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Space Environment Effects: Model for Emission of Solar Protons (ESP)—Cumulative and Worst-Case Event Fluences

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1. INTRODUCTION

1.1 Background and Overview

The effects that solar proton events have on microelectronics and solar arrays are important considerations for spacecraft in geostationary and polar orbits and for interplanetary missions. Designers of spacecraft and mission planners are required to assess the performance of microelectronic systems under a variety of conditions. A number of useful approaches exist for predicting information about solar proton event fluences and, to a lesser extent, peak fluxes. This includes the cumulative fluence over the course of a mission [1,2,3,4,5], the fluence of a worst case event during a mission [5], the frequency distribution of event fluences [6], and the frequency distribution of large peak fluxes [7]. Information about single events supplements the long-term information, and it is useful for assessing worst case scenarios.

Two models commonly used for cumulative fluence estimates are the SOLPRO model [8], based on King's analysis of spacecraft measurements from solar cycle 20 data, [1] and a model from JPL which was initially based on ground data from solar cycle 19 and spacecraft measurements from solar cycles 20 and 21 [3]. An updated version of the JPL model incorporates cycles 20, 21, and part of cycle 22 [4]. Because the SOLPRO model was based on a solar cycle in which one solar proton event dominated the total fluence for that solar cycle (the August 1972 event), the model predicts the number of extremely large events expected for a given mission length and confidence level. Using additional data from solar cycles 19 and 21, the Feynman team later showed that the severity of solar proton events actually forms a continuum between very small events and the "anomalously" large events of the magnitude of the August 1972 event. Spacecraft measurements from solar cycle 22 gave further evidence that extremely large events are not an anomalous occurrence with six events occurring that had fluence levels > 1.0×10^9 protons-cm^{-2} at energies greater than 30 MeV.

The SOLPRO and JPL models have been very useful for predicting event fluences for long-term degradation but do have limitations due to the incomplete nature of the data sets upon which they were based. The first limitation is the energy (E) range. The SOLPRO model covers energies > 10 to > 100 MeV and the most recent JPL model covers energies > 1 MeV to > 60 MeV. The fluence levels below 10 MeV are desirable for accurate predictions of solar cell degradations, whereas, the higher energy particles, with their greater ability to penetrate shielding, are important to consider for total dose degradation and single event effects in system electronics. Clearly, a model that has adequate energy range for all applications is needed. Also, note that neither model includes the full three solar cycles for which high quality space data are available. This is important because these three cycles are dissimilar from one another. Cycle 20 had one extremely large* solar proton event that accounted for most of the accumulated fluence, cycle 21 had no extremely large proton events, and solar cycle 22 had six extremely large events with two occurring within a one month period (September-October 1989). Another limitation of these two models is that they do not describe the worst case solar proton event during a mission. This is usually characterized by the event fluence and peak flux.

Spacecraft designers often assume that the worst case solar proton event that will be encountered during a space mission is the same as a well-known large event such as the one which occurred in October 1989 [9]. A current NASA guideline recommends that a worst case event be taken as a composite of the February 1956 and August 1972 events [10]. However, more useful information can be provided to the designer if the worst case magnitudes are known as a function of confidence level and mission duration. Then the designer can balance the trade-offs between risk and cost in a more systematic way. In addition, it could be useful if a practical upper limit to the event magnitude were established. This would provide a guideline for designing the spacecraft to operate through any event encountered during a mission.

1.2 Summary

Naval Research Laboratory (NRL) and NASA/Goddard Space Flight Center, under the sponsorship of NASA's Space Environment and Effects (SEE) program, have developed a new model for predicting cumulative solar proton fluences and worst case solar proton events as functions of mission duration and user confidence level. Peak flux distributions will be added to the model at a later date. This model is called the Emission of Solar Protons (ESP) model.

The ESP model predicts integral omnidirectional solar proton fluences for interplanetary space at 1 astronomical unit (AU). The model will be expanded to include attenuation by the magnetosphere for geocentric orbits and for distances outside of the magnetosphere other than 1 AU. The energy range of the statistical model is > 1 to > 100 MeV. Unfortunately, satellite instrument measurements for higher energies are not sufficient for a true statistical model. Therefore, for energies from > 100 to > 300 MeV, an empirical approach was taken to the modeling based on spacecraft measurements for solar cycle 22.

The statistical model was developed using a new approach for analyzing the database of spacecraft measurements. The approach recognizes that the nature of the data set is incomplete and uses a mathematical formalism to select arguably the best statistical distribution for the data.

* Extremely large events are defined as those with total fluence levels exceeding 1.0×10^9 protons-cm^{-2} at energies greater than 30 MeV.

2. Data Source

Instruments have been measuring proton fluxes in space since 1963. Data for the years prior to 1963 are from riometers, balloons, and rockets. Space applications require that these early non-spacecraft measurements be extended through the atmosphere to interplanetary space. Such data were not used for this model because of concerns for the accuracy of the extrapolation methods. This includes the data from 1956 through 1962 commonly used to describe solar cycle 19 fluences. [11,12]

The ESP model is based on satellite measurements from 1963 through 1996, covering solar cycles 20, 21, and 22. Several previous analyses of solar proton satellite data were reviewed for this study, including those by King, Armstrong, Goswami, Feynman, and Shea and Smart. In 1974 King analyzed data from the IMP series of satellites for the time periods of 1966 through 1972 [1]. In 1983 Armstrong et al. presented an analysis of data covering the time period of 1963 through 1982 using data from IMP satellites and OGO-1 [11]. A 1988 paper by Goswami et al. presented an analysis of measurements from IMP-7 and –8 covering the time period of 1972 through 1986 [13]. Feynman et al. reviewed the King and Armstrong data sets for the 1991 JPL solar proton model [3]. In 1992 Shea and Smart reviewed all available data for the time period of 1955 through 1986 [14]. In 1996 Stassinopoulos et al. presented an analysis of data from the GOES-5, -6, and -7 satellites for solar cycle 22 [15]. Table 2-1 gives the satellite and energy range for each solar cycle included in the data base for the ESP model. These data will be discussed in more detail in Section 2.3.

Table 2-1
Data Source and Energy Ranges for the Solar Cycle 20, 21, & 22 Data

Solar Cycle	Data Source	Satellite Name(s)	Instrument Name	Time Period	Energy Range (>MeV)
20	King [1]	IMP-3 IMP-4 IMP-5	APL/JHU (SPME) Bell Labs NASA/GSFC U. of Chicago	July 1966 to August 1972	10-100
	Goswami [13]	IMP-7 IMP-8	NASA/GSFC (GME)	October 1972 To September 1974	1-92
21	Goswami [13]	IMP-8	NASA/GSFC (GME)	April 1976 to April 1984	1-92
22	Stassinopoulos [15]	GOES-5 GOES-6 GOES-7	NOAA (SEM)	February 1986 to August 1996	1-500

2.1 Spacecraft

The IMP satellites were a series of eight spin-stabilized spacecraft that were part of NASA's Explorer program. The IMP spacecraft were instrumented to measure energetic particles, cosmic rays, magnetic fields, and plasmas. The IMP program began with the launch of IMP-1 in November of 1963. The final satellite in the series, the IMP-8, was launched in October 1973 and is still operational.

The GOES series of satellites is operated by NOAA primarily for meteorology studies. Two goals of the GOES mission are to maintain reliable storm warning systems to protect life and property and to monitor the Earth's surface space environmental conditions. GOES monitors the space environment via the space environment monitor (SEM). The three main components monitored by SEM are X-rays, energetic particles, and magnetic field.

2.2 Orbital Coverage

The IMP series of spacecraft were in geocentric, highly elliptical orbits. The IMP-4 and -5 data sets were corrected for magnetospheric particles by restricting the coverage times to when the satellites were beyond 10 radii in distance from the Earth. IMP-7 and -8 were in trajectories well outside of the magnetospheric particle regions.

The GOES series of satellites are in geostationary orbits. The electron channel and the lowest energy proton channel (E > 1 MeV) of the GOES energetic particle sensor (EPS) respond to trapped outer-zone particles. The higher energy proton channels respond to particles originating outside of the magnetosphere.

2.3 Detectors and Instrument Analysis

In his analysis of solar cycle 20 solar proton events, King used all available proton flux data from instruments on the IMP-3, -4, and -5 satellites. He performed a detailed study of IMP-4 data from Bostrom,[*] Lanzerotti,[†] McDonald,[‡] and Simpson[§]. All four instrument data sets, spanning the energy range 10-100 MeV, were available for the period of May 1967 through May 1969. King found that the event integrated values for all four instruments agreed to within 25% [16]. King concluded that the IMP-4 data were "quite reliable" and that, because the IMP-5 instruments were essentially the same as those flown on IMP-4, the data for the IMP-5 period from June 1969 through December 1972 were similarly reliable. Armstrong et al. examined data from the Johns Hopkins University/Applied Physics Lab (JHU/APL) instrument on IMP-4 and –5 and the University of Chicago instrument on OGO-1 and developed a data set [11]. When the Feynman team compared the Armstrong and King data sets, they concluded that the differences were small enough that they did not affect their analysis and model development [3].

An analysis by Goswami et al. provides a detailed description of Goddard's medium energy (GME) instrument on IMP-7 and –8 [13]. To check the reliability of the fluences

[*] Johns Hopkins University, Applied Physics Laboratory
[†] Bell Telephone Laboratories
[‡] NASA Goddard Space Flight Center
[§] University of Chicago

of the GME instrument, they compare overlapping data from the IMP-6 solar proton monitor (SPME) and the IMP-7 charged particle monitor (CPME), both from APL/JHU, to the GME. Comparisons were good for two solar proton events, however, the third event showed a more complex pattern. From the descriptions of the SPME and GPME instruments, Goswami et al. concluded that the GME design may provide a better discrimination against background contamination.

The environmental sensing system on GOES includes the space environment monitor (SEM). The SEM monitors energetic proton fluxes from E >1 to E > 685 MeV. The energetic particle sensor (EPS) monitors fluxes from E > 1 to E > 100 MeV and the high energy proton and alpha detector (HEPAD) monitors protons in the energy range of E > 355 to E > 685 MEV. The EPS contains two detector assemblies, a solid state telescope and a set of wide-aperture dome detectors. The sampling rate is once every 10.2 or 20.5 seconds, and the dynamic range is from cosmic ray background to the largest solar particle events. The HEPAD is a Cerenkov solid-state telescope. A description of the sensor elements and analysis of the instrument data is given by Sauer [17,18].

3. Data Processing

Solar proton events were identified following the practice of NOAA, as published in *Solar Geophysical Data Reports* [19], where the beginning and end of an event are defined by threshold proton flux. Thus, a large event may consist of several rises and falls in flux. As has been done previously, only solar active years are considered in the model [4]. A definition of a solar active year based on the work of Feynman et al. [3] was adopted. A solar cycle typically lasts eleven years with seven years of high solar activity (referred to as solar active or solar maximum) and four years of low solar activity (referred to as solar inactive or solar minimum). The 7 active years are assumed to span a starting point 2.5 years before and an ending point 4.5 years after the date of the peak sunspot number. The dates of the peak sunspot numbers for cycles 20, 21, and 22 were 1968.9, 1979.9, and 1989.9. Table 3-1 lists the time span of the active years of the solar cycles and the satellite coverage used for each solar cycle.

Table 3-1
Time Span and Data Source for the 7 Active Years of Each Solar Cycle

Solar Cycle	Date of Sunspot Peak (year)	Start Date (year)	End Date (year)	Satellite Coverage
20	1968.9	1966.4	1973.4	IMP-3 IMP-4 IMP-5 IMP-7 IMP-8
21	1979.9	1977.4	1984.4	IMP-8
22	1989.9	1987.4	1994.4	GOES-5 GOES-6 GOES-7

Only high quality, corrected data from the sources described in Section 2.3 above were used in the final data set. The data were organized by using Microsoft® EXCEL workbooks. The data set includes energy dependent proton counts for solar proton events for the seven-year active phases of three solar cycles.

4. Model Development

The approach used to model the solar proton fluences was to first define the underlying distribution of the events. Then using that distribution, the cumulative and worst case event fluences were derived. The process is described here.

4.1 Initial Distribution of Solar Proton Event Fluences

Previous approaches to modeling solar proton event fluence distributions have been largely empirical in nature. Lognormal distributions have been used to describe large event fluences, but deviate from the measured distributions for smaller event fluences [1,3]. Power laws have also been used. These describe the smaller events very well, but overestimate the probability of large events [6]. Both of these types of approaches have merit. However, they do not accurately describe the complete distribution, allow for the possibility of infinitely large events, and lack strong physical and mathematical justification.

The basic difficulty in describing solar proton event fluence distributions arises from the incomplete nature of the data, especially for large fluence events. For example, in the last three complete solar cycles, only three separate events have produced an E > 10 MeV fluence of approximately 1.0×10^{10} cm^{-2} or greater [19]. Characterizing the probabilities of these very large events is particularly crucial for radiation effects applications.

The maximum entropy principle provides a mathematical procedure for generating or selecting a probability distribution when the data are incomplete [20,21]. It states that the distribution that should be used is the one that maximizes the entropy, a measure of uncertainty, subject to constraints imposed by available information. Such a choice results in the least biased distribution in the face of missing information. Here we will see that the application of the maximum entropy principle results in a distribution that describes solar proton event data very well.

The procedure is presented in detail for a study of peak fluxes during solar proton events [22]. An outline of the procedure is presented here as it applies to solar proton event fluences [23].

The distribution's entropy S, is defined [20,22]

$$S = -\int p(M)\ln[p(M)]dM \qquad (1)$$

where $p(M)$ is the probability density of the random variable M, which for this application is the base 10 logarithm of the event fluence, ϕ. A series of mathematical constraints are imposed on the distribution, using known information. The resulting system of equations are used along with equation (1) to find the solution $p(M)$ that maximizes S [21,22]. The method of accomplishing this is the Lagrange multiplier technique [24]. Once $p(M)$ is known, it can be shown that the frequency distribution of event fluences is a "truncated" power law.

$$N = N_{tot}\left[\frac{\phi^{-b} - \phi_{\max}^{-b}}{\phi_{\min}^{-b} - \phi_{\max}^{-b}}\right] \quad (2)$$

N is the number of events per active year of the solar cycle having a fluence greater than or equal to ϕ. N_{tot} is the total number of events per active year having a fluence greater than or equal to a chosen lower fluence limit ϕ_{min}. The power law index is b, and ϕ_{max} is the maximum event fluence. The result given by equation (2) and in reference 23 is more general than the corresponding equation in reference 22 because the above result incorporates an arbitrary lower limit ϕ_{min}.

Regression fits to equation (2) have been performed for the solar proton event fluence distributions with threshold energies ranging from > 1 to > 100 MeV. An example of this is shown in Figure 4-1 for the > 30 MeV threshold. The figure shows the quantity N as a function of event fluence, ϕ. Data are shown by the points, and the line is the best fit to equation (2). It is seen that the model describes the data remarkably well over its full 3.5 orders of magnitude. The best fit parameters are N_{tot}=4.41 events per solar active year, b=0.36, and ϕ_{max} = 1.32 x 10^{10} cm^{-2}, using a lower limit of ϕ_{min} = 3.0 x 10^{6} cm^{-2}. The choice of the lower limit only affects the value of N_{tot}. It is interesting to note that the index obtained here for the truncated power law given in equation (2) is close to the value of 0.40 reported by Gabriel and Feynman for an ordinary power law [6]. Whether or not this distribution is truncated should ultimately be determined by the data. It is clearly seen in Figure 4-1 that the measured event frequencies begin to tail off noticeably above about 10^{9} cm^{-2}, thus supporting the truncated distribution obtained with the maximum entropy principle. The maximum event fluence that is predicted, ϕ_{max}, is about 1.5 times the largest observed > 30 MeV fluence to date.

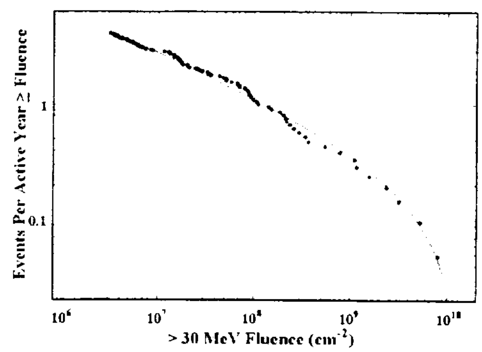

Figure 4-1: Comparison of the distribution of > 30 MeV solar proton event fluences predicted by equation (2) to data.

4.2 Worst Case Solar Proton Event Fluences

Since the initial distribution of solar proton event fluences has been described in Section 4.1, we can now determine the worst case event as a function of mission duration and confidence level. Assuming that the occurrence of solar proton events is a Poisson process [3], we have previously shown using results from extreme value theory that a cumulative, worst case distribution for T solar active years is given by [7]

$$F_T(M) = \exp\{-N_{tot}T[1 - P(M)]\} \quad (3)$$

Here, the cumulative probability, $F_T(M)$, is equal to the desired confidence level. $P(M)$ is the cumulative distribution corresponding to the known probability density $p(M)$. It can be written explicitly in terms of the fluence, ϕ, since $M = \log(\phi)$:

$$P(\phi) = \frac{\phi_{\min}^{-b} - \phi^{-b}}{\phi_{\min}^{-b} - \phi_{\max}^{-b}} \quad (4)$$

Applying equations (3) and (4) to the results discussed above for > 30 MeV protons, the worst case event distributions shown in Figure 4.2-1 are obtained. The ordinate represents the probability that the worst case event encountered during a mission will exceed the event fluence indicated on the abscissa. This is shown for mission lengths of 1, 3, 5 and 10 solar active years. Also shown in Figure 4.2-1 by the vertical line denoted by "Design Limit" is the maximum event fluence, ϕ_{max}. In order to illustrate the use of this figure, suppose that a designer is interested in a mission having a duration of 1 solar active year. If a 30% risk or exceedance probability is acceptable, the expected worst case, > 30 MeV event fluence is 9.6 x 10^8 cm^{-2}. For a lesser risk of 10 %, the event fluence increases to 4.6 x 10^9 cm^{-2}. At 1% risk, it is 1.2 x 10^{10} cm^{-2}. If the designer desires to take essentially no risk then the maximum event fluence of ϕ_{max} = 1.32 x 10^{10} cm^{-2} should be used.

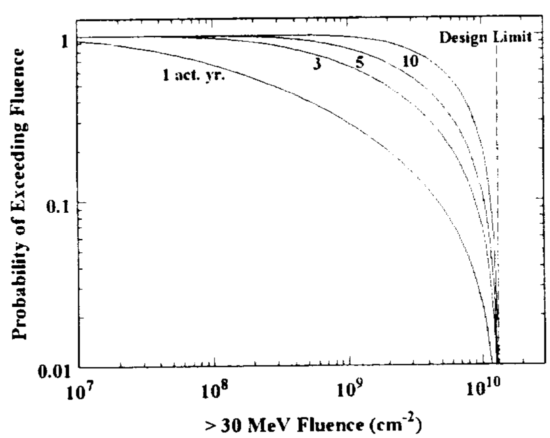

Figure 4.2-1: Probability the worst case solar proton event fluence encountered during a mission exceeds the value shown on the abscissa for missions with 1, 3, 5 and 10 active year periods. The probability of exceeding the design limit shown is essentially zero.

4.3 Cumulative Solar Proton Event Fluences

Given the initial distribution of solar proton event fluences, its mean and variance are known. Solar proton event fluences are described by Poisson statistics. The number of events is a Poisson variable, and the event magnitude is also a variable. The cumulative fluence variable, Φ, is therefore the sum of a random number of random variables. The general relations for the mean and variance of the sum distribution in terms of the mean and variance of the initial distribution are described in probability theory by the variance theorem of Burgess [25]. Thus, the parameters of the cumulative fluence distributions are also known.

If the form of this distribution is now known for time periods corresponding to realistic space missions, the model is complete. Due to its Poissonian nature, the distribution is unbounded. Assuming that it is normalizable, the maximum entropy principle can be used to show that the best choice of a distribution consistent with the constraints in this section is a lognormal distribution in the cumulative fluence. We have performed a variety of simulations to validate this. For example, summing simulated event fluences determined by the underlying distribution and assuming the event numbers are Poisson probabilities results in a lognormal distribution. Bootstrap-like methods also indicate that a lognormal distribution is appropriate [5]. Perhaps most convincing, however, is to examine the actual satellite data for a given period of time. This is shown in the Figure 4.3-1 for 1 year intervals during solar active periods. The y-axis indicates the summed fluence during each solar active year. The cumulative probability of each 1 active year fluence total is calculated as $m/(N+1)$, where m is the rank and N is the total number of data points [26]. The probability paper used for Figure 4.3-1 is constructed so that a lognormal distribution appears as a straight line. Thus, it is seen that the cumulative fluence distributions are well described as lognormal. In order to interpret this figure, note that for a cumulative probability or confidence level of 0.90, the annual fluence for > 100 MeV protons is about 2.6 x 10^8 cm^{-2}. This means that 90% of the total fluences for 1 active year periods are less than or equal to 2.6 x 10^8 cm^{-2}.

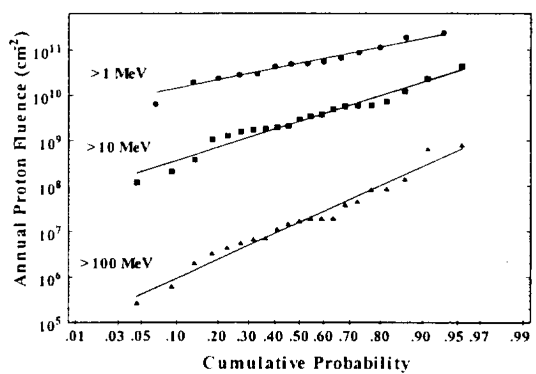

Figure 4.3-1: Probability plot, constructed on lognormal probability paper, of the total annual solar proton event fluence observed at 1 AU for active years. Satellite data for solar cycles 20-22 are shown for proton energies greater than 1, 10 and 100 MeV.

Thus, in the ESP model the distribution of cumulative fluences Φ, for any time period is described as the cumulative lognormal function

$$F_{CUM} = \frac{1}{\sigma\sqrt{2\pi}} \int_{0}^{\Phi} \frac{1}{\Phi'} \exp\left\{ -\frac{1}{2\sigma^2} \left[\ln(\Phi') - \mu\right]^2 \right\} d\Phi' \quad (5)$$

The value of F_{CUM} is the confidence level for observing a total proton fluence Φ over T active years. The lognormal parameters σ and μ are dependent on T in a simple way. They are obtained from the lognormal parameters of the fitted total annual fluence distributions such as those shown in Figure 4.3-1. This is described in Section 5.1.

4.4 High Energy Data

The lack of high energy proton measurements for all three solar cycles prevents the implementation of a statistical model for energies greater than 100 MeV. Instead, an empirical approach was taken by reviewing the available high energy data and using that data to extrapolate the spectra generated by the statistical model. A review of the high energy data is given here.

In reference 1 King describes a > 200 MeV measurement from a USSR stratospheric balloon experiment. The Russians obtained an intensity-time profile for the flux of protons above 200 MeV for the large August 1972 solar particle event. King integrated the area under the curve that was published by the experimenters [27] and estimated the > 200 MeV fluence as 1.3×10^7 cm^{-2}.

The GOES HEPAD instrument provides proton measurements at energies greater than 100 MeV for solar cycle 22. These measurements were analyzed and included in the solar cycle 22 data set for proton fluences up to > 500 MeV. Sauer [18] provided a description of the high energy measurements. Because these high energy measurements were not available for solar cycles 20 and 21, they were not included in the ESP statistical model.

Figure 4.4-1 compares the high energy data for the USSR > 200 MeV point and the solar cycle 22 GOES EPS and HEPAD measurements for six extremely large events. The August 1972 event from solar cycle 20 is also plotted. The dashed line between the > 100 MeV point of the August 1972 event and the USSR balloon measurement at > 200 MeV represents the commonly used extrapolation of the IMP-5 measurements.

Tylka et al. also used proton data from GOES for the extremely large October 1989 event to define the 99% worst case solar particle event for CREME96. The 99% worst case prediction as calculated by the CREME96 "worst day" model* is also plotted in Figure 4.4-1. In reference 9 Tylka et al. point out that the original King data for the August 1972 event contained substantial electron contamination, explaining the large differences between the description of that solar cycle 20 event in the < 100 MeV energy range and the measurements for solar cycle 22. This is clearly seen in Figure 4.4-1. The figure shows the substantial improvement in the definition of the solar proton energy spectrum that is possible with the later measurements, especially in the high energy regime.

Several additional, smaller solar proton events were examined for the shape of their energy spectra and were found to be very similar to the six large events plotted here and to the CREME96 solar proton model. A comparison was also made to the ESP statistical model (1 < E < 100 MeV) for a confidence level range of 50-99% and a mission duration range of one to seven solar active years. Based on these comparisons, it was determined that the spectral shape for the high energy GOES measurements is a good approximation

* For the comparison to these data, the CREME96 model is cut off at E > 500 MeV. CREME96 predicts solar protons out to E > 100,000 MeV.

for high energy model predictions. Thus, the high energy data shown in Figure 4.4-1 were scaled to extend the ESP statistical model spectra to > 300 MeV.

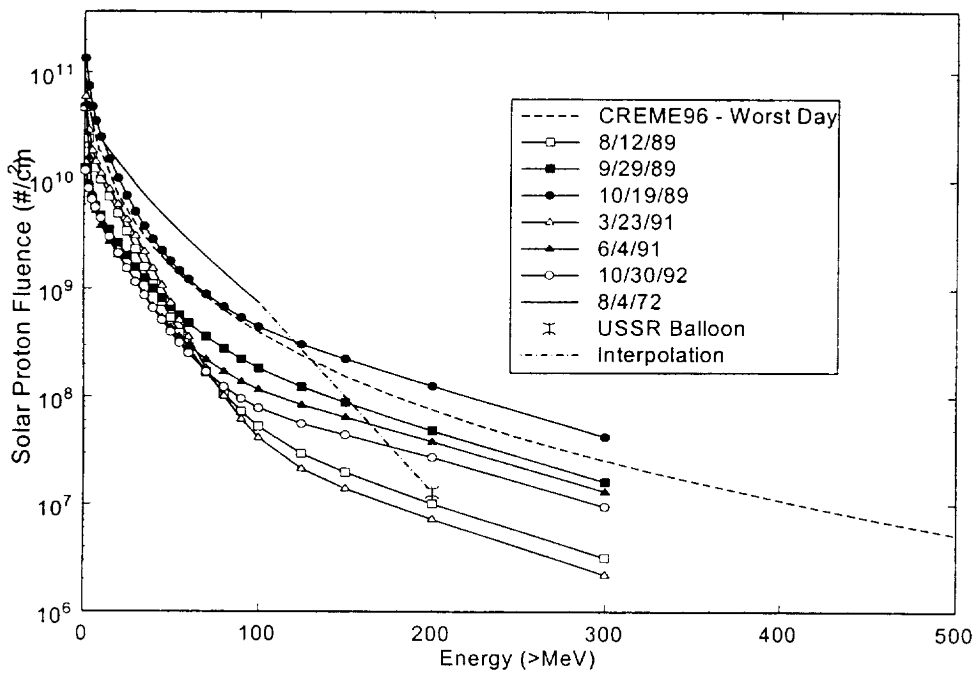

Figure 4.4-1: High energy data for extremely large solar cycle 22 events, CREME96 model, and 8/72 USSR balloon experiment are compared. The dashed-dotted line is the commonly used interpolation between the 8/72 event and the USSR balloon measurement.

5. SOFTWARE DEVELOPMENT

A convenient way to calculate cumulative solar proton fluences and worst case event fluences is with computer software. A code for the ESP model with a Windows® interface was developed at Goddard Space Flight Center. The implementation of the model into computer code and the results obtained with the code are given in Sections 5.1 and 5.2. The code is described in Appendix A.

5.1 Implementation of Analytical Model

The inputs required of the program user are the desired confidence level and starting and ending dates for the space mission. Using these input dates, the program evaluates the number of solar active years for the mission. The expected total fluence and worst case event fluence are then calculated for the specified confidence level and mission duration. In addition, results for other commonly used confidence levels are calculated.

The total fluence over the course of the mission is specified by equation (5). This is a cumulative lognormal function and must be evaluated numerically. Many tabulations of normal and lognormal distributions can be found and used to evaluate this function and its inverse. For this purpose, we have used the tabulation provided in reference 28. The lognormal parameters σ and μ used for a distribution of T solar active years is obtained from the distribution for $T = 1$ solar active year in the following manner. The lognormal parameters for 1 solar active year are taken as the best fit values obtained from plots such as those shown in Figure 4.3-1. These parameters are then related to the mean and relative variance of the 1 active year distribution by the following [29]:

$$\Phi_{mean} = \exp\left(\mu + \frac{\sigma^2}{2}\right) \quad (6)$$

$$\Phi_{RV} = \exp(\sigma^2) - 1 \quad (7)$$

The mean for a T active year distribution is then equal to $T \times \Phi_{mean}$. The relative variance for a T active year distribution equals Φ_{RV}/T. Equations (6) and (7) can now be used to calculate the lognormal parameters for the T active year distribution. Inserting the resulting parameters into equation (5) allows the cumulative fluence to be evaluated for the desired confidence level.

The worst case event fluence for a given level of confidence and mission duration is calculated in a straight forward fashion using equations (3) and (4). Evaluation of the parameters required in these equations is discussed in Section 4.2.

5.2 *Model Results*

Solar proton fluence predictions were calculated using the ESP model for a range of confidence levels, mission durations, and energy levels. These calculations are not meant to be inclusive but are given to acquaint the user with the energy range of the ESP model and to show the fidelity of the predictions. Comparisons are made to other models where possible. Results are given for the cumulative and worst case event models.

5.2.1 Cumulative Fluence Model

Results are presented here for the ESP cumulative fluence model. Figures 5.2.1-1 through 5.2.1-4 show the dependence of the predicted integral solar proton fluences on the mission duration, energy level, and confidence level. Figure 5.2.1-1 plots the solar proton energy spectra for a range of confidence levels commonly considered for mission analyses. The data are for one year during the active phase of the solar cycle. Figure 5.2.1-2 gives energy spectra for mission durations ranging from one to seven years during the active phase of the solar cycle. The confidence level is 95%. Figures 5.2.1-3 and 5.2.1.4 show the dependence of the fluence predictions on mission duration with Figure 5.2.1-3 giving the fluences for various confidence levels and Figure 5.2.1-4 giving the fluences for various energies.

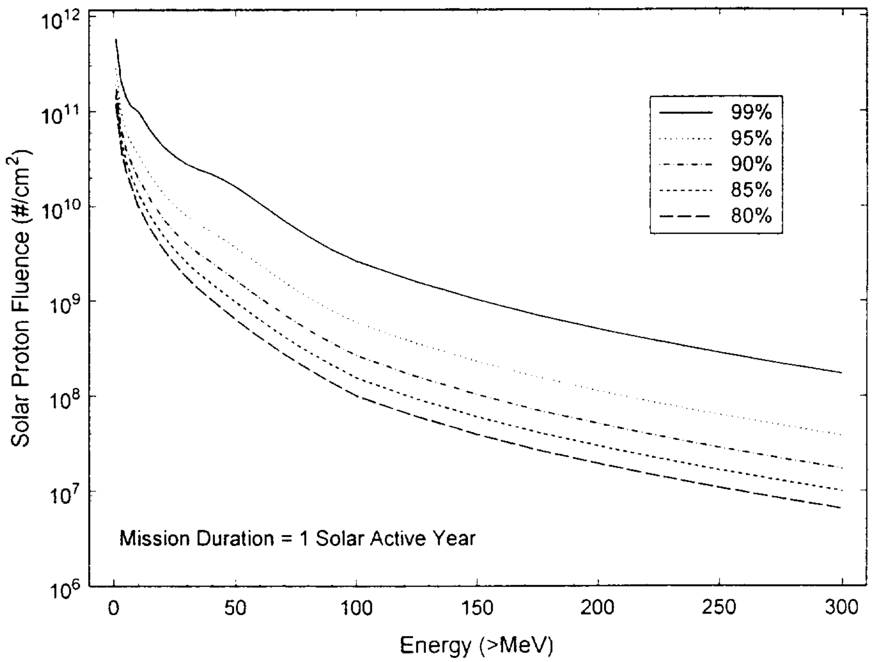

Figure 5.2.1-1: Integral solar proton energy spectra are given for various confidence levels for 1 solar active year.

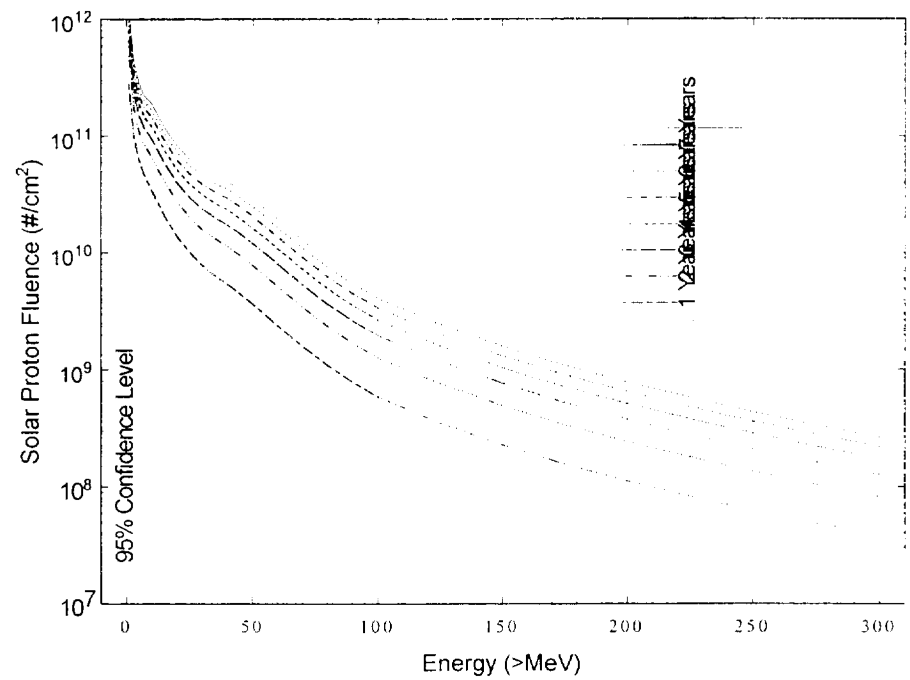

Figure 5.2.1-2: Integral solar proton energy spectra are given for various mission durations for a 95% confidence level.

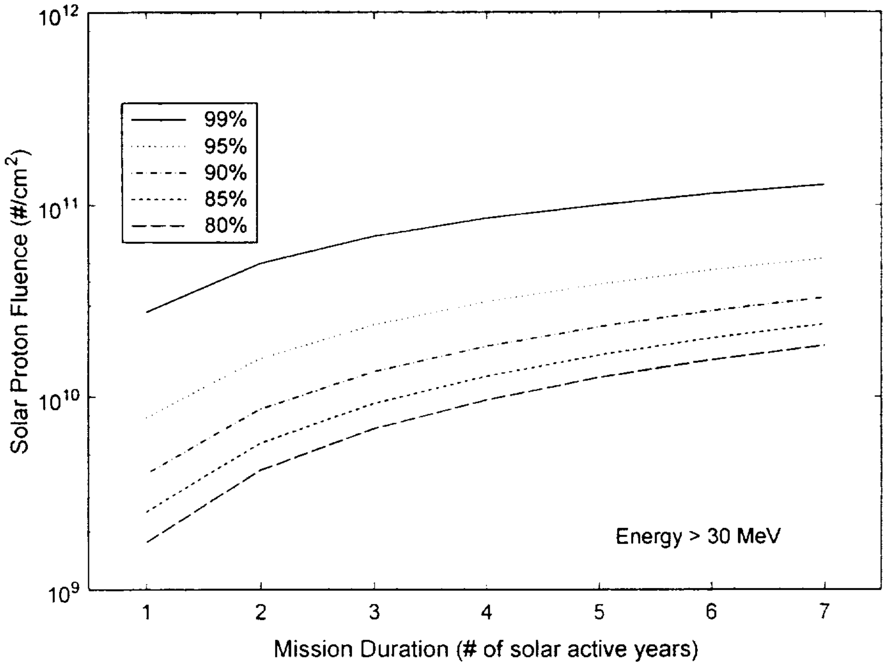

Figure 5.2.1-3: E > 30 MeV solar proton fluences are given as a function of mission duration for various confidence levels.

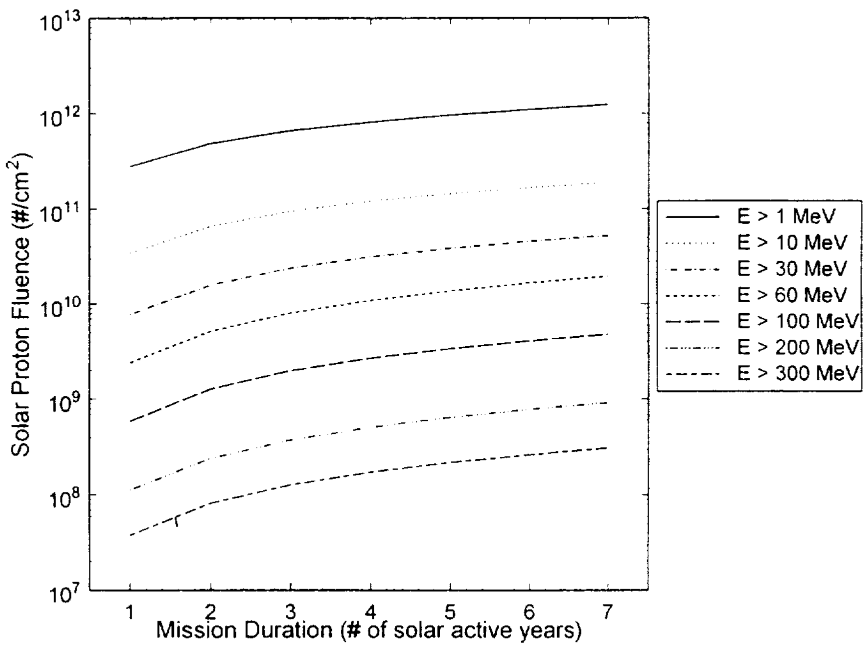

Figure 5.2.1-4: Integral solar proton fluences are given as a function of mission duration for various energy levels for a 95% confidence level.

5.2.2 Worst Case Event Model

Results are presented here for the ESP worst case event fluence model. Figures 5.2.2-1 through 5.2.2-4 show the dependence of the predicted solar proton fluences on the mission duration, energy level, and confidence level. Figure 5.2.2-1 plots the solar proton energy spectra for a range of confidence levels commonly considered for mission analyses. The data are for one year during the active phase of the solar cycle. Figure 5.2.2-2 gives energy spectra for one and seven solar active years. The confidence level is 95%. Figures 5.2.2-3 and 5.2.2.4 show the dependence of the fluence predictions on mission duration with Figure 5.2.2-3 giving the fluences for various confidence levels and Figure 5.2.2-4 giving the fluences for various energies. Note that, as one would expect, increasing the number of solar active years does not significantly increase the predicted worst case event fluence levels for mission durations greater than 3 years.

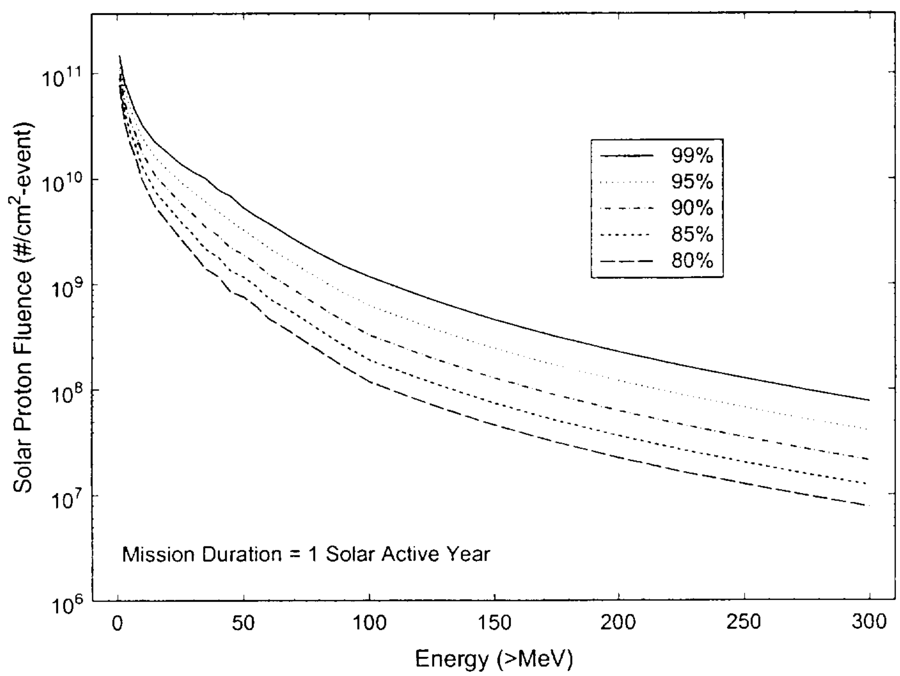

Figure 5.2.2-1: Solar proton energy spectra are given for various confidence levels for 1 solar active year.

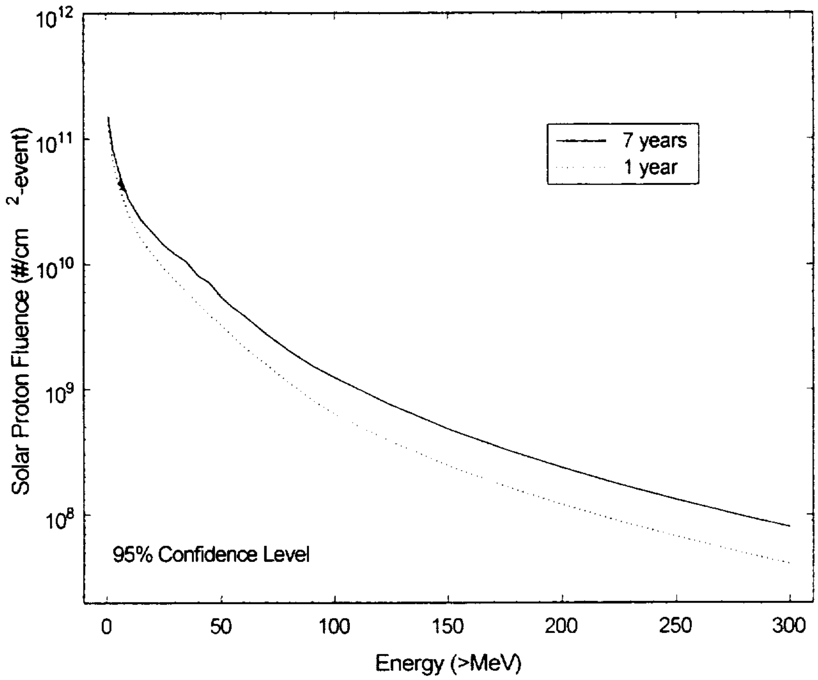

Figure 5.2.2-2: Solar proton energy spectra are given for various mission durations for a 95% confidence level.

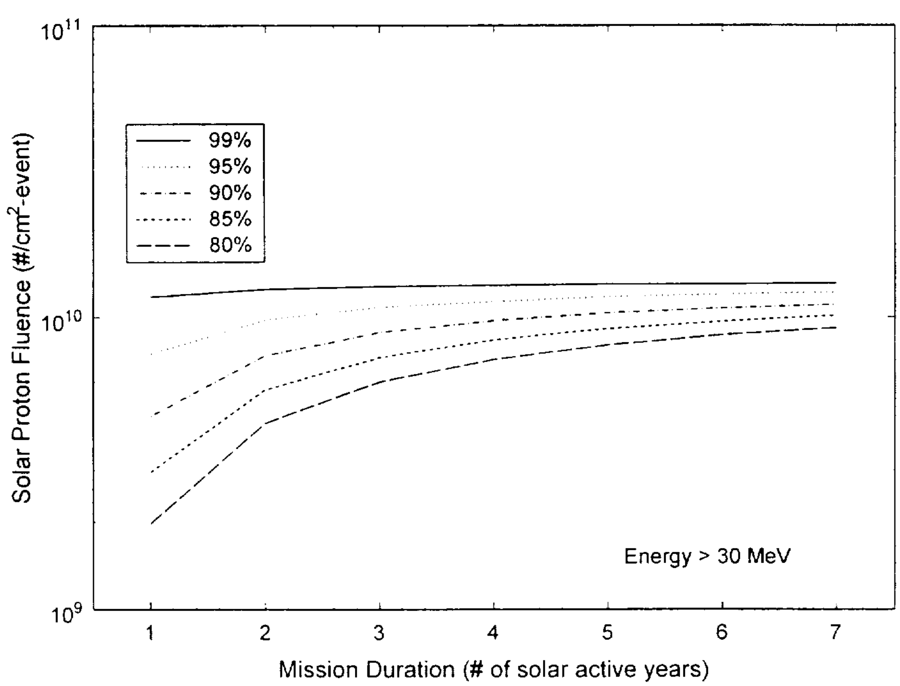

Figure 5.2.2-3: E > 30 MeV solar proton fluences are given as a function of mission duration for various confidence levels.

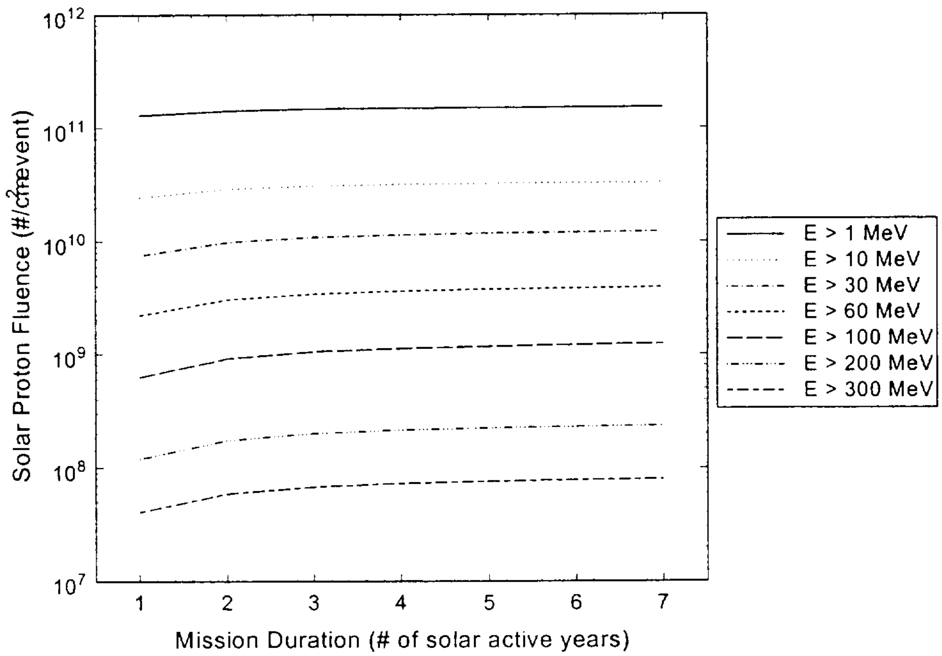

Figure 5.2.2-4: Solar proton fluences are given as a function of mission duration for various energy levels for a 95% confidence level.

5.3 Comparison to Other Models

The integral fluences obtained from the ESP cumulative and worst case event models were compared to other models. Figure 5.2-1 shows the ESP cumulative model results plotted with predictions for the SOLPRO and JPL model for 1, 3, and 7 solar active years. Predictions from the SOLPRO model for seven active years are not included because the maximum mission duration for that model is six years. The addition of the solar cycle 22 measurements did not result in significant differences between the three models. This was not unexpected based on the analysis of the event distributions described in Section 4.1. Note the difference in the SOLPRO and ESP models at high energies is due to the improved high energy data base.

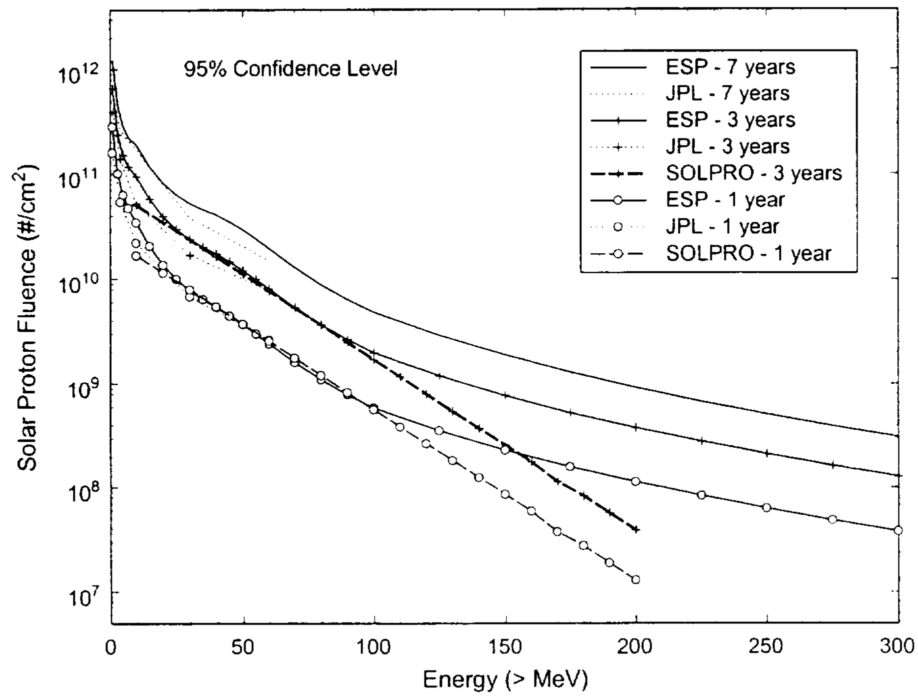

Figure 5.3-1: Cumulative solar proton fluence models are compared for a 95% confidence level. The fluences are integral.

Figure 5.3-2 shows a comparison of the worst case event model, integral fluences with predictions from the "worst week" CREME96 model.* This model was based on GOES proton measurements made during the October 1989 solar particle event. Note that although this has been defined in CREME96 as a 99% worst case model, statistically, it is closer to the 90% worst case event model for on solar active year.

* The proton energy spectra from the "worst week" CREME96 model were converted to omnidirectional protons-cm^{-2}, time integrated over one week, and integrated over energy. This comparison assumes that the event fluences are accumulated in one week which is reasonable assumption considering that most events last from two to four days.

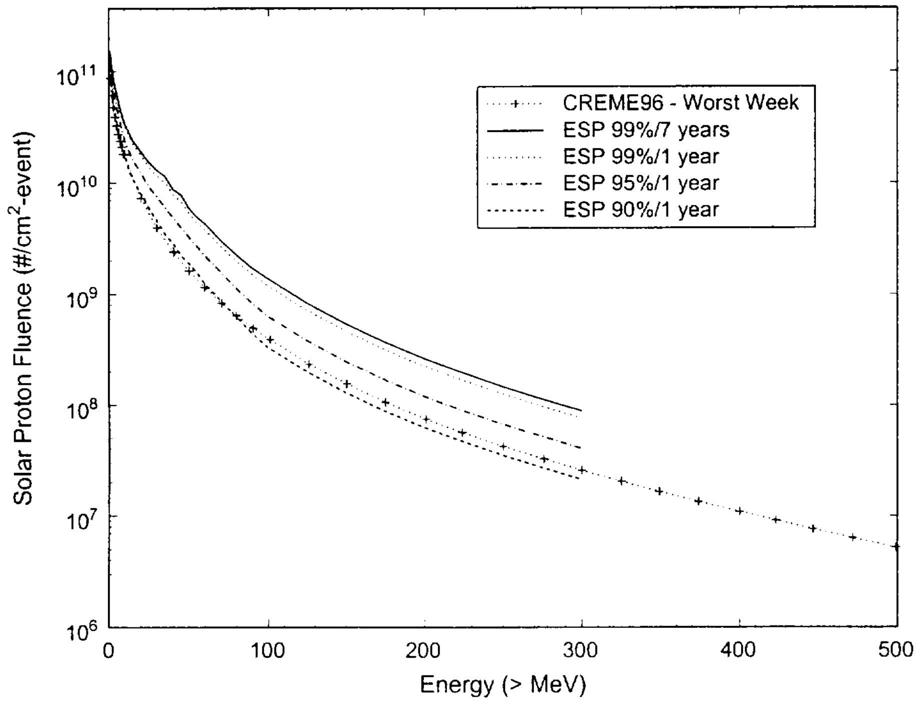

Figure 5.3-2: Worst case event solar proton fluence models are compared. The fluences are integral.

6. SUMMARY AND CONCLUSIONS

The ESP model is based on a more complete data set than previous solar proton event models. It includes satellite data from the last three complete solar cycles (20-22), and a proton energy range from > 1 to > 300 MeV. This should prove sufficient for a wide range of applications. Unlike previous models, it uses a non-empirical approach that takes into account the nature of solar particle event occurrences. The model is valid for a wide range of confidence levels and mission times.

The model development included a review of all available solar proton spacecraft measurements from solar cycles 20 and 21 and relied heavily on the excellent work done by King, Armstrong et al., Feynman et al., and Goswami et al. We found that, when the predictions were updated by the solar cycle 22 data, they were similar to the predictions provided by the SOLPRO and JPL models in the overlapping energy ranges.

The model has important engineering uses including the ability to calculate solar cell degradation, total ionizing dose degradation, and displacement damage on optical components in electronics (e.g., optocouplers). The future plans for the model are to include peak flux predictions as a function of mission duration and confidence level which will be useful for single event effects analysis. Also, it is planned to include the effects of geomagnetic shielding and effects of solar distances other than 1 AU so that the model can be used for earth orbiting and deep-space missions.

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Appendix- ESP Model Code Description

A-1 Menu Description

The ESP model code is provided with a Windows® interface. The software allows the user to create input files and to view, print, and save results. Windows® help files are provided. The menu items are File, View, Run, Defaults, and Help. Table 1 contains a listing of the options under each menu item. Each action listed in the table is explained in the Help file listings in Table 2. As the user runs the code, the Help files can be used to understand the program parameters.

Table 1
Menu Items and Options in ESP Model Code

File	**View**	**Run**	**Defaults**	**Help**
Open	Input	Run	Load	About
Save	Output		Save	Contents
Save As				Disclaimer
Clear				
Select Font				
Print				
Exit				

Table 2
Description of Menu Actions in ESP Model Code

File (Menu)	**Description**
Open	Open saved input or output files.
Save	Save the information in the active view to the current filename.
SaveAs	Save the information in the active view to a new filename
Clear	Use in the "Output View" to clear the screen.
Select Font	Select the font that the user wants for display.
Print	Print the active view to the printer.
Exit	End the program.
View (Menu)	
Input	Change to the input screen.
Output	Change to the output screen.
Run (Menu)	
Run	Calculate the results and output to the screen.
Defaults (Menu)	
Load	Load default values for the active view.
Save	Save the active view as the default.
Help (Menu)	
About	Quick description of the program.
Contents	Start up the Windows® help for the program at the index.
Disclaimer	Start up the Windows® help for the program at the disclaimer.

A-2 Input Description

The user selects three input parameters to run the ESP model: the starting year of the mission, the ending year of the mission, and the desired confidence level for the solar proton fluence predictions. Valid ranges are listed in Table 3 and a sample input window is given in Figure 1. The code calculates the number of solar active years within the user specified range and uses this result and the confidence level to generate the cumulative and worst case event fluences. For example, if the user inputs Starting Year = 1998 and Ending Year = 1999, the calculation is done for 2 solar active years because 1998 and 1999 are both during the active phase of the solar cycle. If the input is Starting Year = 2003 and Ending Year = 2005, the calculations are performed for 2 solar active years because 2003 and 2004 are during the active phase, however, 2005 is during the inactive phase. If the user inputs a range of years that is entirely during the inactive phase of the solar cycle, the fluences are all zero.

Table 3
Ranges for Input Parameters

Input Parameter	Minimum Value	Maximum Value	Default	Type
Starting Year	1970	2020	1998	Whole Year
Ending Year	1970	2020	1999	Whole Year
Cumulative Confidence Level	50	99	90	Percent
Worst Case Confidence Level	50	100	90	Percent

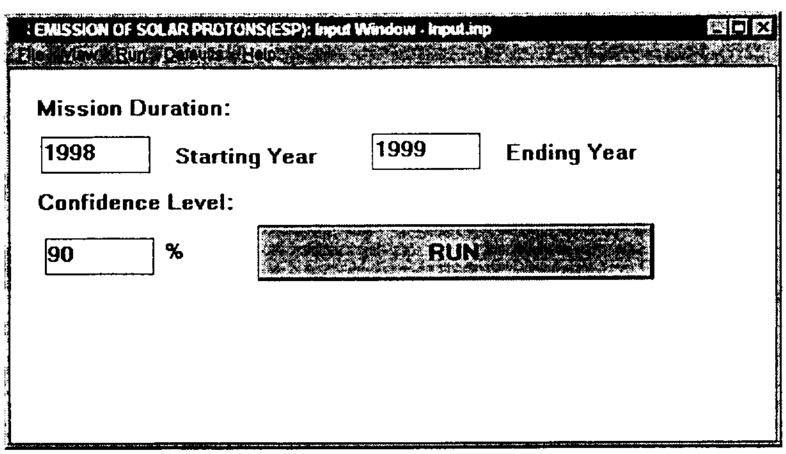

Figure 1: Input Window for ESP Program.

For the years 1970-1999, the active and inactive years are based on actual observations. For year 2000-2020, the active and inactive years are based on the eleven-year average cycle length with 7 years as solar active and 4 years as solar inactive. The data for solar inactive and solar active times are in the ACTIVE.DAT file.

A-3 Output Description

The user obtains integral solar proton fluence predictions by clicking the "Run" button or selecting "Run" from the menu. The output window appears with the results of the calculation in energy-fluence tables. There are four tables, two with cumulative energy-fluence spectra and two with worst case event energy-fluence spectra. The first table in each set contains energy-fluence spectra for five commonly used confidence levels of 80, 85, 90, 95, and 99%. The second table in each output set contains the energy-fluence spectra that were requested by the user in the input box. The energies are in units of > MeV, the integral cumulative fluences are given in units of protons per square centimeter per mission duration, and the integral worst case event spectra are given in units proton per square centimeter per event.

Sample output is given in Figure 2. The user has the option of printing the fluences given in the output window or saving them to a file. The saved files are easily imported into spreadsheet or plotting programs for further analysis.

```
2       // TYPE (1=Input,2=Output)
1998,1999,90    //INPUTS (Start Year,End Year,Confidence Level)
TOTAL PROTON FLUENCE FOR MISSION
Results for a mission of 1998 to 1999.(2 Active Years)

                    GENERAL CONFIDENCE LEVEL TABLE
-----------------------------------------------------------------
                         Integral Proton Fluence(cm^-2)
Energy Levels                      Confidence Levels()
   (>MeV)              80         85         90         95         99
-------------      ---------  ---------  ---------  ---------  ---------
       1           2.44E+011  2.89E+011  3.56E+011  4.85E+011  8.68E+011
       3           8.62E+010  1.02E+011  1.27E+011  1.74E+011  3.17E+011
       5           5.09E+010  6.16E+010  7.82E+010  1.11E+011  2.16E+011
       .               .          .          .          .          .
       .               .          .          .          .          .
       .               .          .          .          .          .
     275           2.03E+007  3.02E+007  4.97E+007  1.04E+008  4.19E+008
     300           1.59E+007  2.37E+007  3.91E+007  8.20E+007  3.29E+008

   USER CONFIDENCE LEVEL TABLE
   ---------------------------
                    Integral Proton
Energy Levels        Fluence at User
   (>MeV)          Confidence: 90
     1                3.56E+011
     3                1.27E+011
     5                7.82E+010
     .                    .
     .                    .
     .                    .
   275                4.97E+007
   300                3.91E+007

---------------------------------------------------
WORST CASE EVENT PROTON FLUENCE FOR MISSION
Results for a mission of 1998 to 1999.(2 Active Years)

                    GENERAL CONFIDENCE LEVEL TABLE
-----------------------------------------------------------------
                         Integral Proton Fluence(cm^-2)
Energy Levels                      Confidence Levels()
   (>MeV)              80         85         90         95         99
-------------      ---------  ---------  ---------  ---------  ---------
       1           1.06E+011  1.17E+011  1.29E+011  1.41E+011  1.52E+011
       3           5.28E+010  5.98E+010  6.78E+010  7.68E+010  8.49E+010
       5           3.57E+010  4.13E+010  4.79E+010  5.56E+010  6.27E+010
       .               .          .          .          .          .
       .               .          .          .          .          .
       .               .          .          .          .          .
     275           2.53E+007  3.54E+007  5.07E+007  7.51E+007  1.06E+008
     300           1.99E+007  2.78E+007  3.99E+007  5.90E+007  8.33E+007

   USER CONFIDENCE LEVEL TABLE
   ---------------------------
                    Integral Proton
```

```
Energy Levels        Fluence at User
  (>MeV)            Confidence: 90
     1                  1.29E+011
     3                  6.78E+010
     5                  4.79E+010
     .                      .
     .                      .
     .                      .
   275                  5.07E+007
   300                  3.99E+007

*Note 1: A -1.00E+00 means that there were data missing.
*Note 2: Fluences for energies over 100 Mev have been extrapolated.
```

Figure 2: Sample Output Window

A-4 System Requirements

The recommended system requirements are:

Operating System: Windows95, Windows98, or Windows NT
Processor: 486
Memory: 32Mb or greater.
Hard Drive: 1Mb (for installation of executable and support files)

A-5 Files Required to Run Code

All files required to run the code are included in the package. There is no need for the user to access these files directly. Necessary file changes are made through the Windows® menu. The required files are:

ESP.exe	Executable code
Active.dat	Active/Inactive years file
Const1.dat	Constants file 1
Const2.dat	Constants file 2
Helpfile.hlp	Help file
Input.dft	Default input file
Output.dft	Default output file
Stats.dat	Constant statistics file

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13. ABSTRACT *(Maximum 200 words)*
The effects that solar proton events have on microelectronics and solar arrays are important considerations for spacecraft in geostationary and polar orbits and for interplanetary missions. Designers of spacecraft and mission planners are required to assess the performance of microelectronic systems under a variety of conditions. A number of useful approaches exist for predicting information about solar proton event fluences and, to a lesser extent, peak fluxes. This includes the cumulative fluence over the course of a mission, the fluence of a worst-case event during a mission, the frequency distribution of event fluences, and the frequency distribution of large peak fluxes.

Naval Research Laboratory (NRL) and NASA Goddard Space Flight Center, under the sponsorship of NASA's Space Environments and Effects (SEE) Program, have developed a new model for predicting cumulative solar proton fluences and worst-case solar proton events as functions of mission duration and user confidence level. This model is called the Emission of Solar Protons (ESP) model.

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