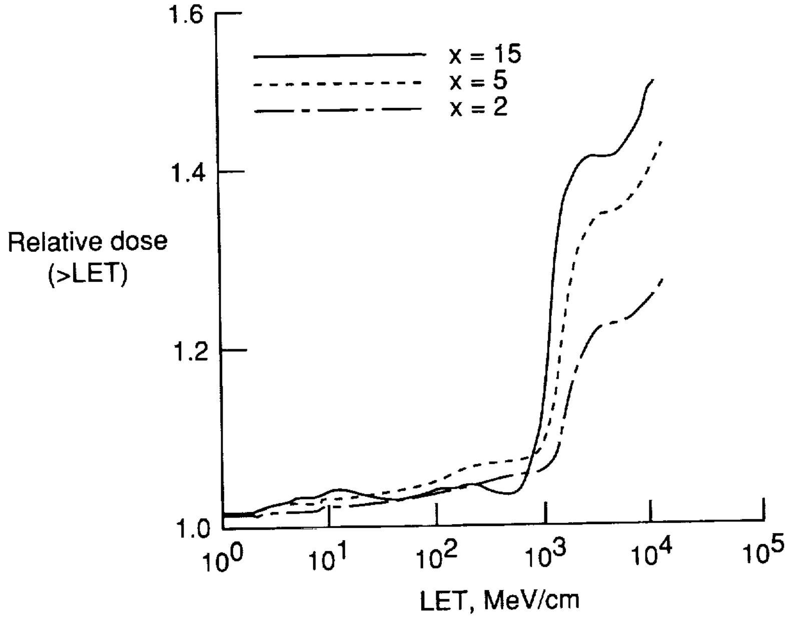
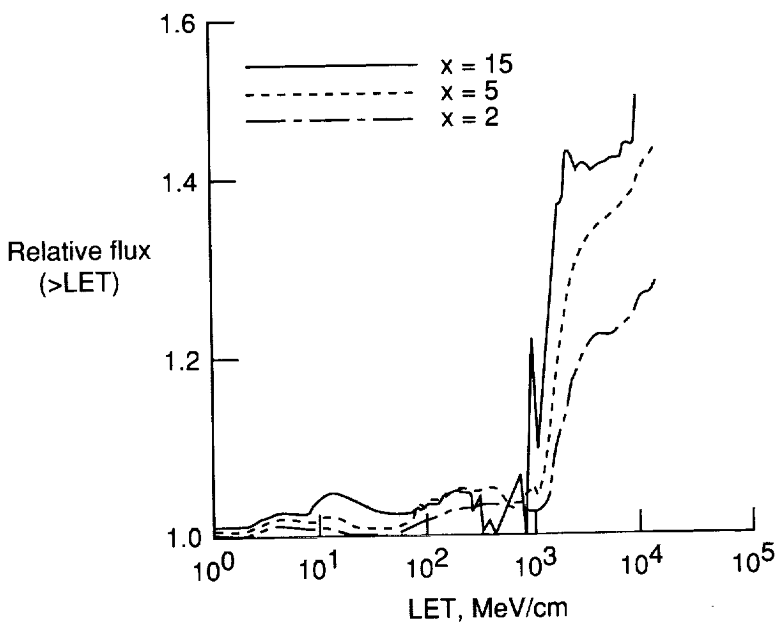


Figure 6. Comparisons of differential flux (in transformed coordinates) ψ of vanadium, manganese, and cobalt between energy-dependent and energy-independent calculations at a depth of 2 g/cm^2 water shield exposed to galactic cosmic rays at solar minimum per year.



(a) Relative dose (>LET).



(b) Relative flux (>LET).

Figure 7. Ratios of LET spectra calculated with energy-dependent cross sections to LET spectra calculated with energy-independent cross sections at various depths of liquid hydrogen shield exposed to galactic cosmic rays at solar minimum.

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