General Disclaimer

One or more of the Following Statements may affect this Document

JPL Publication 83-26

Radiation Protection
for
Manned Space Activities

Thomas M. Jordan

March 1983

NASA
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Radiation Protection for Manned Space Activities

Thomas M. Jordan

March 1983

ABSTRACT

The Earth's natural radiation environment poses a hazard to manned space activities directly through biological effects and indirectly through effects on materials and electronics. A preliminary review of radiation protection indicates a requirement for Standard Practices that address: (1) environment models for all radiation species including uncertainties and temporal variations; (2) upper bound and nominal quality factors for biological radiation effects that include dose, dose rate, critical organ, and linear energy transfer variations; (3) particle transport and shielding methodology including system and man-modeling and uncertainty analysis; (4) mission planning that includes active dosimetry, minimizes exposure during extravehicular activities, subjects every mission to a radiation review, and specifies operational procedures for forecasting, recognizing, and dealing with large solar flares. The Space Transportation System and space station missions should be addressing radiation protection uncertainties and worst case issues now.

ACKNOWLEDGMENTS

PRECEDING PAGE BLANK NOT FILMED

CONTENTS

Figures

Tables

SECTION I

INTRODUCTION

Manned space activities involve a number of unique hazards, e.g., launch/landing, micrometeoroids, zero gravity, and the space radiation environment. Each of the threats to man must be factored into some overall cost/benefit equation that in some sense minimizes the threat effect.

The radiation hazard has several unique characteristics. First, the environment for many missions is highly variable, with fluctuations of orders of magnitude. Second, the degraded environment seen by man depends strongly upon the protection afforded by the system, i.e., the protection factor can vary by orders of magnitude from inside the Shuttle or space station to extravehicular activities (EVA). Finally, radio biological effects for high specific ionization particles (cosmic rays) are often single-event phenomena that are not adequately addressed by conventional dose criteria.

The radiation environment also poses an indirect hazard to manned activities through effects in materials and electronics. These effects also fluctuate with the environment and protection factors. For applications of microelectronics to manned activities (e.g., microprocessor control of life support systems), single-event phenomena for high specific ionization particles are an immediate concern.

Radiation protection of man in space has been the subject of several major conferences. For example, the Second Symposium on Protection Against Radiation in Space (Reference 1) and the Proceedings of the National Symposium on Natural and Man-Made Radiation in Space (Reference 2) indicate the topics addressed by radiation concerns.

This review divides radiation protection into four topics: radiation environment, radiation effects, radiation transport, and mission/operation. Each topic is examined and uncertainties and deficiencies are noted. Conclusions and recommendations are then given. The appendix contains quantitative figures and tables.

SECTION II

RADIATION ENVIRONMENT

The Earth's radiation environment is a complex mixture of neutral and charged particles. Three major categories of the natural environment are identified: trapped electrons and protons, galactic cosmic rays (protons and ions), and solar flare particles (protons and ions). Additionally, some misions must consider neutron and photon radiation from nuclear auxilliary power systems (radioisotopic thermoelectric generators and nuclear reactors) or nuclear weapons.

The natural environment varies by orders of magnitude as a function of orbit altitude, latitude, and longitude. In addition, there are enormous temporal variations caused by day/night, general solar activity (solar minimum to solar maximum), specific solar activity (solar flares), and magnetic storms and substorms.

A.   TRAPPED ENVIRONMENT

The low-energy natural environment (plasma) is charged particles with energies less than 100 keV. This environment must be considered for surface effects generally and for spacecraft charging specifically. The plasma environment is potentially harmful to man during EVA because of charging of spacesuit materials. A review of quantitative plasma models has been made by Garrett (Reference 3), and spacecraft charging phenomena have been discussed extensively (e.g., Reference 4).

The high-energy natural environment (electrons and protons with energies above 100 keV) is modeled by the National Space Science Data Center (NSSDC). The models produce integral fluxes that represent averages of missions of 6 months duration or longer. Short-term variations may be very large. Electron levels, for example, can vary by a factor of 20 because of local time effects at altitudes above 5 Earth radii, and will vary by factors of 100 to 1000 during magnetic storms and substorms at altitudes above 2 Earth radii.

Several models are used, in conjunction with detailed orbit traces, to obtain mission specific environments, as shown below:

Trapped Protons	AP8-MAX (solar maximum)	Ref. 5
$0.1 \leq E(MeV) < 500$	AP8-MIN (solar minimum)	Ref. 5
Trapped Electrons	AE6 (solar maximum, inner zone)	Ref. 6
$0.1 \leq E(MeV) < 7$	AE5 (solar minimum, inner zone)	Ref. 7
	AE17-HI (outer zone)[a]	
	AE17-LO (outer zone)[a]	

---

[a] Different models of flux for E < 2 MeV

The proton models have an uncertainty of a factor of 2. The electron models have an uncertainty that varies from a factor of 2 to 10 with a nominal uncertainty of 5 for the inner zone and 2 for the outer zone.

For low Earth orbits with inclinations less than 50 deg, the natural radiation environment is dominant in the South Atlantic Anomaly. At higher inclinations and similar altitudes, the horns of the trapped radiation belts also contribute to the orbit's averaged environment. The general character of low Earth orbit environment is indicated in Reference 8 although the actual levels presented therein no longer apply.

B.   COSMIC RAYS

The cosmic-ray environment consists of protons, alphas, and other heavy ions with energies from 0.1 MeV to 10^{16} MeV per nucleon. Galactic cosmic rays originate outside the solar system and vary in level by approximately a factor of 2 over the solar cycle with a maximum at solar minimum. Adams and others have reviewed the literature on the cosmic-ray environment and have suggested a model for the galactic cosmic rays (Reference 9) that includes relative ion abundance and spectra for solar minimum and maximum.

C.   SOLAR FLARE PARTICLES

Solar flare particles also include protons, alphas, and other heavy ions. However, the relative abundance of each ion varies for each flare. Solar flare particles are emitted during a magnetic disturbance on the Sun's surface. These particles travel outward from the Sun. However, only specific flare sites will result in particles intercepting the Earth. The arrival of the proton component of a flare caused by a solar disturbance has been modeled by Smart and Shea (Reference 10). The average solar flare environment has been modeled statistically based on data from prior solar cycles (e.g., Reference 11). The model distinguishes between ordinary and anomalously large events. If an anomalously large flare does occur, it dominates the ordinary flares. Flare data from the last solar cycle have not been integrated into the statistical models.

D.   GEOMAGNETIC SHIELDING

Both cosmic-ray and solar flare particle environments are affected by the Earth's magnetic field. A detailed model of ion trajectories in this field has been developed by Smart and Shea (Reference 12). This model has been used by Heinrich and Spill (Reference 13) to predict average geomagnetic shielding factors for specific orbits. A similar effort has been done by Adams and Letaw (Reference 14), including a software listing for analyzing various orbits. In low Earth orbit, cosmic rays and flare particles are almost entirely shielded at inclinations of 40 deg or less.

SECTION III

RADIATION EFFECTS

Particulate radiation in space includes both neutral and charged particles. The dominant species of interest are photons, neutrons, electrons, and ions (protons, alphas, and higher atomic number nuclei). Some of these particle species dominate the free space environment. Other species are produced by complex interactions with space systems and may dominate the environment inside a system.

Particulate radiation produces many effects in materials, e.g., energy deposition, atomic displacements, bond breaking. The effects result from interactions of radiation with the atomic electrons and/or nuclei of the atoms comprising the materials. These same interactions complicate the prediction of effects since interactions may change the direction, energy, and species of radiation emanating from the interaction.

A fundamental measure of radiation effects is the linear energy transfer (LET), the mean energy loss per unit pathlength of radiation in a material. The mean energy loss definition involves an average of all interactions that a particle could have, and is a strong function of particle energy and type. The gray (Gy), corresponding to an absorbed energy (dose) of 1 J/kg, or the rad (10^{-2} Gy = 100 ergs/g) is used to express the combined effect of different particles.

The LET values not only depend upon the particles species and energies but also vary with composition and other properties of the material. Of course, the energy lost by a particle is taken up by the recoil electrons or nuclei of the material constituents and appears as other particles emerging from the interaction. In many calculations of effects, a detailed accounting of recoils and other post interaction particles (their interactions with other atoms of the material) is necessary to fully predict and understand macroscopic radiation effects.

Other measures of radiation effects in materials are used besides LET. These measures result when the effect is not proportional to deposited energy (dose). These measures include current for single-event phenomena, stopping densities for electrical charging, and equivalent monoenergetic flux for displacement damage.

Radiation effects in materials generally, and electronics specifically, are amenable to indepth understanding. The development and testing of effects models are limited primarily by schedules and budgets. The results of ongoing research are presented at the annual IEEE Nuclear and Space Radiation Effects Conference (e.g., Reference 15).

Biological radiation effects have the same underlying particle interactions as other material effects. The understanding of these effects is made difficult, however, by the structure and replicative nature of biological materials. It becomes necessary to consider cell death, damage, repair, and,

if a cell is damaged, how and in what form the damage is propagated to subsequent generations. Because some effects are not apparent until tens of years after radiation exposure and because the same effects can be initiated by other causes, the measure of biological radiation effects is often inferred statistically with low accuracy.

The fundamental measure of biological radiation effects is also linear energy transfer but modified by a multiplicative quality factor. The quality factor expresses the experimental fact that, for the same dose (deposited energy), high microscopic LET particles produce more biological damage than low microscopic LET particles. The LET is qualified as microscopic because it is necessary to look at fundamental interactions and post interaction particles to see the true picture of dose on the geometric scale of biological cells.

The quality factor is a legislated quantity - a consensus of opinion on perceived relative biological effects. For LETs of 35 MeV/cm (3.5 keV/μm) or less in water, the quality factor is unity. For more than 35 MeV/cm, the quality factor increases with LETs to a value of 20 at 1750 MeV/cm. The LETs more than 1750 MeV/cm are given a quality factor of 20.

These quality factors apply to charged particles, where the dominant term of the LET is energy loss to electrons, i.e., creation of ion pairs. For neutrons the quality factor is applied to the recoil nuclei (charged ions) that emerge from neutron collisions. Photon interactions yield electrons, positrons, and other photons so that quality factors for electrons apply. Electrons generally have LETs less than 35 MeV/cm so that a quality factor of unity applies.

Biological radiation effects are expressed in sieverts (Sv) (J/kg) or rem (10^{-2} Sv). The numerical value of the biological dose in Sv (rem) is the physical dose in grays (rad) of low LET (<35 MeV/cm) radiation required to produce the same biological effect, provided that the quality factor is indicative of the true relative biological effectiveness of the radiation.

Some biological effects are not expressed well in dose equivalence (Reference 16). For example, individual energetic ions cause opacities in the lens of the eye, a "single-event" phenomenon. Finally, cause and effect data on humans are extracted from populations exposed to specific levels and particle species and energies, a difficult and speculative process.

Benton and Henke (Reference 17) have reviewed the dose received by astronauts on various Gemini, Apollo, Vostok, Soyuz Skylab, Apollo-Soyuz Test Project, and Space Transportation System (STS) missions. The physical dose rates vary from 6 mrad/day for STS No. 3 (240-km altitude, 38-deg inclination) to 90 mrad/day for Skylab 4 (435-km altitude, 50-deg inclination) based on thermoluminescent dosimetry.

SECTION IV

RADIATION TRANSPORT AND SHIELDING

Radiation transport and shielding calculations are one of the better understood elements of radiation protection. However, even this topic has several areas of uncertainty.

Transport and shielding relate to the penetration of energetic particles through spacecraft and man, including materials used to reduce radiation levels. Two levels of analysis are employed:

(1) The simpler analysis level employs one-dimensional geometries, usually slabs and spheres, so that radiation levels are understandable functions of the interactions that occur in materials.

(2) The more complicated analyses use three-dimensional geometry mockups and either approximate transport models or Monte Carlo methods.

A. PROTONS AND HEAVY IONS

The transport of protons and heavier ions is adequately modeled by straight-ahead continuous slowing down. Angular deflections of individual particles become important for energies less than about 1 MeV/nucleon. These deflections are important for monoenergetic sources because they distribute particles about the mean range. However, the continuous energy dependence of the natural environment obscures the importance of individual particle ranges.

For the nominal thicknesses encountered in most spacecraft, 2 to 10 g/cm^2, the physical dose (energy deposition) from ions (protons and heavier) can be determined quite accurately by ignoring all interactions except ionization. However, for biological effects where the quality factors emphasize high LET particles, an explicit treatment of secondaries (neutrons and nuclei fragments) is necessary. For portions of the proton energy range less than 10 MeV, elastic recoil nuclei have marginal importance.

Secondary production cross sections are the weakest link in ion transport. At present, the semi-empirical formula of Tsau and Silberburg (Reference 18) is being used, for example, by Heinrich (Reference 19), while McNulty (Reference 20) and others rely on intranuclear cascade models. The improvement of cross sections is the subject of several efforts including those of Townsend and Wilson (Reference 21).

The attenuation of ions by materials depends critically upon the high energy content of the ion environment. For example, soft flare spectra (enhanced low energy content) attenuate rapidly. Hard flare spectra (enhanced high energy content) may require tens of g/cm^2 for a factor of 10 decrease in dose. The dose from geomagnetically shielded cosmic rays can actually increase for material thicknesses of conceivable interest for radiation protection (geomagnetic shielding eliminates low energy/high LET particles, which are then replenished by slowing of high energy particles in the spacecraft materials).

Because straight-ahead transport models can be applied to continuous energy spectrum ion sources, the effects of man and spacecraft geometry are readily calculated. For instance, slab shields attenuate dose more rapidly than spherical shields because of the longer paths that are encountered in the slab shield. The understanding of geometric effects in more complicated geometries, e.g., the Shuttle and man, uses solid angle weighting of typical particle paths each modeled by straight-ahead continuous slowing down.

B.   ELECTRONS AND BREMSSTRAHLUNG

The transport of electrons and bremsstrahlung requires explicit treatment of the electron angular deflections because these deflections are substantial over the entire energy range of the natural environment. Because of these deflections, the use of the straight-ahead continuous slowing down approximation is not adequate for electrons since it underpredicts the relative attenuation of materials.

The cross sections employed for electron and secondary bremsstrahlung photons yield excellent agreement between experimentally measured and calculated quantities such as physical dose. Minor discrepancies occur for detailed quantities such as energy and angular flux with monoenergetic sources. However, the continuous (in energy and direction) character of the natural electron environment negate these discrepancies.

An understanding of electron transport characteristics is also provided by one-dimensional calculations. It has been shown (Reference 22) that the doses behind slab and solid sphere shields are related as if straight-ahead transport models were applied. However, the dose at the center of a spherical shell shield has attenuation more like a slab shield than a solid sphere shield until the primary electron dose is dominated by the secondary bremsstrahlung dose.

This difference in spherical shield attenuation, shell or solid, does not occur for ions. The difference between solid and shell sphere dose for electrons can be greater than a factor of 10. However, the bremsstrahlung dose finally dominates the primary electron dose effectively, limiting the difference for solid and shell spheres to less than a factor of 10. The difference in solid and shell sphere dose for electrons means that the solid angle weighting-type analysis in spacecraft and man can err substantially unless primary electrons are completely shielded.

Two methods have been devised to address electron transport in three-dimensional geometries and were used extensively for the Voyager and Galileo Projects:

(1)   An approximate method that determines upper and lower bounds on dose using solid angle weighting of slab and sphere attenuation models.

(2)   The more accurate method employs adjoint Monte Carlo (Reference 23) for efficient computations of radiation doses at points in three-dimensional spacecraft mockups.

SECTION V

MISSION OPERATIONS

Radiation protection of astronauts must address the environment, effects, and shield issues concurrently. Primary inputs are the mission (orbit, launch date, duration), models of the spacecraft and man, and criteria on maximum radiation levels deemed acceptable. Given the mission, nominal environmental models are constructed with uncertainty factors and temporal variations. Transport/shielding calculations using the environment then determine the expected radiation levels received by the astronauts. For new missions and spacecraft, there is feedback, based on the environment and transport/shielding calculations, that can modify the spacecraft design and/or the mission parameters. For existing spacecraft, mission parameters are the major variation allowed. Solar flare particles are the major environmental variable for high-inclination low Earth orbits or geostationary missions.

The National Aeronautics and Space Administration – Johnson Space Center (NASA-JSC) flight rules have procedures to be followed for major solar flares, dose limit violation, and enhanced environment indications. These procedures include contact with the National Oceanic and Atmospheric Administration – Space Environment Service Center (NOAA-SESC).

Co-located with the NOAA-SESC is a branch of the U.S. Air Force's Global Weather Central [(AFGWC), which is headquartered at Offutt Air Force Base in Nebraska]. These two organizations serve as the clearinghouses for real-time observations, predictions, alerts, and, in a more-restricted sense, archival data concerning solar flares. Table 5-1 lists the principle data sources available to NOAA-SESC and AFGWC. These data and the predictions made from them (Table 5-2) are disseminated by a variety of techniques, including (as for the first Shuttle flight) a telephone call (Table 5-3). Unfortunately, current predictive techniques are considered speculative. On the time scales of months or longer, predictions are based on statistical fits to previous observations. In the absence of accurate physical models of the processes associated with the propagation of solar flare particles to the Earth, short-term predictions such as would be appropriate for the Shuttle are based primarily on "experience". Even so, current practices could be significantly improved with incorporation of the latest flare warning techniques and improvements in data transferal between NASA-JSC and NOAA-SESC.

At low Earth orbit and low inclinations, the flare hazard is negligible because of geomagnetic shielding. For a space Shuttle polar orbit, where a substantial fraction of the orbit is over the polar caps and geomagnetic shielding is minimal, it is possible to hypothesize a prohibitive dose, particularly during EVA, before maneuvers could reduce the environment. For intermediate inclinations, analysis is needed to bracket the maximum credible incident, i.e., considering flare size, rise time, spectrum, type of activity, geomagnetic shielding, etc. At an inclination of 50 deg, the fraction of time per orbit spent at the latitude extremes (least geomagnetic shielding) may be small enough so that any credible flare onset can be handled by present procedures.

Table 5-1. Data Sources[a]

Type	Wavelength or Energy Range	Time Resolution	Primary Sources
Solar Patrol			
X-rays	1-8 Å, 0.5-4 Å	1-minute averages	GOES
Optical	Hydrogen Alpha	Continuous	Several
Radio	202-15, 400 MHz	1 minute	Several
Solar Synoptic			
Hydrogen Alpha Images		Several daily	Boulder
White Light Images		Several daily	Boulder
Ca K Images		Daily	Sac Peak
He 10830 Images		Daily	Kitt Peak
Magnetograms (Full Disk and Regional)		Daily	Kitt Peak, Huntsville
Sunspot Magnetic Fields		Daily	Mt. Wilson, Boulder
Ca K Scaled Reports		Daily	McMath
Sunspot Reports		Several daily	Several
Solar Mean Field		Daily	Stanford
10.7 cm Radio Flux	2800 MHz	3 times daily	Ottawa (Algonquin)
East-West Radio Drift Scan	2800 MHz	Daily	Ottawa (Algonquin)
Energetic Particle Patrol			
Synchronous Orbit	Protons: 06-500 MeV Alphas: 4.0-329 MeV Electrons: ≥2 MeV	1-minute averages	GOES
Polar Orbit	Protons	30 keV-850 MeV	TIROS-N
Magnetometer Patrol			
Synchronous Orbit	3 Components	1-minute averages	GOES
Terrestrial	3 Components	10 seconds	IMS North Amercian Chain
		10 seconds	Boulder
		15 minutes	Air Force Real Time Chain
		15 minutes	Thule
		15 minutes	Vostok
Miscellaneous			
Neutron Monitor		15 minutes	Thule
High Latitude Riometers	30 MHz	15 minutes	Alaskan Chain, Thule
Auroral Backscatter Radar	50 MHz	15 minutes	Anchorage
Interplanetary Scintillation	74 MHz	Daily	UCSD
Ionosondes	f_oF2, M3000, F_{min}	1 hour or 6 hours	Several

[a]Source: Reference 24.

Table 5-2. Observed Indices and Activity Summaries[a]

Solar Active Region Summary Report

Sunspot Number

Flare (and Other Event) Lists

Solar Neutral Line Analysis and Synoptic Maps

10-cm Flux

Solar Proton Events and Proton Flux

SST Radiation Levels

Geomagnetic A- and K-indices

Substorm Log

Section Boundaries (at 1 AU)

Table 5-3. Distribution Systems[a]

Telephone:

FTS (Federal Telephone Service)

WATS (Wide-Area Telephone Service)

Commercial Telephone Service

Dedicated Telephone Lines (Hot Lines)

Recorded Information Numbers

Teletype:

ATN (Astro-Geophysical Teletype Network)

AUTODIN (U.S. Government Teletype Service)

Commercial Teletype Services

Secondary Networks

Computer Links:

Space Environment Laboratory Data Acquisiton and
  Display System (SELDADS) Public User Access

Dedicated Data Links

WWV Shortwave Broadcast

Mail

---

[a]Source: Reference 24.

Several concerns arise as orbits are pushed to higher altitudes and inclinations. Simple altitude increases at low inclinations intercept more intensive trapped radiation belts. The dose increase, or protection factor requirement, is related to the environment increase in a roughly proportional way. The major concern for these higher doses is how far to push astronauts on their daily, quarterly, and lifetime exposure tables while also addressing the costs of training and/or recycling.

At high inclinations and at geosynchronous altitudes, both galactic cosmic rays and solar cosmic rays (solar flares) can partially or totally penetrate the Earth's magnetic field. For both sources of cosmic rays, there is an immediate question of assessing the relative effect of these particles. These particles have high specific ionization and quality factors that vary from 1 to 20. Unfortunately, there are indications that the quality factor at high LET may exceed 20 for some biological effects, and the high LET particles should be treated as single-event phenomena for which protection criteria do not exist.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

The elements of radiation protection for man in space have uncertainties that are potentially catastrophic. The dominant concern for the natural environment is the occurrence of a large solar particle event, which incorporates most of the major uncertainties, i.e., recognition of onset, rise time and duration, spectrum, magnitude, geomagnetic shielding versus orbit position, ion composition, relative biological effectiveness of high LET particles, nuclei fragmentation in the spacecraft and man, unambiguous and unattended active dosimetry of the event, temporary loss of communications with the control center, and practiced procedures for mission changes to minimize radiation effects.

Missions at low Earth orbits and nominal inclinations are protected from the large solar particle events by geomagnetic shielding. However, low Earth orbit missions at inclinations above 50 deg, and potential missions such as a geostationary space station, must explicitly consider the impact of a major flare.

There is a major uncertainty in the electron dose received during EVA where spacesuits do not stop the electrons. This uncertainty must be addressed for Shuttle missions that intercept the horns of the belts, i.e., inclinations above 45 deg, and other missions that encounter trapped electrons during EVA.

Microprocessors are being employed in life-support systems such as the manned maneuvering unit. These applications must be reviewed to verify immunity to single-event latchup and upset.

An engineering standard is recommended for the radiation protection of man in space. This standard should be subject to periodic reviews by NASA Centers and should contain sections on environmental models, radiation effects, transport/shielding, and mission planning and contingencies. Each section should address standard practices, temporal effects, and worst case as well as nominal, suggested, and legislated standards. During the drafting, the standard should be applied to a detailed evaluation of a Shuttle mission(s) at high inclination, and to a "typical" space station concept. This application would clarify the strengths and weaknesses of the standard while providing a definitive assessment of radiation protection for current STS and near-term space station missions.

SECTION VII

REFERENCES

1. *Second Symposium on Protection Against Radiation in Space*, NASA-SP-71, Arthur Reetz, Jr. (Editor), Washington, D.C., 1965.

2. *Proceedings of the National Symposium on Natural and Man-Made Radiation in Space*, NASA TM X-2440, Warman, E.A. (Editor), Washington, D.C., January 1972.

3. Garrett, H.B., "Review of Quantitative Models of the 0 to 100 keV Near-Earth Plasma," *Review of Geophysics and Space Physics*, Vol. 17, No. 3, pp. 397-417, 1979.

4. *Spacecraft Charging Technology 1980*, NASA Conference Publication 2182, AFGL-TR-81-0270, Air Force Geophysics Laboratory, 1981.

5. Sawyer, D.M., and Vette, J.I., *AP-8: Trapped Proton Environment for Solar Maximum and Solar Minimum--Computer Accessible Models*, NSSDC-WDC-A-R/S 76-06, NASA TM X-72605, National Space Science Data Center, December 1976.

6. Teague, M.J., Chan, K.W., and Vette, J.I., *AE6: A Model Environment for Trapped Electrons and Solar Maximum*, NSSDC-WDC-A-R/S 76-04, National Space Science Data Center, March 1974.

7. Teague, M.J., and Vette, J.I., *The Inner Electron Model AE5*, NSSD 72-10, National Space Science Data Center, September 1972.

8. Stassinopoulos, E.G., *World Maps of Constant B, L, and Flux Contours*, NASA-SP-3054, Washington, D.C., 1970.

9. Adams, J.H., Jr., Silberburg, R., and Tsao, C.H., *Cosmic Ray Effect on Microelectronics, Part I, The Near-Earth Particle Environment*, NRL Memorandum Report 4506, Naval Research Laboratory, August 1981.

10. Smart, D.F., and Shea, M.A., "PPS76 - A Computerized Event Mode Solar Proton Forecasting Technique," *Solar-Terrestrial Predictions Proceedings*, Vol. 1, Richard F. Donnelly (Editor), National Oceanic and Atmospheric Administration, August 1979.

11. Stassinopoulos, E.G., *SOLPRO: A Computer Code to Calculate Probabilistic Energetic Solar Proton Fluences*, NSSDC-75-11, NASA TM X-72573, National Space Science Data Center, April 1975.

12. Shea, M.A., and Smart, D.F., *Environment Research Papers*, AFCRL-TR-75-0185, Air Force Cambridge Research Laboratories, April 1975.

13. Heinrich, W., and Spill, A., "Geomagnetic Shielding of Cosmic Rays for Different Satellite Orbits," COSPAR, Planetary Meeting, 1978.

14. Adams, James H., Jr., and Letaw, John, The Geomagnetic Cutoff Transmittance Function, NRL Interim Report, Naval Research Laboratory, September 1982.

15. IEEE Transactions on Nuclear Science, IEEE Annual Conference on Nuclear and Space Radiation Effects, Vol. NS-28, No. 6, December 1981.

16. Blakely, Eleanor A., et al., "Inactivation of Human Cells by High-Energy Monoenergetic Heavy-ion Beams," Radiation Research 80, pp. 122-160, 1979.

17. Benton, E.V., and Henke, R.P., "Radiation Exposure During Spaceflight and Their Measurement," to appear in Space Research, Spring or Summer 1983.

18. Silberberg, R., Tsao, C.H., and Shapiro, M.M., Spallation Nuclear Reactions and Their Applications, B.S.P. Shen and M. Meeker (Editors), Vol. 59, p. 49, 1976.

19. Heinrich, W., "Calculation of LET Spectra of Heavy Cosmic Ray Nuclei at Various Absorber Depths," Radiation Effects, Vol. 34, pp. 143-148, 1977.

20. McNulty, Peter J., Farrell, Gary E., and Tucker, William P., "Proton-Induced Nuclear Radiation in Silicon," IEEE Transactions on Nuclear Science, Vol. NS-28, No. 6, December 1981.

21. Wilson, J.W., and Townsend, L.W., "An Optical Model for Composite Nuclear Scattering," Canadian Journal of Physics, Vol. 59, 1981.

22. Jordan, T.M., Electron Dose Attenuation Kernels for Slab and Spherical Geometries, AFWL-TR-81-43, Air Force Weapons Laboratory, November 1981.

23. Jordan, T.M., An Adjoint Charged Particle Transport Method, EMP.L76.071, Experimental & Mathematical Physics Consultants, Santa Monica, California, July 1976.

24. Heckman, G.R., "Predictions of the Space Environment Services Center," Solar-Terrestrial Predictions Proceedings, Vol. 1., Richard F. Donnelly (Editor), National Oceanic and Atmospheric Administration, August 1979.

APPENDIX

Figures A-1 and A-2 (Reference A-1) show typical electron and proton flux contours at an altitude of 400 km. Figures A-3 and A-4 (Reference A-2) indicate the electron and proton flux variation with altitude and inclination. Figures A-5, A-6, and A-7 (Reference A-3) indicate daily electron flux averages and experimental/model comparisons, respectively. Figures A-8 and A-9 (Reference A-4) show geomagnetic shielding factors and the effect of the spectrum of cosmic-ray iron nuclei.

Figure A-10 (Reference A-5) shows the solar electromagnetic spectrum and perturbations that accompany flares. Figure A-11 (Reference A-5) indicates solar flare events relative to solar cycles. Figures A-12 through A-15 (Reference A-6) indicate dose for various altitudes and shield thicknesses. Figure A-16 (Reference A-7) shows the different attenuation character of one-dimensional shield geometries for electrons.

Table A-1 (Reference A-6) lists the effects of whole-body dose. Table A-2[1] gives the flight rules for radiation control on Shuttle flights. Table A-3 (Reference A-8) summarizes the dose received on various United States manned spaceflights.

---

[1]Hardy, A.C., personal communication, October 1982.
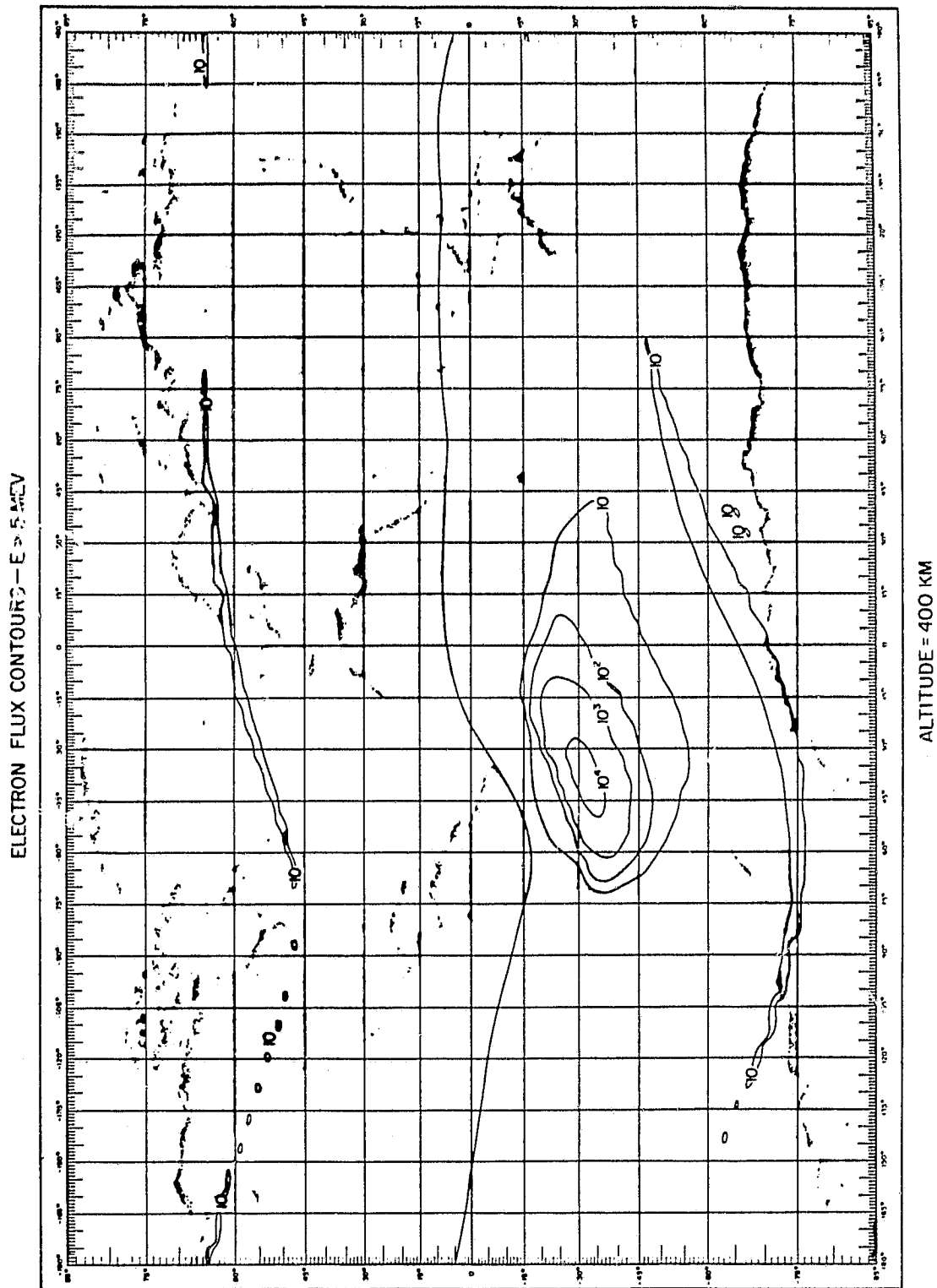
Figure A-1. Electron Flux Contours (Source: Reference A-1)
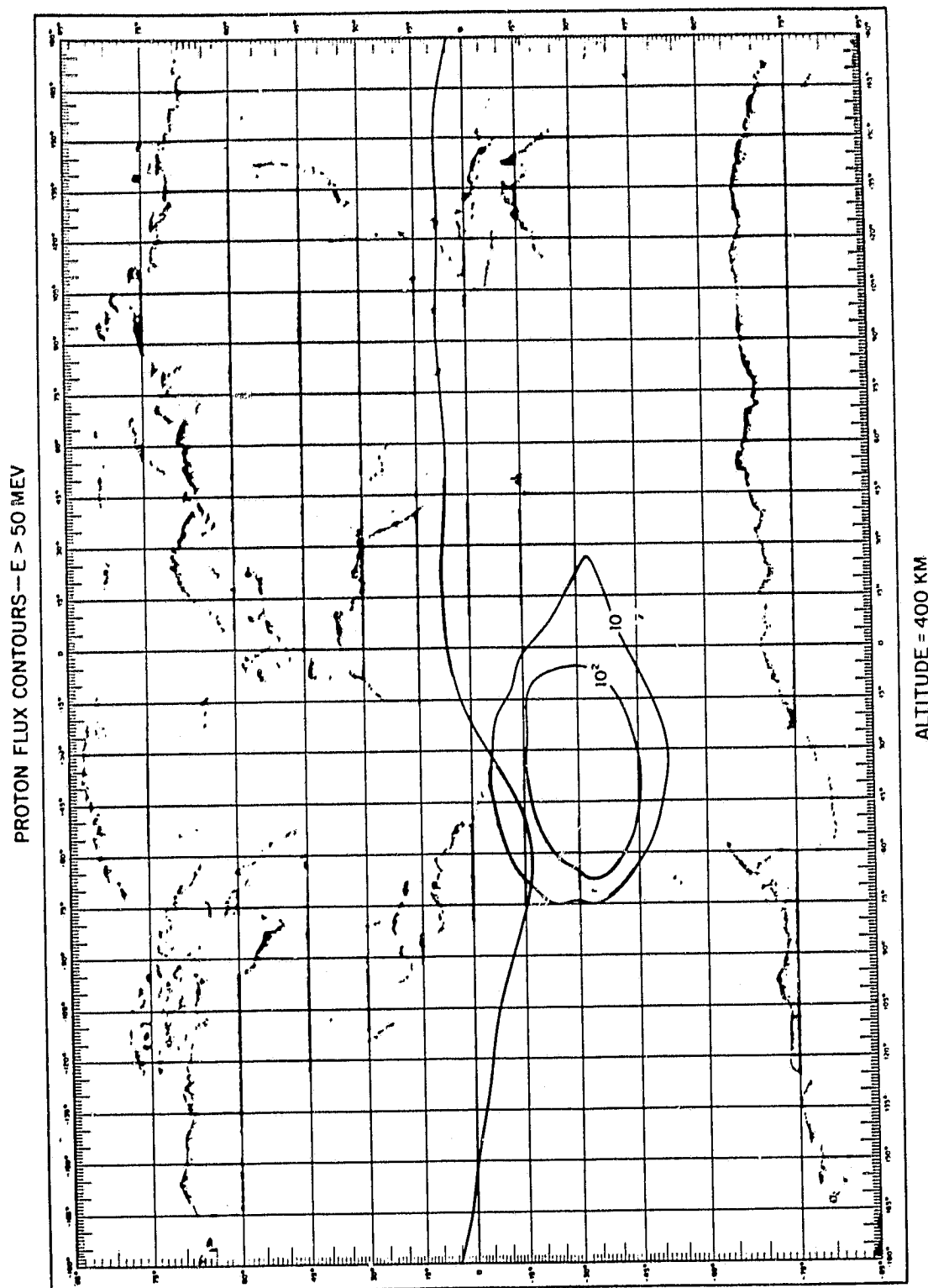
Figure A-2. Proton Flux Contours (Source: Reference A-1)

Figure A-3.   Electron Distribution in the Earth's Field
              (Source: Reference A-2)

Figure A-4.   Proton Distribution in the Earth's Field
              (Source: Reference A-2)
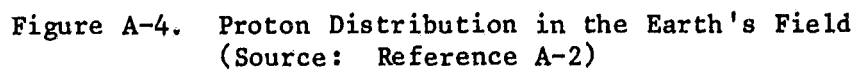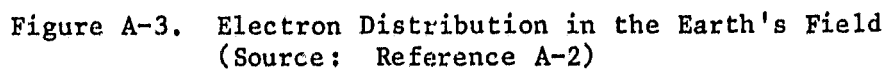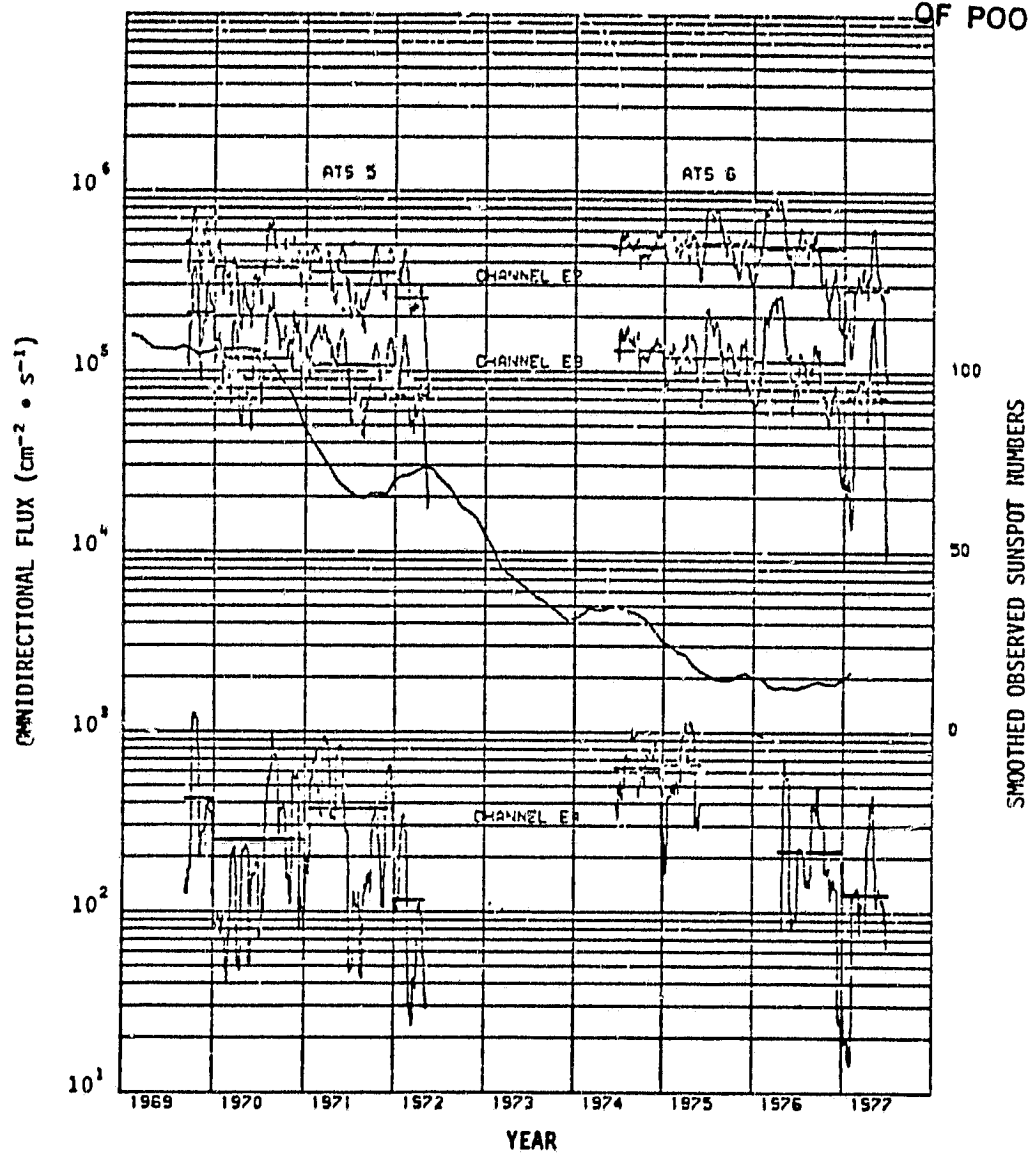
Figure A-5. ATS 5 and ATS 6 Daily Flux Averages With Sunspot Numbers
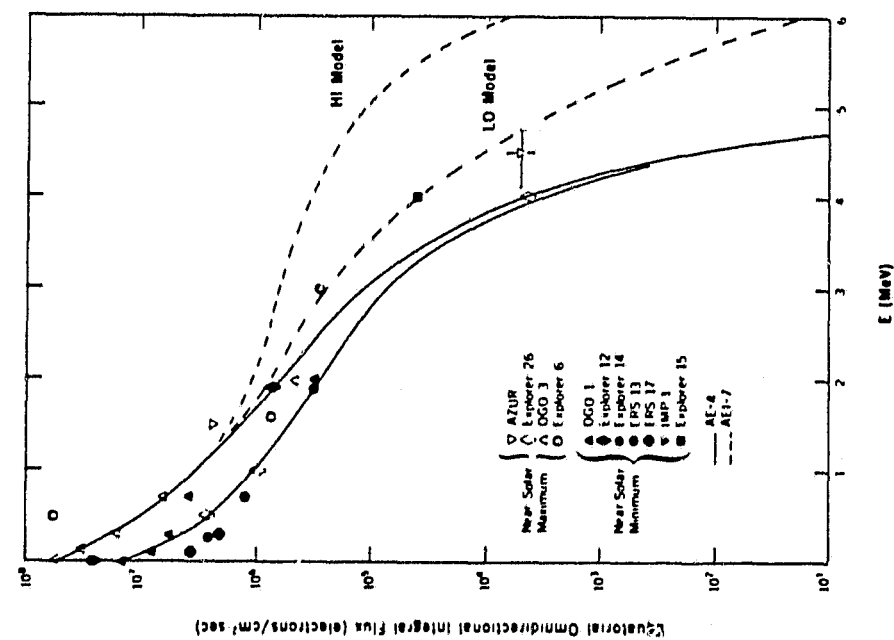   (Source: Reference A-3)

Figure A-7. Comparison of AEI-7 Model Spectra With Various Data Set at L = 6.6 (Source: Reference A-3)

Figure A-6. Comparison of AEI-7 Model Spectra With Various Data Set at L = 4. The HI model curve is mainly based on the OV1-19 observations from Vampola (Source: Reference A-3)
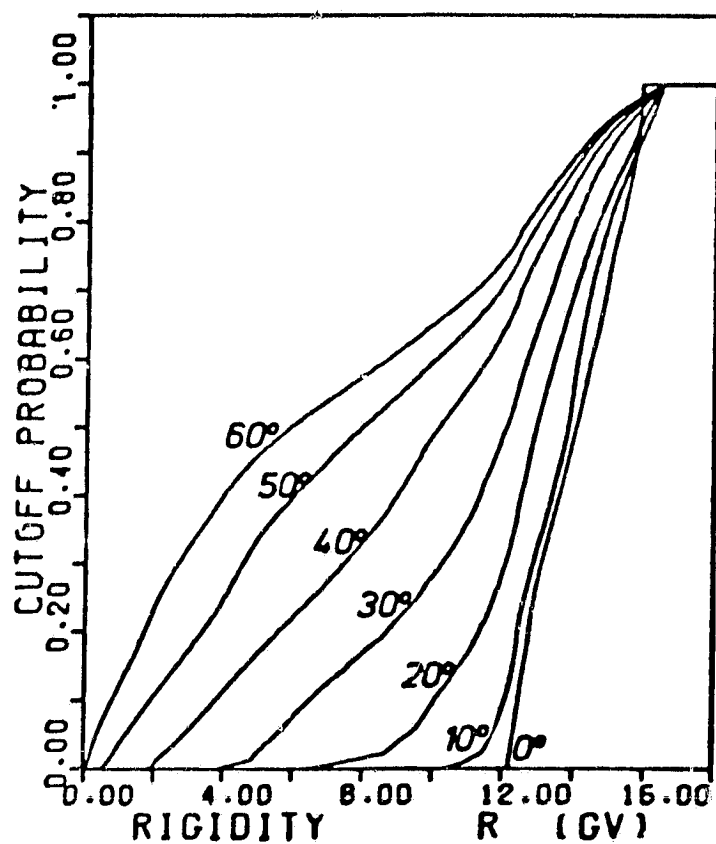
Figure A-8. Geomagnetic Sheilding Factors at 223 km
(Source: Reference A-4)
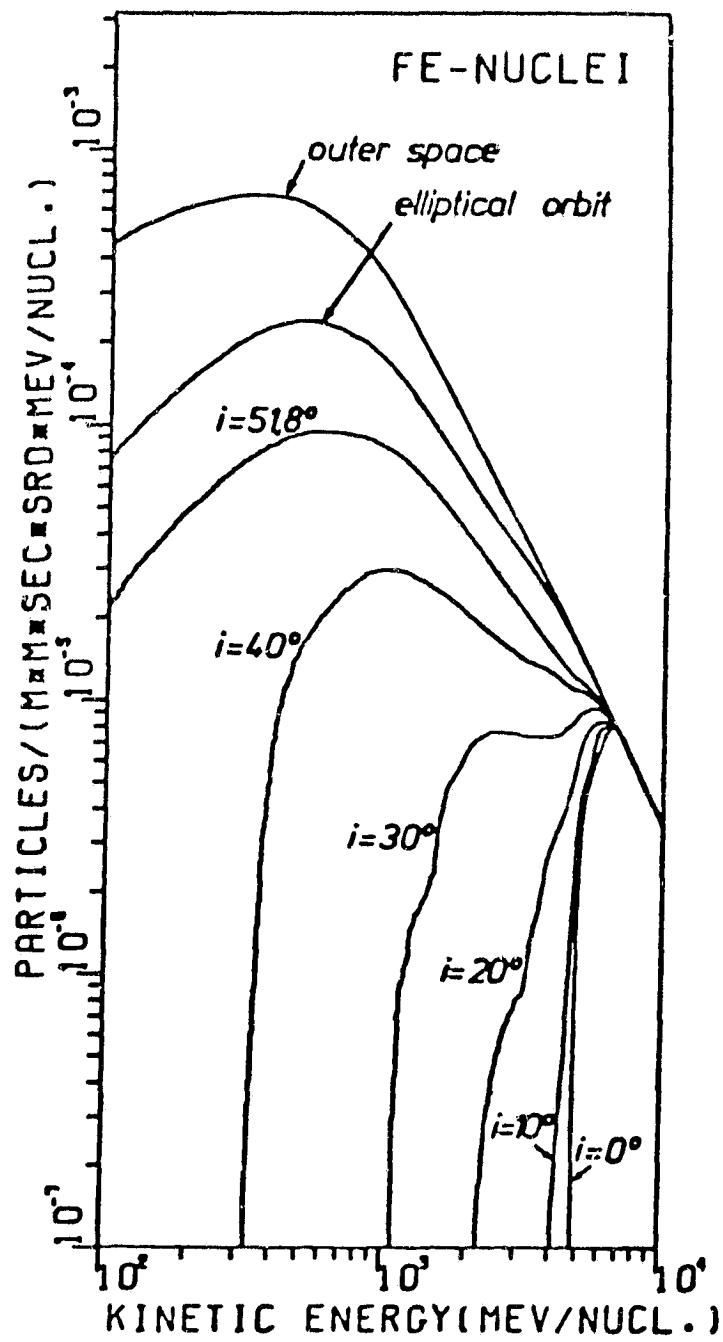
Figure A-9. Geomagnetically Shielded Iron Spectra
(Source: Reference A-4)
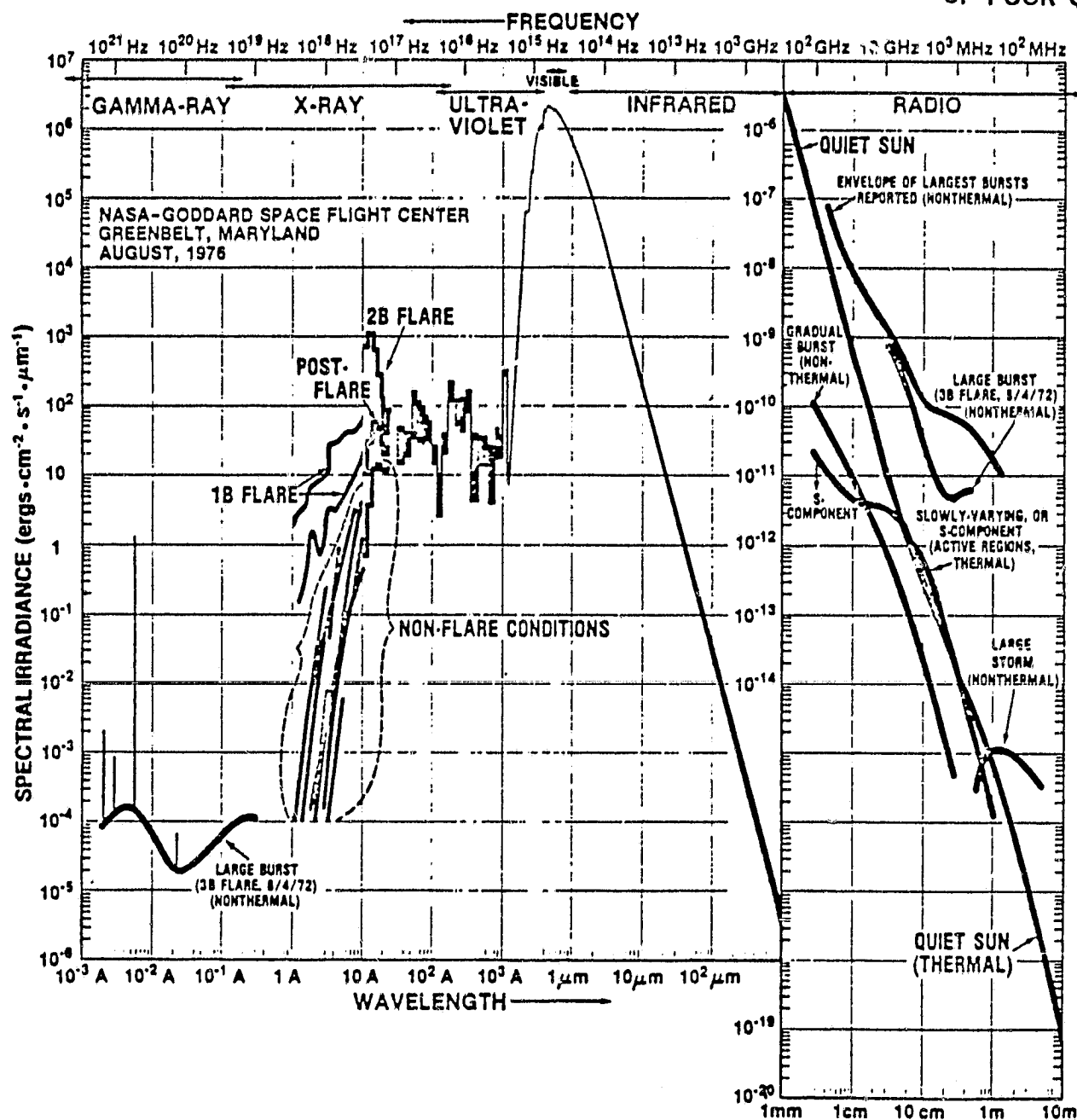
Figure A-10.   The Solar Spectrum
(Source: Reference A-5)
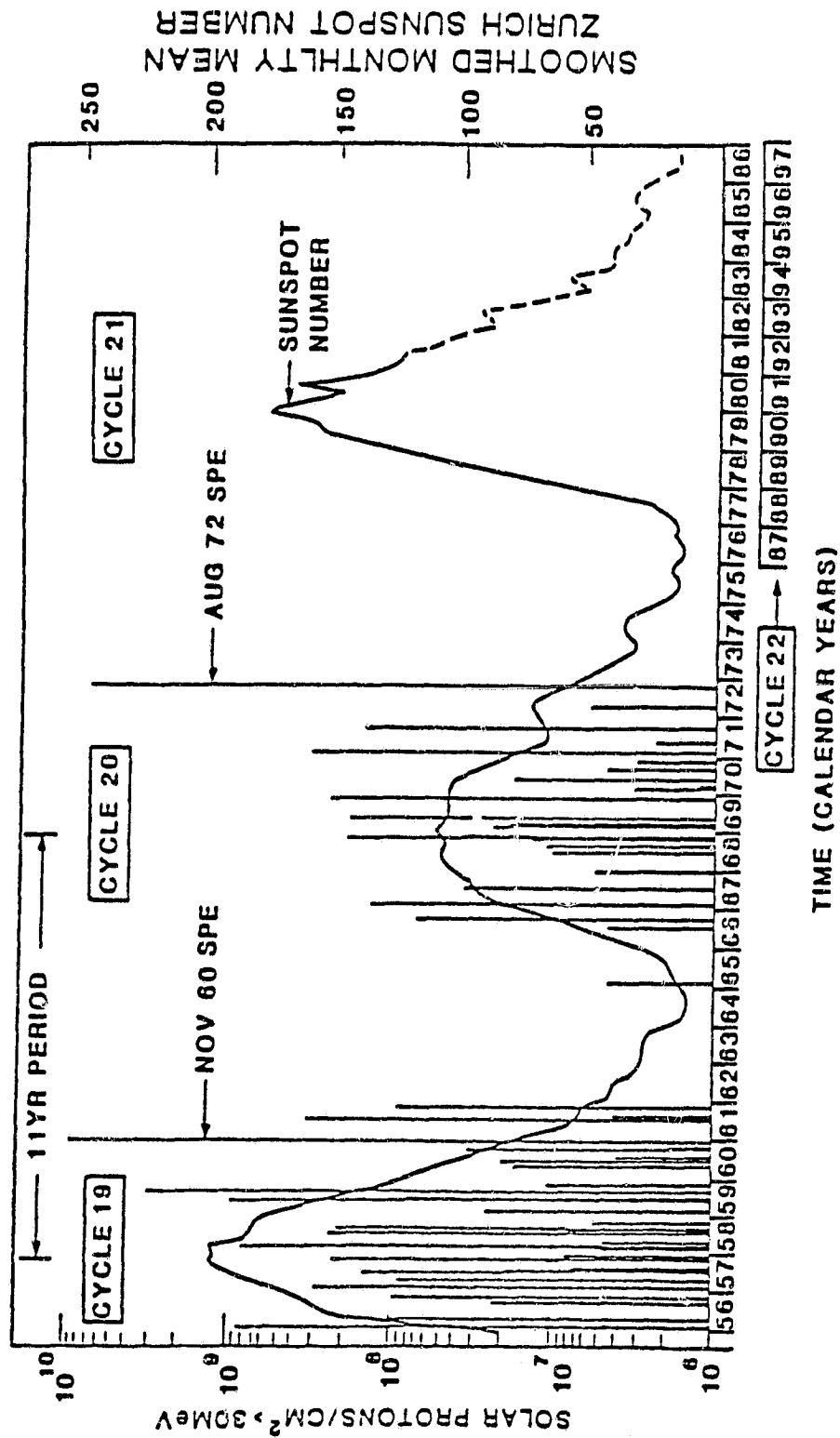
Figure A-11. Solar Activity (Source: Reference A-5)
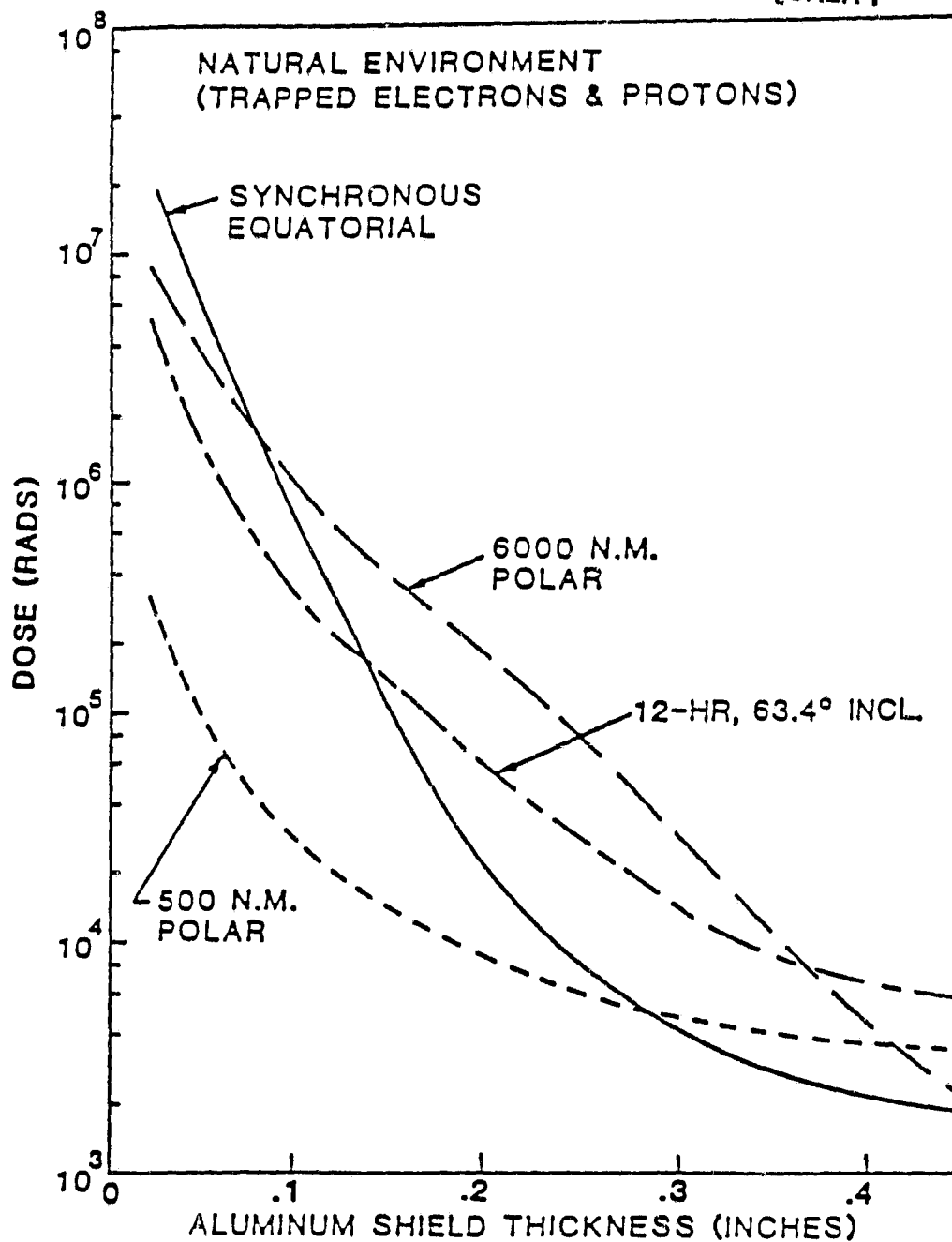
Figure A-12.   Dose versus Spherical Aluminum Shield Thickness for 5-year
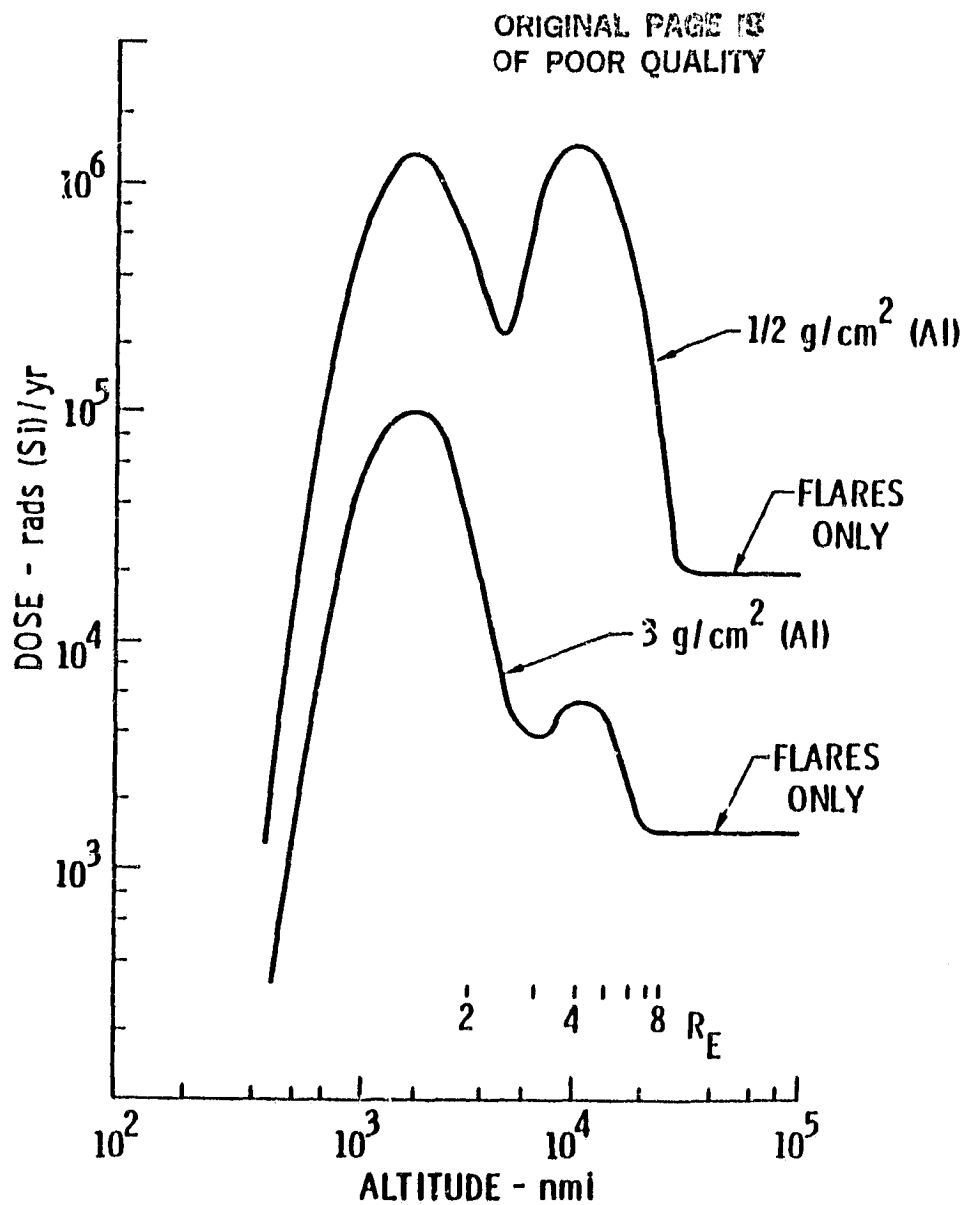Mission Lifetime in Various Orbits (Source: Reference A-6)

Figure A-13.   Dose versus Altitude for 0-deg Inclination, Circular
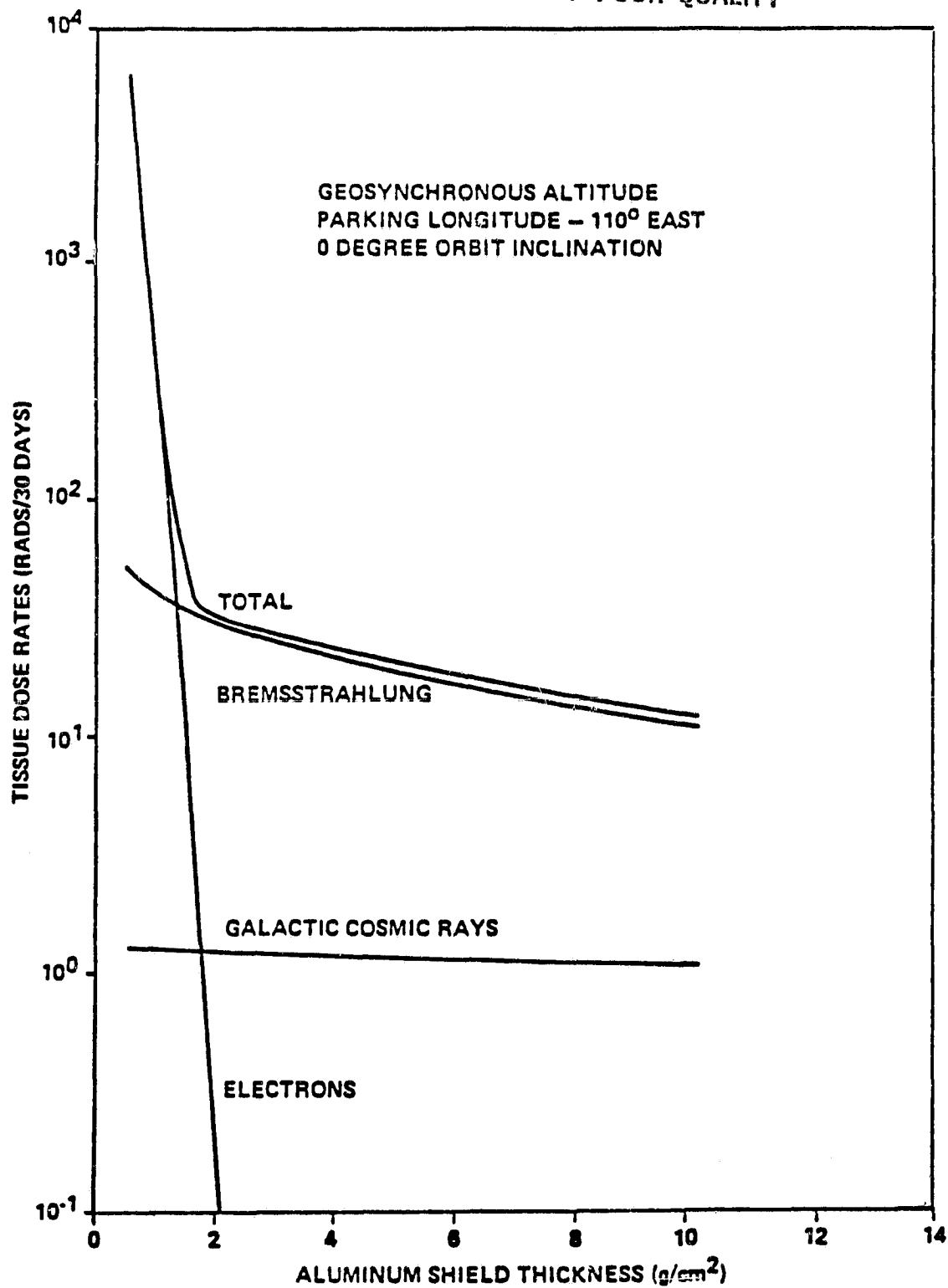Orbits Using Spherical Shielding Geometry
(Source: Reference A-6)

Figure A-14. Geosynchronous Dose versus Shield Thickness
(Source: Reference A-6)

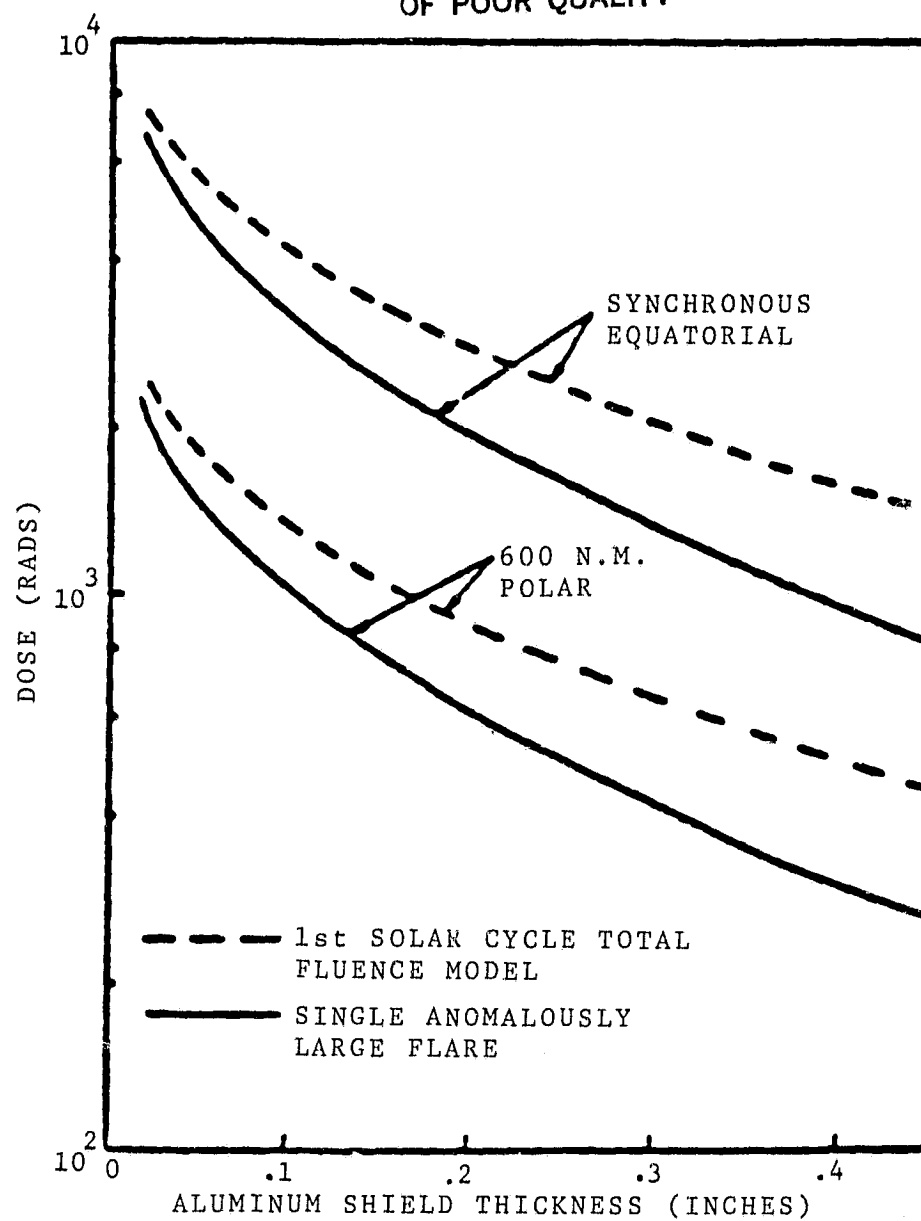Figure A-15.   Dose from Solar Flare Protons versus Spherical Aluminum
Shield Thickness (Source: Reference A-6)
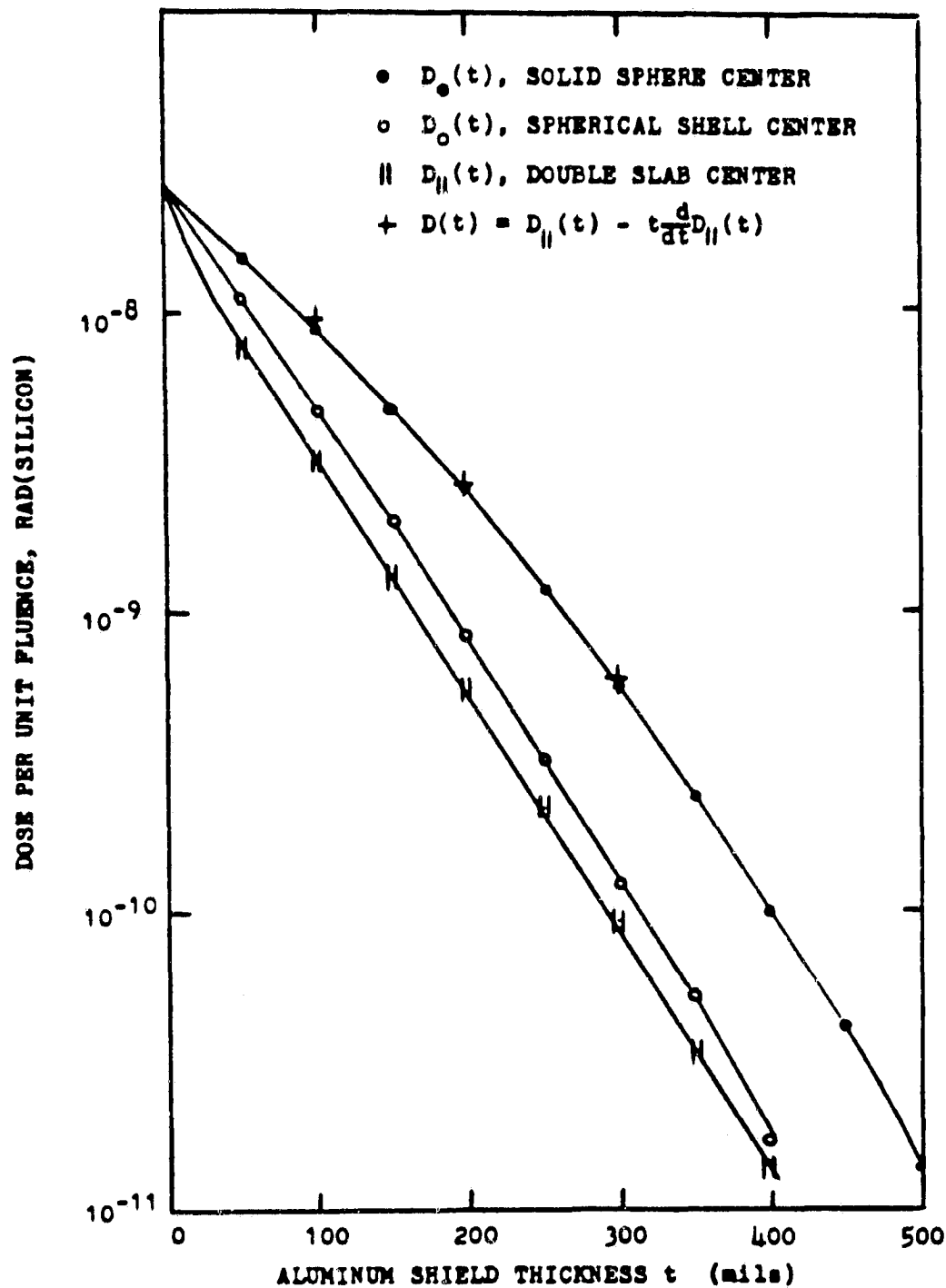
Figure A-16.   Fission Electron Dose Attentuation
(Source: Reference A-7)

Table A-1. Expected Effects of Acute Whole-Body Radiation Doses
(Source: Reference A-6)

ACUTE DOSE (REM)	PROBABLE EFFECT
0 TO 50	NO OBVIOUS EFFECT, EXCEPT POSSIBLE MINOR BLOOD CHANGES
80 TO 120	VOMITING AND NAUSEA FOR ABOUT 1 DAY IN 5 TO 10 PERCENT OF EXPOSED PERSONNEL. FATIGUE BUT NO SERIOUS DISABILITY
130 TO 170	VOMITING AND NAUSEA FOR ABOUT 1 DAY, FOLLOWED BY OTHER SYMPTOMS OF RADIATION SICKNESS IN ABOUT 25 PERCENT OF PERSONNEL. NO DEATHS ANTICIPATED
180 TO 220	VOMITING AND NAUSEA FOR ABOUT 1 DAY, FOLLOWED BY OTHER SYMPTOMS OF RADIATION SICKNESS IN ABOUT 50 PERCENT OF PERSONNEL. NO DEATHS ANTICIPATED
270 TO 330	VOMITING AND NAUSEA IN NEARLY ALL PERSONNEL ON FIRST DAY, FOLLOWED BY OTHER SYMPTOMS OF RADIATION SICKNESS. ABOUT 20 PERCENT DEATHS WITHIN 2 TO 6 WEEKS AFTER EXPOSURE; SURVIVORS CONVALESCENT FOR ABOUT 3 MONTHS
400 TO 500	VOMITING AND NAUSEA IN ALL PERSONNEL ON FIRST DAY, FOLLOWED BY OTHER SYMPTOMS OF RADIATION SICKNESS. ABOUT 50 PERCENT DEATHS WITHIN 1 MONTH. SURVIVORS CONVALESCENT FOR ABOUT 6 MONTHS
500 TO 750	VOMITING AND NAUSEA IN ALL PERSONNEL WITHIN 4 HOURS FROM EXPOSURE, FOLLOWED BY OTHER SYMPTOMS OF RADIATION SICKNESS. UP TO 100 PERCENT DEATHS; FEW SURVIVORS CONVALESCENT FOR ABOUT 6 MONTHS
1000	VOMITING AND NAUSEA IN ALL PERSONNEL WITHIN 1 TO 2 HOURS. PROBABLY NO SURVIVORS FROM RADIATION SICKNESS
5000	INCAPACITATION ALMOST IMMEDIATELY. ALL PERSONNEL WILL BE FATALITIES WITHIN 1 WEEK

Table A-2.   NASA-Johnson Space Center Flight Rules[a]

R	ITEM	

SECTION 14 - SPACE ENVIRONMENT

GENERAL

14-1   DEFINITIONS:

A.   IMPENDING ARTIFICIAL EVENT - AN ARTIFICIAL EVENT THAT IS PREDICTED BY ANY SOURCE.

B.   UNCONFIRMED ARTIFICIAL EVENT - AN ARTIFICIAL EVENT NOT CONFIRMED BY THE PROPER SUPPORT DATA SOURCE.

C.   CONFIRMED ARTIFICIAL EVENT - AN ARTIFICIAL EVENT THAT IS REPORTED BY THE PROPER SUPPORT DATA SOURCE AND THAT MEETS THE PREDETERMINED CRITERIA FOR DETONATION MAGNITUDE, ALTITUDE, AND GEOGRAPHIC POSITION.

D.   PROJECTED OPERATIONAL DOSE LIMIT VIOLATION - A DOSE EXTRAPOLATION THAT VIOLATES AN OPERATIONAL LIMIT (BASED UPON ANALYTICAL PROJECTIONS WITH ACCUMULATION RATES CONFIRMED BY ONBOARD DOSIMETRY READOUT).

E.   MAJOR SOLAR FLARE - A RADIO NOISE LEVEL $\geq$ 500 FLUX UNITS ABOVE BACKGROUND OR A FLARE AREA $\geq$ 15 SQUARE DEGREES.

F.   ENHANCED RADIATION - WHEN THE OBSERVED RADIATION RATES ARE HIGHER THAN THE NOMINAL EXPECTED RATES.

RULES 14-2 THRU 14-5 ARE RESERVED.

STS-2	BASIC	7/1/81	14	SPACE ENVIRONMENT	GENERAL	14-1
MISSION	REV	DATE		SECTION	GROUP	PAGE NO.

[a]Source: Hardy, A.C., personal communication, October 1982.

Table A-2.   NASA-Johnson Space Center Flight Rules (Cont'd)

R	ITEM	

MANAGEMENT

14-6   ALL CREW SAFETY DECISIONS WILL BE BASED ON CONFIRMED MEASUREMENTS AND/OR EVENTS AND PROJECTIONS BASED ON CONFIRMED EVENTS. A CONFIRMED EVENT IS DEFINED AS AN EVENT THAT HAS BEEN MEASURED BY TWO OR MORE INDEPENDENT SOURCES. A CONFIRMED ARTIFICIAL EVENT IS BY DEFINITION CONFIRMED.

14-7   THE EXISTING AND PROJECTED DOSE WILL BE ASSESSED PRIOR TO THE FOLLOWING GO/NO-GO DECISIONS AS RADIATION CONDITIONS DICTATE.

  ● LAUNCH

14-8   THE FOLLOWING OPERATIONAL CREW EXPOSURE LIMITS WILL BE ADHERED TO:

EXPOSURE LIMITS (REM)

CONSTRAINT	BONE MARROW (5 CM)	SKIN (0.1 MM)	EYE (3 MM)
30 DAY MAX	25	75	37
QUARTERLY MAX	35	105	52
YEARLY MAX	75	225	112
CAREER LIMIT	400	1200	600

14-9   IF A POCKET CHAMBER DOSIMETER READING DIFFERS FROM EXPECTED VALUES IN AN INCONSISTENT MANNER FOR MORE THAN 3 CONSECUTIVE READOUTS, DISCONTINUE CREW READOUT FROM THAT FAILED POCKET CHAMBER DOSIMETER.

STS-2	BASIC	7/1/81	14	SPACE ENVIRONMENT	MGMT	14-2
MISSION	REV	DATE		SECTION	GROUP	PAGE NO.

Table A-2.   NASA-Johnson Space Center Flight Rules (Cont'd)

R   ITEM

SPECIFIC

RADIATION CONDITION	FLIGHT PHASE		
	PRELAUNCH	ORBITAL	EVA
AN IMPENDING ARTIFICIAL EVENT	①	①	①
AN UNCONFIRMED ARTIFICIAL EVENT HAS BEEN REPORTED	①	①	①
A CONFIRMED ARTIFICIAL EVENT HAS OCCURRED	② ⑤	③ ④ ⑤	③ ⑤
PROJECT OPERATIONAL DOSE LIMIT VIOLATION	⑤	⑤	⑤
CONFIRMED MAJOR SOLAR FLARE	③	③	③
CONFIRMED ENHANCED RADIATION ENVIRONMENT INDICATED FROM ONBOARD DOSIMETRY	N/A	③	③

NOTES: ① PURSUE CONFIRMATION FROM ALL DATA SOURCES

② HOLD LAUNCH

③ PURSUE MAXIMUM DATA RECOVERY FROM SPACECRAFT INSTRUMENTATION AND/OR OTHER SOURCES

④ CONSIDER MISSION CHANGE TO LOWER DOSE WITHOUT INCREASING TOTAL RISK TO CREW (LOWER ALTITUDE, AVOID HIGH RATE CREW STATIONS, ETC)

⑤ NASA MANAGEMENT RISK VS GAIN DECISION REQUIRED

STS-2	BASIC	7/1/81	14	SPACE ENVIRONMENT	SPECIFIC	14-3
MISSION	REV	DATE		SECTION	GROUP	PAGE NO.

Table A-3.   Dosimetry Data from United States Manned Spaceflights*
(Source: Reference A-8)

Flight	Duration (hr)	Inclination (deg)	Apogee-Perigee (km)	Average Dose (mrad)	Average Dose Rate (mrad/day)
Gemini 4	97.25	32.5	296 - 166	46	11
Gemini 6	25.25	28.9	311 - 283	25	23
Apollo 7*	260.1			160	15
Apollo 8*	147		lunar orbital flight	160	26
Apollo 9*	241			200	20
Apollo 10*	192		lunar orbital flight	480	60
Apollo 11*	194		lunar orbital flight	180	22
Apollo 12*	244.5		lunar orbital flight	580	57
Apollo 13*	142.9		lunar orbital flight	240	40
Apollo 14*	216		lunar orbital flight	1140	127
Apollo 15*	295		lunar orbital flight	300	24
Apollo 16*	265.8		lunar orbital flight	510	46
Apollo 17*	301.8		lunar orbital flight	550	44
Skylab 2**	28 days	50	alt = 435	1596	57 $\pm$ 3
Skylab 3**	59 days	50	alt = 435	3835	65 $\pm$ 5
Skylab 4**	90 days	50	alt = 435	7740	86 $\pm$ 9
ASTP	9 days	50	alt = 220	106	12
STS-1	54 hrs	40.3	alt = 280	⁻20	8.9
STS-2	57.5 hrs	38	alt = 240	11.8 $\pm$ 1.8	5.0
STS-3	194.5 hrs	38	alt = 240	46.1 $\pm$ 2.6	5.7

* Doses quoted for the Apollo flights are skin doses. The doses to the blood-forming organs are approximately 40% lower than the values measured at the body surface.

** Mean thermoluminescent dosimeter (TLD) dose rates from crew dosimeters.

For orbital flights about the Earth, the dose rates vary from about 6 mrad/day for Space Transportation System No. 3 up to nearly 90 mrad/day for higher altitude and greater orbital inclination in Skylab 4. However, the exact shielding of dosimeters on STS-3 is not known. The average dose rate inside the heavily shielded film vault drawers B (16-30 g/cm²) and F (30-50 g/cm²) of Skylab 2 and 3 were 39.5 and 33.5 mrad/day respectively, suggesting that even very heavy shielding is ineffective in reducing the dose rate.

APPENDIX

REFERENCES

A-1.   Stassinopoulos, E.G., _World Maps of Constant B, L, and Flux Contours_, NASA-SP-3054, Washington, D.C., 1970.

A-2.   West, G.S., Jr., Wright, J.J., and Euler, H.C., _Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development_, NASA Technical Memorandum 78119, 1977 (Revision).

A-3.   Vette, James I., Chan, King W., and Teague, Michael J., _Problems in Modeling the Earth's Trapped Radiation Environment_, AFGL-TR-78-0130, Air Force Geophysics Laboratory, December 1977.

A-4.   Heinrich, W., and Spill, A., "Geomagnetic Shielding of Cosmic Rays for Different Satellite Orbits," COSPAR, Planetary Meeting, 1978.

A-5.   Reagan, Joseph B., "Solar Particle Events," _Space Systems and Technology Workshop II_, Natural Environments Panel, Billy M. McCormac (Chairman), September 1982.

A-6.   Rugge, H.R., "Space Radiation and Its Possible Effects on Man in Space," _Space Systems and Technology Workshop II_, Natural Environments Panel, Billy M. McCormac (Chairman), September 1982.

A-7.   Jordan, T.M., "Adjoint Monte Carlo Electron Shielding Calculations," _ANS Transactions_, Vol. 41, June 1982.

A-8.   Benton, E.V., and Henke, R.P., "Radiation Exposure During Spaceflight and Their Measurement," to appear in _Space Research_, Spring or Summer 1983.