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Abstract

Nuclear fragmentation cross sections of Silberberg and Tsao that are more accurate for a hydrogen target have been implemented in the data base to replace those of Rudstam for a galactic cosmic ray transport code (HZETRN). Sample calculations have been made for the transported galactic cosmic ray flux through a liquid hydrogen shield at solar minimum condition to determine the effect of such a change. The transported flux based on the Silberberg-Tsao semiempirical formalism contains fewer high-LET (linear energy transfer) components but more low-LET components than the results based on Rudstam's formalism; and this disparity deepens as the shield thickness increases. A comparison of the results obtained from using both energy-dependent and energy-independent cross sections of Silberberg and Tsao indicates that the energy-independent assumption results in an underestimation of high-LET flux above 100 keV/μm by approximately 40 percent for a 15-g/cm^2 thickness of liquid hydrogen. Similar results were obtained in a previous study (NASA TP-3243) when both energy-dependent and energy-independent cross sections of Rudstam were considered. Nonetheless, the present study found that an energy-independent calculation would be best accomplished by using Rudstam's cross sections as done in the past for various engineering applications.

Introduction

Estimates of galactic cosmic ray exposure and the required shielding for astronauts during their interplanetary mission rely on radiation transport codes that accurately describe the interactions and propagation of these radiation fields throughout the bulk medium (ref. 1). HZETRN (ref. 2), which is a state-of-the-art galactic cosmic ray transport code developed at the Langley Research Center, contains detailed descriptions of physical processes such as energy loss, nuclear absorption, and fragmentation cross sections of projectile ions. However, the uncertainties of nuclear fragmentation cross sections existing in the code remain fairly large because of the lack of reliable experimental data (ref. 3). This condition is especially true for collisions of heavy ions on heavy ions for which the results of NUCFRG (ref. 4), based on a semiempirical abrasion-ablation model, are used as inputs to HZETRN. (Note that an improved version of a heavy ion fragmentation model will be available for use as inputs in the immediate future.) For collisions of heavy ions on protons, Rudstam's semiempirical parameterization (ref. 5) has been used in the existing HZETRN.

Rudstam and Metropolis et al. (refs. 5 and 6, respectively) were the pioneers who systematized high-energy cross section measurements into a useful analytical relationship describing nuclear reactions. These analytical relationships have been revised and improved by many new researchers as new cross-section data become available. The most comprehensive set of semiempirical estimates of cross sections for a hydrogen target is perhaps due to Silberberg and Tsao (refs. 7 and 8), and to the most recent work of Webber, Kish, and Schrier (ref. 9). In the present study, the formulation of Silberberg and Tsao for a hydrogen target will replace that of Rudstam in HZETRN, and the effect of such a replacement will be examined for estimates of galactic cosmic ray exposure using liquid hydrogen as a shield.

Transport Methods

As energetic ions traverse through bulk matter, they lose energy through their interaction with atomic electrons along their trajectories. On occasion, they interact violently with nuclei of the matter and thus produce ion fragments or secondary nucleons moving in the forward direction and low-energy fragments of the struck target nucleus. The transport problem for the short-range target fragments can be easily solved in closed form in terms of collision density (ref. 10) and treated separately. Hence, the projectile-ion fragment or secondary nucleon transport is the remaining problem of interest. In the previous work (ref. 10), the projectile-ion fragments and secondary nucleons were treated as if all went straight ahead (ref. 11). The straight-ahead approximation is found to be quite accurate for the nearly isotropic cosmic ray fluence (ref. 10).

Because of the long range of the coulomb force and the large percentage of the material volume being occupied by electrons, the electron interactions can, to a good approximation, be treated as a continuous slowing-down process over any finite path length. Although the energy lost by an ion over some fixed path length fluctuates about a mean value, this fluctuation amounts to no more than a few percent (refs. 12–15) and is of no importance in the study of space radiation. In the following, a continuous slowing-down theory will be assumed, and the relevant quantity is the average loss per unit of path length.

With the straight-ahead approximation and the target secondary fragments neglected (refs. 10 and 11), 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 (continuous slowing-down approximation) 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

$$\nu_j = \frac{Z_j^2}{A_j} \tag{2}$$

The solution to equation (1) is found to be subject to the boundary condition at $x = 0$ (that is, $\phi_j(0, E)$), which is the incident beam spectrum.

By transforming the heavy ion transport equation to an integral along the characteristic curve of that particular ion (ref. 10) and using the perturbation theory (ref. 16), the solution to equation (1) is given as a stepping procedure with step size h in the x-direction (ref. 17). Thus,

$$\begin{aligned} \psi_j(x + h, r) \approx {} & \exp[-\zeta_j(r, h)]\, \psi_j(x, r + \nu_j h) \\ & + \sum_k \int_0^h \int_r^\infty \exp[-\zeta_j(r, z) - \zeta_k(r', h - z)]\, \overline{f}_{jk}(r + \nu_j z, r') \\ & \times \psi_k[x, r' + \nu_k(h - z)]\, dr'\, dz \end{aligned} \tag{3}$$

where

$$\psi_j(x, r_j) = S(E)\, \phi_j(x, E)$$

r_j is the residual range of ion j given by

$$r_j(E) = \int_0^E \frac{dE'}{S_j(E')}$$

and the exponential is the integrating factor with

$$\zeta_j(r, t) = \int_0^t \sigma_j(r + \nu_j t')\, dt'$$

Currently, we assume for $Z_j > 1$ and $k > j$ that

$$\overline{f}_{jk}(r, r') = f_{jk}(r')\, \delta(r - r') \tag{4}$$

Using equation (4), equation (3) now becomes

$$\begin{aligned}\psi_j(x+h,r) \approx {} & \exp[-\zeta_j(r,h)]\ \psi_j(x,r+\nu_j h) \\ & + \sum_k \int_0^h dz\ \exp[-\zeta_j(r,z) - \zeta_k(r',h-z)]\ \sigma_{jk}(r') \\ & \times \psi_k[x, r' + \nu_k(h-z)] \end{aligned} \tag{5}$$

with $r' = r + \nu_j z$. Equation (5) is further approximated as

$$\begin{aligned}\psi_j(x+h,r) & \approx \exp[-\zeta_j(r,h)]\ \psi_j(x,r+\nu_j h) \\ & \quad + \sum_k \int_0^h dz\ \exp[-\zeta_j(r,z) - \zeta_k(r,h-z)]\ \sigma_{jk}(r)\ \psi_k[x, r + \nu_j z + \nu_k(h-z)] \\ & \approx \exp[-\sigma_j(r)\ h]\ \psi_j(x,r+\nu_j h) \\ & \quad + \sum_k \sigma_{jk}(r) \left\{ \frac{\exp[-\sigma_j(r)\ h] - \exp[-\sigma_k(r)\ h]}{\sigma_k(r) - \sigma_j(r)} \right\} \psi_k(x, r+\nu_j h) \\ & \quad + O[(\nu_k - \nu_j)h] \end{aligned} \tag{6}$$

Equation (6) is the stepping formalism with energy-dependent cross sections for $k > {}^4\mathrm{He}$. The corresponding stepping formalism for nucleons has been discussed in detail in references 8–19. These stepping formalisms are then used to march the solution from the surface boundary to the desired shield thickness.

Nuclear Fragmentation Data Base

Even though the accuracy of the experimental data may improve for specific reactions, a reasonable means of representing data in computational procedures for cosmic ray transport calculation is still a challenge. For HZETRN and other radiation transport codes developed at Langley (refs. 18 and 20), a point representation of the data is avoided because large multidimensional arrays will eventually rival computer storage. Instead, various semiempirical methods suitable for certain target or fragment groups are put together in generating the data base. These semiempirical methods, which are built on available experimental data and some theoretical base describing approximately the systematic variation of reaction cross sections, offer the possibility of implementing any additional necessary correction factors or adjusting some existing parameters.

When a nucleus is collided by high-energy nucleons, some individual nuclear constituents are ejected by direct knockout (ref. 21). The remaining nuclear structure is left in an excited state which seeks an equilibrium minimum-energy configuration through particle emission (ref. 5). This state is the basis of Rudstam's formulation for the systematics of spallation products produced in such collisions. In his formalism, the distribution of resultant isotopes that are related to the statistical nature of the evaporation process (ref. 22) is assumed to be Gaussian centered at the nuclear stability line, and the total change in nuclear mass and the dependence on the incident projectile energy are treated empirically. Following Rudstam's work, Silberberg and Tsao (refs. 7 and 8) later added more corrective factors to the formalism as more experimental data became available. In addition, they added a scaling factor that relates the fragmentation cross section produced on a hydrogen target to that on the heavier target.

Samples of fragmentation cross section σ_{jk} used as inputs to HZETRN are shown as a function of projectile-ion charge Z_k and fragment-ion charge Z_j in figures 1 and 2 for a liquid hydrogen target and in figures 3 and 4 for a water target at various energies of the projectiles. Figures 1 and 3 reflect the results produced by using Rudstam's formalism for the fragments with $Z_j > 2$, whereas figures 2 and 4 reflect those by using the Silberberg-Tsao formalism. For nucleon and helium fragments, the cross sections were obtained from the results of Bertini et al. (refs. 23 and 24). (Note that the cross section shown in the figures has been reduced, for convenience, by a factor of 10 for nucleon fragments and a factor of 4 for helium fragments.) Because the scaling factor in the formalism of Silberberg and Tsao does not give adequate results for a target heavier than hydrogen (ref. 25), the semiempirical abrasion-ablation model (ref. 4) is used in obtaining the cross sections contributed by the oxygen ions in the water target.

For all the cross sections shown in figures 1–4 at three separate projectile energies (150, 600, and 2400 MeV/amu), the peak of the fragments spectra (at constant Z_k) is generally higher as predicted by Rudstam than that predicted by Silberberg and Tsao. Conversely, the spread from the peak to the fragments with lower Z is lower for Rudstam, whereas the zig-zag shape over even and odd Z charges is more pronounced for Silberberg and Tsao. At energies below 150 MeV/amu, some results (not shown) given by Rudstam's formalism are erroneous; thus, for the transport calculations presented herein, the values of cross section at 150 MeV/amu have been extrapolated to below 150 MeV for projectile ions with $Z > 20$, as has been done in reference 17.

Results

By using Rudstam's formalism, several studies were made in the past that involved galactic cosmic ray (GCR) transport calculations through a shield that contained hydrogen atoms, such as water (tissue equivalent) (refs. 26 and 27) or liquid hydrogen (ref. 28). In these calculations, the cross sections were assumed to be energy independent and set equal to the asymptotic values at high energy. Recently, improvements were made to HZETRN by removing the energy-independent assumption; and the effects of such changes to the existing results were examined in terms of LET spectra that showed a substantial enhancement of high-LET components (ref. 17). In the present study, Rudstam's formalism was replaced by that of Silberberg and Tsao, and the effect of that replacement was then examined by comparing the GCR exposure levels behind the liquid hydrogen shield at the solar minimum condition given by the CREME model of reference 29.

The high-LET radiation components are usually degraded to lower LET components as a result of nuclear interactions between projectile and target nuclei, and such processes become more significant as the particles penetrate farther into the shield medium. This degradation is illustrated in figure 5 in which the annual differential dose and dose equivalent are plotted as a function of LET (or L) for 2–, 5–, and 15 g/cm^2 thicknesses of the shield. The spikes seen in the figures correspond to the zero slope of stopping power ($dS/dE = 0$) at minimum ionization (ref. 30) of each ion, with protons starting at the lowest LET followed by increasing Z for the increasing L. Because the LET coordinate is plotted on a logarithm scale, the differential dose $L\ dN/dL$ is converted to $L^2\ dN/dL$ (where $N = \int \phi\ dE$) so that the area under the curve is linearly proportional to the total dose. Similarly, the differential dose equivalent is plotted as $QL^2\ dN/dL$, where the quality Q is a function of L. The magnification in dose equivalent at the high-LET region is a result of the ICRP 60 quality factor (ref. 31).

The differences between the spectra for the fragmentation cross section by Rudstam's formalism (fig. 1) and those by Silberberg and Tsao (fig. 2) as discussed earlier are reflected in the calculated LET spectra for the transported flux through the liquid hydrogen shield. In figure 6(a), the ratio of the LET spectra for the differential flux calculated by using Silberberg and Tsao relative to that by using Rudstam is displayed for the three thicknesses of the shield. The Silberberg-Tsao model produces more lower Z fragments and fewer higher Z fragments, and therefore more lower LET components and fewer higher LET components according to the spikes identified for each ion in figure 5. As a result, the ratio (fig. 6(a)) is higher at LET values near the 100-MeV/cm region and lower at higher values of LET. These deviations from unity become more pronounced as the shield thickness increases. A similar comparison of integral flux LET spectra is shown in figure 6(b) in which the ratio at the lowest LET is almost identical to unity; this indicates that the total flux does not change appreciably because of differences in the fragmentation model.

In the previous study (ref. 17), the removal of the energy-independent assumption was important in the risk assessment of GCR exposure. Using the liquid hydrogen shield as an example, the LET components above 100 keV/μm (or 1000 MeV/cm), which could contribute some biological-risk orders of magnitude higher than the lower components, were shown to increase by 40 percent at a 15-g/cm^2 thickness because of the removal of the assumption. This conclusion was based on the use of Rudstam's formalism. Similar results were obtained in figure 7 with the data base given by Silberberg and Tsao. Note in figure 5 that the region near 10 000 keV/μm was not as critical because of the diminishing flux in this region.

A comparison is made with the transport calculations using the energy-dependent Silberberg-Tsao data base and the energy-independent data base from Rudstam to serve as a reference for the earlier GCR exposure studies made with the old data base and the assumption of an energy-independent cross section which is taken to be the asymptotic value at 2 GeV/amu. The ratio of the two calculations in LET spectra, for both differential and integral flux shown in figures 8(a) and 8(b), respectively, displays almost an oscillatory behavior over a wide range of LET. Thus, some of the differences are probably cancelled out. One arrives at the interesting observation that an energy-independent calculation using the Rudstam cross sections yields results similar to those of an energy-dependent calculation using the Silberberg-Tsao values.

Concluding Remarks

Nuclear fragmentation cross sections of Silberberg and Tsao that are more accurate for a hydrogen target have been placed in the data base for calculations of galactic cosmic ray (GCR) transport. When compared with the old data base of Rudstam, the Silberberg-Tsao model produces fewer higher charge fragments but more lower charge fragments. Sample calculations of GCR transport with a liquid hydrogen shield reflect such differences of cross sections in that the transported flux based on the Silberberg-Tsao model contains fewer high-LET (linear energy transfer) components but more lower LET components. This disparity deepens as the shield thickness increases. When the Silberberg-Tsao cross sections are assumed to be energy independent in the data base, the comparative results indicate an underestimation of the LET components above 100 keV/μm by approximately 40 percent for a 15-g/cm^2 thickness of liquid hydrogen caused by the assumption. Moreover, the present study found that an energy-independent calculation would be best accomplished by using Rudstam's cross sections as done in the past.

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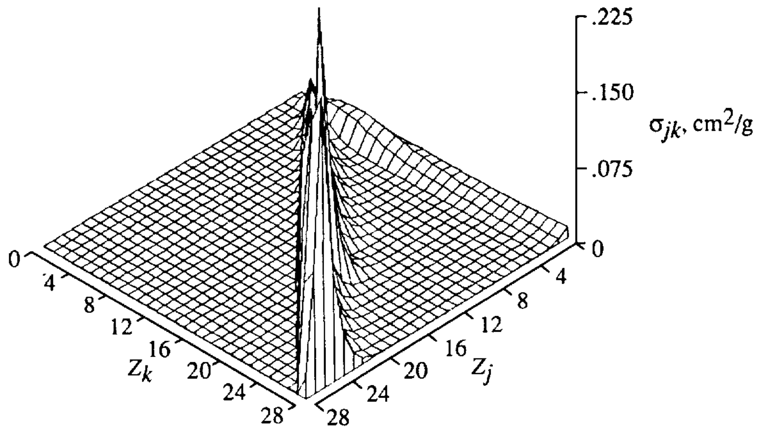
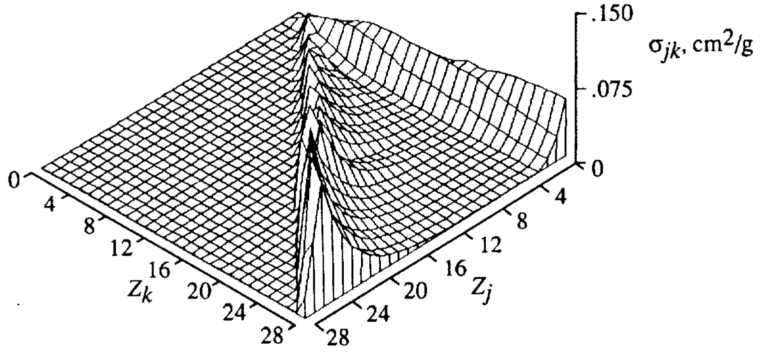


(a) Projectile energy = 150 MeV/amu.



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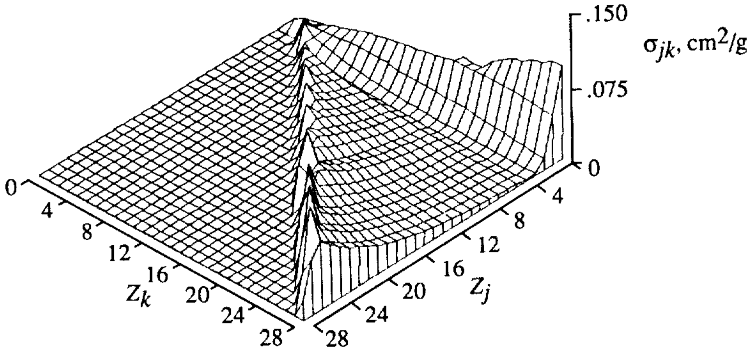
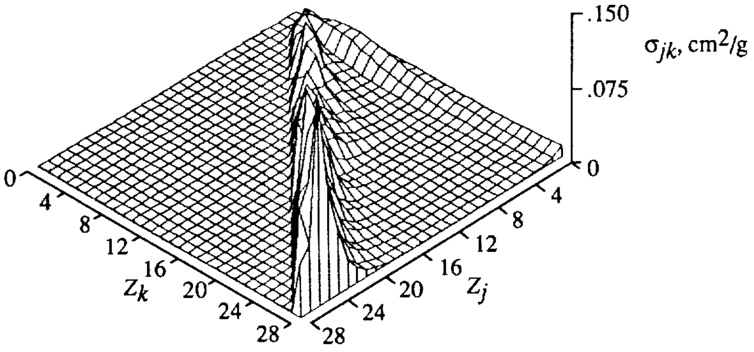


(c) Projectile energy = 2400 MeV/amu.

Figure 1. Semiempirical, differential fragmentation cross section for liquid hydrogen target as function of projectile-ion charge Z_k and fragment-ion charge Z_j according to Rudstam's formalism for fragments heavier than helium. Cross sections shown for nucleon and helium fragments have been reduced by factors of 10 and 4, respectively. (1 cm^2/g converts to 1.67 barns.)



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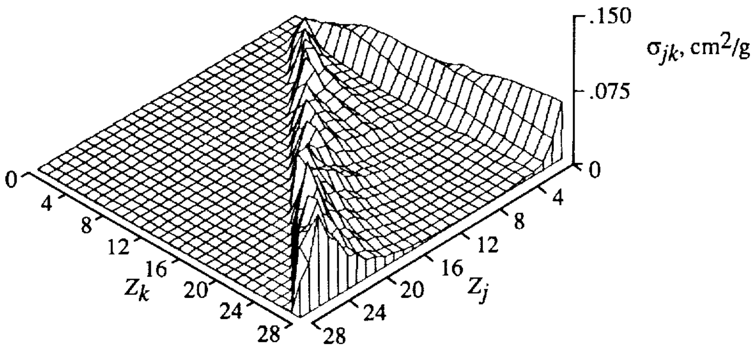

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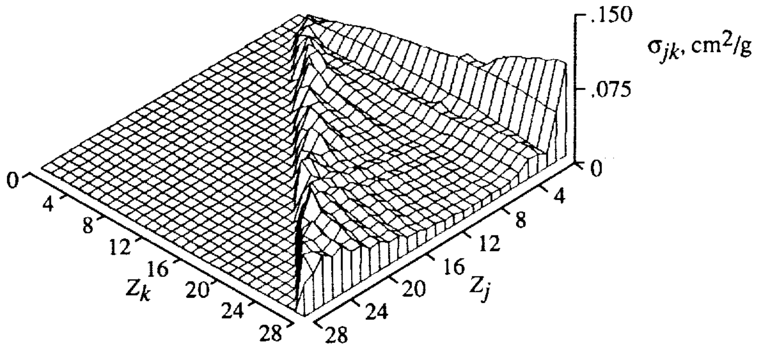
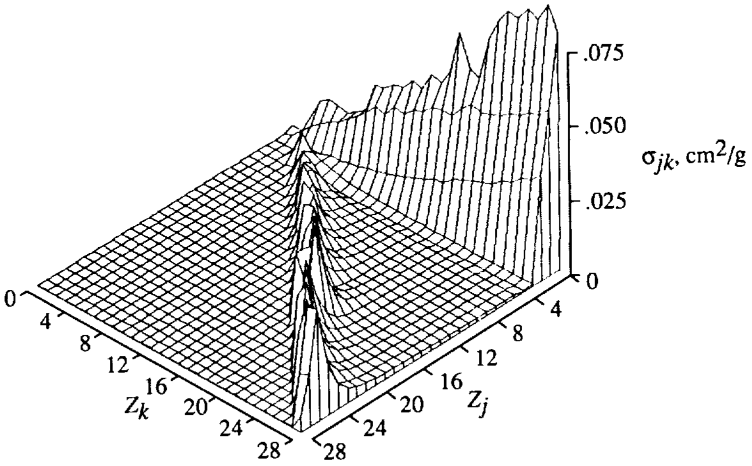


(c) Projectile energy = 2400 MeV/amu.

Figure 2. Semiempirical, differential fragmentation cross section for liquid hydrogen target as function of projectile-ion charge and fragment-ion charge according to Silberberg-Tsao formalism for fragments heavier than helium. Cross sections shown for nucleon and helium fragments have been reduced by factors of 10 and 4, respectively. (1 cm^2/g converts to 1.67 barns.)



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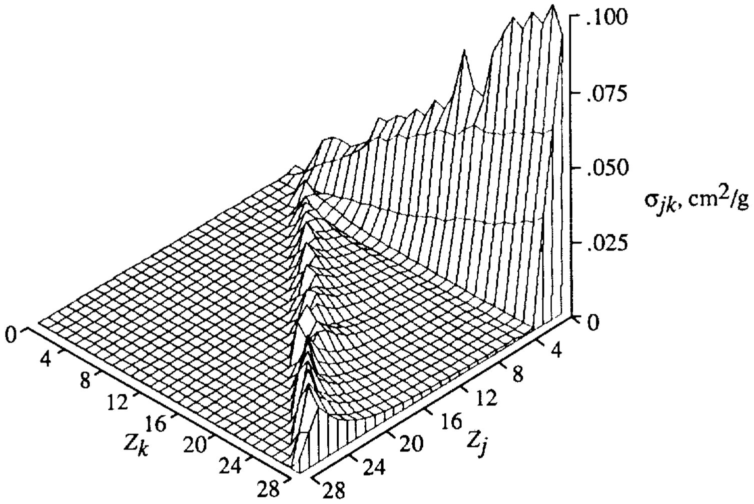
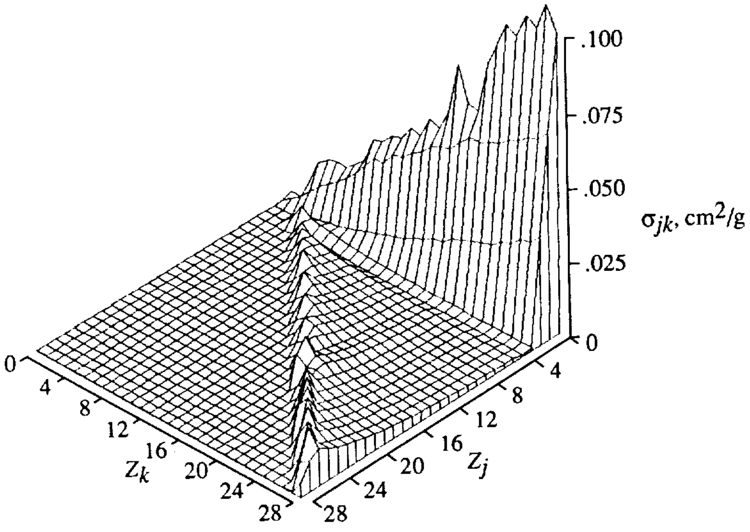
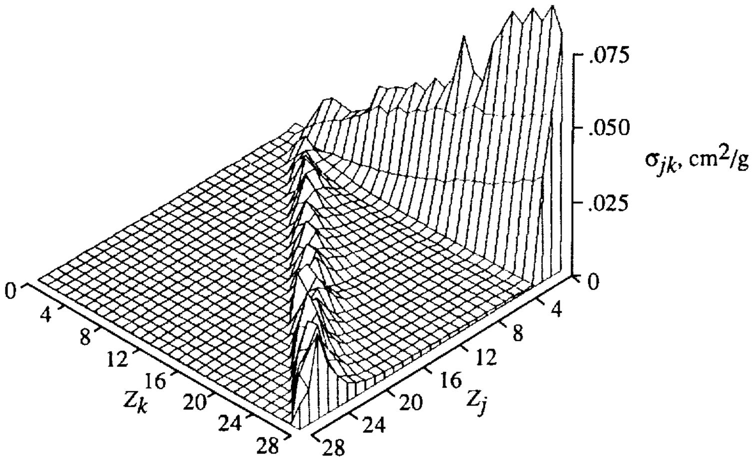


(b) Projectile energy = 600 MeV/amu.



(c) Projectile energy = 2400 MeV/amu.

Figure 3. Semiempirical, differential fragmentation cross section for water target as function of projectile-ion charge and fragment-ion charge according to Rudstam's formalism for fragments heavier than helium. Cross sections shown for nucleon and helium targets have been reduced by factors of 10 and 4, respectively. (1 cm^2/g converts to 29.9 barns.)



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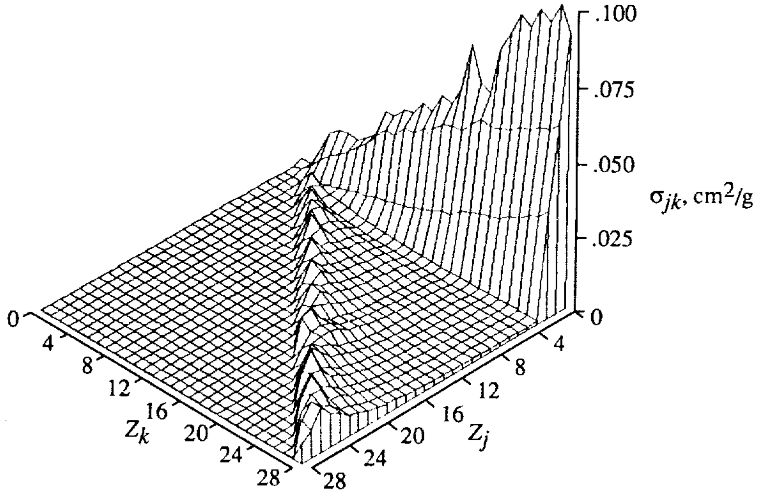
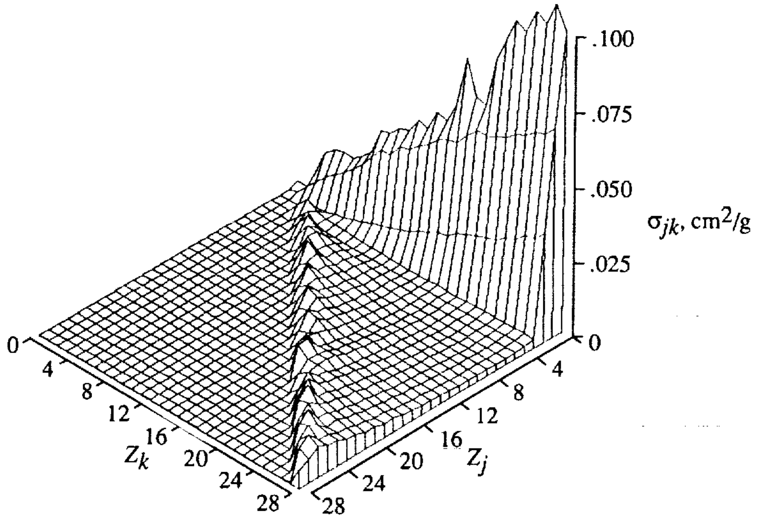
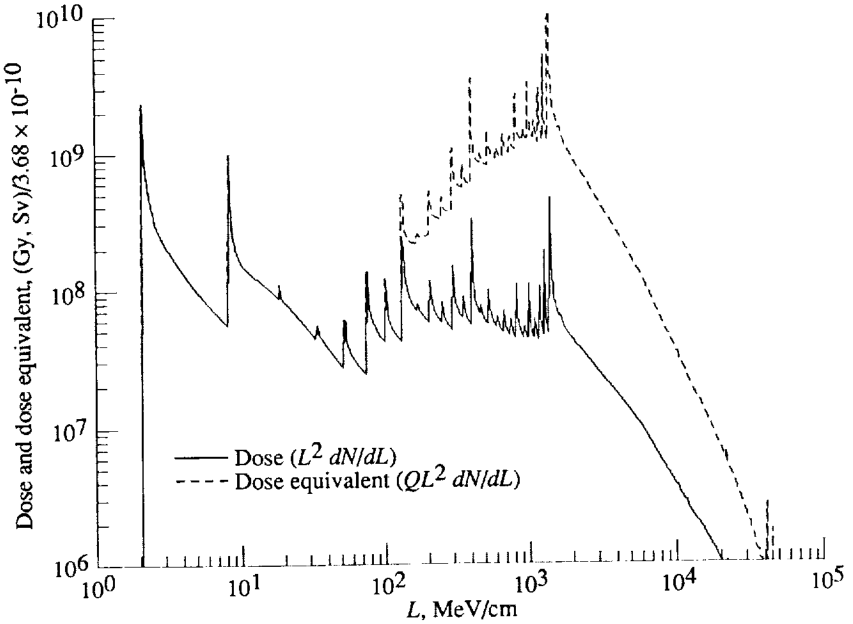


(b) Projectile energy = 600 MeV/amu.

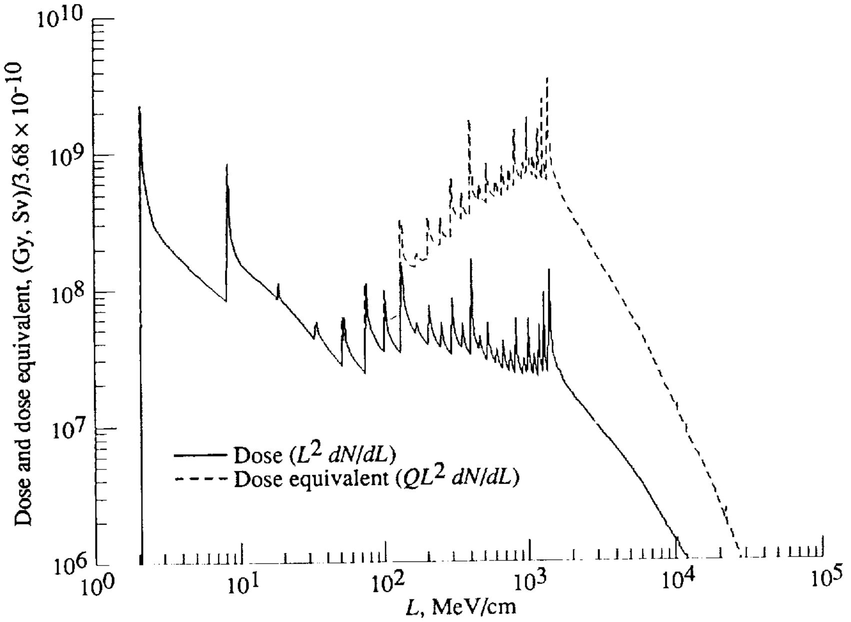


(c) Projectile energy = 2400 MeV/amu.

Figure 4. Semiempirical, differential fragmentation cross section for water target as function of projectile-ion charge and fragment-ion charge according to Silberberg-Tsao formalism for fragments heavier than helium. Cross sections shown for nucleon and helium fragments have been reduced by factors of 10 and 4, respectively. (1 cm^2/g converts to 29.9 barns.)

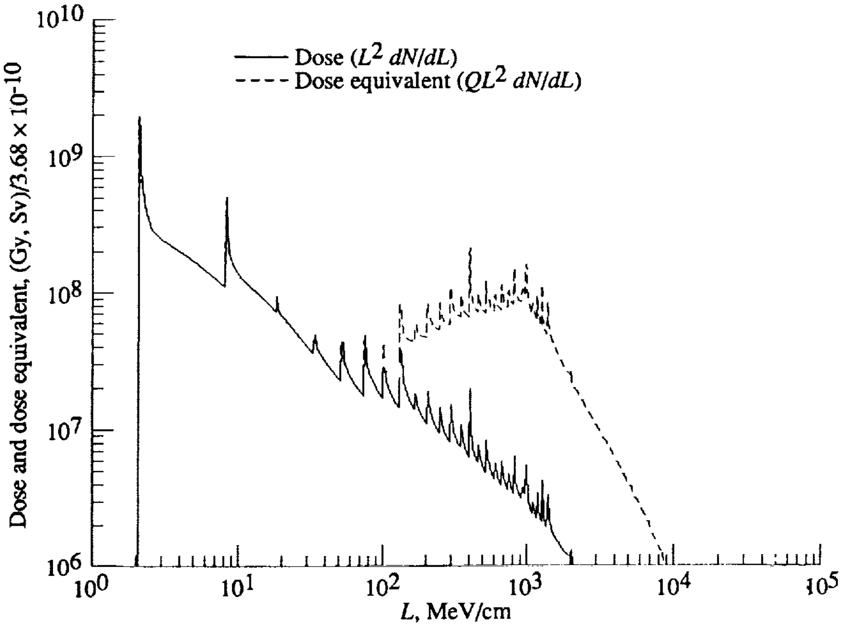


(a) 2-g/cm^2 thickness.



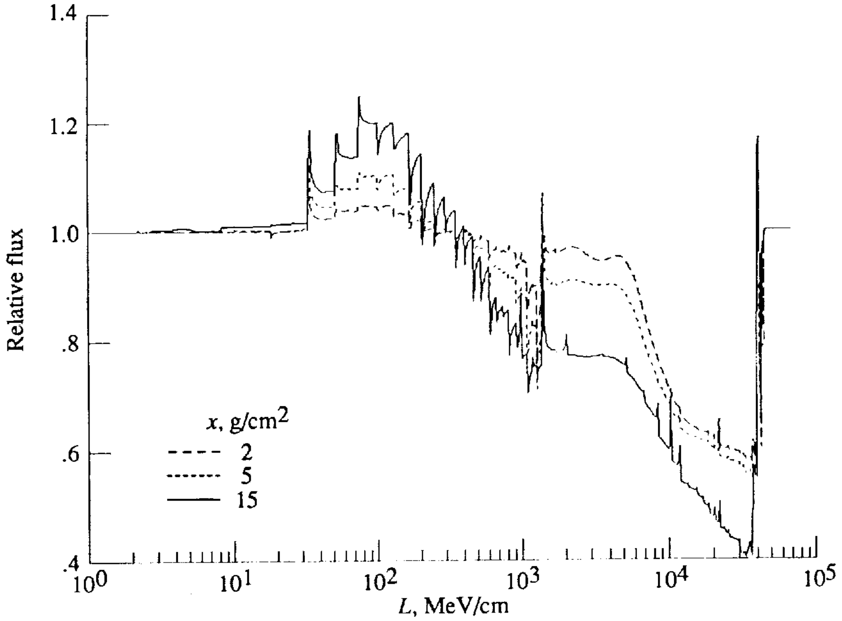
(b) 5-g/cm^2 thickness.

Figure 5. Differential LET spectra for annual dose equivalent behind various thicknesses of liquid hydrogen shield exposed to GCR at solar minimum.

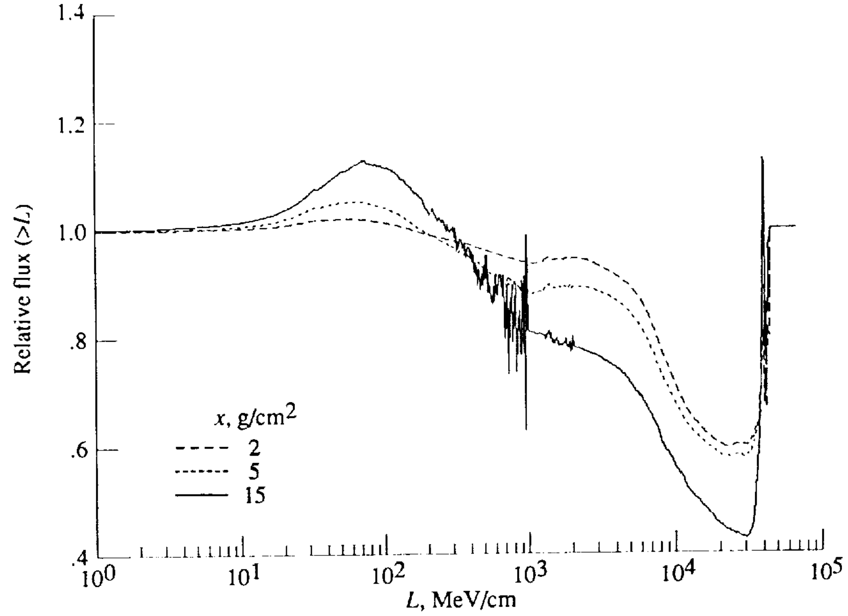


(c) 15-g/cm^2 thickness.

Figure 5. Concluded.

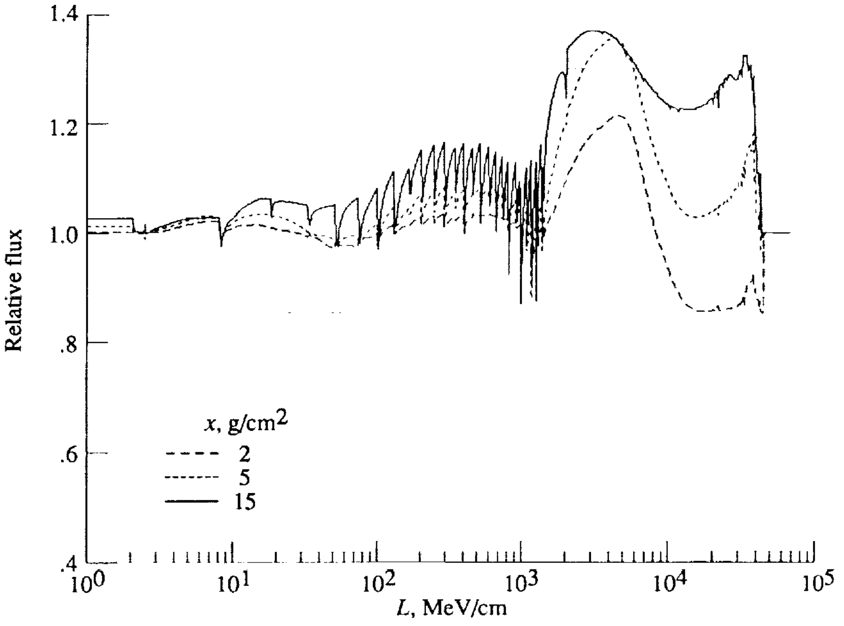


(a) Differential LET spectra.

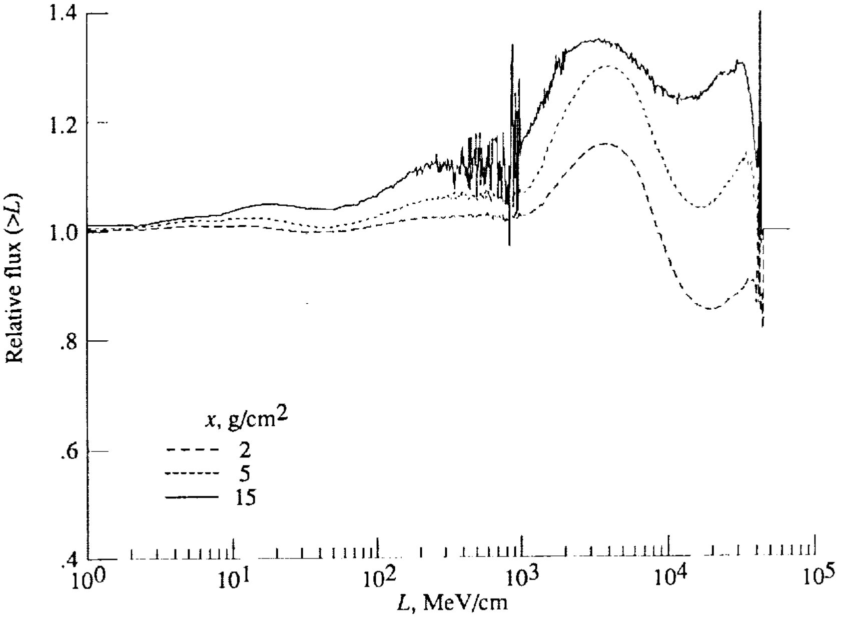


(b) Integral LET spectra.

Figure 6. Comparison of LET spectra for transmitted GCR flux calculated by using Silberberg-Tsao energy-dependent cross sections relative to the flux by Rudstam through several thicknesses of liquid hydrogen shield at solar minimum.

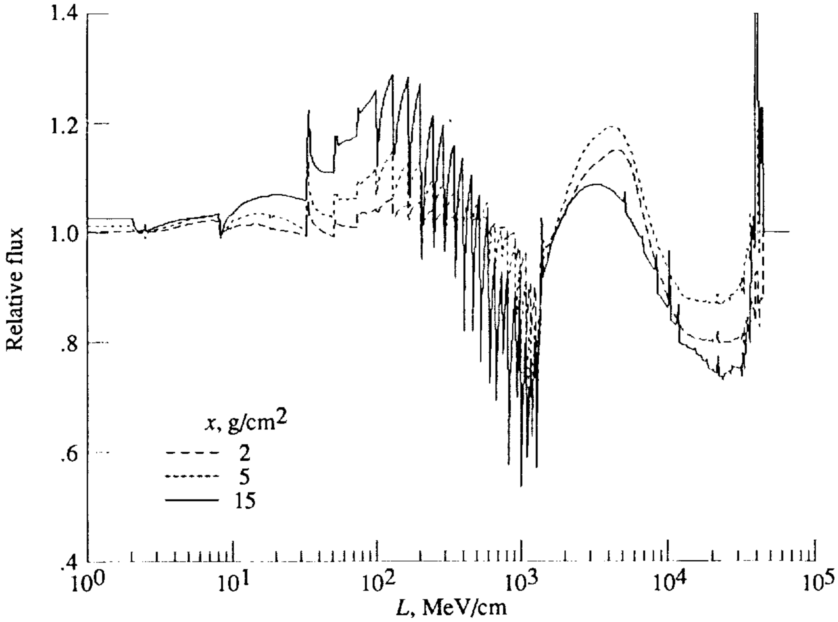


(a) Differential LET spectra.

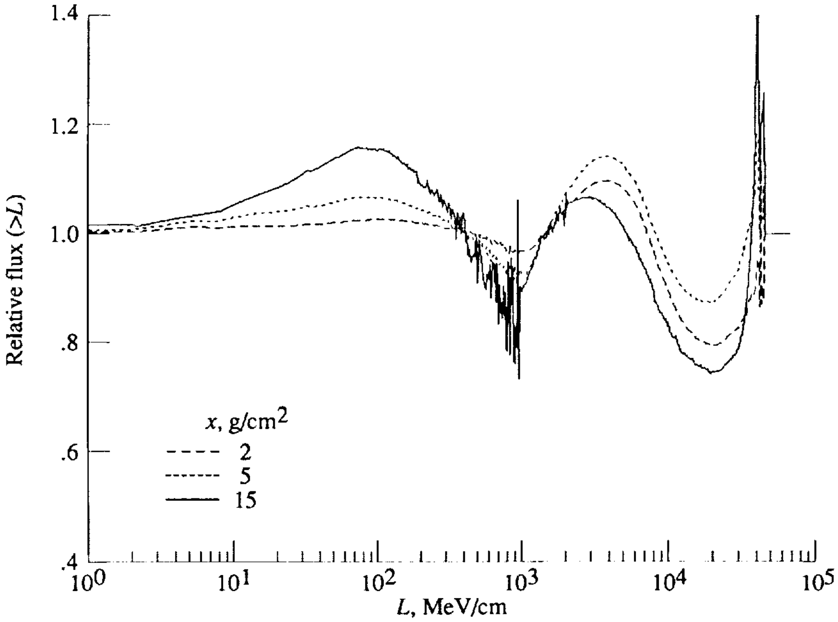


(b) Integral LET spectra.

Figure 7. Comparison of LET spectra for transmitted GCR flux calculated by using Silberberg-Tsao energy-dependent cross sections relative to the flux by energy-independent cross sections through several thicknesses of liquid hydrogen shield at solar minimum.



(a) Differential LET spectra.



(b) Integral LET spectra.

Figure 8. Comparison of LET spectra for transmitted GCR flux calculated by using Silberberg-Tsao energy-dependent cross sections relative to the flux by Rudstam energy-independent cross sections through several thicknesses of liquid hydrogen shield at solar minimum.

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13. ABSTRACT *(Maximum 200 words)*

Nuclear fragmentation cross sections of Silberberg and Tsao that are more accurate for a hydrogen target have been implemented in the data base to replace those of Rudstam for a galactic cosmic ray transport code (HZETRN). Sample calculations have been made for the transported galactic cosmic ray flux through a liquid hydrogen shield at solar minimum condition to determine the effect of such a change. The transported flux based on the Silberberg-Tsao semiempirical formalism contains fewer high-LET (linear energy transfer) components but more low-LET components than the results based on Rudstam's formalism; and this disparity deepens as the shield thickness increases. A comparison of the results obtained from using both energy-dependent and energy-independent cross sections of Silberberg and Tsao indicates that the energy-independent assumption results in an underestimation of high-LET flux above 100 keV/μm by approximately 40 percent for a 15-g/cm^2 thickness of liquid hydrogen. Similar results were obtained in a previous study (NASA TP-3243) when both energy-dependent and energy-independent cross sections of Rudstam were considered. Nonetheless, the present study found that an energy-independent calculation would be best accomplished by using Rudstam's cross sections as done in the past for various engineering applications.

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