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Mean occurrence frequency and temporal risk analysis of solar particle events

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Abstract

The protection of astronauts from space radiation is required on future exploratory class and long-duration missions. For the accurate projections of radiation doses, a solar cycle statistical model, which quantifies the progression level within the cycle, has been developed. The resultant future cycle projection is then applied to estimate the mean frequency of solar particle events (SPEs) in the near future using a power law function of sunspot number. Detailed temporal behaviors of the recent large event and two historically large events of the August 1972 SPE and the November 1960 SPE are analyzed for dose-rate and cumulative dose equivalent at sensitive organs. Polyethylene shielded "storm shelters" inside spacecraft are studied to limit astronauts' total exposure at a sensitive site within 10 cSv from a large event as a potential goal that fulfills the ALARA (as low as reasonably achievable) requirement.
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1. Introduction

Accurate projections of radiation doses to astronauts are needed for future space mission planning. The interplanetary space radiation environment is affected by the degree of solar disturbance that is related to the number and types of sunspots in the solar surface. Sunspot number is a single quantity defined by Wolf in 1848; the monthly mean sunspot numbers from January 1749 to the present can be obtained from National Geophysical Data Center, National Oceanic and Atmospheric Administration (NOAA) (2004). Using only the numbered cycles (1755 to the present), a statistical model based on the accumulating historical cycle sunspot data has been developed to estimate future levels of solar cycle activity (Wilson et al., 1999b; Kim and Wilson, 2000). Since the sunspot cycle affects the near-Earth environment, the data is coupled to a space-related quantity, the mean occurrence frequency of solar particle events (SPEs), which is of interest in radiation protection.

A systematic way of short range projection of future sunspot cycles is made from statistically independent patterns of odd even cycles, where cycles 1–22 are treated as two separate populations in the model (Wilson et al., 1999b). Because of the odd–even behavior, the correct adjustment of solar minimum for the current cycle 23 is important for estimating future cycle activity levels (Kim and Wilson, 2000). Critical parameters in cycle prediction include not only the date of solar minimum occurrence, but also the date of solar maximum occurrence in each cycle. Therefore, separate calculations of activity levels for the rising and declining phases in solar cycle 23 resulted in improved projection of sunspots in the remainder of the current cycle 23 (Kim et al., 2004). Because a fundamental understanding of the transition from cycle to cycle has not been developed, it is assumed for projection purposes that solar cycle 24 will continue at the same activity level observed in the declining phase of the cycle 23 (Kim et al., 2004). Projection errors in solar cycle 24 can be corrected as the cycle progresses and observations become available, because this model is shown to be self-correcting.

One important characteristic of SPEs is their mean frequency of occurrence, which is dependent on solar activity (Nymmik, 1999). We consider the frequency calculated from a power law function of sunspot number and compare to data obtained from the NOAA's GOES satellite measurements of proton integral flux in recent years (NOAA, 2004). Projections of the future

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mean frequency of SPE occurrence will be estimated with the solar cycle prediction. To estimate dose and dose-rate distributions to astronauts from exposures to large SPEs, the temporal behaviors of organ dose rate and cumulative dose for three historically large events of November 1960, August 1972, and October 2003 are analyzed behind various aluminum thicknesses. Total spectra of large SPEs including the event of February 1956 are also considered to estimate shielding requirements from total exposure of SPE. The current analyses are made with only proton components of SPEs.

2. Methods

2.1. Solar cycle statistical model for projections of cycles and application to the mean occurrence frequency of SPEs

The monthly averaged sunspot numbers for the cycles from 1 to 22 (NOAA, 2004) have been used in deriving a statistical model for solar cycle projection, in which we considered the possibility that the statistical populations depend on the orientation of the solar dipole moment (Bobcock, 1961). Given the time of solar minimum, an appropriate population data according to odd or even cycle was collected for each successive month and the associated cumulative frequency spectrum was generated (Wilson et al., 1999b; Kim and Wilson, 2000; Kim et al., 2004). The percentile levels for each month from the time at cycle 23 minimum were calculated by interpolation/extrapolation of each measured sunspot number with the associated cumulative frequency spectrum. As the observation of the current cycle 23 increased each month, the cycle's cumulative mean percentile level and statistical fluctuations of the sample data were calculated for the range of percentile groups, by which the solar activity levels of the current cycle 23 were represented.

It has been shown that all 11 historical odd–even sunspot cycles are reasonably consistent with each activity level during the rising phase (Kim and Wilson, 2000). When separate calculation of activity level was made beginning at the time of solar maximum and with the consideration of the each cycle's length, the declining phase of a cycle also showed consistent trend of cycle activity level for all 11 historical odd–even sunspot cycles (Kim et al., 2004). These modifications resulted in improved projection of sunspots in the remainder of the cycle 23 (Kim et al., 2004). Projections into the next cycle are difficult because they introduce uncertainty not only in the future amplitude, but also reflect uncertainty in the cycle duration. The date of solar minimum for cycle 24 cannot be determined precisely until well into this cycle. However, it was assumed to occur

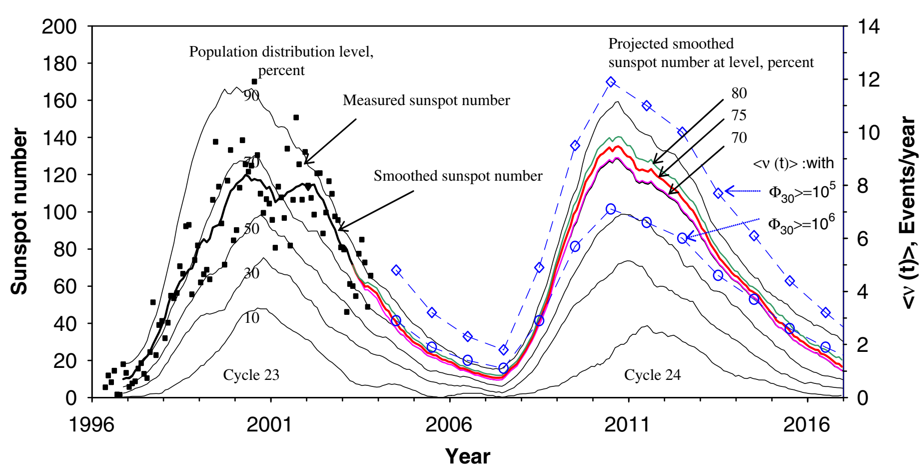


Fig. 1. Sunspot sampling distribution and projections of solar cycles and mean occurrence frequency of SPE.

Table 1
Total proton fluences and the mean occurrence frequency of SPE in year 2003

Particle event		$\Phi_p(\geqslant 30\,\text{MeV})$, protons/cm^2	Annual mean sunspots	The mean occurrence frequency of SPE per year	
Start	Peak			$\Phi_{30} \geqslant 10^6$	$\Phi_{30} \geqslant 10^5$
28–May 23:35	29–May 15:30	1.10×10^6	63	4.0	6.7
31–May 00:40	31–May 06:45	1.95×10^6			
18–Jun 20:50	19–Jun 04:50	4.17×10^5			
26–Oct 18:25*	26–Oct 22:35	3.25×10^9			
2–Nov 11:05*	3–Nov 08:15	1.50×10^8			
4–Nov 22:25*	5–Nov 06:00	1.87×10^7			
21–Nov 23:55	22–Nov 02:30	4.24×10^5			
2–Dec 15:05	2–Dec 17:30	7.33×10^5			

*For the combined SPE: $\Phi_p(\geqslant 30\,\text{MeV}) = 3.42 \times 10^9$ protons/cm^2.

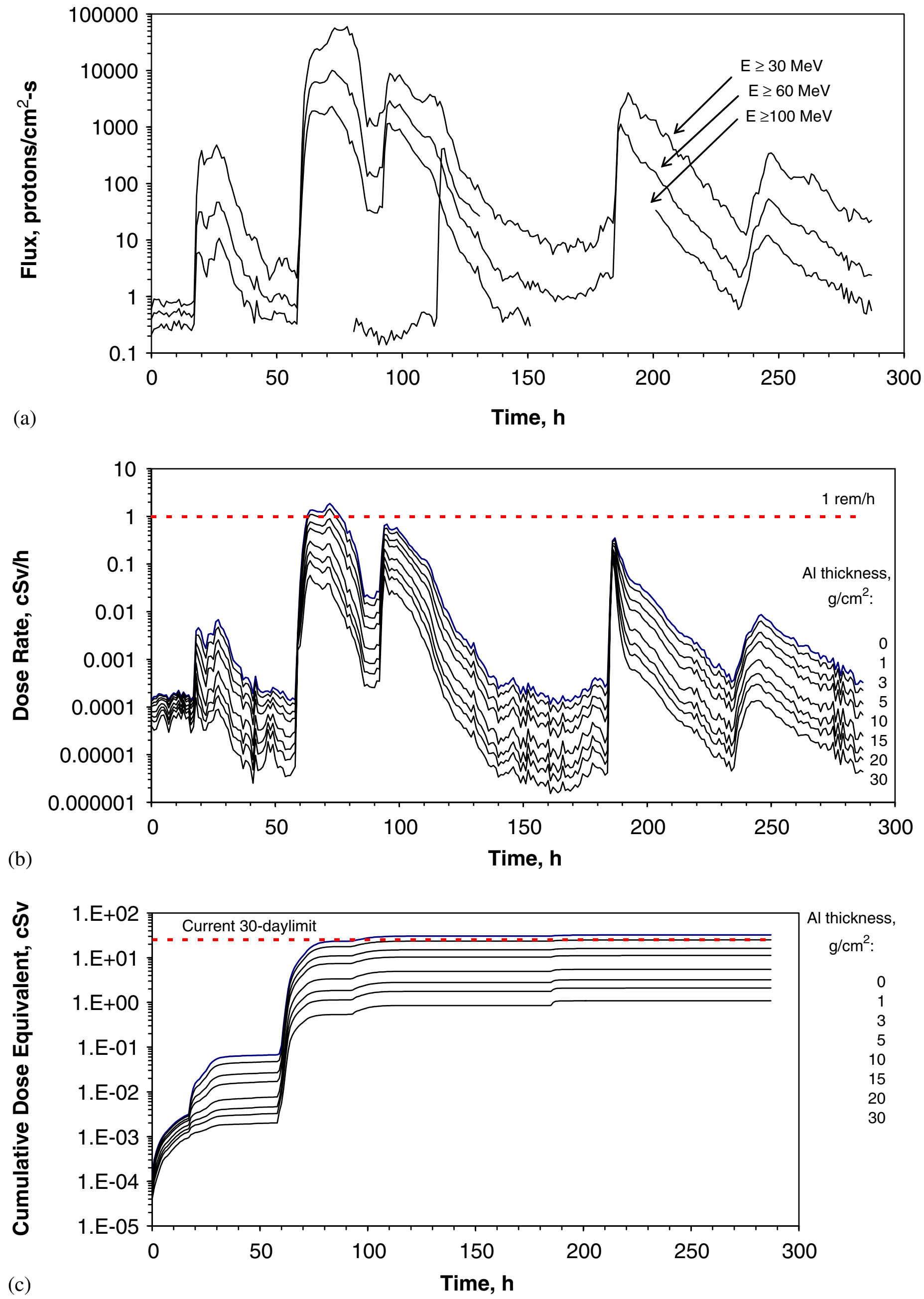


Fig. 2. (a) Hourly averaged proton flux during October 26–November 6, 2003 SPE; (b) BFO dose rate during October 26–November 6, 2003 SPE; (c) cumulative BFO dose equivalent during October 26–November 6, 2003 SPE.

in December 2006 based on the behavior of the odd–even solar cycles (Kim and Wilson, 2000; Kim et al., 2004). Because the appropriate percentile grouping of cycle 24 cannot be made at present, the current progressive activity trend of 75% ± 5% (Kim et al., 2004) is assumed to continue into the next cycle for the projection purpose only. The resultant projections of cycles 23 and 24 are shown in Fig. 1 with the distribution of observed sunspot data in solar cycle 23.

One important characteristic of SPEs is their mean frequency of occurrence, $\langle v \rangle$, which is a function of solar activity (sunspot number, W) with different fluences for energies greater than 30 MeV (Φ_{30}) (Nymmik, 1999)

$$\langle v(t)\rangle = 0.18W(t)^{0.75} \text{ events/yr} \quad \text{with } \Phi_{30} \geqslant 10^6 \text{ protons/cm}^2, \tag{1}$$

$$\langle v(t)\rangle = 0.3W(t)^{0.75} \text{ events/yr} \quad \text{with } \Phi_{30} \geqslant 10^5 \text{ protons/cm}^2. \tag{2}$$

Under varying solar activity, the probabilities for SPE in the near future are calculated from the above equations with projected solar cycle, which are shown in Fig. 1 for planning purpose only. During the solar active years, up to seven events

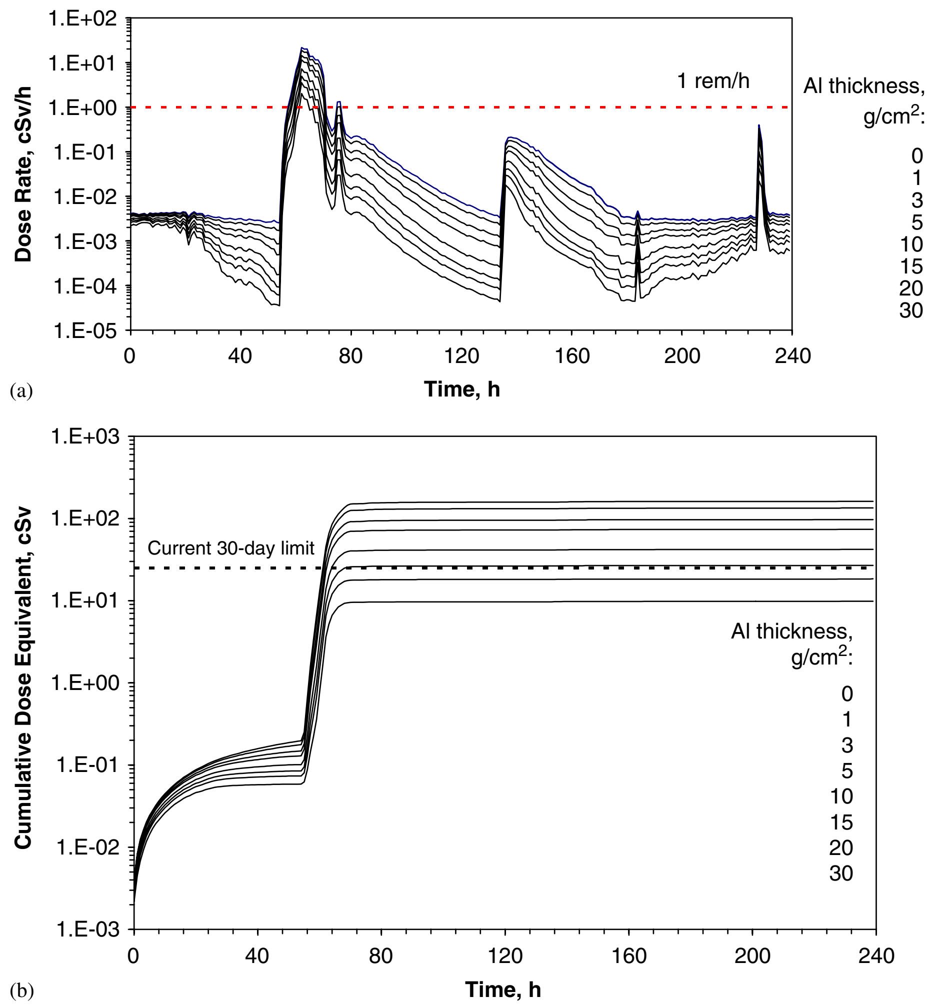
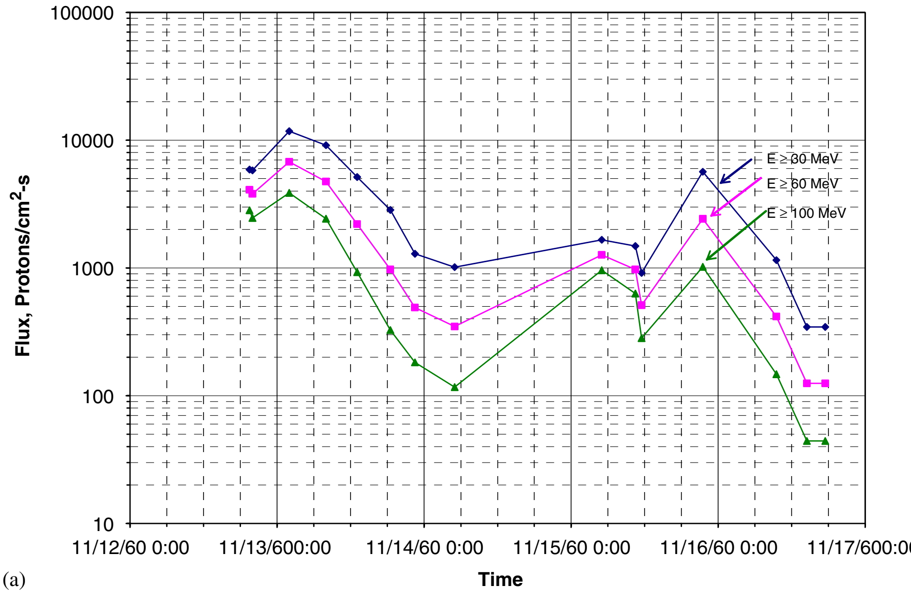


Fig. 3. (a) BFO dose rate during August 2–11, 1972 SPE; (b) Cumulative BFO dose equivalent during August 2–11, 1972 SPE.

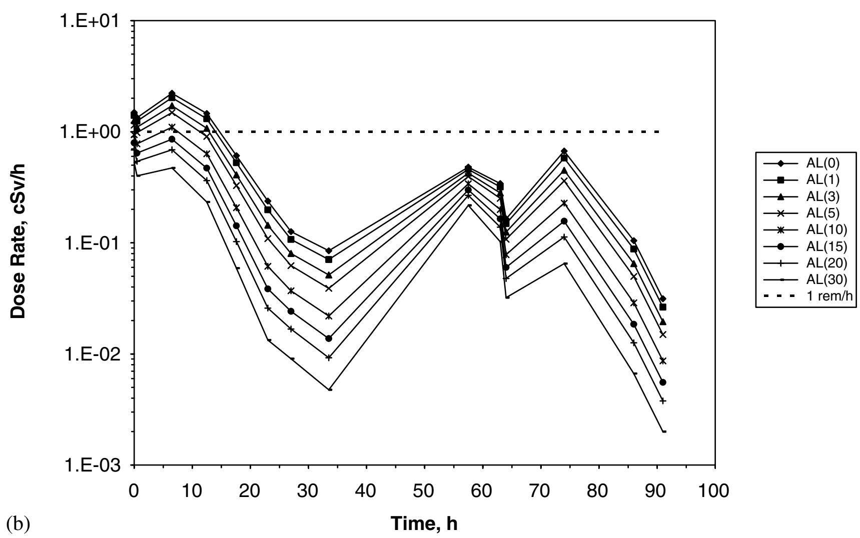
Table 2
Exponential spectral determinations for integral fluences during November 12–16, 1960 Solar Particle Event Freier and Webber (1963)

Date of SPE	Time of optical maximum	Time of measurement	J_0 (protons/cm^2 s sr)	P_0 (MV)
November 12, 1960	1329	11/12/60 19:30	1100	280
		11/12/60 20:00	1250	240
		11/13/60 02:00	3400	185
		11/13/60 08:00	3400	155
		11/13/60 13:05	3000	120
		11/13/60 18:30	2800	95
		11/13/60 20:00	2800	95
		11/13/60 22:30	1000	105
		11/14/60 05:00	1000	95
November 15, 1960	0221	11/15/60 05:00	250	375
		11/15/60 10:30	320	240
		11/15/60 11:30	285	175
		11/15/60 12:30	285	175
		11/15/60 21:30	3300	120
		11/16/60 09:30	1000	100
		11/16/60 14:30	300	100
		11/16/60 17:30	300	100

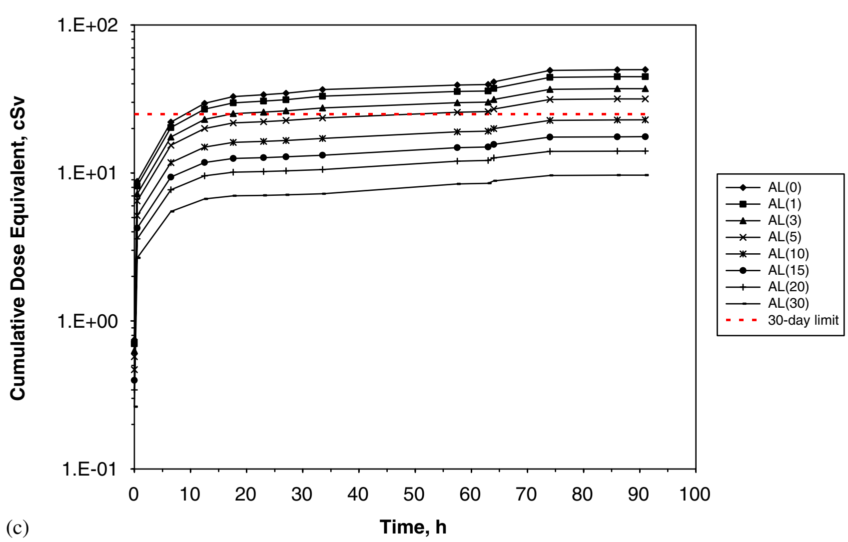
November 12, 1960 SPE event spectrum $= 3.68 \times 10^9 e^{-P(E)/158.6}$.
November 15, 1960 SPE event spectrum $= 2.47 \times 10^9 e^{-P(E)/136.6}$.
November 12–16, 1960 SPE spectra $= 5.51 \times 10^9 e^{-P(E)/153.1}$.



(a)



(b)



(c)

Fig. 4. (a) Proton flux at time of measurement during November 12–16, 1960 SPE; (b) BFO dose rate during November 12–16, 1960 SPE; (c) cumulative BFO dose equivalent during November 12–16, 1960 SPE.

per year are expected with $\Phi_{30} \geqslant 10^6$ protons/cm^2. These calculated mean frequencies are compared with the data obtained from the NOAAs GOES satellite measurements of proton integral flux in year 2003 in Table 1. When three major peaks occurred during 26 October – 6 November are combined as one event, the event-integrated fluence is 3.42×10^9 protons/cm^2 for energies above 30 MeV, by which this SPE is one of the largest SPEs recorded since August 1972. This event and the historically large events of November 1960 and August 1972 are considered further for the dose/dose rate distributions.

2.2. The hourly distribution of SPE fluence for dose/dose-rate distribution

Aside from the total fluence, the dose rate is an extremely important parameter for the biological response models. Because biological damage depends on dose-rates for low-LET radiation such as protons (NCRP, 2000; Simonsen et al., 1993), a dose rate dependent factor on irradiation time is expected to be important. To see the temporal behavior for the large events, hourly exponential rigidity spectra are calculated with continuity of hourly integrated proton fluences at 30 and 60 MeV using GOES data for October 2003 SPE (NOAA, 2004), and using hourly proton fluence values reported previously for August 1972 SPE (King, 1972), respectively. For November 1960 SPE, 14 exponential spectral determinations made by Freier and Webber (1963) are used for the analysis. The resultant proton differential energy spectra at each hour and measurements are transported through the various thicknesses of spacecraft and body tissue materials to evaluate the particle spectra at the sensitive sites using the BRYNTRN Wilson et al. (1989) and the computerized anatomical man (CAM) model (Billings and Yucker, 1973).

Hourly averaged proton fluxes of GOES data are shown in Fig. 2a during October 26–November 6, 2003 SPE. Time analyses for BFO dose-rate and its cumulative dose equivalent are shown in Figs. 2b and c, respectively. Since the frequency of chromosomal aberrations is influenced significantly by dose-rate, hourly BFO dose-rates behind various spacecraft thicknesses are compared in Fig. 2b. Considering the dose rate of 1 cSv/h (1 rem/h) as the start of a transition from low to high dose-rates, the temporal behavior at BFO of this event indicates that October 2003 SPE is rather a low dose rate event except at the first major pulse. Furthermore, the protection during high dose rate exposure times can be easily achieved by adding a small amount of spacecraft material as shown in Fig. 2b. Over the entire event of 12 days, the cumulative dose equivalent in Fig. 2c indicates the amount of exposure incurred in major peaks.

Dose rate effects were considered during the certain period of exposure times for the event of August 2–11, (King, 1972). Its total fluence ($\Phi_{30} = 8.08 \times 10^8$ protons/cm^2) is less than that of October 26, 2003 event, but the temporal behavior suggests significant dose-rates at the first major peak times shown in Fig. 3a. During this peak times, rather heavy shielding (up to 30 g/cm^2) provided by spacecraft material of aluminium is not enough to reduce the BFO dose-rate to 1 cSv/h. As the current 30-day exposure limit at BFO (25 cSv) is considered, the recommended exposure limit is easily exceeded when only the conventional amount of spacecraft material is provided to protect BFO from this class of SPE as shown in Fig. 3b.

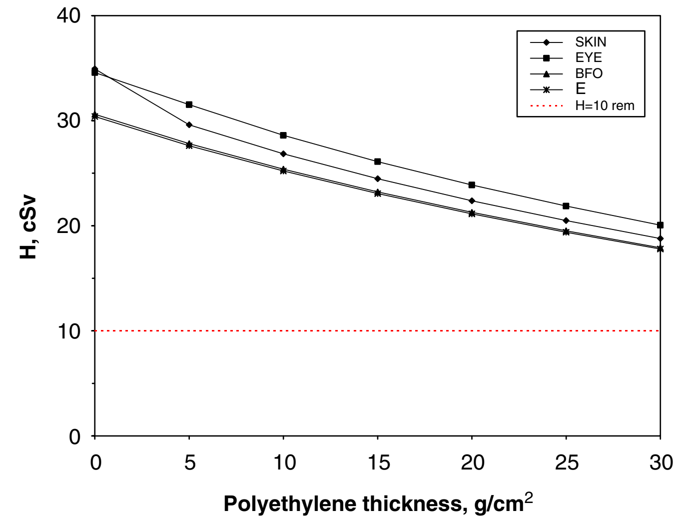


Fig. 5. Dose equivalents at sensitive sites with various polyethylene shields inside 20 g/cm^2 of aluminum from February 23, 1956 SPE.

A wide variety of techniques using balloons and rockets have been used to measure the proton spectrum of all significant SPEs occurring in solar cycle 19 (Curtis, 1974). There is rather detailed coverage for the event from November 12–16, 1960 (Biswas et al., 1962). Fourteen limited spectral determinations of characteristic rigidity, P_0 (MV), and the constant, J_0 (protons/cm^2 s sr), for the proton exponential spectra of November 12–16, 1960 SPE were derived using all available measurements by Freier and Webber (1963) and listed here in Table 2. The discrete time variation of proton flux and dose-rate at each measurement are calculated with these spectral parameters shown in Figs. 4a and b, respectively. In Fig. 4b, the peak in dose-rate is within the several hours after optical flare, and about 15 g/cm^2 of spacecraft material of aluminum is required to reduce the dose rate to low dose-rate of 1 cSv/h at BFO during the peak period. Again, the recommended current 30-day exposure limit at BFO is exceeded with the usual spacecraft-thicknesses from this event as shown in Fig. 4c.

There is one other event of interest and it occurred on February 23, 1956 (Wilson et al., 1999a). Its striking feature was a large number of high-energy particles early in the event. Total dose equivalents are greater than 10 cSv at sensitive sites of skin, eye, BFO, and effective tissue/organ from the exposure of this event, even if various polyethylene shieldings are added to 20 g/cm^2 of spacecraft material as shown in Fig. 5. For other historical events, keeping total BFO dose equivalent to below 10 cSv is possible using a polyethylene lining to enhance a storm shelter. To reduce overall exposure at BFO to below 10 cSv (10 rem) for August 1972 SPE, the required polyethylene shields are 11, 7, and 3 g/cm^2 inside 0, 5, and 10 g/cm^2 thicknesses of spacecraft material of aluminum, respectively. These are shown in Fig. 6 with exposures at skin, eye, and effective tissue/organ.

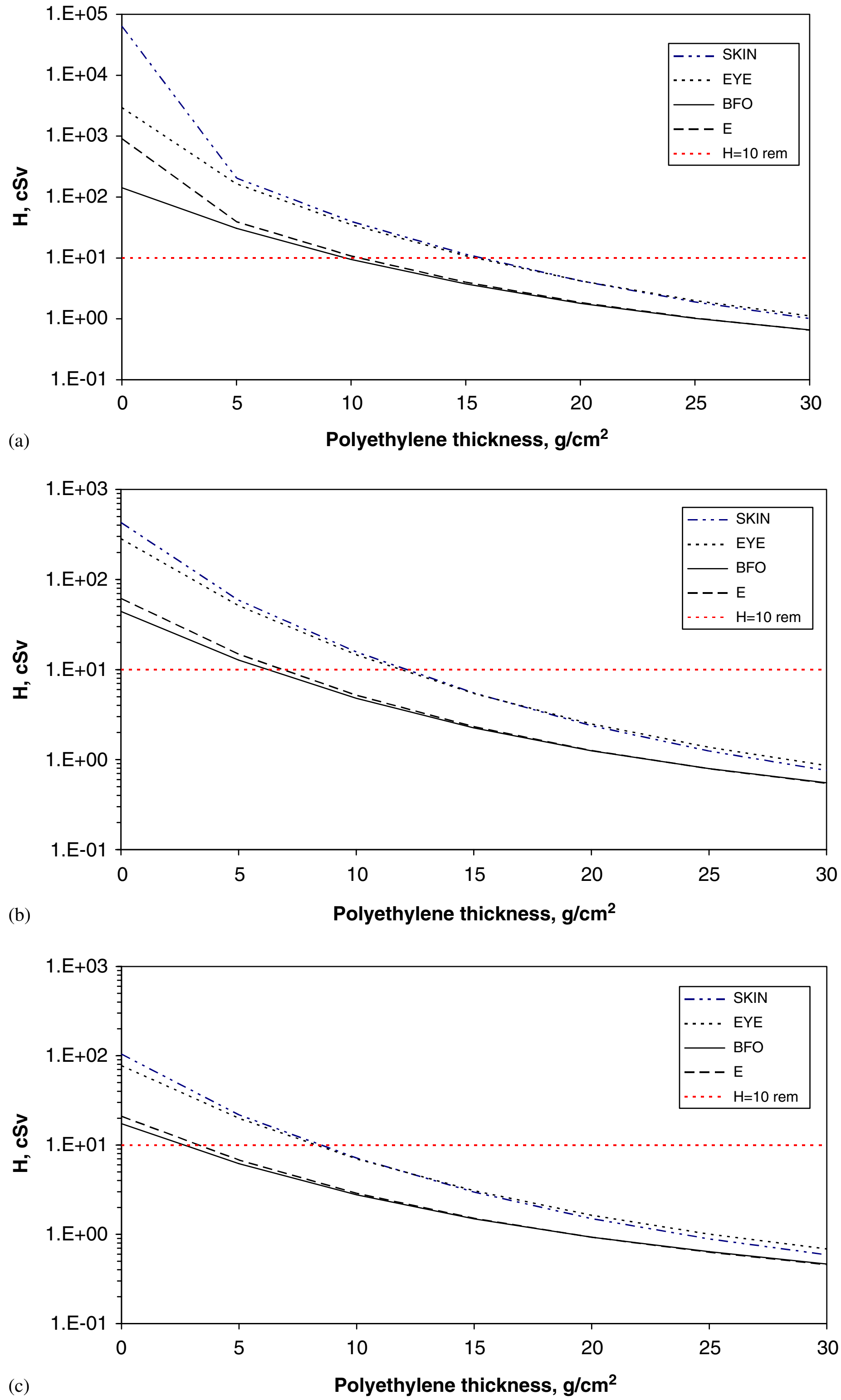


Fig. 6. Dose equivalents at sensitive sites from August 1972 SPE with various polyethylene shielding inside (a) 0; (b) 5, and (c) 10 g/cm^2 of aluminum.

3. Concluding remarks

A statistical model based on the odd–even behavior of historical sunspot cycles has been developed for the calculation of solar activity levels by separating a cycle into rising and declining phases. The resultant projections of sunspots are used to estimate the mean occurrence frequency of solar particle events (SPEs). In solar active years, up to seven events with large fluence ($\Phi_{30} \geqslant 10^6$ protons/cm^2) are expected annually. Because dose rate dependent factors are expected to be important for biological responses, the detailed temporal behavior of one large event measured in October 2003 is analyzed. From this analysis, the doses received from the event are shown to be of low dose-rates. In contrast, August 1972 event and November 1960 event, whose event-integrated integral fluences are lower than that of October 2003 SPE, requires additional protection during certain periods of time at the major peak to avoid high dose-rates. In the case of having an event at high dose or dose-rates in the future, astronauts require remaining in heavily shielded areas during peak dose-rate times. For the reduction of overall exposure levels at BFO and other sensitive sites to less than 10 cSv from this kind of SPE, it can be achieved by adding polyethylene shielding to various spacecraft thicknesses. Because dose-rates can be reduced to less than 5 cSv/h inside polyethylene storm shelter ($\sim 10\,\text{g/cm}^2$), they can be characterized as low dose-rates for all historical SPE events except February 1956 SPE.

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