

Time Exceedances for High Intensity Solar Proton Fluxes

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Abstract—A model is presented for times during a space mission that specified solar proton flux levels are exceeded. This includes both total time and continuous time periods during missions. Results for the solar maximum and solar minimum phases of the solar cycle are presented and compared for a broad range of proton energies and shielding levels. This type of approach is more amenable to reliability analysis for spacecraft systems and instrumentation than standard statistical models.

Index Terms—solar particle event, time exceedance, worst case flux

I. INTRODUCTION

Developing and implementing strategies to deal with the space radiation environment is critical for new robotic and manned exploration initiatives. In order to have reliable and cost-effective spacecraft design and implement new space technologies accurate models that view things from varying perspectives are needed for estimating radiation risks. Underestimating radiation levels leads to excessive risk and can result in degraded system performance and loss of mission lifetime. Overestimating radiation levels can lead to use of excessive shielding, reduced payloads, over-design and increased cost.

Evaluating the risk due to solar particle events is a significant concern for all space missions, especially those away from the protective shielding effects of the Earth's magnetic field. Due to the difficulty in forecasting the occurrence and magnitude of solar particle events [1] probabilistic approaches are widely used to characterize events. In this regard, useful models have been developed to describe cumulative fluences [2-6] and worst case events [7,8] at a given level of confidence over the course of a mission. For the situation of worst case events it is also common to pick a severe event such as the well known one that occurred

in October 1989 and assume this is worst case for the mission, as is done in the CREME96 suite of codes [9].

When trying to establish a worst case environment additional information can be required by the space system designer. It is also useful for the designer to know how much total time during the mission that a pre-determined flux level is exceeded. This allows a straight forward assessment of the mission time period during which there should be reliable system or instrument operation. In many instances this is closely related to the design goals of the mission. For example, within the NASA Living With a Star (LWS) program the goal of the Solar Dynamics Observatory (SDO) instrumentation is to capture essentially complete data over 22 72-day periods during its 5 years of operations. This allows for data loss due to planned and unplanned events, the latter of which includes radiation. Another example within LWS is the Space Environment Testbed (SET) payload, which has a full mission success criterion of delivering 95% of the data for 40 weeks out of the 1 year of planned operations. The SET payload will be flown on the US Air Force Research Laboratory's Demonstration and Science Experiment (DSX) spacecraft. Another emerging development is that compact radiation monitors such as QinetiQ's Merlin [10], and ESA's Standard Radiation Environment Monitor (SREM) [11] are being flown with increasing frequency. An application of such monitors is to send out alerts when specified radiation levels are exceeded. Thus, quantitative prediction of the periods of high radiation levels is becoming increasingly important during the mission design phase.

Besides the total time during a mission that a radiation flux level is exceeded, it can also be important to evaluate the longest *continuous* time period that a given level is exceeded. This is significant for evaluating single event effects in microelectronics as well as imagers such as CCDs.

This work develops an approach for analyses of solar proton fluxes that contributes directly to these spacecraft design requirements. It evaluates both the expected total time and longest continuous time during a mission that a specified solar proton flux level is exceeded. These time intervals can be viewed as the periods during which an instrument or system may not operate reliably. Corresponding flux-energy spectra bounding the expected periods of unreliability are then constructed. This is done for both spacecraft incident protons and for shielding levels that are appropriate for modern

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spacecraft. The results complement currently available models for solar protons used for spacecraft design.

II. METHODS

A. Data Base

The solar proton flux data used for this study span a 36 year period from November 1973 through October 2009. Given a conventional 7-year definition of solar maximum during a solar cycle [3] this represents exactly 21 total years during solar maximum and 15 total years during solar minimum. The first 28 years were during a time period when the Goddard Medium Energy (GME) instrument on the Interplanetary Monitoring Platform-8 (IMP-8) spacecraft operated nearly continuously [12]. The IMP-8 spacecraft orbit was a near circular one at approximately 35 Earth radii and was therefore well positioned to measure interplanetary particle fluxes. The GME data have a proton energy range from 0.88 to 485 MeV divided into 29 non-overlapping energy bins. These data have been supplemented with data obtained from the Geostationary Operational Environmental Satellites (GOES) beginning in 1986. The reason is that the GME instrumentation saturates during very high flux levels while the GOES instrumentation performs better in this regard. Reference 12 gives the details of how these data sets were combined so the best features of each could be taken advantage of. Thereafter the IMP-8 data became intermittent and the spacecraft was eventually decommissioned.

For the last approximately 8 years the Space Environment Monitors (SEM) on the GOES-8 and GOES-11 spacecraft were used as data sources. Due to both the GOES orbit and the SEM design these solar proton flux measurements are not as accurate as those obtained with the scientific instrumentation on the IMP-8 spacecraft. Thus, the GOES-8 SEM was calibrated against the GME instrument measurements during the approximately 4-year period beginning in 1998 through the end of the GME data. Since the GOES-8 data end in May 2003 and the GOES-11 data begin in June 2003 it was not possible to directly cross calibrate these two similar instruments. Thus, it was assumed that the same calibration factors applied to the GOES-11 SEM that were obtained for the GOES-8 SEM. Examination of the GOES-11 energy spectra with and without these corrections indicated that they were reasonable and resulted in improved energy spectra.

B. Model Calculations

This model is based on relatively straight forward, although computationally intensive, direct analyses of the solar proton flux time series (flux vs. time measurements) in the 36-year data base that has been developed. The direct analysis of the time series avoids some of the usual difficulties that are encountered when constructing probabilistic solar particle event models. One such difficulty is the unavoidably arbitrary definition of an event, including start and stop times. This can

be particularly difficult when there are several rises and falls in the flux values before the flux returns to the background rate. Once events are defined it is commonly assumed that they are independent of one another, although this may not be the case [1].

The above difficulties are avoided in the current analyses. The approach is to choose a time period during the solar cycle corresponding to the mission of interest and evaluate the amount of time during this period that a pre-determined flux level is equaled or exceeded. This is done for both the total time and the longest continuous time that flux level is equaled or exceeded. The flux level is then incremented and the calculation repeated. This is continued until the maximum observed flux for that time period is reached. In order to combine data from different solar cycles, time periods are referenced to the peak period of each solar cycle as determined by the maximum sunspot number. This is taken as 1968.9, 1979.9, 1989.9 and 2000.2 for the last 4 cycles. The above procedure is repeated for all energies in the time series of flux values. The integral energy spectra of the data base range from > 0.88 to > 327 MeV.

These results are most useful for mission planners if they are determined for different shielding levels. For lightly shielded and heavily shielded applications, “worst case” fluxes may arise from different events. It is therefore useful to transport the time series of energy spectra through various shielding thicknesses before the flux levels are evaluated according to the procedure outlined above. Transport calculations were done whenever at least one energy bin had a flux level above background during a 30-minute measurement period. This was done using the NOVICE code [13] for a shielding thickness range of 50 to 500 mils in solid aluminum sphere geometry. Calculations for the amount of time that specified flux levels were equaled or exceeded during the period of interest were then repeated for each shielding level.

III. RESULTS

A. Total Time Exceedances

The model can be implemented for any time period during the solar cycle. Due to the large number of possibilities, results shown are restricted to the solar maximum and solar minimum time periods. A conventional definition is used where solar maximum is assumed to be the 7-year period consisting of 2.5 years prior and 4.5 years after the time of the peak sunspot number [3], the latter of which is given in section IIB for solar cycles 20-23. The solar minimum period is the remaining time during each solar cycle. Calculations were done as described in the previous section. Results presented here incorporate either the entire 21 years of data measured during solar maximum or the entire 15 years of data measured during solar minimum.

Figure 1 is a plot of the total number of hours per solar maximum year that the proton flux equals or exceeds the value shown on the x-axis in units of protons per square

centimeter per second per steradian. Note that the y-axis value is not a continuous time period. It was determined by summing distinct time periods during the 21 years of solar maximum data. Results were divided by 21 years so the normalized data could be compared to solar minimum. The flux range shown in the figure extends 2 orders of magnitude down from the maximum flux for each energy bin. As an example suppose one is interested in the > 11.1 MeV energy bin. It is seen that a flux level of 10^4 p/(cm²-s-sr) is exceeded about 2 hours per year on average while a flux level of 10^3 is exceeded about 1 day per year on average during solar maximum. Note that the continuous range of information available from this analysis is more complete than that obtained from analysis of a single worst case situation. The different perspective of “time exceedance” analysis lends itself to evaluation of reliable periods of operation of spacecraft instrumentation.

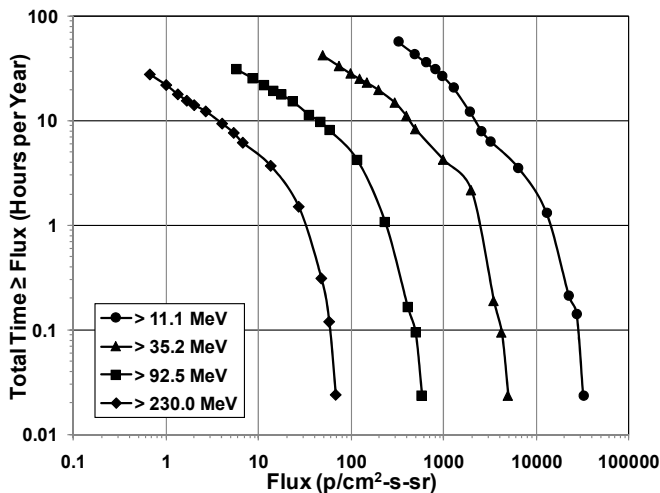


Fig. 1. Total number of hours per year during solar maximum that the proton flux equaled or exceeded the value shown on the abscissa for 4 energy groups: > 11.1, > 35.2, > 92.5 and > 230 MeV. Results are for surface incident fluxes.

The results displayed in figure 1 can be compared to those shown in figure 2 for solar minimum. It is generally seen that the same time exceedance values occur at lower fluxes during solar minimum, as would be expected. For example, the energy bin at > 11.1 MeV shows that for the same time exceedances during solar minimum, fluxes are approximately an order of magnitude lower. Although the solar minimum results do not represent worst case situations in general they may be useful for missions that occur entirely during this period of time.

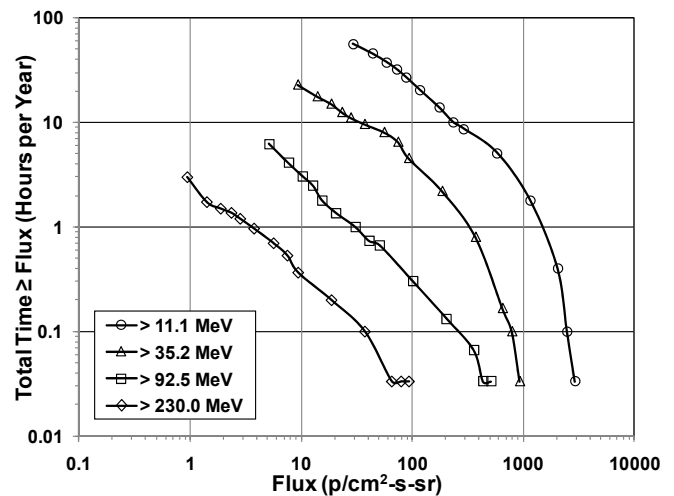


Fig. 2. Total number of hours per year during solar minimum that the proton flux equaled or exceeded the value shown on the abscissa for 4 energy groups: > 11.1, > 35.2, > 92.5 and > 230 MeV. Results are for surface incident fluxes.

Up to this point results shown have been for unshielded incident protons. As discussed before these results would be more useful if they were calculated for different levels of shielding. Thus, proton transport calculations were done for each 30 minute long energy spectrum in the 36 year data base whenever fluxes were above background. This was done for 50, 100, 200, 300 and 500 mils of aluminum shielding in solid sphere geometry. This resulted in various time series for flux values that span 36 years for each shielding level and energy bin considered. Example results for solar maximum are shown in figures 3-5 for > 11.1, > 35.2 and > 92.5 MeV protons. It is seen that in all cases the time exceedance is noticeably affected by the amount of shielding present. For example, the > 35.2 MeV flux level at 10^3 p/(cm²-s-sr) was equaled or exceeded for 4.2 hours per year without shielding, 1.6 hours per year with 200 mils of Al and about 0.1 hour per year with 500 mils of Al shielding. Examination of the figures clearly shows that the differences between the unshielded and shielded cases are more pronounced for low energies than for high energies. It should also be noted that the results obtained do not always yield perfectly smooth curves. As the value of flux increases along the x-axis, the time exceedance value can undergo a sudden decrease as events are no longer counted within that flux range. However, the data base does contain enough events to smooth out the results quite a bit.

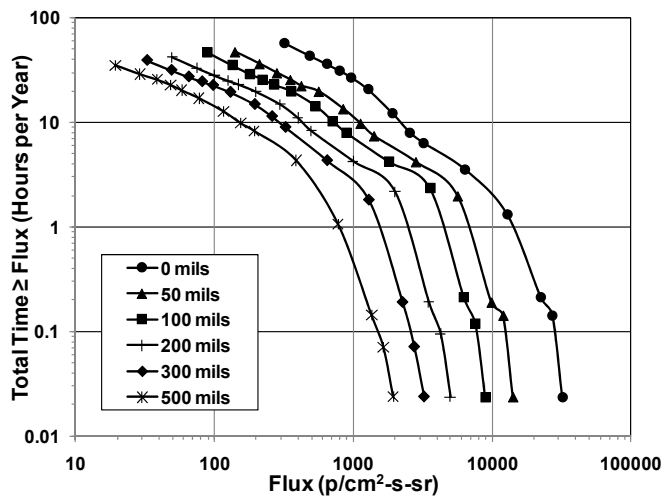


Fig. 3. Total number of hours per year during solar maximum that the proton flux equaled or exceeded the value shown on the abscissa for > 11.1 MeV protons with 0, 50, 100, 200, 300 and 500 mils of aluminum shielding in solid sphere geometry.

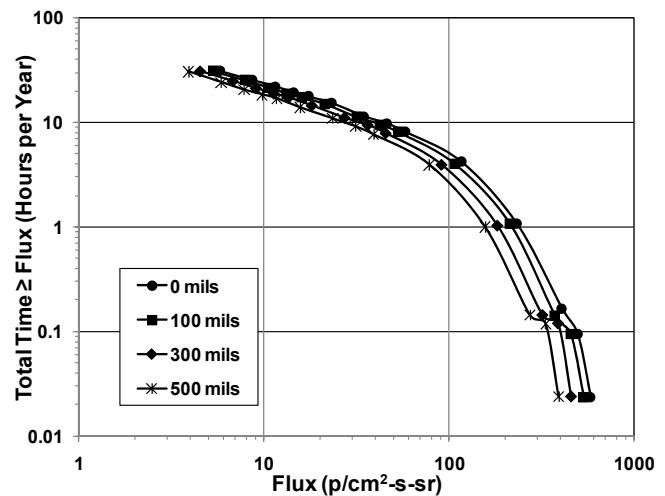


Fig. 5. Total number of hours per year during solar maximum that the proton flux equaled or exceeded the value shown on the abscissa for > 92.5 MeV protons with 0, 100, 300 and 500 mils of aluminum shielding in solid sphere geometry.

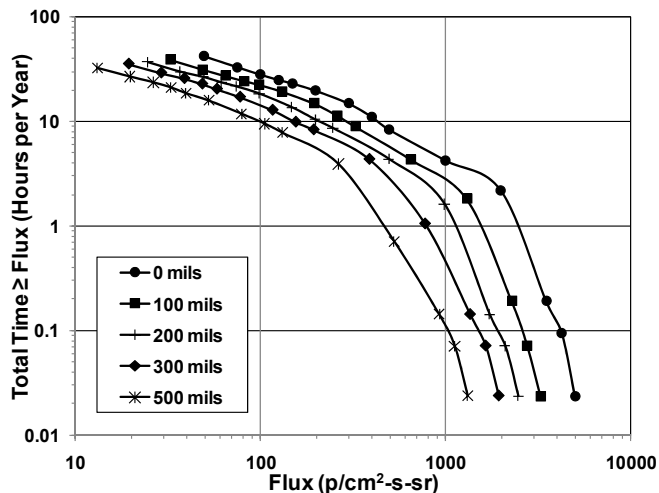


Fig. 4. Total number of hours per year during solar maximum that the proton flux equaled or exceeded the value shown on the abscissa for > 35.2 MeV protons with 0, 100, 200, 300 and 500 mils of aluminum shielding in solid sphere geometry.

Since this methodology has generated a lot of results it is of interest to look for a more compact way to view them. One possibility is to calculate a flux vs. energy spectrum for a given time exceedance level. As an example, suppose a mission can afford to lose only one hour of data per solar maximum year due to high intensity solar proton fluxes. A proton flux vs. energy plot for the one hour per year exceedance can be constructed by using results such as those shown in figure 1. The various flux levels corresponding to a y-axis value of 1 hour per year are determined for each energy group. A plot of flux vs. energy can then be made as shown in figure 6 for the unshielded case. Each point on this plot represents the flux for the corresponding energy bin that will be exceeded one hour per year on average. This 1-hour per year exceedance time holds only for individual points on the curve. It is not the case that the entire spectrum is exceeded 1 hour per year. As such the results can be viewed as a worst case flux vs. energy spectrum that defines the 1-hour total time exceedance criterion. Results for the shielded cases were obtained in a similar fashion and are also shown in figure 6. This is a particularly attractive representation because of its compactness as well as its similarity to measured solar proton event spectra.

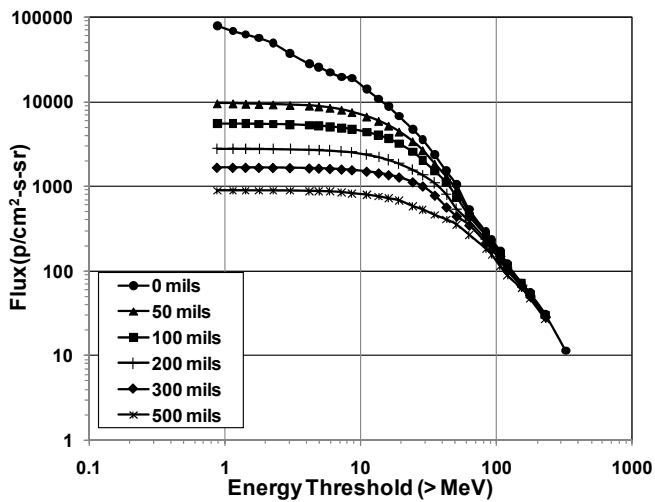


Fig. 6. Flux vs. proton energy spectra for a 1-hour per year time exceedance during solar maximum. See text for interpretation. Results are shown for 0, 50, 100, 200, 300 and 500 mils of aluminum shielding.

B. Continuous Time Exceedances

If the supposition is accepted that a system or instrument does not operate reliably beyond some flux threshold, then there are two important considerations in terms of time exceedances that need to be evaluated. The first is the *total* time during the mission that flux threshold is exceeded. That was discussed in the previous section. The second is the longest *continuous* time during the mission that threshold is exceeded. In the case of an instrument this would represent a worst case scenario of how long it could spend in a continuous state of unreliable operation. For example, this might occur when an imager is flooded with noise caused by the high proton flux.

Figures 7 and 8 show results for the longest continuous time period that the flux value on the x-axis is equaled or exceeded. Calculations for figure 7 were done for the 21 years of solar maximum data while those for figure 8 were done for the 15 years of solar minimum data. Much like the situation shown in the previous section it is seen that for a given flux level, the time exceedances are noticeably greater during the solar maximum period.

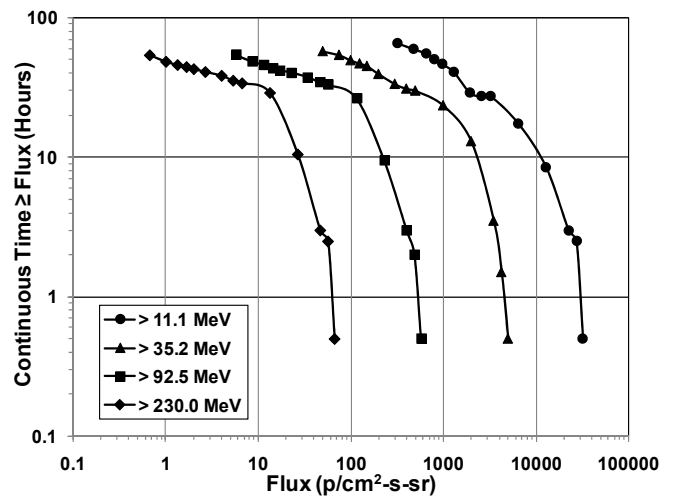


Fig. 7. Worst case number of continuous hours during solar maximum that the proton flux equaled or exceeded the value shown on the abscissa for 4 energy groups: > 11.1, > 35.2, > 92.5 and > 230 MeV. Results are for surface incident fluxes.

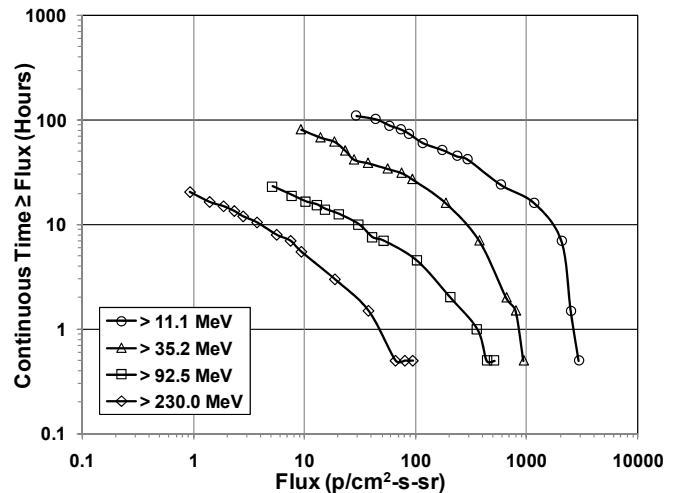


Fig. 8. Worst case number of continuous hours during solar minimum that the proton flux equaled or exceeded the value shown on the abscissa for 4 energy groups: > 11.1, > 35.2, > 92.5 and > 230 MeV. Results are for surface incident fluxes.

It is also desirable to construct worst case flux vs. energy spectra for a given time window. The results shown in figure 7 represent the longest continuous time interval that the flux equals or exceeds a value. Thus, it does not necessarily represent the worst case fluence for the time window when there are successive rises and falls in the flux values during a single event. Worst case spectra must be derived by first selecting a shielding thickness and energy bin. A time window with a fixed width is then moved across the entire time series, one 30-minute increment at a time, to evaluate the maximum fluence seen at any position in the time series during that time window. This subtle distinction from using results such as those in figure 7 becomes more important as longer time windows are considered. Results are shown in figures 9 and 10 for 1-hour and 24-hour time windows during solar maximum, respectively. Since each data point in the figures is calculated independently, this leaves open the

possibility that different points could result from different solar proton events. For the results shown in figure 9, however, all data turned out to come from the well known event of October 1989. This is consistent with the use of this event by the CREME96 suite of codes as worst case. On the other hand, for the worst case 24 hour period shown in figure 10, the spectra are made up of data from 3 separate events. This includes the events of July 2000 and November 2000 along with the October 1989 event. As can be seen in the figure, the October 1989 event contributes the worst case fluxes at energies greater than about 50 MeV while the other 2 events make up the majority of the spectra at lower energies. Thus, while the October 1989 event is often a suitable choice as a worst case situation, this may not always be true. For example, some highly scaled technologies are susceptible to single event upset by protons close to their end of range [14]. For this situation one of the events that occurred in the year 2000 would represent a worst case flux. The particular choice would depend on the level of shielding. Finally, it is worth noting that a comparison of figures 9 and 10 indicate how much the worst case flux levels vary when the desired period of continuous unreliable operation is reduced from 1 day to 1 hour. The increased reliability of the system or instrument requires devices and/or mitigation schemes that are more robust to single event effects as shown by the increased flux levels in the figures.

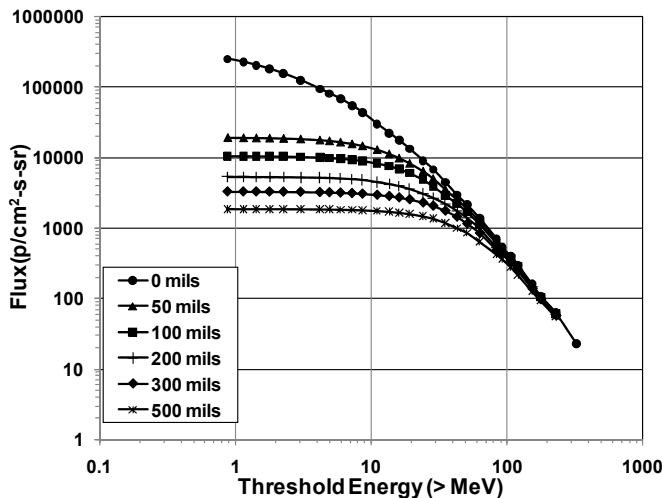


Fig. 9. Worst case flux vs. proton energy spectra for a 1-hour time window during solar maximum. Results are shown for 0, 50, 100, 200, 300 and 500 mils of aluminum shielding. Each data point comes from the October 1989 event.

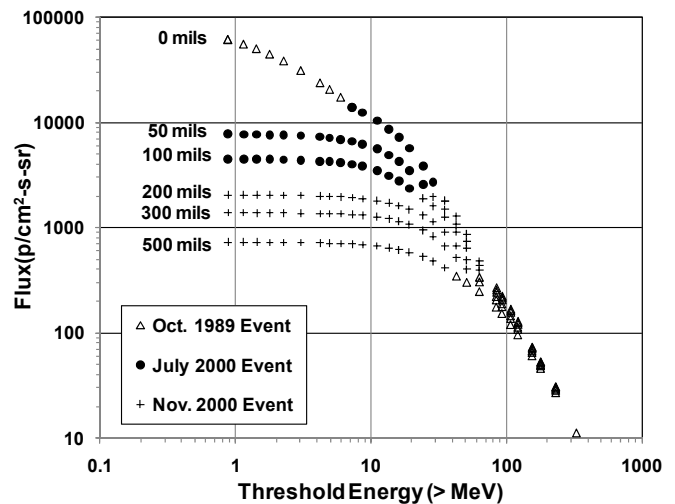


Fig. 10. Worst case flux vs. proton energy spectra for a 24-hour time window during solar maximum. Results are shown for 0, 50, 100, 200, 300 and 500 mils of aluminum shielding. The event that each worst case point comes from is shown in the legend.

IV. SUMMARY AND CONCLUSIONS

This paper has presented a model of high intensity solar proton fluxes that is free from many of the assumptions that are made for statistical models of solar proton events. Results show the amount of time that high intensity solar proton flux levels are expected to be equaled or exceeded during the entire mission and during a single continuous period. Analyses have been done on the time series of flux values transported through varying shield thicknesses, making the results more relevant for spacecraft applications. From these results, worst case flux vs. energy spectra have been derived that can be used by designers to bound periods of unreliable operation of space systems and instrumentation. This is a natural way to tie the model to design goals of projects, especially those of data requirements for instrumentation.

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