

The University of Chicago
Pioneer 10/11 Low Energy Telescope

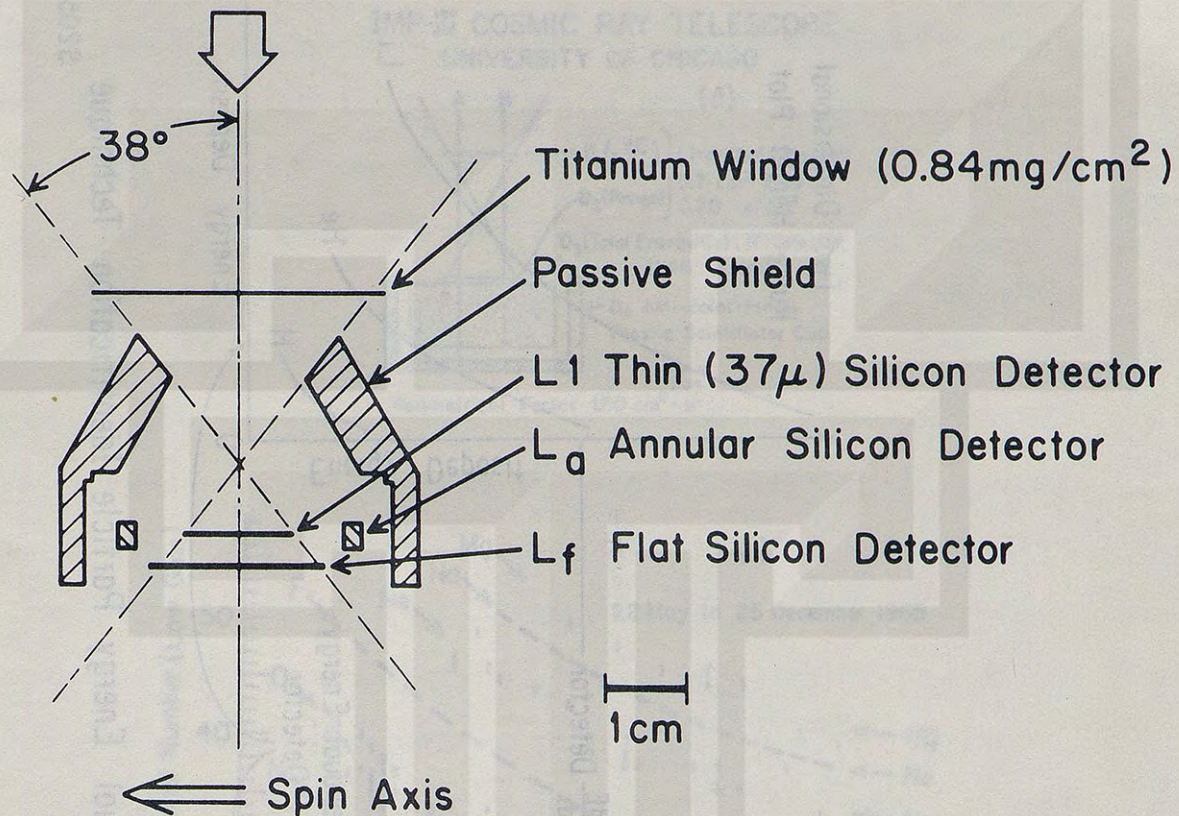


Figure 15: Schematic diagram of the low energy telescope employed in the Pioneer 10/11 experiments.

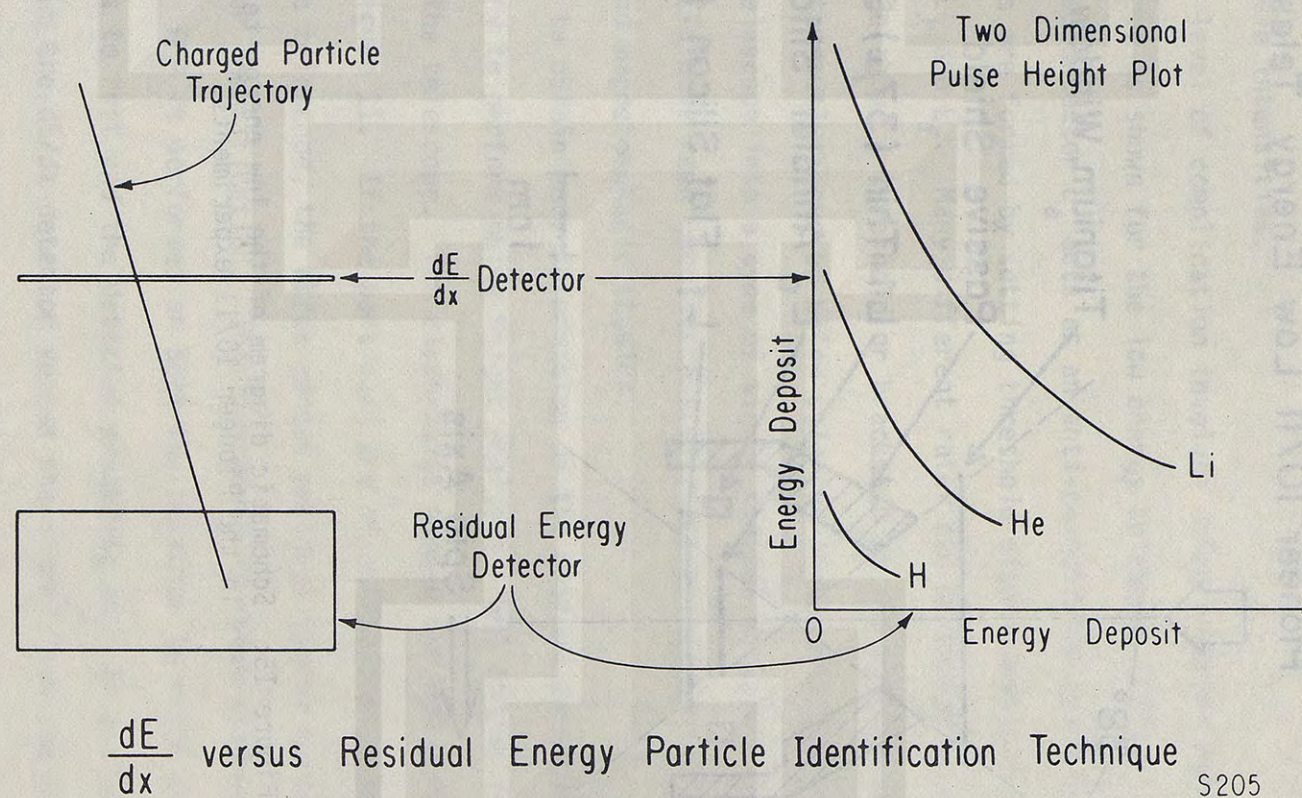


Figure 16: A schematic representation of particle identification by the dE/dx versus residual energy technique.

IMP-III COSMIC RAY TELESCOPE UNIVERSITY OF CHICAGO

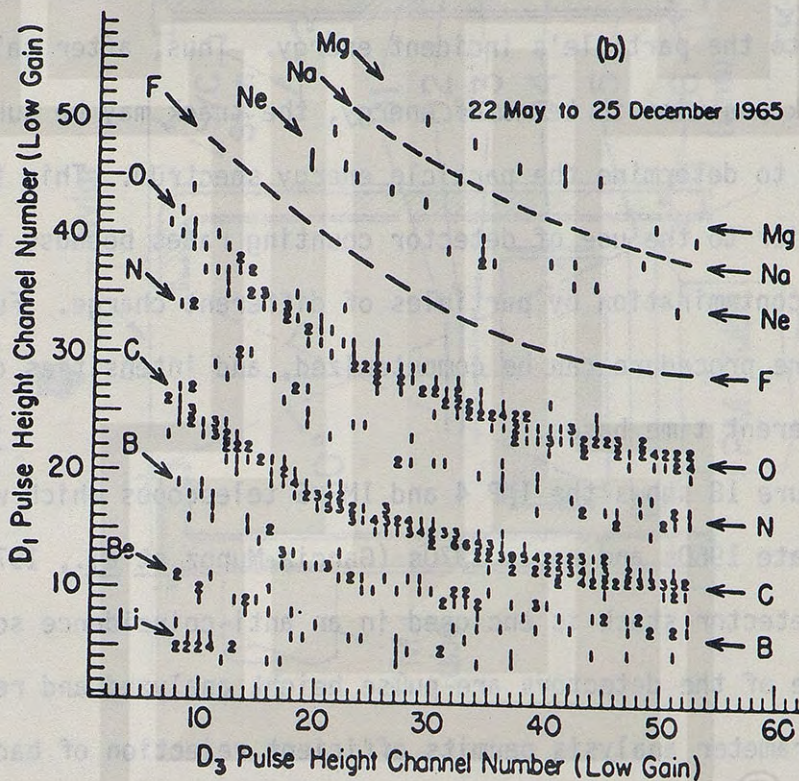
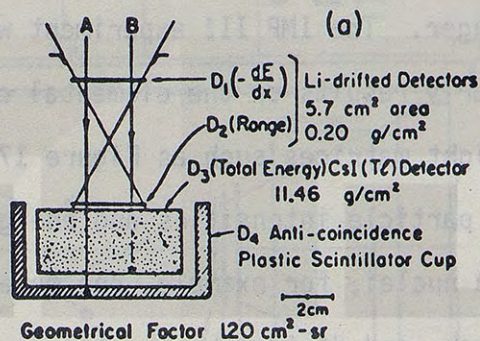


Figure 17: Part (a): diagram of the IMP III charged particle telescope.
Part (b): the dE/dx versus residual energy matrix obtained by IMP III in about 6 months of data collection.

D2 restricts the acceptance cone, and D4 is used in anti-coincidence to restrict analysis to particles that stop in the CsI (Tl) detector. The pulse height matrix reveals good charge resolution with little "background" for elements through oxygen, but the statistics for heavier nuclei are meager. The IMP III experiment was quite successful, providing some of the early results on the elemental composition of heavy nuclei.

Pulse height matrices such as Figure 17 can also be used to obtain clean data on particle intensities and energy spectra. To obtain the flux of carbon nuclei, for example, one merely counts the events within the carbon track, and divides by the time and the instrument geometrical factor. The position of a given event along the carbon track is directly related to the particle's incident energy. Thus, after calibrating the track position in terms of energy, the track may be subdivided and used to determine the particle energy spectrum. This technique is superior to the use of detector counting rates because it is relatively free of contamination by particles of different charge. Further, the entire procedure can be computerized, and intensities calculated for different time bases.

Figure 18 shows the IMP 4 and IMP 5 telescopes which were flown in the late 1960s and early 1970s (Garcia-Munoz et al., 1973). The entire detector stack is enclosed in an anti-coincidence scintillator and three of the detectors are pulse height analyzed and recorded. Three parameter analysis permits efficient rejection of background events and increased confidence in the charge measurements. The residual energy detector is a large CsI (Tl) scintillator viewed by photodiodes, which is divided into two separate pieces in the IMP 5 design. In

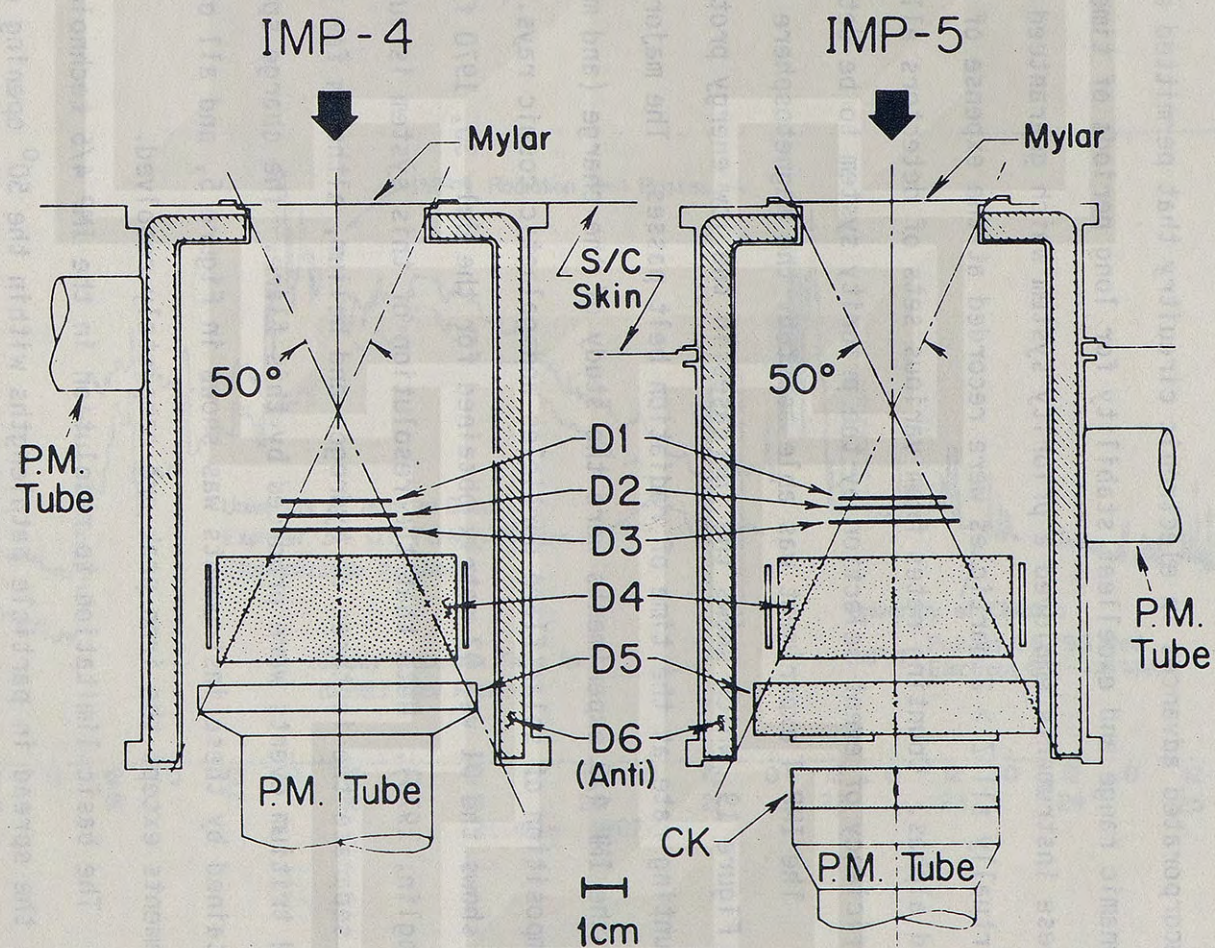


Figure 18: Diagram of the University of Chicago charged particle telescopes on-board the IMP 4 and IMP 5 spacecraft.

addition, IMP 5 incorporated a sapphire Cherenkov counter to extend the energy range over which measurements were made. Along with improvements in detector technology and telescope design, the IMP 4/5 instruments incorporated advances in electronic circuitry that permitted a wide dynamic range and excellent stability for long periods of time. Further, these instruments employed a priority system which guaranteed that virtually all $Z > 2$ particles were recorded at the expense of protons and alphas. Counting rates from various sets of detectors allow the efficiency of event selection by the priority system to be determined.

The IMP 4 experiment was able to study the magnetosphere as illustrated in Figure 19, which shows the increases in the low energy proton/electron counting rate at the time of radiation belt passes. The major objectives of the IMP 4/5 experiments were the study of the charge (and mass) composition of solar flare particles and galactic cosmic rays. Figure 20 shows the D1 vs. D2 matrix obtained for the July 30, 1970 flare (Anglin, 1975). Note that the resolution of this system is sufficient to separate the isotopes of hydrogen and helium, although few deuterium and tritium events were produced by this flare. The charge spectrum obtained by these instruments was shown in Figure 5, and all of the elements except the iron peak are completely resolved.

The basic limitation to resolution in the IMP 4/5 technology was the spread in particle pathlengths within the 50° opening cone of the telescopes. This pathlength variation leads to a broadening of the tracks in the matrix, and thereby limits the isotope resolution capability. Figure 21 shows the results of a Monte Carlo study of this pathlength distribution. For a flat detector, the deviation

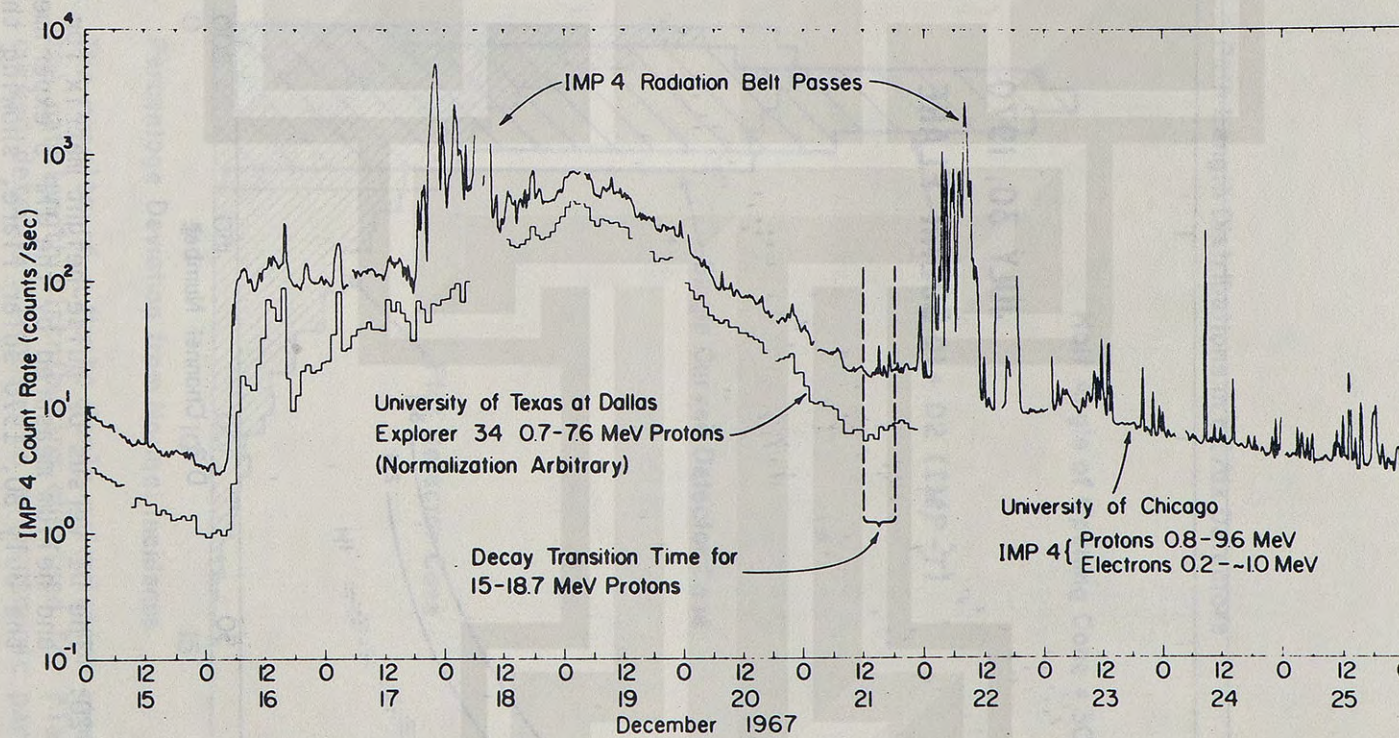


Figure 19: Time profile of the low energy proton/electron counting rate observed by the IMP 4 experiment compared to a similar rate measured by Explorer-34. Passes through the radiation belts are indicated.

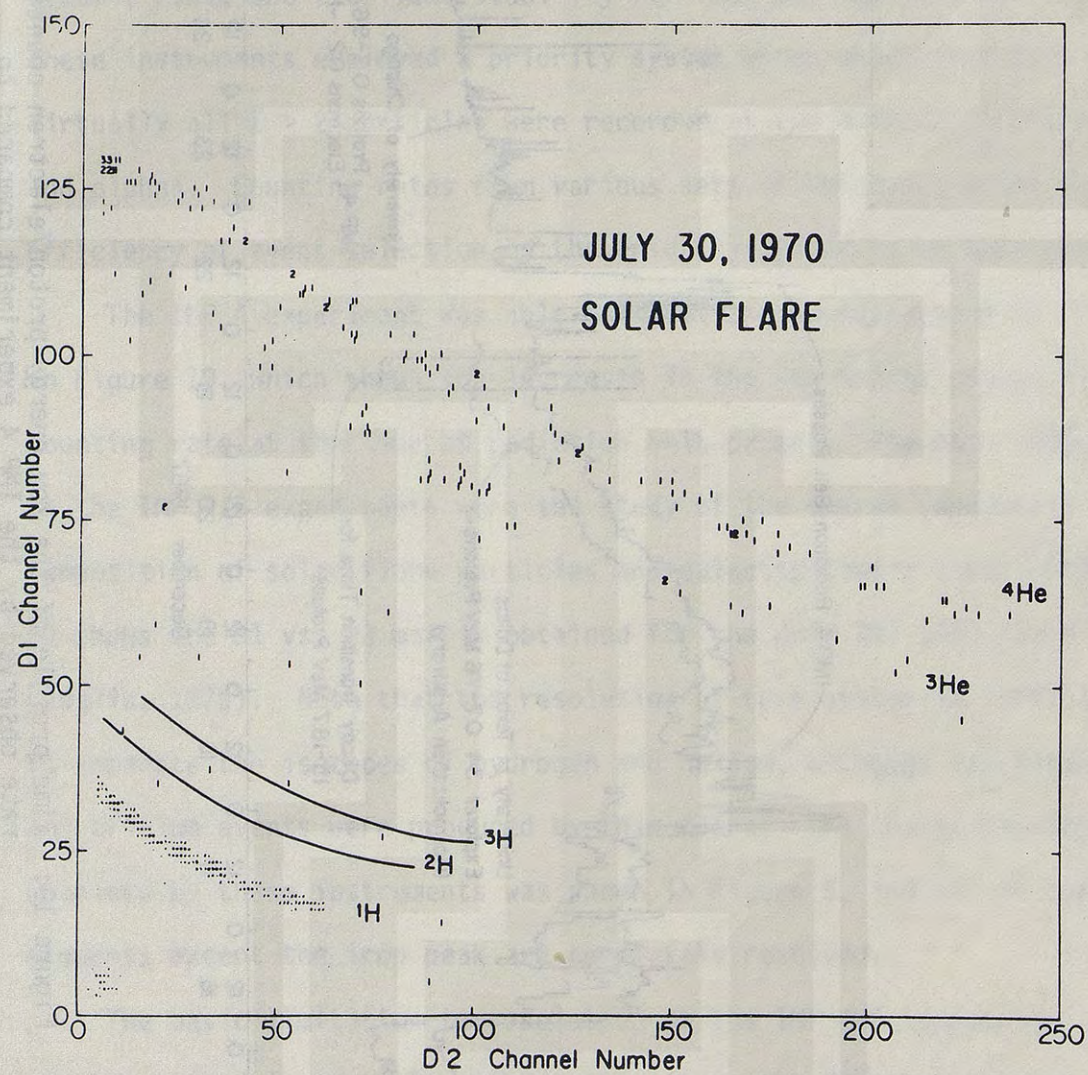


Figure 20: The D1 versus D2 pulse-height matrix for hydrogen and helium measured by the IMP 5 experiment for the July 30, 1970 solar flare, showing the separation of the isotopes of helium.

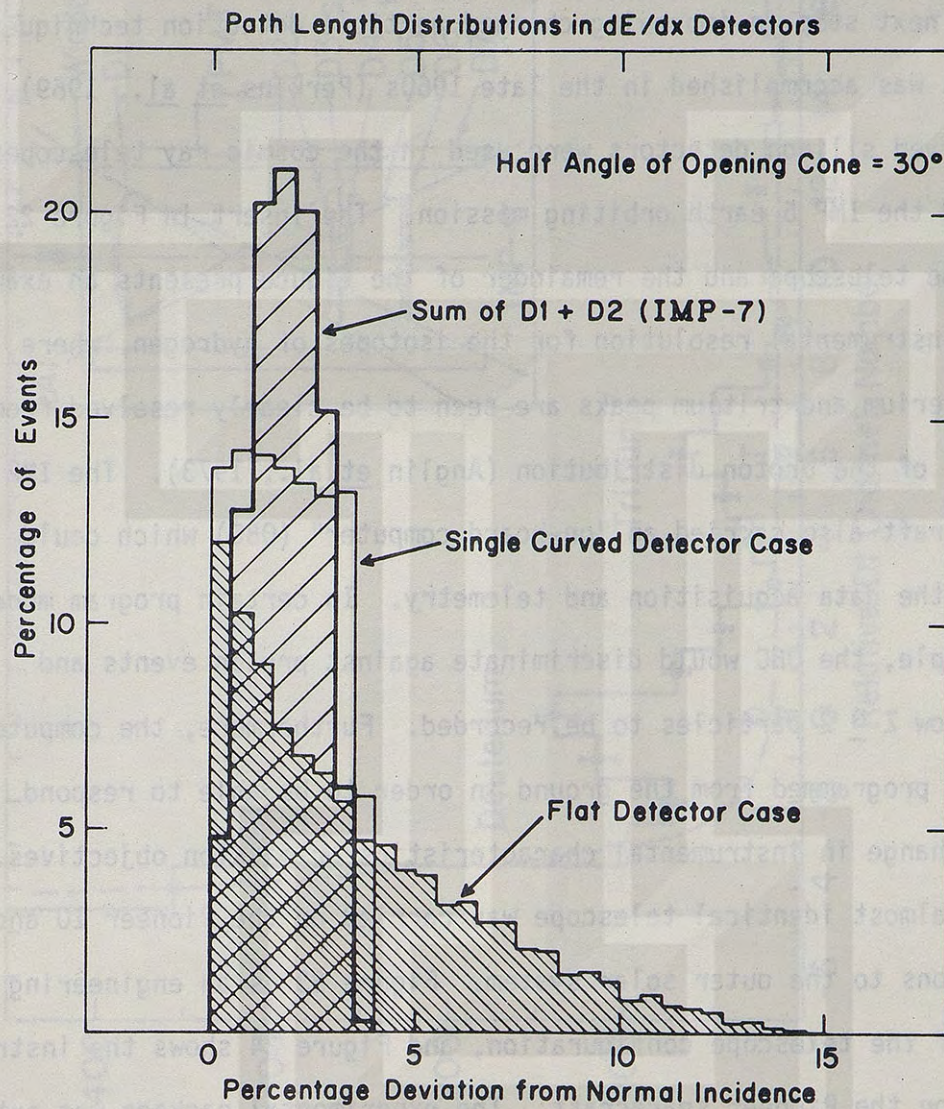


Figure 21: The results of a Monte Carlo calculation comparing the pathlength distribution obtained for flat and curved detectors exposed to an isotropic particle flux.

extends to about 15%. However, if the detectors are formed as sections of a sphere, the deviation is reduced to under 5% for a single detector and to about 4% if two curved detectors are used simultaneously. Thus, the development of a technology for constructing curved silicon detectors was the next step in improving charged particle detection techniques, and this was accomplished in the late 1960s (Perkins et al., 1969).

Curved silicon detectors were used in the cosmic ray telescopes on board the IMP 6 earth orbiting mission. The insert in Figure 22 shows the telescope and the remainder of the figure presents an example of the instrumental resolution for the isotopes of hydrogen, where the deuterium and tritium peaks are seen to be clearly resolved from the tail of the proton distribution (Anglin et al., 1973). The IMP 6 spacecraft also carried an "on-board computer" (OBC) which could control the data acquisition and telemetry. In certain program modes, for example, the OBC would discriminate against proton events and only allow $Z \geq 2$ particles to be recorded. Furthermore, the computer could be programmed from the ground in order to be able to respond to any change in instrumental characteristics or mission objectives.

An almost identical telescope was carried on the Pioneer 10 and 11 missions to the outer solar system. Figure 23 is an engineering sketch of the telescope configuration, and Figure 24 shows the instruments mounted on the Pioneer spacecraft. The experimental package was extremely small and light-weight, characteristic of all experiments on spacecraft to the outer solar system. Nevertheless, the Pioneer missions have been extremely productive in the study of Jupiter and its environs, for investigations of solar modulation and solar particle propagation,

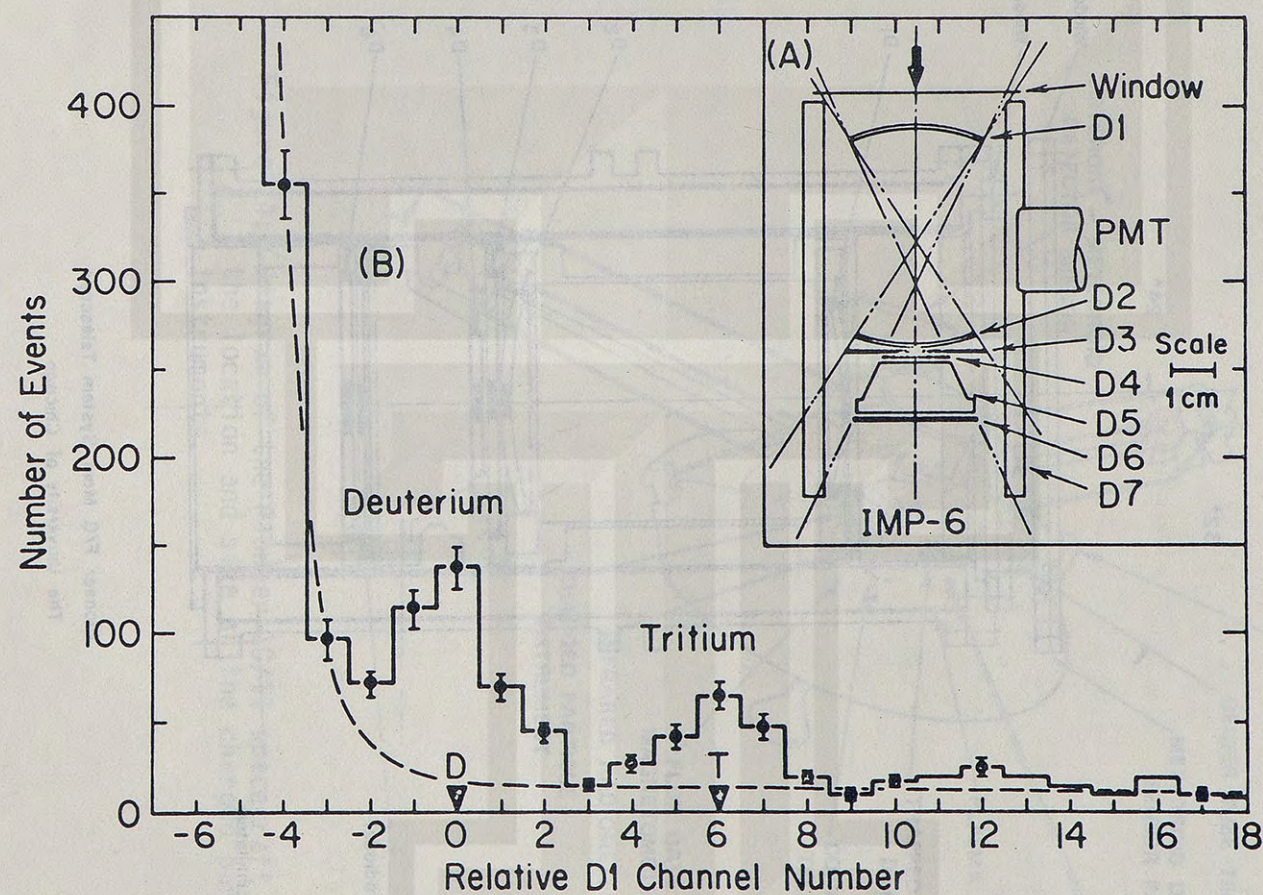


Figure 22: Part (a): diagram of the IMP 6 particle telescope employing curved silicon detectors.
 Part (b): results of the IMP 6 analysis of the isotopes of hydrogen showing separation of the deuterium and tritium peaks from the tail of the proton distribution.

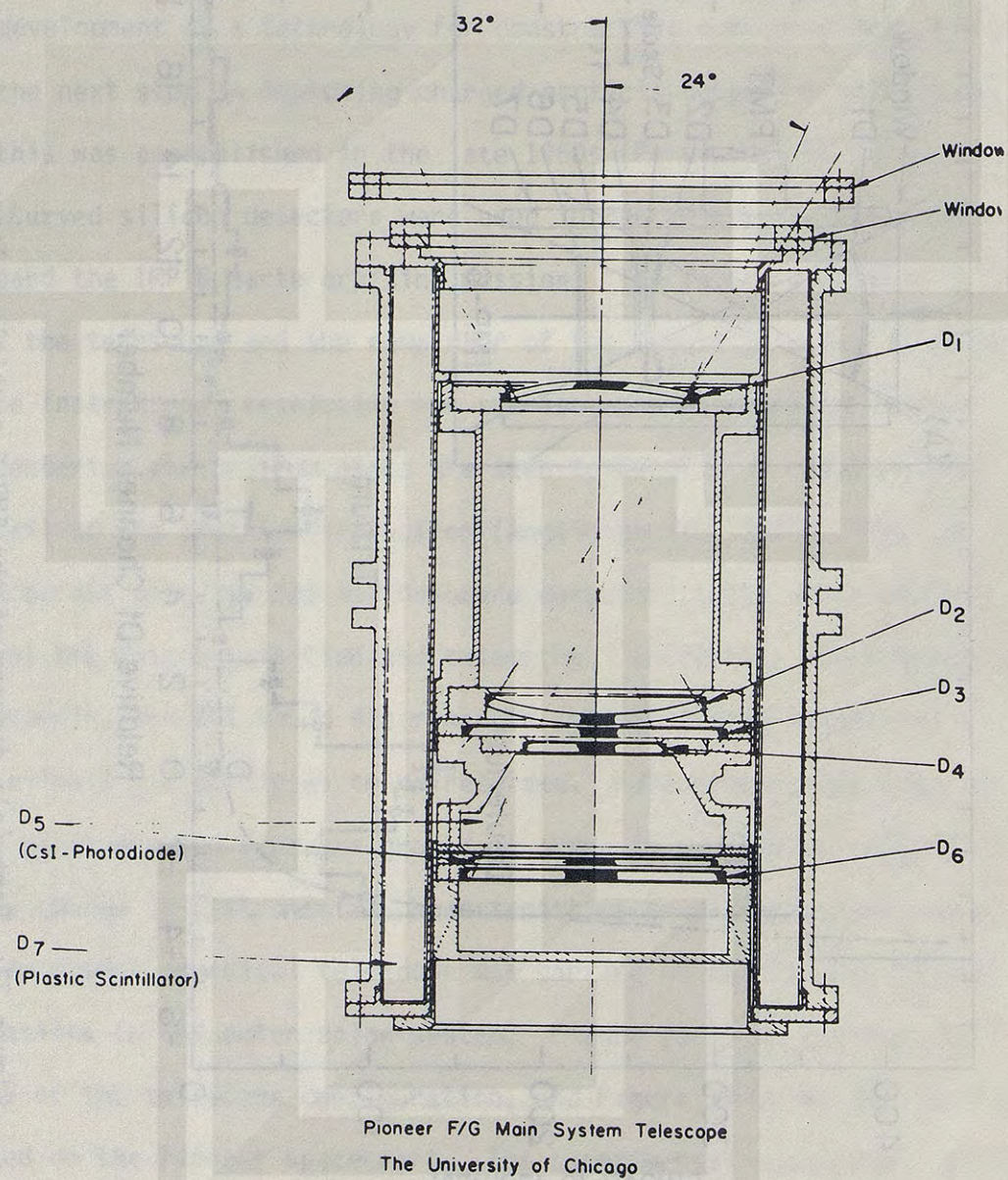


Figure 23: Mechanical assembly drawing for the University of Chicago Pioneer 10/11 (F/G) charged particle telescope.

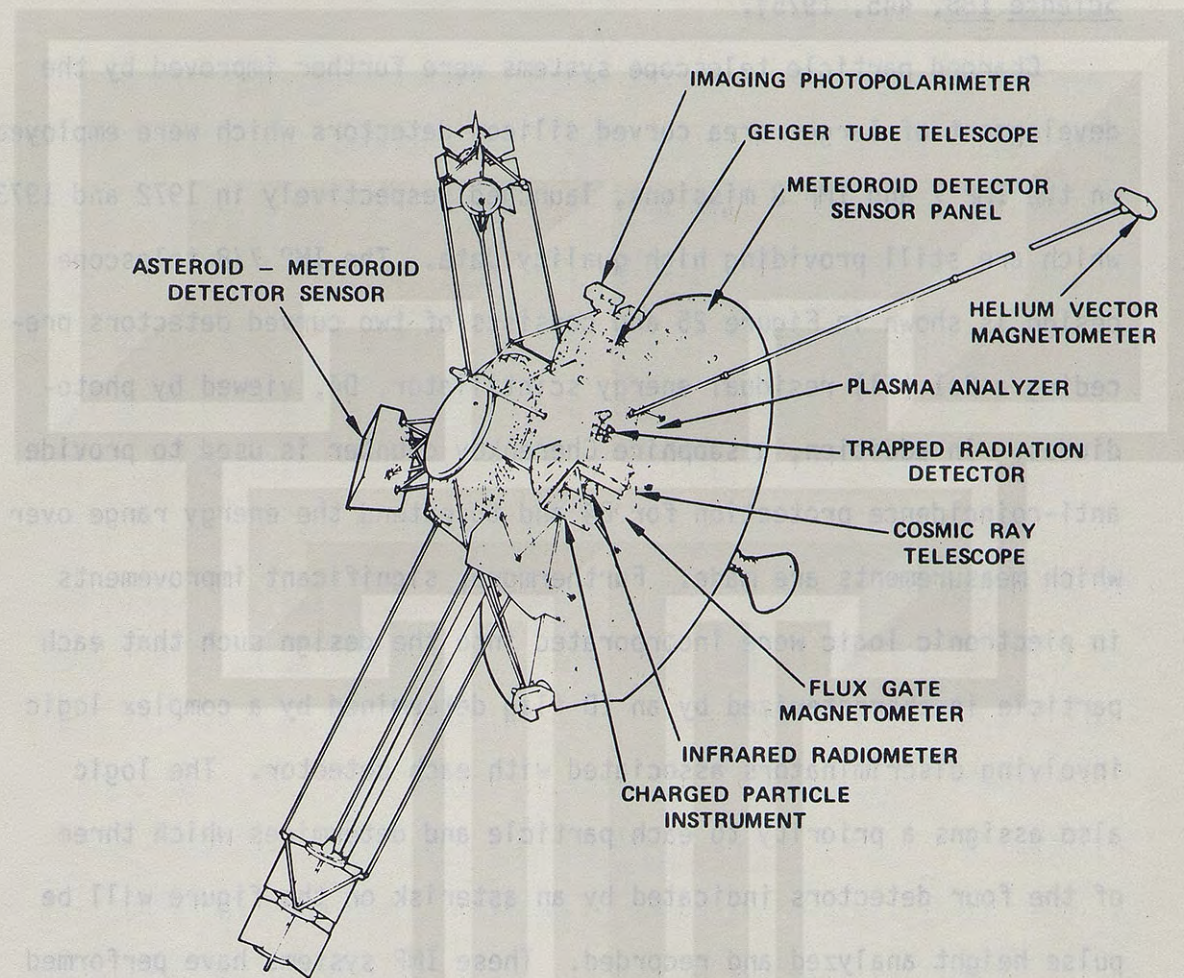


Figure 24: Diagram of the Pioneer 10/11 spacecraft indicating the location and size of the charged particle instruments.

and for the study of interplanetary processes (see the summary in Science 188, 445, 1975).

Charged particle telescope systems were further improved by the development of larger area curved silicon detectors which were employed on the IMP 7 and IMP 8 missions, launched respectively in 1972 and 1973, which are still providing high quality data. The IMP 7/8 telescope design is shown in Figure 25 and consists of two curved detectors preceding a CsI (Tl) residual energy scintillator, D4, viewed by photodiodes. In addition, a sapphire Cherenkov counter is used to provide anti-coincidence protection for D4 and to extend the energy range over which measurements are made. Furthermore, significant improvements in electronic logic were incorporated into the design such that each particle is characterized by an ID flag determined by a complex logic involving discriminators associated with each detector. The logic also assigns a priority to each particle and determines which three of the four detectors indicated by an asterisk on the figure will be pulse height analyzed and recorded. These IMP systems have performed quite well and yielded a wealth of data which is currently being analyzed.

An example of the data returned by the IMP 7/8 instruments is shown in Figure 26 where the left hand portion is the raw data matrix and the right side shows, for comparison, the location of various isotopes. The "knees" in the curves represent an amplifier gain switching point. The amplifiers each have three separate gain regions in order to achieve sufficient dynamic range to study all elements between hydrogen and nickel. With some imagination, separate tracks can be observed for the Be, B, and N isotopes, and over a limited range the

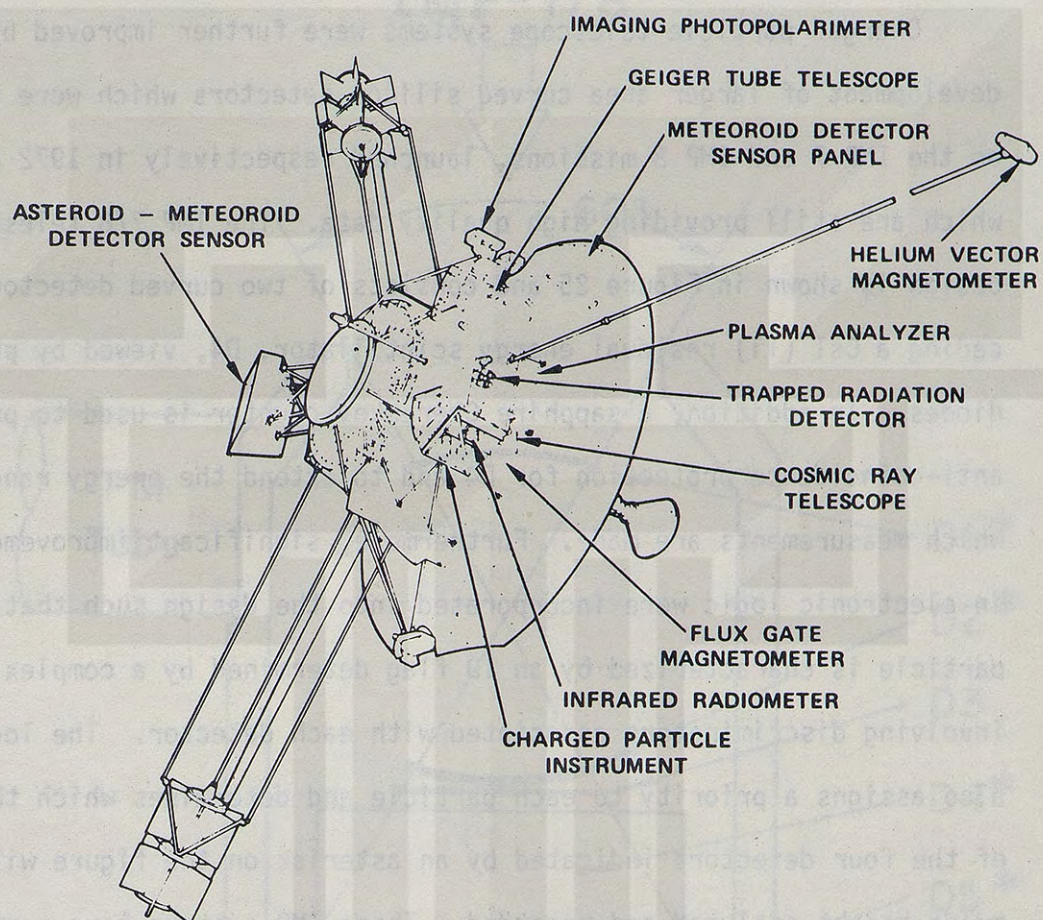


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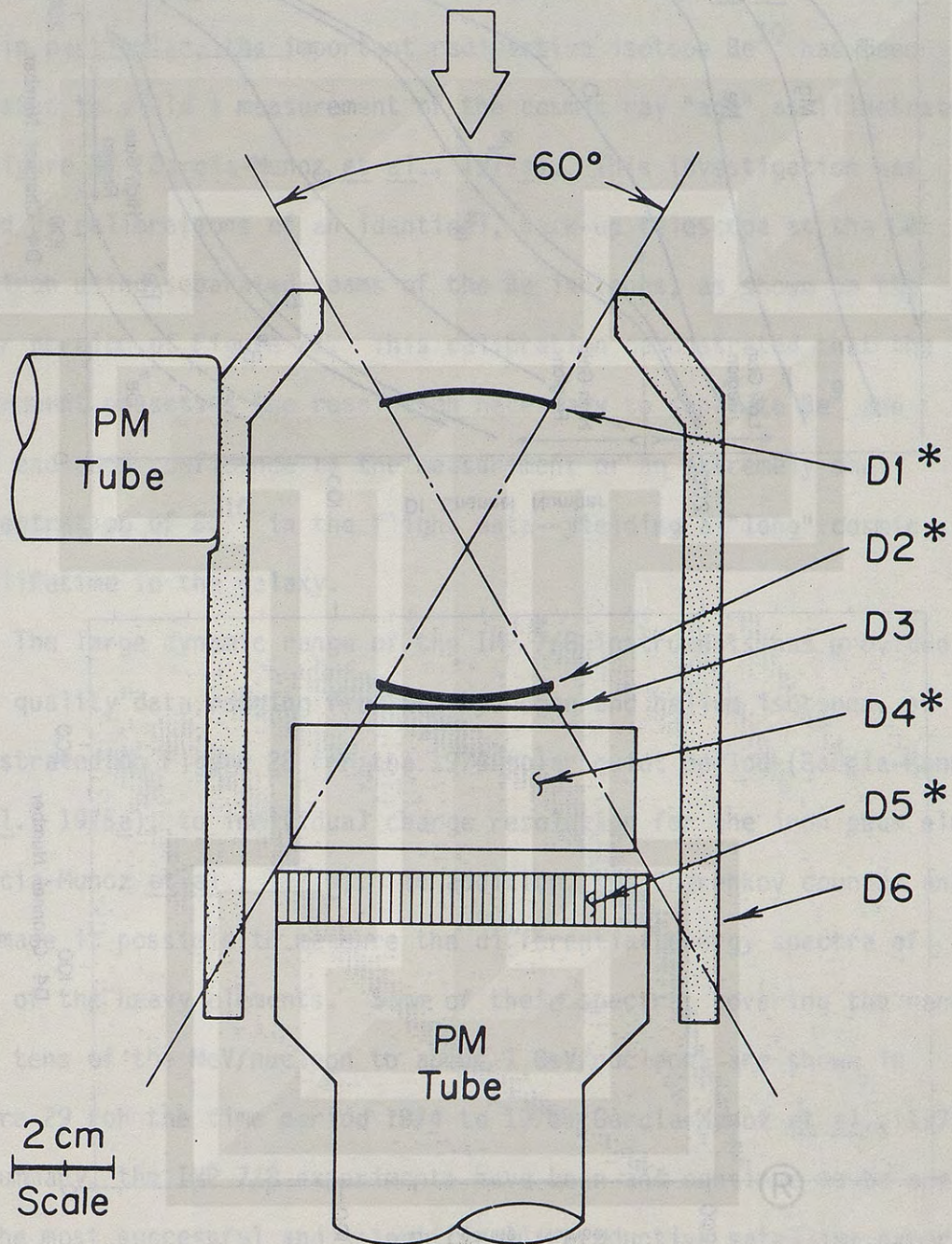


Figure 25: Diagram of the IMP 7/8 telescope system from the University of Chicago. The asterisks indicate detectors which are pulse-height analyzed.

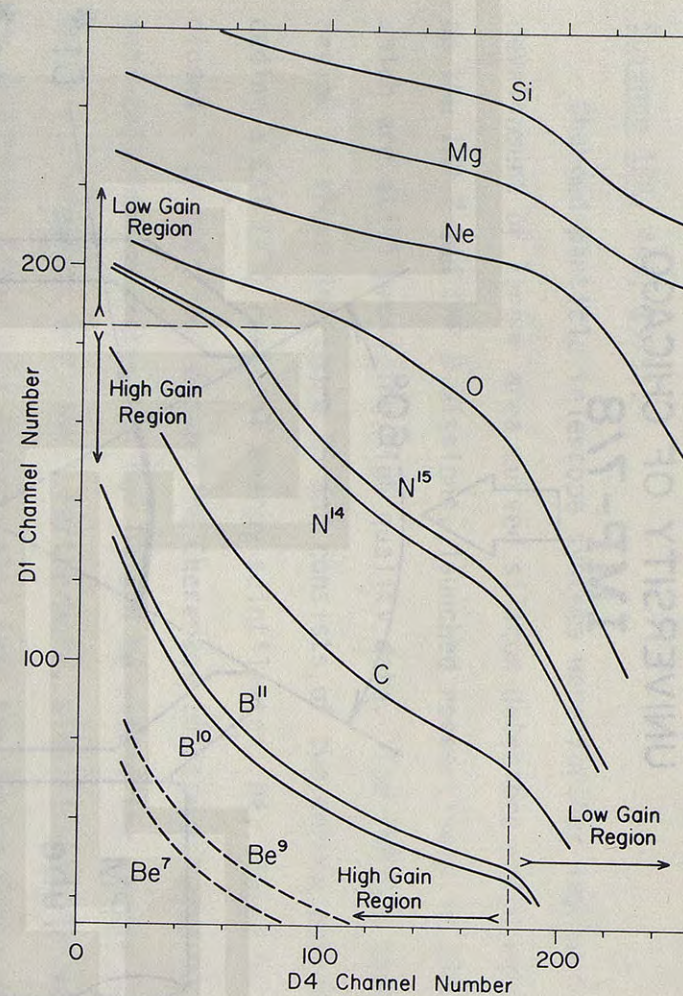
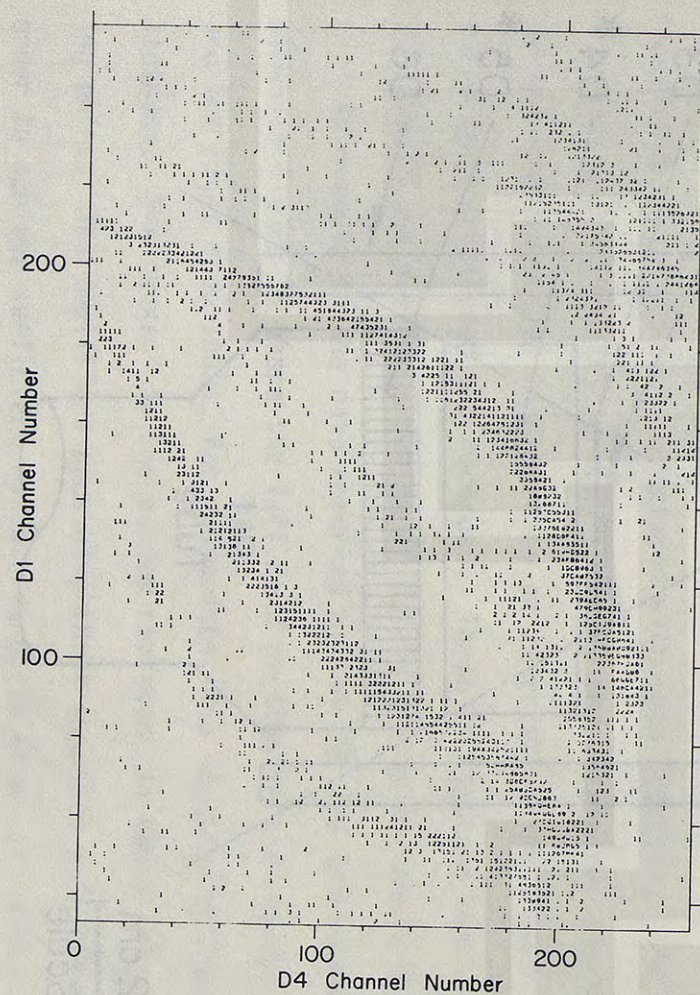


Figure 26: Raw data returned by the IMP 7 experiment (left) compared to the expected positions of the tracks for various isotopes and elements.

isotopic composition of neon can also be measured (Garcia-Munoz et al., 1978). With the IMP 7/8 system, the isotopic composition of the light elements, Li, Be, B, has been studied (Garcia-Munoz et al., 1975b) and in particular, the important radioactive isotope Be^{10} has been isolated to yield a measurement of the cosmic ray "age" as illustrated in Figure 27 (Garcia-Munoz et al., 1977a). This investigation was aided by calibrations of an identical, back-up telescope at the LBL Bevatron using separated beams of the Be isotopes, as shown on the lower portion of Figure 27. This calibration demonstrated that the instrument possesses the resolution necessary to separate Be^9 and Be^{10} and adds confidence to the measurement of an extremely small concentration of Be^{10} in the flight data--yielding a "long" cosmic ray lifetime in the galaxy.

The large dynamic range of the IMP 7/8 instruments has provided high quality data ranging from the hydrogen and helium isotopes, as illustrated on Figure 28 for the 1974 solar quiet period (Garcia-Munoz et al., 1975a), to individual charge resolution for the iron peak elements (Garcia-Munoz et al., 1977b). In addition, the Cherenkov counter analysis has made it possible to measure the differential energy spectra of many of the heavy elements. Some of these spectra, covering the range from tens of the MeV/nucleon to about 1 GeV/nucleon, are shown in Figure 29 for the time period 1974 to 1976 (Garcia-Munoz et al., 1977c). In summary, the IMP 7/8 experiments have been and continue to be one of the most successful and scientifically productive satellite experiments of the past decade.

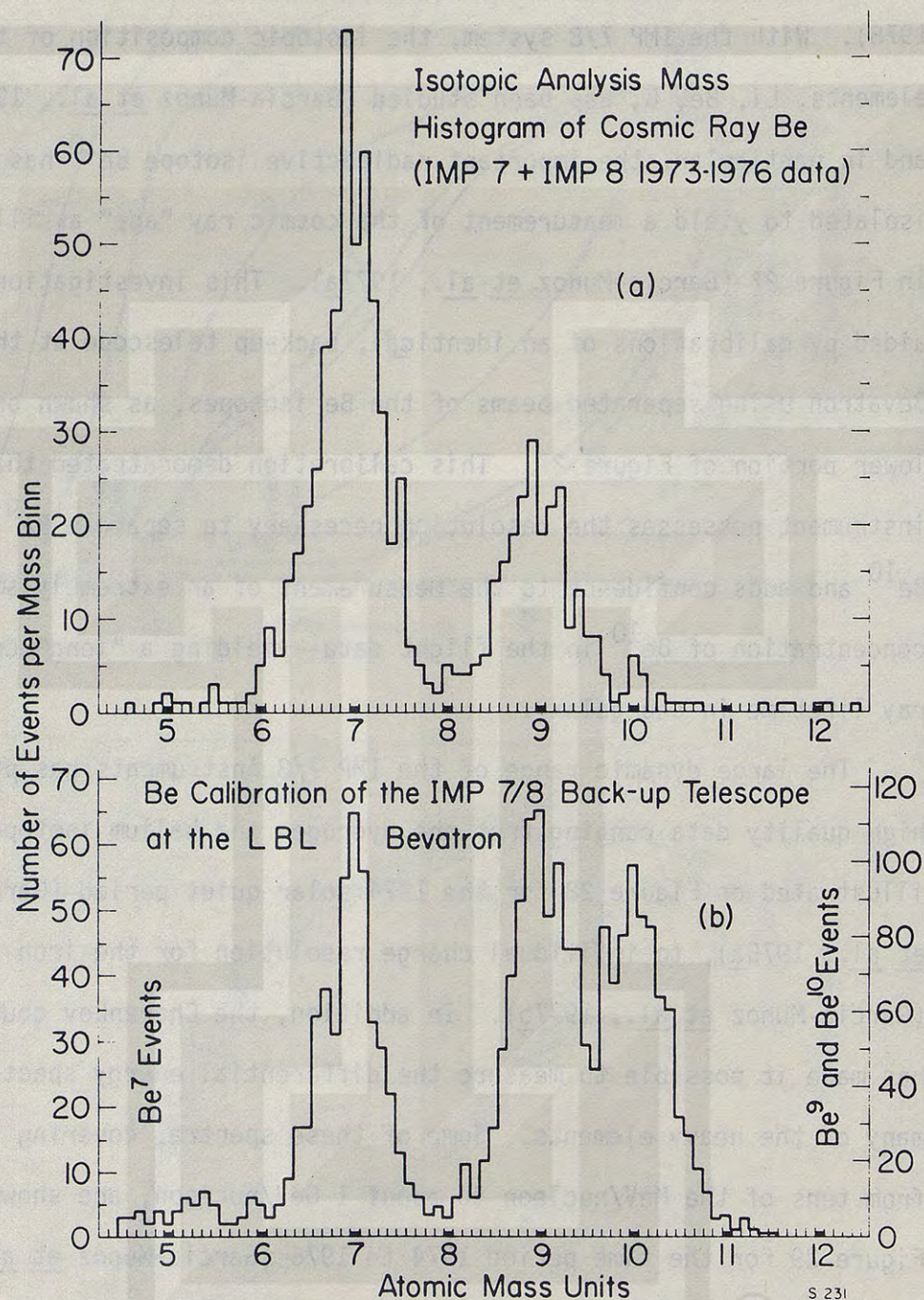


Figure 27: Part (a): isotopic distributions for Be cosmic rays recorded by the IMP 7/8 experiments. Part (b): isotopic distributions for Be heavy ions from the LBL Bevatron recorded in the IMP back-up telescope.

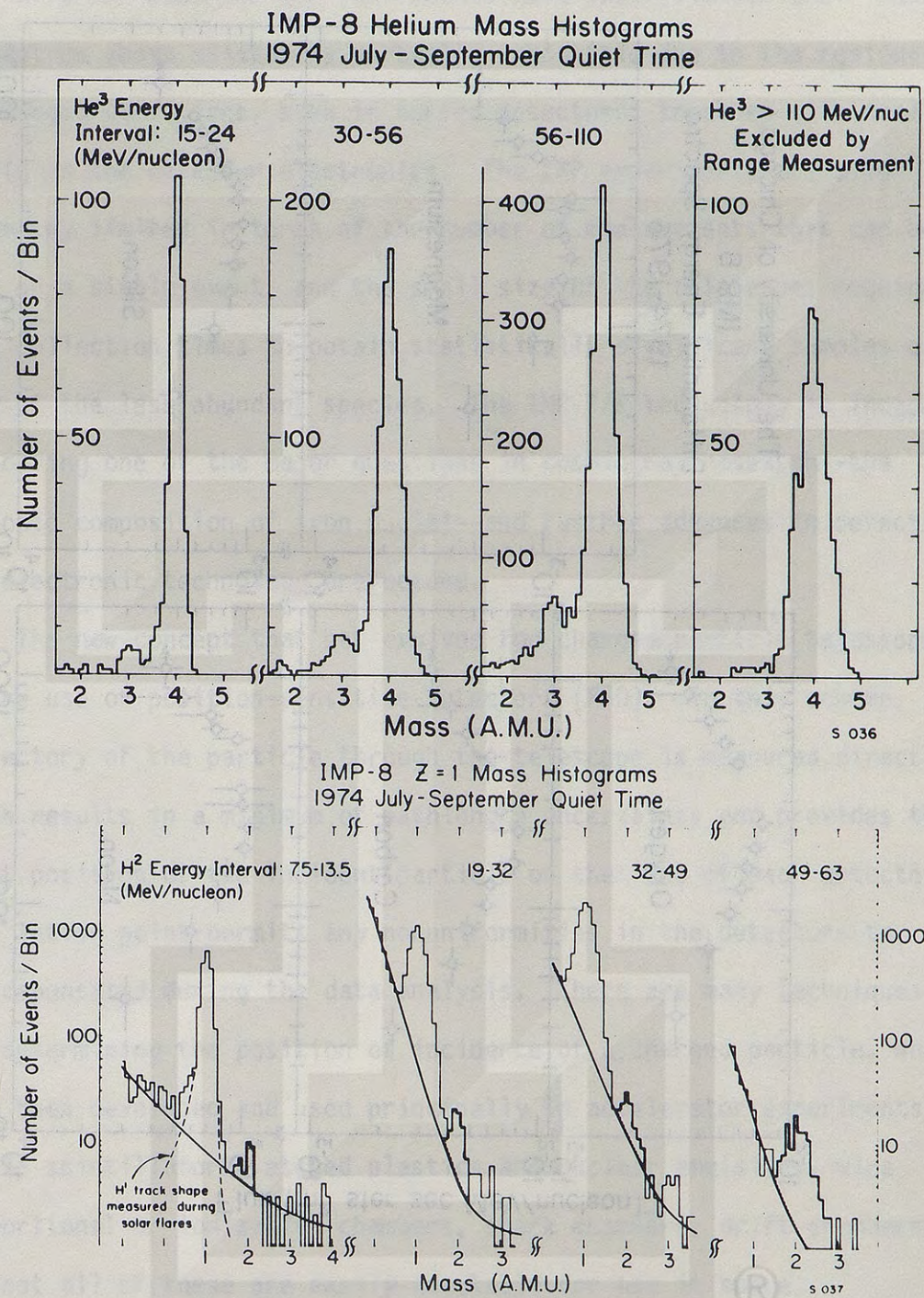


Figure 28: Mass histograms for hydrogen and helium in various energy intervals measured by the IMP 8 experiment for solar quiet periods.

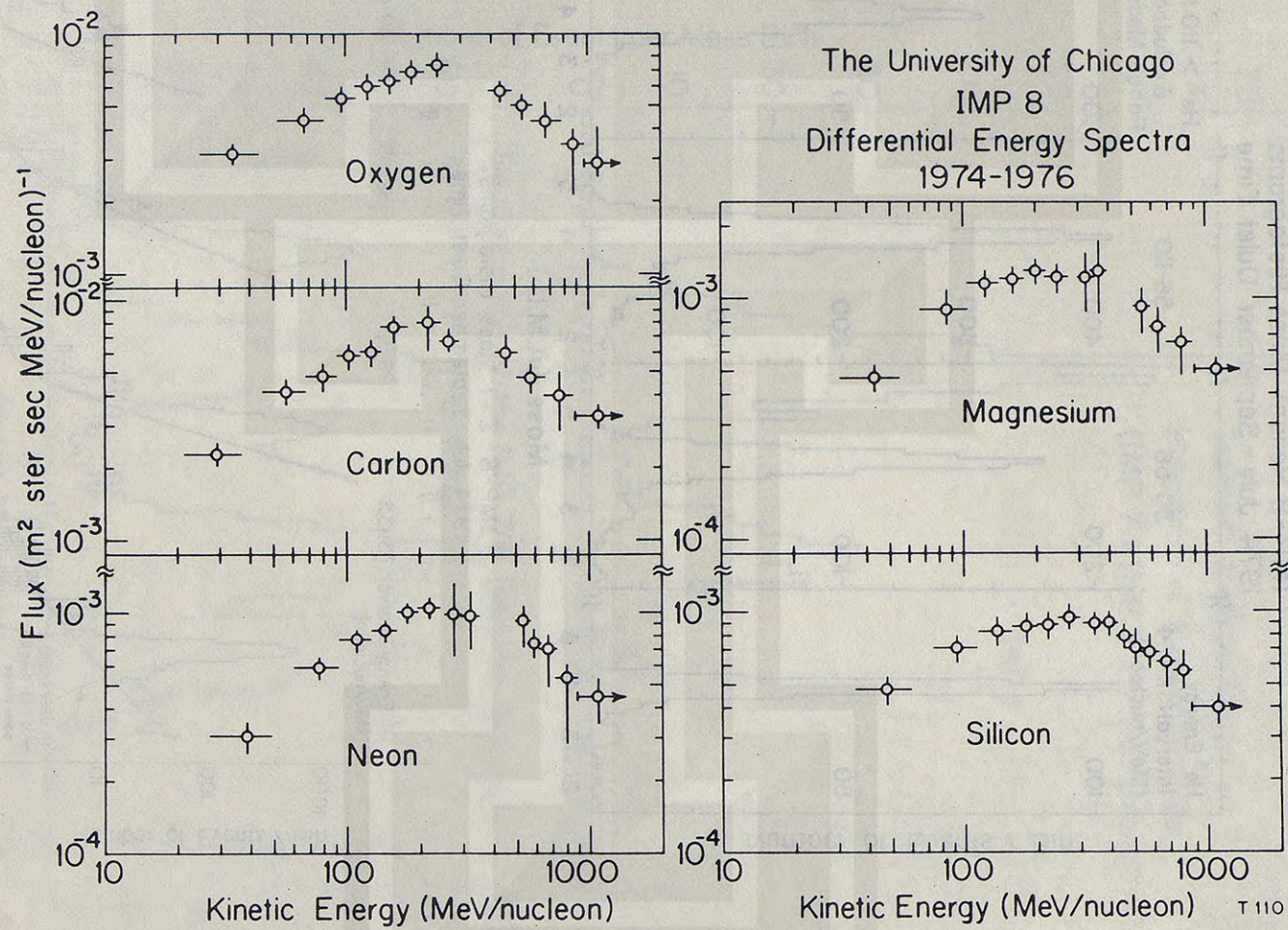


Figure 29: Differential energy spectra of heavy particles measured by the IMP 8 telescope over the period 1974 to 1976.

Nevertheless, the IMP instruments have their limitations. Mass resolution above silicon is virtually impossible due to the residual pathlength variations, even in curved detectors, together with small shifts in the detector electronics. The IMP experiments are also telemetry limited in terms of the number of measurements that can be made on a single event, and the small size of the telescopes requires long collection times to obtain statistically significant samples of many of the less abundant species. The IMP 7/8 technology is incapable of solving one of the major questions in cosmic ray research--the isotopic composition of iron nuclei--and further advances in detector and electronic technology are needed.

The new concept that has evolved for charged particle telescopes is the use of position-sensitive detectors (PSD). In this scheme, the trajectory of the particle through the telescope is measured directly which results in a minimum of pathlength uncertainty and provides the exact position of the incident particle on the face of each detector. This latter point permits any nonuniformities in the detectors to be compensated during the data analysis. There are many techniques for determining the position of incidence of a charged particle, which have been developed and used principally in accelerator experiments (strip scintillators, etched plastics and nuclear emulsions, wire proportional or ionization chambers, spark chambers, drift chambers), but not all of these are easily adaptable for use in space.

Figure 30 shows a sketch of a silicon position sensing detector that has been developed at the University of Chicago (Lamport et al., 1976). The electrical contact on one surface of the silicon wafer

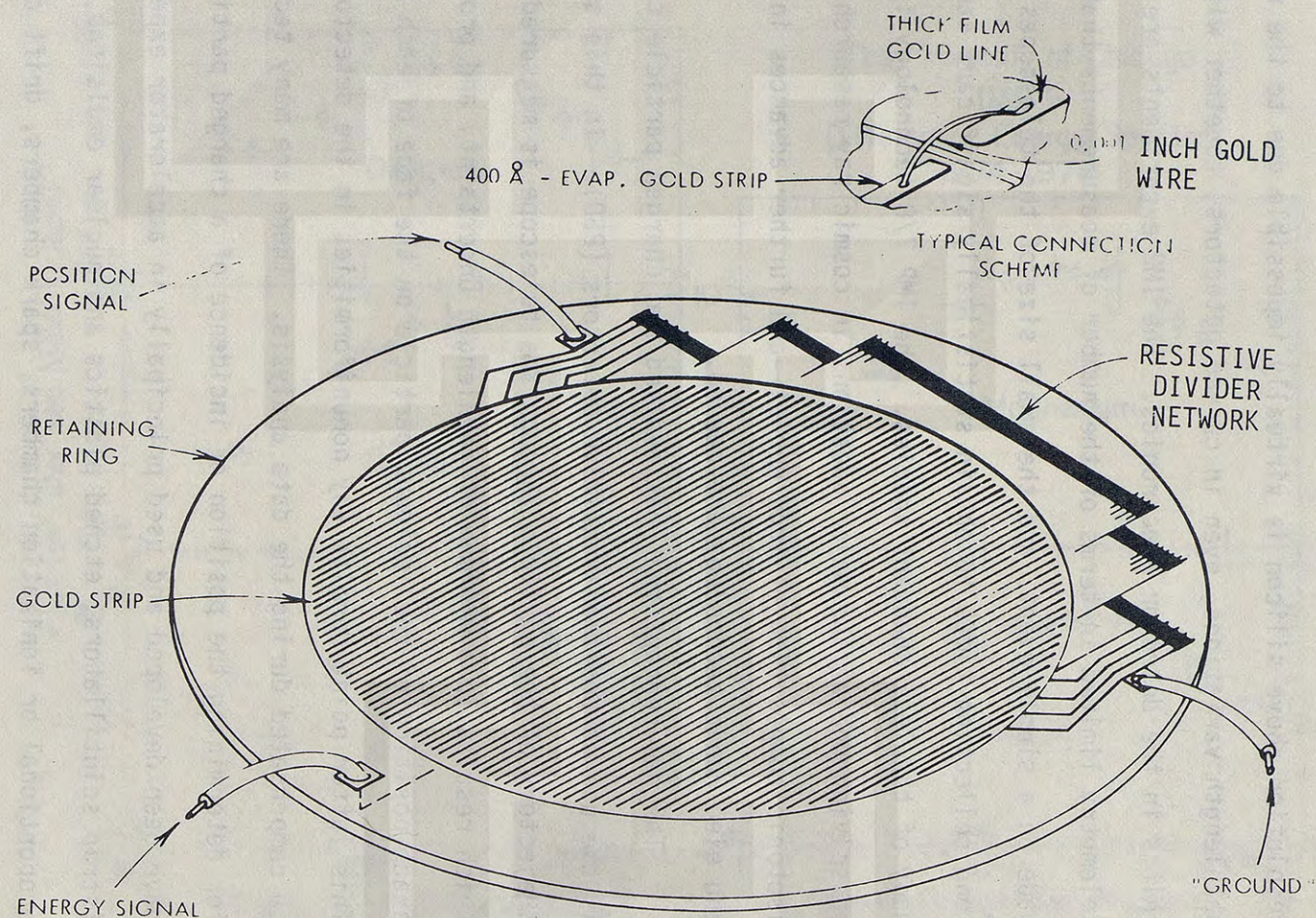
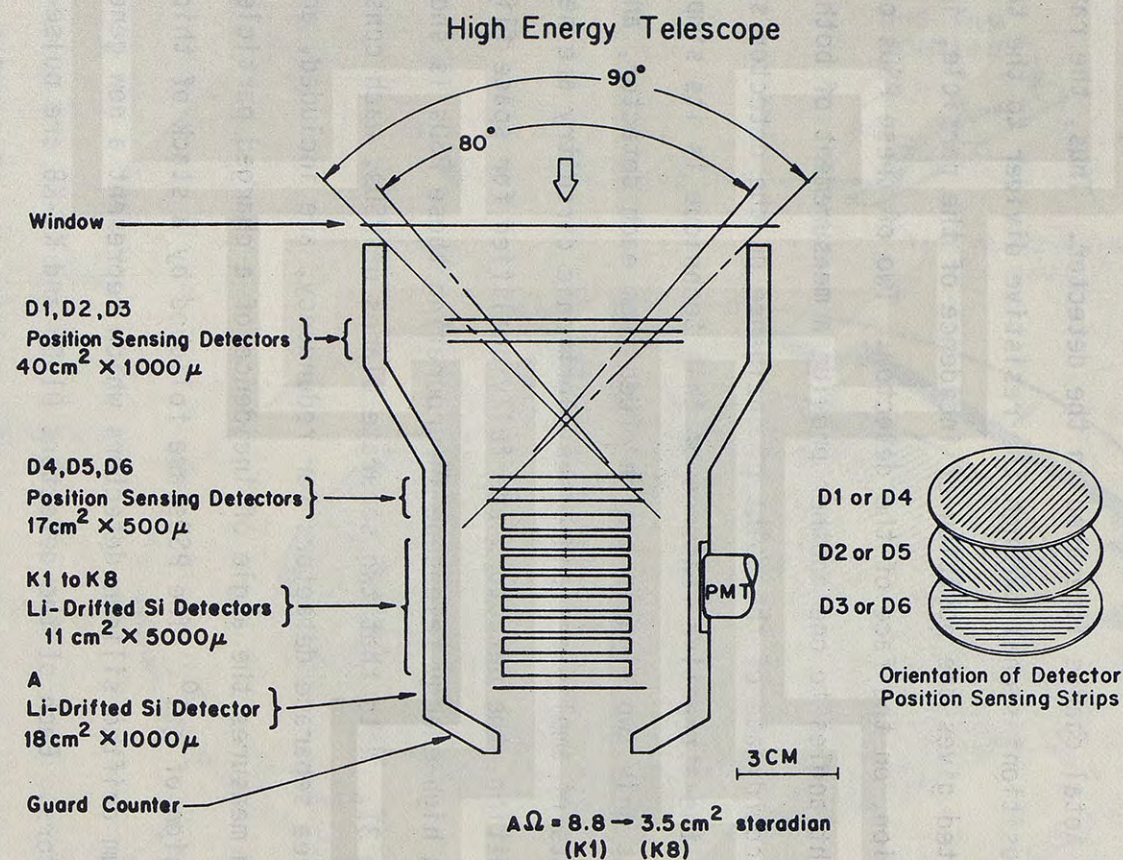


Figure 30: Schematic representation of a one-dimensional position sensitive silicon detector. Note the resistive divider network for read-out.

is divided into many separate gold strips. The two strips nearest the trajectory of the charged particle collect the signal which is then read out through a resistive divider network. The opposite side of the detector is a single contact which provides a signal proportional to the total charge liberated in the detector. Thus, the ratio of the "position" signal through the resistive divider to the total charge collected gives the position of incidence of the particle, in one dimension, on the face of the detector. Two of these PSDs oriented at right angles to one another provide a measurement of both the X and Y coordinate of the point of incidence on the detector surface. One of the attractive features of this technique is its simplicity in that only two signals are recorded from each detector, and only two sets of amplifiers and other electronic circuitry are needed. In addition, the detectors are fully qualified for space flight.

A high energy telescope incorporating these PSDs is shown in Figure 31. Note that two separate planes of PSDs, each consisting of three separate detectors for redundancy, are included, and this system measures the angle of incidence of a charged particle with a precision of $\leq 1^\circ$. The PSDs are followed by a stack of thick (0.5 cm) lithium drifted silicon detectors which represent a new generation of detectors. Each of the detectors D1-D6 and K1-K8 are pulse-height analyzed with 12 bit ADCs, and this information along with all discriminator flag bits and detector counting rates is recorded, giving over 300 bits of information per particle. This bit rate represents a giant step over systems such as the IMP 7/8 experiments, but this type of detail is needed for measurements at the subpercent level



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Figure 31: Diagram of the University of Chicago high energy telescope employing six one-dimensional PSDs.

of accuracy required for separation of the iron isotopes.

The development of a telescope system such as that shown in Figure 31 would have been almost impossible without the availability of high energy, heavy ion (HZE) beams at the Bevalac. The HZE beams have permitted telescopes to be designed, tested, modified, and retested to ensure, before launch, that all components function as designed and that the total system resolution is sufficient for a successful experiment. During this process, several unexpected effects in both the detectors and the electronics have been discovered and corrected. Without the calibrations at the Bevalac, these effects would have been discovered after launch when corrective action is impossible. Figure 32 shows a summary of the mass resolution achieved by the high energy telescope of Figure 31, compared to a theoretical prediction of the expected resolution. Points are shown for nitrogen, magnesium, argon, and iron beams. Figure 33 shows the mass histogram obtained with the Fe^{56} beam in the first two of the thick detectors in the stack. Data are presented for only a single angle, but the trajectory measuring system of the telescope is employed to determine the incidence angle used in the analysis. Figure 34 shows a plot of the mass resolution observed in the same detector pair for various angles of incidence of the Fe^{56} ions. The resolution is approximately constant for both positive and negative angles indicating that the PSD performance is not the limiting factor in the resolution. The measured isotopic resolution, in this preliminary data, is sufficient to study the relative abundances of the iron isotopes in the galactic cosmic radiation.

Detector systems similar to this high energy telescope have been

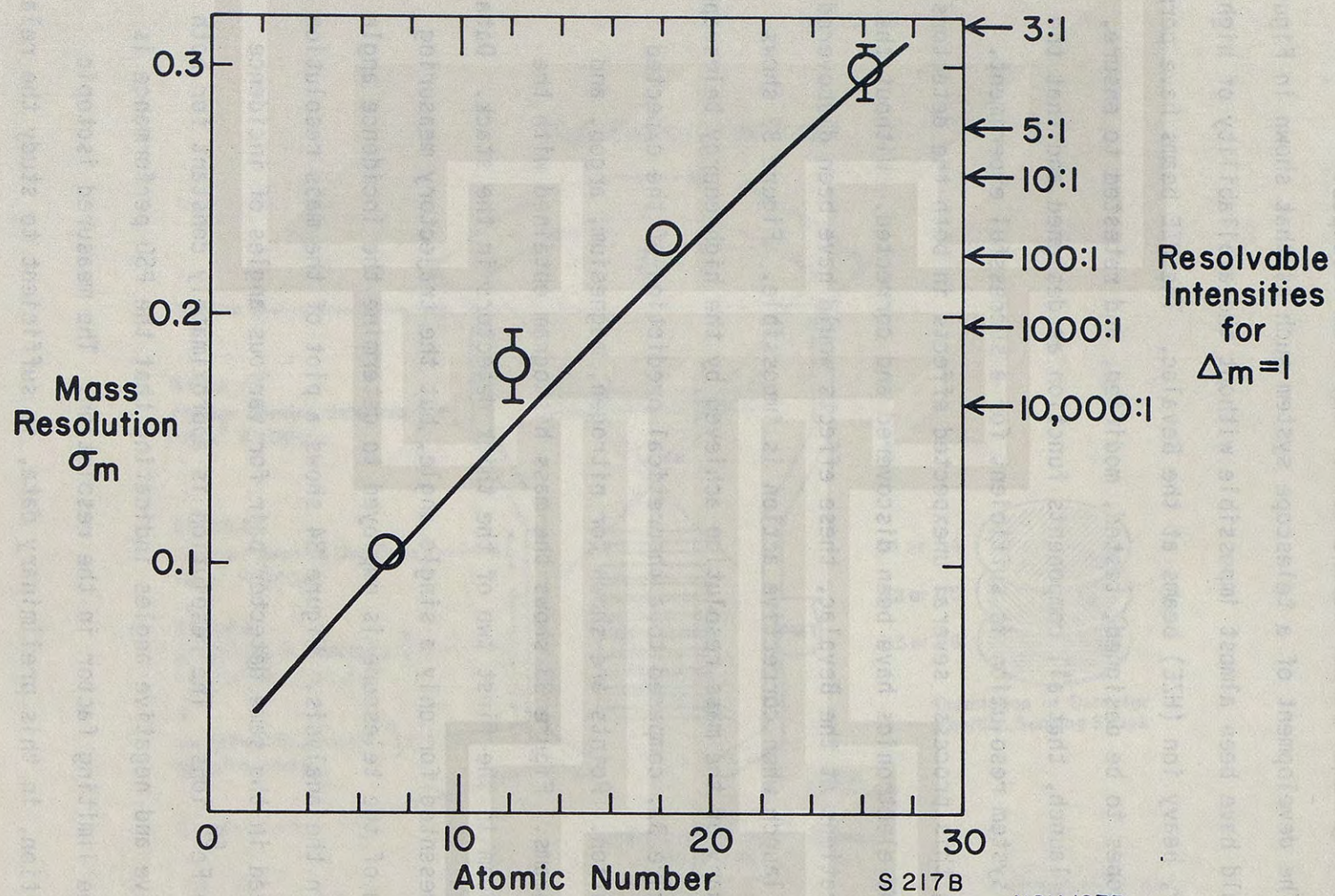


Figure 32: Preliminary mass resolution measured for heavy ion beams of nitrogen, magnesium, argon, and iron in the University of Chicago high energy telescope.

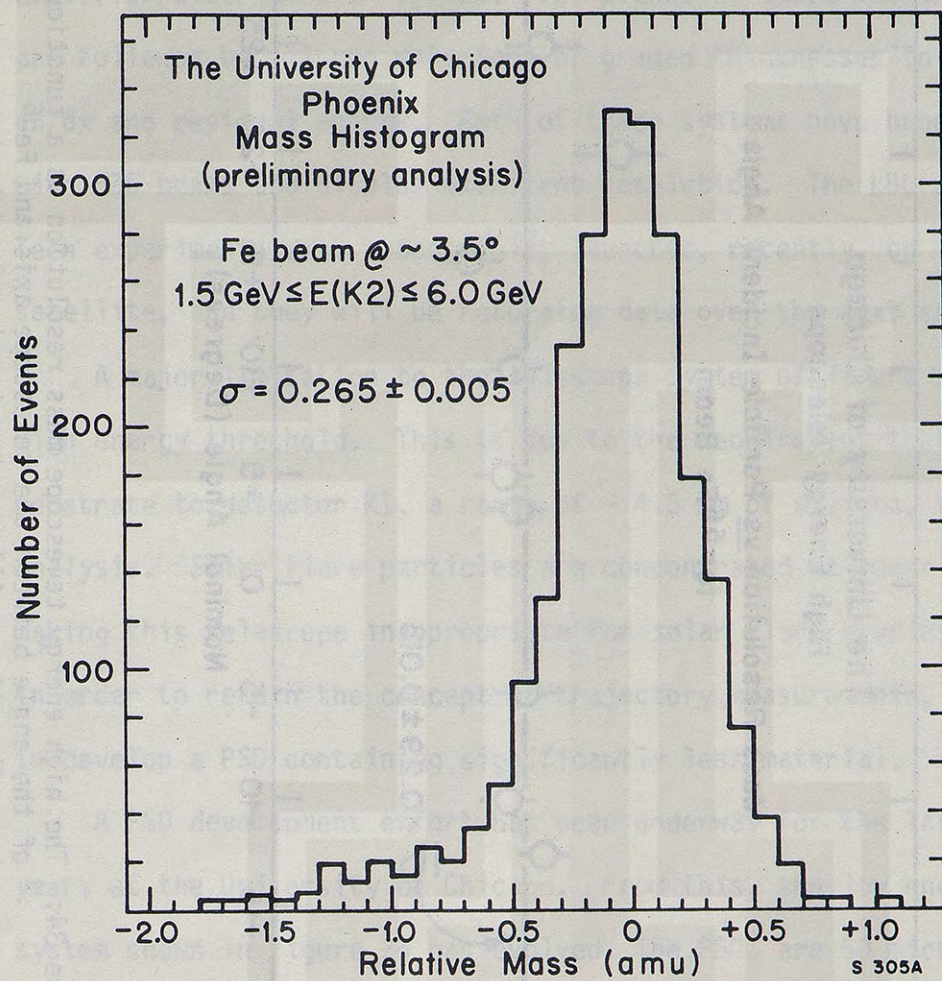


Figure 33: Fe^{56} mass histogram from an analysis of events stopping in detector K2 of the high energy telescope.

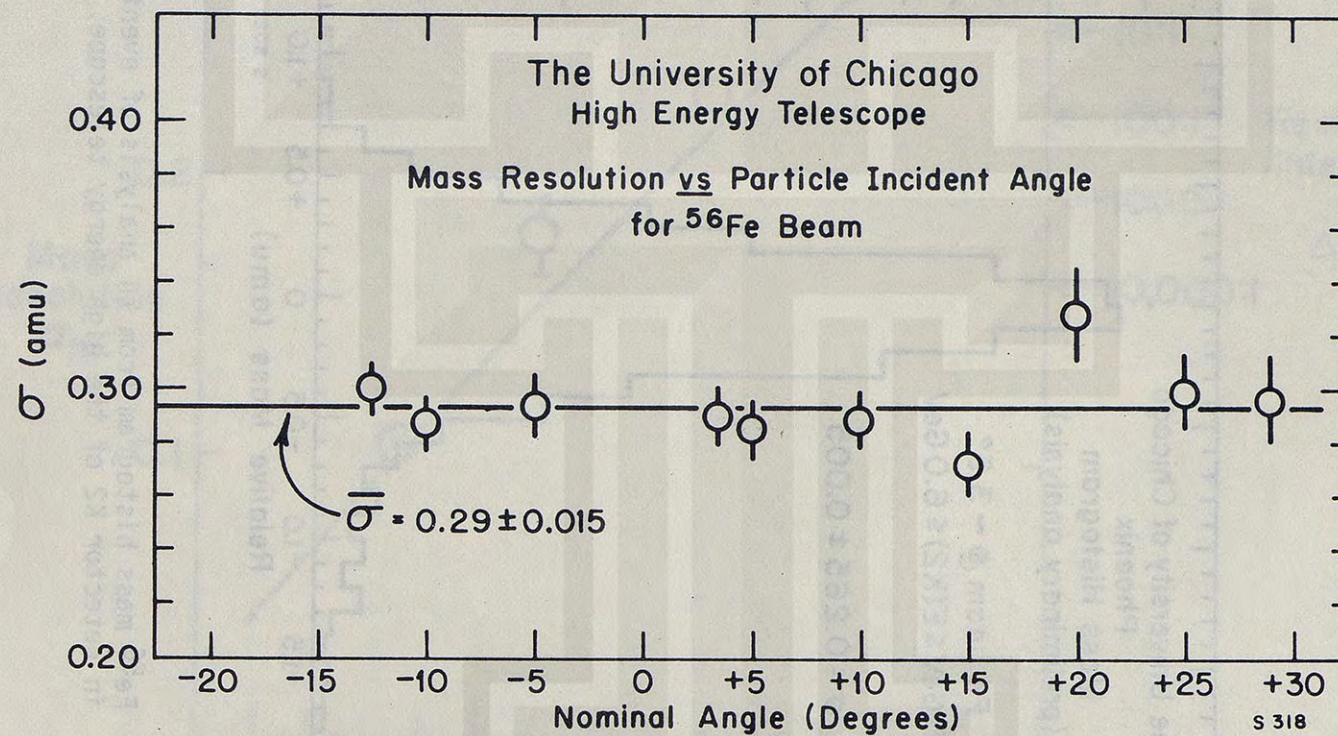


Figure 34: The high energy telescope mass resolution as a function of the angle between the telescope axis and Fe^{56} beam direction. All events stopping in detector K2 are included in the analysis.

developed by LBL and Cal Tech. The LBL technique uses drift chambers for position determination, followed by a stack of ten thick silicon detectors. The Cal Tech experiment, at somewhat lower energies, employs strip silicon detectors in which each strip is connected to its own amplifier/discriminator system. Two planes of these matrix detectors are followed by silicon detectors of graded thicknesses to record the dE/dx and residual energy. Both of these systems have been calibrated with HZE beams and display excellent resolution. The LBL and Cal Tech experiments were successfully launched, recently, on the ISEE-C satellite, and they will be returning data over the next several years.

A major limitation to the telescope system of Figure 31 is its high energy threshold. This is due to the requirement that particles penetrate to detector K1, a range of ~ 4.5 mm of silicon, for isotopic analysis. Solar flare particles are concentrated at lower energies, making this telescope inappropriate for solar flare studies. Thus, in order to retain the concept of trajectory measurements, it is necessary to develop a PSD containing significantly less material.

A PSD development effort has been underway for the last several years at the University of Chicago. From this, the low energy telescope system shown in Figure 35 has evolved. The PSDs are 50 micron wafers of silicon containing a set of strips to measure the X position on the top surface and another set of strips, rotated 90° , on the bottom surface to record the Y position. Each set of strips is read out through a resistive divider network. Two of these detectors, arranged as shown, provide excellent trajectory information with only 0.1 mm of material in the particle's path, which permits measurements down

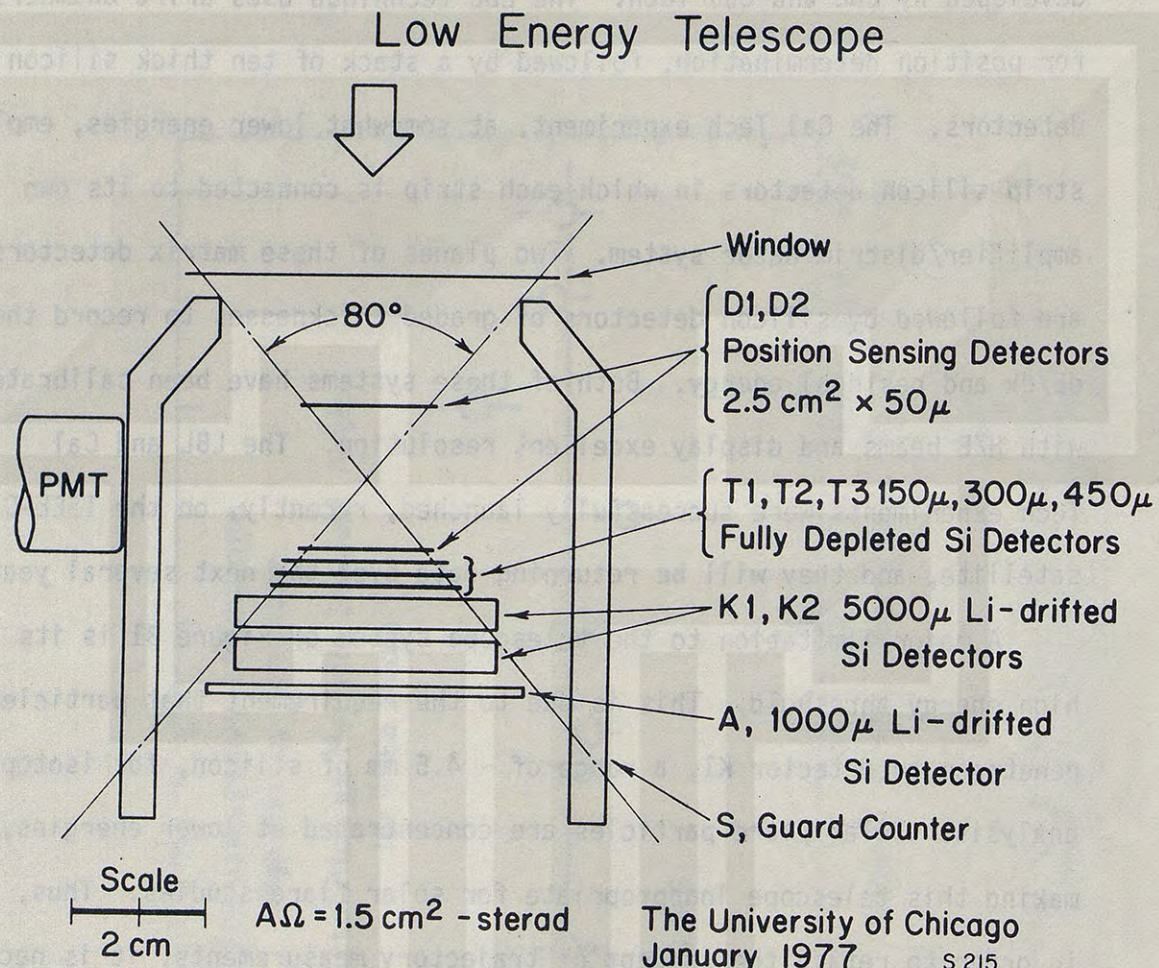


Figure 35: Diagram of the University of Chicago low energy telescope employing two-dimensional PSDs.

to MeV energies. Following the PSDs are a set of three totally depleted silicon detectors of graded thickness, and two 5-mm thick lithium-drifted silicon detectors. This stack provides multiple dE/dx measurements for stopping particles over a total energy interval which overlaps the energy range of the high energy telescope shown in Figure 31. The low energy telescope system has been calibrated at the Bevalac and exhibits resolution comparable to that obtained with the high energy instrument. The high and low energy telescopes, along with a monitor telescope similar to that shown in Figure 13, are combined into a single instrument package, whose electronic block diagram is shown in Figure 36, for launch into a polar orbit in the near future. This instrument array will study galactic cosmic rays, solar flare particles, and low energy radiation penetrating or trapped in the magnetosphere.

The high and low energy telescope systems represent the current state of the art in charged particle telescope systems, and future advances will depend upon the performance of these systems in space. The high and low energy telescopes, along with the experiments of other groups, will begin the painstaking task of mapping, with high resolution, the characteristics of the charged particle radiation in space. However, this is only part of the job that must be done. Figure 37 shows a schematic representation of the heliosphere with the region that has been and will be explored by these experiments indicated. Note that most of the heliosphere remains unexplored, and it is to be expected that the charged particle populations studied to date in the ecliptic plane will not be the same elsewhere in the heliosphere. In particular, it is possible that in the north and

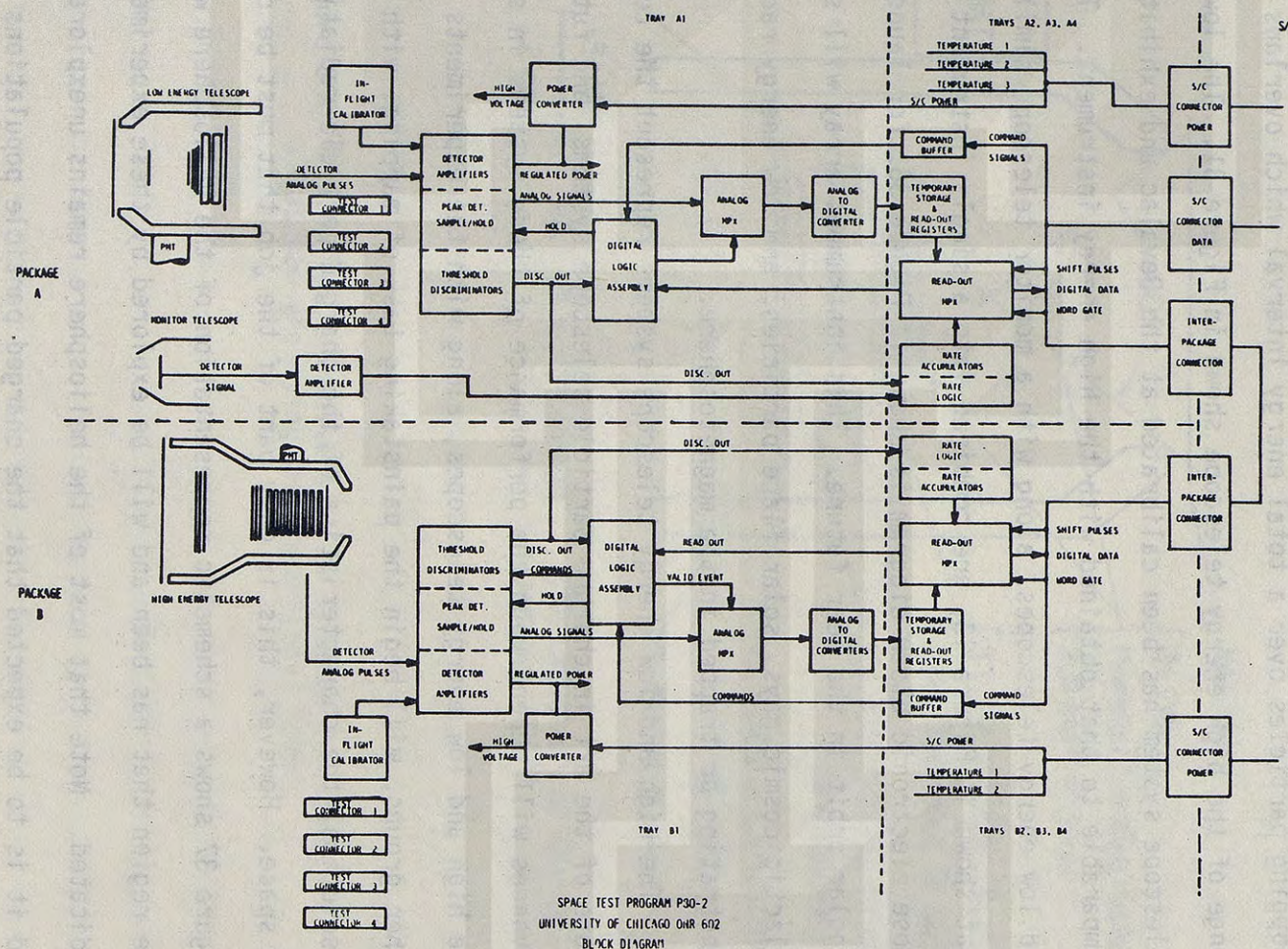
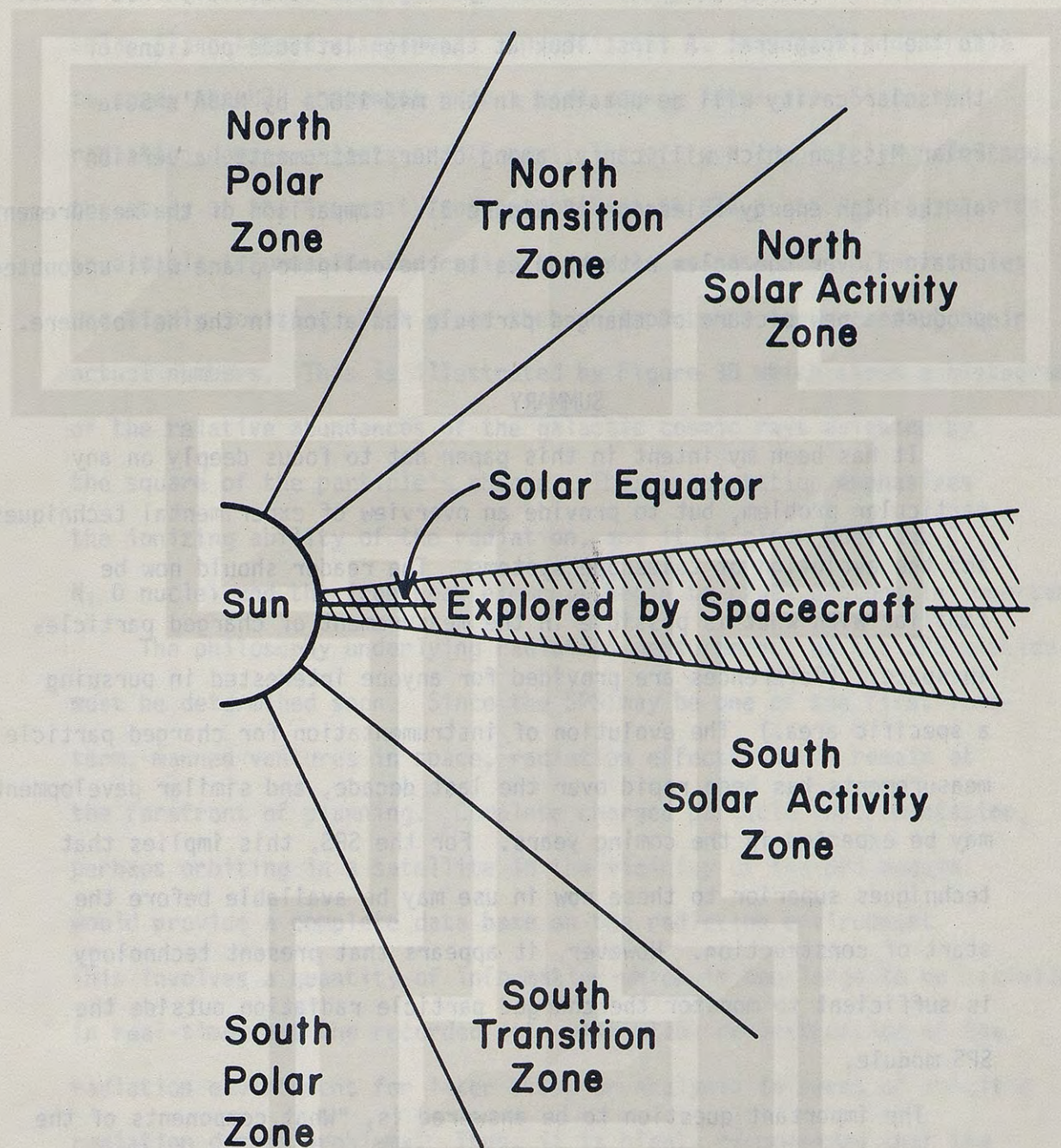


Figure 36: Electronic block diagram for the combined instrument package including a high energy telescope, a low energy telescope, and a monitor telescope.



Idealized Meridional Diagram of Solar Regions Connecting with the Interplanetary Medium

Figure 37: Schematic view of the heliosphere indicating the various solar regions. The region of the ecliptic plane is shaded.

south polar zones, galactic cosmic rays may have relatively free access to the heliosphere. A first look at the high latitude portions of the solar cavity will be obtained in the mid-1980s by NASA's Solar Polar Mission which will carry, among other instruments, a version of the high energy telescope of Figure 31. Comparison of the measurements obtained over the poles with studies in the ecliptic plane will undoubtedly produce a new picture of charged particle radiation in the heliosphere.

SUMMARY

It has been my intent in this paper not to focus deeply on any particular problem, but to provide an overview of experimental techniques and the evolution of telescope systems. The reader should now be familiar with what is possible in the measurement of charged particles in space. (References are provided for anyone interested in pursuing a specific area.) The evolution of instrumentation for charged particle measurements has been rapid over the last decade, and similar development may be expected in the coming years. For the SPS, this implies that techniques superior to those now in use may be available before the start of construction. However, it appears that present technology is sufficient to monitor the charged particle radiation outside the SPS module.

The important question to be answered is, "What components of the radiation should be monitored?" The answer to this question depends, in detail, on the importance of the different components in producing radiation damage to people or materials. In addition, the answer defines the design parameters for the charged particle instrumentation. It seems necessary, as a minimum, to monitor the intensity of low

energy protons and electrons in order to provide real-time data for solar flare hazard assessment. In addition, it is probably desirable to study the HZE component over a wide energy interval. Since the radiation damage effects of HZE particles are not completely understood, the study of the intensity and composition of HZE particles may provide invaluable information for radiation damage assessment. HZE particles are highly ionizing which gives them an importance far exceeding their actual numbers. This is illustrated by Figure 38 which shows a histogram of the relative abundances of the galactic cosmic rays weighted by the square of the particle's charge. This presentation emphasizes the ionizing ability of the radiation, and it is clear that the C, N, O nuclei and the iron peak elements begin to rival protons in importance.

The philosophy underlying radiation measurements on the SPS mission must be determined soon. Since the SPS may be one of the first long-term, manned ventures in space, radiation effects should remain at the forefront of planning. Complete charged particle instrumentation, perhaps orbiting in a satellite in the vicinity of the SPS module, would provide a complete data base on the radiation environment. This involves a quantity of information which is too large to be assimilated in real-time, but the recorded data will allow reconstruction of the radiation environment for later study or analysis in terms of specific radiation damage problems. Thus, it is highly recommended that the external radiation monitoring on the SPS mission include an entire complement of charged particle experiments to investigate, in detail, the complete radiation environment of the SPS satellites.

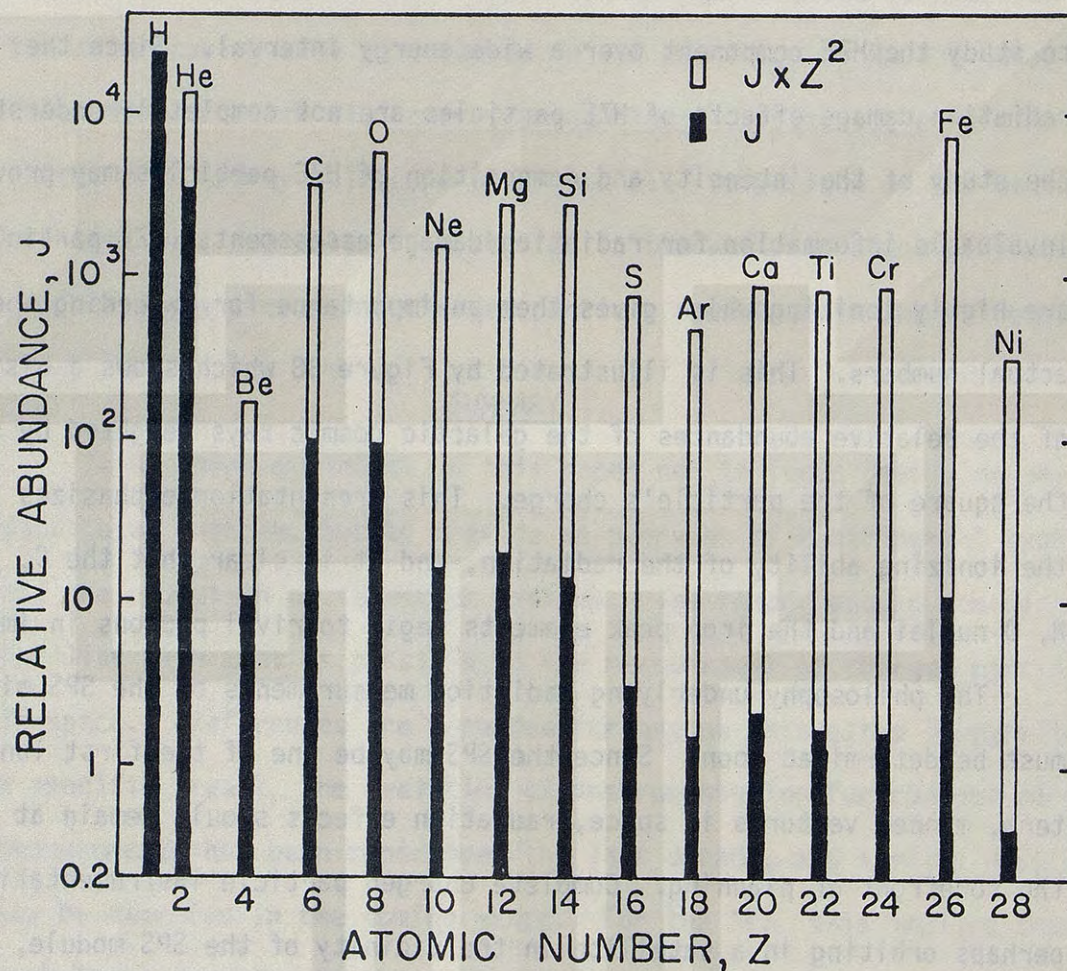


Figure 38: Histogram showing the relative abundances of the even numbered galactic cosmic ray nuclei (solid bars) compared to these abundances weighted by the square of the particle's charge to give a measure of the "ionizing power" of each element (open bars).

ACKNOWLEDGMENTS

The author would like to thank A.J. Tuzzolino for a critical review of the manuscript. Thanks are due to the staff of the Laboratory for Astrophysics and Space Research for the design and construction of the University of Chicago experiments described in this paper, and to the National Aeronautics and Space Administration for support over many years. The preparation of this manuscript was supported by NASA grant NGL 14-001-006 and contract NAS 5-11067.

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A PRELIMINARY STUDY OF THE CHARGED PARTICLE RADIATION
FOR THE SATELLITE POWER SYSTEM

E. G. Stassinopoulos

NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

INTRODUCTION

A preliminary radiation study was performed for the SPS project in order to determine the energetic charged particle environment for the three major phases of an SPS mission: the low earth orbit (LEO), the transfer ellipse (TE), and the synchronous geostationary trajectory (GEO).

For that purpose, extensive calculations were performed and a large data base was generated, processed, and analyzed. The results of this effort may be used as guidelines in other studies investigating the effects of radiation on materials and humans.

The external (surface incident) charged particle intensities, predicted for the SPS in each mission phase, were determined by orbital flux integration from the latest environment models.

Magnetic field definitions for the three trajectories were obtained from a current field model.

Spatial and temporal variations or conditions were considered and accounted for, wherever possible.

Limited shielding and dose evaluations were performed for a simple geometry.

The study, although comprehensive, is designated as "preliminary" because it was based on very tentative nominal flight path configurations. At a later time, as planning advances and mission parameters become better defined, it may be necessary to re-evaluate the SPS radiation predictions with new (firmer) orbital elements and information.

ORBIT SPECIFICATION

The analysis was performed for three nominal trajectories corresponding to the three phases of the SPS mission: a circular low earth orbit (LEO), a synchronous geostationary orbit (GEO), and singular outward parabolic transfer ellipse (TE) starting in the vicinity of LEO and terminating near a GEO. Specifically, each flight path was defined as follows:

LEO: inclination $i = 30^\circ$, altitude $h = 500$ km

GEO: inclination $i = 0^\circ$, altitude $h = 35790$ km, parking
longitudes $\phi_p = 70^\circ\text{W}$ and $\phi_p = 160^\circ\text{W}$

TE: initial position: longitude $\phi = 172^\circ\text{W}$, geocentric
latitude $\lambda = 13^\circ\text{N}$, altitude $h = 191$ km
final position: longitude $\phi = 73^\circ\text{W}$, geocentric latitude
 $\lambda = 12^\circ\text{S}$, altitude $h = 35621$ km.

TRAJECTORY GENERATION

A flight path ephemeris was generated for each trajectory (Stassinopoulous *et al.*, 1973) for the indicated conditions:

LEO: for a 24-hour duration defined at two-minute intervals

GEO: for a 24-hour duration defined at three-minute intervals

TE: for a 5.25-hour duration defined at one-minute intervals

The length of simulated orbit time and the integration step size were especially selected in each case to provide sufficient point density

to ensure an adequate sampling of the ambient radiation environment when flying the trajectories through the models.

The trajectories were subsequently converted from geodetic polar to magnetic B-L coordinates with Hassit and McIlwain's INVAR program (1967) and the field routine ALLMAG (Stassinopoulos and Mead, 1972), utilizing the BARRACLOUGH 1975 field model (Barracough et al., 1975). The spherical harmonic expansion coefficients of the field were extrapolated to tentative mission epochs with linear time terms representing secular variations of the field. (Note: The BARRACLOUGH 1975 model has replaced the older POGO 8/69 in the ALLMAG routine.)

CHARGED PARTICLE DOMAINS IN THE MAGNETOSPHERE

A brief discussion on this topic was given in a previous paper (Stassinopoulos, 1979). Of interest here is the distinction of electron populations into inner zone and outer zone constituents, and the limited range of energetic proton trapping.

The levels of radiation experienced by a satellite in a given orbit depends on the amount of visitation time in the volume of space occupied by each particle species, and on the extent to which the trajectory penetrates into the peak intensity regions of the different domains.

FLIGHT PATH EXPOSURE TO TRAPPING DOMAINS

The investigated flight-path configurations display distinctly different exposure characteristics.

LEO: The trajectory lies entirely within (a) the inner zone region of the electron environment, which is more benign and softer

than that of the outer zone, and (b) the energetic proton domain.

Also, LEO enters regions of space dominated by atmospheric cut-off conditions (loss of trapped particles due to interaction with atmospheric constituents) for about 22% of its time; that is, certain trajectory segments have a combination of B and L values that place them outside the atmospheric cut-off limits of the models.

GEO: A detailed description of synchronous geostationary trajectories was given elsewhere (Stassinopoulos, 1979). This class of orbits is quite unique. They lie outside the energetic proton trapping region, in the outer-zone electron domain, and they are 100% exposed to cosmic rays of galactic or solar origin (no geomagnetic shielding). Also, these orbits, having a range of L values from about 6.60 to about 7.02 earth radii, remain well above the peak intensity region of the outer-zone electrons, which occurs at about $L = 4$ earth radii. Since the flux variations over the possible GEO L-range ($6.60 \leq L \leq 7.02$) are significant, a GEO at each range end point was considered in the analysis, providing respectively worst and best case conditions.

TE: The particular TE selected for this study is supposed to represent a "typical" straight ascent trajectory for this type of mission as to force, shape, direction, start- and end-point location, velocity, epoch, etc. It yields certain specific radiation intensities that are unique to this TE. Any changes in flight path would affect this predicted vehicle-encountered flux values, conceivably by as much as several orders of magnitude. As it is, the TE passes through the inner and outer zone electron domains, the energetic proton region, and spends about 60% of its time in regions of space accessible to cosmic rays.

TRAPPED PARTICLE ENVIRONMENT

The fluxes in this study were obtained from current standard NASA models of the environment, as issued by the National Space Science Data Center (NSSDC) at Goddard Space Flight Center:

AE5: inner zone electrons for solar minimum conditions
(Teague and Vette, 1972)

AE6: inner zone electrons for solar maximum conditions
(Teague et al., 1976)

AE17-HI: outer zone electrons (no solar cycle dependence)
(Hills et al., 1979)

AP8-MAC: trapped protons for solar maximum (MAC) and solar
AP8-MIC minimum (MIC) conditions (Sawyer and Vette, 1976)

All models describe average static environments at a fixed epoch.

The new AP8 replaces all previously issued trapped proton models, each of which was valid over specific energy ranges. The AP8 now covers the entire energy spectrum. It also reflects solar cycle variations: the AP8-MIN describes an average solar minimum and the AP8-MAX an average solar maximum environment.

The AEI7 is a new interim model that has recently replaced the older outer zone AE4. For energies above 1.5 MeV, this interim model contains upper (AEI7-HI) and lower (AEI7-LO) limit values to account for the discrepancy between existing data sets. There is recent evidence that these discrepancies may be due to stochastic differences in yearly averaged flux levels. If this proves to be true, then these two limits bound the predictive uncertainty that will always exist at these high energies.

Further comments on the AEI7 and on modeling procedures in general are contained in another paper (Stassinopoulos, 1979).

ORBITAL FLUX INTEGRATIONS

Orbital flux integrations (OFI) for all mission phases were performed with advanced complex software systems (Stassinopoulos and Gregory, 1978; Stassinopoulos et al., 1977). The results were statistically processed and analyzed. Some OFI data were subsequently used in the dose and shielding evaluation.

FLUX DATA: TYPE, QUALITY, AND VARIATIONS

The computed trapped particle fluxes represent omnidirectional, integral intensities that one would expect to obtain as average values over periods in excess of six months. Over most regions of magnetospheric trapping space ($L \gtrsim 2$ earth radii), short term excursions can vary from these values by factors of 10^2 to 10^3 , depending on the particle energies and type and intensity of event. The impact of these variations from the model-predictions on the three SPS phases may be summarized as follows.

LEO. Even a short-duration LEO mission is not affected by such fluctuations because of the low-inclination/low-altitude orbit (L value always less than 1.8 earth radii).

GEO. Activity areas with short-range concerns should be aware of the possibility for the occurrence of these fluctuations and take them into account; considerations for long-range effects need not concern themselves with these excursions.

TE. If the mission duration, to be finally determined for this phase, is as short as the one used in this work (5.25 hours), then the satellite could experience those excursions over most of its flight path.

Other variations affecting the trapped particle populations are:

(a) the local time dependence, and (b) the solar cycle dependence.

Both are briefly discussed relative to GEO by Stassinopoulos (1979). However, the impact of these variations on the LEO and TE environments is different. LEO does not experience any local time variations, while TE will be affected over the segment of its trajectory that has L-values above 5 earth radii.

In contrast, regarding these two orbits, the exact opposite is true for solar cycle variations; LEO does experience these long-term changes, while TE does not when $L > 5$ earth radii.

It is necessary to emphasize that the calculations, although based on the best data available for past epochs, can only serve as approximations for the future.

It should also be noted that the following basic uncertainty factors (u.f.) are attached to the flux values of the corresponding models.

AE5: u.f. = 2

AE6: u.f. = 5 : average value for this model (u.f. is a function of energy E and magnetic parameter L).

AP8: u.f. = 2 : same value for solar maximum and for solar minimum version.

AEI7-HI: in this particular case the electron results may be considered an upper limit (worst case) since this version of the AEI7 predicts the highest flux levels in accordance with Vampola's OVI-19 data and the ATS-6 data of Paulikas and Blake. If any uncertainties were to be attached to these data, it should be a fractional (reducing) factor of maybe 0.5, to bring the flux levels down and more in line with the other satellite measurements that indicate lower values.

No uncertainty factors were applied to the data contained in this report.

GEOMAGNETIC SHIELDING AND SOLAR FLARE PROTONS

A detailed description of this topic is given elsewhere (Stassinopoulos, 1979), particularly in reference to GEO. Therefore, only some comments relative to LEO and TE are presented here.

LEO. This trajectory is at all times 100% geomagnetically shielded from cosmic rays of galactic or solar origin in the investigated energy range from $E > 10$ MeV to $E < 200$ MeV.

TE. The flight path may be divided into two segments:

A. $L < 5$: shielded (1.90 hours)

B. $L > 5$: unshielded (3.35 hours)

Where $L = 5$ defines an average approximate cut-off shell of dipolar magnetic field lines for the indicated energy range. Because of the very short exposure duration (3.35 hours), TE need not be concerned with energetic solar proton fluxes (whether produced by ordinary event activity or by anomalously large event activity); accumulations for this part of the mission would be insignificant.

DOSE AND SHIELDING EVALUATION

Doses were calculated from the total orbit-integrated, surface incident, omnidirectional, functionally differentiated particle fluences by existing shielding codes (Watts and Burrell, 1971).

"Electron," "bremsstrahlung," "proton," and "total" aluminum doses were obtained by a plain straightforward approach: from a simple two-dimensional, infinite-slab geometry (2π steradian omnidirectional incidence) with a cosine law for the incident spectra.

More sophisticated procedures (solid angle sectoring or three-dimensional geometry) may be followed, if necessary, at a later evaluation.

STUDY RESULTS: DISCUSSION AND CONCLUSIONS

The results of this analysis are presented in tabular and graphical form, separately for each mission phase:

LEO. The orbit integrated, omnidirectional, integral daily electron and proton fluxes are given in Table 1 for both solar minimum and maximum conditions. The respective spectra are plotted in Figure 1 for the electrons and in Figure 2 for the protons. Noteworthy are the soft inner zone electron spectra, especially in regards to the steep falloff to zero flux in the energy range above 4 MeV. The apparent cutoff at these energies was established from experimental measurements after the higher energy artificials from the "Starfish" nuclear explosion had decayed down to natural background levels (Teague and Stassinopoulos, 1972).

With regard to the protons, the data display relatively hard spectra above 20 MeV.

A most interesting and potentially useful item is "flux-free" time where flux-free is defined as less than one particle per square centimeter for electrons with $E > 0.5$ MeV and protons with $E > 5$ MeV. The LEO orbit is about 86% of its total lifetime flux-free. This holds for both species of particles. In terms of continuous, uninterrupted, flux-free time intervals, the trajectory has about six consecutive revolutions per day in that category, for a maximum duration of about 10 hours.

Figures 3 and 4 show the dose contributions and the total aluminum dose for solar minimum and solar maximum conditions, respectively. When making a comparison of these dose-depth curves, it is necessary

ORBITAL RADIATION STUDY

(SOURCE: E. G. STASSINOPOULOS, NASA — GSFC, 1978)

LOW EARTH ORBIT RADIATION ENVIRONMENT: LEO

(CIRCULAR ORBIT, INCLINATION 30°, ALTITUDE = 500 km)

DAILY TRAPPED PARTICLE FLUXES

(AVERAGE ORBIT INTEGRATED, OMNIDIRECTIONAL, INTEGRAL, DAILY INTENSITIES)

ELECTRONS*			PROTONS*		
E (>MeV)	SOLAR MIN	SOLAR MAX	E (>MeV)	SOLAR MIN	SOLAR MAX
.1	4.587E 09	1.036E 10	5.0	9.344E 06	5.140E 06
.5	1.532E 08	2.253E 08	10.0	8.584E 06	4.712E 06
1.0	2.760E 07	2.761E 07	20.0	7.568E 06	4.204E 06
1.5	1.041E 07	1.041E 07	30.0	6.902E 06	3.862E 06
2.0	4.613E 06	4.613E 06	40.0	6.038E 06	3.557E 06
2.5	2.119E 06	2.119E 06	50.0	5.771E 06	3.279E 06
3.0	3.595E 05	3.595E 05	60.0	5.224E 06	3.005E 06
3.5	4.046E 04	4.046E 04	70.0	4.734E 06	2.758E 06
4.0	1.744E 03	1.745E 03	80.0	4.296E 06	2.533E 06
4.5	—	—	90.0	3.901E 06	2.329E 06
5.0	—	—	100.0	3.546E 06	2.143E 06
5.5	—	—	150.0	2.108E 06	1.320E 06
6.0	—	—	200.0	1.272E 06	8.261E 05
6.5	—	—	300.0	4.668E 05	3.040E 05
7.0	—	—	400.0	1.747E 05	1.139E 05
			500.0	6.632E 04	4.281E 04

* UNCERTAINTY FACTORS WERE NOT APPLIED TO THE DATA

EPOCH: 1979

MODELS: FIELD-BARRACLOUGH/75

ELECTRONS = IZ AE6 (SOLAR MAX)

= IZ AE5 (SOLAR MIN)

TRAPPED PROTONS = AP8 - MAC (SOLAR MAX)

= AP8 - MIC (SOLAR MIN)

MISSION DURATION: T = 1 DAY

Table 1

ORBITAL RADIATION STUDY

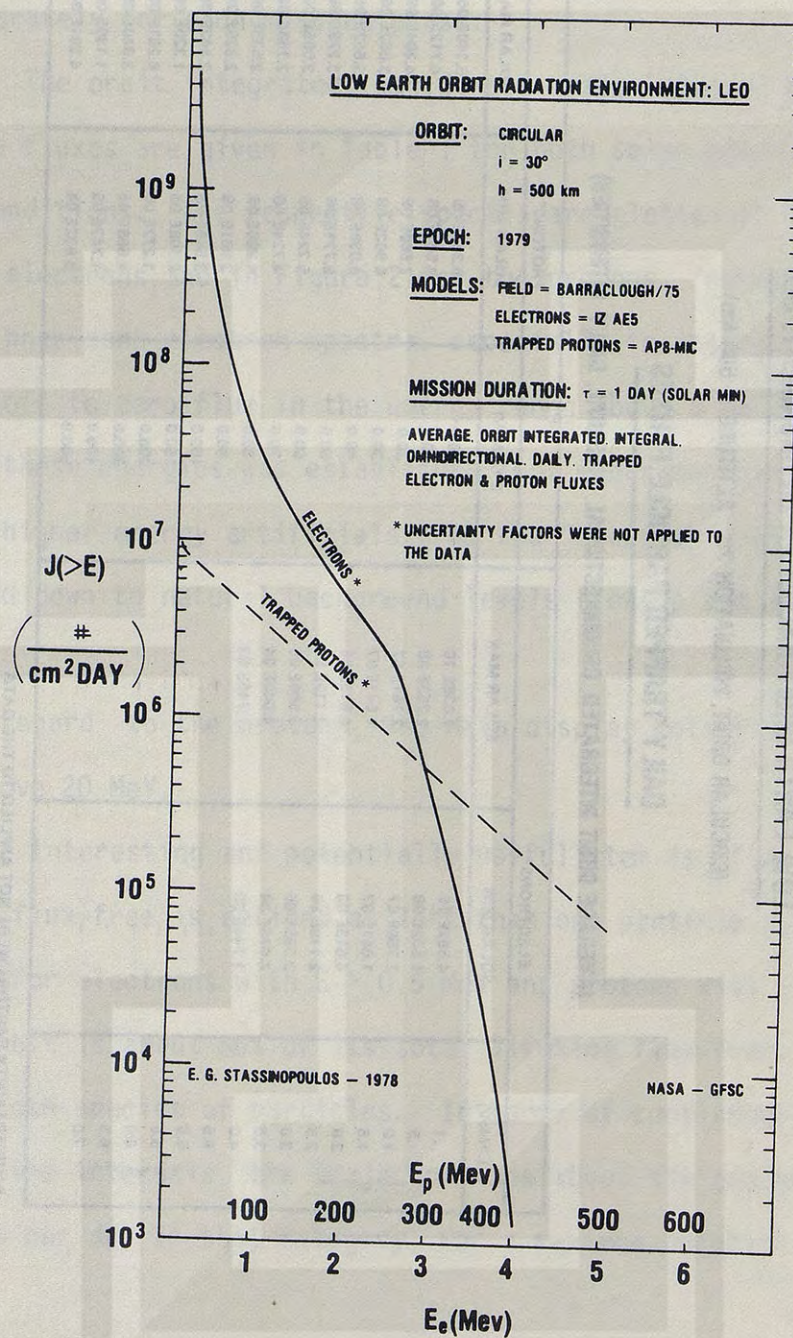


Figure 1. LEO: Electron and proton spectral profiles of orbit-integrated daily fluxes for solar minimum.

ORBITAL RADIATION STUDY

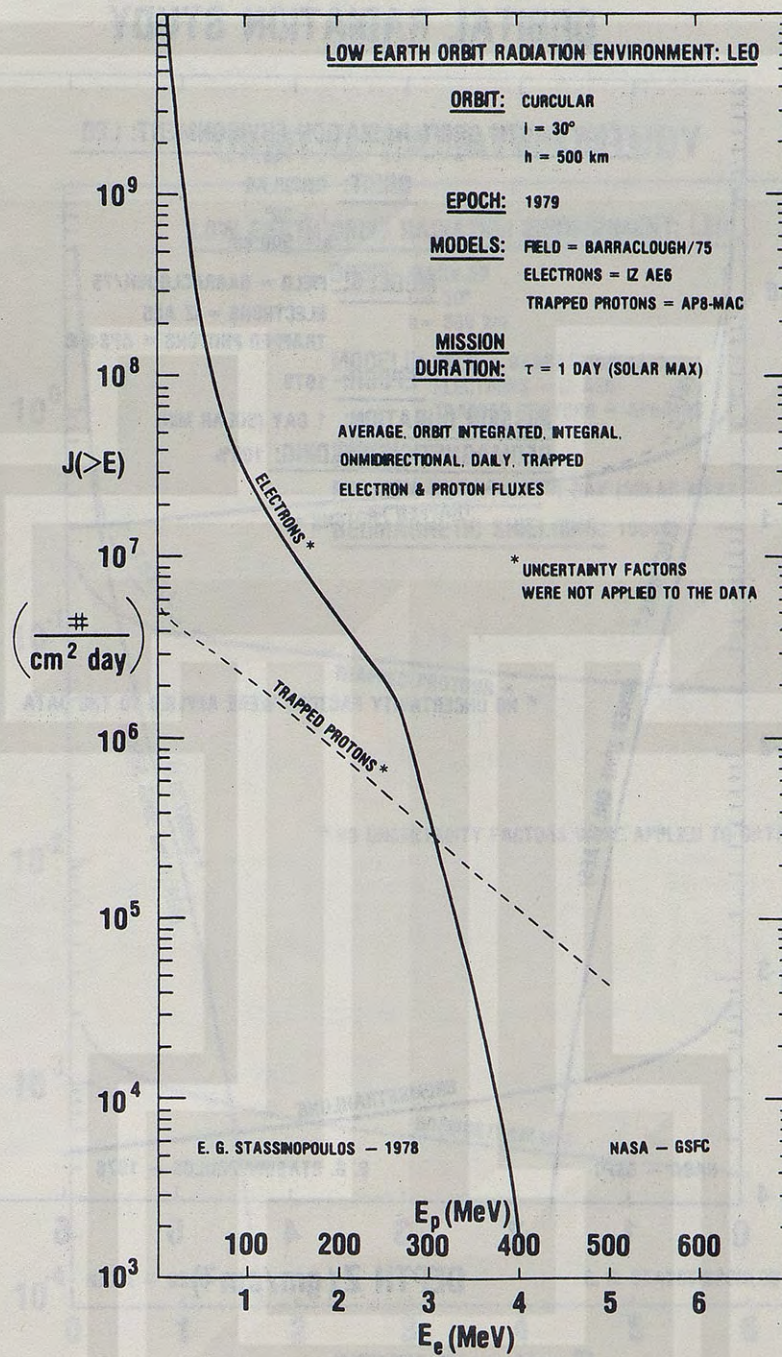


Figure 2. LEO: Electron and proton spectral profiles of orbit-integrated daily fluxes for solar maximum.

ORBITAL RADIATION STUDY

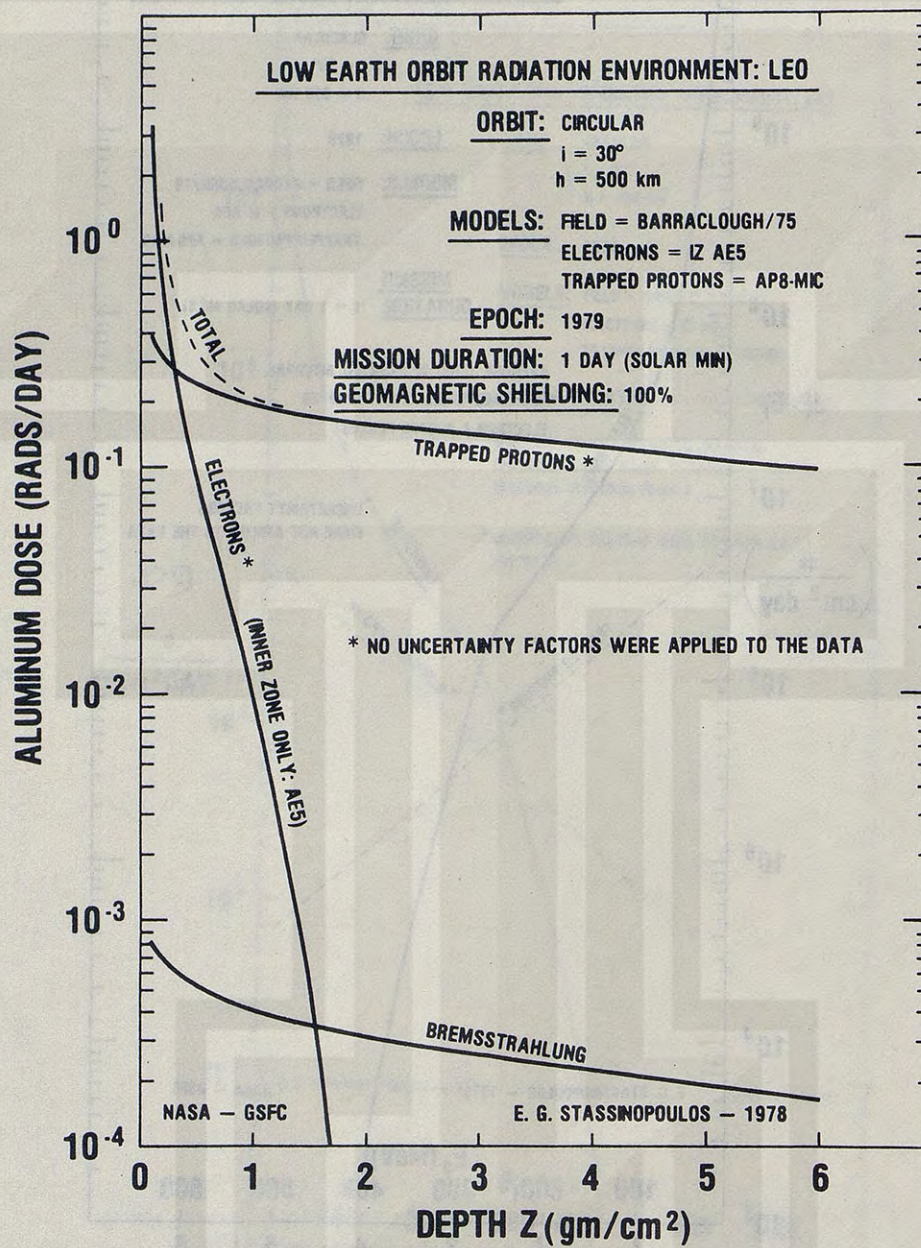


Figure 3. LEO: Dose-depth curves for solar minimum.

ORBITAL RADIATION STUDY

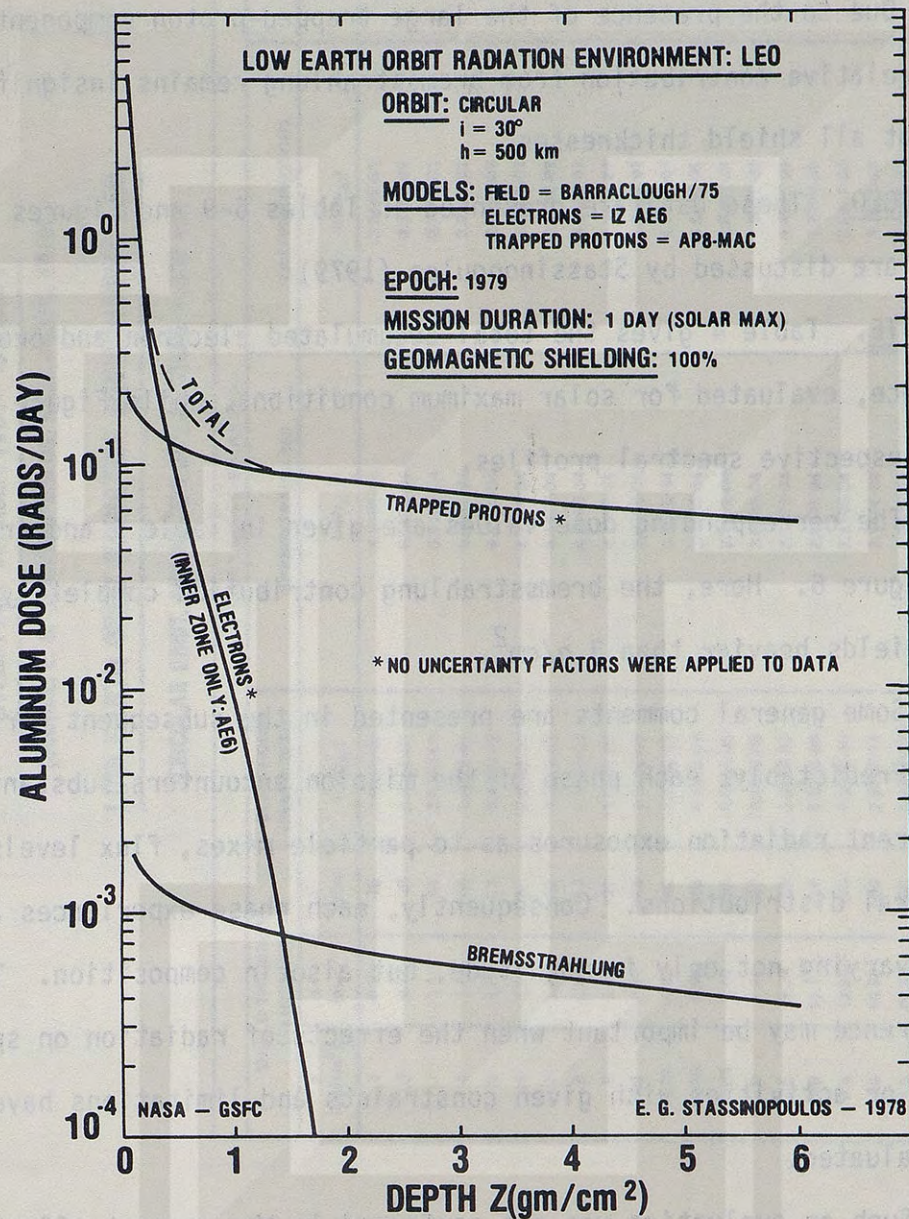


Figure 4. LEO: Dose-depth curves for solar maximum.

to remember that electron intensities are higher during solar maximum, and hence so is the dose from bremsstrahlung, while proton intensities are higher during solar minimum.

Due to the presence of the large trapped-proton component, the relative contribution from bremsstrahlung remains insignificantly low at all shield thicknesses.

GEO. These data are presented in Tables 6-9 and Figures 7-11. They are discussed by Stassinopoulos (1979)

TE. Table 4 gives the total accumulated electron and proton fluence, evaluated for solar maximum conditions, while Figure 5 plots the respective spectral profiles.

The corresponding dose values are given in Table 5 and are plotted in Figure 6. Here, the bremsstrahlung contribution completely dominates at shields heavier than 3 g/cm^2 .

Some general comments are presented in the subsequent paragraphs.

Predictably, each phase of the mission encounters substantially different radiation exposures as to particle mixes, flux levels, and spectral distributions. Consequently, each phase experiences a dose rate varying not only in magnitude, but also in composition. This difference may be important when the effects of radiation on specific tasks or activities with given constraints and limitations have to be evaluated.

Such an evaluation was not performed in the present effort. It was not in the scope of this study to determine the impact of the particular radiation estimates on specific mission objectives.

ORBITAL RADIATION STUDY

(SOURCE: E. G. STASSINOPOULOS, NASA—GSFC, 1978)

LOW EARTH ORBIT RADIATION ENVIRONMENT: LEO

(CIRCULAR ORBIT, INCLINATION 30°, ALTITUDE = 500 km)

DAILY DOSES: SOLAR MIN.						
SHIELD THICKNESS (ALUMINUM)			ELECTRONS (INNER ZONE)	BREMSSTRAHLUNG	TRAPPED PROTONS	TOTAL DOSE
z (gm/cm ²)	t (mm)	t (mils)	(rads _{Al})	(rads _{Al})	(rads _{Al})	(rads _{Al})
.1	0.37	15	2.935E-00	8.200E-04	3.844E-01	3.318E-00
.2	0.74	29	6.905E-01	6.681E-04	3.110E-01	1.011E-00
.3	1.11	44	2.929E-01	5.913E-04	2.732E-01	5.666E-01
.4	1.48	58	1.561E-01	5.406E-04	2.498E-01	4.064E-01
.5	1.85	73	9.293E-02	5.033E-04	2.331E-01	3.264E-01
.6	2.22	87	5.827E-02	4.738E-04	2.209E-01	2.797E-01
.7	2.59	102	3.738E-02	4.497E-04	2.114E-01	2.492E-01
.8	2.96	117	2.399E-02	4.296E-04	2.032E-01	2.257E-01
.9	3.33	131	1.514E-02	4.121E-04	1.962E-01	2.118E-01
1.0	3.70	146	9.294E-03	3.967E-04	1.903E-01	2.022E-01
1.25	4.63	182	2.278E-03	3.651E-04	1.786E-01	1.812E-01
1.50	5.56	219	4.323E-04	3.403E-04	1.695E-01	1.703E-01
1.75	6.48	255	6.858E-05	3.197E-04	1.620E-01	1.624E-01
2.0	7.41	292	9.453E-06	3.023E-04	1.567E-01	1.559E-01
2.5	9.26	365	1.210E-07	2.737E-04	1.457E-01	1.460E-01
3.0	11.11	437	6.878E-09	2.507E-04	1.377E-01	1.380E-01
3.5	12.96	510	4.358E-10	2.314E-04	1.291E-01	1.293E-01
4.0	14.81	583	2.929E-11	2.147E-04	1.202E-01	1.204E-01
4.5	16.67	656	2.030E-12	2.000E-04	1.126E-01	1.128E-01
5.0	18.52	729	1.413E-13	1.869E-04	1.065E-01	1.067E-01
5.5	20.37	802	9.620E-15	1.750E-04	1.018E-01	1.020E-01
6.0	22.22	875	6.260E-16	1.641E-04	9.779E-02	9.798E-02

Table 2

ORBITAL RADIATION STUDY

(SOURCE: E. G. STASSINOPOULOS, NASA-GSFC, 1978)

LOW EARTH ORBIT RADIATION ENVIRONMENT: LEO

(CIRCULAR ORBIT, INCLINATION 30°, ALTITUDE = 500 km)

DAILY DOSE: SOLAR MAX.						
SHIELD THICKNESS (ALUMINUM)			ELECTRONS (INNER ZONE)	BREMSSTRAHLUNG	TRAPPED PROTONS	TOTAL DOSE
z (gm/cm ²)	t (mm)	t (mils)	(rads _{Al})	(rads _{Al})	(rads _{Al})	(rads _{Al})
.1	0.37	15	5.528E-00	1.892E-03	2.038E-01	5.735E-00
.2	0.74	29	8.539E-01	1.543E-03	1.630E-01	1.018E-00
.3	1.11	44	3.128E-01	1.367E-03	1.432E-01	4.574E-01
.4	1.48	58	1.588E-01	1.249E-03	1.313E-01	2.913E-01
.5	1.85	73	9.328E-02	1.163E-03	1.230E-01	2.174E-01
.6	2.22	87	5.833E-02	1.095E-03	1.169E-01	1.763E-01
.7	2.59	102	3.737E-02	1.040E-03	1.122E-01	1.506E-01
.8	2.96	117	2.400E-02	9.932E-04	1.084E-01	1.330E-01
.9	3.33	131	1.516E-02	9.530E-04	1.044E-01	1.206E-01
1.0	3.70	146	9.292E-03	9.174E-04	1.014E-01	1.115E-01
1.25	4.63	182	2.278E-03	8.450E-04	9.514E-02	9.831E-02
1.5	5.56	219	4.324E-04	7.870E-04	9.041E-02	9.162E-02
1.75	6.48	255	6.859E-05	7.399E-04	8.654E-02	8.735E-02
2.0	7.41	292	9.452E-06	6.991E-04	8.318E-02	8.393E-02
2.5	9.26	365	1.643E-07	6.331E-04	7.799E-02	7.862E-02
3.0	11.11	437	7.010E-09	5.801E-04	7.392E-02	7.449E-02
3.5	12.96	510	4.359E-10	5.351E-04	6.958E-02	7.010E-02
4.0	14.81	583	2.927E-11	4.966E-04	6.519E-02	6.571E-02
4.5	16.67	656	2.029E-12	4.625E-04	6.152E-02	6.198E-02
5.0	18.52	729	1.413E-13	4.320E-04	5.857E-02	5.897E-02
5.5	20.37	802	9.620E-14	4.044E-04	5.632E-02	5.671E-02
6.0	22.22	875	6.260E-16	3.793E-04	5.437E-02	5.476E-02

Table 3

ORBITAL RADIATION STUDY

(SOURCE: E. G. STASSINOPOULOS, NASA - GSFC, 1978)

ORBIT: TRANSFER ELLIPSE

INITIAL POSITION: $\phi = -172^\circ$, $\lambda = 13^\circ$, $h = 191$ km

FINAL POSITION: $\phi = -73^\circ$, $\lambda = -12^\circ$, $h = 35621$ km

TRAPPED PARTICLE FLUENCES FOR $\tau = 5.25$ HR.

(TOTAL, FLIGHT-PATH INTEGRATED, OMNIDIRECTIONAL, INTEGRAL FLUENCES)

E (>MeV)	ELECTRONS*			E (>MeV)	PROTONS* (p/cm ²)
	INNER ZONE (e/cm ²)	OUTER ZONE (e/cm ²)	TOTAL (e/cm ²)		
.10	3.264E 09	3.987E 11	4.020E 11	5.	7.910E 06
.50	4.555E 07	8.756E 10	8.762E 10	10.	9.164E 05
1.00	1.513E 06	3.020E 10	3.020E 10	20.	1.714E 05
1.25	8.019E 05	1.912E 10	1.912E 10	30.	7.557E 04
1.50	4.303E 05	1.235E 10	1.235E 10	40.	4.635E 04
1.75	2.326E 05	8.139E 09	8.139E 09	50.	2.974E 04
2.00	1.263E 05	5.462E 09	5.463E 09	60.	2.135E 04
2.25	6.568E 04	3.979E 09	3.979E 09	70.	1.541E 04
2.50	3.430E 04	2.926E 09	2.926E 09	80.	1.237E 04
2.75	1.508E 04	2.168E 09	2.168E 09	90.	8.271E 03
3.00	6.568E 03	1.616E 09	1.616E 09	100.	6.101E 03
3.25	3.009E 03	1.311E 09	1.311E 09	125.	3.003E 03
3.50	1.395E 03	1.066E 09	1.066E 09	150.	1.503E 03
4.00	3.498E 02	7.060E 08	7.060E 08	175.	7.929E 02
4.50	-	3.414E 08	3.414E 08	200.	3.629E 02
5.00	-	1.655E 08	1.655E 08	250.	-
5.50	-	4.917E 07	4.917E 07	300.	-
6.00	-	1.464E 07	1.464E 07	350.	-
6.50	-	1.411E 06	1.411E 06	400.	-
7.00	-	-	-	500.	-

*UNCERTAINTY FACTORS WERE NOT APPLIED TO THE DATA

EPOCH: 1979

MODELS: FIELD = BARRACLOUGH/75

ELECTRONS = IZ AE6

OZ AE17-HI

TRAPPED PROTONS = AP8 - MAC

MISSION DURATION: TRANSFER FLIGHT

TIME $\tau = 5.25$ HOURS

Table 4

(SOURCE: E. G. STASSINOPOULOS, NASA — GSFC, 1978)

INITIAL POSITION: $\phi = -172^\circ$, $\lambda = 13^\circ$, $h = 191$ km

FINAL POSITION: $\phi = -73^\circ$, $\lambda = -12^\circ$, $h = 35621$ km

ALUMINUM DOSE FOR $\tau = 5.25$ HOURS						
SHIELD THICKNESS (ALUMINUM)			ELECTRONS	BREMSSTRAHLUNG	TRAPPED PROTONS	TOTAL DOSE
z (gm/cm ²)	t (mm)	t (mils)	(rads _{Al})	(rads _{Al})	(rads _{Al})	(rads _{Al})
.10	0.37	15	1.293E 03	3.985E-01	5.536E-01	1.294E 03
.20	0.74	29	5.610E 02	2.903E-01	1.339E-01	5.614E 02
.30	1.11	44	2.980E 02	2.513E-01	6.473E-02	2.983E 02
.40	1.48	58	1.728E 02	2.275E-01	3.725E-02	1.731E 02
.50	1.85	73	1.075E 02	2.106E-01	2.381E-02	1.077E 02
.60	2.22	87	7.030E 01	1.975E-01	1.690E-02	7.051E 01
.70	2.59	102	4.773E 01	1.870E-01	1.281E-02	4.793E 01
.80	2.96	117	3.350E 01	1.782E-01	1.001E-02	3.369E 01
.90	3.33	131	2.419E 01	1.706E-01	8.085E-03	2.437E 01
1.00	3.70	146	1.791E 01	1.640E-01	6.700E-03	1.808E 01
1.25	4.63	182	9.110E 00	1.506E-01	4.633E-03	9.265E 00
1.50	5.56	219	4.901E 00	1.401E-01	3.514E-03	5.045E 00
1.75	6.48	255	2.608E 00	1.315E-01	2.826E-03	2.742E 00
2.00	7.41	292	1.307E 00	1.242E-01	2.339E-03	1.434E 00
2.50	9.26	365	2.535E-01	1.125E-01	1.701E-03	3.677E-01
3.00	11.11	437	3.502E-02	1.032E-01	1.317E-03	1.395E-01
3.50	12.96	510	3.770E-03	9.547E-02	1.052E-03	1.003E-01
4.00	14.81	583	3.685E-04	8.894E-02	8.606E-04	9.017E-02
4.50	16.67	656	3.578E-05	8.324E-02	7.282E-04	8.400E-02
5.00	18.52	729	3.450E-06	7.815E-02	6.257E-04	7.878E-02
5.50	20.37	802	3.233E-07	7.366E-02	5.485E-04	7.421E-02
6.00	22.22	875	2.885E-08	6.952E-02	4.851E-04	7.001E-02

Table 5

ORBITAL RADIATION STUDY

(SOURCE: E. G. STASSINOPOULOS, NASA — GSFC, 1978)

ORBIT: SYNCHRONOUS—GEOSTATIONARY

(INCLINATION = 0°, ALTITUDE = 35790 km, PARKING LONGITUDE = 160°W & 70°W)

TRAPPED ELECTRON FLUXES

(AVERAGE, ORBIT INTEGRATED, OMNIDIRECTIONAL, INTEGRAL, DAILY INTENSITIES)

E (> MeV)	WORST CASE:	BEST CASE:
	$\phi_p = 160^\circ\text{W}$ (e/cm ² DAY)	$\phi_p = 70^\circ\text{W}$ (e/cm ² DAY)
.1	1.878E 12	1.446E 12
.5	2.789E 11	1.769E 11
1.0	5.861E 10	3.018E 10
1.5	1.375E 10	6.243E 09
2.0	3.224E 09	1.292E 09
2.5	8.832E 08	2.800E 08
3.0	2.419E 08	6.069E 07
3.5	1.313E 08	2.716E 07
4.0	7.122E 07	1.215E 07
4.5	3.153E 07	4.443E 06
5.0	1.396E 07	1.624E 06
5.5	3.862E 06	3.749E 05
6.0	1.069E 06	6.070E 04
6.5	—	—
7.0	—	—

NOTE: THESE FLUXES REPRESENT LOCAL-TIME (LT) AVERAGED VALUES

ELECTRON MODEL: OZ AE17-HI: THE AE17 IS AN INTERIM MODEL THAT HAS REPLACED THE OLDER AE4 MODEL. FOR ENERGIES ABOVE 1.5 MeV THIS INTERIM MODEL CONTAINS UPPER AND LOWER LIMIT VALUES TO ACCOUNT FOR THE DISCREPANCY BETWEEN EXISTING DATA SETS. THE AE17-HI FAVORS VAMPOLA'S FIT TO THE OV1-19 DATA WHILE THE AE17-LO IS MORE REPRESENTATIVE OF ALL DATA SETS PRESENTLY AVAILABLE TO NSSDC.

Table 6

ORBITAL RADIATION STUDY

(SOURCE: E. G. STASSINOPOULOS, NASA — GSFC, 1978)

ORBIT: SYNCHRONOUS—GEOSTATIONARY

(PARKING LONGITUDE: ANY)

ENERGETIC SOLAR FLARE PROTONS

(UNATTENUATED, INTERPLANETARY, OMNIDIRECTIONAL, INTEGRAL PROTON FLUENCES)

E (> MeV)	OR* FLUENCES (p/cm ²) ⁺	AL** FLUENCES (p/cm ²) ⁺⁺	TOTAL (p/cm ²)
10	4.842E 08	1.680E 10	1.728E 10
20	4.134E 08	1.152E 10	1.193E 10
30	3.530E 08	7.900E 09	8.253E 09
40	3.014E 08	5.417E 09	5.718E 09
50	2.574E 08	3.714E 09	3.971E 09
60	2.197E 08	2.547E 09	2.767E 09
70	1.876E 08	1.746E 09	1.934E 09
80	1.602E 08	1.197E 09	1.357E 09
90	1.368E 08	8.210E 08	9.578E 08
100	1.168E 08	5.629E 08	6.797E 08
	ENCOUNTERED IN 90-DAY PERIOD WHEN NO AL EVENT OCCURS		ENCOUNTERED IN 90-DAY PERIOD WHEN ONE AL EVENT OCCURS

EPOCH: 1979

MODELS: FIELD = BARRACLOUGH/75
SOLAR FLARE PROTONS = SOLPRO

* OR = ORDINARY EVENT

**AL = ANOMALOUSLY LARGE EVENT

+ TOTAL FLUENCES FOR $\tau = 90$ DAYS

++ TOTAL FLUENCES FOR 1 AL EVENT

Table 7

ORBITAL RADIATION STUDY

(SOURCE: E. G. STASSINOPOULOS, NASA-GSFC, 1978)

ORBIT: SYNCHRONOUS—GEOSTATIONARY

(CIRCULAR, INCLINATION 0°, ALTITUDE = 35790 km, PARKING LONGITUDES = 160°W & 70°W)

DAILY DOSE								
SHIELD THICKNESS (ALUMINUM)			PARKING LONGITUDE: 70°W			PARKING LONGITUDE: 160°W		
			ELECTRONS (OUTER ZONE)	BREMSSTRAHLUNG	TOTAL	ELECTRONS (OUTER ZONE)	BREMSSTRAHLUNG	TOTAL
Z (gm/cm ²)	t (mm)	t (mils)	(rads _{Al})	(rads _{Al})	(rads _{Al})	(rads _{Al})	(rads _{Al})	(rads _{Al})
.1	0.37	15	2.805E 03	6.060E-01	2.804E 03	4.356E 03	9.756E-01	4.359E 03
.2	0.74	29	8.307E 02	4.797E-01	8.312E 02	1.429E 03	7.625E-01	1.430E 03
.3	1.11	44	3.134E 02	4.216E-01	3.137E 02	5.879E 02	6.682E-01	5.885E 02
.4	1.48	58	1.308E 02	3.841E-01	1.312E 02	2.631E 02	6.079E-01	2.637E 02
.5	1.85	73	5.951E 01	3.567E-01	5.986E 01	1.267E 02	5.644E-01	1.272E 02
.6	2.22	87	2.841E 01	3.356E-01	2.874E 01	6.384E 01	5.304E-01	6.436E 01
.7	2.59	102	1.399E 01	3.181E-01	1.430E 01	3.326E 01	5.027E-01	3.375E 01
.8	2.96	117	7.047E 00	3.036E-01	7.351E 00	1.786E 01	4.795E-01	1.834E 01
.9	3.33	131	3.630E 00	2.910E-01	3.921E 00	9.890E 00	4.595E-01	1.035E 01
1.0	3.70	146	1.918E 00	2.800E-01	2.198E 00	5.663E 00	4.422E-01	6.107E 00
1.25	4.63	182	4.496E-01	2.574E-01	7.068E-01	1.664E 00	4.063E-01	2.071E 00
1.5	5.56	219	1.383E-01	2.396E-01	3.778E-01	6.351E-01	3.781E-01	1.013E 00
1.75	6.48	255	5.186E-02	2.250E-01	2.770E-01	2.825E-01	3.551E-01	6.375E-01
2.0	7.41	292	2.030E-02	2.127E-01	2.330E-01	1.274E-01	3.356E-01	4.630E-01
2.5	9.26	365	2.733E-03	1.926E-01	1.953E-01	2.254E-02	3.038E-01	3.263E-01
3.0	11.11	437	3.071E-04	1.765E-01	1.768E-01	3.504E-03	2.786E-01	2.822E-01
3.5	12.96	510	3.400E-05	1.632E-01	1.632E-01	5.595E-04	2.576E-01	2.582E-01
4.0	14.81	583	3.926E-06	1.517E-01	1.517E-01	9.271E-05	2.397E-01	2.398E-01
4.5	16.67	656	4.600E-07	1.417E-01	1.417E-01	1.542E-05	2.239E-01	2.239E-01
5.0	18.52	729	5.337E-08	1.328E-01	1.328E-01	2.517E-06	2.099E-01	2.100E-01
5.5	20.37	802	5.995E-09	1.247E-01	1.247E-01	3.959E-07	1.974E-01	1.974E-01
6.0	22.22	875	6.414E-10	1.174E-01	1.174E-01	5.948E-08	1.859E-01	1.859E-01

Table 8

ORBITAL RADIATION STUDY

(SOURCE: E. G. STASSINOPOULOS, NASA-GSFC, 1978)

ORBIT: SYNCHRONOUS—GEOSTATIONARY

(CIRCULAR, INCLINATION 0°, ALTITUDE = 35790 km, PARKING LONGITUDES = 160°W & 70°W)

DOSE FOR 90 DAYS								
SHIELD THICKNESS (ALUMINUM)			PARKING LONGITUDE: 70°W			PARKING LONGITUDE: 160°W		
			ELECTRONS (OUTER ZONE)	BREMSSTRAHLUNG	TOTAL	ELECTRONS (OUTER ZONE)	BREMSSTRAHLUNG	TOTAL
z (gm/cm ²)	t (mm)	t (mils)	(rads _{Al})	(rads _{Al})	(rads _{Al})	(rads _{Al})	(rads _{Al})	(rads _{Al})
.1	0.37	15	2.525E 05	5.454E 01	2.525E 06	3.921E 05	8.781E 01	3.923E 05
.2	0.74	29	7.476E 04	4.318E 01	7.481E 04	1.286E 05	6.862E 01	1.287E 05
.3	1.11	44	2.821E 04	3.795E 01	2.823E 04	5.292E 04	6.014E 01	5.296E 04
.4	1.48	58	1.177E 04	3.457E 01	1.181E 04	2.368E 04	5.472E 01	2.373E 04
.5	1.85	73	5.356E 03	3.210E 01	5.388E 03	1.140E 04	5.079E 01	1.145E 04
.6	2.22	87	2.557E 03	3.021E 01	2.587E 03	5.745E 03	4.774E 01	5.792E 03
.7	2.59	102	1.259E 03	2.863E 01	1.287E 03	2.993E 03	4.525E 01	3.038E 03
.8	2.96	117	6.342E 02	2.732E 01	6.616E 02	1.607E 03	4.315E 01	1.651E 03
.9	3.33	131	3.267E 02	2.619E 01	3.528E 02	8.901E 02	4.135E 01	9.316E 02
1.0	3.70	146	1.726E 02	2.520E 01	1.978E 02	5.097E 02	3.980E 01	5.496E 02
1.25	4.63	182	4.046E 01	2.316E 01	6.362E 01	1.497E 02	3.657E 01	1.864E 02
1.50	5.56	219	1.244E 01	2.157E 01	3.400E 01	5.716E 01	3.403E 01	9.121E 01
1.75	6.48	255	4.668E 00	2.025E 01	2.493E 01	2.542E 01	3.196E 01	5.738E 01
2.0	7.41	292	1.827E 00	1.914E 01	2.097E 01	1.147E 01	3.021E 01	4.167E 01
2.5	9.26	365	2.459E-01	1.733E 01	1.758E 01	2.029E 00	2.735E 01	2.937E 01
3.0	11.11	437	2.764E-02	1.589E 01	1.592E 01	3.154E-01	2.508E 01	2.540E 01
3.5	12.96	510	3.060E-03	1.469E 01	1.469E 01	5.035E-02	2.319E 01	2.324E 01
4.0	14.81	583	3.533E-04	1.366E 01	1.366E 01	8.344E-03	2.157E 01	2.158E 01
4.5	16.67	656	4.140E-05	1.275E 01	1.275E 01	1.388E-03	2.016E 01	2.016E 01
5.0	18.52	729	4.803E-06	1.195E 01	1.195E 01	2.265E-04	1.890E 01	1.890E 01
5.5	20.37	802	5.395E-07	1.122E 01	1.122E 01	3.563E-05	1.776E 01	1.776E 01
6.0	22.22	875	5.772E-08	1.056E 01	1.056E 01	5.353E-06	1.673E 01	1.673E 01

Table 9

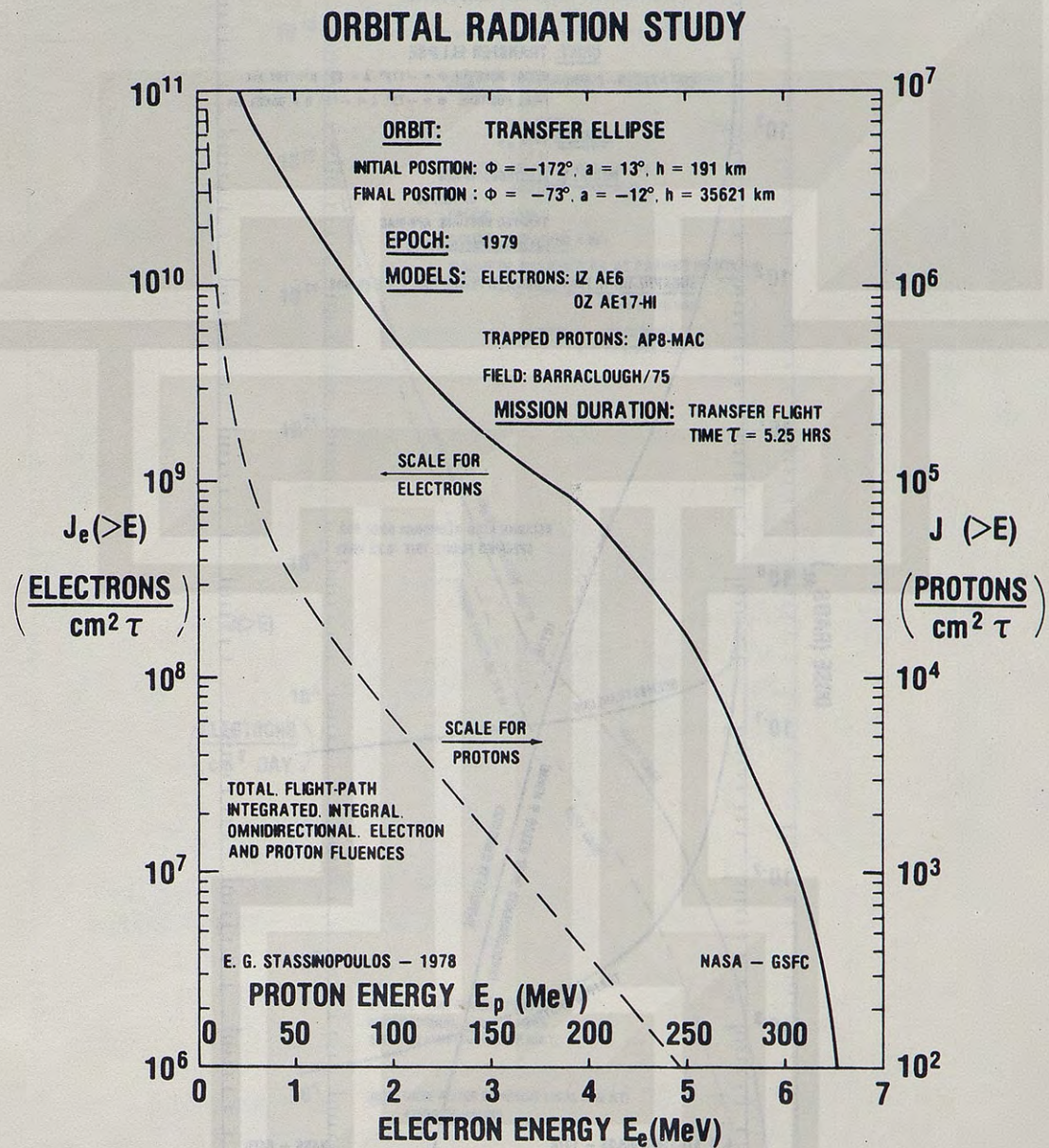


Figure 5. TE: Electron and proton spectral profiles of total accumulated fluences for solar maximum.

ORBITAL RADIATION STUDY

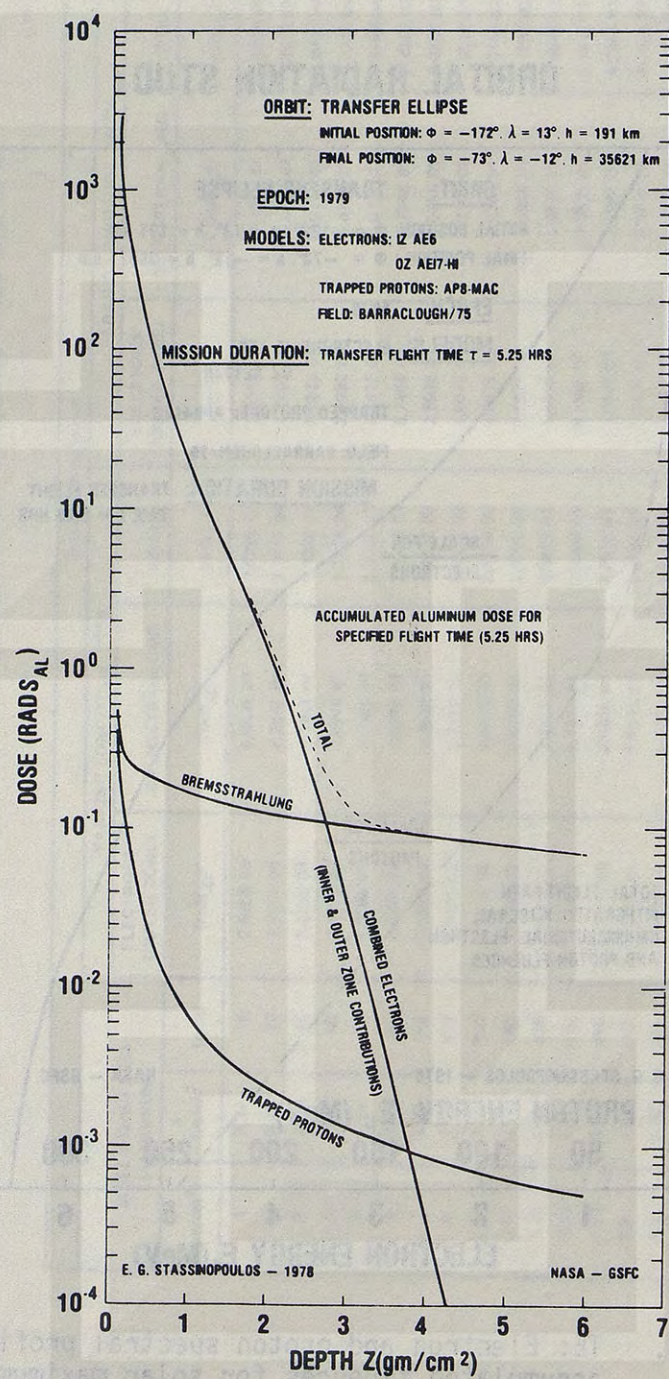


Figure 6. TE: Dose-depth curves for solar maximum.

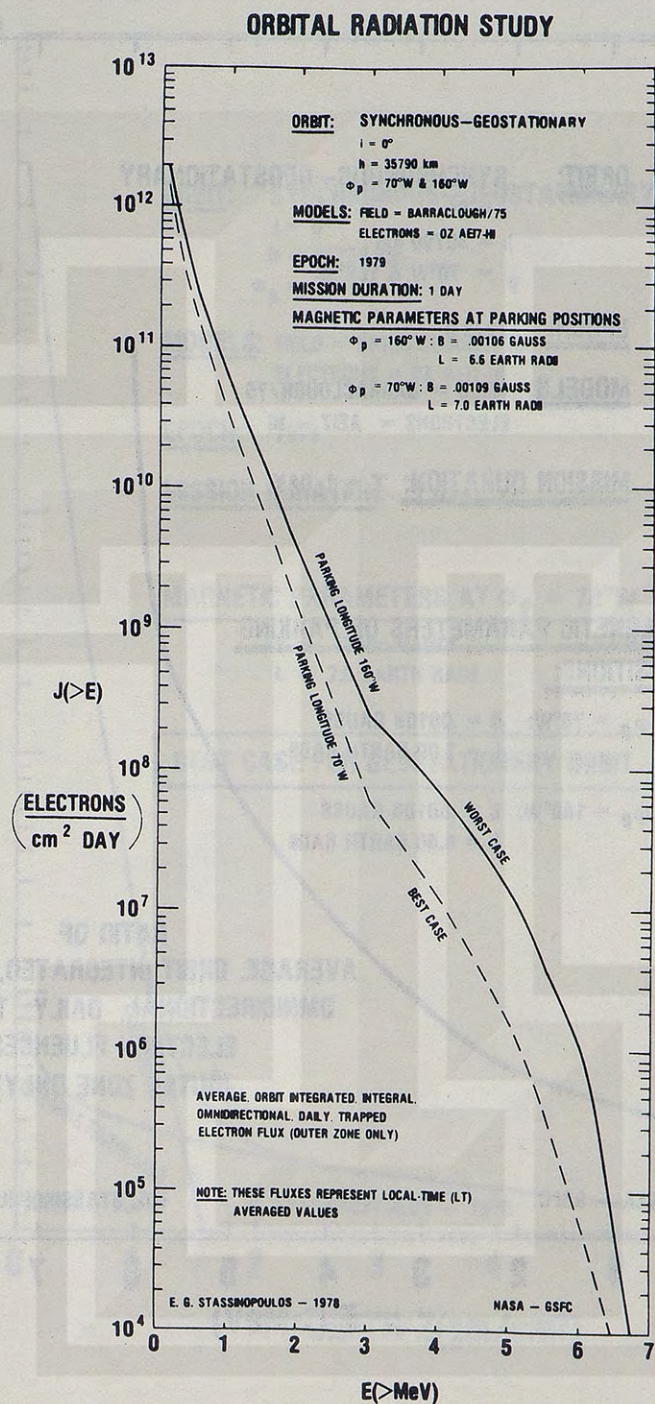


Figure 7. GEO: Electron spectral profiles for best and worst case longitudinal parking positions.

ORBITAL RADIATION STUDY

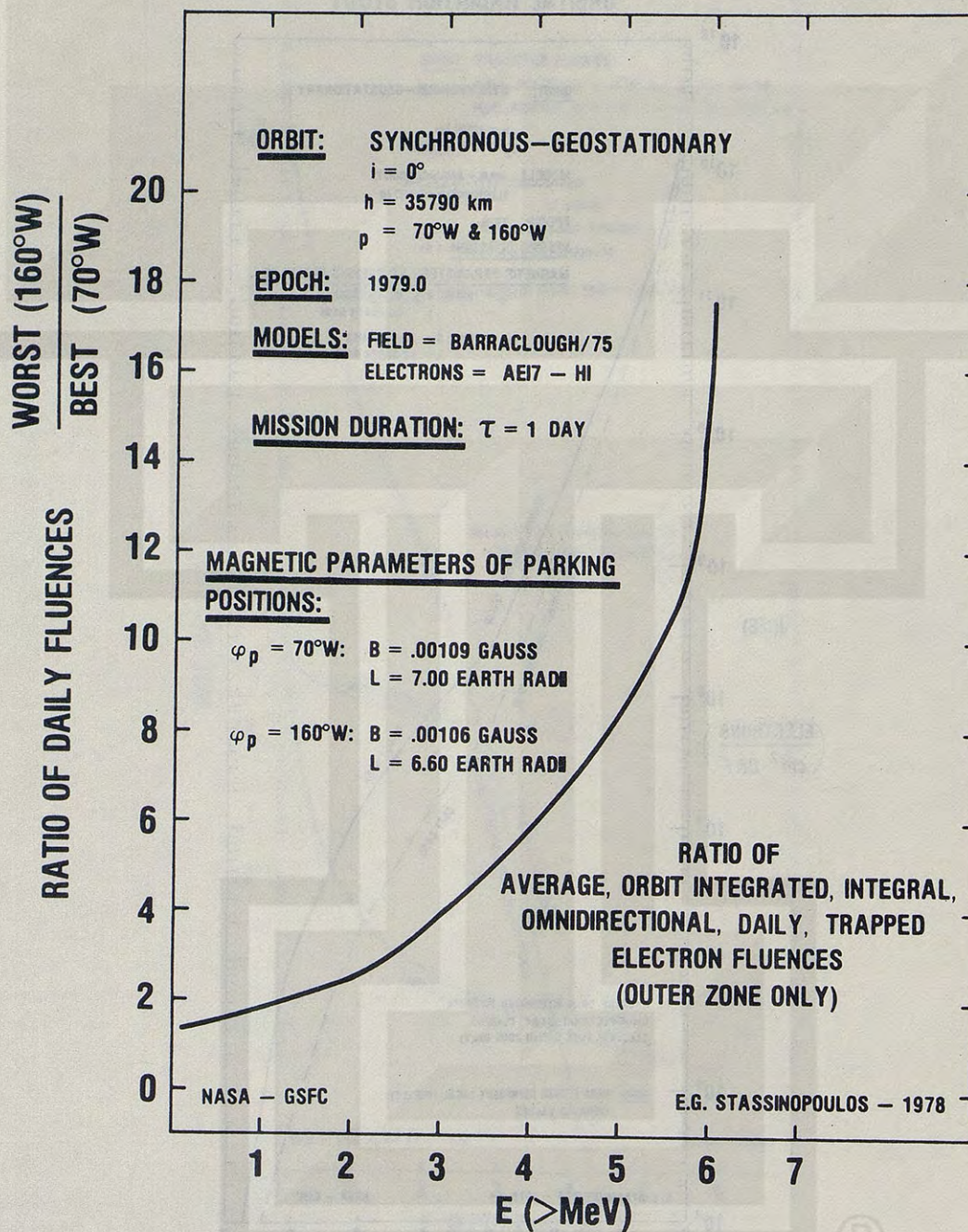


Figure 8. GEO: Ratio of worst to best case daily electron fluences.

ORBITAL RADIATION STUDY

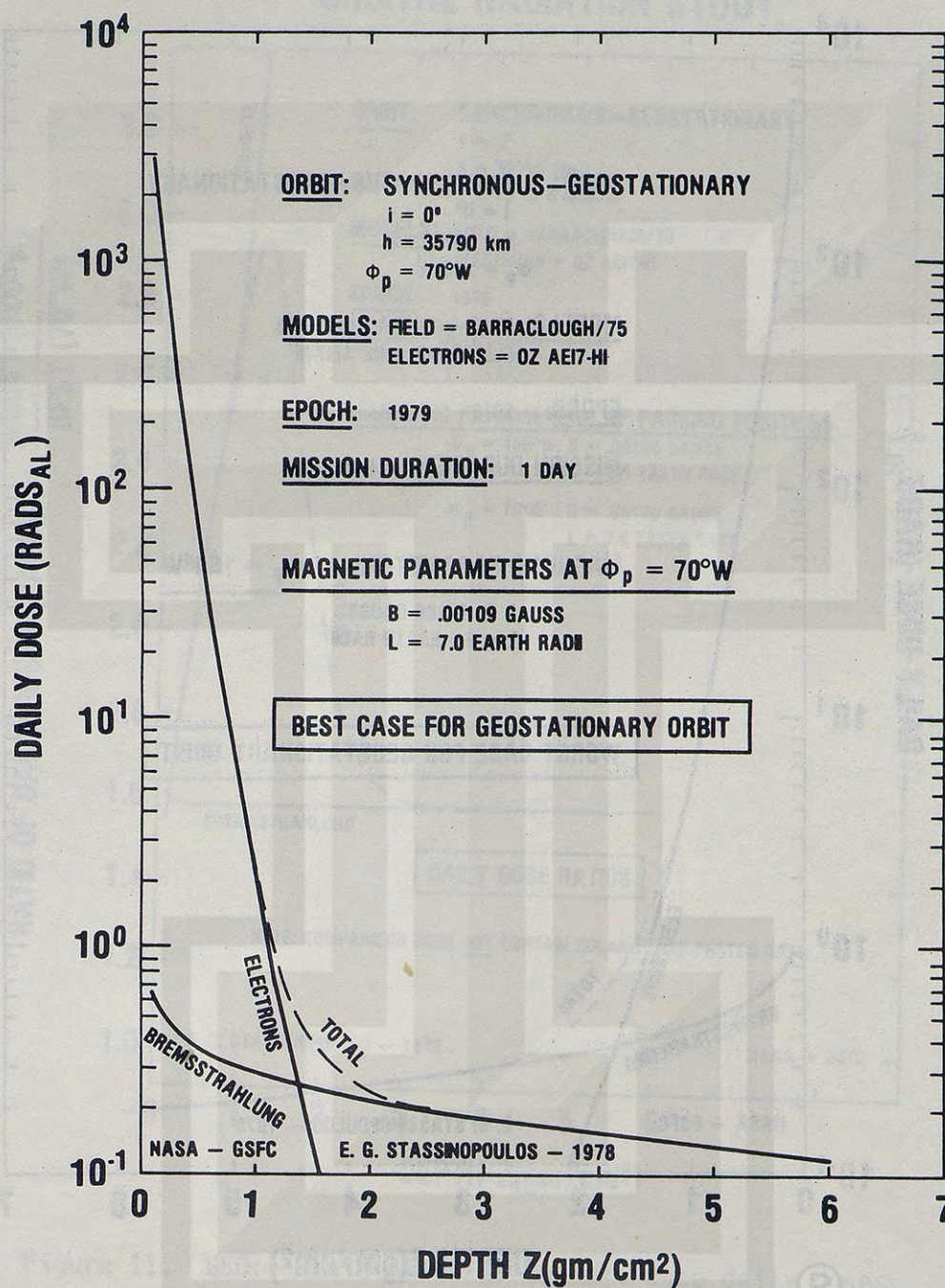


Figure 9. GEO: Dose-depth curves for best case in longitudinal parking position.

ORBITAL RADIATION STUDY

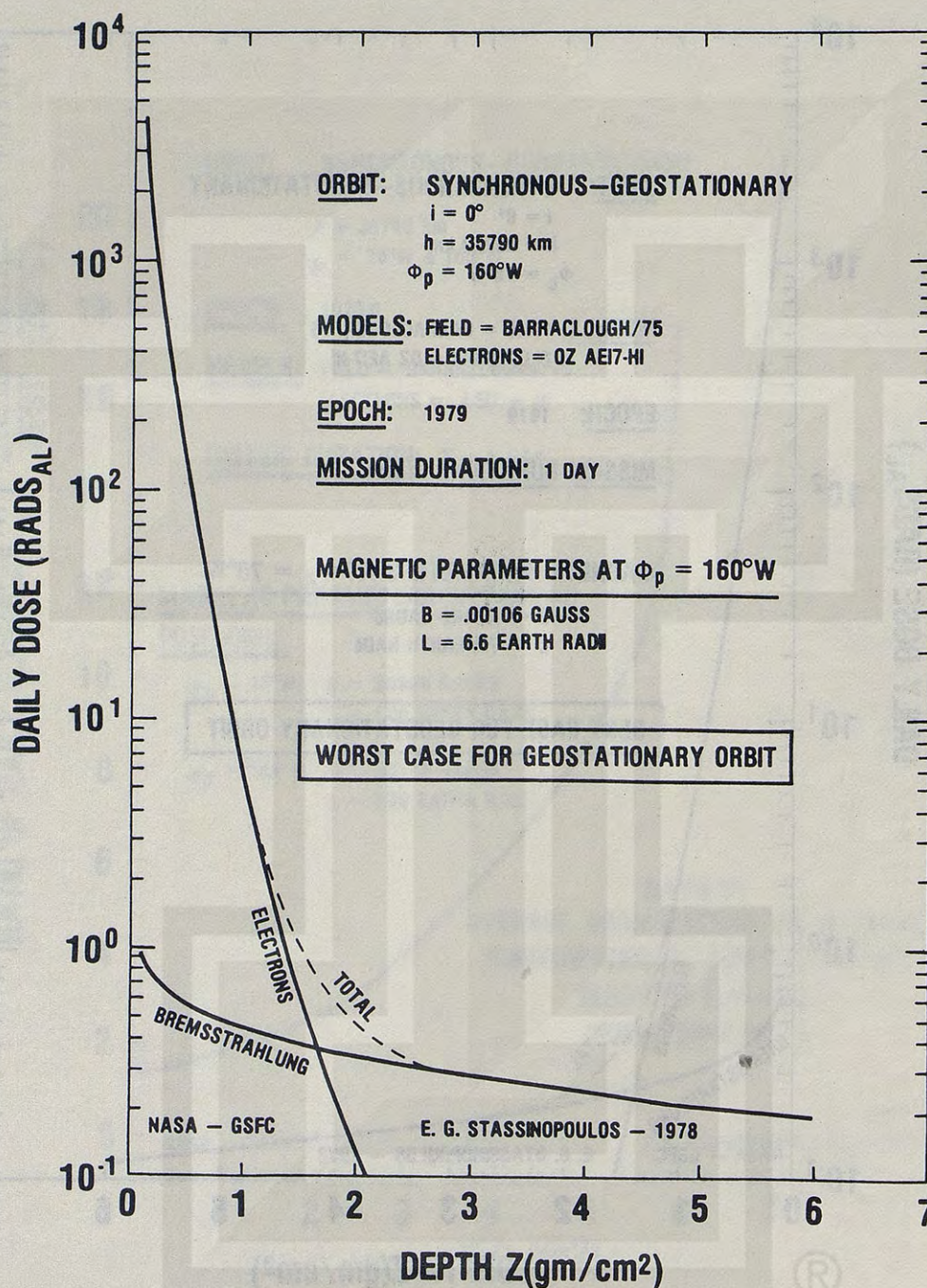


Figure 10. GEO: Dose-depth curves for worst case in longitudinal parking position.

ORBITAL RADIATION STUDY

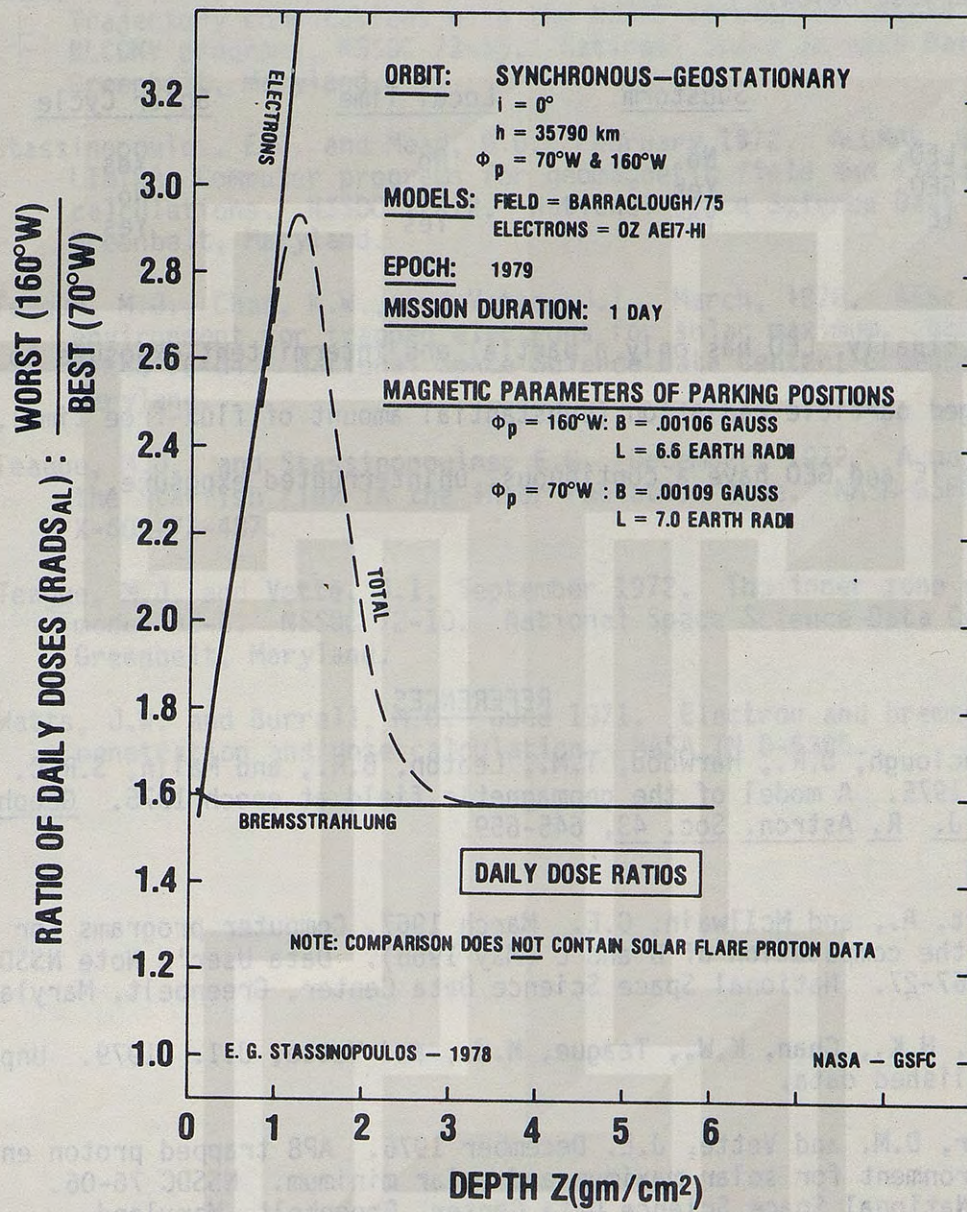


Figure 11. GEO: Ratio of worst to best case daily doses.

There is one other point of interest. The individual phases are not identically affected by variations in the environment, as summarized below.

	<u>Substorm</u>	<u>Local Time</u>	<u>Solar Cycle</u>
LEO	No	No	Yes
GEO	Yes	Yes	No
TE	Yes	Yes	Yes

Finally, LEO has only a partial and intermittent exposure to charged particle radiation (substantial amount of flux-free time), while TE and GEO have a continuous, uninterrupted exposure.

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A PRELIMINARY EVALUATION OF THE IONIZING-RADIATION
ENVIRONMENT OF THE SATELLITE POWER SYSTEM

Richard Madey

Kent State University
Kent, Ohio 44242

SATELLITE POWER SYSTEM

A Satellite Power System (SPS) consists of many satellites in geostationary orbits. Each satellite generates electrical power from the sun, and then transmits that power to the earth by means of a microwave beam. Glaser (1968) first suggested this concept. Typically, each satellite provides 5,000 electrical megawatts (= 5 GW) of power at the utility interface on the ground. This power generation capacity is sufficient to meet the requirements of a major city such as Chicago or Los Angeles. An SPS program with a buildup rate to 300 GW would require 60 satellites with 5 GW capacity each.

Large solar cell arrays convert solar energy to dc electrical energy. Klystron power amplifiers, operating at a frequency of 2.45 GHz, perform the dc-to-rf conversion with an efficiency of 85% at a power level of 50 kW. A rectifying antenna (rectenna) on the ground collects and rectifies the rf energy with high efficiency (~ 80%) to dc electrical energy, which is then converted to 60 cycle ac for distribution by the utility system. The overall efficiency of the design in the current DOE/NASA Reference System Report (1979) is about 60%. At the earth's surface, the microwave beam has a maximum intensity

of 23 mW/cm^2 (which is less than one-fourth of the solar constant) and an intensity of less than 1 mW/cm^2 outside the rectenna fence line. The current U.S. exposure limit is 10 mW/cm^2 .

Because of the large size and mass of each satellite, it is necessary to construct the satellites in orbit. A typical satellite has a solar collection area of about 55 km^2 and a mass of about 50-million kg. The most straightforward approach to the construction and installation of each satellite is to transport the flight hardware to a geostationary earth orbit and to construct the entire satellite there at the operational location. In this approach, orbit-transfer vehicles (OTVs) transport the necessary construction material from a low-earth orbit (LEO) to the geostationary-earth orbit (GEO). An alternative approach with potential cost savings is to construct the power generation modules for each satellite in the LEO and to use their power-generating capability to drive them to the GEO base by electric rocket propulsion. The trip time for electric rocket propulsion is 180 days. If the satellite is constructed only partially in LEO, the remainder of the material required to complete assembly and construction in GEO is transported¹ to GEO with the power-generation modules. The LEO base is located nominally in a 500-km circular orbit at the 28.5° inclination of the

¹In the Boeing System Definition Study (1978), the LEO base has an altitude of 478 km and an inclination of 31° ; the Rockwell International SPS Concept Definition Study (1978) treated a 500-km orbital altitude at approximately 28.5° ; the Grumman Aerospace Corporation Study (1977) considered a 300 n mi (= 480 km) altitude and an inclination of 28.5° . The current concept in the Reference System Report (1979) developed jointly by DOE and NASA is largely a product of the two system definition studies conducted by Boeing (1978) and by Rockwell International (1978) combined with in-house efforts at the Johnson Space Center (JSC) and the Marshall Space Flight Center (MSFC), and several smaller contracted studies.

launch site at the Kennedy Space Center, and the GEO base in a geosynchronous (24-hour period) circular orbit at 0° inclination. The latter is presently the preferred inclination, although other inclinations are being considered (Reference Systems Report, 1979). A satellite in a circular geosynchronous orbit corotates with the geoid, as if rigidly attached, at an altitude of 35,800 km or about 5.6 earth radii. When the orbit lies in the equatorial plane, the satellite appears to be stationary to an earth observer at the equator in a meridian that is determined by conditions at injection. The satellite position at this meridian is called the parking longitude. Parking longitudes for an SPS program to meet U.S. power needs will be determined by the locations of the rectenna sites throughout the U.S. A report by Eberhardt (1977) discusses candidate locations for SPS rectifying antennas. The total crew size in orbit is about 700 at any one time, constructing two satellites simultaneously.² The construction crew works ten hours per day, six days per week. A personnel orbital transfer vehicle (POTV) delivers personnel and consumable supplies from LEO to GEO, and rotates personnel from GEO to LEO at 90-day intervals. A vehicle fueled with liquid oxygen and liquid hydrogen (LOX-LH₂) can make the trip in several hours.

RADIATION ENVIRONMENT

During the assembly, construction, operation, and maintenance of each SPS station, space workers will be exposed to the natural space radiation environments in LEO, in GEO, and in the region between

²The actual number of personnel in orbit will depend on options being evaluated (see Reference System Report, 1979).

these two orbits during orbital transfer. The penetrating radiations in space consist of protons and electrons in the geomagnetically trapped radiation, and energetic particles of solar and nonsolar origin.

The geomagnetically trapped radiation consists of two zones-- an inner zone within about 2.8 earth radii and an outer zone beyond 2.8 earth radii. The region between 2 and 3 earth radii is sometimes called the electron "slot" because of a minimum in the electron intensity; there is no "slot" in the proton distribution. The average proton energy decreases continuously with increasing distance from the earth. The omnidirectional differential flux spectra of protons can be represented by an empirical exponential formula of the form

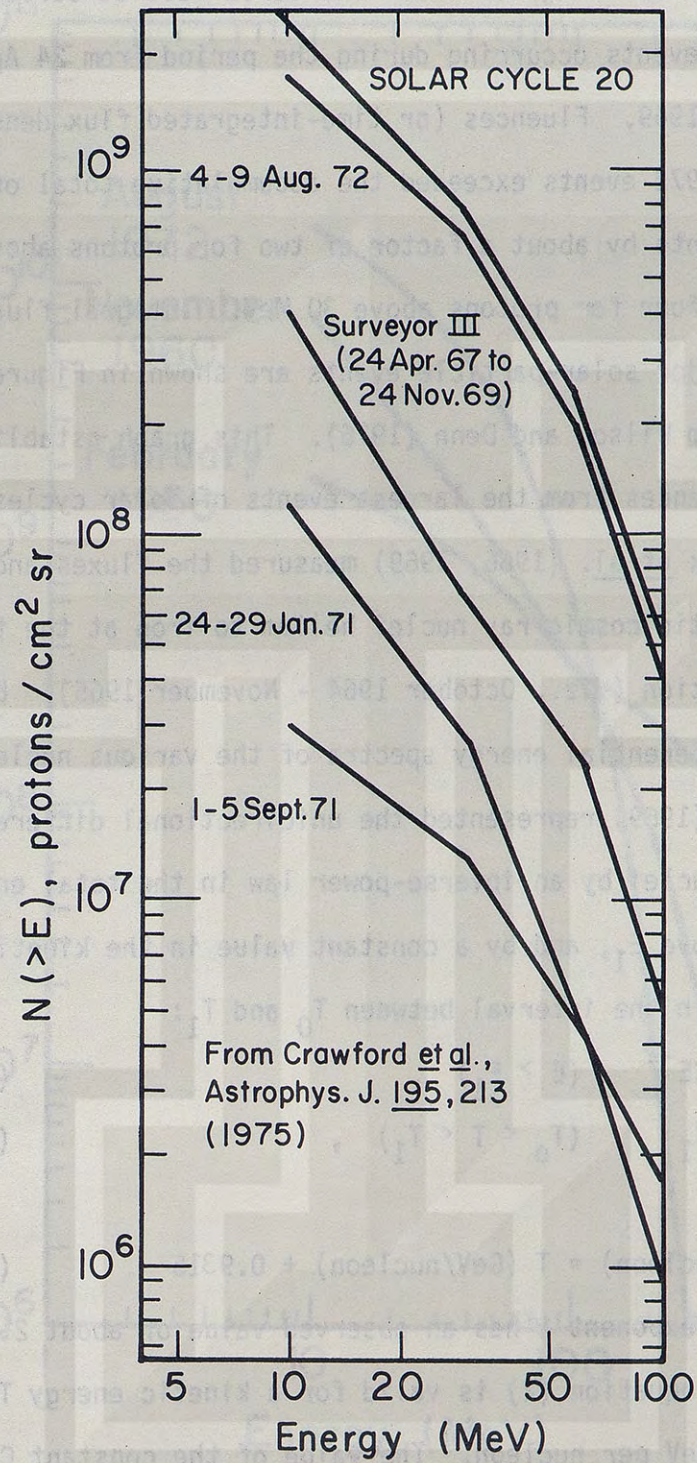
$$j(E) = C \exp (-E/E_0).$$

The characteristic proton energy E_0 varies approximately as the negative fifth power of the magnetic shell parameter L for the real geomagnetic field. For a perfect dipole field, L is the equatorial distance (measured in units of the earth's radius) to a particular magnetic field line. Time variations of the trapped proton spectrum occur as a result of atmospheric density changes with solar activity. A time-varying atmosphere causes time-varying losses since both the ionization-energy-loss rate and the nuclear-interaction-loss rate are proportional to the atmospheric density. The effect of the increase in the atmospheric density with increased solar activity is to reduce the trapped proton flux at the lower altitudes and lower energies.

The National Space Science Data Center at the NASA Goddard Space Flight Center prepares quantitative descriptions of the radiation environment in space from published data. As new data are compiled,

existing models of the electron and proton radiation environments are revised and updated. The electron and proton models are referred to as the AE and AP series, respectively. Teague and Vette (1972) describe model AE-5 and Teague et al. (1976) describe model AE-6 for the electron environments in the inner zone during periods of minimum and maximum solar activity, respectively. Sawyer and Vette (1976) describe the AP-8 models for the trapped proton environment, which are designated AP-8 MIN and AP-8 MAX for periods of minimum and maximum solar activity. Based on the assimilation of new data, there has been a significant revision of the electron environment in the outer zone. The latest model is an interim model AEI-7 developed by Teague and Vette (1978) in two versions: AEI-7HI and AEI-7LO. The former model favors fits by Vampola to the data from the OVI-19 satellite; the latter is more representative of all data sets presently available to the National Space Science Data Center. Since measurements revealed more high-energy electrons than previously assumed, computed doses in the literature need to be revised upward.

Major solar particle events are more probable during a period of high solar activity than during the solar-quiet portion of the solar cycle; specifically, experience has shown that large events tend to occur on the ascending and descending portions of the solar cycle. Typically, only a few large events produce most of the total particle fluence during a solar cycle. The total fluence per steradian for solar cycle 20 from 1964 to 1975 is shown in the uppermost curve in Figure 1, which is based on data from King (1973). The fluence in this cycle was dominated by the three events occurring during the



XBL759-4570

Figure 1. Integral proton fluxes for solar particle events during solar cycle 20. (From King, 1973)

period from 4 to 9 August 1972. The curve labeled Surveyor III includes seven major events occurring during the period from 24 April 1967 to 24 November 1969. Fluences (or time-integrated flux densities) from the August 1972 events exceeded the accumulative total of all other cycle 20 events by about a factor of two for protons above 10 MeV and a factor of four for protons above 30 MeV. Integral fluence spectra for three major solar-particle events are shown in Figure 2, which is taken from Wilson and Denn (1976). This graph establishes the range of fluences from the largest events of solar cycles 19 and 20.

Comstock et al. (1966, 1969) measured the fluxes and energy spectra of the galactic cosmic-ray nuclei helium to iron at the time of minimum solar modulation (viz., October 1964 - November 1965). Based on the reported differential energy spectra of the various nuclei, Madey and McNulty (1969) represented the unidirectional differential flux spectra of nuclei by an inverse-power law in the total energy per nucleon E above E_1 , and by a constant value in the kinetic energy per nucleon in the interval between T_0 and T_1 :

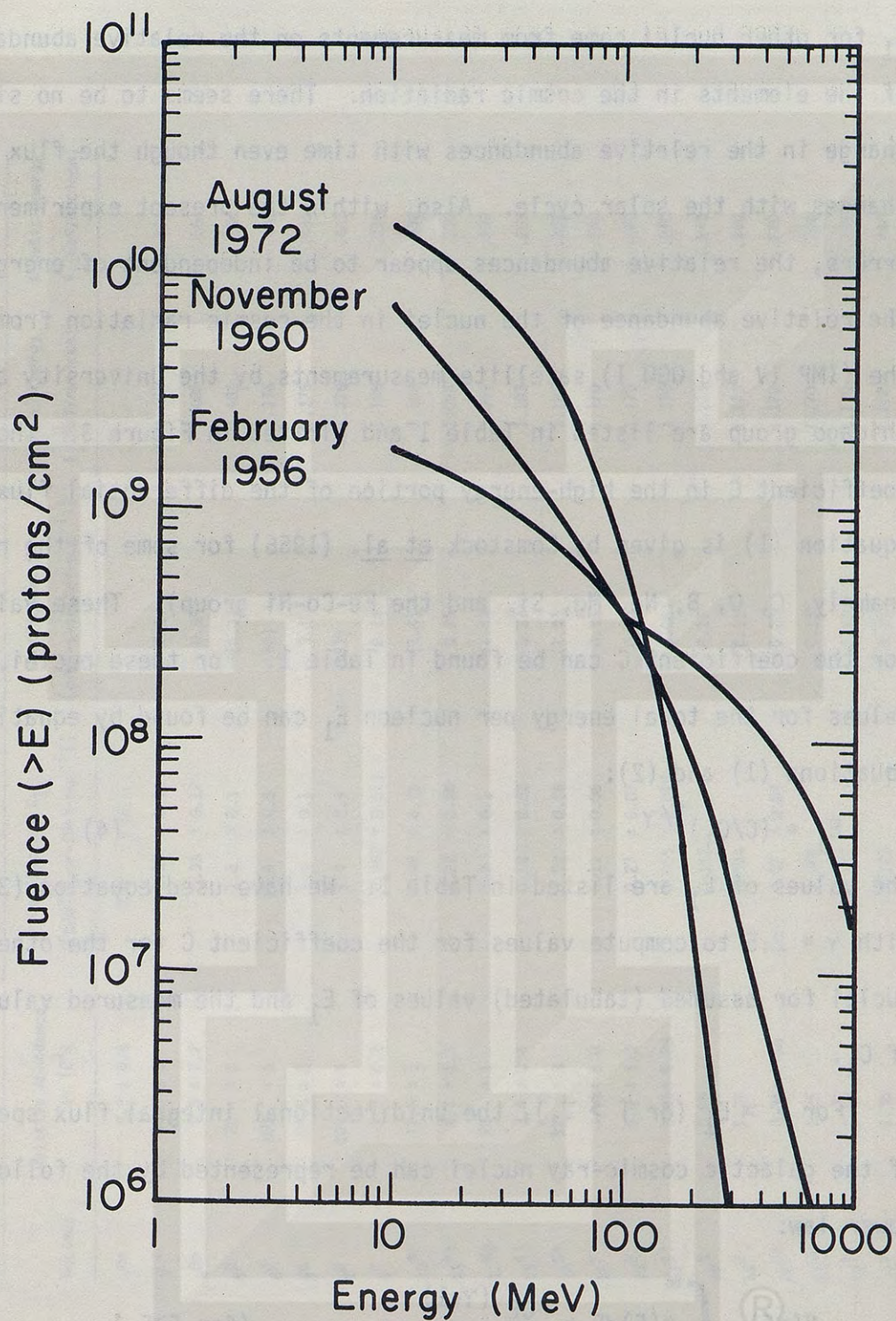
$$n(E) = CE^{-\gamma} \quad (E > E_1) \quad , \quad (1)$$

$$n(T) = C_1 \quad (T_0 < T < T_1) \quad , \quad (2)$$

where

$$E(\text{GeV/nucleon}) = T(\text{GeV/nucleon}) + 0.9315 \quad . \quad (3)$$

The spectral exponent γ has an observed value of about 2.5. The representation in equation (2) is valid for a kinetic energy T_0 in the neighborhood of 100 MeV per nucleon. The value of the constant C_1 for oxygen, as reported by Comstock et al. (1966), is $5.4 \text{ nuclei/m}^2\text{-sec-sr-(GeV/nucleon)}$ in the time interval from October to November 1964. The values of



XBL7811-12343

Figure 2. Integral proton fluence spectra for the three solar particle events of February 1956, November 1960, and August 1972. (From Wilson and Denn, 1976)

C_1 for other nuclei come from measurements on the relative abundance of the elements in the cosmic radiation. There seems to be no significant change in the relative abundances with time even though the flux level changes with the solar cycle. Also, within the present experimental errors, the relative abundances appear to be independent of energy. The relative abundance of the nuclei in the cosmic radiation from the (IMP IV and OGO I) satellite measurements by the University of Chicago group are listed in Table 1 and plotted in Figure 3. The coefficient C in the high-energy portion of the differential flux equation (1) is given by Comstock et al. (1966) for some of the nuclei (namely, C, O, B, Ne, Mg, Si, and the Fe-Co-Ni group). These values for the coefficient C can be found in Table 1. For these nuclei, values for the total energy per nucleon E_1 can be found by equating equations (1) and (2):

$$E_1 = (C/C_1)^{1/\gamma} \quad (4)$$

The values of E_1 are listed in Table 1. We have used equation (3) with $\gamma = 2.5$ to compute values for the coefficient C for the other nuclei for assumed (tabulated) values of E_1 and the measured values of C_1 .

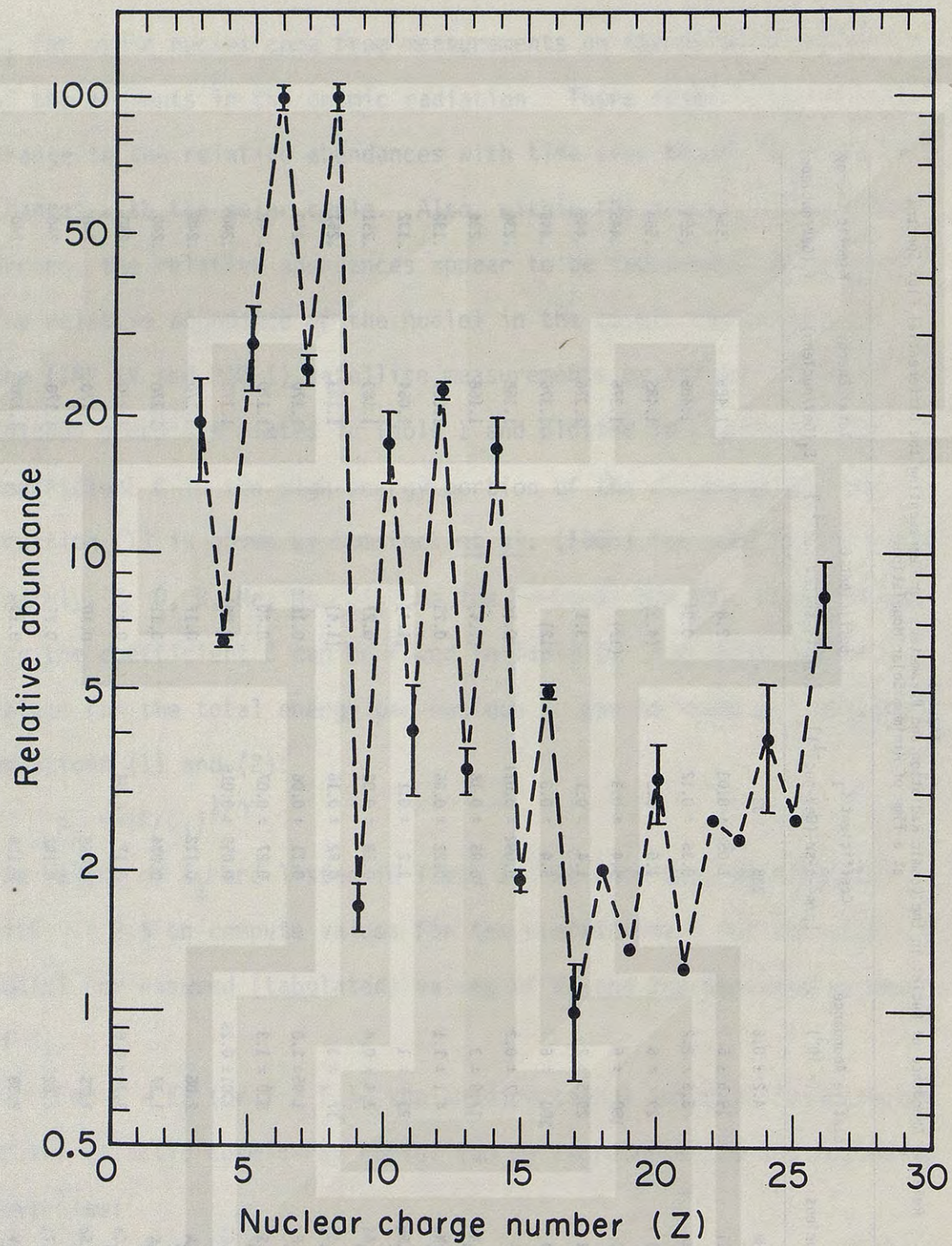
For $E > E_1$ (or $T > T_1$), the unidirectional integral flux spectra of the galactic cosmic-ray nuclei can be represented by the following power law:

$$N(>E) = \int_E^{\infty} n(E) dE = \frac{CE^{-(\gamma-1)}}{\gamma-1} \quad (\text{for } E > E_1) \quad (5)$$

For $E_0 < E < E_1$ (or $T_0 < T < T_1$), the unidirectional integral flux

TABLE 1
Relative Abundance of Nuclei in the Cosmic Radiation and Parameters for Representing the Differential Flux Spectra
at a Time of Minimum Solar Modulation.

Nucleus	Relative Abundance ($\times 10^3$)	Coefficient C_1 [p/m ² -s-sr-(GeV-nuc ⁻¹)]	Coefficient C [p/m ² -s-sr(GeV-nuc ⁻¹)]	Total Energy E_1 (GeV/nucleon)	Kinetic Energy T_1 (GeV/nucleon)
² He	4.2 $\pm$ 0.6	228 $\pm$ 32			
³ Li	19.5 $\pm$ 5	1.05 $\pm$ 0.03	2.8	1.485	.554
⁴ Be	6.5 $\pm$ 2.2	0.35 $\pm$ 0.12	0.94	1.485	.554
⁵ B	29 $\pm$ 6	1.6 $\pm$ 0.3	(4.3)	1.485	.554
⁶ C	100 $\pm$ 6	5.4 $\pm$ 0.3	(12)	1.376	.445
⁷ N	25.5 $\pm$ 2	1.4 $\pm$ 0.1	3.1	1.376	.445
⁸ O	100 $\pm$ 6	5.4 $\pm$ 0.3	(12)	1.376	.445
⁹ F	1.7 $\pm$ 0.2	0.092 $\pm$ 0.011	0.14	1.168	.236
¹⁰ Ne	17.5 $\pm$ 3	0.95 $\pm$ 0.16	(1.4)	1.168	.236
¹¹ Na	4.1 $\pm$ 1.1	0.22 $\pm$ 0.06	0.25	1.064	.132
¹² Mg	23 $\pm$ 1	1.2 $\pm$ 0.1	(1.4)	1.064	.132
¹³ Al	3.4 $\pm$ 0.4	0.18 $\pm$ 0.02	0.27	1.183	.251
¹⁴ Si	17 $\pm$ 3	0.92 $\pm$ 0.16	(1.4)	1.183	.251
¹⁵ P	1.95 $\pm$ 1.0	0.11 $\pm$ 0.06	0.16	1.170	.240
¹⁶ S	5.0 $\pm$ 1.3	0.27 $\pm$ 0.07	0.40	1.170	.240
¹⁷ Cl	1.01 $\pm$ 0.29	0.055 $\pm$ 0.016	0.081	1.170	.240
¹⁸ A	2.08	0.112	0.17	1.170	.240
¹⁹ K	1.37	0.074	0.11	1.170	.240
²⁰ Ca	3.24 $\pm$ 0.65	0.17 $\pm$ 0.04	0.25	1.170	.240
²¹ Sc	1.25	0.068	0.10	1.170	.240
²² Ti	2.62	0.142	0.21	1.170	.240
²³ V	2.38	0.129	0.19	1.170	.240
²⁴ Cr	3.99 $\pm$ 1.25	0.215 $\pm$ 0.068	0.32	1.170	.240
²⁵ Mn	2.65	0.143	0.21	1.170	.240
²⁶ Fe- ²⁷ Co- ²⁸ Ni	8.15 $\pm$ 1.73	0.44 $\pm$ 0.09	(1.4)	1.589	.657



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Figure 3. The relative abundance of nuclei in the galactic cosmic radiation.

spectra of galactic cosmic-ray nuclei can be represented as follows:

$$N(>E) = \int_E^{E_1} n(E) dE + N(>E_1) = C_1(E_1 - E) + \frac{C}{\gamma-1} E_1^{-(\gamma-1)}. \quad (6)$$

Values of the coefficient $C/(\gamma-1)$ for integral flux spectra of galactic cosmic-ray nuclei for an integral spectral exponent $\gamma-1 = 1.5$ at a time of minimum solar modulation are listed in Table 2. Also listed in Table 2 are unidirectional integral fluxes above a total energy of 1.4 GeV per nucleon, which corresponds to a kinetic energy of 468 MeV per nucleon.

RADIATION DOSES

It is convenient to categorize radiation exposures of personnel in the SPS into two types: (1) predictable and (2) unpredictable. In the predictable category are exposures to the geomagnetically trapped protons, the geomagnetically trapped electrons and their associated bremsstrahlung, the proton and the helium fluxes in the galactic cosmic radiation, and radiations from isotopes or nuclear systems which may be carried aboard the SPS. Exposures from these sources are predictable in the sense that they can be calculated and measured. Control of exposures to these radiation sources involves tradeoffs between acceptable exposure levels and the weight of shielding. The unpredictable category includes exposures from solar-particle events, the high-charge ($Z > 2$) and high-energy (HZE) particle component of cosmic radiation, artificially trapped electrons and their associated bremsstrahlung, emergency extravehicular activities (EVA), and emergency repair of nuclear systems which may be carried aboard the SPS. The time of occurrence of solar particle

TABLE 2

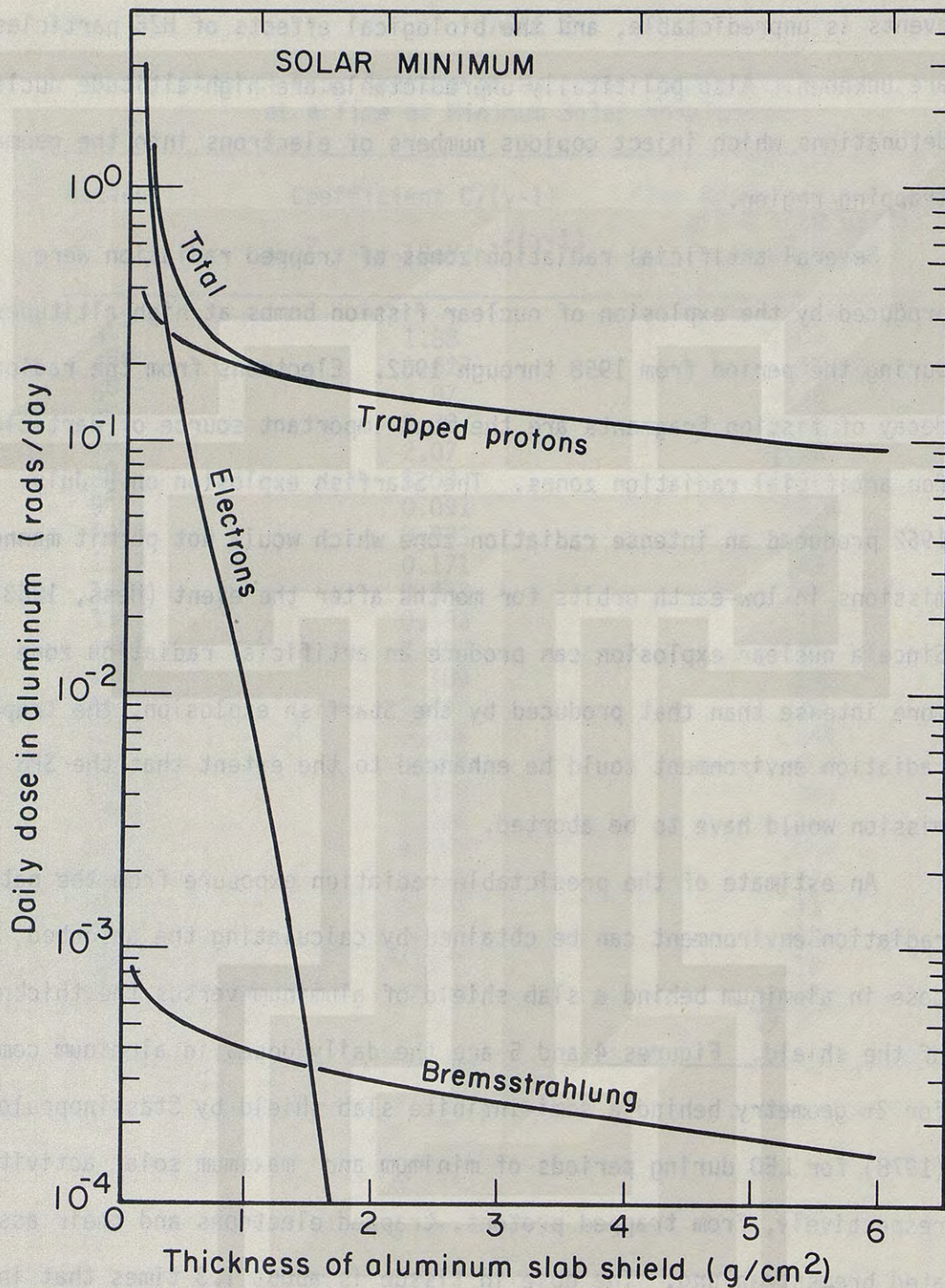
Integral Flux Spectra of Galactic Cosmic-Ray Nuclei
at a Time of Minimum Solar Modulation

Nucleus	Coefficient $C/(\gamma-1)$ $\text{p/m}^2\text{-s-sr-(GeV/n)}^{-(\gamma-1)}$	Flux Above Total Energy E $N(E > 1.40 \text{ GeV/n})$ $(\text{p/m}^2\text{-s-sr})$
³ Li	1.88	1.04
⁴ Be	0.627	.60
⁵ B	2.87	1.58
⁶ C	8.00	4.94
⁷ N	2.07	1.28
⁸ O	8.00	4.94
⁹ F	0.091	.076
¹⁰ Ne	0.933	.78
¹¹ Na	0.171	.43
¹² Mg	0.933	.97
¹³ Al	0.183	.15
¹⁴ Si	0.933	.77
¹⁵ P	0.109	.091
¹⁶ S	0.267	.22
¹⁷ Cl	0.054	.045
¹⁸ A	0.107	.090
¹⁹ K	0.073	.061
²⁰ Ca	0.168	.14
²¹ Sc	0.067	.056
²² Ti	0.140	.17
²³ V	0.127	.11
²⁴ Cr	0.212	.18
²⁵ Mn	0.141	.18
²⁶ Fe- ²⁷ Co ²⁸ Ni	0.933	.47
		19.37

events is unpredictable, and the biological effects of HZE particles are unknown. Also politically unpredictable are high-altitude nuclear detonations which inject copious numbers of electrons into the geomagnetic trapping region.

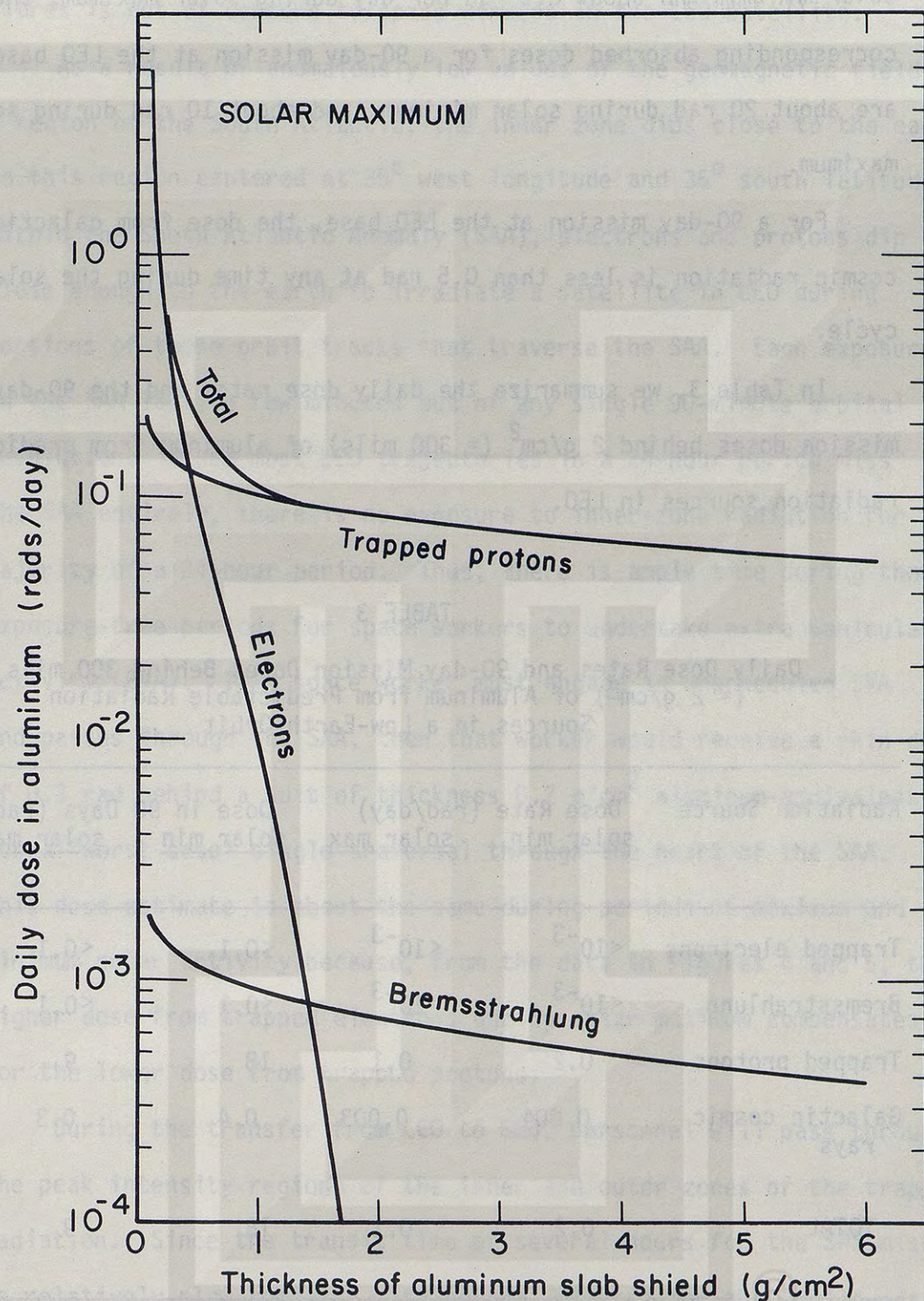
Several artificial radiation zones of trapped radiation were produced by the explosion of nuclear fission bombs at high altitudes during the period from 1958 through 1962. Electrons from the radioactive decay of fission fragments are the most important source of particles for artificial radiation zones. The Starfish explosion on 9 July 1962 produced an intense radiation zone which would not permit manned missions in low-earth orbits for months after the event (Hess, 1963). Since a nuclear explosion can produce an artificial radiation zone more intense than that produced by the Starfish explosion, the trapped radiation environment could be enhanced to the extent that the SPS mission would have to be aborted.

An estimate of the predictable radiation exposure from the natural radiation environment can be obtained by calculating the absorbed dose in aluminum behind a slab shield of aluminum versus the thickness of the shield. Figures 4 and 5 are the daily doses in aluminum computed for 2π geometry behind a semi-infinite slab shield by Stassinopoulos (1978) for LEO during periods of minimum and maximum solar activity, respectively, from trapped protons, trapped electrons and their associated bremsstrahlung. The dose in tissue is about 1.3 times that in aluminum. Note that the trapped protons constitute the dominant radiation hazard in LEO. The absorbed dose rate in tissue from trapped protons behind 300 mils ($=2 \text{ g/cm}^2$) of aluminum is about 0.2 rad per day during



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Figure 4. The dose in aluminum behind a slab shield of aluminum versus the aluminum shield thickness for a 50° km, 30° orbit during a period of minimum solar activity. (From Stassinopoulos, 1978)



XBL78II-12350

Figure 5. The dose in aluminum behind a slab shield of aluminum versus the aluminum shield thickness for a 500 km, 30° orbit during a period of maximum solar activity. (From Stassinopoulos, 1978)

solar minimum and about 0.1 rad per day during solar maximum; the corresponding absorbed doses for a 90-day mission at the LEO base are about 20 rad during solar minimum, and about 10 rad during solar maximum.

For a 90-day mission at the LEO base, the dose from galactic cosmic radiation is less than 0.5 rad at any time during the solar cycle.

In Table 3, we summarize the daily dose rates and the 90-day mission doses behind 2 g/cm^2 ($= 300 \text{ mils}$) of aluminum from predictable radiation sources in LEO.

TABLE 3

Daily Dose Rates and 90-day Mission Doses Behind 300 mils
($= 2 \text{ g/cm}^2$) of Aluminum from Predictable Radiation
Sources in a Low-Earth Orbit

Radiation Source	Dose Rate (rad/day)		Dose in 90 Days (rad)	
	<u>solar min</u>	<u>solar max</u>	<u>solar min</u>	<u>solar max</u>
Trapped electrons	$<10^{-3}$	$<10^{-3}$	<0.1	<0.1
Bremsstrahlung	$<10^{-3}$	$<10^{-3}$	<0.1	<0.1
Trapped protons	0.2	0.1	18	9
Galactic cosmic rays	0.004	0.003	0.4	0.3
TOTAL	0.2	0.1	18	9

Since the geomagnetic field diverts the paths of charged particles from the LEO satellite, exposure to energetic particles from solar

flares is not of concern to space workers in the LEO satellite.

As a result of anomalously low values of the geomagnetic field in a region of the South Atlantic, the inner zone dips close to the earth in this region centered at 35° west longitude and 35° south latitude. Within the South Atlantic Anomaly (SAA), electrons and protons dip close enough to the earth to irradiate a satellite in LEO during portions of those orbit tracks that traverse the SAA. Each exposure in the SAA lasts a few minutes out of any single 90-minute orbital revolution. Since most LEO trajectories in a 24-hour period miss the SAA entirely, there is no exposure to inner-zone radiation for the majority of a 24-hour period. Thus, there is ample time during these exposure-free periods for space workers to undertake extra vehicular activity (EVA). If a space worker must engage in unscheduled EVA and passes through the SAA, then that worker would receive a skin dose of 0.3 rad behind a suit of thickness 0.2 g/cm^2 aluminum-equivalent for a "worst case" single traversal through the heart of the SAA. This dose estimate is about the same during periods of maximum and minimum solar activity because, from the data in Figures 4 and 5, the higher dose from trapped electrons during solar maximum compensates for the lower dose from trapped protons.

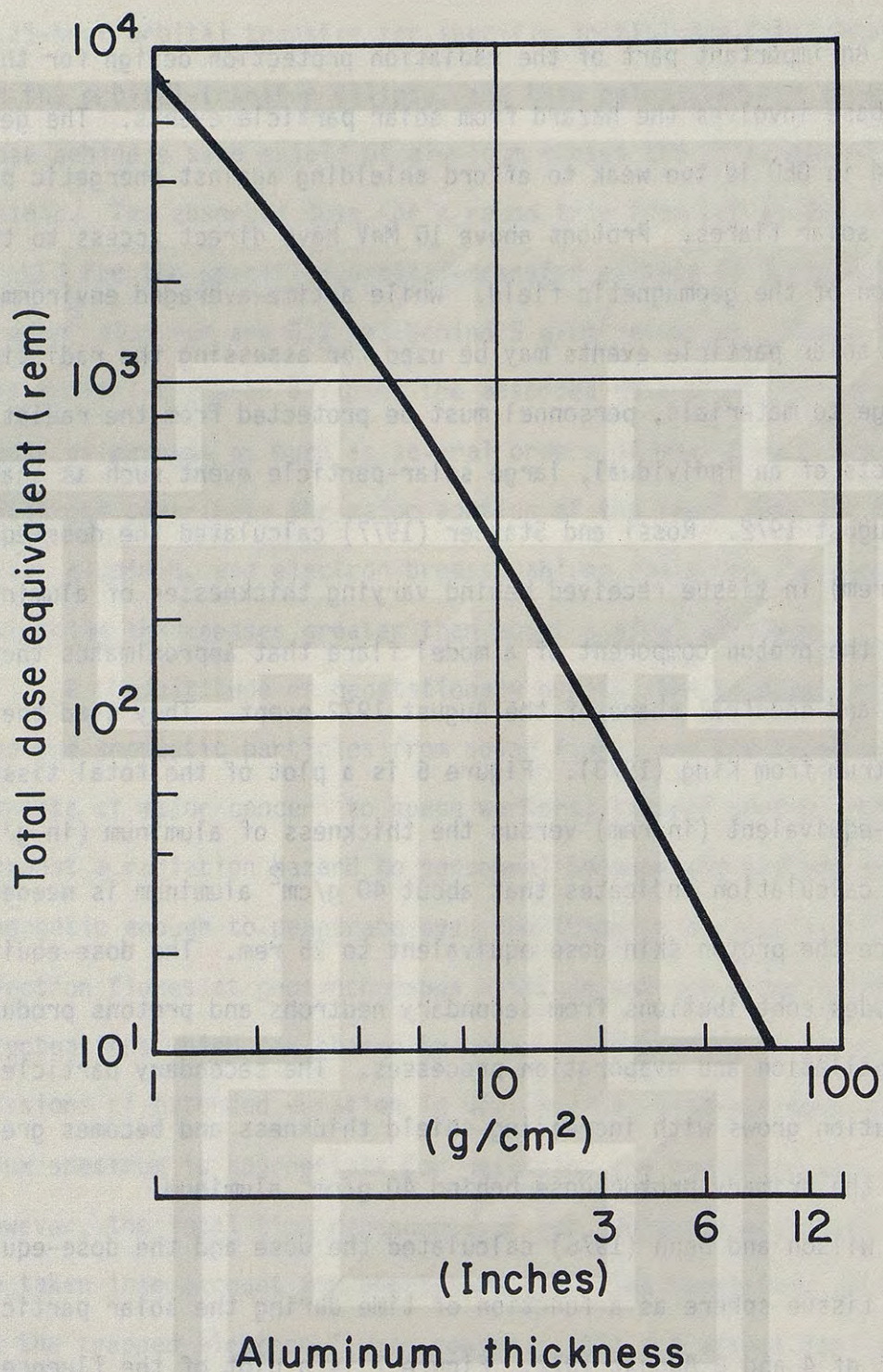
During the transfer from LEO to GEO, personnel will pass through the peak intensity regions of the inner and outer zones of the trapped radiation. Since the transit time of several hours for the SPS mission is relatively slow compared with several minutes for the Apollo mission, the potential exposure is great. Stassinopoulos (1979) calculated the fluence of trapped electrons and protons encountered during a

5.25-hour orbital transfer for specific initial and final positions on the orbital-transfer ellipse, and then calculated the absorbed dose behind a slab shield of aluminum versus the thickness of the shield. The absorbed dose for a round trip from LEO to GEO and back to LEO for the specified orbital-transfer ellipse is 3 rad behind 2 g/cm² aluminum and 0.2 rad behind 5 g/cm² aluminum. For a different orbital-transfer ellipse, the absorbed dose might be higher or lower by perhaps as much as several orders of magnitude. Trapped electrons contribute the major portion of the total dose behind 2 g/cm² aluminum, and electron bremsstrahlung dominates the dose behind shielding thicknesses greater than about 3 g/cm² aluminum.

At the altitude of geostationary orbits, the trapped electrons and the energetic particles from solar flares are the radiation components of major concern to space workers; trapped protons do not present a radiation hazard to personnel because the protons are not energetic enough to penetrate even the thinnest spacesuit. Trapped electron fluxes at geosynchronous altitude undergo large temporal fluctuations which can change by orders of magnitude in hours. For missions of extended duration in GEO, a local time-averaged energy-flux spectrum is appropriate for assessing the radiation exposure; however, the local time dependence of the ambient electron flux must be taken into account for short-term EVA. The short-term variations of the trapped electron fluxes constrain EVA and affect radiation shield requirements. It is necessary to take into account the maximum intensities of the trapped electrons in determining minimum requirements of the vehicle shield.

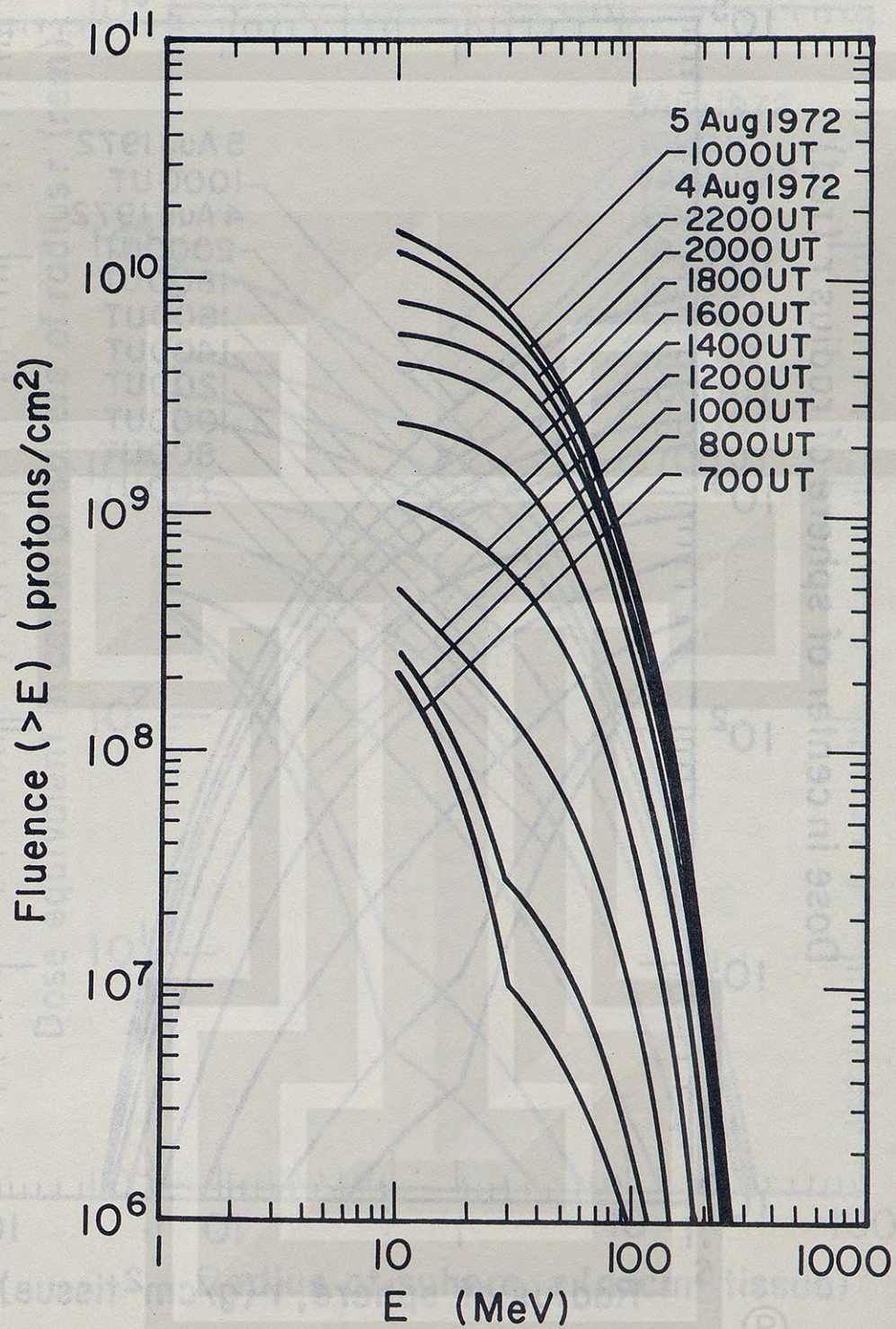
An important part of the radiation protection design for the GEO base involves the hazard from solar particle events. The geomagnetic field in GEO is too weak to afford shielding against energetic particles from solar flares. Protons above 10 MeV have direct access to this region of the geomagnetic field. While a time-averaged environment from solar particle events may be used for assessing the radiation damage to materials, personnel must be protected from the radiation effects of an individual, large solar-particle event such as that of August 1972. Rossi and Stauber (1977) calculated the dose-equivalent (in rem) in tissue received behind varying thicknesses of aluminum from the proton component of a model flare that approximates the integral flux and spectral shape of the August 1972 event. They used the flux spectrum from King (1973). Figure 6 is a plot of the total tissue dose-equivalent (in rem) versus the thickness of aluminum (in g/cm^2). This calculation indicates that about 40 g/cm^2 aluminum is needed to reduce the proton skin dose equivalent to 25 rem. The dose-equivalent includes contributions from secondary neutrons and protons produced in spallation and evaporation processes. The secondary particle contribution grows with increasing shield thickness and becomes greater than the primary proton dose behind 40 g/cm^2 aluminum.

Wilson and Denn (1976) calculated the dose and the dose-equivalent in a tissue sphere as a function of time during the solar particle event of 4 and 5 August 1972. Figure 7 is a plot of the fluence spectra from the August 1972 solar particle event as a function of energy for various times during the event. The lowest curve is the accumulated fluence approximately 40 minutes after the observation of the optical



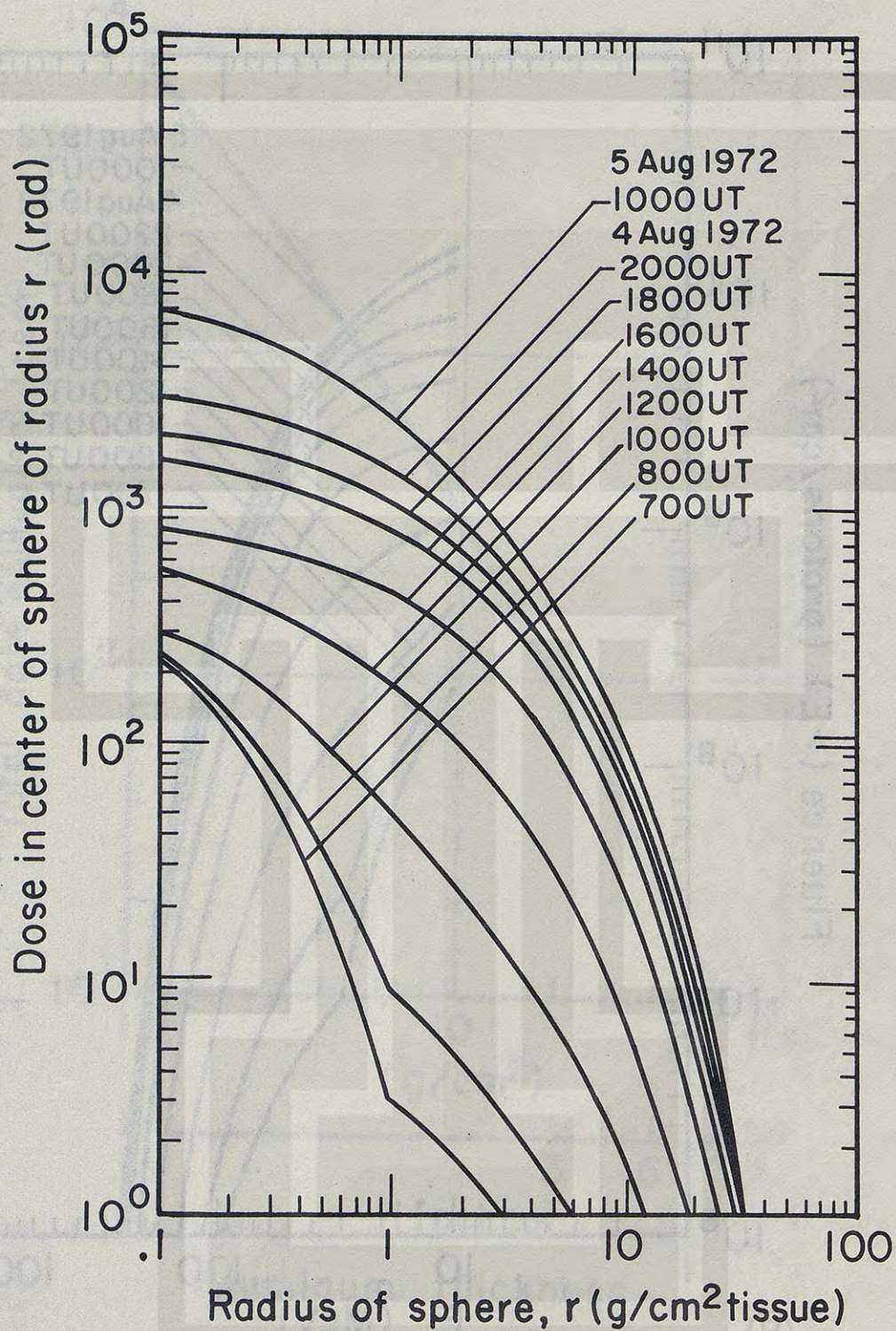
XBL 7811-12347

Figure 6. The total dose-equivalent in tissue from the solar proton event of August 1972 versus the thickness of aluminum shielding. (From Rossi and Stauber, 1977)



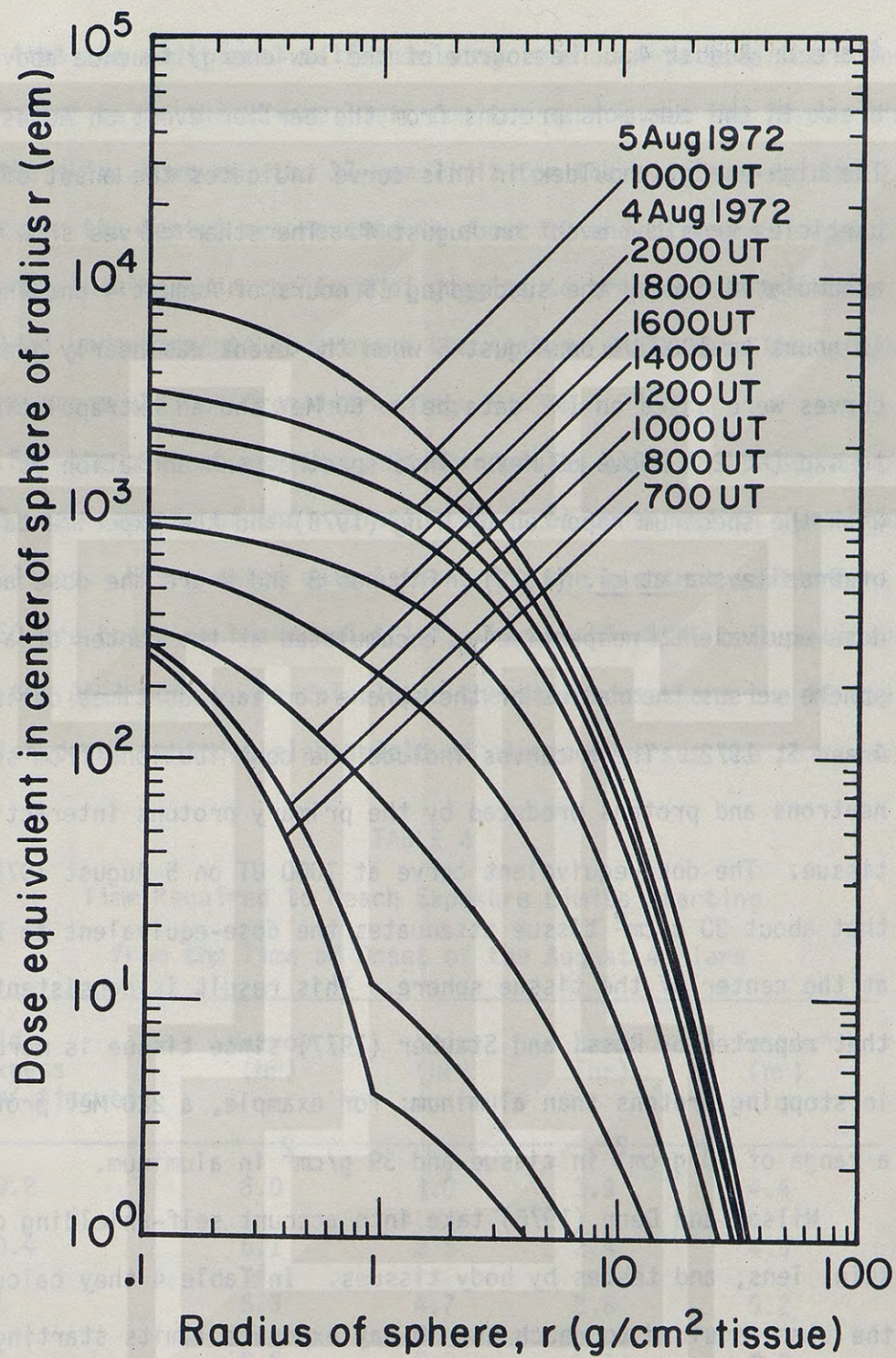
XBL7811-12346

Figure 7. Fluence spectra from the August 1972 solar particle event as a function of time. (From Wilson and Denn, 1976)



XBL7811-12345

Figure 8. Absorbed dose at the center of a tissue sphere as a function of time during August 4 and 5, 1972, versus the radius of the sphere. (From Wilson and Denn, 1976)



XBL7811-12348

Figure 9. Dose-equivalent at the center of a tissue sphere as a function of time during August 4 and 5, 1972, versus the radius of the sphere. (From Wilson and Denn, 1976)

flare on August 4. The source of the low-energy fluence above the break in the curve is protons from the earlier event on August 2. The high-energy shoulder in this curve indicates the onset of energetic particles from the event on August 4. The other curves show the fluence accumulated during the succeeding 15 hours of August 4 and the next 12 hours to 1000 UT on August 5 when the event was nearly over. These curves were based on IMP data below 60 MeV and an extrapolation according to $\exp(-E/28)$ above 60 MeV. This spectral extrapolation is consistent with the spectrum reported by King (1973) and the experimental measurement of Brazilevska *et al.* (1973). Figures 8 and 9 are the dose and the dose-equivalent, respectively, accumulated at the center of a tissue sphere versus the radius of the sphere for various times during August 4 and 5, 1972. These curves include the contributions from secondary neutrons and protons produced by the primary protons interacting with tissue. The dose-equivalent curve at 1000 UT on 5 August 1972 indicates that about 30 g/cm^2 tissue attenuates the dose-equivalent to 25 rem at the center of the tissue sphere. This result is consistent with that reported by Rossi and Stauber (1977) since tissue is more effective in stopping protons than aluminum; for example, a 220 MeV proton has a range of 30 g/cm^2 in tissue and 39 g/cm^2 in aluminum.

Wilson and Denn (1976) take into account self-shielding of marrow, skin, lens, and testes by body tissues. In Table 4 they calculate the time required to reach the 30-day exposure limits starting from the time of onset of energetic particles from the flare of 4 August 1972. With a shield thickness capable of stopping protons of about 120 MeV corresponding to an aluminum thickness of 13.7 g/cm^2 , they

find that the additional self-shielding is enough to keep the dose-equivalent below the 25-rem limit for the marrow and the 75-rem limit for the skin; however, the 37-rem limit for the eye lens and the 13-rem limit for the testes are reached in about 12 and 13 hours, respectively. Personal shielding in the form of goggles to protect the eye lens and lead undergarments to protect the testes would keep the weight of the storm shelter from increasing.

For the present workshop, Stassinopoulos (1979) updated his previous (1973) assessments of the radiation doses to personnel in synchronous satellites. His updated calculations for the electron environment in GEO are based on the model AEI-7, whereas his 1973 calculations used the AE-4 model. He calculated the daily doses and the 90-day mission doses behind a slab shield of aluminum versus the thickness

TABLE 4
Time Required to Reach Exposure Limits Starting
from the Time of Onset of the August 4 Flare

Shield Thickness (g/cm ² tissue)	Marrow (hr)	Skin (hr)	Lens (hr)	Testes* (hr)
0.2	6.0	3.0	1.9	4.4
0.4	6.1	3.5	2.4	4.9
1	6.3	4.7	3.6	5.2
5	8.9	8.0	6.5	7.3
10	∞	∞	11.7	12.7

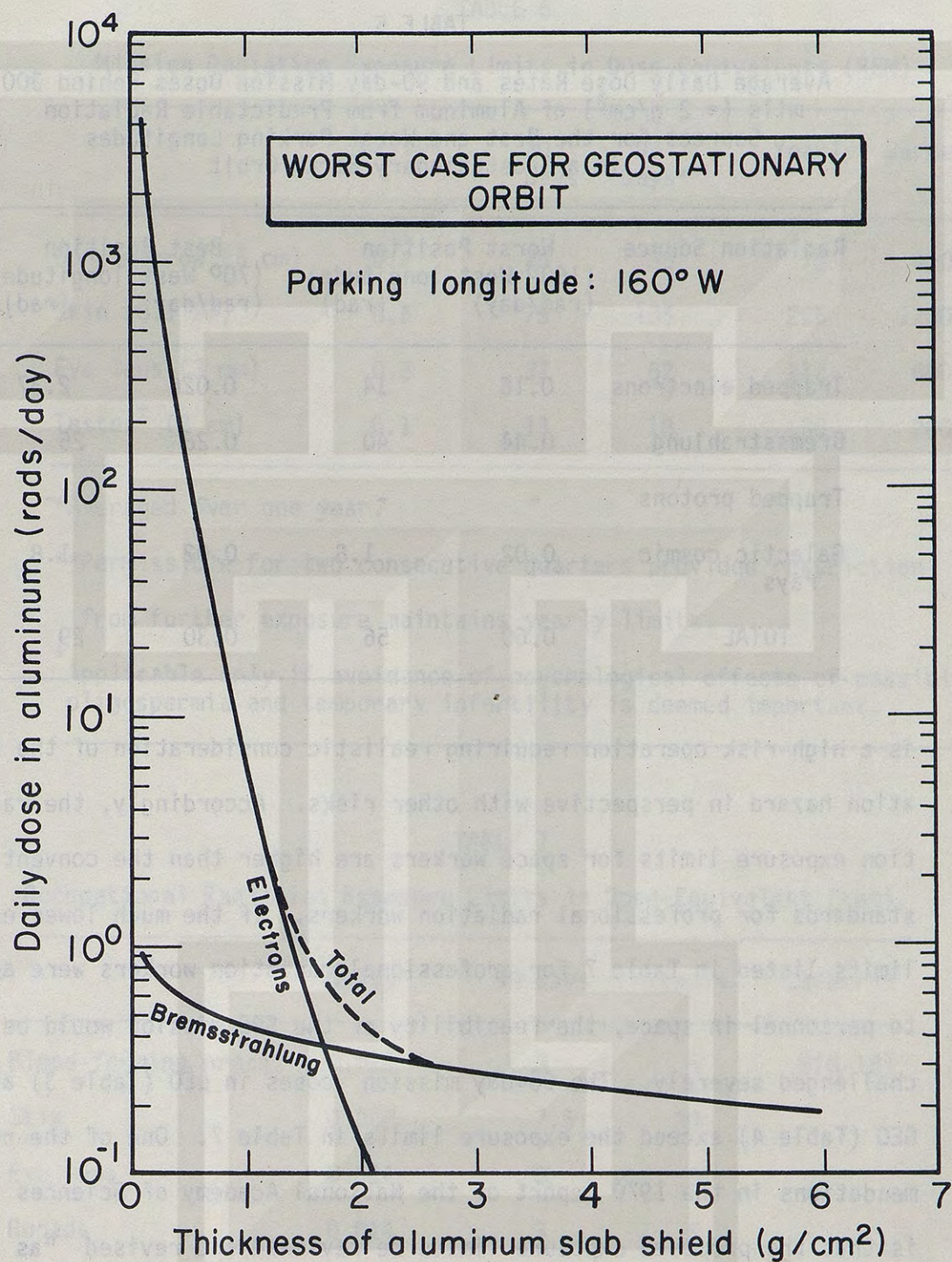
*Values are overestimated since the testes dose is taken to be the same as the marrow dose.

of the shield. The results depend on the parking longitude because of the asymmetry of the geomagnetic field. The worst position is at 160° west longitude; the best, at 70° west longitude. Figure 10 is a plot of the daily doses in aluminum as a function of aluminum thickness for the worst position. In Table 5, we summarize the time-averaged daily dose rates and 90-day mission doses behind 300 mils ($= 2 \text{ g/cm}^2$) of aluminum from predictable radiation sources for the best and worst parking longitudes in a geostationary orbit. More detailed information on the analysis of the radiation environment in GEO is contained in a companion paper by Stassinopoulos (1979).

There is a need to monitor and evaluate exposure to HZE particles during an extended mission in space because their biological effects are unknown. The dominant contribution to the fluence of HZE particles comes from the galactic cosmic radiation rather than from solar-particle events. Since the conventional absorbed dose is the integral of the product of the differential (in energy) flux spectrum and the energy deposition rate, the conventional absorbed dose is small. Curtis (1976) estimated the absorbed dose rates from galactic cosmic rays at roughly 10 rad per year with 35% coming from particles with $Z > 2$, and 10% from particles with $Z > 20$.

RADIATION EXPOSURE LIMITS

Radiation exposure limits in current use for the SPS mission are listed in Table 6. The Space Science Board of the National Academy of Sciences (1970) proposed these exposure limits to serve as radiation-protection guides and constraints for vehicle-design studies and mission planning. The recommended exposure limits assume that the space mission



XBL7812-12355

Figure 10. Daily dose in aluminum behind a slab shield of aluminum versus the aluminum shield thickness for the worst (160°) parking longitude in a geostationary orbit. (From Stassinopoulos, 1978)

TABLE 5

Average Daily Dose Rates and 90-day Mission Doses Behind 300
mils ($= 2 \text{ g/cm}^2$) of Aluminum from Predictable Radiation
Sources for the Best and Worst Parking Longitudes
in a Geostationary Earth Orbit

Radiation Source	Worst Position (160° West longitude) (rad/day) (rad)		Best Position (70° West longitude) (rad/day) (rad)	
Trapped electrons	0.16	14	0.026	2.37
Bremsstrahlung	0.44	40	0.28	25
Trapped protons	-	-	-	-
Galactic cosmic rays	0.02	1.8	0.02	1.8
TOTAL	0.60	56	0.30	29

is a high-risk operation requiring realistic consideration of the radiation hazard in perspective with other risks. Accordingly, the radiation exposure limits for space workers are higher than the conventional standards for professional radiation workers. If the much lower exposure limits listed in Table 7 for professional radiation workers were applied to personnel in space, the feasibility of the SPS mission would be challenged severely. The 90-day mission doses in LEO (Table 3) and GEO (Table 4) exceed the exposure limits in Table 7. One of the recommendations in the 1970 report of the National Academy of Sciences is that the proposed exposure limits be reviewed and revised "as additional pertinent information becomes available and before application to actual operations." Because of the impact of the exposure limits on the feasibility of the SPS mission, the recommended review of the

TABLE 6

Mission Radiation Exposure Limits in Dose-Equivalents (REM)

	Daily*	30 Days	90 Days**	Yearly	Career
Bone marrow (5 cm)	0.2	25	35	75	400
Skin (0.1 mm)	0.6	75	105	225	1200
Eye lens (3 mm)	0.3	37	52	112	600
Testes ⁺ (3 cm)	0.1	13	18	38	200

*Averaged over one year.

**Permissible for two consecutive quarters provided restriction from further exposure maintains yearly limits.

⁺ Applicable only if avoidance of psychological effects of possible oligospermia and temporary infertility is deemed important.

TABLE 7

Occupational Radiation Exposure Limits in Dose-Equivalent (rem)

	Daily*	90 days	Yearly	Career**
Blood-forming organs	0.014	3	5	5(N-18)
Skin	0.082	7.5	30	
Eye lens	0.014	3	5	
Gonads	0.014	3	5	

*Averaged over one year.

**The accumulated occupational dose to the whole body shall not exceed 5(N-18) rem, where N is the individual's age in years.

exposure limits needs to be accomplished at an early date.

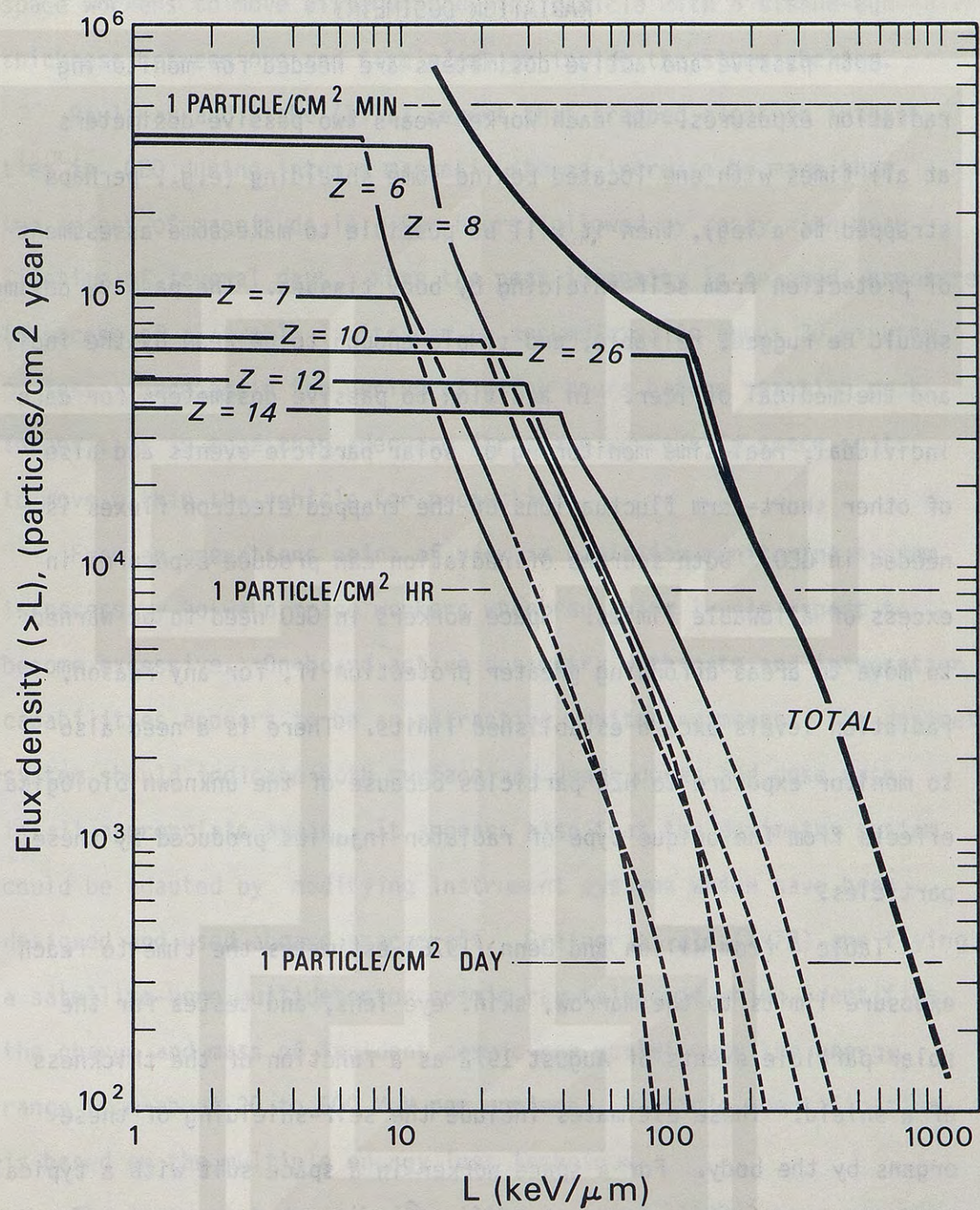
The radiation exposure limits in Table 6 are based on the primary reference risk recommended by the Radiobiological Advisory Panel of the Committee on Space Medicine of the Space Science Board. The primary reference risk corresponds to an added probability of radiation-induced leukemia and other neoplastic diseases over a period of about 20 years that is equal to the natural probability for the specific population at risk. The panel recommended also that the primary reference risk exposure be taken as a dose-equivalent of 400 rem at the mean (5 cm) depth of the bone marrow irrespective of the exposure rate.

The exposure limits in Table 6 are dose-equivalents in rem at the specified mean depth of interest, where the dose-equivalent is the product of the absorbed dose D in rads and a quality factor Q . The quality factor takes into account differences in biological effectiveness of radiation of different quality, which is measured by the linear energy transfer (LET) or rate of dissipation of energy along the path of the charged particle. The purpose of introducing the quality factor in radiation protection is to ensure that the risk from a specified maximum permissible dose of high-LET radiation does not exceed that from a maximum permissible dose of low-LET radiation. The relationship between Q and LET recommended by the International Commission on Radiological Protection (1966) assumes that Q has a constant value of 20 beyond an LET of $175 \text{ keV}/\mu\text{m}$. Barendsen *et al.* (1963) and Todd (1967) reported that the relative biological effectiveness (RBE) for killing cultured dividing mammalian cells reaches a maximum of 6 to 8 in the LET range of 100 to $200 \text{ keV}/\mu\text{m}$, and decreases to

unity at 1000 keV/ μ m. Thus, the Q-LET relationship may overestimate the dose-equivalent for production of neoplastic, skin, testicular, and possibly ocular lens responses by very densely ionizing radiation. On the other hand, it is known that RBE increases as the dose decreases, so that the large value of Q may not be unreasonable for the doses considered here.

The establishment of exposure limits that are less restrictive than those for conventional occupational exposure requires quantitatively reliable information on the levels of human response as a function of dose and conditions of exposure. The quantity and nature of existing data are inadequate to derive confidence limits for space conditions. One uncertainty arises because of the lack of information on the interaction of radiation exposure with exposure to other stresses such as weightlessness in the space environment. Other uncertainties arise because of inadequate information on biological effects of the HZE particle component of cosmic radiation. These very highly ionizing particles produce a unique type of biological damage which normally cannot be produced by other types of radiation. An HZE particle damages many contiguous cells along the particle track, and produces a microscopic lesion. Malachowski *et al.* (1978) observed this type of injury in recent laboratory studies. The radiation exposure limits in Table 6 are not applicable to biological effects such as this microlesion type of injury which can be produced only by HZE particles and not by other radiations of different quality. Also, the concept of quality factor breaks down when the biological effect cannot be produced by the low-LET reference radiation. To assess the damage from HZE particles,

it is necessary to acquire radiobiological information that will permit the prediction of dose-response relationships for the HZE particles. Measurements are needed of the probability for inactivation by HZE particles of nondividing cells that compose the primary functional portion of the central nervous system. It is necessary also to determine the degree of redundancy in the brain and the possible consequences of progressive destruction of nondividing nerve cells during space missions of extended duration. There is a need also to introduce a new physical parameter other than the conventional absorbed dose in order to quantify the exposure. In the National Academy of Sciences (1973) report entitled "HZE-Particle Effects in Manned Spaceflight," it was suggested as a first approximation that a critical or threshold ionization level may be required to inactivate or impair cells. Below the threshold, the biological effect does not occur; and above the threshold, the biological effect occurs with probability of 100%. The threshold-LET concept resulted in the introduction of a physical quantity called the specific track length (or track length per unit mass) for specifying the exposure to HZE particles. The specific track length (in units of cm/g) is the fluence of particles above the threshold ionization level in the organ divided by the density of the organ. Calculation of the specific track length must take into account the slowing down and nuclear fragmentation of the incident HZE particles in the material shielding the organ of interest. Figure 11 is a plot of the integral-number LET spectrum for the major components of HZE particles at solar minimum under no shielding (Curtis, 1973). The ordinate is the flux density (in particles/cm²-year) above a given LET, and the abscissa is LET (in keV/μm of tissue).



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Figure 11. Integral number LET spectrum for the major components of HZE particles at solar minimum under no shielding. (From Curtis, 1973)

RADIATION DOSIMETRY

Both passive and active dosimeters are needed for monitoring radiation exposures. If each worker wears two passive dosimeters at all times with one located behind some shielding (e.g., perhaps strapped to a leg), then it will be possible to make some assessment of protection from self-shielding by body tissues. The passive dosimeters should be rugged, reliable, and simple enough to be read by the individual and the medical officer. In addition to passive dosimeters for each individual, real-time monitoring of solar particle events and also of other short-term fluctuations of the trapped electron fluxes is needed in GEO. Both sources of radiation can produce exposures in excess of allowable limits. Space workers in GEO need to be warned to move to areas affording greater protection if, for any reason, radiation levels exceed established limits. There is a need also to monitor exposure to HZE particles because of the unknown biological effects from the unique type of radiation injuries produced by these particles.

Table 4 from Wilson and Denn (1976) estimates the time to reach exposure limits to the marrow, skin, eye lens, and testes for the solar particle events of August 1972 as a function of the thickness of a shield. These estimates include the self-shielding of these organs by the body. For a space worker in a space suit with a typical tissue-equivalent thickness of 0.3 g/cm^2 , the results of Table 4 indicate that dose-equivalent limit to the skin would be reached in about three hours. The space suit helmet would give the eyes protection for a longer time. This three-hour period is more than adequate for such

space workers to move either inside the vehicle with a tissue-equivalent thickness between one and five g/cm^2 or inside the storm shelter.

Paulikas and Blake (1971) report that trapped electron intensities in GEO during intense magnetic storms increase by more than two orders of magnitude in a few hours followed by decay with mean lifetime of several days. When the peak intensity is reached, exposures in excess of allowable limits can be accumulated in about 30 minutes or less. Here again the period of a few hours before reaching peak intensities is more than adequate for space workers in space suits to move within the vehicle for protection.

From an operations point of view, a radiation monitoring system is necessary to warn space workers when radiation levels expect to become excessive. On-board active dosimetry with rate and integration capabilities appears to be an attractive monitoring means. The dosimetry system should indicate both surface and depth doses and dose rates in all appropriate areas. It appears also that the dosimetry system could be adapted by modifying instrument systems which have been designed and used aboard spacecraft. Greiner et al. (1978) are flying a satellite-born multidetector cosmic-ray telescope which identifies the charge and mass of incident cosmic-ray nuclei over the energy range from about 20 to 500 MeV per nucleon. Particle identification is based on the multiple energy loss technique.

The instrument described by Althouse et al. (1978) measures the isotopic composition of solar and galactic cosmic rays for the elements Li through Ni in the energy range from about 5 to 250 MeV per nucleon. The instrument described by von Rosenvinge et al. (1978) measures the

charge composition of energetic particles over wide regions in energy (from about 1 to 500 MeV per nucleon) and in charge (from $Z = 1$ to 28). Individual isotopes are resolvable for $Z = 1$ through 7 over a restricted energy range. This instrument measures electrons also from 2 to 10 MeV.

At this workshop, Wefel (1979) reviewed the rapid evolution of instrumentation for charged particle measurements in space that has taken place over the last decade. While present technology is sufficient to monitor the ionizing-radiation environment of the SPS, the continued rapid development anticipated in the coming years implies that techniques superior to those now in use may be available before SPS construction begins.

The development of the latest generation of space radiation instrument systems was accelerated greatly because of the availability of heavy ions (HZE particles) at the Bevalac. The heavy-ion beams permitted testing, modification, retesting, and calibration of the instruments to ensure before launch that all components functioned as designed. During this process, unexpected effects in both the detectors and electronics were discovered and corrected. Corrective action would have been impossible if these effects had been discovered after launch.

In addition to real-time monitoring of the relevant components of the radiation environment, there is interest in including an entire complement of charged-particle instruments, perhaps orbiting in a satellite in the vicinity of the SPS, to produce a complete data base on the radiation environment. Although the quantity of information would be too large to be assimilated in real-time, the recorded data

will permit reconstruction of the radiation environment for use in connection with unanticipated radiation problems.

CONCLUSIONS

To conclude this evaluation of the ionizing-radiation environment of the satellite power system, we summarize the preliminary assessment of the radiation doses and highlight some potential problem areas. As presently conceived, the SPS mission might involve 270 thousand space workers over a period of 30 years.³

1. In LEO, nearly all of the radiation dose comes from the geomagnetically trapped protons in the South Atlantic Anomaly. A preliminary estimate indicates that the 90-day mission dose behind 300 mils ($\approx 2 \text{ g/cm}^2$) of aluminum is about 20 rads at solar minimum; the dose at solar maximum is about one-half that at solar minimum.

2. In the orbital transfer from LEO to GEO, the trapped electron fluence is responsible for the major portion of the total dose, with trapped electrons dominating behind a shield thickness less than about 2 g/cm^2 aluminum and electron bremsstrahlung dominating behind thicker shields. A preliminary estimate of the dose for a round trip from LEO to GEO and back to GEO for a one-way transfer time of 5.25 hours⁴ is typically 3 rad behind 2 g/cm^2 aluminum and 0.2 rad behind 5 g/cm^2 aluminum.

³Tentatively, there will be about 350 construction workers rotated every 90 days for each of 60 satellites during an eighteen month construction phase, and about twenty maintenance workers rotated every 90 days for each of 60 satellites during the thirty-year operational phase. The actual numbers of space workers will depend on options still under evaluation (see Reference System Report, 1979).

⁴This transfer time was that assumed by Stassinopolis (1979). Longer transfer times would, of course, increase the absorbed doses.

3. In GEO, the dose from predictable radiation sources comes from penetrating electrons and the associated bremsstrahlung. A preliminary estimate based on the interim model (AEI-7) for the electron environment indicates that the 90-day mission dose behind 300 mils ($= 2 \text{ g/cm}^2$) of aluminum varies from about 29 rad for the best parking longitude of 70° west to about 56 rad for the worst parking longitude of 160° west. Since the major contribution comes from electron bremsstrahlung, it is possible to reduce these doses significantly by designing the walls of the work areas with an additional layer of heavy metal, such as tantalum or lead, to attenuate the electron bremsstrahlung more effectively.

4. A critical question affecting the design and possibly the feasibility of the SPS is whether or not the radiation exposure limits in current use will be reduced. In order to introduce stability into the planning for the SPS mission, it is necessary to settle this question at an early date.

5. There is a major uncertainty in the assessment of the radiation hazards because of the lack of information on the biological effects of the HZE particles. There is a need to generate this information with HZE particle beams from the Bevalac. The need to monitor exposure to HZE particles will remain as long as there are unknown biological effects from the unique type of radiation injuries produced by these particles.

6. High-altitude nuclear detonations represent a politically unpredictable source of radiation. The injection of copious numbers of high-intensity electrons into the geomagnetic trapping region will

require plans for returning all personnel to earth until radiation levels have decreased to lower values.

7. An important part of the radiation protection design for the GEO base involves the hazard to personnel from solar particle events. A heavily-shielded shelter is necessary to protect personnel from large solar particle events such as those of August 1972. To minimize the design weight of the storm shelter, it is necessary to take into account self-shielding of critical organs by body tissues and to use personal shielding such as goggles to protect the eye lens and lead undergarments to protect the testes and ovaries. While self-shielding by body tissues provides time for space workers to move to the protective shelter before reaching the mission exposure limits, an early warning system is desirable to minimize the exposure.

8. Both passive and active dosimeters are needed for monitoring radiation exposures. In addition to rugged, reliable, and simple passive dosimeters for each individual, real-time monitoring is needed of unpredictable radiation sources, such as nuclear detonations, solar particle events, and short-term fluctuations of trapped electron fluxes in GEO. Space workers in GEO must be warned to move to areas affording greater protection whenever exposures from unpredictable radiations may exceed established limits. There is a need also to monitor exposure to HZE particles because of the unknown biological effects from the unique type of injuries produced by these particles. The design of appropriate active dosimeters can be based on the technology of existing space-operational instruments.

9. The radiation requirements for each portion of the SPS mission

must be determined from the combined exposures for the total mission; for example, the allowable exposure within the vehicle at GEO depends on the exposures in LEO, during orbital transfer, during scheduled and unscheduled EVA, and as anticipated from solar particle events. It is necessary to re-evaluate the radiation shielding requirements in terms of the exposure budget for each portion of the mission. Since there are large uncertainties in the existing models of the space radiation environment, re-evaluation of the shielding requirements must be updated as the models are improved; for example, an important improvement needed in the model of the electron environment for GEO is the dependence on the solar cycle. The numbers quoted above for the preliminary estimates of doses do not take into account the uncertainties in models.

RECOMMENDATIONS FOR CONTINUING RESEARCH EFFORT

It is clear from the foregoing analysis that several unanswered questions should be attacked without delay. The recommendations made below emerge from these considerations, and would seem to constitute the minimum activity that must be supported, based on our present knowledge of the problems involved.

1. One of the major unresolved questions is the extent of the hazard from the HZE component of the radiation in GEO. Two types of studies are recommended in this regard:

- a. Early initiation of appropriate studies of the biological effects of HZE particles on critical organs. This question was not addressed in the present study. It is recommended that a committee be constituted to examine this question,

and to arrive at a series of experiments to be conducted with available heavy-ion beams to assess the biological effects of the critical body organs assumed to be the most vulnerable to the accumulation of damage from the HZE component.

- b. Realistic calculations of 90-day HZE exposure for a "typical" space worker as a function of shielding thickness. For an adequate evaluation of the hazards to be made, it is recommended that reasonable estimates be obtained of the fluences of the HZE component expected in the various critical organs determined in (a) above. Although the number of variables involved precludes a precise determination, it is important that the spacecraft designer is aware of the consequences of increasing the thickness of materials available for shielding. Although the absolute magnitude of the fluences may not be determinable with accuracy, the relative variation of fluence with thickness could give valuable information on the effects of a given increase in thickness. This could impact the risk vs. cost analysis for the ultimate design chosen.

2. Re-evaluation of the radiation exposure limits to be used in spacecraft design. It is clear that the radiation doses expected to be encountered by a space worker during a 90-day SPS mission may exceed the limits recommended by the NCRP and ICRP for radiation workers. Since there will be a large number of workers who will potentially receive a significant radiation exposure, the career limits established by the NAS committee for astronauts may not be appropriate. In any case, this question should be examined in detail. It is recommended

that an appropriate committee be constituted to study the question of what the appropriate exposure limits should be for workers involved with the construction and maintenance of SPS.

On the basis of the limits determined by this committee, estimations of doses throughout an entire 90-day mission must be recalculated, using realistic shielding configurations, so that the spacecraft designer will have guidance in supplying sufficient shielding to appropriately limit radiation exposure from predictable sources. In addition, strategies for dealing with the unpredictable sources must be developed at an early stage, as these may have significant impact on the final design.

ACKNOWLEDGMENTS

This preliminary evaluation of the ionizing-radiation environment of the satellite power system was carried out in conjunction with the Workshop on "The Radiation Environment of the Satellite Power System" held at the Lawrence Berkeley Laboratory on 15 September 1978. The author gratefully acknowledges Dr. Walter Schimmerling, Dr. John W. Wilson, and particularly Dr. Stanley Curtis for reading and commenting on this report.

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This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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TO:

Dr. Sherman Vinograd

Medical Director

St. Mary's Hospital

707 South Mills Street

Madison, Wisconsin 53715