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An Improved Analytic Model for Microdosimeter Response

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Abstract

An analytic model used to predict energy deposition fluctuations in a microvolume by ions through direct events is improved to include indirect delta ray events. The new model can now account for the increase in flux at low lineal energy when the ions are of very high energy. Good agreement is obtained between the calculated results and available data for laboratory ion beams. Comparison of GCR (galactic cosmic ray) flux between Shuttle TEPC (tissue equivalent proportional counter) flight data and current calculations draws a different assessment of developmental work required for the GCR transport code (HZETRN) than previously concluded.

Introduction

As the space program enters an era of extended manned space operations, the protection of astronauts from galactic cosmic ray (GCR) exposure becomes an important issue (refs. 1 and 2). The interaction of high-energy heavy ions originating in deep space with nuclei of shielding structures and body tissues results in energy degradation and nuclear fragmentation. These nuclear fragmentations produce secondary- and subsequent-generation reaction products that alter the elemental and isotopic composition of the transported radiation fields. The altered radiation level and energy spectrum of each ion species can be best estimated by using a computationally efficient GCR transport code (HZETRN) (refs. 3, 4, and 5) developed at the Langley Research Center. Only with the knowledge of radiation fields at specified organ locations of astronauts, can one start to estimate the risk of their exposure to space radiations.

Although the HZETRN code was developed by using state-of-the-art nuclear models (refs. 6 and 7) that had been reasonably tested with laboratory data (ref. 8), an integral validation of the code including environmental models, atomic and nuclear physics, transport algorithm, and vehicle geometry models was needed (ref. 9). In previous studies (refs. 9 and 10), we compared our results with measurements made with a tissue equivalent proportional counter (TEPC) onboard the Space Shuttle for both low (28°) and high (57°) inclination orbits. The agreement of predicted and measured lineal energy spectra for GCR was within 70 percent for the region above 2 keV/μm but within a factor of 2.3 underpredicted for the region below this value. The predicted lineal energy spectra were calculated by using HZETRN and postprocessing the results with an analytic code that describes fluctuations in energy deposition from direct ionization events as the ions penetrate through the TEPC detector volume. Although the cause for the underprediction at low lineal energy is conjectured to be a neglect of pions in the HZETRN, indirect delta ray events should be considered in the TEPC response model before any definite conclusion can be made.

Monte Carlo simulations have been the traditional method to model energy deposition by ions in microvolumes. Although such simulations have proven to be valuable, they involve sophisticated computer codes and time-consuming scoring techniques, require large quantities of input information, and are often tedious to interpret the results. For complex radiation fields such as GCR, it can be a very time-consuming process or virtually impossible to use a Monte Carlo method to cover all the species and energy range. The analytic method of Xapsos et al. (ref. 11) used in the previous studies (refs. 9 and 10) is suitable for such complex radiation fields and will be extended here to include indirect delta ray events. In this paper, we outline the method that describes energy deposition fluctuation for both direct and indirect events, compare our calculated result with available data for single ion and energy, and improve our computation in comparison with the Shuttle TEPC data.

Analytic Model

The ability of the earlier analytic model by Xapsos et al. (ref. 11) in predicting TEPC response in complex radiation fields results from the use and the observation that the energy-loss straggling approximates a lognormal distribution with the parameters given in terms of relative variance of the random variables involved in the energy deposition process. The derived (ref. 11) formulations for relative variance depend only on easily obtainable macroscopic quantities such as LET (linear energy transfer) and range data. Herein, we consider only the single event of ions and secondary (direct or indirect) delta rays as appropriate for the space environment and assume a wall-less microvolume. The method outlined begins with the calculation of the energy (or ionization) distribution for ion (direct) events, followed by an analogous calculation for electron (indirect) events and, finally, the combination of the two distributions.

Distribution for Ion Events

When assuming that the ion loses only a small fraction of its energy as it traverses through the target, the average energy deposited is given by (ref. 11)

$$\bar{\varepsilon}_{\text{ion}} = F_{\text{ion}} L_{\text{ion}} s_{\text{ion}} \tag{1}$$

where L_{ion} is the LET of the traversing ion; s_{ion}, the path length through the target; and F_{ion}, the fraction of energy initially deposited which remains within the site, that is, the fraction not carried out of the site as kinetic energy of secondary electrons. The average number of electron-hole pairs produced in the target as the ion traverses a path length of s_{ion} is then given by

$$x_{\text{ion}} = \frac{\bar{\varepsilon}_{\text{ion}}}{W_{\text{ion}}} \tag{2}$$

where W_{ion} is the average energy required to produce an electron-hole pair.

The relative variance of energy deposited for the ionization event is given by

$$V_{\text{ion}} = V_{\text{str,ion}} + V_{F,\text{ion}} \tag{3}$$

where $V_{\text{str,ion}}$ is the energy-loss straggling contribution and $V_{F,\text{ion}}$ is the contribution of Fano fluctuations. The latter contribution is included if ionization is the process of concern as in the case of TEPC. It is omitted if energy deposition is the process of concern. These two quantities can be determined as described in reference 10.

One of the key features of the energy deposition distribution is how to describe the energy-loss straggling process. A number of treatments of energy-loss straggling distributions are well known, such as those of Landau (ref. 12) and Vavlilov (ref. 13). However, for a given incident ion, each of these distributions is applicable only over a limited target size. The use of lognormal distribution by Xapsos et al. (ref. 11) was first motivated by the work of Condon and Breit (ref. 14), Burke (ref. 15), Wilson, Metting, and Paretzke (ref. 16), and an abstract by Lepson (ref. 17) stating that classical straggling models for high atomic number media are not as accurate as results obtained using a two-parameter lognormal distribution. Furthermore, by virtue of central limit theorem (ref. 18), the lognormal distribution results because with each collision the ion loses some random fraction of its energy that is proportional to its energy before the collision.

As described previously, the standard deviation and the mean of the lognormal distribution are related to x_{ion} and V_{ion} by the relations (ref. 11)

$$\sigma_{\text{ion}}^2 = \ln\,(1 + V_{\text{ion}}) \tag{4}$$

$$\mu_{\text{ion}} = \ln\,(x_{\text{ion}}) - 0.5\sigma_{\text{ion}}^2 \tag{5}$$

where all the variables are a function of ion path length s_{ion}. The normalized probability of producing x_{ion} electron-hole pairs within the target site when the ion takes a path length s_{ion} through the site is

$$p_{\text{ion}}(x_{\text{ion}}, s_{\text{ion}}) = \frac{1}{\sqrt{2\pi}\,x_{\text{ion}}\sigma_{\text{ion}}} \times \exp\left\{\frac{-1}{2\sigma_{\text{ion}}^2}\,[\ln\,(x_{\text{ion}}) - \mu_{\text{ion}}]^2\right\} \tag{6}$$

This equation must be integrated over all possible ion path lengths as

$$f_{\text{ion}}(x_{\text{ion}}) = \int p_{\text{ion}} c(s_{\text{ion}})\; ds_{\text{ion}} \tag{7}$$

where $c(s_{\text{ion}})$ is the normalized path length distribution of the target microvolume. The quantity $f_{\text{ion}}(x_{\text{ion}})$ is the normalized probability density that a single ion produces x_{ion} electron-hole pairs within the restricted target volume upon crossing the site.

Distribution for Electron Events

If the ion misses the target site, there is still a probability that energy can be deposited in it by an electron (indirect) event. Compared with ion events, electron events are more complicated to deal with because they have a distribution of energies throughout the irradiated medium. The average energy and average number of electron-hole pairs deposited in the target by an electron traveling a distance s_e are given by

$$\bar{\varepsilon}_e = L_e s_e \tag{8}$$

$$x_e = \frac{\bar{\varepsilon}_e}{W_e} \tag{9}$$

where L_e is the average, slowed electron LET, which is obtained by assuming a $1/L_e$ slowing-down spectrum and by assuming a $1/E^2$ spectrum with E being the electron energy initially produced by the incident ion (ref. 19), and W_e is the average energy required to produce an electron-hole pair.

The path-length-dependent relative variance of ionization for electron events is given by

$$V_e = V_{L,e} + V_{\mathrm{str},e} + V_{F,e} \tag{10}$$

where $V_{L,e}$ is the relative variance of the LET distribution; $V_{\mathrm{str},e}$, relative variance of energy-loss straggling; and $V_{F,e}$, relative variance of Fano fluctuations. Again, these quantities can be calculated as described in reference 19.

Given the complication that the electrons are not monoenergetic, it might at first seem as though the lognormal distribution would not be directly applicable. However, examination of figure 7 in reference 15 indicates otherwise. It clearly shows that the lognormal distribution closely describes the ionization produced by a Co^{60} source in a simulated 0.92-μm-diameter sphere of tissue-equivalent material. Because we now know that the straggling process is described by the lognormal distribution, this implies that the path length and LET distributions of the Compton electrons and photoelectrons are relatively unimportant in determining the ionization distribution. In the current work, we are concerned with site sizes ranging from micrometers to nanometers. The smaller the site size, the greater is the relative importance of energy-loss straggling. Therefore the conclusion can be made that the electron ionization distributions are controlled by energy-loss straggling and can therefore be approximated by a lognormal distribution over the complete range of interest. We can thus proceed in an analogous manner to that in the section "Distribution for Ion Events" and obtain equations similar to equations (4) through (7) for electron events.

Combined Distribution

The remaining problem is how to combine the normalized probability density for ion events $f_{\mathrm{ion}}(x)$ with the normalized probability density for electron events $f_e(x)$ with x being the number of electron-hole pairs produced without distinguishing the events. The combined ionization distribution $f(x)$ is given by

$$f(x) = P\, f_{\mathrm{ion}}(x_{\mathrm{ion}}) + (1 - P)\, f_e(x_e) \tag{11}$$

where P is the fraction of ion events. We know from an earlier work that the fraction of electron events is given by (ref. 19)

$$1 - P = \frac{(1 - F_{\mathrm{ion}})\bar{x}}{\bar{x}_e} \tag{12}$$

where $\bar{x}$ is the average number of ionizations of combined distribution. Further $\bar{x}$ can be expressed in terms of known quantities as follows:

$$\frac{1}{\bar{x}} = \frac{F_{\mathrm{ion}}}{\bar{x}_{\mathrm{ion}}} + \frac{1 - F_{\mathrm{ion}}}{\bar{x}_e} \tag{13}$$

where $\bar{x}_{\mathrm{ion}}$ and $\bar{x}_e$ are calculated for the average path lengths $\bar{s}_{\mathrm{ion}}$ and $\bar{s}_e$. Equation (11) is now ready to be tested for single ion and energy before being used in predicting Shuttle TEPC results.

Results

Monoenergetic Beam

The earlier model which treats direct events only has been tested against experiments and Monte Carlo results for various cases of monoenergetic beam as described in reference 10. In general, the model was successful in predicting the results except for ions with very high energy. Some discrepancy was seen between the model and the experiment for a wall-less, 2-μm-diameter spherical TEPC which measures dose distribution in a water column irradiated by 3.9-GeV nitrogen ion beam (ref. 20). The underprediction in the low y (lineal energy) region is mainly a result of neglecting the indirect events since their contribution tends to become significant as the beam energy per amu increases for a given sensitive volume. For comparison purpose, the earlier result for the case is reproduced here from reference 10. (See fig. 1(a).) The current model with both direct and indirect events is seen to improve the results greatly. (See fig. 1(b).)

For a moderately low-energy ion beam, the indirect event also becomes important when the sensitive site decreases to a submicron size. Shown in figure 2(a) is the probability density distribution of ion pairs produced by 0.3-MeV/amu alpha particles incident on a 20-nm-diameter spherical site as calculated by Olko and Booz (ref. 21) by using Monte Carlo simulation and also by the current analytic model. The model compares reasonably well with the Monte Carlo results but seems to slightly underpredict the indirect events, and the peak associated with direct events is at slightly higher ionization value than the Monte Carlo results. In this calculation, the fraction of energy deposited in the volume due to ion events F_{ion} is about 94 percent. It is notable that the expression for F_{ion} as given in reference 22 slightly overestimates in the range just below unity when compared with the results of Olko and Booz as shown in figures 3 and 4 of reference 22. It is also shown in reference 21 that this fraction varies somewhat among the results obtained by Olko and Booz (ref. 21), Kellerer (ref. 23), and Guenter and Schultz (ref. 24). Recalculation of the case for 0.3-MeV/amu alpha particles is thus made by arbitrarily decreasing the fraction to 92 percent and a much better agreement is reached as shown in figure 2(b). Considering the simplicity and crudeness of the approach used in evaluating the fraction (ref. 22), the slight disagreement shown in figure 2(a) is quite reasonable.

Flight Experiment

The recalculated lineal energy spectra for GCR flux are shown in figures 3(a) and 3(b) for STS-56 (57° inclination orbit) and STS-51 (28° inclination orbit), respectively. These results are obtained by using the same version of HZETRN as in previous studies (refs. 9 and 10) so that the impact of indirect events added to the response function can be identified when compared with the previous results which are reproduced here in figure 4. The improved TEPC model tends to raise the predicted flux in the lower y region and to lower in the higher y region as was expected but still with good agreement for the STS-51 flight. For the STS-56 flight, there is an overall underestimate across the entire spectrum by the improved model. This underestimate suggests there might be a systematic problem such as the crudeness in geomagnetic transmission function (a simple vertical cutoff model) used in our LEO (lower Earth orbit) GCR environment of the transport code that could affect high inclination orbit more than low inclination orbit. The rather large underestimate below 2 keV/μm in previous results is now reduced to a level consistent throughout the entire spectrum. An improvement to the current geomagnetic transmission function is needed.

Concluding Remarks

The improved analytic model for predicting energy deposition fluctuations has been shown to agree well with laboratory data and Monte Carlo calculations for monoenergetic beam even when there is a significant contribution from indirect delta ray events. These events are important when the ions are of very high energy relative to the sensitive site size. Comparison of current prediction for GCR (galactic cosmic ray) flux in LEO (low Earth orbit) with measurements obtained by Shuttle TEPC indicates there may be an underestimate by the transport code for high inclination orbit; this underestimate may result from the crudeness of the geomagnetic transmission function used in the environmental model and possibly other physical processes yet to be included. Still good agreement exists for the low inclination Shuttle flight, and the most noticeable difference between the data and calculations below 2 keV/μm found in previous studies has decreased with the current model.

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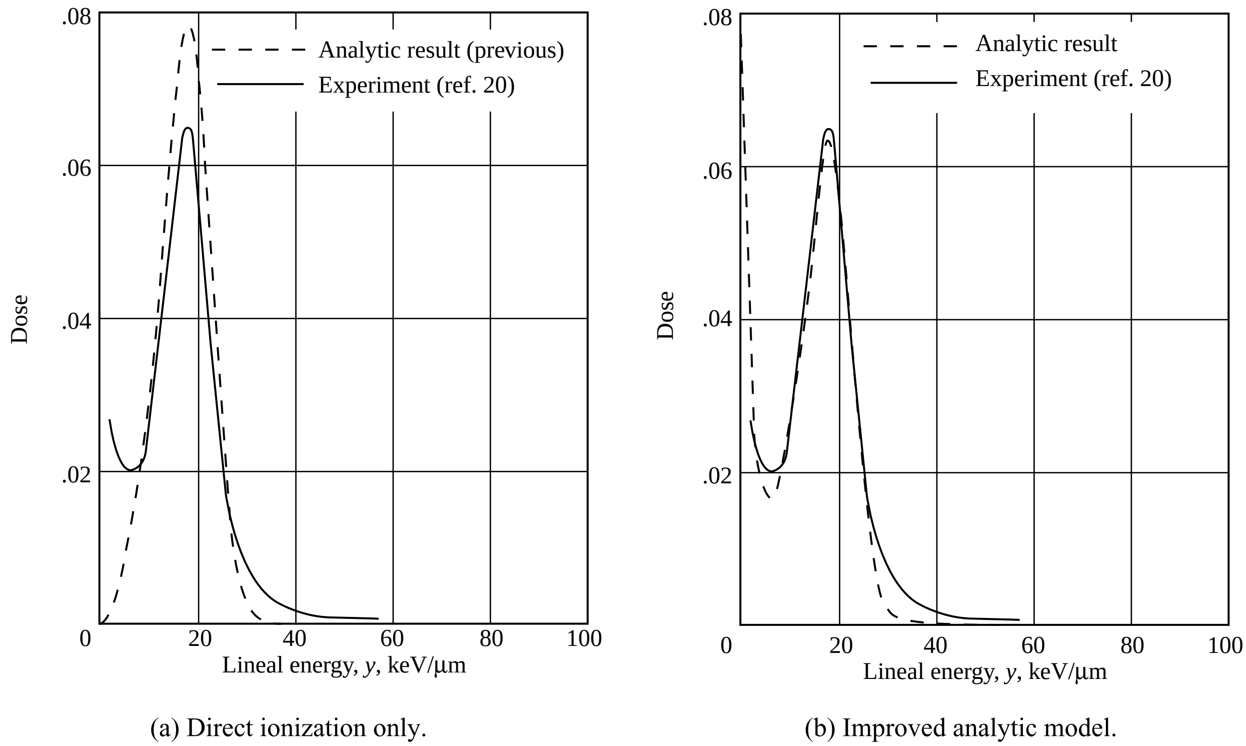


Figure 1. Dose distributions measured by 2-μm-diameter spherical, wall-less TEPC 2-cm depth in water column irradiated by 3.9-GeV nitrogen ion beam.

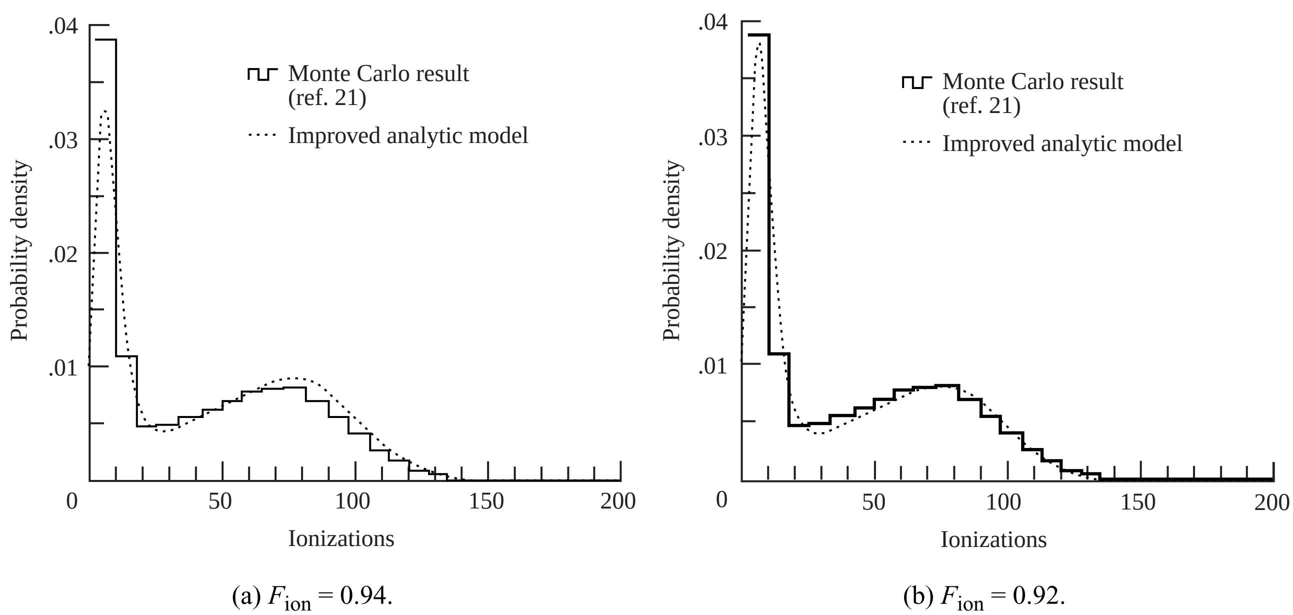
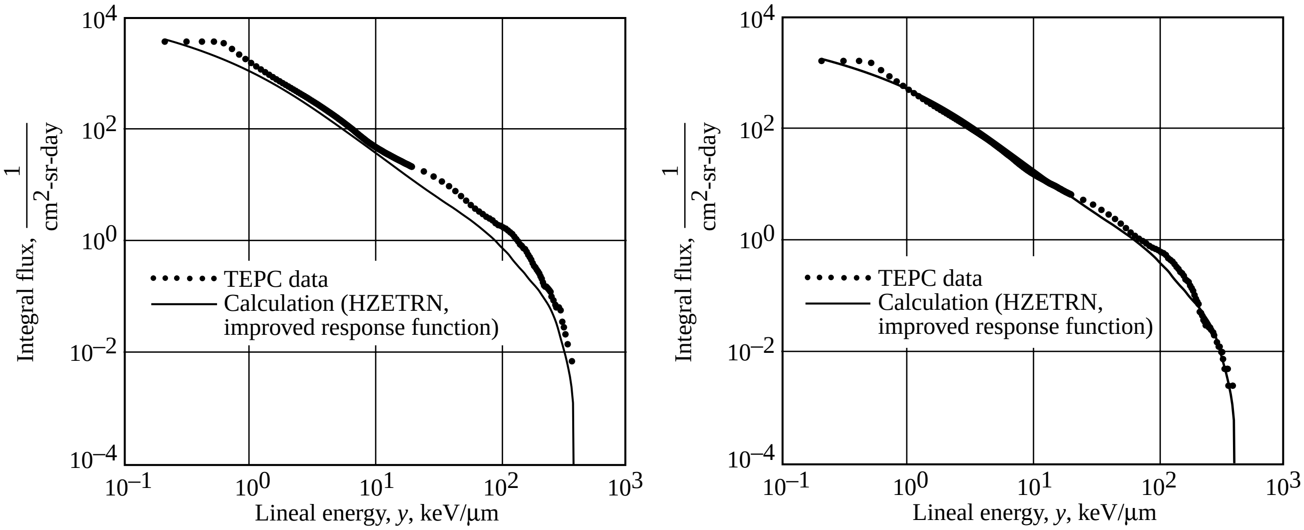


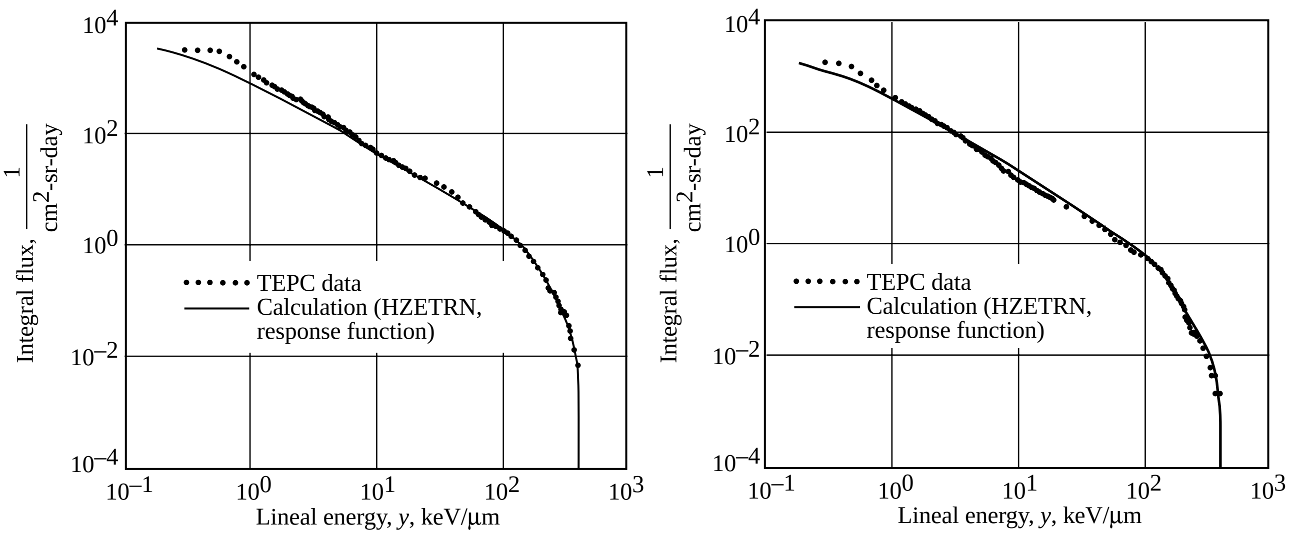
Figure 2. Probability density distribution of ionizations produced by 0.3-MeV/amu alpha particles on a 20-nm-diameter water sphere.



(a) STS-56.

(b) STS-51.

Figure 3. Calculated GCR spectrum and Shuttle TEPC flight data with TEPC response model used in postprocessing HZETRN results including both direct and indirect events.



(a) STS-56.

(b) STS-51.

Figure 4. Calculated GCR spectrum and Shuttle TEPC flight data with TEPC response model used in postprocessing HZETRN results considering only direct events.

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