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Lunar Reconnaissance Orbiter Project

Radiation Environment Specification

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LUNAR RECONNAISSANCE ORBITER PROJECT

DOCUMENT CHANGE RECORD

Sheet: 1 of 1

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

1.0 INTRODUCTION

The purpose of this document is to define the radiation environment for the evaluation of degradation due to total ionizing and non-ionizing dose and of single-event effects (SEEs) for the Lunar Reconnaissance Orbiter (LRO). The analysis takes into account the radiation exposure for one to five-year missions at the 50 kilometer (km) polar lunar orbit and assumes a launch date in 2008 according to the preliminary mission profile. The transfer trajectory out to lunar orbit will last about four days. This evaluation does not include the impact of passing through the Van Allen belts during the transfer orbit. Generally, transfer trajectories do not contribute significantly to degradation effects; however, SEEs and deep dielectric charging effects must be taken into consideration especially if critical maneuvers are planned during the Van Allen belt pass.

2.0 DOCUMENTS

2.1 APPLICABLE DOCUMENTS

431-RQMT-000045	Lunar Reconnaissance Orbiter Radiation Requirements

2.2 REFERENCE DOCUMENTS

[1] A. Holmes-Siedle and L. Adams, Handbook of Radiation Effects, p. 16, Oxford University Press, Oxford, 1993.

[2] A. R. Frederickson, “Upsets Related to Spacecraft Charging,” IEEE Trans. on Nucl. Science, Vol. 43, No. 2, pp. 426-441, April 1996.

[3] R. C. Elphic, W. C. Feldman, D. J. Lawrence, O. M. Gasnault, S. Maurice, R. Little, T. H. Prettyman, and A. H. Binder, “The Lunar Neutron Leakage Flux and its Measurement by Lunar Prospector Neutron Spectrometers,” XXXII Lunar and Planetary Science Conference, 2001.

[4] M. A. Xapsos, J. L. Barth, E. G. Stassinopoulos, E.A. Burke and G. B. Gee, “Model for Emission of Solar Protons (ESP) – Cumulative and Worst Case Event Fluences,” Marshall Space Flight Center, Huntsville, AL, NASA Report TP-1999-209763, Dec. 1999.

[5] A. J. Tylka, J. H. Adams, Jr., P. R. Boberg, W. F. Dietrich, E.O. Flueckiger, E.L. Petersen, M.A. Shea, D.F. Smart, and E.C. Smith, “CREME96: A Revision of the Cosmic Ray Effects on Micro-Electronics Code: to be published in IEEE Trans. On Nuc. Sci., December 1997.

3.0 RADIATION ENVIRONMENT

The natural space radiation environment of concern for damage to spacecraft electronics is classified into two populations, 1) the transient particles which include protons and heavier ions of all of the elements of the periodic table, and 2) the trapped particles which include protons, electrons and heavier ions. The trapped electrons have energies up to about 10 Mega-electron Volts (MeV) and the trapped protons and heavier ions have energies up to 100s of MeV. The transient radiation consists of galactic cosmic ray particles and particles from solar events (coronal mass ejections and flares). The cosmic rays have low-level fluxes with energies up to Terra-electron Volts (TeV). The solar eruptions periodically produce energetic protons, alpha particles, heavy ions, and electrons. The solar protons have energies up to 100's MeV and the heavier ions reach the Giga-electron Volt (GeV) range. All particle fluxes are isotropic and omnidirectional to the first order.

Space also contains low energy plasma of electrons and protons with fluxes up to 10^{12} centimeter $(cm)^2$/second (sec). The plasmasphere environment and the low energy (< 0.1 MeV) component of the charged particles are a concern in the near-earth environment. In the outer regions of the magnetosphere and in interplanetary space, the plasma is associated with the solar wind. Because of its low energy, thin layers of material easily stop the plasma so it is not a hazard to most spacecraft electronics. However, it is damaging to surface materials and differentials in the plasma environment can contribute to spacecraft surface charging and discharging problems [1,2].

3.1 DESCRIPTION OF RADIATION EFFECTS

Radiation effects that are important to consider for instrument and spacecraft design fall roughly into three categories: degradation from total ionizing dose (TID), degradation from non-ionizing energy loss (NIEL), and SEEs. Total ionizing dose in electronics is a cumulative, long-term degradation mechanism due to ionizing radiation—mainly primary protons and electrons and secondary particles arising from interactions between these primary particles and spacecraft materials. It causes threshold shifts, leakage current and timing skews. The effect first appears as parametric degradation of the device and ultimately results in functional failure. It is possible to reduce TID with shielding material that absorbs most electrons and lower energy protons. As shielding is increased, shielding effectiveness decreases because of the difficulty in slowing down the higher energy protons. When a manufacturer advertises a part as "rad-hard", he is almost always referring to its total ionizing dose characteristics. Rad-hard does not usually imply that the part is hard to non-ionizing dose or SEES. In some cases, a "rad-hard" part may perform significantly worse in the space radiation environment than in the test environment (e.g., Enhanced Low Dose Rate Sensitivity [ELDRS] in linear bipolar devices.)

Displacement damage is cumulative, long-term non-ionizing damage due to protons, electrons, and neutrons. These particles produce defects in optical materials that result in charge transfer degradation. Displacement damage affects the performance of optocouplers (often a component in power devices), solar cells, Change-Coupled Devices (CCDs), and linear bipolar devices. The effectiveness of shielding depends on the location of the device. For example, coverglasses over solar cells reduce electron damage and proton damage by absorbing the low energy particles.

Increasing shielding beyond a critical threshold, however, is not usually effective for optoelectronic components because the high-energy protons penetrate the most feasible spacecraft electronic enclosures. For detectors in instruments it is necessary to understand the instrument technology and geometry to determine the vulnerability to the environment.

SEEs result from ionization by a single charged particle as it passes through a sensitive junction of an electronic device. SEEs are caused by heavier ions, but for some devices, protons and neutrons can also contribute. In some cases SEEs are induced through direct ionization by the proton, but in most instances for protons and in all instances for neutrons, induced effects result from secondary particles produced when the proton or neutron interacts with a nucleus in the device material. Some SEEs are non-destructive, as in the case of single-event upsets (SEUs), single-event transients (SETs), multiple bit errors (MBEs), single-event hard errors (SHEs), etc. SEEs can also be destructive as in the case of single-event latchups (SELs), single-event gate ruptures (SEGRs), and single-event burnouts (SEBs). The severity of the effect can range from noisy data to loss of the mission, depending on the type of effect and the criticality of the system in which it occurs. Shielding is generally not an effective mitigation for SEEs, which are often induced by very penetrating high-energy particles. The preferred method for dealing with destructive failures is to use SEE-hard parts. When SEE-hard parts are not available, latchup protection circuitry is sometimes used in conjunction with failure mode analysis. (**Note**: Care is necessary when using SEL protection circuitry, because SEL may damage a microcircuit and reduce its reliability even when it does not cause outright failure.) For non-destructive effects, mitigation takes the form of error-detection and correction codes (EDACs), filtering circuitry, etc.

TID is primarily caused by protons and electrons trapped in the Van Allen belts and solar event protons. As electrons are slowed down, their interactions with orbital electrons of the shielding material produce a secondary photon radiation known as bremsstrahlung. Generally, the dose due to galactic cosmic ray ions and proton secondaries is negligible compared to other sources. For surface degradation, it is also important to include the effects of very low energy particles.

SEEs can be induced by heavy ions (solar events and galactic cosmic rays) and, in some devices, protons (trapped and solar events) and neutrons[*]. Displacement damage is primarily due to trapped and solar protons and also neutrons[*]. High-energy electrons can also contribute to displacement damage, especially for lightly shielded applications. Spacecraft charging can occur on the surface of the spacecraft due to low energy electrons. Deep dielectric charging occurs when high-energy electrons penetrate the spacecraft and collect in dielectric materials.

3.2 THE LUNAR RECONNAISANCE ORBITER MISSION

The LRO spacecraft will be transferred out to its final lunar orbit via a four-day trajectory. While in the transfer, LRO will pass through the trapped proton and electron belts. During the transfer trajectory, LRO will also encounter varying levels of galactic cosmic ray heavy ions and possibly protons and heavier ions from solar events. These exposures could result in SEEs

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[*] Neutrons in space are produced by interactions of primary particles with spacecraft materials and planet soils. In avionics applications it is also necessary to consider neutrons that are produced by interactions of primary particles with the atmosphere.

during some maneuvers as well as a deep dielectric charging risk but will not contribute to significant total dose degradation effects.

Once LRO reaches its final orbit, its mission requirement is one to five years. With the expected 2008 launch year, the LRO mission will occur during the active phase of the solar cycle. During the active phase of the Sun, the likelihood that the spacecraft will be exposed to particles from solar events (either solar flare or coronal mass ejections) increases significantly. Figure 3-1 shows a projection of the solar cycle during the LRO mission, based on the solar activity data of solar cycles 22 and 23. The lunar orbit radiation environment encountered by the LRO will consist of protons and heavier ions from solar events, galactic cosmic ray heavy ions, neutrons emitted by the lunar soil, and solar wind plasma consisting of low energy protons, electrons, and heavier ions.

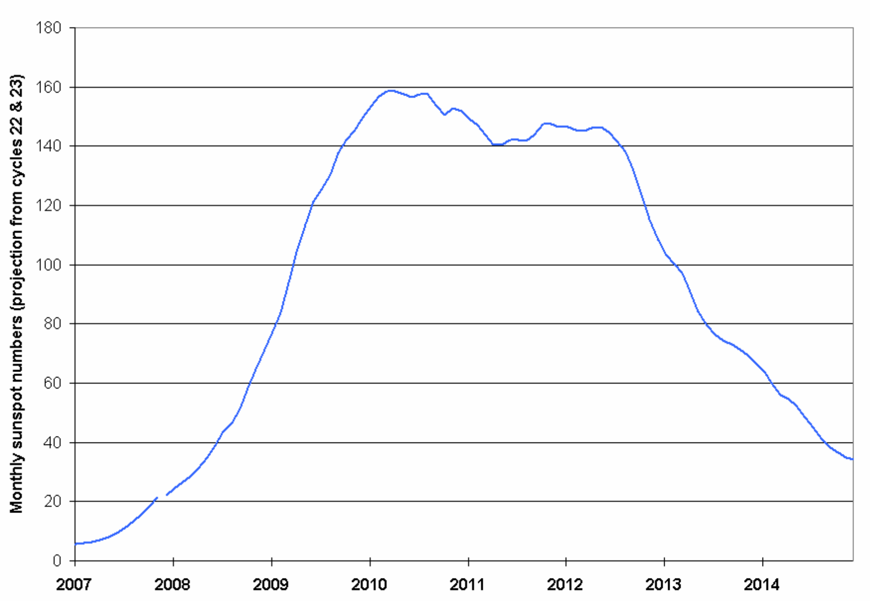

Figure 3-1. Projection of the Solar Activity during the LRO Mission

3.3 TOTAL DOSE AND DEGRADATION

The TID accumulation causes performance degradation and failure on memories, power converters, etc. Non-ionizing energy loss in materials (atomic displacement damage) causes degradation of solar cells, optoelectronics, and detectors. The low energy particles also contribute to the erosion of surfaces.

3.3.1 <u>Degradation Environment</u>

3.3.1.1 The Plasma Environment

At the LRO final orbit, low energy particles from the solar wind plasma inside and outside the magneto tail contribute to the degradation of surface materials and also cause charging effects. These charging effects should be considered in the spacecraft design. However, the plasma environment does not contribute to significant degradation effects.

3.3.1.2 High Energy Particles – Spacecraft Incident Fluences

The spacecraft incident proton fluence levels given in this document are most often used for standard solar cell analyses that take into account the coverglass thickness of the cell. There are four possible sources of high energy particles: trapped protons and trapped electrons encountered in the transfer trajectory, neutrons emitted by the lunar soil, and protons from solar events that can occur anytime during the one to five solar active years of the mission. The trapped particles encountered in the transfer trajectory are usually not a factor in degradation analyses. The neutrons emitted by the lunar soil are also not a factor in degradation analysis, because their intensity is very small compared to those of solar protons [3]. The proton fluence levels are also used to determine displacement damage effects, however, most analysis methods require that the surface incident particles be transported through the materials surrounding the sensitive components. The proton fluences behind nominal aluminum shield thicknesses are given in Section 3.3.1.3.

The solar proton levels were estimated from the Emission of Solar Protons (ESP) model [4]. The ESP model is based on satellite data from solar cycles 20, 21, and 22. The distribution of the fluences for the events is obtained from maximum entropy theory, and design limits in the worst-case models are obtained from extreme value theory.

Total integral solar proton fluences were estimated for one to five solar active years. Tables A-1 through A-5 give the fluence levels as a function of particle energy for 85, 90, 95, and 99% confidence levels. Figures 3-2 through 3-6 are plots of the energy-fluence spectra for the given confidence levels. The energies are threshold energies, given in units of >MeV and the fluences are integral fluences in units of protons/cm^2. These values do not include a design margin. The solar proton predictions are based on probability distributions and are therefore not linear with increasing time. Only the mean value of the distribution increases linearly. Therefore, these estimates at high confidence levels may be invalid if extrapolated to longer or shorter mission durations.

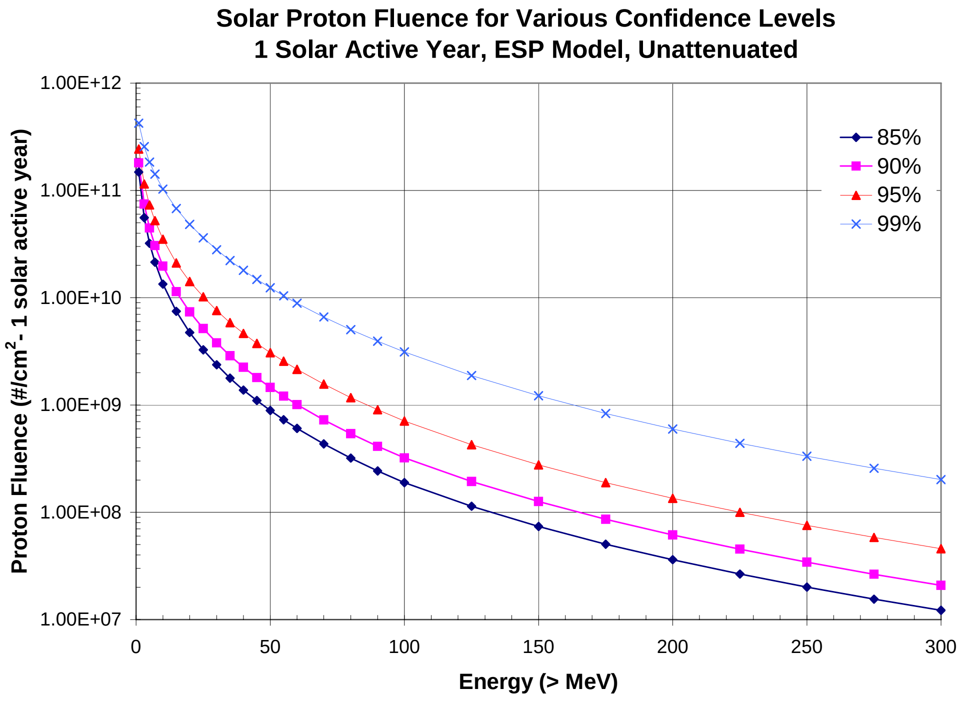

Figure 3-2. Solar Proton Fluences for 1 Solar Active Year for Various Confidence Levels

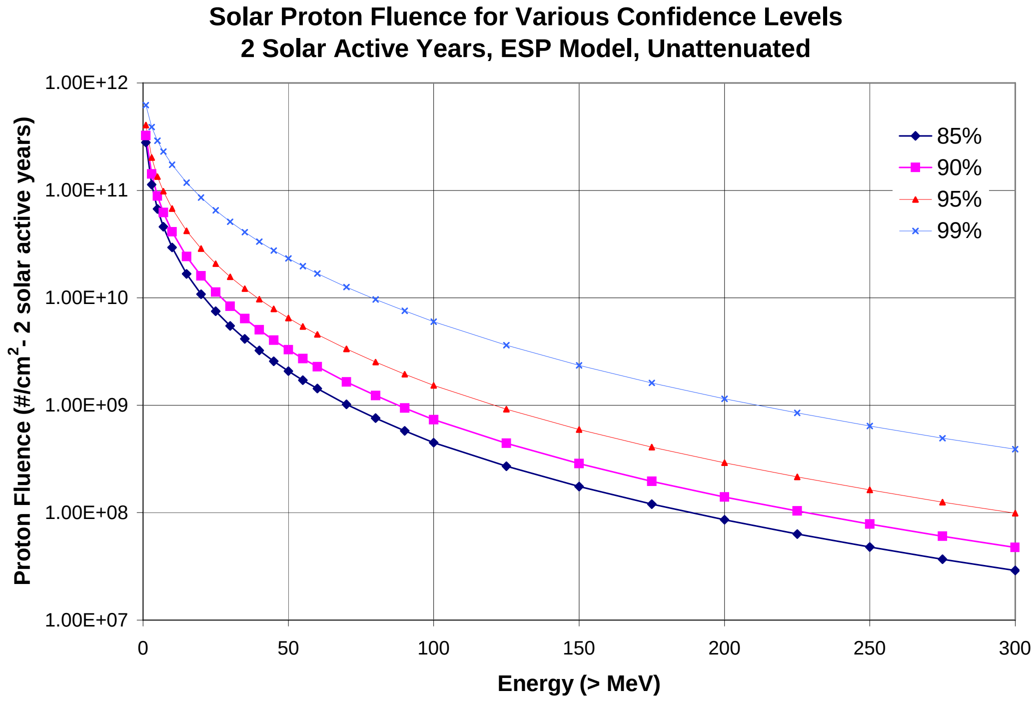

Figure 3-3. Solar Proton Fluences for 2 Solar Active Years for Various Confidence Levels

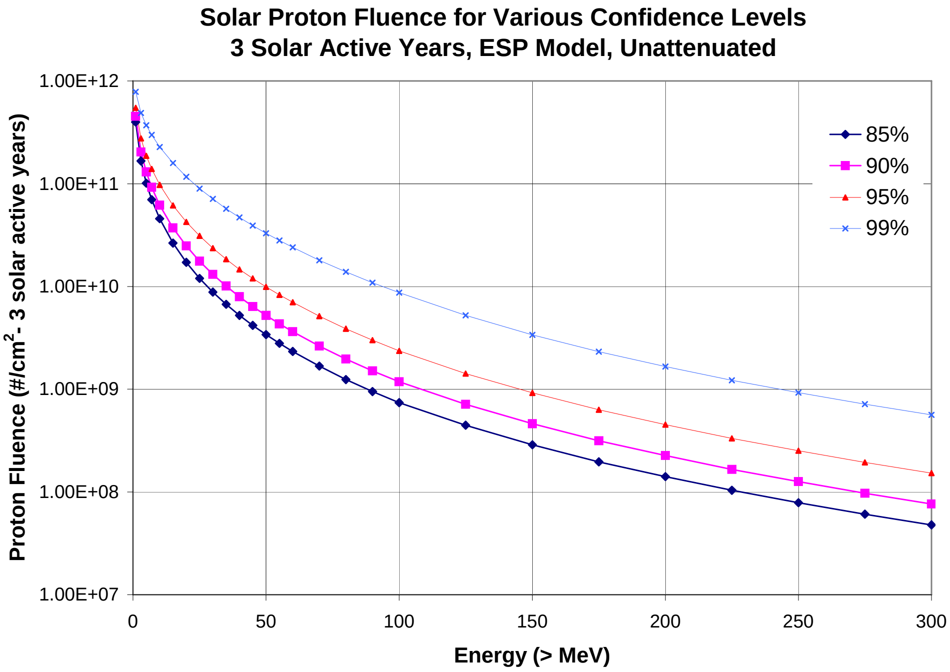

Figure 3-4. Solar Proton Fluences for 3 Solar Active Years for Various Confidence Levels

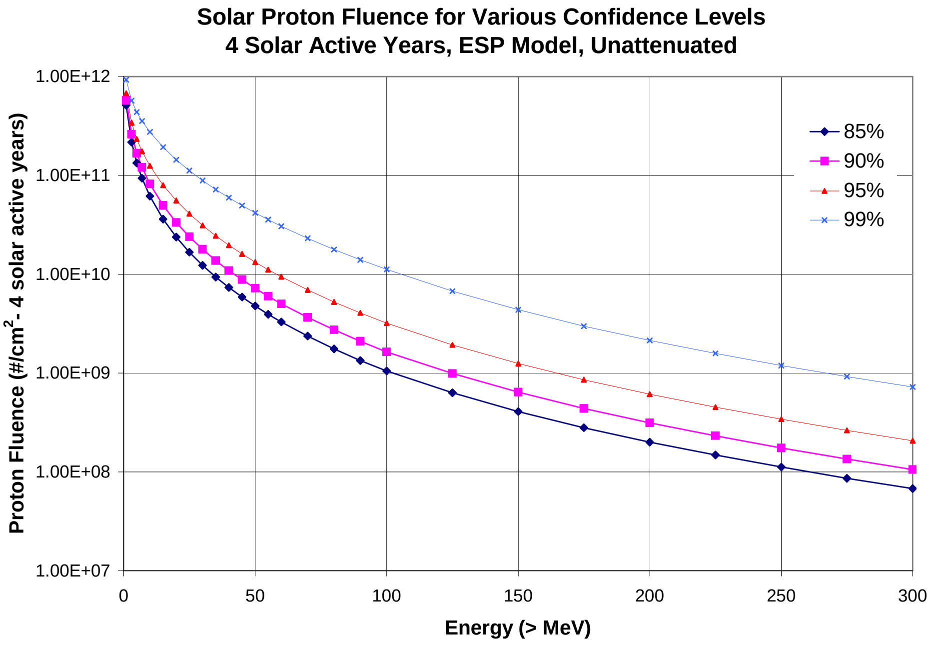

Figure 3-5. Solar Proton Fluences for 4 Solar Active Years for Various Confidence Levels

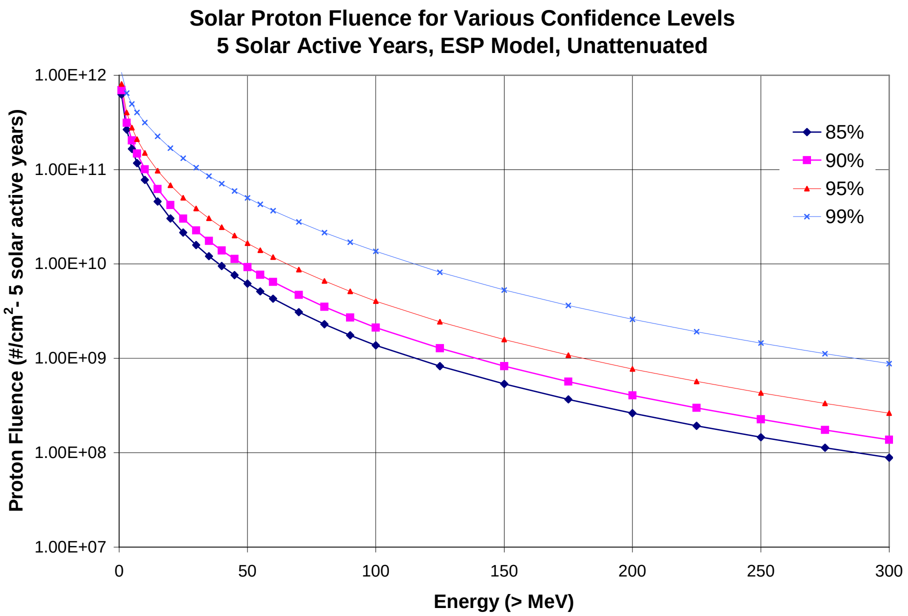

Figure 3-6. Solar Proton Fluences for 5 Solar Active Years for Various Confidence Levels

Figure 3-7 gives the mission fluences for one to five years that will be considered. For one-year mission we use a 95% confidence level, and for two to five year missions we use a 90% confidence level. This recommended choice in confidence levels results because the accuracy of the statistical model improves for longer periods of time.

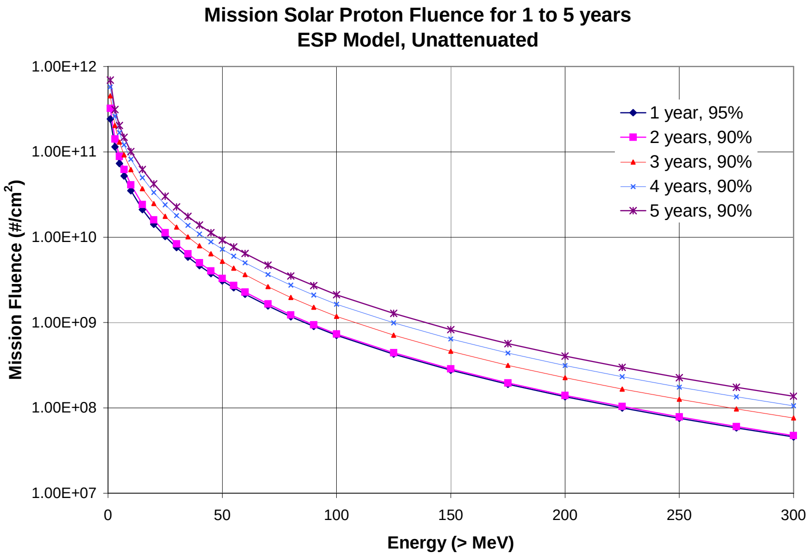

Figure 3-7. Mission Solar Proton Fluences for 1 to 5 Years Missions

3.3.1.3 High Energy Particles – Shielded Fluences

Evaluation of non-ionizing energy loss damage requires the use of shielded fluence levels. For this analysis, nominal shielding thicknesses of 100 mils of aluminum were used for generic solid sphere geometry. The mission spacecraft incident, solar proton estimates for the one to five year missions were transported through the shield thickness to obtain fluence estimates behind the shielding. Table A-6 gives the degraded energy spectra. The spectra are plotted in Figure 3-8. It can be seen from the figures that even though low-energy particles are absorbed by the shielding, the low energy range of the spectrum is filled in by the higher energy protons as they are degraded by passing through the material.

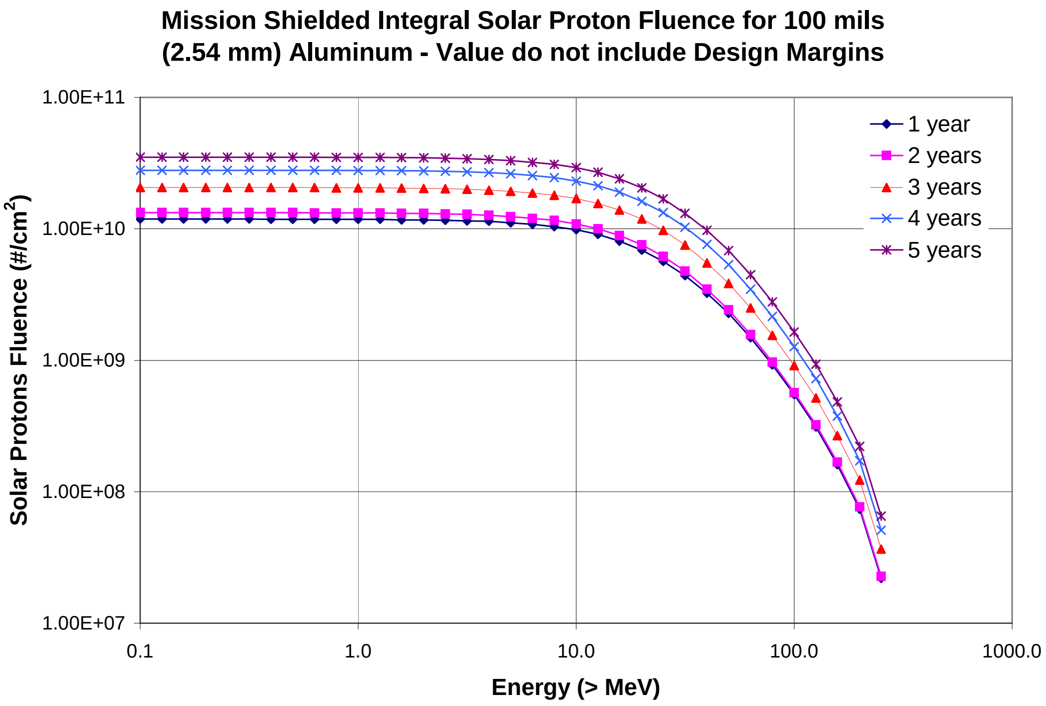

Figure 3-8. Shielded Solar Proton Energy Spectra for 100 mils Aluminum, 1 to 5 year Mission

3.3.2 Total Dose Estimates

3.3.2.1 Top Level Ionizing Dose Requirements

Doses are calculated from the surface incident integral fluences as a function of aluminum shield thickness for a simple geometry. The geometry model used for spacecraft applications is the solid sphere. The solid sphere doses represent an upper boundary for the dose inside an actual spacecraft and are used as a top-level requirement. In cases where the amount of shielding surrounding a sensitive location is difficult to estimate, a more detailed analysis of the geometry of the spacecraft structure may be necessary to evaluate the expected dose levels. This is done by modeling the electronic boxes or instruments and the spacecraft structure. The amount of shielding surrounding selected sensitive locations is estimated using solid angle sectoring and 3-

dimensional ray tracing. Doses obtained by sectoring methods must be verified for at least 5-10% of the sensitive locations with full Monte Carlo simulations of particle trajectories through the structure for many histories.

Table A-7 and Figure 3-9 give the top-level TID requirement for the one to five year LRO mission. T he doses are calculated here as a function of aluminum shield thickness in units of krads in silicon (krad-Si). For the nominal 100 mils of equivalent aluminum shielding and the five years mission, the dose requirement is about 14 krad-Si with no design margin. A minimum design margin of x 2 is recommended.

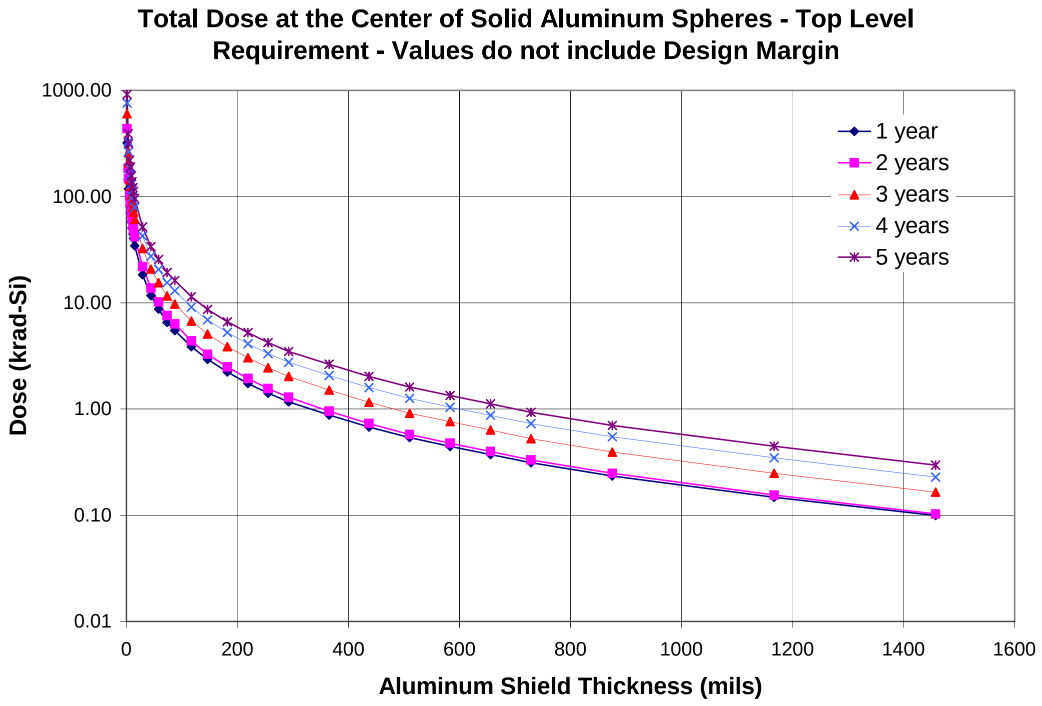

Figure 3-9. Total Ionizing Dose from Solar Proton Events

3.3.2.2 Dose at Specific Spacecraft Locations

In cases where parts cannot meet the top level design requirement and a “harder” part cannot be substituted, it is often beneficial to employ more accurate methods of determining the dose exposure for some spacecraft components to qualify the parts. One such method for calculating total dose, solid angle sectoring/3-dimensional (3-D) ray tracing, is accomplished in three steps:

- Model the spacecraft structure:
  - Develop a 3-D model of the spacecraft structures and components
  - Develop a material library
  - Define sensitive locations
- Model the radiation environment:

  - Define the spacecraft incident radiation environment
  - Develop a particle attenuation model using theoretical shielding configurations (similar to dose-depth curves)

- Obtain results for each sensitive location:
  - Divide the structural model into solid angle sectors
  - Ray trace through the sectors to calculate the material mass distribution
  - Use the ray trace results to calculate total doses from the particle attenuation model

Once the basic structural model has been defined, total doses can be obtained for any location in the spacecraft in a short time (in comparison to Monte Carlo methods). The value of dose mitigation measures can be accurately evaluated be adding the changes to the model and recalculating the total dose. For spacecraft with strict weight budgets, the 3-D ray trace method, the total dose design requirement can be defined at a box or instrument level avoiding unnecessary use of expensive or increasingly unavailable radiation hardened parts.

As the design of the LRO evolves, it may become necessary to estimate the doses at specific locations in the spacecraft or instruments. Often the dose requirement can be met by modeling the surrounding electronic box only or by modeling only the instrument.

3.3.3 <u>Displacement Damage Estimates</u>

Total non-ionizing energy loss damage is evaluated by combining the shielded proton energy spectra given in Section 3.3.1.2 with the NIEL response curves for the material and the results of laboratory radiation of the devices sensitive to atomic displacement damage. The level of the hazard is highly dependent on the device type and can be process specific. For the LRO mission, it is important to keep in mind that some optoelectronic devices experience enough damage during one large solar proton event to cause the device to fail. It is necessary that the parts list screening for radiation also include a check for devices that are susceptible to displacement damage.

3.4 SINGLE EVENT EFFECTS ANALYSIS

3.4.1 <u>Heavy Ion Induced Single Event Effects</u>

Some electronic devices are susceptible to SEEs (e.g., SEUs, SELs, SEBs). Since heavy ions such as Galactic Cosmic Rays (GCR) and solar heavy ions cause SEEs by the direct deposit of charge, the metric used to describe SEEs is the ion's linear energy transfer (LET). The LET is the energy lost by the ion per unit path length in the material of interest. In order to parameterize SEEs in terms of LET, the heavy ion abundances and energy distributions in the environment are converted to LET spectra. Once specific parts are selected for the mission and, if necessary, characterized by laboratory testing, the LET spectra for the heavy ions in the space radiation environment are integrated with the device characterization to calculate SEE rates.

3.4.1.1 Galactic Cosmic Rays

The cosmic ray fluxes for elements hydrogen through uranium were used to calculate daily LET spectra for a nominal shielding thickness of 100 mils aluminum. Results are given in Table A-8 and Figure 3-10. The range of the cosmic ray abundances is bounded by the extrema of the solar active and inactive phases of the solar cycle with the highest values occurring during the solar inactive phase and the lowest during the solar active phase. The LET fluence values are given for the highest and lowest point of the solar cycle. The CREME96 [5] model was used to obtain the cosmic ray heavy ion abundances. This model has an accuracy of 25-40%. For the LRO SEE analysis, we recommend to use the highest fluxes.

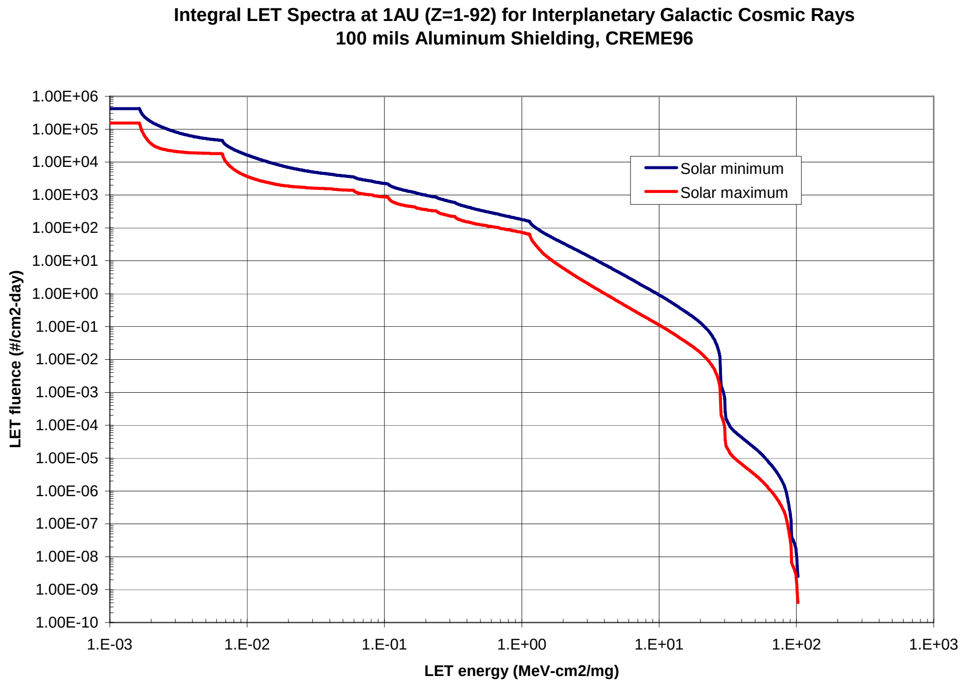

Figure 3-10. Integral LET Spectra are Shown for Galactic Cosmic Ray Ions Hydrogen through Uranium

3.4.1.2 Solar Heavy Ions

The heavy ions from solar flares and coronal mass ejections can also produce SEEs. The solar event fluxes for the elements hydrogen through uranium were used to calculate daily LET spectra for 100 mils aluminum shielding in units of average LET flux per second. The intensity of the fluxes varies over the duration of an event; therefore, values are averaged over the worst week of the solar cycle, the worst day of the solar cycle, and the peak of the October 1989 solar event. Table A-9 and Figure 3-11 give the worst-case solar heavy ion LET predictions for the LRO mission, obtained from CREME96. An uncertainty factor for the solar heavy ion model has not been released.

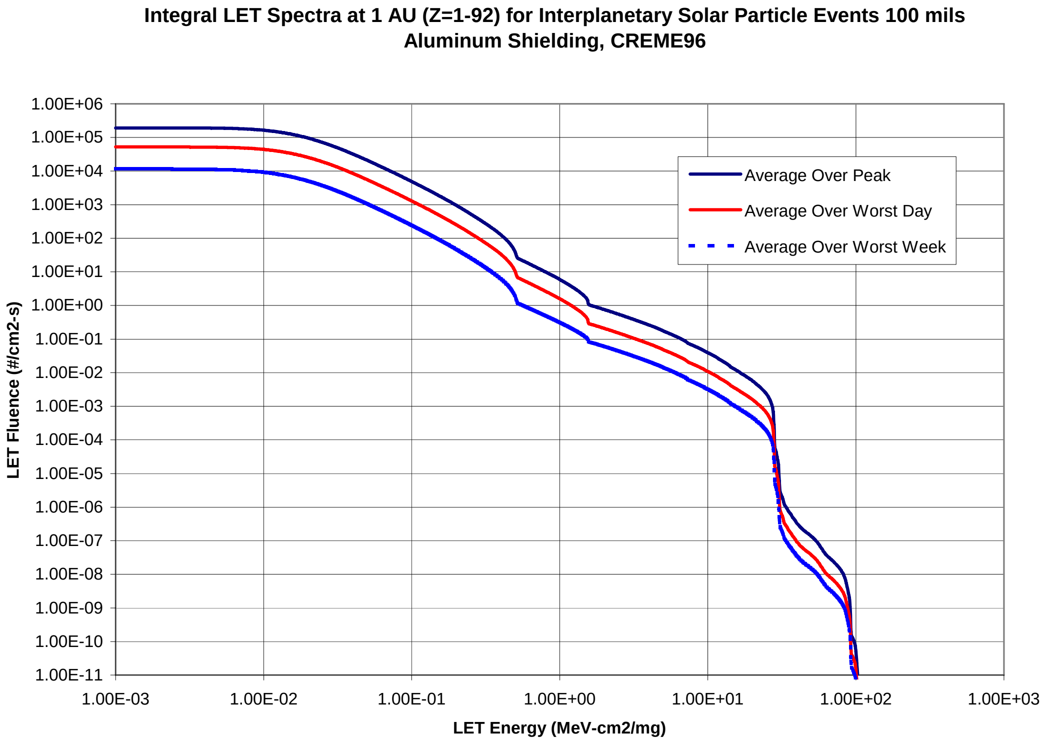

Figure 3-11. Integral LET Spectra are shown for Hydrogen through Uranium for the October 1989 Solar Particle Event

3.4.2 Proton Induced Single Event Effects

In some devices, SEEs are also induced by protons and neutrons. In most cases, protons do not generate sufficient ionization (LET < 1 MeV-cm^2 /mg) to produce the critical charge necessary for SEEs to occur in most electronics. More typically, protons cause SEEs through secondary particles via nuclear interactions, that is, spallation and fractionation products. Because the proton energy is important in the production (and not the LET) of the secondary particles that cause the SEEs, device sensitivity to these particles is typically expressed as a function of proton energy rather than LET. Neutrons can only cause SEEs through secondary particles via nuclear interactions, that is, spallation and fractionation products.

3.4.2.1 Trapped Protons

Trapped protons can be a concern for SEEs during the transfer trajectory passes through the trapped particle radiation belts. The proton fluxes in the intense regions of the belts reach levels that are high enough to pose a significant risk for upsets or latchups. The timing of critical operations during the transfer trajectory should be analyzed to determine the trapped proton environment at the time of the operation.

3.4.2.2 Neutrons

The neutron fluxes at the LRO 50km altitude above moon surface are very small compared to those of solar protons [3]. Therefore, neutrons are not a SEE concern for most LRO electronics parts. They may be a concern for some instrument detectors as they will add noise.

3.4.2.3 Solar Protons

Protons from solar events can also be a SEEs hazard for the LRO spacecraft. These enhanced levels of protons could occur anytime during the one to five year mission. As with the worst-case solar heavy ion LET, solar proton fluxes are averaged over worst day, worst week, and the peak of the October 1989 solar event. The worst-case proton flux averages for a nominal 100 mils of shielding are given in Table A-10 and are shown in Figure 3-12.

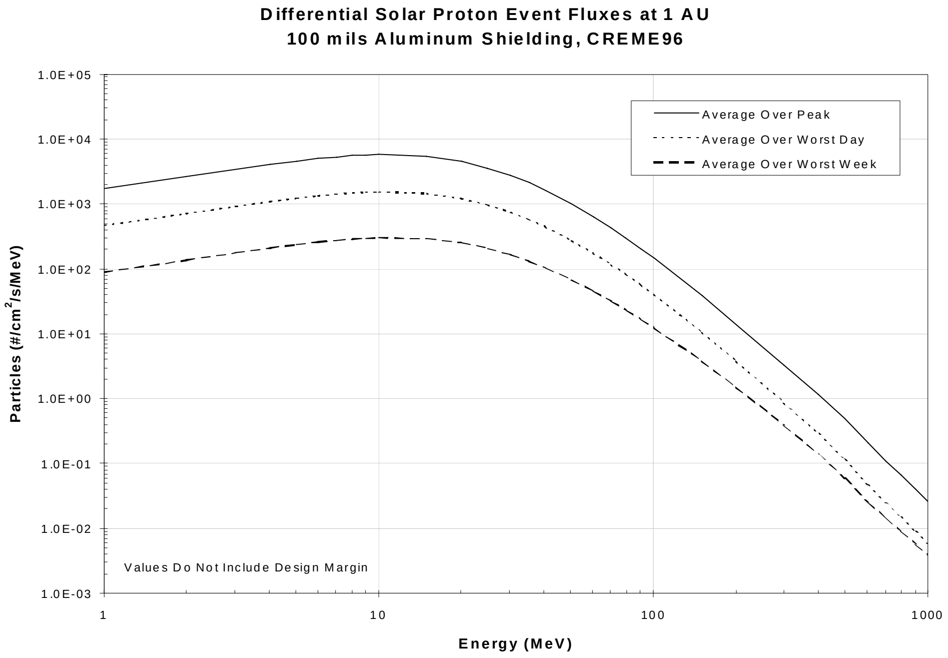

Figure 3-12. Solar Proton Fluxes for Single Event Effects Evaluation

3.5 SPACECRAFT CHARGING AND DISCHARGING

Surface charging and deep dielectric charging must also be evaluated for the LRO mission. Both are potential problems in transfer trajectory through the Van Allen belts. During the pass through the belts, the spacecraft can accumulate high levels of electron build-up on spacecraft surfaces (low energy electrons) in the dielectrics (high energy electrons). Surface charging will also be a concern during the entire mission when the spacecraft reaches its final orbit due to the plasma environment.

3.6 SUMMARY

A top-level radiation environment specification was presented for the LRO mission. Although the environment is considered “moderate”, the environment poses challenges to mission designers because of its highly variable nature caused by activity on the Sun.

Spacecraft and instrument designers must be made aware that some newer technologies and commercial-off-the-shelf (COTS) devices are very soft to radiation effects. COTS devices that lose functionality at 5 krads of dose are not uncommon. One extremely large solar proton event can cause enough displacement damage degradation in some optocoupler devices to cause failure. Increasingly, SEEs require careful part selection and mitigation schemes. With its full exposure to galactic cosmic ray heavy ions and particles from solar events, LRO must have a carefully planned radiation engineering program.

Appendix A. Fluences, TIDs, LET Spectra, and Fluxes

Table A-1. Spacecraft Incident Solar Proton Fluences for 1 Solar Active Year

Proton Energy (>MeV)	Proton Fluence(cm^-2)				
	Confidence Levels (%)				
	80	**85**	**90**	**95**	**99**
1	1.26E+11	1.48E+11	1.81E+11	2.43E+11	4.23E+11
3	4.43E+10	5.58E+10	7.46E+10	1.15E+11	2.56E+11
5	2.47E+10	3.21E+10	4.47E+10	7.32E+10	1.84E+11
7	1.61E+10	2.14E+10	3.06E+10	5.22E+10	1.42E+11
10	9.84E+09	1.34E+10	1.97E+10	3.51E+10	1.03E+11
15	5.35E+09	7.46E+09	1.14E+10	2.11E+10	6.78E+10
20	3.34E+09	4.75E+09	7.37E+09	1.42E+10	4.83E+10
25	2.27E+09	3.27E+09	5.16E+09	1.02E+10	3.61E+10
30	1.63E+09	2.37E+09	3.79E+09	7.59E+09	2.80E+10
35	1.22E+09	1.78E+09	2.88E+09	5.86E+09	2.22E+10
40	9.40E+08	1.38E+09	2.25E+09	4.64E+09	1.80E+10
45	7.41E+08	1.10E+09	1.80E+09	3.75E+09	1.48E+10
50	5.96E+08	8.88E+08	1.46E+09	3.08E+09	1.24E+10
55	4.87E+08	7.29E+08	1.21E+09	2.56E+09	1.04E+10
60	4.04E+08	6.06E+08	1.01E+09	2.15E+09	8.89E+09
70	2.87E+08	4.33E+08	7.27E+08	1.57E+09	6.61E+09
80	2.11E+08	3.20E+08	5.40E+08	1.17E+09	5.05E+09
90	1.60E+08	2.43E+08	4.12E+08	9.03E+08	3.93E+09
100	1.24E+08	1.89E+08	3.22E+08	7.09E+08	3.12E+09
125	7.45E+07	1.14E+08	1.94E+08	4.27E+08	1.88E+09
150	4.82E+07	7.37E+07	1.26E+08	2.77E+08	1.22E+09
175	3.30E+07	5.04E+07	8.60E+07	1.89E+08	8.34E+08
200	2.36E+07	3.61E+07	6.15E+07	1.35E+08	5.97E+08
225	1.74E+07	2.66E+07	4.53E+07	9.99E+07	4.40E+08
250	1.32E+07	2.01E+07	3.43E+07	7.55E+07	3.33E+08
275	1.02E+07	1.55E+07	2.65E+07	5.83E+07	2.57E+08
300	7.99E+06	1.22E+07	2.08E+07	4.58E+07	2.02E+08

Values Do Not Include Design Margins

Table A-2. Spacecraft Incident Solar Proton Fluences for 2 Solar Active Years

Proton Energy (>MeV)	Proton Fluence (cm^-2)				
	Confidence Levels (%)				
	80	**85**	**90**	**95**	**99**
1	2.47E+11	2.79E+11	3.24E+11	4.06E+11	6.21E+11
3	9.33E+10	1.13E+11	1.42E+11	2.02E+11	3.89E+11
5	5.39E+10	6.72E+10	8.87E+10	1.34E+11	2.90E+11
7	3.59E+10	4.58E+10	6.23E+10	9.82E+10	2.30E+11
10	2.25E+10	2.94E+10	4.11E+10	6.78E+10	1.73E+11
15	1.25E+10	1.67E+10	2.42E+10	4.20E+10	1.18E+11
20	7.89E+09	1.08E+10	1.60E+10	2.87E+10	8.56E+10
25	5.41E+09	7.50E+09	1.13E+10	2.08E+10	6.51E+10
30	3.91E+09	5.47E+09	8.36E+09	1.57E+10	5.10E+10
35	2.93E+09	4.14E+09	6.40E+09	1.22E+10	4.08E+10
40	2.27E+09	3.23E+09	5.03E+09	9.71E+09	3.34E+10
45	1.79E+09	2.57E+09	4.03E+09	7.88E+09	2.76E+10
50	1.45E+09	2.08E+09	3.29E+09	6.49E+09	2.32E+10
55	1.18E+09	1.71E+09	2.72E+09	5.41E+09	1.97E+10
60	9.83E+08	1.43E+09	2.28E+09	4.57E+09	1.68E+10
70	7.00E+08	1.02E+09	1.65E+09	3.34E+09	1.26E+10
80	5.16E+08	7.58E+08	1.23E+09	2.52E+09	9.65E+09
90	3.91E+08	5.77E+08	9.40E+08	1.94E+09	7.55E+09
100	3.03E+08	4.49E+08	7.34E+08	1.53E+09	6.01E+09
125	1.83E+08	2.71E+08	4.43E+08	9.20E+08	3.62E+09
150	1.18E+08	1.75E+08	2.87E+08	5.95E+08	2.35E+09
175	8.10E+07	1.20E+08	1.96E+08	4.08E+08	1.61E+09
200	5.79E+07	8.57E+07	1.40E+08	2.92E+08	1.15E+09
225	4.27E+07	6.32E+07	1.04E+08	2.15E+08	8.47E+08
250	3.23E+07	4.78E+07	7.83E+07	1.63E+08	6.40E+08
275	2.49E+07	3.69E+07	6.04E+07	1.25E+08	4.94E+08
300	1.96E+07	2.90E+07	4.75E+07	9.87E+07	3.89E+08

Values Do Not Include Design Margins

Table A-3. Spacecraft Incident Solar Proton Fluences for 3 Solar Active Years

Proton Energy	Proton Fluence(cm^-2)				
	Confidence Levels (%)				
(>MeV)	80	85	90	95	99
1	3.61E+11	3.99E+11	4.54E+11	5.48E+11	7.83E+11
3	1.41E+11	1.66E+11	2.04E+11	2.76E+11	4.88E+11
5	8.32E+10	1.01E+11	1.30E+11	1.87E+11	3.70E+11
7	5.63E+10	7.01E+10	9.23E+10	1.39E+11	2.98E+11
10	3.58E+10	4.56E+10	6.19E+10	9.75E+10	2.28E+11
15	2.01E+10	2.64E+10	3.71E+10	6.15E+10	1.59E+11
20	1.29E+10	1.72E+10	2.48E+10	4.25E+10	1.17E+11
25	8.88E+09	1.20E+10	1.76E+10	3.11E+10	8.99E+10
30	6.44E+09	8.83E+09	1.31E+10	2.36E+10	7.10E+10
35	4.85E+09	6.71E+09	1.01E+10	1.84E+10	5.72E+10
40	3.76E+09	5.24E+09	7.95E+09	1.47E+10	4.70E+10
45	2.98E+09	4.18E+09	6.39E+09	1.20E+10	3.91E+10
50	2.41E+09	3.40E+09	5.23E+09	9.92E+09	3.29E+10
55	1.98E+09	2.80E+09	4.33E+09	8.29E+09	2.80E+10
60	1.64E+09	2.33E+09	3.64E+09	7.01E+09	2.40E+10
70	1.17E+09	1.68E+09	2.63E+09	5.14E+09	1.80E+10
80	8.65E+08	1.24E+09	1.97E+09	3.88E+09	1.39E+10
90	6.56E+08	9.49E+08	1.51E+09	3.00E+09	1.09E+10
100	5.09E+08	7.39E+08	1.18E+09	2.36E+09	8.69E+09
125	3.07E+08	4.46E+08	7.12E+08	1.42E+09	5.24E+09
150	1.99E+08	2.88E+08	4.61E+08	9.22E+08	3.39E+09
175	1.36E+08	1.97E+08	3.15E+08	6.32E+08	2.32E+09
200	9.73E+07	1.41E+08	2.26E+08	4.52E+08	1.66E+09
225	7.18E+07	1.04E+08	1.66E+08	3.33E+08	1.22E+09
250	5.43E+07	7.87E+07	1.26E+08	2.52E+08	9.26E+08
275	4.19E+07	6.08E+07	9.71E+07	1.94E+08	7.15E+08
300	3.29E+07	4.78E+07	7.63E+07	1.53E+08	5.62E+08

Values Do Not Include Design Margins

Table A-4. Spacecraft Incident Solar Proton Fluences for 4 Solar Active Years

Proton Energy	Proton Fluence(cm^-2)				
	Confidence Levels (%)				
(>MeV)	80	85	90	95	99
1	4.70E+11	5.14E+11	5.76E+11	6.80E+11	9.30E+11
3	1.87E+11	2.17E+11	2.61E+11	3.42E+11	5.71E+11
5	1.12E+11	1.34E+11	1.68E+11	2.34E+11	4.37E+11
7	7.68E+10	9.38E+10	1.21E+11	1.76E+11	3.55E+11
10	4.93E+10	6.18E+10	8.20E+10	1.25E+11	2.75E+11
15	2.81E+10	3.62E+10	4.98E+10	7.98E+10	1.94E+11
20	1.81E+10	2.38E+10	3.35E+10	5.57E+10	1.44E+11
25	1.25E+10	1.67E+10	2.40E+10	4.10E+10	1.12E+11
30	9.13E+09	1.23E+10	1.79E+10	3.13E+10	8.89E+10
35	6.90E+09	9.38E+09	1.38E+10	2.45E+10	7.20E+10
40	5.36E+09	7.35E+09	1.09E+10	1.97E+10	5.94E+10
45	4.26E+09	5.87E+09	8.81E+09	1.61E+10	4.95E+10
50	3.45E+09	4.78E+09	7.22E+09	1.33E+10	4.18E+10
55	2.83E+09	3.94E+09	5.99E+09	1.11E+10	3.57E+10
60	2.35E+09	3.29E+09	5.03E+09	9.43E+09	3.06E+10
70	1.68E+09	2.37E+09	3.66E+09	6.94E+09	2.31E+10
80	1.24E+09	1.76E+09	2.74E+09	5.25E+09	1.78E+10
90	9.44E+08	1.34E+09	2.10E+09	4.06E+09	1.40E+10
100	7.33E+08	1.05E+09	1.64E+09	3.20E+09	1.12E+10
125	4.42E+08	6.32E+08	9.92E+08	1.93E+09	6.75E+09
150	2.86E+08	4.09E+08	6.42E+08	1.25E+09	4.37E+09
175	1.96E+08	2.80E+08	4.40E+08	8.56E+08	2.99E+09
200	1.40E+08	2.00E+08	3.14E+08	6.12E+08	2.14E+09
225	1.03E+08	1.48E+08	2.32E+08	4.52E+08	1.58E+09
250	7.81E+07	1.12E+08	1.75E+08	3.41E+08	1.19E+09
275	6.03E+07	8.62E+07	1.35E+08	2.64E+08	9.21E+08
300	4.74E+07	6.78E+07	1.06E+08	2.07E+08	7.24E+08

Values Do Not Include Design Margins

Table A-5. Spacecraft Incident Solar Proton Fluences for 5 Solar Active Years

Proton	**Proton Fluence(cm^-2)**				
Energy	**Confidence Levels (%)**				
(>MeV)	**80**	**85**	**90**	**95**	**99**
1	5.77E+11	6.26E+11	6.93E+11	8.06E+11	1.07E+12
3	2.32E+11	2.66E+11	3.14E+11	4.04E+11	6.46E+11
5	1.41E+11	1.66E+11	2.04E+11	2.78E+11	4.95E+11
7	9.70E+10	1.17E+11	1.48E+11	2.10E+11	4.04E+11
10	6.29E+10	7.77E+10	1.01E+11	1.50E+11	3.15E+11
15	3.62E+10	4.60E+10	6.22E+10	9.72E+10	2.25E+11
20	2.34E+10	3.04E+10	4.21E+10	6.82E+10	1.69E+11
25	1.63E+10	2.15E+10	3.03E+10	5.05E+10	1.32E+11
30	1.19E+10	1.59E+10	2.27E+10	3.87E+10	1.05E+11
35	9.03E+09	1.21E+10	1.76E+10	3.05E+10	8.55E+10
40	7.03E+09	9.52E+09	1.39E+10	2.45E+10	7.08E+10
45	5.59E+09	7.62E+09	1.13E+10	2.00E+10	5.92E+10
50	4.53E+09	6.21E+09	9.24E+09	1.66E+10	5.01E+10
55	3.73E+09	5.13E+09	7.68E+09	1.40E+10	4.28E+10
60	3.10E+09	4.29E+09	6.46E+09	1.18E+10	3.68E+10
70	2.22E+09	3.09E+09	4.70E+09	8.72E+09	2.79E+10
80	1.64E+09	2.30E+09	3.52E+09	6.61E+09	2.15E+10
90	1.25E+09	1.76E+09	2.71E+09	5.12E+09	1.70E+10
100	9.70E+08	1.37E+09	2.12E+09	4.04E+09	1.36E+10
125	5.85E+08	8.27E+08	1.28E+09	2.44E+09	8.18E+09
150	3.79E+08	5.36E+08	8.28E+08	1.58E+09	5.30E+09
175	2.59E+08	3.67E+08	5.67E+08	1.08E+09	3.63E+09
200	1.86E+08	2.62E+08	4.05E+08	7.73E+08	2.59E+09
225	1.37E+08	1.93E+08	2.99E+08	5.70E+08	1.91E+09
250	1.03E+08	1.46E+08	2.26E+08	4.31E+08	1.45E+09
275	7.98E+07	1.13E+08	1.74E+08	3.33E+08	1.12E+09
300	6.28E+07	8.87E+07	1.37E+08	2.62E+08	8.78E+08

Values Do Not Include Design Margins

Table A-6. Integral Solar Proton Fluence Levels behind Solid Sphere Aluminum Shields 100 mils (2.54 mm) Aluminum Shielding

Degraded Energy	**Shielded Solar Proton Fluence (#/cm^2)**				
(> MeV)	**1 year**	**2 years**	**3 years**	**4 years**	**5 years**
0.10	1.19E+10	1.33E+10	2.06E+10	2.79E+10	3.51E+10
0.13	1.19E+10	1.33E+10	2.06E+10	2.79E+10	3.51E+10
0.16	1.19E+10	1.33E+10	2.06E+10	2.79E+10	3.51E+10
0.20	1.19E+10	1.33E+10	2.06E+10	2.79E+10	3.51E+10
0.25	1.19E+10	1.33E+10	2.06E+10	2.79E+10	3.51E+10
0.32	1.19E+10	1.33E+10	2.06E+10	2.79E+10	3.51E+10
0.40	1.18E+10	1.33E+10	2.06E+10	2.79E+10	3.51E+10
0.50	1.18E+10	1.33E+10	2.06E+10	2.79E+10	3.51E+10
0.63	1.18E+10	1.32E+10	2.06E+10	2.79E+10	3.51E+10
0.79	1.18E+10	1.32E+10	2.05E+10	2.79E+10	3.50E+10
1.00	1.18E+10	1.32E+10	2.05E+10	2.78E+10	3.50E+10
1.26	1.18E+10	1.32E+10	2.05E+10	2.78E+10	3.49E+10
1.58	1.17E+10	1.31E+10	2.04E+10	2.77E+10	3.48E+10
2.00	1.17E+10	1.31E+10	2.03E+10	2.76E+10	3.47E+10
2.51	1.16E+10	1.30E+10	2.02E+10	2.74E+10	3.45E+10
3.16	1.15E+10	1.29E+10	2.00E+10	2.71E+10	3.41E+10
3.98	1.14E+10	1.27E+10	1.97E+10	2.68E+10	3.37E+10
5.01	1.11E+10	1.24E+10	1.93E+10	2.62E+10	3.30E+10
6.31	1.08E+10	1.20E+10	1.87E+10	2.54E+10	3.20E+10
7.94	1.04E+10	1.16E+10	1.80E+10	2.45E+10	3.09E+10
10.00	9.83E+09	1.09E+10	1.70E+10	2.31E+10	2.92E+10
12.60	9.06E+09	1.00E+10	1.56E+10	2.13E+10	2.69E+10
15.80	8.05E+09	8.90E+09	1.39E+10	1.90E+10	2.40E+10
20.00	6.88E+09	7.57E+09	1.19E+10	1.62E+10	2.05E+10
25.10	5.65E+09	6.18E+09	9.73E+09	1.33E+10	1.69E+10
31.60	4.40E+09	4.77E+09	7.54E+09	1.03E+10	1.31E+10
39.80	3.24E+09	3.48E+09	5.51E+09	7.61E+09	9.75E+09
50.10	2.28E+09	2.42E+09	3.85E+09	5.34E+09	6.84E+09
63.10	1.49E+09	1.57E+09	2.50E+09	3.48E+09	4.47E+09
79.40	9.23E+08	9.67E+08	1.55E+09	2.16E+09	2.78E+09
100.00	5.48E+08	5.67E+08	9.10E+08	1.27E+09	1.64E+09
126.00	3.11E+08	3.23E+08	5.17E+08	7.23E+08	9.32E+08
158.00	1.61E+08	1.68E+08	2.67E+08	3.76E+08	4.83E+08
200.00	7.38E+07	7.68E+07	1.23E+08	1.72E+08	2.21E+08
251.00	2.20E+07	2.27E+07	3.66E+07	5.10E+07	6.52E+07

Values Do Not Include Design Margins

Table A-7. Total Ionizing Dose at the Center of Aluminum Spheres Due to Solar Proton Events

Aluminum Shield Thickness			**Total Dose (krad-Si)**				
g/sqcm	**mm**	**mils**	**1 year**	**2 years**	**3 years**	**4 years**	**5 years**
0.007	0.03	1.02	320.00	436.00	604.00	763.00	916.00
0.021	0.08	3.06	146.00	185.00	260.00	328.00	390.00
0.027	0.10	3.94	118.00	148.00	209.00	264.00	315.00
0.041	0.15	5.98	81.40	102.00	145.00	184.00	220.00
0.048	0.18	7.00	70.60	87.70	126.00	160.00	191.00
0.062	0.23	9.04	57.60	71.20	103.00	131.00	157.00
0.069	0.26	10.06	50.40	62.10	89.90	115.00	138.00
0.082	0.30	11.96	44.40	54.50	78.90	101.00	122.00
0.089	0.33	12.98	40.20	49.20	71.40	92.20	112.00
0.103	0.38	15.02	34.50	42.00	61.20	79.30	96.10
0.199	0.74	29.02	18.40	21.90	32.50	42.70	52.00
0.302	1.12	44.06	11.70	13.80	20.80	27.50	33.90
0.398	1.47	58.03	8.73	10.20	15.50	20.60	25.60
0.501	1.86	73.07	6.56	7.60	11.60	15.50	19.30
0.597	2.21	87.05	5.54	6.38	9.81	13.10	16.30
0.686	2.54	100.04	4.63	5.29	8.15	10.90	13.70
0.802	2.97	116.93	3.83	4.33	6.67	9.02	11.30
1.001	3.71	145.94	2.93	3.29	5.08	6.91	8.68
1.248	4.62	181.97	2.23	2.49	3.87	5.27	6.63
1.502	5.56	219.02	1.74	1.94	3.04	4.12	5.24
1.749	6.48	255.04	1.41	1.56	2.45	3.32	4.21
2.003	7.42	292.09	1.17	1.29	2.03	2.76	3.48
2.503	9.27	364.96	0.88	0.96	1.51	2.07	2.64
2.997	11.10	437.01	0.68	0.73	1.16	1.59	2.03
3.498	12.96	510.24	0.54	0.58	0.91	1.26	1.61
3.998	14.81	583.07	0.45	0.48	0.76	1.04	1.34
4.499	16.66	655.91	0.37	0.40	0.63	0.87	1.12
4.999	18.51	728.74	0.31	0.33	0.53	0.73	0.93
6.001	22.23	875.20	0.23	0.25	0.39	0.55	0.70
8.003	29.64	1166.93	0.15	0.16	0.25	0.35	0.45
9.999	37.03	1458	0.10	0.10	0.17	0.23	0.30

Values Do Not Include Design Margins

Table A-8. Integral LET Spectrum for Interplanetary Galactic Cosmic Rays (Z=1-92)

LET	LET Fluence	LET	LET Fluence
MeV*cm/mg	#/sqcm/day	MeV*sqcm/mg	#/sqcm/day
	Solar Minimum		Solar Maximum
1.00E-03	4.25E+05	1.00E-03	1.54E+05
1.65E-03	4.24E+05	1.65E-03	1.54E+05
1.69E-03	3.29E+05	1.69E-03	1.07E+05
1.70E-03	3.04E+05	1.70E-03	9.42E+04
1.72E-03	2.84E+05	1.72E-03	8.46E+04
1.77E-03	2.54E+05	1.77E-03	7.02E+04
1.81E-03	2.30E+05	1.81E-03	5.98E+04
1.85E-03	2.12E+05	1.85E-03	5.20E+04
1.91E-03	1.90E+05	1.91E-03	4.34E+04
1.98E-03	1.72E+05	1.98E-03	3.75E+04
2.01E-03	1.67E+05	2.01E-03	3.59E+04
2.13E-03	1.46E+05	2.13E-03	3.05E+04
2.28E-03	1.27E+05	2.28E-03	2.69E+04
2.53E-03	1.07E+05	2.53E-03	2.39E+04
3.01E-03	8.29E+04	3.01E-03	2.11E+04
3.54E-03	6.87E+04	3.54E-03	1.98E+04
4.52E-03	5.55E+04	4.52E-03	1.88E+04
5.56E-03	4.90E+04	5.56E-03	1.83E+04
6.54E-03	4.58E+04	6.54E-03	1.82E+04
7.52E-03	2.76E+04	7.52E-03	7.46E+03
8.55E-03	2.13E+04	8.55E-03	5.04E+03
9.60E-03	1.75E+04	9.60E-03	3.97E+03
1.97E-02	7.02E+03	1.97E-02	1.88E+03
2.96E-02	5.07E+03	2.96E-02	1.63E+03
4.00E-02	4.33E+03	4.00E-02	1.55E+03
5.04E-02	3.81E+03	5.04E-02	1.43E+03
6.00E-02	3.50E+03	6.00E-02	1.36E+03
6.97E-02	2.91E+03	6.97E-02	1.08E+03
8.01E-02	2.66E+03	8.01E-02	1.01E+03
9.00E-02	2.40E+03	9.00E-02	9.12E+02
1.01E-01	2.23E+03	1.01E-01	8.74E+02

Table A-8 (Continued)

LET	**LET Fluence**	**LET**	**LET Fluence**
MeV*cm/mg	#/sqcm/day	MeV*sqcm/mg	#/sqcm/day
	Solar Minimum		Solar Maximum
2.00E-01	9.84E+02	2.00E-01	3.59E+02
4.02E-01	4.33E+02	4.02E-01	1.52E+02
6.03E-01	2.90E+02	6.03E-01	1.10E+02
7.96E-01	2.23E+02	7.96E-01	8.84E+01
1.00E+00	1.79E+02	1.00E+00	7.22E+01
2.01E+00	3.39E+01	2.01E+00	5.88E+00
3.02E+00	1.43E+01	3.02E+00	2.03E+00
3.99E+00	7.76E+00	3.99E+00	1.02E+00
5.03E+00	4.59E+00	5.03E+00	5.81E-01
5.99E+00	3.07E+00	5.99E+00	3.80E-01
8.00E+00	1.55E+00	8.00E+00	1.90E-01
1.01E+01	9.00E-01	1.01E+01	1.10E-01
1.11E+01	7.17E-01	1.11E+01	8.75E-02
1.20E+01	5.76E-01	1.20E+01	7.04E-02
1.30E+01	4.67E-01	1.30E+01	5.71E-02
1.40E+01	3.85E-01	1.40E+01	4.72E-02
1.50E+01	3.16E-01	1.50E+01	3.88E-02
1.60E+01	2.61E-01	1.60E+01	3.20E-02
1.70E+01	2.20E-01	1.70E+01	2.71E-02
1.80E+01	1.85E-01	1.80E+01	2.27E-02
1.91E+01	1.54E-01	1.91E+01	1.89E-02
2.00E+01	1.30E-01	2.00E+01	1.60E-02
2.49E+01	4.45E-02	2.49E+01	5.50E-03
3.00E+01	6.27E-04	3.00E+01	8.18E-05
3.49E+01	6.86E-05	3.49E+01	1.06E-05
4.01E+01	4.18E-05	4.01E+01	6.50E-06
4.50E+01	2.83E-05	4.50E+01	4.42E-06
5.00E+01	2.00E-05	5.00E+01	3.13E-06
5.06E+01	1.92E-05	5.06E+01	3.00E-06
5.55E+01	1.34E-05	5.55E+01	2.11E-06
6.02E+01	9.38E-06	6.02E+01	1.49E-06

Table A-8 (Continued)

LET	**LET Fluence**	**LET**	**LET Fluence**

MeV*cm/mg	#/sqcm/day	MeV*sqcm/mg	#/sqcm/day
	Solar Minimum		Solar Maximum
6.53E+01	6.32E-06	6.53E+01	1.01E-06
7.00E+01	4.40E-06	7.00E+01	7.01E-07
7.50E+01	2.83E-06	7.50E+01	4.52E-07
8.04E+01	1.65E-06	8.04E+01	2.63E-07
8.52E+01	7.71E-07	8.52E+01	1.23E-07
9.03E+01	1.94E-07	9.03E+01	3.10E-08
9.57E+01	2.88E-08	9.57E+01	4.60E-09
1.00E+02	1.19E-08	1.00E+02	1.89E-09
1.01E+02	5.27E-09	1.01E+02	8.41E-10
1.03E+02	2.54E-09	1.03E+02	4.05E-10

Values Do Not Include Design Margins

100 mils Aluminum Shielding

Table A-9. Integral LET Spectrum for the October 1989 Solar Particle Event (Z=1-92)

LET	LET Fluence	LET Fluence	LET Fluence
MeV*cm^2/mg	#/cm^2/s	#/cm^2/s	#/cm^2/s
	Average Over Peak	Average Over Worst Day	Average Over Worst Week
1.00E-03	1.93E+05	5.21E+04	1.15E+04
2.01E-03	1.93E+05	5.21E+04	1.15E+04
3.01E-03	1.93E+05	5.20E+04	1.14E+04
4.02E-03	1.92E+05	5.17E+04	1.13E+04
5.01E-03	1.90E+05	5.11E+04	1.11E+04
6.03E-03	1.86E+05	5.02E+04	1.08E+04
7.02E-03	1.82E+05	4.90E+04	1.05E+04
7.97E-03	1.77E+05	4.76E+04	1.01E+04
8.95E-03	1.71E+05	4.60E+04	9.68E+03
1.01E-02	1.64E+05	4.40E+04	9.19E+03
1.99E-02	9.60E+04	2.55E+04	5.07E+03
2.99E-02	5.39E+04	1.43E+04	2.78E+03
4.00E-02	3.23E+04	8.56E+03	1.65E+03
4.98E-02	2.11E+04	5.59E+03	1.07E+03
6.00E-02	1.45E+04	3.84E+03	7.33E+02
6.97E-02	1.06E+04	2.81E+03	5.34E+02
8.01E-02	7.91E+03	2.09E+03	3.96E+02
9.00E-02	6.16E+03	1.63E+03	3.08E+02
9.99E-02	4.90E+03	1.29E+03	2.44E+02
2.00E-01	9.50E+02	2.51E+02	4.67E+01
3.01E-01	3.15E+02	8.31E+01	1.53E+01
4.02E-01	1.25E+02	3.32E+01	6.08E+00
5.01E-01	3.82E+01	1.01E+01	1.80E+00
6.03E-01	1.86E+01	4.94E+00	8.78E-01
7.01E-01	1.35E+01	3.58E+00	6.52E-01
8.05E-01	9.85E+00	2.62E+00	4.91E-01
9.04E-01	7.55E+00	2.02E+00	3.87E-01
1.00E+00	5.88E+00	1.57E+00	3.10E-01
2.01E+00	7.49E-01	2.06E-01	5.99E-02
3.02E+00	4.11E-01	1.13E-01	3.33E-02
3.99E+00	2.64E-01	7.29E-02	2.14E-02
5.03E+00	1.74E-01	4.80E-02	1.42E-02
6.06E+00	1.21E-01	3.36E-02	9.92E-03
7.04E+00	8.68E-02	2.40E-02	7.11E-03
8.00E+00	6.39E-02	1.77E-02	5.26E-03
8.99E+00	5.04E-02	1.40E-02	4.13E-03
1.01E+01	3.85E-02	1.07E-02	3.15E-03
2.00E+01	5.75E-03	1.60E-03	4.63E-04

Table A-10. Integral LET Spectrum for the October 1989 Solar Particle Event (Z=1-92)

(Continued)

LET	**LET Fluence**	**LET Fluence**	**LET Fluence**
MeV*cm^2/mg	#/cm^2/s	#/cm^2/s	#/cm^2/s
	Average Over Peak	Average Over Worst Day	Average Over Worst Week
2.52E+01	2.14E-03	5.95E-04	1.72E-04
3.00E+01	1.83E-05	5.10E-06	1.55E-06
3.53E+01	7.23E-07	2.01E-07	7.14E-08
4.01E+01	3.26E-07	9.08E-08	3.43E-08
4.50E+01	1.95E-07	5.44E-08	2.12E-08
5.00E+01	1.36E-07	3.78E-08	1.48E-08
5.55E+01	8.43E-08	2.35E-08	9.31E-09
6.02E+01	4.92E-08	1.37E-08	5.58E-09
6.53E+01	3.28E-08	9.12E-09	3.75E-09
7.00E+01	2.49E-08	6.92E-09	2.84E-09
7.50E+01	1.80E-08	5.00E-09	2.04E-09
8.04E+01	1.20E-08	3.34E-09	1.36E-09
8.52E+01	6.69E-09	1.86E-09	7.56E-10
9.03E+01	2.03E-09	5.64E-10	2.29E-10
9.46E+01	1.33E-10	3.71E-11	1.51E-11
1.00E+02	5.01E-11	1.39E-11	5.66E-12
1.01E+02	2.22E-11	6.19E-12	2.51E-12
1.03E+02	1.07E-11	2.99E-12	1.21E-12

Values Do Not Include Design Margins
100 mils Aluminum Shielding

Table A-11. Differential Proton Fluxes for the October 1989 Solar Particle Event

Energy	**Proton Flux**	**Proton Flux**	**Proton Flux**
MeV	#/cm^2/s	#/cm^2/s	#/cm^2/s
	Average Over Peak	Average Over Worst Day	Average Over Worst Week
1.00	1.75E+03	4.62E+02	8.85E+01
2.00	2.68E+03	7.09E+02	1.36E+02
3.02	3.47E+03	9.17E+02	1.76E+02
4.04	4.11E+03	1.09E+03	2.09E+02
5.04	4.62E+03	1.22E+03	2.36E+02
6.03	5.03E+03	1.33E+03	2.58E+02
7.02	5.33E+03	1.41E+03	2.75E+02
8.06	5.56E+03	1.47E+03	2.88E+02
9.00	5.69E+03	1.51E+03	2.96E+02
10.05	5.76E+03	1.53E+03	3.01E+02
14.99	5.41E+03	1.44E+03	2.92E+02
20.03	4.50E+03	1.21E+03	2.52E+02
24.98	3.57E+03	9.65E+02	2.07E+02
30.31	2.73E+03	7.40E+02	1.64E+02
35.27	2.11E+03	5.75E+02	1.31E+02
40.49	1.61E+03	4.42E+02	1.04E+02
50.50	9.91E+02	2.73E+02	6.79E+01
60.43	6.33E+02	1.75E+02	4.58E+01
70.33	4.20E+02	1.17E+02	3.20E+01
79.63	2.94E+02	8.18E+01	2.33E+01
90.17	2.03E+02	5.65E+01	1.68E+01
100.69	1.44E+02	4.01E+01	1.24E+01
150.25	3.84E+01	1.06E+01	3.80E+00
200.77	1.39E+01	3.79E+00	1.50E+00
299.59	3.32E+00	8.62E-01	3.88E-01
400.31	1.16E+00	2.85E-01	1.39E-01
499.23	4.97E-01	1.16E-01	5.96E-02
605.64	2.07E-01	4.64E-02	2.54E-02
704.94	1.10E-01	2.48E-02	1.44E-02
798.17	6.61E-02	1.48E-02	9.03E-03
903.74	3.95E-02	8.88E-03	5.66E-03
995.41	2.65E-02	5.96E-03	3.94E-03

Values Do Not Include Design Margins

100 mils Aluminum Shielding, CREME96

Note: Spectra were cut off at E =1 MeV and E=1000 MeV

Appendix B. Abbreviations and Acronyms

Abbreviation/ Acronym	DEFINITION
3-D	Three Dimensional
CCD	Charge Coupled Device
cm	centimeter
COTS	Commercial-off-the-Shelf
CRÈME	Cosmic Ray Effects on Micro-Electronics
EDACs	Error Detection and Correction Codes
ELDRS	Enhanced Low Dose Rate Sensitivity
ESP	Emission of Solar Protons
g/sqcm	grams per square centimeter
GCR	Galactic Cosmic Ray
GeV	Giga electron Volt
km	kilometer
krad	Kilorad
Krad-Si	Kilorad-Si
LET	Linear Energy Transfer
LRO	Lunar Reconnaissance Orbiter
MBE	Multiple Bit Error
MeV	Mega electron Volt
mg	milligram
mil	.001 inch
mm	millimeter
NIEL	Non-Ionizing Energy Loss
SEB	Single Event Burnout
sec	second
SEE	Single Event Effect
SEGR	Single Event Gate Rupture
SEL	Single Event Latchup
SET	Single Event Transient
SEU	Single Event Upset
SHE	Single Event Hard Error
sqcm	Square centimeter
TeV	Terra electron Volt
TID	Total Ionizing Dose