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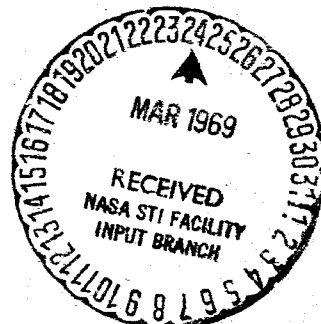
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HANDBOOK OF SPACE ENVIRONMENTAL EFFECTS ON SOLAR CELL POWER SYSTEMS

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**HANDBOOK OF
SPACE ENVIRONMENTAL
EFFECTS ON SOLAR CELL
POWER SYSTEMS**

by
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and
Matthew J. Barrett

January 1968

Prepared For

**THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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FOREWORD

Since the "Handbook of Space Radiation Effects on Solar Cell Power Systems" (NASA SP-3003) was published in July 1963, much additional data has been generated on radiation effects in the space environment. This volume revises, up-dates and expands the earlier handbook and includes data on instrumentation techniques and also on solar flare and meteoroid effects which were not included in the first volume.

The objective of this new handbook is to provide a single source of analytical methods and experimental data in a convenient and useable format which can be applied by engineers in designing solar cell power systems to operate satisfactorily in the space radiation and meteoroid environments.

ACKNOWLEDGMENT

The assistance of Messrs. Ralph M. Sullivan, Richard L. Statler and Robert G. Lyle is gratefully acknowledged, as well as the cooperation of many other individuals and organizations in providing data. The authors assume responsibility for the selection of source material and apologize to any authors who may believe their work has not been given adequate coverage. It was necessary to be selective because of the large volume of data available and the desire to present the data in as simple and general a format as possible.

The support and cooperation of Mr. Arvin H. Smith in NASA Headquarters has made this work possible.

The final draft has received the benefit of criticisms, comments, and additions generated during a two-day review by a committee under the chairmanship of Arvin H. Smith. We are indebted to the members of this committee: Bruce Anspaugh, Paul Berman, William Billerbeck, Wayne Brown, R.G. Downing, A.G. Holmes-Siedle, Daniel Lott, Werner Luft, John Martin, Henry Oman, Joseph Peden, Wayne Picciano, Duncan Reynard, Dante Tosca, John Vesel, and Arthur Wilbur. We have, however, been selective in the use of comments from the committee, owing to a desire not to delay publication.

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HANDBOOK OF SPACE ENVIRONMENTAL EFFECTS ON
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I. INTRODUCTION

Bombardment of solar cells by energetic electrons, protons and micrometeoroids in space produces damage which decreases their power output. Earth satellites may encounter appreciable numbers of high energy charged particles which are trapped in the earth's magnetic field. Interplanetary spacecraft may encounter sudden high intensities of energetic protons released by the sun. In the design of solar cell power systems, consideration should be given to these electrons and protons and their energy spectra during the proposed mission, the type of solar cells, the type and thickness of shielding material, the solar cell operating voltage, and the expected operating temperature range. This handbook is intended to provide a review of research data and analytical methods which can be used to design radiation resistant silicon solar cell power systems for earth satellites which have orbits passing through the magnetosphere and for spacecraft exposed to solar flares and micrometeoroids.

Only limited data are included on the damage by low energy protons (below 5 MeV) because an adequate analytical method for predicting their effects is not yet available.

Data on solar cells made of materials other than silicon (e.g., gallium arsenide, cadmium sulfide and cadmium telluride) have been omitted because production cells are not generally available for space applications.

Instrumentation techniques which have become obsolete and data on solar cells of a type which are no longer available have in most cases been omitted.

II. THEORY OF THE SILICON SOLAR CELL

A. SEMICONDUCTOR MATERIALS

A semiconductor material has an electrical resistivity generally in the range of 10^{-2} to 10^{+9} ohm-cm, which is intermediate between that of conductors and insulators. Most semiconductors owe their conductivity to the presence of impurities or doping atoms. For example, when crystalline silicon is doped with a concentration of a few atoms of arsenic or phosphorus for every 10 million atoms of silicon, its resulting electrical resistivity is of the order of 1 to 10 ohm-centimeters. This is the range of resistivity values which is typical of the silicon used for the base material of solar cells.

When Group V elements having 5 valence electrons, like arsenic and phosphorus, are used to dope silicon, they supply excess electrons which are available for electron conduction. The resulting silicon is called n-type, because the majority charge carriers (electrons) are negative.

When Group III elements, having only 3 valence electrons, like boron and aluminum, are used to dope silicon, there is a deficit of one electron per dopant atom (a "hole") which can move from atom to atom providing "hole" conduction. The resulting silicon is called p-type, because the majority charge carriers (holes) are positive.

B. THE P-N JUNCTION

It is possible to convert silicon from n to p type or vice versa by adding doping atoms in a concentration sufficient to overcome the effect of the initial doping. Therefore, for example, a thin layer near the surface of a crystal of n-type silicon can be converted to p-type by diffusing in an excess of a Group III element like boron or aluminum. Similarly an n-type layer may be produced on p-type silicon by diffusing in

arsenic or phosphorus. A solar cell consists essentially of a wafer of semiconductor material with a surface layer of opposite type and a p-n junction near the illuminated surface.

C. THE PHOTOVOLTAIC EFFECT

When a p-n junction is produced in a crystal, electrons from the n-side thermally diffuse into the p-region where they are called minority carriers. Similarly, holes from the p-side become minority carriers in the n-region. These minority carriers rapidly become neutralized by recombining with the majority carriers. Since each region was initially electrically neutral, the loss of electrons from the n-region and the loss of holes from the p-region each contributes to establishing a potential difference across the junction with a plus voltage on the n-side. This built in electric field can be used for power generation because it acts to separate any electrons or holes which are generated within the crystal and which diffuse into the region of electric field.

When a photon of light is absorbed in a crystal it will release an electron, leaving a hole, and thereby producing an electron-hole pair. After a short burst of illumination, the electrons and holes which have been injected both diffuse until they find a carrier of opposite charge and recombine. The length of time for a minority carrier to recombine (the lifetime, τ) depends on the density of recombination centers, which are crystal defects that provide sites where minority carriers can be captured and recombined readily with majority carriers. Recombination centers are electrically charged defects which act to capture either electrons or holes.

The mean "crow flight" distance travelled by a minority carrier before recombining is called the minority carrier diffusion length, L , which is related to the lifetime, τ , by:

$$L = \sqrt{D\tau} \quad (\text{II-1})$$

where D is the diffusion constant. In silicon, the value of D is about $38 \text{ cm}^2/\text{sec.}$ for electrons and $13 \text{ cm}^2/\text{sec.}$ for holes at 300°K. The typical range of values for the

lifetime τ is approximately 0.1 to 10 microseconds in silicon. The corresponding range of values for the diffusion length is about 10 to 200 microns (one micron is 10^{-4} cm.). Both L and τ are dependent on the type and concentration of recombination centers, which are controlled by the impurity content and the crystal perfection. The primary effect of radiation damage is to increase the concentration of recombination centers and thereby to decrease L and τ . The parameters L , D and τ are also increasing functions of the temperature.

When light is absorbed in the region near the p-n junction of a solar cell, which is usually 0.25 to 1 micron below the surface, some of the electrons and holes will diffuse to the junction. At this point, the charges will be separated by the built-in electric field at the junction, thereby providing a current which can flow to an external load through electrodes attached to the front and rear. This method for direct conversion of photon energy to electrical power is known as the photovoltaic effect.

The depth in silicon at which carriers are released depends on the wave length spectrum of the light source as well as the variation of silicon absorption with wavelength as shown in figure II-1. The long wavelength infrared radiation penetrates more deeply into the cell before absorption.

When a solar cell is illuminated by red light or infrared radiation, which penetrates into the silicon and produces electron-hole pairs as much as several hundred microns below the junction, the current output is dependent on the diffusion of minority carriers from their point of release. Only a portion of the minority carriers reach the p-n junction. The fraction which manage to reach the junction depends on the magnitude of the diffusion length for minority carriers in the base region. Therefore, exposure to radiation which produces recombination centers, primarily affects the response of a solar cell to long wavelength illumination.

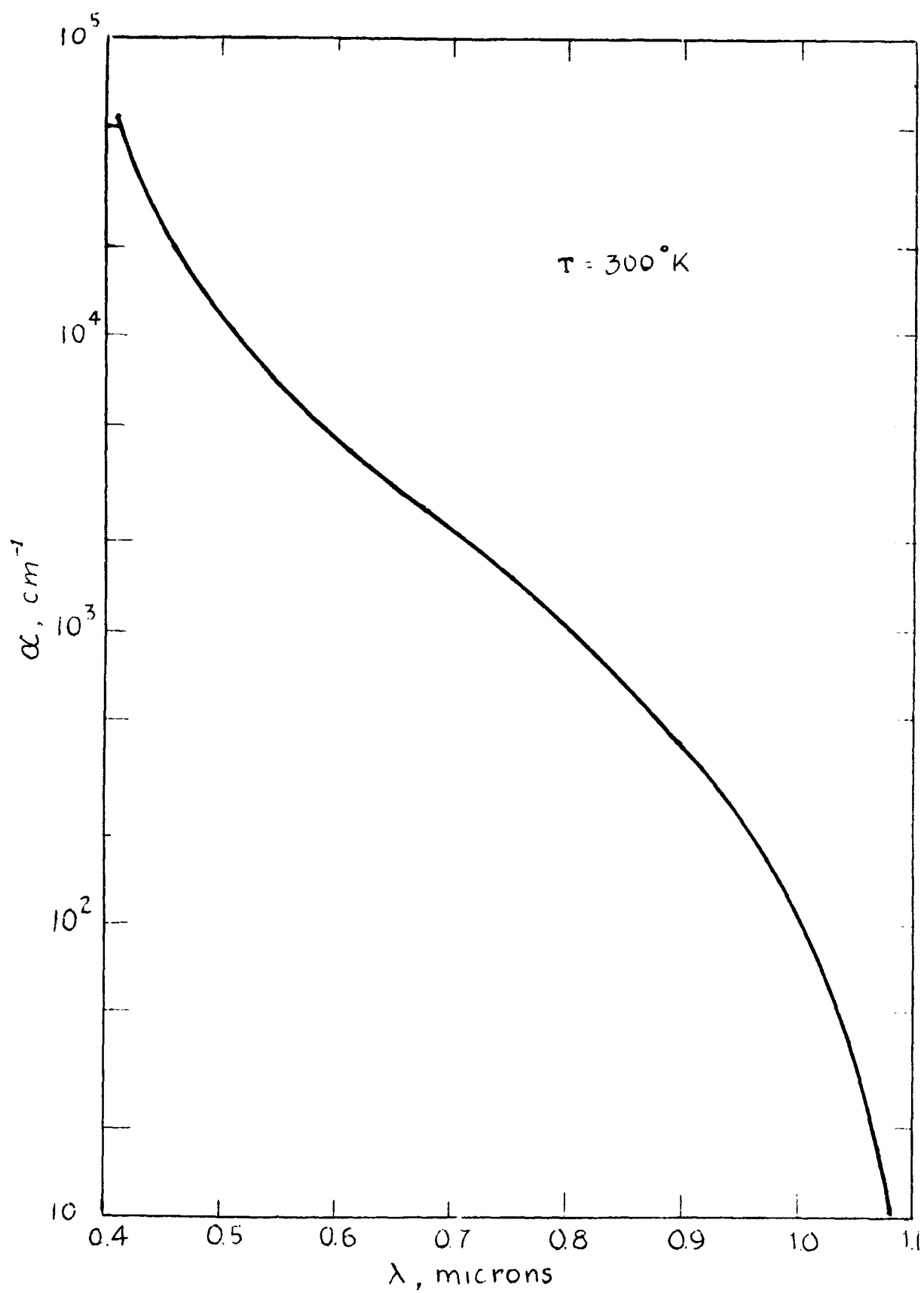


Figure II-1. Absorption Constant α vs. Wavelength λ for Light in Silicon (ref. 230)

D. SOLAR CELL DESIGN

A typical solar cell consists of a rectangular wafer of high purity semiconductor crystal with a p-n junction formed near the front surface and electrical connections applied to the front layer and to the base region, as shown in figure II-2. Usually a conducting grid is used on the front surface to reduce the internal resistance to lateral current flow in the thin surface layer.

Until 1963 most solar cells in the United States were made with a p-type layer on n-type silicon (p/n cell). The development of radiation resistant n-on-p silicon cells by Mandelkorn (ref. 182) has lead to their selection for most satellites.

The improved performance of n-on-p cells under radiation can be attributed partly to the fact that electrons, which are the minority carriers in the p-type base material, have about a three times greater diffusion constant than holes do in the n-type base of

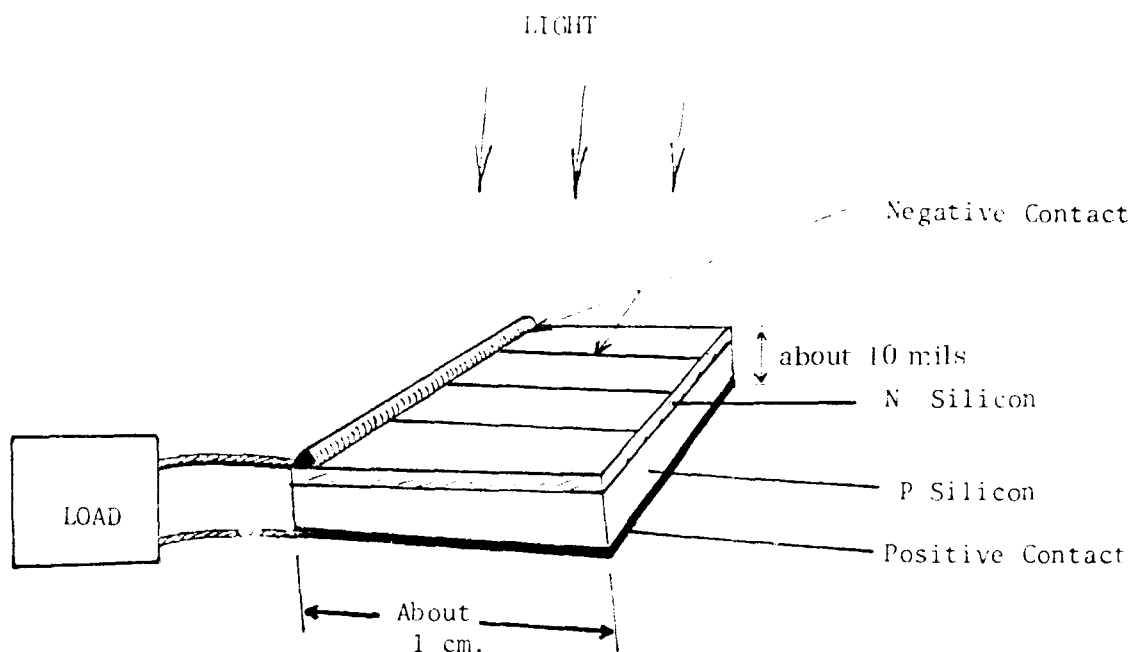


Figure II-2. N on P Silicon Solar Cell

p-on-n cells. A contributing factor is that the types of recombination centers produced by radiation in p-type silicon are less effective in capturing minority carriers (electrons) than those produced in n-type silicon are in capturing holes.

Optimization of solar cell design for radiation resistant performance requires locating the p/n junction only about 0.25 micron below the front surface to maximize the collection of current generated by photons near the blue end of the visible spectrum, which are absorbed and produce electron-hole pairs very near the surface. Cells designed in this way are called shallow-diffused or blue-shifted cells. They derive a smaller fraction of their power from the red end of the solar spectrum and are therefore less sensitive to degradation of the diffusion length in the base.

E. SOLAR CELL PERFORMANCE

The relation between current and voltage from a photovoltaic cell is given by the solar cell equation (ref. 314).

$$I = I_L - I_O \left[\exp \left\{ \frac{q(V + IR_s)}{AkT} \right\} - 1 \right] \quad (\text{II-2})$$

where

- I = current through the load
- I_O = saturation current for the p-n junction
- I_L = photovoltaic current across the junction
- V = voltage across the external load
- R_s = internal resistance of the cell
- A = a constant, normally 2-3 for silicon
- k = Boltzmann's constant, 1.38×10^{-23} joules/°K
- T = temperature, °K
- q = electronic charge, 1.6×10^{-19} coulombs

The direct current behavior of a solar cell is well-characterized by the equivalent circuit shown in figure II-3.

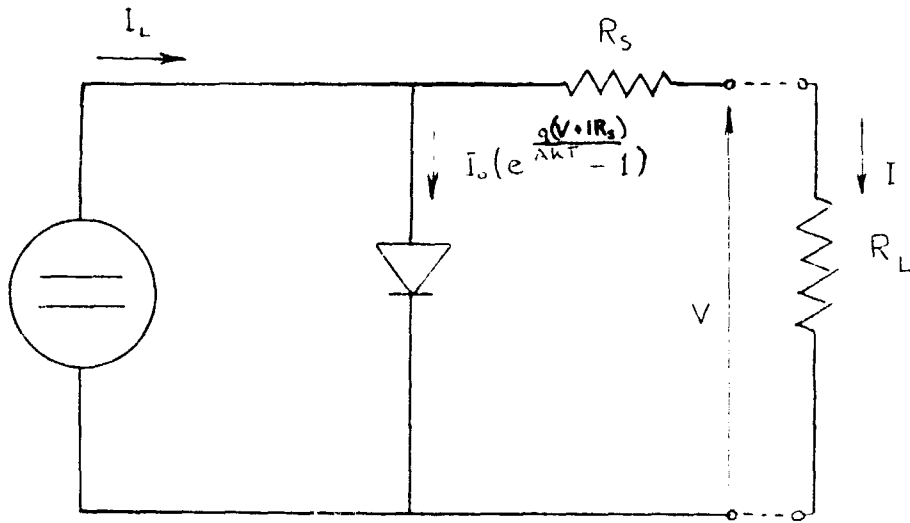


Figure II-3. Equivalent Circuit Diagram of Solar Cell.

The solar cell equation is found to closely approximate the experimentally measured I-V curves for a solar cell. However, the parameters I_0 , A and R_s are found to depend on temperature and radiation exposure. Also the light-generated current I_L is a function of the intensity and the spectral (color) distribution of the light source.

Equation II-2 cannot be solved explicitly to yield the value of current (I) at an arbitrary voltage. However, in cases where the internal resistance of the cell (R_s) is negligible, then the measurable short-circuit current (I_{sc}) is equal to the photovoltaic current across the junction (I_L). This leads to simpler equations for approximating the I-V relation in solar cells which often are used in analytical correlations and computer calculations.

Kleinman (ref. 161) has analyzed the effect of minority carrier diffusion length on the short circuit current. Similar analyses have been reported by Oliver (ref. 218) and Beatty and Hill (ref. 22). The results show an increase of short circuit current

with an increase of base diffusion length. The dependence is most pronounced for long wavelength photons and is smallest for short wavelengths. This is caused by the variation of silicon absorption with wavelength (refs. 76, 314). For example, at a wavelength of 1 micron, the absorption coefficient is 110 cm^{-1} and the photon attenuation length is 91 microns. In this case, appreciable numbers of photons penetrate to depths greater than 100 microns in a solar cell before absorption.

The use of minority carrier diffusion length (or lifetime) to correlate radiation damage effects is recommended because it is an accurately measurable quantity (see next section) which is sensitive to damage by penetrating radiation and is independent of other solar cell parameters like surface optical reflectivity, surface recombination velocity for minority carriers, cell thickness, and junction depth, all of which influence measurements of current and power.

In nearly all space applications a glass, silica or sapphire coverslide is used over the cell to reduce reflection losses, to aid in radiative heat rejection and to carry a spectrally selective filter as well as to provide radiation shielding and protection in ground handling.

III. INSTRUMENTATION TECHNIQUES FOR MEASURING SOLAR CELL PARAMETERS

(This Section was prepared by Richard L. Statler)

A. INTRODUCTION

This section summarizes instrumentation techniques for measurement of current, voltage, power, efficiency, spectral response and minority carrier diffusion length of solar cells, as well as calibration methods using sunlight and solar simulators.

B. CURRENT-VOLTAGE CHARACTERISTICS

The solar cell parameter of chief importance is the current-voltage (I-V) characteristic which is obtainable by three methods. The most frequently used, and most valid for power system design, is the photovoltaic output characteristic. This method uses a fixed illumination of known intensity and a variable resistive load across the cell terminals while measuring the voltage across and the current out of the terminals. This is the normal mode of operation of the cell, and typical I-V characteristic curves for 1 by 2 cm N-on-P 10 ohm - cm cells are shown in figure III-1.

Ideally, the I-V characteristic should be determined under illumination equal to the solar spectrum in space. For experimental convenience, measurements are made under various light sources including tungsten filament bulbs, carbon and xenon arcs, and commercial solar simulators and the results corrected to solar spectrum conditions.

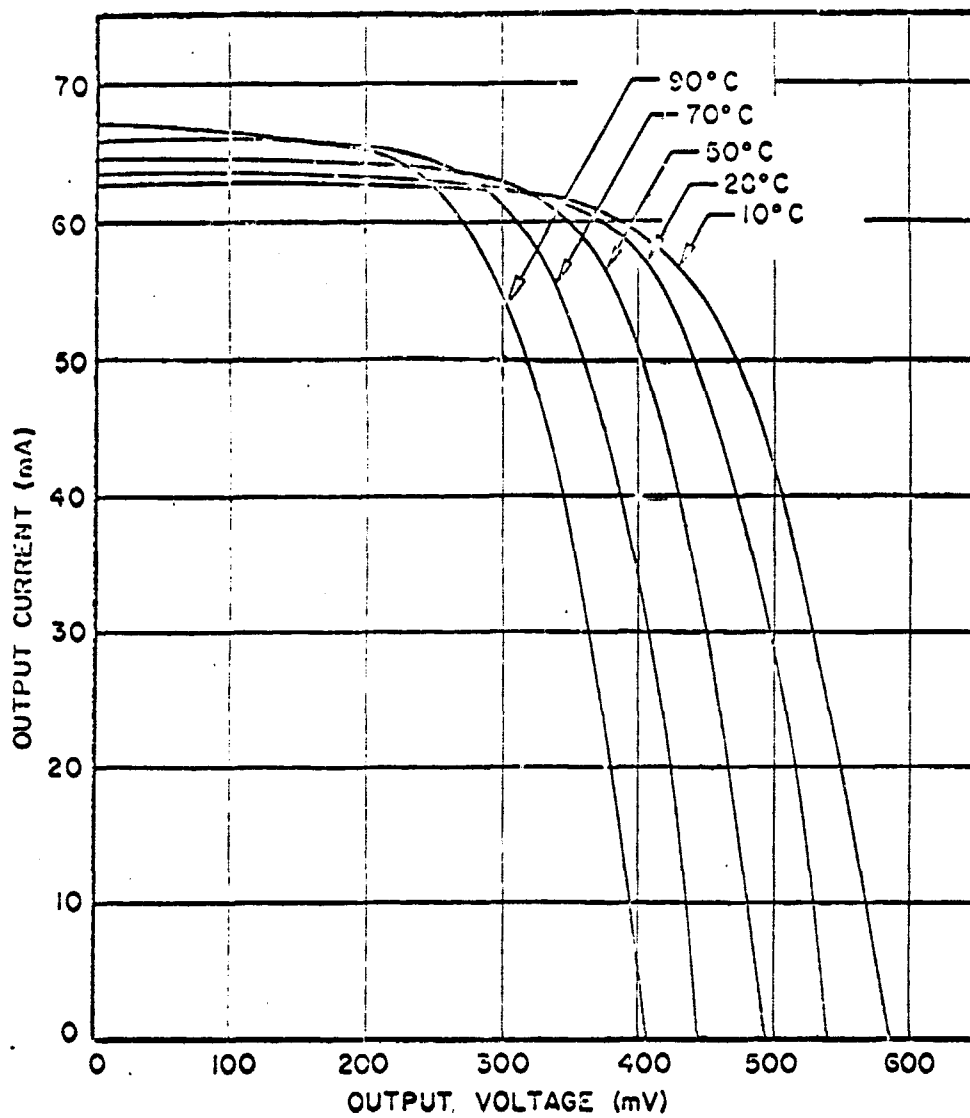


Figure III-1. Current vs. Voltage Curves for n/p 10 ohm-cm Silicon Solar Cells at Various Cell Temperatures Measured in Simulated (AMO) Sunlight Using a Spectrosun Simulator (after ref. 191)

1. Light Sources

a. Tungsten bulbs

The color temperature* of the tungsten source is normally set at 2800°K by calibrating with an appropriate color temperature meter and regulating the bulb-voltage or current to the required value. The light intensity is determined by measuring the output of a standard solar cell at various distances between the surface of the cell and the source. Usually the light intensity is adjusted to correspond to a standard cell current output at 140 milliwatts/cm², of sunlight at air mass zero. (Air mass one is the equivalent absorption of Earth atmosphere at sea level to solar light when the sun is at zenith; air mass zero refers to the spectrum in space.)

The light uniformity should be mapped at the test plane with a small area solar cell (approximately 0.25 cm²). Uniformity can be improved by diffusing the light by sandblasting the bulb or using etched glass filters placed between the light and the test plane. Typically, a uniformity of $\pm 2\%$ is attained.

The solar cell temperature can be controlled by a water-cooled holder, and the temperature of the cell can be related to a thermocouple or thermistor embedded in the holder. Vacuum ports in the cell holder, as well as pressure contacts, provide for good thermal transfer from cell to holder. Forced-air cooling can be used as well. Normally, the I-V characteristic is measured at 25° - 28°C. The open circuit voltage of a silicon cell decreases about 2 millivolts for each degree rise in temperature.

Water filters have been used to reduce the near-infrared energy in the tungsten spectrum. These comprise about 3 cm of deionized water in a glass, Plexiglas, or Lucite container. Current practice is to use a heat-absorbing glass filter which is less temperature sensitive, easier to handle, and not subject to contamination by marine growth.

*The temperature of an incandescent body, determined by observing the wavelength at which it is emitting with peak intensity and using that value in Wien's Law which relates wavelength of maximum radiation intensity for a black body to the temperature of the radiating black body by, $\lambda_m = b/T$, where b is the Wien displacement constant (0.28978 centimeter-degree) and T is expressed in degrees Kelvin.

b. Carbon arc

Carbon arcs have been used for thirty-five years for simulating solar energy for test purposes. The carbon arc spectrum is continuous from 0.26 to over 5 microns and is rated at a color temperature of 6000°K. Decollimation angles of 1 1/2° have been achieved (compared to the sun of 32 minutes). Automatic carbon-rod feed mechanisms are available for continuous duty. Typical manufacturers are Genarco, Inc., RCA Service Company, and the Strong Electric Corporation (refs. 119, 167).

c. Xenon arc

Xenon arc simulators are made by Aerospace Controls Corporation, Optical Coating Laboratory, Inc., (refs. 4, 285) and Spectrolab (ref. 186). There are two general classes: (1) Xenon arc only, requiring filters to remove the high energy bands between 0.8 and 1 micron; and (2) Xenon arc combined with a tungsten filament source, where each light source provides part of the spectrum and the light is mixed together using dichroic mirrors. A typical spectrum for an OCLI solar simulator is compared with sunlight in Figure III-2.

Some problems associated with solar simulators are spectrum matching, intensity, collimation, uniformity of the light beam (both in time and space), stability, and ripple. Maintenance and calibration procedure vary with each type. All require the use of calibrated solar cells as standards for adjusting and checking the beam. Accepted standard cells are those which have been sunlight calibrated at Table Mountain, California or on airplane or balloon-flights. The short-circuit current of such a cell, extrapolated to a value for space sunlight, is used as the calibration point for the simulator.

2. Variable load

For recording the photovoltaic output characteristic of a single cell, it is sufficient to put a 1000 ohm variable resistor across the terminals and draw the I-V curve on an X-Y recorder as the resistor is varied manually. To do this for a solar array

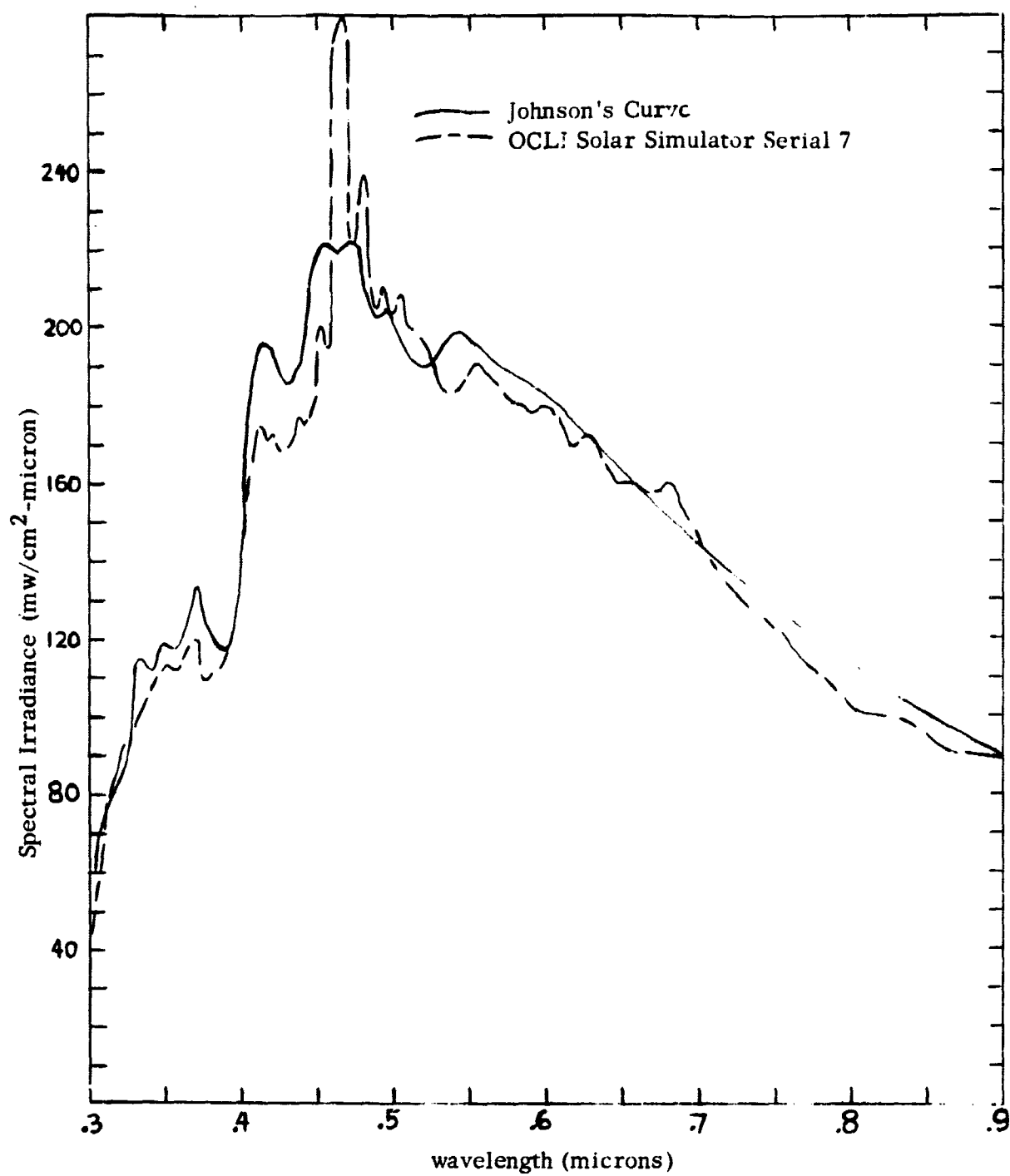


Figure III-2. Spectral Distribution of Solar Simulator Output Compared to Space Sunlight (Johnson's Curve)

requires the use of a higher wattage-rated load. Several types have been designed, incorporating various degrees of automatic operation. One such device, by Sullivan and Burke (ref. 278) is capable of dissipating up to 10 amperes and 300 watts. See figure III-3. When this load is used for single cell measurements or cell modules with power up to one ampere and 5 watts, the transistors are shorted out with switch S 1. For higher power operation where the power is dissipated through the transistors, solar array voltage must be at least 1.5 volts because of the 0.5 volts needed to drive the transistors. The motor-driven logarithmic potentiometers provide a smooth and uniform plot of the I-V characteristic from open circuit to short circuit conditions. Hand-cranked operation is possible when required.

A more complex load has been developed by Spectrolab and designated the model D-55^a Electronic load. This may be used with individual cells or solar panels with up to 250 watts output. This instrument can sense the maximum power point, read out current, voltage, efficiency, I_{sc} , and V_{oc} , as well as current at a fixed voltage and voltage at a fixed current.

Another type of variable load has been built at the John Hopkins University Applied Physics Laboratory after a suggested circuit by RCA (fig. III-4). Short circuit currents of over 200 milliamps can be measured with this circuit, as it sweeps out the I-V curve. R 1 is adjusted to balance out the V_{oc} of the cell under test. Then, with S 1 on "Automatic" and R 6 shorted, R 9 is adjusted to slightly exceed the I_{sc} of test cell. Then, with S 1 on "Manual", R 6 is set for a sweep time compatible with the response time of the X-Y recorder. Now, switching S 1 to "Automatic" will sweep out the I-V curve of the test cell.

A variable load has been built by Hoffman Electronics Corporation. This includes an X-Y recorder and is capable of measuring individual cells or arrays up to 20 amperes and 1000 watts. A power supply biases the cell or array under test such that current at zero voltage can be obtained. Operational amplifiers control the writing rate so that pen and carriage velocities are constant.

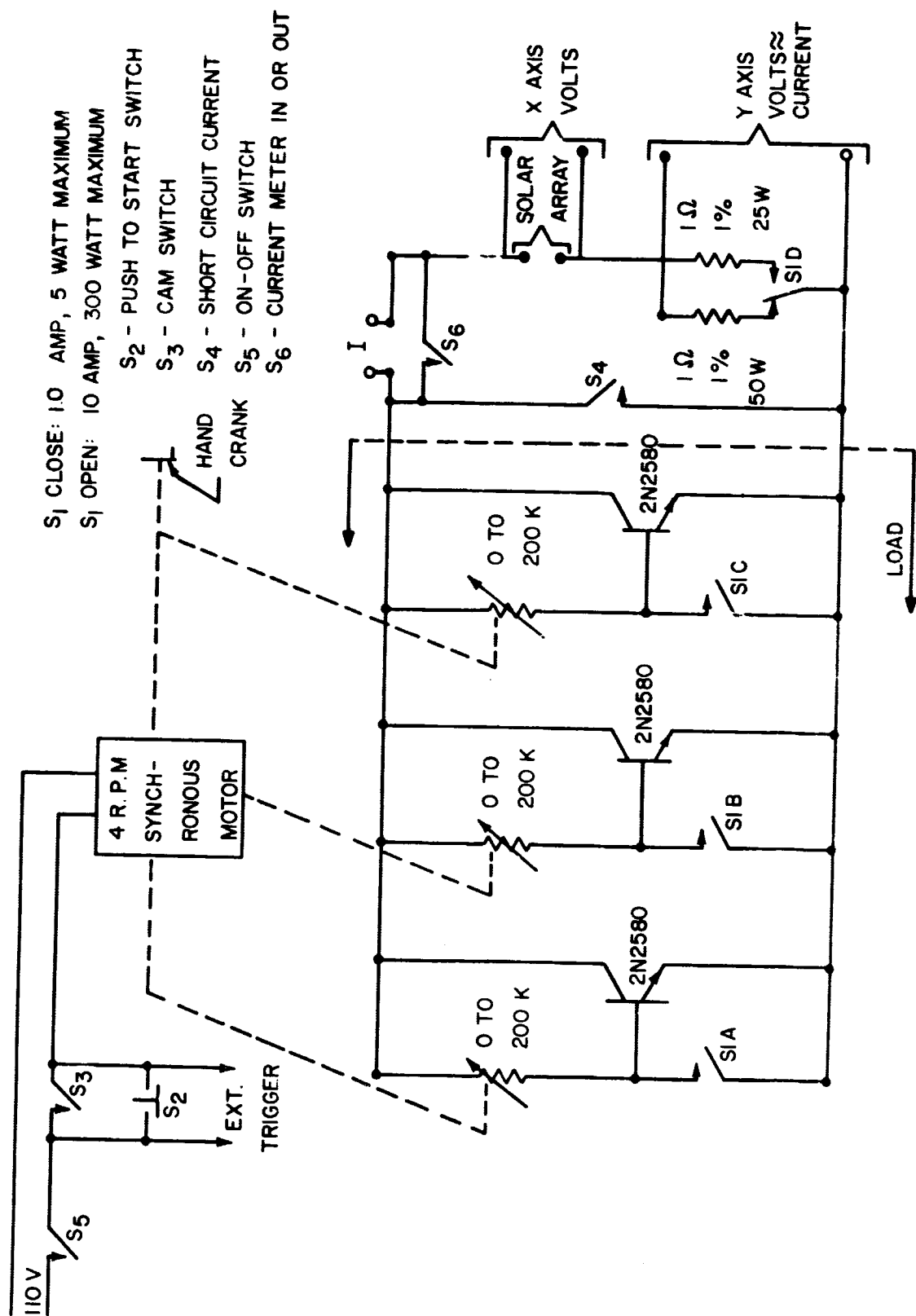


Figure III-3. 10 AMP, 300 Watt Solar Array Load (300 Volts Maximum)

NOTE:

R1, R9 ARE 10 TURN
Q2, Q3 HEAT SINK REQUIRED

SOLAR CELL I-V SWEEP CIRCUIT

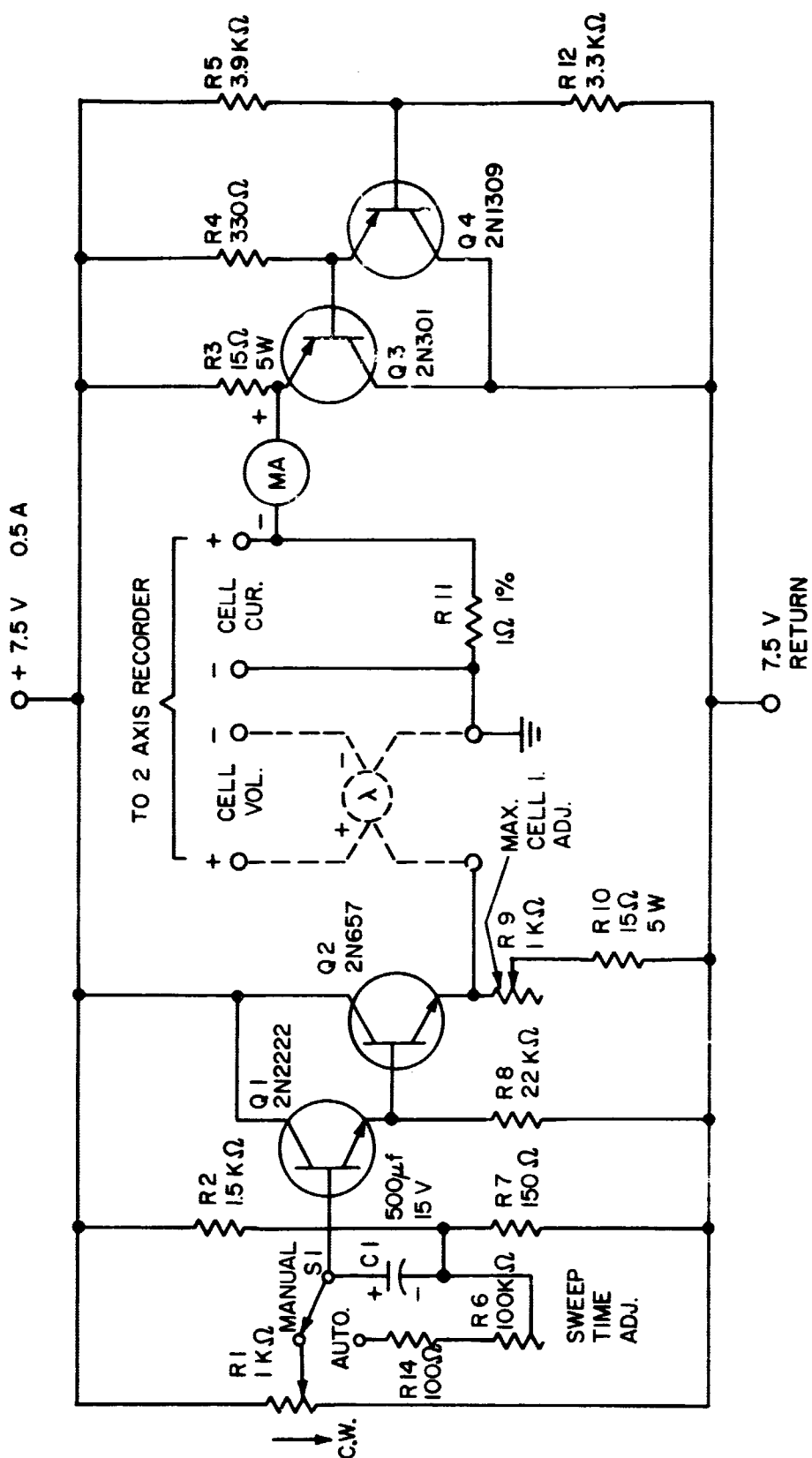


Figure III-4. Solar Cell I-V Sweep Circuit

3. Forward and reverse characteristics

Several parameters of the solar cell can be determined from the I-V characteristic:

- (1) Short-circuit current, I_{sc} , is the value of the current axis intercept (with zero voltage drop across the cell electrodes).
- (2) Open circuit voltage, V_{oc} , is the value of the voltage axis intercept, (the voltage for which there is zero current from the cell electrodes).
- (3) Maximum power output, given by the area of the largest rectangle that can be drawn inside the I-V curve, as well as power at a fixed voltage.
- (4) The series resistance of the cell is determined from two I-V curves run at different intensities, after the method of L. D. Swanson, described by Wolfe and Rauschenbach (ref. 314).
- (5) The reverse saturation current, I_0 , and the junction parameter A can be evaluated by measuring I_L and V_{oc} for a number of different light intensities and finding solutions to equation II-2.
- (6) The diode forward characteristic is plotted by applying an external d-c bias voltage sweep across the solar cell terminals and plotting the current without illumination. This differs from the photovoltaic output characteristic only by the absence of the light-generated current and the reverse direction of the terminal current I, if one increases the observed voltage value by the voltage drop IR_s occurring within the cell.
- (7) A third method for obtaining current-voltage characteristics is to illuminate the cell with various intensities of light and determine the value of light-generated current I_L for each intensity. The measurement consists of plotting values of I_{sc} (which is equal to I_L for typical cells with low series resistance) and V_{oc} for each intensity. This gives a p-n junction characteristic which cannot be derived from the previously mentioned curves by a simple axis translation. A comparison of these three kinds of forward characteristics is shown in figure III-5.

C. SPECTRAL RESPONSE CHARACTERISTICS

1. Definition

The photovoltaic spectral response is defined as the short-circuit current plotted as a function of wavelength for incident light with uniform distribution of spectral energy. Usually the relative spectral response is measured because of the difficulty in making an absolute determination of the incident light energy. The quantum yield, or quantum

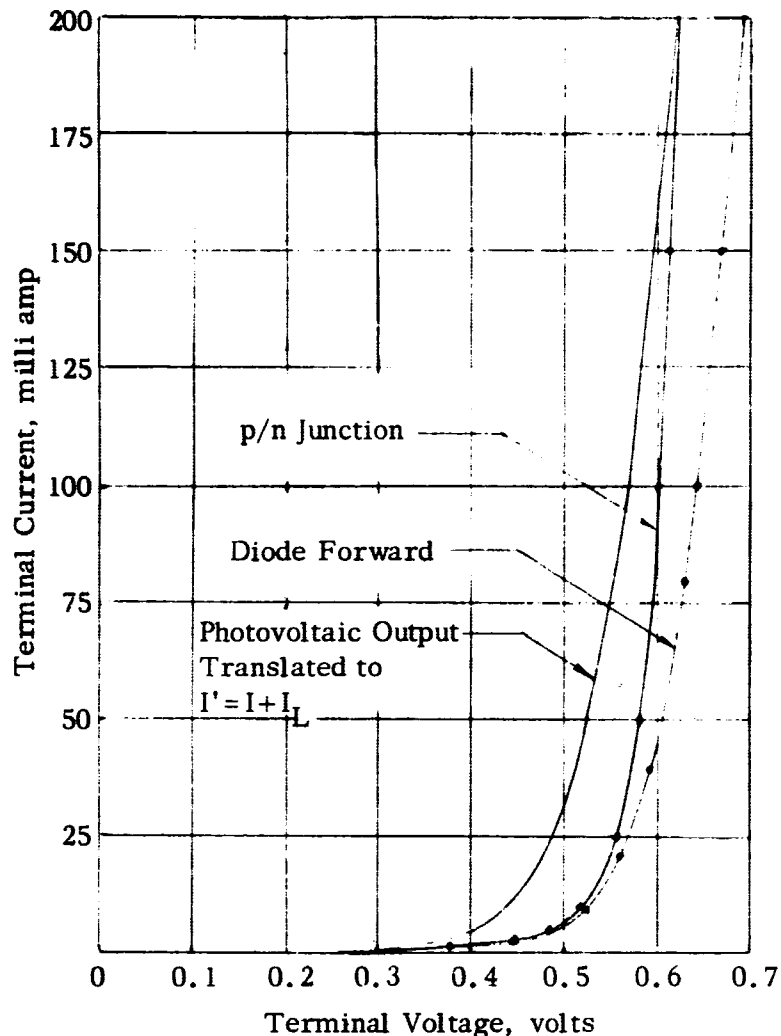


Figure III-5. Current-voltage relationships of a diode, a typical solar cell used as a diode, and as a solar cell. (Ref. 312)

efficiency, is the ratio of minority carriers generated to the number of photons incident upon the cell. This parameter can also be on an absolute basis, if the spectral distribution and intensity of the source are known. Surface reflectivity corrections should be made for greatest accuracy, particularly when comparing different solar cell types with known differences in reflectance.

2. Monochromator

One general technique for these measurements employs a monochromator, either a grating or prism instrument. The system developed at NRL (ref. 164) uses a Bausch

and Lomb 250 mm grating monochromator in a split-beam mode, ratioing the output of the test cell to a multi-junction Reeder thermopile. An on-line analog computer permits data presentation of relative spectral response, relative quantum efficiency, or shortcircuit current response under Johnson's curve (ref. 150) for space sunlight illumination.

A system designed at Goddard Space Flight Center (ref. 97) uses a one-meter McPherson grating monochromator with beam splitting, and ratioing of solar cell and thermocouple outputs by electronic processing of magnetic-tape recorded spectra. Also the reflectance properties of the cell can be measured at the same time with an integrating sphere. Thus the corrected absolute quantum yield can be plotted.

The system of TRW uses a modified Perkin Elmer Model 112 spectrophotometer, with the usual tungsten source replaced by a voltage-regulated projector lamp. Thirty data points are automatically selected by the electronic programmer which normalizes and plots the spectral response in digital form and on a graph. Spectral response curves can be computed for either constant energy input or constant number of photons.

3. Interference filters

The second general method for obtaining monochromatic light for evaluation of spectral response involves use of highly-selective filters, whose pass bands have a width of the order of 15 millimicrons. Generally unchopped light from a projector bulb is used in this method, producing a higher level of illumination than the monochromator. One of the earliest designs of an automated system of this type was developed by H.K. Gummel and F.M. Smits (ref. 125) at Bell Telephone Laboratories. This system uses 8 filters with "weighting factors" or normalizing constants carefully predetermined by extensive calibration with solar cells at Table Mountain. The filters are transported automatically on a wheel through successive positions, and the data are recorded on punch cards for computer processing. Absolute accuracies of 2 to 3 percent are claimed for this system.

An adaptation of this system was made by J. Mandelkorn (ref. 183) at Lewis Research Center, using the same type of filters but with less automation. The accuracy of any filter system is dependent on the validity of the weighting factors for the filters, since there is usually no ratioing of the cell output to a standard thermocouple detector.

Another system used at Lewis Research Center by H.W. Brandhorst (ref. 42) for CdS cells uses a tungsten bulb to illuminate the cells in addition to monochromatic filtered light. This is necessary in this case because readings in the infrared exhibit a time decay without the "biasing" effect of white light. It should be noted that some silicon cells have shown a dependence of diffusion length on intensity of light, with consequent changes in spectral response. The changes show up at current densities between one and 100 microamps/cm². Thus, in spectral response measurements where the light intensity is low, large errors may occur. These errors are generally not found in filter wheel instruments, and may be removed by d. c. white-light biasing of the sample in chopped-light monochromators.

4. Reflectance of coatings

The reflectivity of the cell surface should be taken into account when applying corrections to the quantum yield curve. Reflectivity is usually measured in an integrating sphere attachment for a monochromator. In another technique used at Heliotek and described by Ralph and Wolf (ref. 233), a light beam is collimated into a small area of the surface by means of an optical system. Intensity of the beam is measured with a solar cell detector, larger in area than the light beam. The specimen cell is placed into the beam and the intensity of reflected light is measured with the same detector which is rotated to various angles from the reflecting surface. The effect of applying anti-reflective coatings to silicon cells is seen in figure III-6.

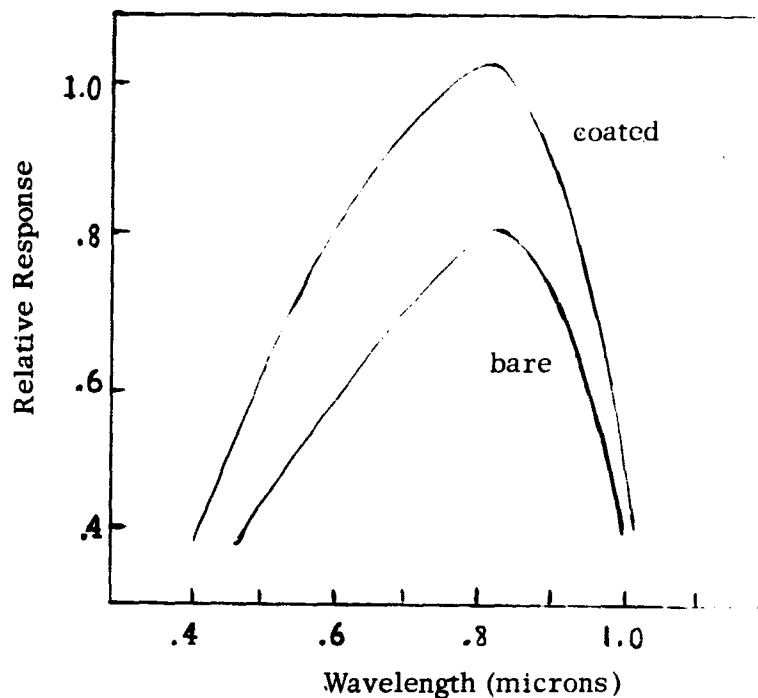


Figure III-6. Typical spectral response of n/p solar cell before and after SiO antireflection coating

D. SOLAR CELL STANDARDS

In order to calibrate light sources for reproducible measurements of solar cells, it is desirable to obtain a calibration for a standard solar cell, with provision for watercooling as shown in figure III-7. Such calibrated standards are available from some solar cell manufacturers. Two general methods for calibration involving sunlight are now in use. In the past, solar cell standard testing was conducted at Table Mountain, California. This site is now used for tests of complete solar cell panels.

To calibrate standards, it is necessary to account for the effects of atmosphere on the incident spectrum. The calibration methods in use are based on a combination of minimizing these effects and then calculating the residual effect on the cell response.

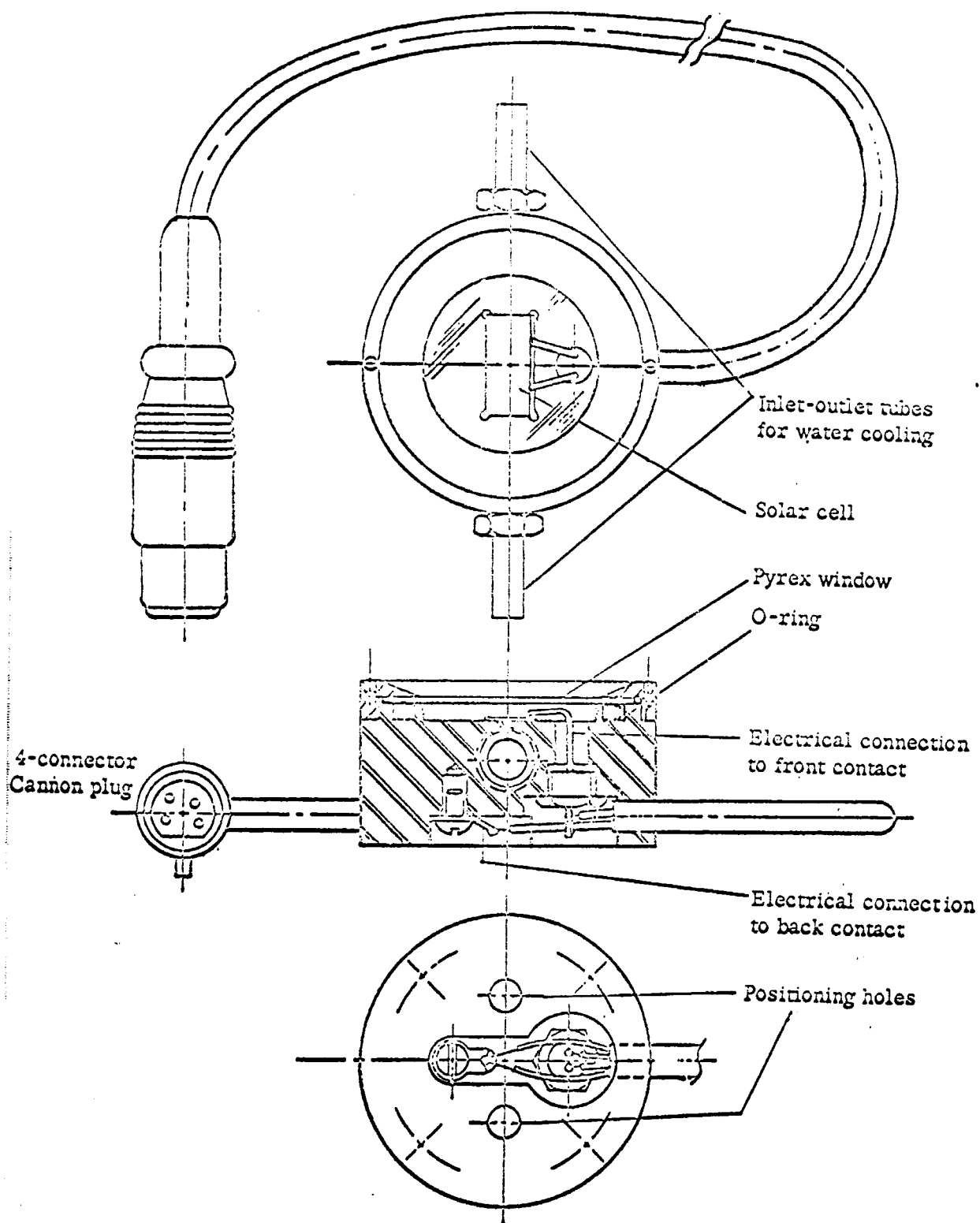


Figure III-7. Standard Solar Cell Encapsulation

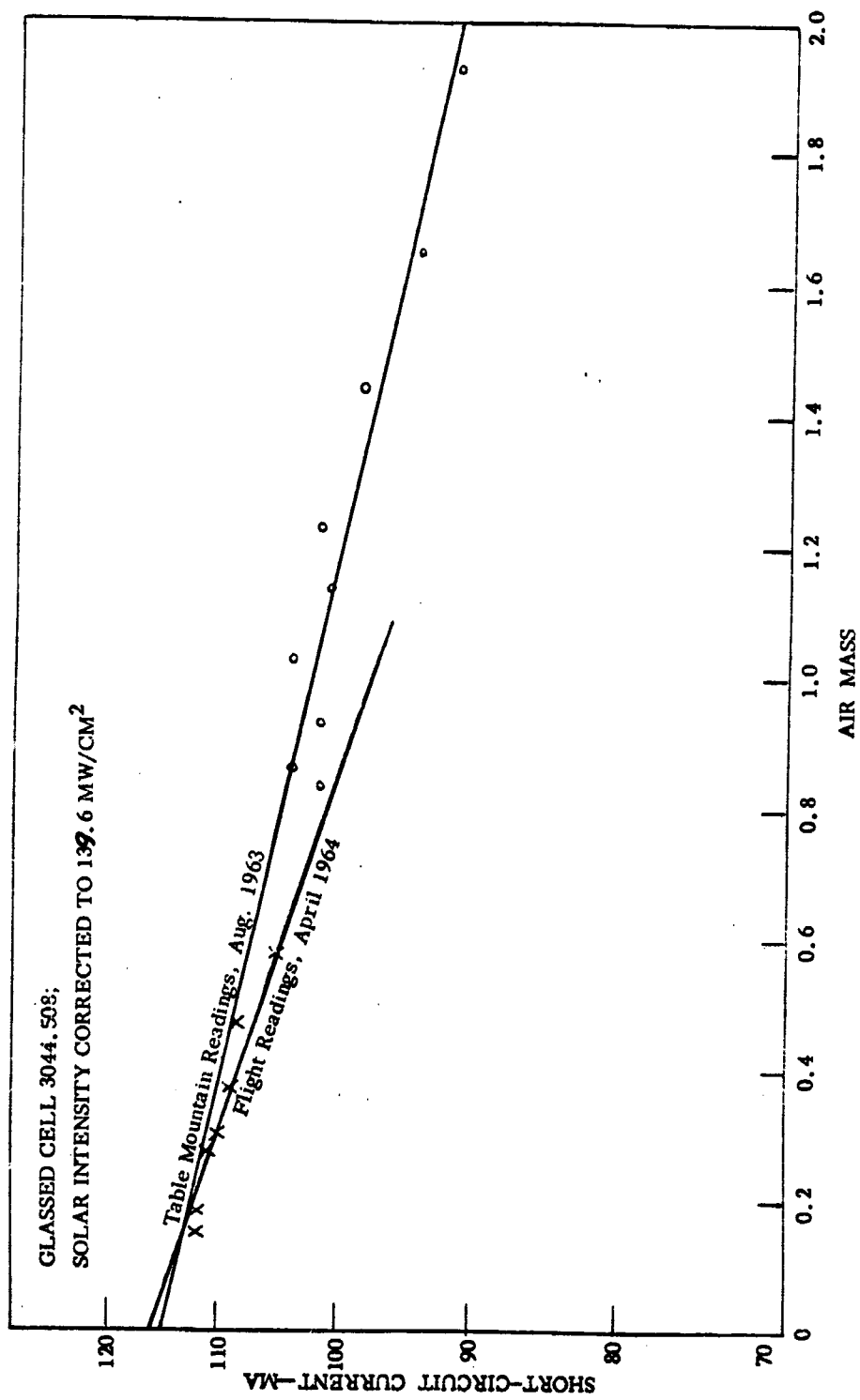


Figure III-8. Extrapolation of Short Circuit Current to Air Mass Zero

A more detailed discussion of the corrections and calculations has been prepared by Zoutendyk (ref. 324).

A method for standard cell calibration which is too detailed to be discussed here is obtainable from Centralab Semiconductor (ref. 220). This technique will give $\pm 1\%$ reproducibility when the necessary atmospheric corrections are made.

1. High-altitude Balloon flights

In order to collect calibration data at higher altitudes where smaller corrections must be made to extrapolate readings to air mass zero conditions, solar cells have been flown on helium filled balloons. Measurements from altitudes of 80,000 feet have been reported, where the remaining air mass is only 0.03 and the solar intensity is 0.5% less than in space. The cells are placed on top of the balloon to eliminate sun and earth albedo reflections from the balloon surface. Solar trackers maintain orientation of the cells to within 4 degrees of normal to the sun.

Short circuit current is measured across a precision one-ohm resistor and is telemetered, with associated temperature measurements, to a ground station. Flight duration is three hours, or longer around solar noon. Repeatability of cell currents as measured on successive flights is within 0.5%. During the two hour time for ascension to maximum altitude, the cell temperatures fall to -10°C while passing through the troposphere (ref. 324).

2. Aircraft flight testing

NASA Lewis Research Center has developed a system for solar cell calibration by means of airplane flights, now in routine use. A B-57B airplane is equipped with a collimated solar cell tube and normal-incidence pyrheliometer which are coaligned with the sun. A flight pattern is flown from 12,000 to 47,000 feet at 5000 foot intervals while data are recorded (ref. 40).

A typical Langley plot is shown in figure III-9. Air mass values vary from about 0.1 to 0.67 in June and 0.3 to 1.4 in January. Corrections to readings include a

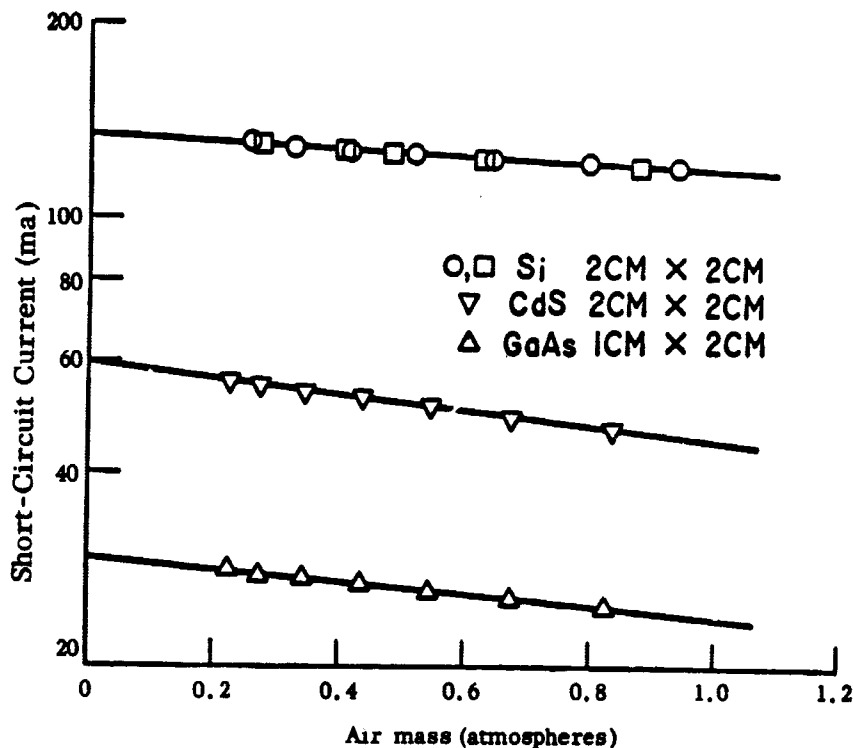


Figure III-9. Typical Langley Plots for Various Types of Cells in Filtered Sunlight

temperature correction for the standard resistors and for nonuniform air mass absorption due to ozone distribution, known as the Chappius band. Solar aspect angle is maintained to within 2° by pilot control of the aircraft using an optical sunsight. An overall system accuracy of $\pm 1\%$ is claimed.

E. MINORITY-CARRIER DIFFUSION LENGTH

The minority-carrier diffusion length is a material parameter of great sensitivity to radiation damage. It is of particular significance in the photovoltaic process because of its direct relation to the transport of charge by minority carriers. It is defined as the average distance traversed by the photon-generated carriers before being reduced to a factor of $1/e$ of their original number through recombination processes. The diffusion length is related to the minority carrier lifetime, τ , through the expression $L^2 = D\tau$, where D is the diffusion coefficient.

Bemski (ref. 26) has reviewed some of the ways to measure diffusion length.

1. Electron injection

The most accurate and widely used technique for solar cells is the electron-beam injection method (ref. 251). This is based on the fact that ionization by electrons will generate excess carriers at a known rate in silicon. The generation rate varies negligibly with depth in silicon. The only measurable current produced in the cell will be by carriers which can diffuse to the junction and be collected. This technique for measuring diffusion length has the advantage of not requiring correction for surface reflectance.

In the case where electron energy is high enough (say, one MeV) so that carriers are generated uniformly in the material, the diffusion length is given by

$$L = J_{sc} / (J_e S_0) \quad (\text{III-3})$$

where J_{sc} is the short-circuit current density, J_e is the particle beam current density, and S_0 is the carrier generation rate. These measurements may be made using a one MeV electron beam with the solar cell mounted in a double-aperture Faraday cup as shown schematically in figure III-10. The evaluation of the generation rate, S_0 , is done in a manner described by Rosenzweig (ref. 251), and has a value near $225 \pm 5\%$ charge-pairs per micron for each 1 MeV electron.

Useful beam current density is in the order of 2 nanoamps/cm², which will generate a short circuit current density of about 90 μ amp/cm² in a cell with $L = 200$ microns. This is conveniently measured across a precision resistor using a micro-voltmeter.

It is possible to measure diffusion length degradation simultaneously with radiation bombardment, provided the particle-generated I_{sc} is monitored and the initial diffusion length is known. This has been done for proton radiation (ref. 252) and gamma radiation (ref. 124), as well as electrons.

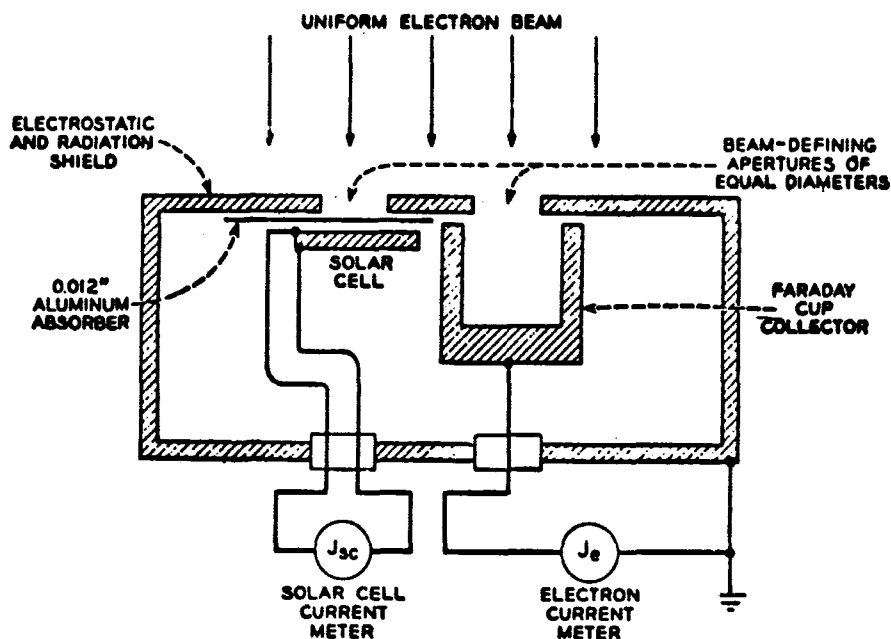


Figure III-10. Schematic diagram of the vacuum Faraday cup used to measure electron flux and minority-carrier diffusion length in solar cells

In the case of proton-irradiated cells, the diffusion length has been seen to be a function of carrier concentration. Thus, it is necessary to flood the cell with white light approaching solar intensity, and use a chopped electron beam to inject carriers with a.c. measuring techniques. The value for diffusion length found this way is accurate to $\pm 5\%$

2. Optical injection

This method can use either steady or chopped monochromatic light of long wavelength. A suitable source is a projection lamp with a 1.0μ narrow-band interference filter. Surface effects are minimized by using one micron light for deep penetration, as in the case using the electron beam. This method has been used to measure cells during a proton bombardment (ref. 22). The diffusion length is given by

$$\frac{1}{L} = \alpha \left[\frac{AH(1-R)}{(h\nu)I} - 1 \right] \quad (\text{III-4})$$

where α is absorption coefficient of silicon at the light wavelength (one micron light) and

A is illuminated area in cm^2

H is light energy density, microwatts/ cm^2

R is reflection coefficient at ν

I is short circuit current in microamps.

$h\nu$ is energy per photon in beam, in eV

A thermopile measures the light energy density, and current is measured across a precision resistor.

This infrared method is more accurate than the direct measurement of lifetime using the method where excess carriers are produced by a pulsed light source and the decay of photoconductivity is observed on an oscilloscope (ref. 11).

3. Spectral response curve

It has been shown to be theoretically possible to calculate the diffusion length from the spectral response curve, knowing the light absorption coefficient for silicon, and the junction depth in the cell (ref. 298). Two points on the spectral response curve must be known: the maximum value and the point on the long wavelength side of half-maximum value. Then L is found from:

$$\left(\frac{\alpha_2 L + 1}{\alpha_1 L + 1} \right) \left(\frac{\alpha_1}{\alpha_2} \right) \exp \left[-X_j (\alpha_1 - \alpha_2) \right] = 2 \quad (\text{III-5})$$

where α_1 , is absorption at maximum, α_2 at half-maximum, and X_j the junction depth. Junction depth is determined by angle lapping and interference methods. If this is not practical, the initial L may be established by some other technique, and the spectral response curve can yield L values for similar cells or irradiated cells.

IV. RADIATION DAMAGE TO SOLAR CELLS

A. PRODUCTION OF DEFECTS AND RECOMBINATION CENTERS

In order for a particle to strike an atom of silicon and knock it from its lattice position, the particle must transfer energy equal to the binding energy of the atom in the lattice. A particle of energy E_0 and mass m is restricted by the laws of conservation of momentum and energy to imparting energy in a single collision which is less than a value E , given by

$$E = mc^2 \frac{2m}{M} \left[\left(\frac{E_0}{mc^2} \right)^2 + 2 \frac{E_0}{mc^2} \right] \quad (\text{IV-1})$$

where mc^2 is the energy-equivalence of the mass of the bombarding particle and M is the mass of the silicon atom, 28 amu for the predominant isotope (ref 296).

When the energy E transferred to the atom is equal to the binding energy, then E_0 , as computed from this equation is the threshold energy of the particle for the production of defects. Loferski and Rappaport (ref. 174) have determined a binding energy for silicon of 12.9 eV. This indicates that electrons below 145 keV and protons below 90 eV cannot dislodge the silicon atom by a simple collision.

Above the threshold energy, the bombarding particle can not only dislodge the silicon atom but also give it kinetic energy. This energy can be sufficient for the atom to dislodge further atoms in a cascade process. The displacement of a single atom is called a Frenkel defect or point defect, and is typical of electron or gamma irradiation. The localized disorder caused by a cascade is often called a cluster defect, and is typical of neutron irradiation. Protons typically cause more limited cascades of 3 to 8 displacements per collision (ref. 217).

Each lattice vacancy created in this manner can diffuse rather freely through the silicon. The vacancy and the associated, but less mobile, interstitial silicon atom it has left behind do not significantly affect the electrical properties of the crystal. However, when vacancies join in stable complexes with other vacancies or with impurity atoms of the crystal, there may be a noticeable deterioration of the minority carrier diffusion length of the material. Such stable complexes which serve as sites where minority carriers easily combine with majority carriers are called recombination centers.

The recombination process occurs as the center first captures a carrier of one sign (an electron or hole) and subsequently captures a carrier of the other sign, thereby annihilating an electron-hole pair. If a defect center has properties such that the first-captured carrier is more likely to be freed by thermal excitation than to be annihilated by recombination, the center is frequently called a trapping center.

The silicon A-center is a stable defect consisting of a substitutional oxygen atom occupying a site in the silicon lattice. The silicon E-center consists of a substitutional phosphorus atom associated with a silicon vacancy. The silicon J-center is related to a divacancy. One model suggested for the silicon K-center is a substitutional oxygen atom bonded to an interstitial silicon atom in the next to nearest site (ref. 59). *

The detailed nature and properties of recombination centers is very complex and not yet well understood. Research is underway using electron paramagnetic resonance and other research techniques. For engineering purposes, the primary parameter of importance is the minority carrier diffusion length of each particular grade of commercially available solar cell material and the degradation of this parameter under particle radiation. However, there is the prospect that silicon can be intentionally doped in such a way that stable defects do not cause the formation of recombination centers (ref. 294). The work of Wysocki (ref. 318) using lithium as a dopant for n-type silicon is particularly interesting in this regard.

*A more recent proposed model for K-center structure is a double A-center, a complex of two vacancies and two oxygen atoms in a chain (ref. 62).

As understanding of the solid state processes involved in the production of recombination centers develops, it should be possible to control radiation effects by suitable manufacture and doping of the crystal.

For example, the oxygen concentration in silicon which has been purified by the float-zone method is much lower than in silicon made by the crucible method. The former type therefore would be less susceptible to formation of oxygen complexes. A second method of controlling recombination center formation would be the intentional addition of a scavenging impurity, which would form complexes that are less detrimental to the electrical properties. Mandelkorn (ref. 185) has explored such a possibility. More recently, Wysocki (ref. 320), has shown how lithium appears to form such a complex. With lithium in oxygen-free silicon, there appears to be a dissociation of the complex, so that after a relatively fast initial recovery the cell proceeds to deteriorate in the absence of radiation (ref. 58). With lithium in crucible grown silicon containing greater oxygen concentration, the recovery rate after fast irradiation is slow, but recovery appears to be stable. At this writing (Nov. 1967), few conclusive results can be reliably reported.

An alternative remedy to the formation of recombination centers is their annealing under high temperatures. Each center has a characteristic annealing temperature; holding the crystal at this temperature for several minutes may result in a dissociation of the complexes and recovery of the electrical properties. This scheme may be impractical when the annealing temperature is higher than the cell and its connections can withstand without degradation of reliability.

The present state of knowledge regarding the specific recombination centers in electron-irradiated silicon is far from satisfactory. Carter, Downing and Flicker (ref. 62) state that "At present, the only way to rationalize all the various results relating to electron damage in n/p solar cells is to hypothesize recombination through an acceptor level 0.15-0.17 ev below the conduction band which is associated with the K center. The alternate is accepting the $E_c - 0.17$ ev level (A-center) or $E_v + 0.3$ ev level (K-center) as the recombination center and discount the conflicting evidence between the two".

The effectiveness of recombination centers in shortening the diffusion length in silicon is generally not directly proportional to the number of atoms which are displaced by radiation, but depends on the types of defects that are introduced by protons and electrons of different energies, which affect the types and concentrations of the recombination centers that are formed by interaction with impurities. Wysocki (ref. 319) has shown that a simpler situation prevails in gallium arsenide, where the damage produced by radiation appears to be proportional to the number of atoms displaced.

A theoretical way to improve the collection efficiency of minority carriers in spite of the presence of recombination centers is to use a "drift-field" solar cell in which the doping is graded to spread out the electrostatic field region at the junction. By this technique, minority carriers from a larger volume of the cell are electrostatically swept to the junction and are less susceptible to capture by the recombination centers that are present (ref. 67).

B. BASIC ASSUMPTIONS

Solar cells are dependent for their current production on the motion of minority charge carriers produced in the base region, to the junction which accomplishes charge separation. This motion is primarily by diffusion except in the drift field type of cell. Recombination centers in the region of diffusion reduce the mean lifetime of the carriers and therefore also reduce the current production.

Mathematical relations describing this process are available. The current density J across a unit area parallel to the junction and at a depth x from the junction is

$$J = q \left[D \frac{dn}{dx} + \mu E n \right] \quad (IV-2)$$

where q is the electronic charge, n the density of minority charge carriers, D their diffusion coefficient, μ their mobility, and E the electric field at depth x in the cell. The first term here describes the net result of diffusion and the second describes the field-induced drift.

A gain-and-loss balance equation relates J to the rate at which minority charge carriers are produced by photon absorption. If this rate is G carriers per $\text{cm}^3\text{-sec}$, then

$$\frac{1}{q} \frac{dJ}{dx} - \frac{n}{\tau} + G = 0 \quad (\text{IV-3})$$

The first term describes the net loss of carriers through the boundaries of the unit volume being considered. The second term describes the loss of carriers, per second, in the unit volume due to recombinations there. The mean lifetime τ of the carriers is inversely proportional to the density of recombination centers. Knowledge of τ and G as functions of depth x in the cell then allows one to solve these equations, with suitable boundary conditions (ref. 310) for the current density J and the density n of minority carriers as functions of depth into the cell.

An assumption which is of great value in simplifying the analysis of solar cells under penetrating radiation is that all the performance parameters of a particular design of solar cell are unique functions of the minority carrier diffusion length in the base region and that this diffusion length is uniform throughout the base region after a given exposure. This is equivalent to the assumption that the only effect of penetrating radiation on a solar cell is to reduce the minority carrier diffusion length uniformly in the base region. The minority carrier diffusion length in the surface region is initially very small so that it is much less affected by radiation damage. Also, the local electric field separates the carriers in this region.

This basic assumption is found to be a good approximation when the change in diffusion length is produced by penetrating particles which generate a fairly uniform concentration of defects throughout the front 200 micron thick layer of a solar cell. In general, protons above 5 MeV in energy and electrons above a few hundred keV in energy impinging on bare solar cells approximately meet this requirement. However, low energy protons below 3 MeV, which penetrate less than 100 microns, will primarily damage the front layer and junction region and the foregoing assumption will be invalid. This more complicated situation is discussed in section IV-F-3.

C. EFFECT OF RADIATION ON DIFFUSION LENGTH

Measurements of diffusion length have been made before, during and after bombardment of solar cells with energetic electrons and protons in particle accelerators such as Van de Graaff machines and cyclotrons in order to measure radiation damage. Experimentally it is found that the minority carrier diffusion length (L) measured at a standard temperature varies with fluence (time-integrated flux) of penetrating charged particles Φ according to:

$$\frac{1}{L^2} = \frac{1}{L_0^2} + K\Phi \quad (\text{IV-4})$$

The damage coefficient K is a function of the type and energy of the particles and of the material and its impurity concentrations. K is by definition equal to

$$\frac{d}{d\Phi} (1/L^2)$$

and is the change in $(1/L^2)$ introduced per unit fluence Φ (particle/cm²). It may be called the damage per particle. If L is in centimeters, K is in the units of (particles)⁻¹

Figure IV-1 shows the diffusion length for n/p solar cells of various base resistivity values as a function of the integrated flux of 1 MeV electrons (ref. 86). After initial degradation to a point where

$$\frac{1}{L_0^2} \ll \frac{1}{L^2}$$

the data can generally be correlated by the approximation:

$$\frac{1}{L^2} \cong K\Phi \text{ or } L \cong (K\Phi)^{-1/2} \quad (\text{IV-5})$$

However, for high resistivity base material, (10 ohm - cm or higher) there are sometimes observed deviations from equations IV-4 and IV-5, which may be associated with

a radiation induced increase in resistivity which makes the diffusion length degrade more slowly than the inverse square of the fluence. Data, as in Fig. IV-1, provide the basis for using either diffusion length or equivalent flux to characterize the damage to a particular type of cell. (See p. XI-27.)

Care must be taken in interpreting diffusion length measurements because:

- (1) For proton — irradiated silicon, the diffusion length increases with the injection level or illumination intensity (see section IV-E-1).
- (2) For low energy particles, such as protons below 3 MeV, the range of the particles is not long compared to the diffusion length and therefore the usual assumption of a linear dependence between short circuit current and diffusion length (equation III-3) is not a valid method for determining diffusion length, (see section IV-E-3).
- (3) The characteristics of the p-n junction may be affected by intense radiation, especially low energy protons, which deposit appreciable damage near the junction.

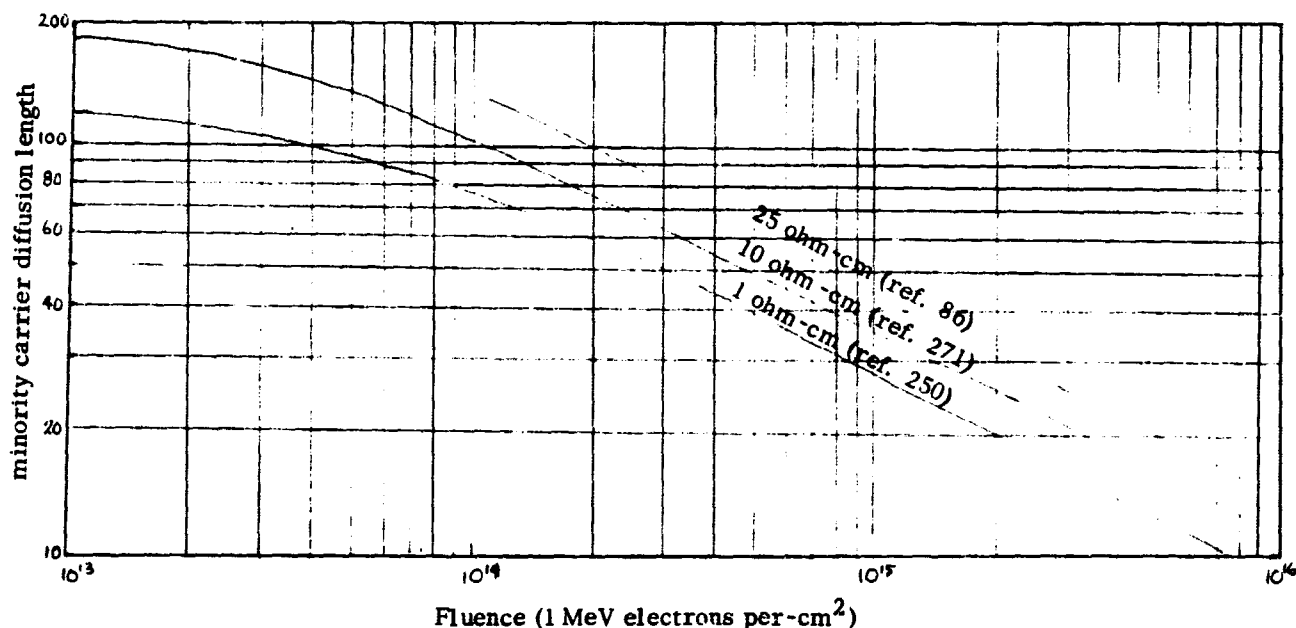


Figure IV-1. Degradation of Diffusion Length in P-Type Silicon as a Function of Electron Fluence

D. ELECTRON DAMAGE COEFFICIENTS

1. Absence of Dependence on Injection Level

All available evidence indicates that the diffusion length damage coefficients for silicon under electron irradiation are independent of the minority carrier injection level. Observed increases of diffusion length with injection level are less than 10% (e.g. see ref. 83, fig. 28). Therefore electron damage coefficients determined by Van de Graaff measurements of the diffusion length at low injection levels can be used to predict L at space sunlight injection levels. However this is not the case for proton-irradiated silicon, (see section IV-E).

2. Energy and Base Resistivity Dependence

Data on the electron damage coefficients for silicon cells of various base resistivity values are presented in figure IV-2 (ref. 287). The damage to p-type silicon increases more rapidly at electron energies above 1 MeV than theory predicts, assuming generation of only simple Frenkel defects. This more rapid energy dependence of damage in n/p solar cell material may be associated with the generation of more deleterious recombination centers associated with divacancies in p-type than in n-type silicon.

The reduction in damage coefficient with increasing base resistivity, shown clearly in figure IV-2, is cross-plotted in figure IV-3. From these data for boron-doped p-type silicon, it appears that the damage coefficient at all energies of interest varies approximately as the inverse square root of the resistivity.

The electron damage coefficients for 1 ohm-cm p/n silicon cells are plotted in figure IV-2. There is considerable scatter of the data, but the curve drawn is believed to be representative of typical p/n cells.

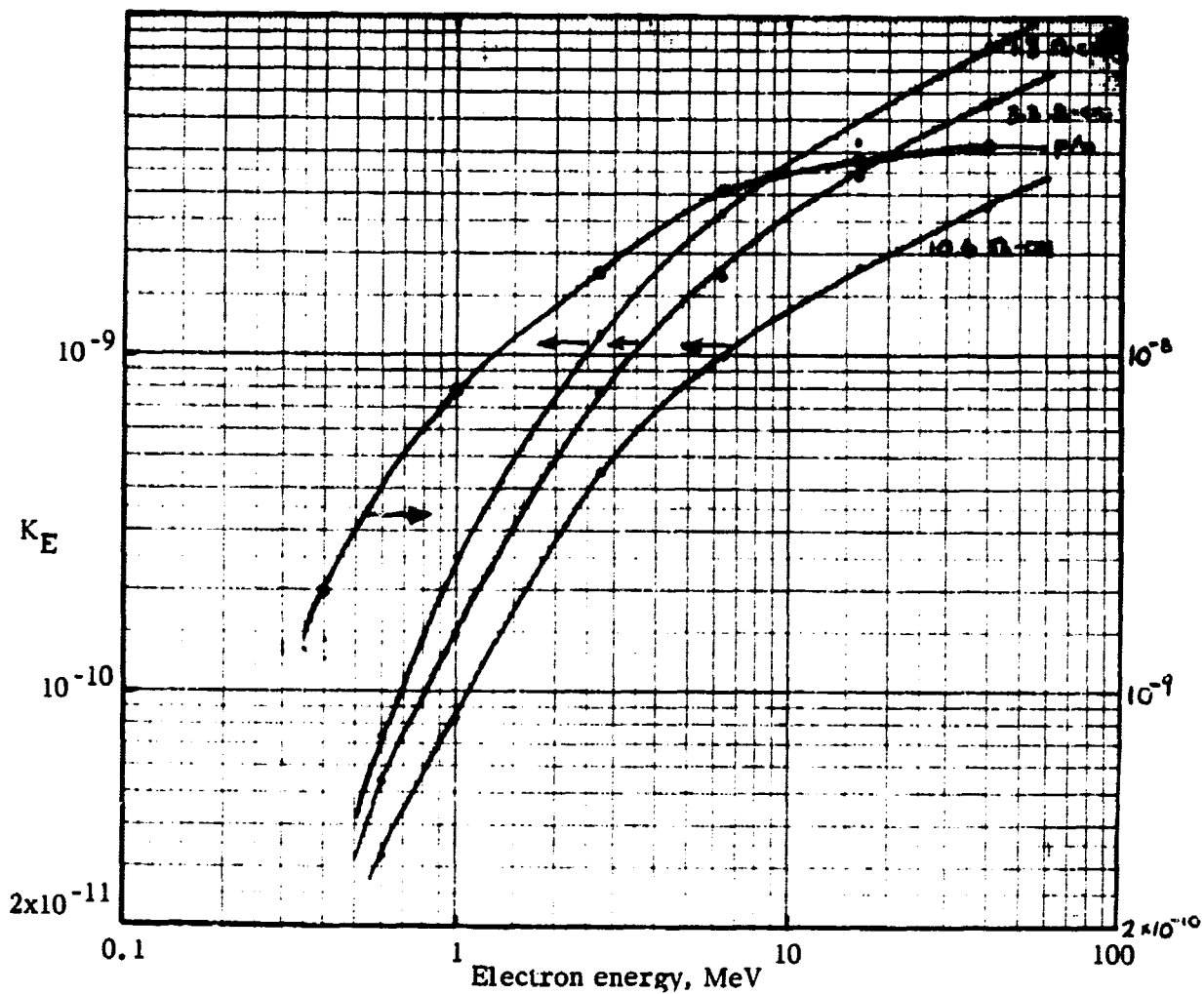


Figure IV-2. Measured Values of Damage Coefficient, K , VS. Electron Energy for Various Resistivity N/P Solar Cells and for Off-The-Shelf, Nominally One ohm-cm P/N Solar Cells

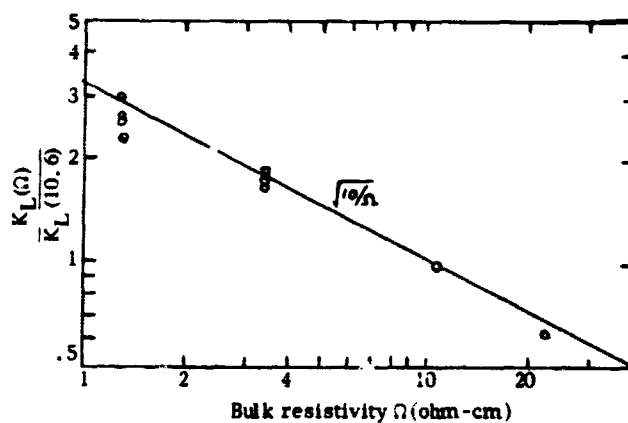


Figure IV-3. The Relationship of Damage Coefficient to N/P Cell Bulk Resistivity

3. Effect of Various Dopants

Tests by Carter and Downing of TRW Systems (ref. 61) using one MeV electrons to irradiate two different lots of boron-doped and two lots of aluminum-doped cells from Texas Instruments Inc. showed significant variations in damage coefficients among the four lots, but no consistent difference between aluminum and boron as a dopant. Differences in the actual trace impurity concentrations of the base material could possibly account for the differences observed. A summary of data for n/p cells made with boron and aluminum doped silicon is shown in figure IV-4.

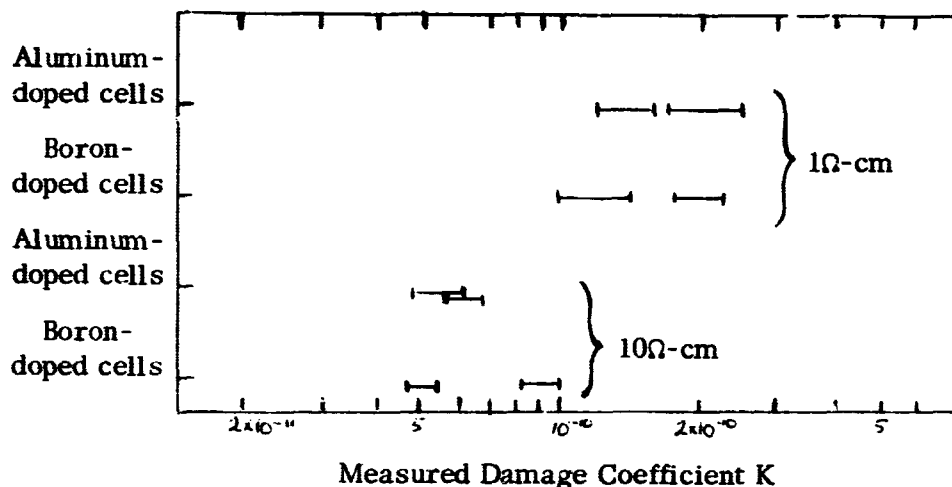


Figure IV-4. One-MeV Electron Damage Coefficient VS. Base Resistivity for P-Type Silicon with Aluminum and Boron Doping (ref. 61)

E. PROTON DAMAGE COEFFICIENTS

1. Effect of Injection Level

Denney et al (ref. 83) as well as Rosenzweig, Smits and Brown (ref. 252) have found that the minority carrier diffusion length increases with the excess carrier density (or injection level) for silicon which is irradiated by protons in the energy range from 4.65 to 95.5 MeV. Denney and Downing (ref. 81) have observed that the diffusion length increases approximately by a given fraction at each value of injection level, independent of the base value of diffusion length as measured at very low (Van de Graaff) injection levels. This variation is shown in figure IV-5 and IV-6. These

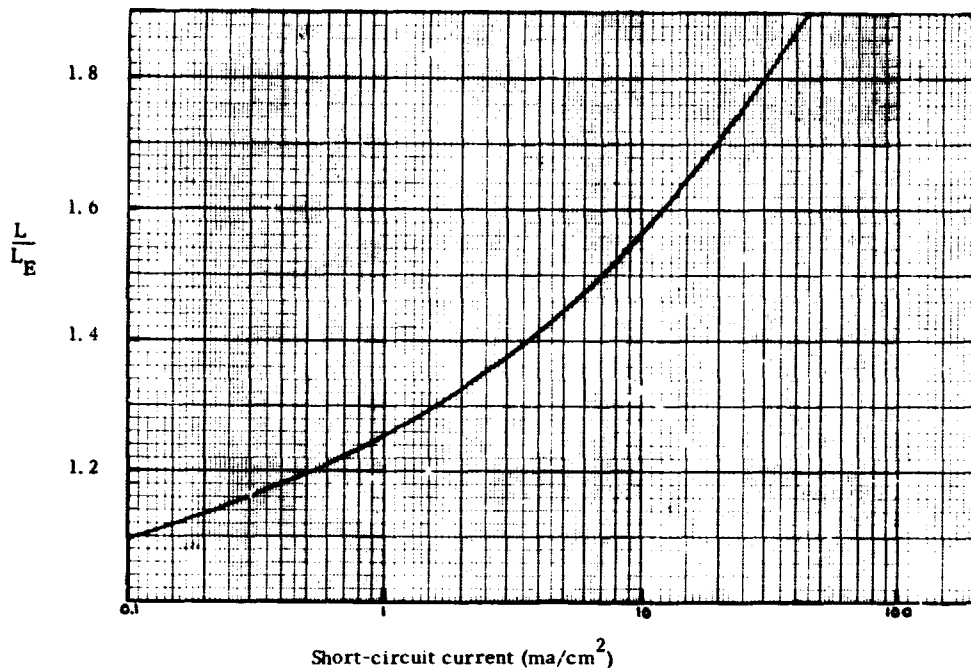


Figure IV-5. Effect of Injection Level on Diffusion Length for Proton-Irradiated Ten ohm-cm N/P Solar Cells

measurements are made by pulse injection of electrons from a Van de Graaff, simultaneously illuminating the cell with tungsten light to increase the excess carrier concentration.

It is seen in figure IV-5 that the diffusion length for 10 ohm-cm n/p cells is larger by a factor of 1.75 at a current density of 25 ma/cm^2 (a typical output under space sun intensity) than at the lowest injection level typical of Van de Graaff injection alone. The experiments show only a small effect of proton energy on the injection level dependence of diffusion length.

The typical method for measuring diffusion length as used by Bell Telephone Laboratories and the Naval Research Laboratory has been to use a Van de Graaff beam to inject electron-hole pairs uniformly through a solar cell. In this case, the carrier injection rate is typically about $10^{17} \text{ cm}^{-3} \text{ sec}^{-1}$, which is several orders of magnitude lower than the values expected at a point very near the p-n junction of a solar cell under sunlight. For proton damage at energies above 17 MeV, the diffusion length as measured

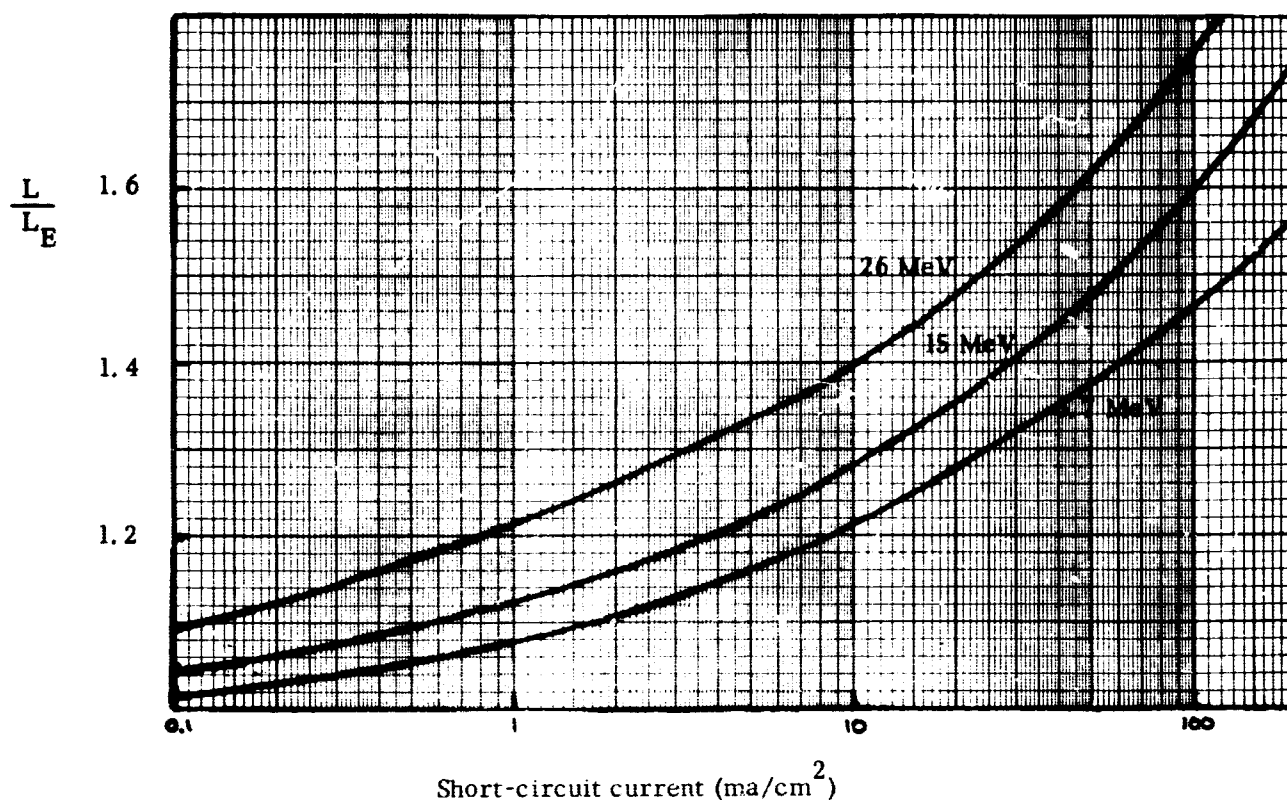


Figure IV-6. Effect of Injection Level on Diffusion Length for 1 ohm-cm N/P Solar Cells Irradiated by 6.7 to 26 MeV Protons

by the Van de Graaff technique must be increased by a factor of approximately 1.4 for one ohm-cm or 1.75 for 10 ohm-cm p-type silicon in order to correct it to the injection level expected in space sunlight. Correspondingly, the damage coefficients as deduced from such measurements of L^2 must be corrected downward by a factor of $(1.4)^2$, or for one ohm-cm and $(1.75)^2$, or 3, for 10 ohm-cm n/p silicon cells.

2. Effect of Proton Range on Measurement of Diffusion Length

The equation used for calculating diffusion length of a solar cell under uniform irradiation (e.g. by Van de Graaff electrons) from the radiation-induced short circuit current J_{SC} density is (ref. 249)

$$L = \frac{J_{SC}}{J_e S_o} \quad (IV-6)$$

where

S_o = average specific ionization per incident particle

J_e = incident radiation current density.

It is often forgotten that this equation is applicable only if the recombination centers in the cell are uniformly distributed which is not the case for cells irradiated by low energy protons. For example, a 3 MeV proton has a range of about 80 microns, which is only a small fraction of the thickness of a typical solar cell. Therefore protons below 3 MeV damage the front of the cell, but leave most of the cell volume unaffected.

Therefore, Eq. IV-6 can not be used to determine the value of L in the damaged region. If it is used, the calculated value is an effective diffusion length, L_E , and the corresponding damage coefficient K_{pLE} must be defined as an "effective" damage coefficient.

It should be noted that the distribution of defects, and consequently of recombination centers due to protons of a given energy is not uniformly distributed in the surface layer within the proton range, but is concentrated near the end of the range. Therefore, the use of an effective damage coefficient is not a very precise concept when applied to solar cells irradiated by low energy protons. An adequate theory to predict damage by low energy protons apparently does not exist.

3. Energy Dependence

The diffusion length damage coefficient for protons generally decreases with proton energy, approximately following the $(\ln E)/E$ energy dependence which is predicted for defect production by Rutherford scattering (ref. 259). However, at low proton energies (below 10 MeV) where the proton range is not large compared to the sample thickness, there are apparent deviations which may be due to nonuniform damage through the

sample. Also for high proton energies (above 50 MeV) the damage coefficient is larger than expected on the basis of Rutherford scattering. This is partially due to a variation in the defect production cross section, but may also be associated with production of more deleterious recombination centers which are associated with complex defects, such as the divacancy. At very high energies (above 100 MeV) the nucleus of silicon can undergo spallation, forming "stars" which extensively damage the crystal in a local region.

A summary of the experimental values of proton damage coefficients as a function of energy are presented in figure IV-7 for both one ohm-cm and 10 ohm-cm p-type silicon as used in n/p solar cells. For each value of resistivity of silicon, three curves are shown which are defined as follows:

- K_p = proton damage coefficient in the damaged region as measured at an injection level equivalent to space sunlight. It varies approximately as $(\ln E)/E$ for energies below 50 MeV.
- K_{pLE} = effective proton damage coefficient as measured by the Van de Graaff method at low injection levels and where L values are assumed to be directly proportional to short circuit current, which is only true for penetrating radiation.
- K_{pL} = proton damage coefficient in the damaged region of the cell for low injection levels. This is obtained by extrapolating values of K_{pLE} for energies above 40 MeV to low energies, assuming a $\ln E/E$ dependence.

The relationship between K_{pLE} and K_p for penetrating radiation is:

$$K_p = \frac{K_{pLE}}{f^2} \quad (IV-7)$$

where

$$f = \frac{L}{L_E} = \text{ratio of diffusion lengths under sun and low injection levels.}$$

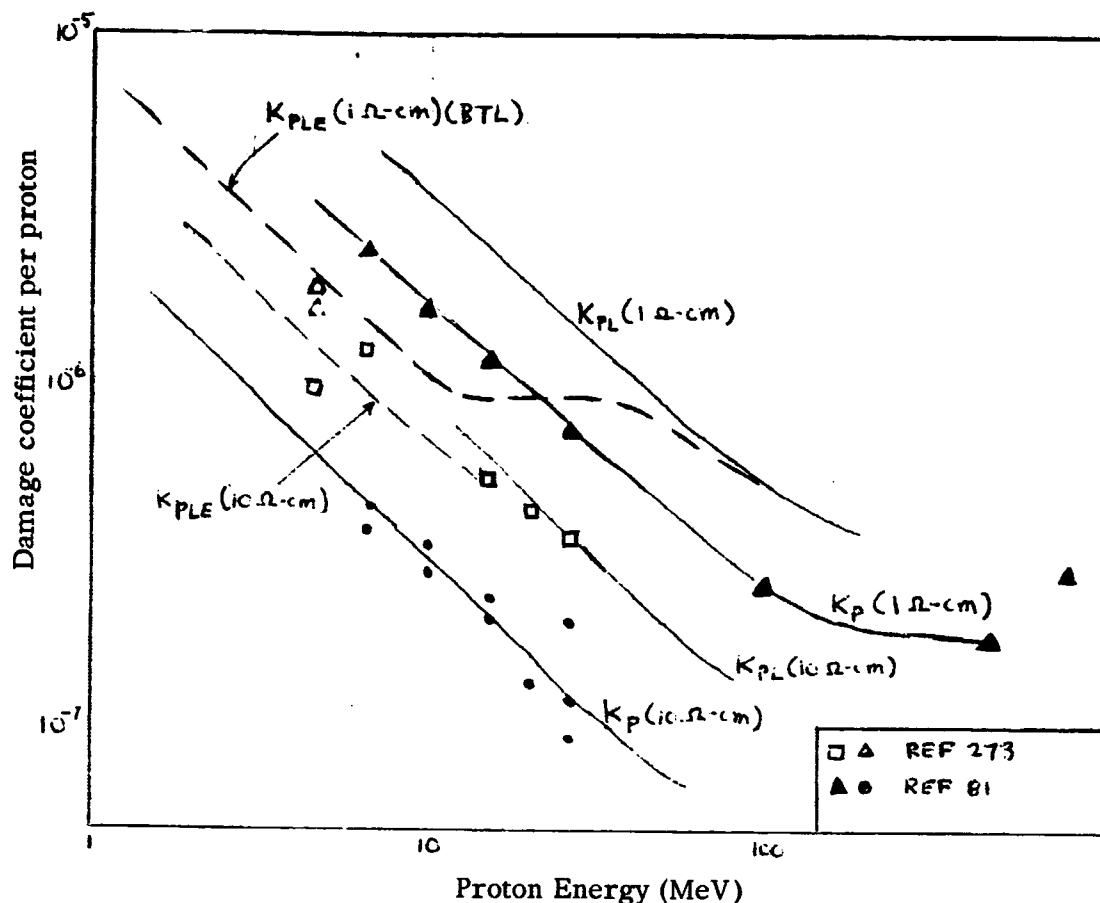


Figure IV-7. Proton Damage Coefficients for P-Type Silicon as a Function of Proton Energy.

Considering first the data for low injection levels, it is seen in figure IV-7, that the effective coefficients K_{pLE} are lower than the coefficients applicable to the damaged region of silicon K_{pL} for proton energies below 10 MeV, i.e. where the proton range is less than 770 microns, which is of the same order of magnitude as the typical solar cell thickness of 250 to 400 microns. This is physically understandable because for proton ranges less than the cell thickness, the damage coefficient averaged over the entire base volume of the cell is lower than the actual value applicable to the region of

silicon which is traversed by the protons. In other words, the thin damaged layer of silicon captures fewer minority carriers in the Van de Graaff injection experiment than if the cell were damaged homogeneously to the same value of L as in the damaged layer. Therefore, the measured short circuit current is higher, the value of L calculated from equation IV-6 is higher, and the effective damage coefficient K_{pLE} is lower than for a cell homogeneously damaged to the same value of L as in the damaged layer.

There seems to be an anomalous behavior of K_{pLE} in the region between an energy of 8 and 40 MeV in that the experimental data for K_{pLE} by Bell Telephone Laboratories shows approximately a constant value in this range. It may be noted that this is the range where the end of the proton track is not inside the solar cell and where the magnitudes of the proton range, solar cell thickness, and minority carrier diffusion length are all near the same order of magnitude. Further investigation of this anomaly is needed to understand why the damage coefficient K_{pLE} does not assume a $(\ln E/E)$ dependence, as predicted for Rutherford scattering, at energies above 8 MeV where the end of the proton track is outside the solar cell.

The proton damage coefficient for 1 ohm-cm p/n silicon cells is plotted vs. proton energy in figure IV-8. There is considerable scatter in the data, but a general similarity to the data for n/p cells, with damage coefficients which are larger by at least a factor of two, for one ohm-cm cells.

4. Effect of Resistivity of Base Material

Proton damage coefficients generally decrease with an increase in the base resistivity of silicon as shown in figure IV-7. This behavior is similar to that observed with electron-irradiated cells.

F. CORRELATION OF SOLAR CELL PERFORMANCE WITH DIFFUSION LENGTH

This section includes data on the spectral response and degradation of short circuit current, maximum power, and open circuit voltage as a function of the minority carrier

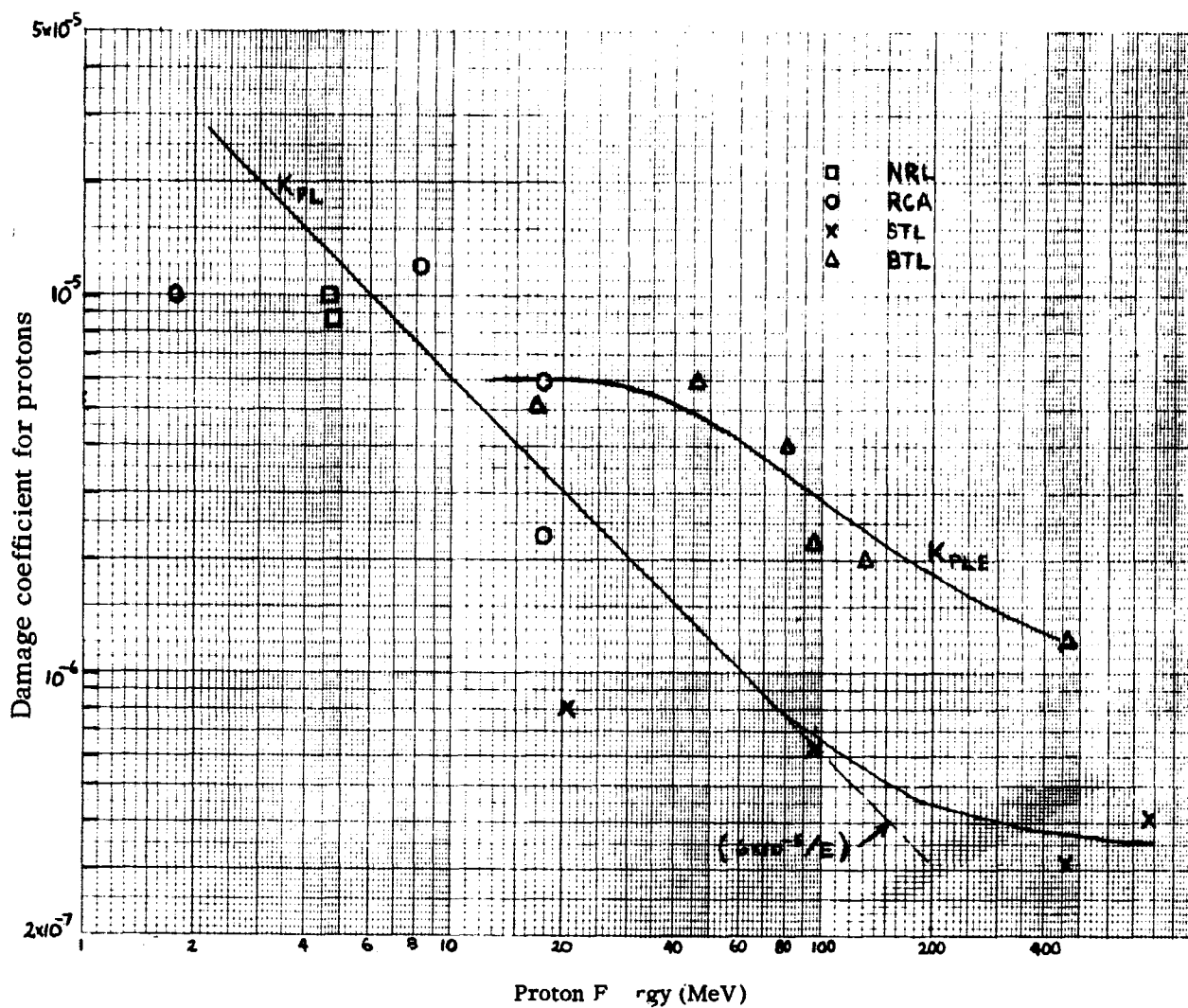


Figure IV-8. Proton Damage Coefficient for P/N Silicon Cells as a Function of Proton Energy

diffusion length in the base region, which is a measure of the radiation damage to the material. The effects of the type of light source and the operating temperature of the cells are also summarized.

1. Spectral Response

A silicon solar cell typically responds to photons in the wavelength range from 0.4 to 1.1 microns. The longer wavelengths penetrate more deeply in the cell, producing minority carriers which must diffuse a longer distance to the junction and are more subject to recombination as the minority carrier diffusion length (or lifetime) of the base material is degraded by radiation. Figure IV-9 shows a typical set of spectral response curves at various stages of irradiation of a 10 ohm-cm n/p silicon cell.

It is seen that radiation damages primarily the long wavelength (red and infrared) response of the cell. This means that the photovoltaic current contributed from the back region of the solar cell base, is most susceptible to radiation damage. Therefore a thin solar cell which does not depend as greatly on its red and infrared response shows a smaller percentage reduction in power than a thicker cell at the same radiation dose. However after severe radiation damage to the point when the diffusion length is small compared to the cell thickness, the power and efficiency of a thin cell are nearly the same as for a thick cell, since the initially greater red response of the thick cell has been nullified. The photovoltaic efficiency of the cell decreases, of course, as its thickness decreases (see figure IV-10), but the power output per unit weight increases. Thus, solar cells of 2 ohm-cm material, 2 mils thick and with an efficiency of 8.5% have been reported (ref. 231). The advantages of a smaller percentage change in power with radiation exposure and the higher power-to-weight ratio for thin cells must be weighed against the disadvantages of fragility and decreased initial power output per unit area.

2. Current-Voltage Characteristics

The I-V characteristic of a solar cell is a function of the temperature, radiation exposure and light source, as well as the solar cell material and design parameters. It is important to consider the combined effects of radiation and temperature on the I - V characteristic for design purposes. The light source used should closely approach the spectrum expected in use.

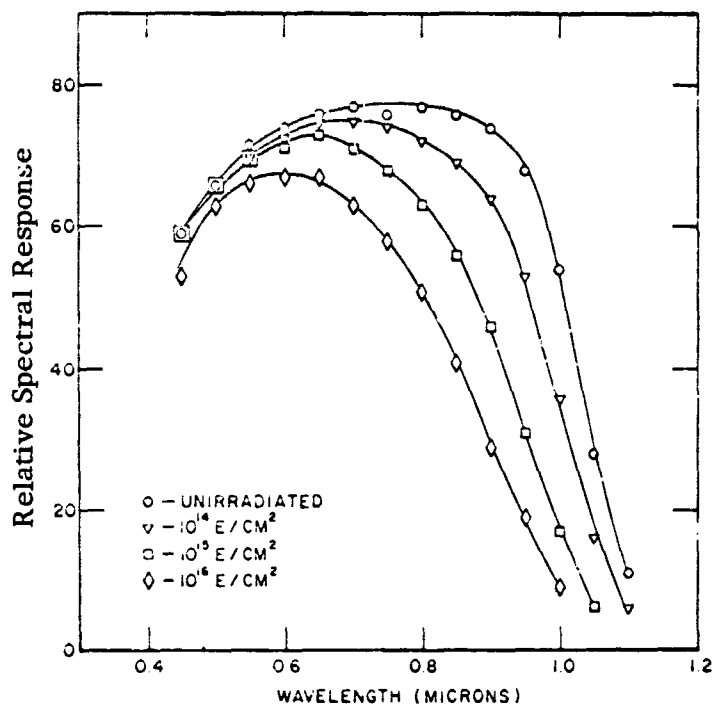


Figure IV-9. Typical Spectral Response Degradation of 10 ohm-cm N/P Solar Cell

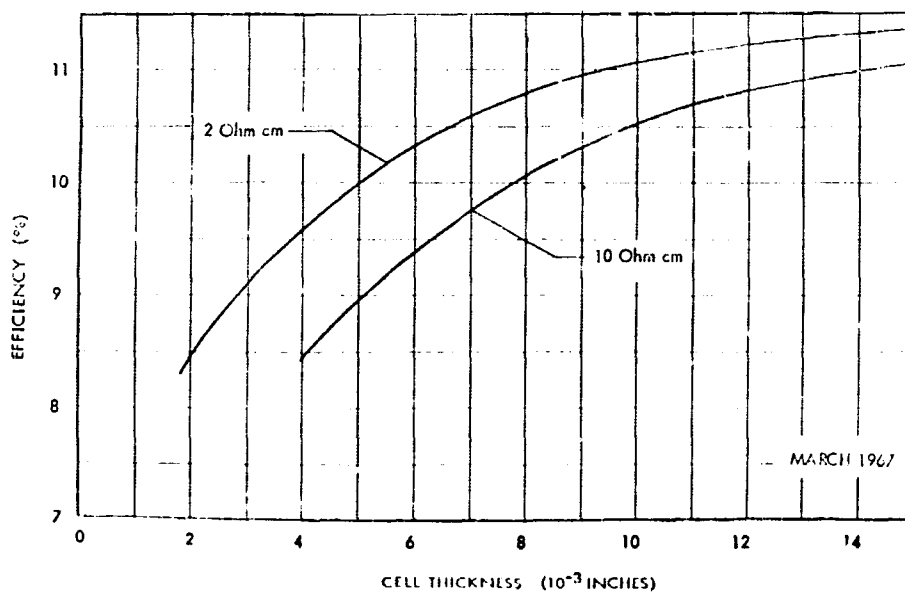


Figure IV-10. Typical N/P Solar Cell Efficiency vs. Silicon Thickness for Nominal 2 and 10 ohm-cm Base Resistivities. Sunlight Simulator (X-25 L Spectrosun) 140mW/cm² Balloon Calibration; Active Area 3.9cm²; Cell Temperature 28°C (ref. 231).

Figures IV-11, IV-12, IV-13, and IV-14 show typical I-V curves for 10 ohm-cm and one ohm-cm n/p cells at various temperatures before and after irradiation to a fluence of 5.2×10^{15} one-MeV electrons/cm². These measurements (ref. 242) were made with a Model 31 OCLI Solar Simulator which has a spectral distribution reasonably approximating that of space sunlight.

3. Short-Circuit Current of Irradiated Solar Cells

When the minority carrier diffusion length L is uniform throughout the base region, its magnitude affects the short-circuit current of a cell under a given light source. When L is not uniform, its value at the junction and its variation in magnitude through the base must both be taken into account. Electrons and also protons of energy greater than 4.6 MeV degrade L uniformly, in accordance with equation IV-4.

Typical production-type cells have an initial diffusion length of about 150 to 200 microns. In this case, with uniform degradation, the fraction of the short-circuit current remaining can be plotted against $K\Phi$ or L since these are related through equation IV-4.

Reynard (ref. 242) measured the short-circuit current before and after bombardment by electrons of 0.6 to 2.0 MeV. An OCLI Model 31 solar simulator was used, and n/p cells of base resistivity 1.3 ohm-cm and 10 ohm-cm were tested. With values of K from figure IV-2, both L and $K\Phi$ were computed for each measurement. The result, figure IV-15, shows good correlation of short circuit current ratio with diffusion length for these different exposures and cells.

However, Reynard's data for solar cells bombarded by low energy protons do not show such good correlation. In this case, the proton is rapidly changing energy as it penetrates the cell, and its damage coefficient K is also rapidly changing. Thus, a calculation of L or $K\Phi$, based on the value near the junction, gives a short-circuit current ratio which is dependent on proton energy. In similar fashion, the use of different light sources affects the relationship. This can be inferred from the

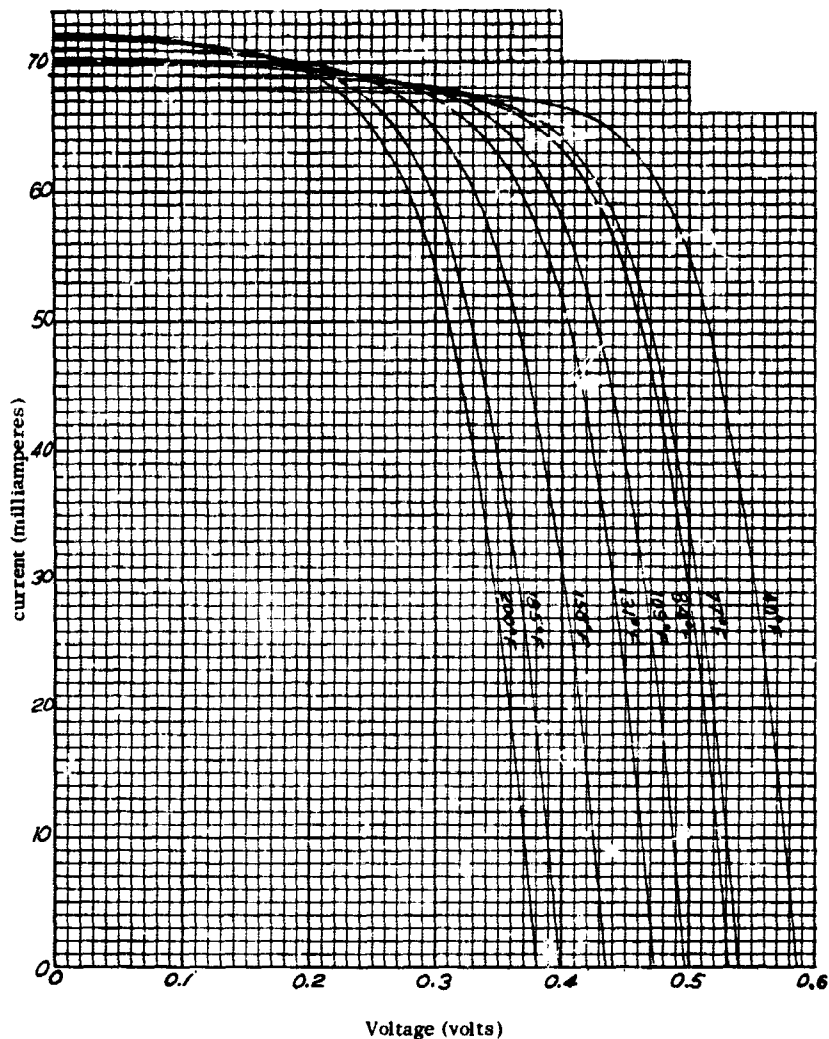
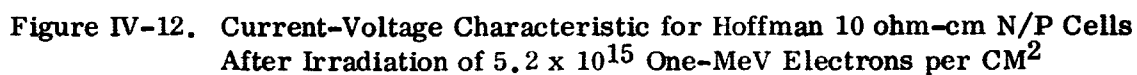


Figure IV-11. Current-Voltage Characteristic for Hoffman 10 ohm-cm N/P Cells at Various Temperatures, Unirradiated (OCLI #7 Simulator)

spectral shift in figure IV-9. Figure IV-16 shows such data for 10 ohm-cm n/p cells. It is seen from the figure that protons of energy 4.6 MeV or greater do generate damage that can be correlated with electron damage, at least under tungsten light.

These data are for typical thickness (nominally 12 mil) cells. For thinner cells, the initial value of the short-circuit current is, of course, smaller but its decrease



IV-22

TABLE IV-1. 10 ohm-cm DEGRADATION DATA (54.4°C)

Wafer Thickness (mils)																
	12	7.8	6	3.7	12	7.8	6	3.7	12	7.8	6	3.7				
Electron fluence	I_{sc} , ma				V_{oc} , volts				P_{max} , mw				Volts at P_{max}			
0	136.9	131.1	125.7	120.2	.534	.524	.510	.499	53.4	49.6	46.4	42.0	.425	.420	.408	.404
1.3×10^{13}	138.1	131.1	126.5	120.9	.530	.515	.504	.501	53.3	49.5	46.5	42.4	.424	.412	.400	.405
5.3×10^{13}	135.9	131.0	125.9	121.0	.526	.519	.507	.503	51.5	48.8	46.1	42.5	.420	.415	.407	.405
10^{14}	134.2	129.1	125.5	121.1	.524	.518	.507	.503	50.0	48.1	45.8	42.5	.417	.410	.405	.405
10^{15}	119.1	117.5	116.6	116.1	.494	.495	.488	.491	40.9	40.9	40.0	39.4	.386	.386	.387	.394
5.1×10^{15}	106.3	104.3	104.2	105.8	.470	.470	.466	.468	34.7	34.4	34.3	34.0	.365	.370	.367	.377

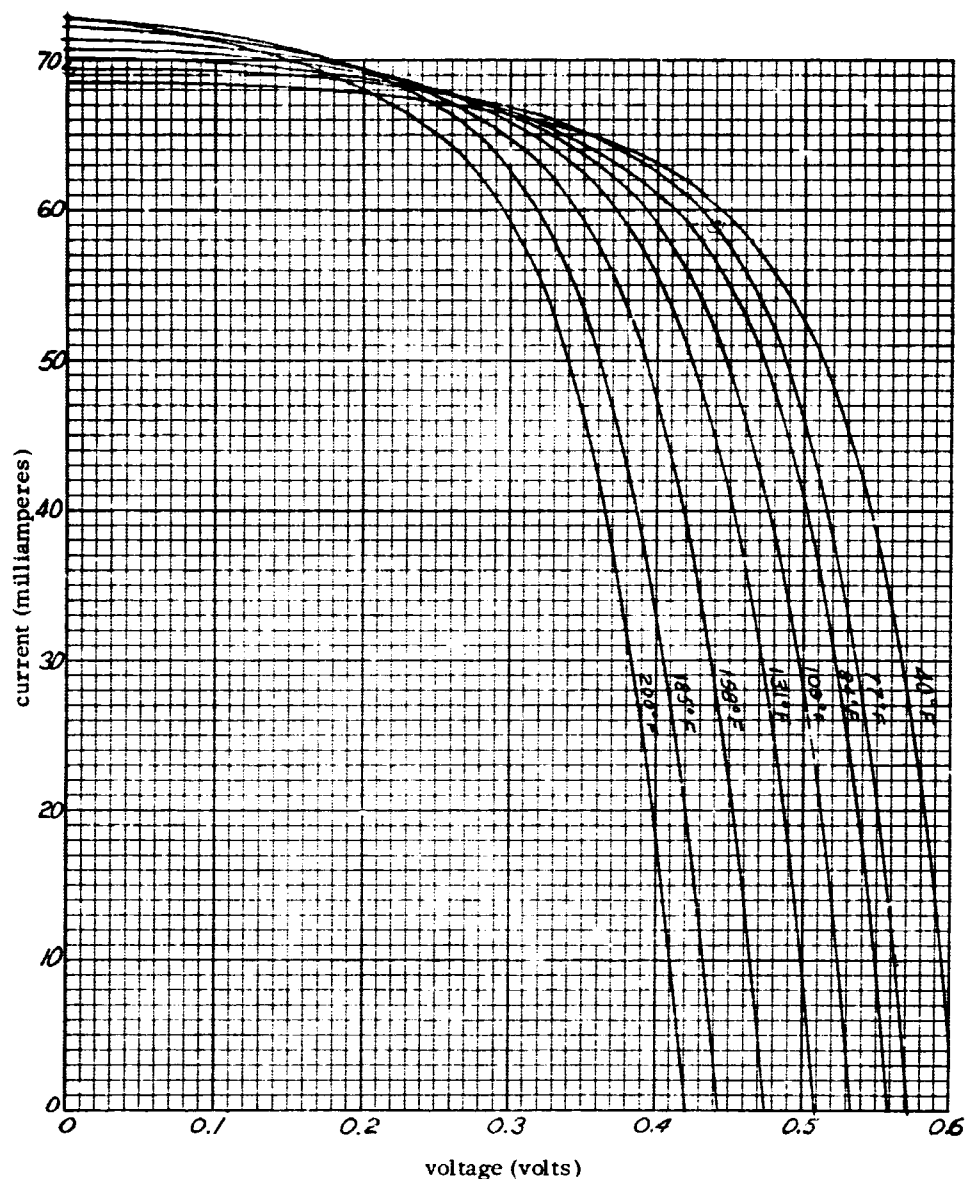


Figure IV-13. Current-Voltage Characteristic for Hoffman One ohm-cm N/P Cells at Various Temperatures, Unirradiated

For protons of energies of 2.7 MeV, which have a range of less than 70 microns in silicon, the cell is only damaged in a surface region of depth less than the proton range. The current does not degrade appreciably until the value of L in the damaged layer has degraded to a value of the same order as the proton range. The upper three solid curves in figure IV-16 show this effect for low energy protons as measured by Reynard

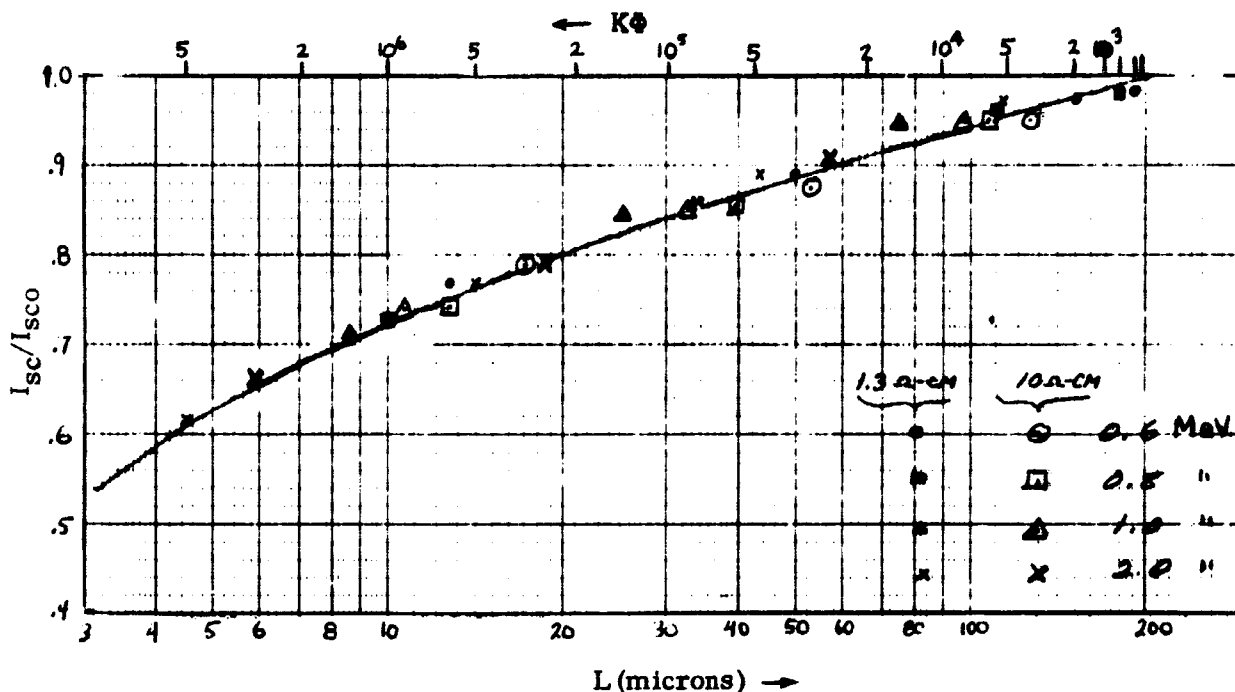


Figure IV-15. Short Circuit Current Ratio VS. L , with OCLI Simulator and Varying Electron Energies for 1.3 and 10 ohm-cm N/P Silicon Cells (Data from Refs. 242 and 287). An initial value of 200 microns is assumed for L .

light as electrons. This anomaly may be related to the nonuniform damage produced by protons near the end of their range, which occurs within a depth of 70 microns for 2.7 MeV protons.

This anomalously large degradation of current with an OCLI Simulator and 2.7 MeV protons apparently does not exist for tests under unfiltered tungsten light and proton energies of 0.2 to 2 MeV as reported by Tada (ref. 279). His analysis has made it possible to identify to a first approximation, the unique character of low energy proton effects on solar cell performance. He assumed that the damage is uniform within a depth equal to the proton range and showed that this simple assumption permits prediction of short circuit current as measured under unfiltered tungsten light as a function of the

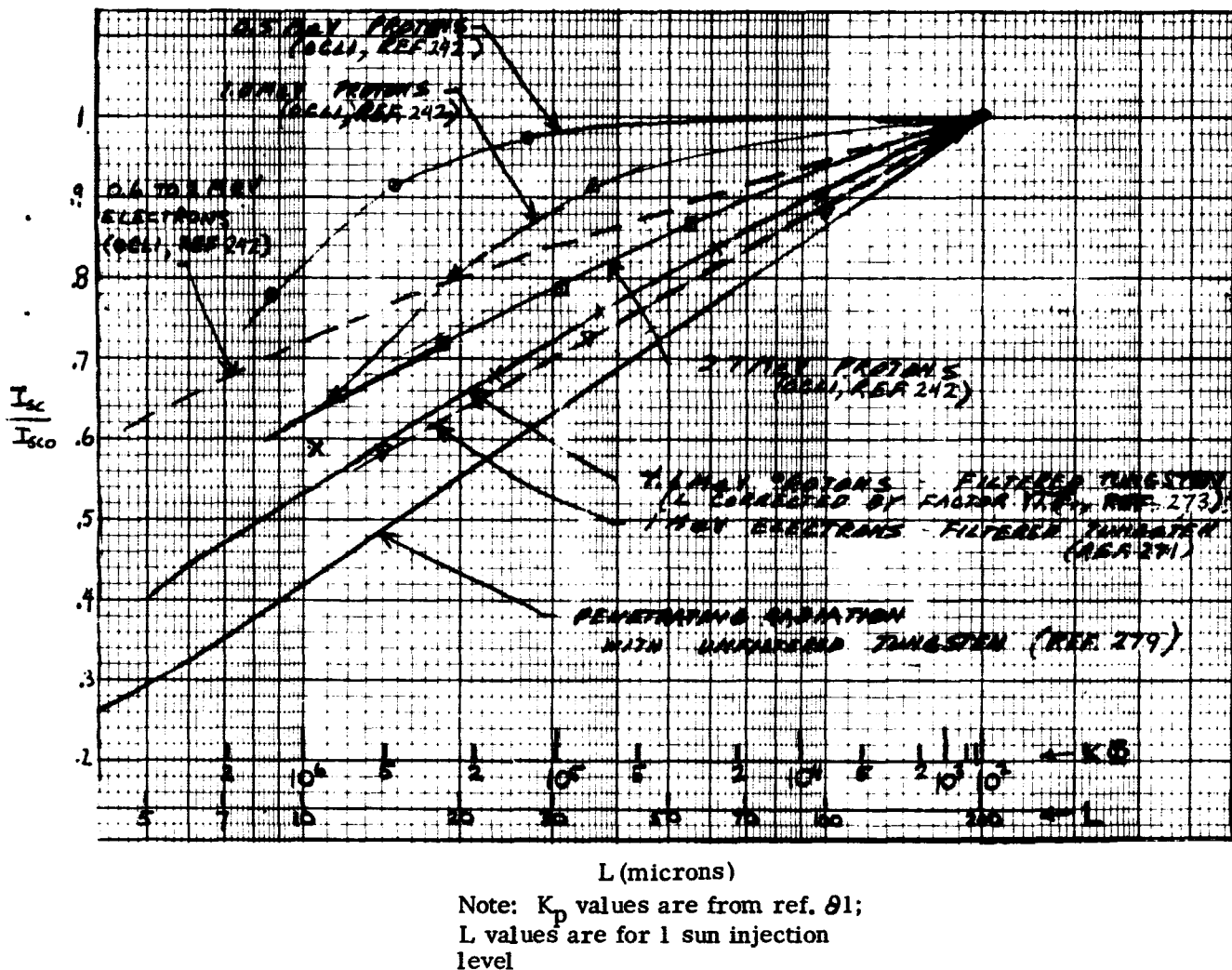


Figure IV-16. Short Circuit Current Ratio VS. L for 10 ohm-cm N/P Silicon Cells under OCL Simulator, Filtered Tungsten and Unfiltered Tungsten Spectra

average diffusion length in the damaged base region for proton energies down to 0.5 MeV. For lower energies, the model is inaccurate and should be improved, taking into account the variation of defect production along the proton path. As one might expect intuitively, cell performance is not severely affected until the diffusion length in the damaged region is reduced to a value approximately equal to the proton range. (At this point a minority carrier has a probability of $1/e$ of diffusing through the damaged layer without recombining.)

At larger doses, minority carriers generated deep in the cell (by infrared) have a small probability of diffusing through the highly damaged layer to the p-n junction without recombining, and the current is severely degraded.

The results of Tada's analysis are summarized in figure IV-17 for short circuit current under unfiltered tungsten light as a function of diffusion length in the damaged region for various proton energies. These data apply to 10 ohm-cm n/p cells and are closely verified by experimental data. The diffusion length damage coefficient which was assumed in order to correlate the data is the value K_p for sunlight injection level as determined by TRW and shown as the lowest curve in figure IV-7.

Data for penetrating radiation on one ohm-cm n/p cells and one ohm-cm p/n cells are shown in figures IV-18 and IV-19 respectively. If an injection level correction of L were introduced for proton-irradiated p/n cells in figure IV-19, the curve would more nearly match that for electron-irradiated cells. However, the correction factor apparently should be dependent on the magnitude of L , being smaller as the value of L decreases (ref. 252).

4. Short Circuit Current Under Various Light Sources

The short circuit current generated by a solar cell under a given light source is a function of the diffusion length distribution with depth below the junction. For penetrating radiation and a cell thickness large compared to diffusion length, the diffusion length is uniform in the base and the short circuit current under monochromatic photons is theoretically (ref. 22).

$$I = C \frac{L/\lambda}{(1 + L/\lambda)} \quad (\text{IV-8})$$

where

C = a constant

L = diffusion length

λ = attenuation length for photons.

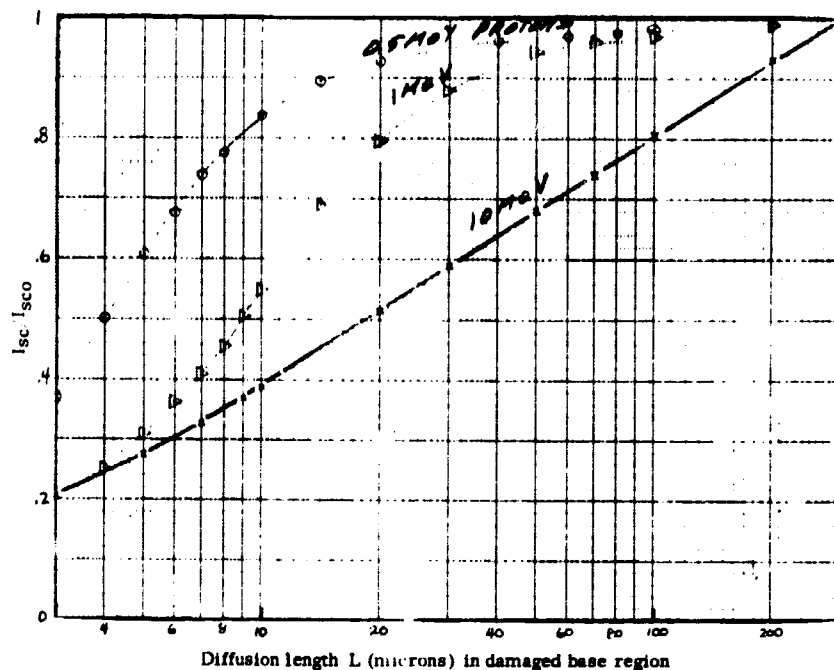


Figure IV-17. Short Circuit Ratio VS. L for 10 ohm-cm N/P Silicon Cells Under Unfiltered Tungsten (2800°K) Light Source

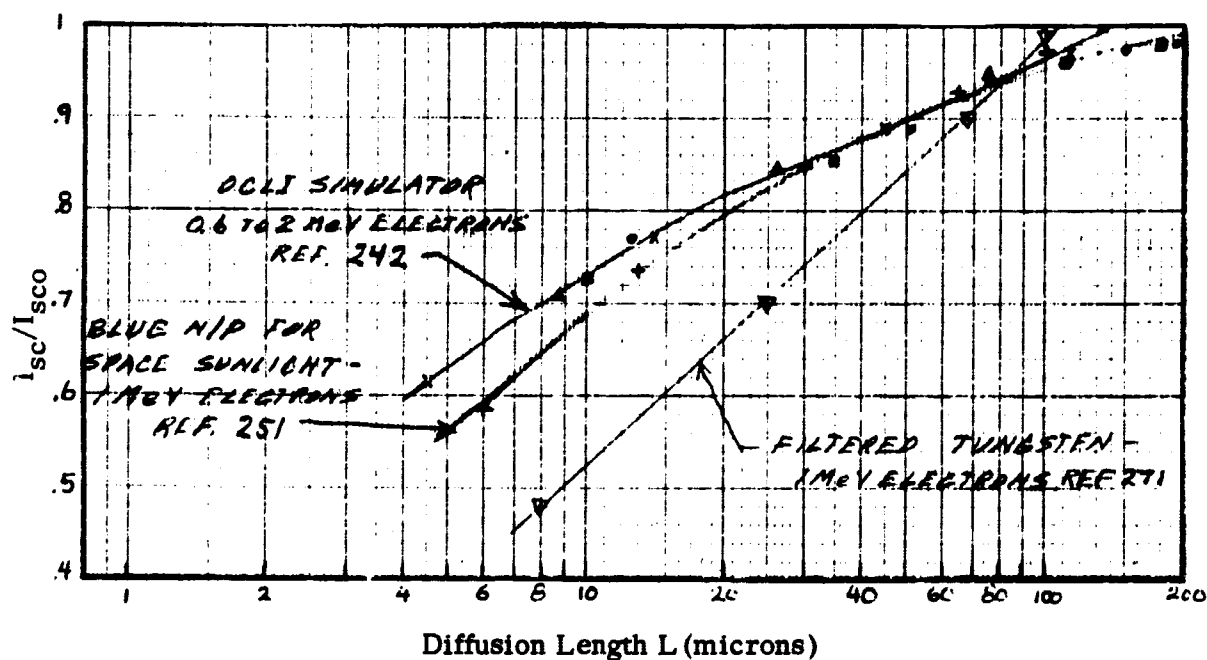


Figure IV-18. Short Circuit Current Ratio VS. L for One ohm-cm N/P Silicon Cells Under Various Light Sources

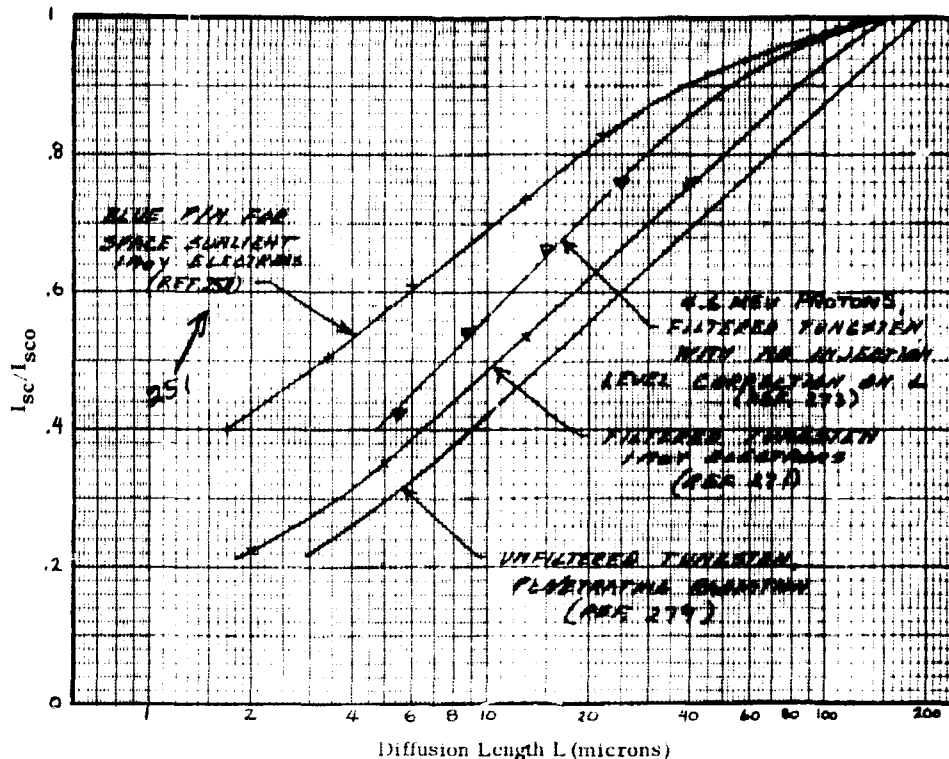


Figure IV-19. Short Circuit Current Ratio VS. L for One ohm-cm P/N Silicon Cells Under Various Light Sources

The equation shows that the short circuit current should be a function of the ratio of diffusion length to photon attenuation length.* For a polychromatic light source, the injection rate of carriers as a function of depth in the cell can be characterized approximately by an "effective photon attenuation length" λ_e , which is a measure of the wavelength of a monochromatic light source which gives a similar depth distribution of injected carriers as the actual light source. The simplifying hypothesis may be made that the short circuit current ratio is only a function of the dimensionless ratio of diffusion length to effective photon attenuation length. Data are plotted in figure IV-20 which shows this hypothesis to be approximately valid for solar cells under penetrating

*Equation IV-8 was derived under the assumption of negligible drift field in the base region.

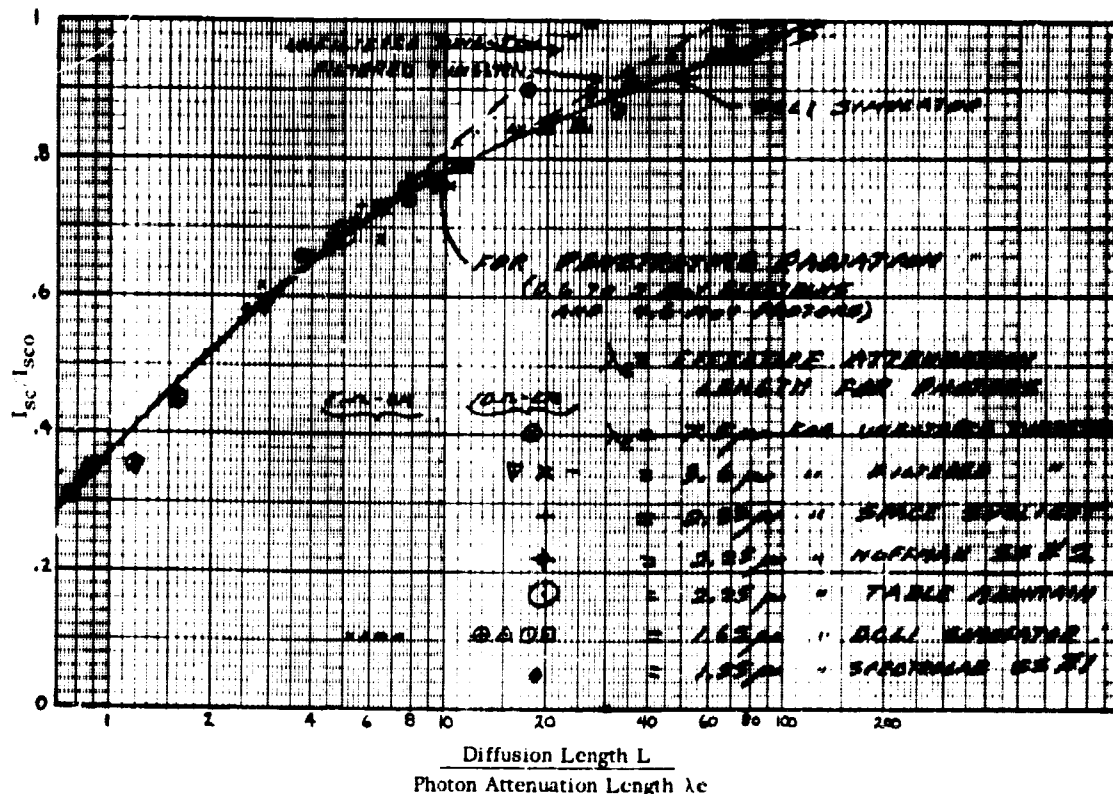


Figure IV-20. Correlation of Short Circuit Current Ratios Measured Under Various Light Sources for One and 10 ohm-cm N/P Silicon Cells with Penetrating Electrons and Protons

radiation in the range where the diffusion length is less than 10 times the effective photon attenuation length. The values of λ_c have been selected for the seven different light sources to best fit the experimental data in this range.

The approximation is not good for the early stages of cell degradation because in this region current is a very sensitive function of red and infrared content of the light source. A source which is relatively rich in infrared content, like unfiltered tungsten, gives a relatively higher output when the cell is only slightly damaged ($L = 75$ to 200 microns). However, figure IV-20 presents a single empirical curve which is useful in approximately correlating short circuit current ratio data from all silicon solar cells under all available light sources for short circuit current ratios below 0.80, the range of interest for design purposes.

5. Maximum Power Ratio Dependence on Diffusion Length

Reynard (ref. 242) has reported data on the degradation of maximum power ratio as measured with a Model 31 Solar Simulator manufactured by Optical Coating Laboratory, Inc. Maximum power ratio data for electron irradiation at energies of 0.6 to 2.0 MeV have been correlated vs. L in figure IV-21. The values of L were computed from equation IV-4 using electron damage coefficients shown in figure IV-2. It is seen that the maximum power ratios of production type solar cells of a given base resistivity correlate with the diffusion length L for penetrating radiation, such as electrons. The data presented in figure IV-21 show that the maximum power ratio for 10 ohm-cm cells under an OCLI simulator is proportional to the logarithm of L and can be approximated by:

$$\frac{P_M}{P_{MO}} = 0.20 + 0.35 \log_{10} L \quad (\text{IV-9})$$

where L is in microns.

The curve for one ohm-cm cells shows higher power at each value of L than for 10 ohm-cm cells and the variation is not as close to a linear dependence on the logarithm of L .

A summary of the data on degradation of 10 ohm-cm cells, including data for proton energies of 2.7 MeV and less is shown in figure IV-22.

The maximum power ratio for one ohm-cm n/p silicon cells is plotted vs. diffusion length for various light sources in figure IV-23. Similar data for one ohm-cm p/n silicon cells is given in figure IV-24. In this case, if a correction were made for injection level dependence of L for the 4.6 MeV proton-irradiated cells, the curve would more nearly match that for electron-irradiated cells, as expected. However, the data suggest that the injection level correction on L should be dependent on the value of L rather than a constant factor.

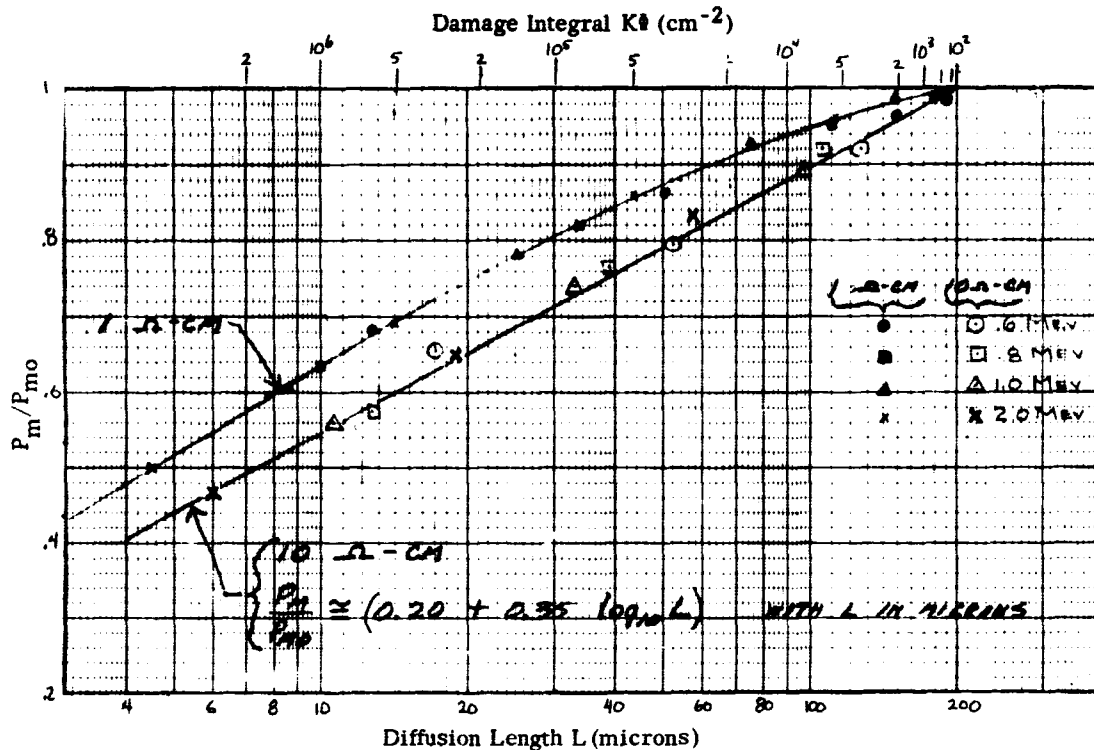
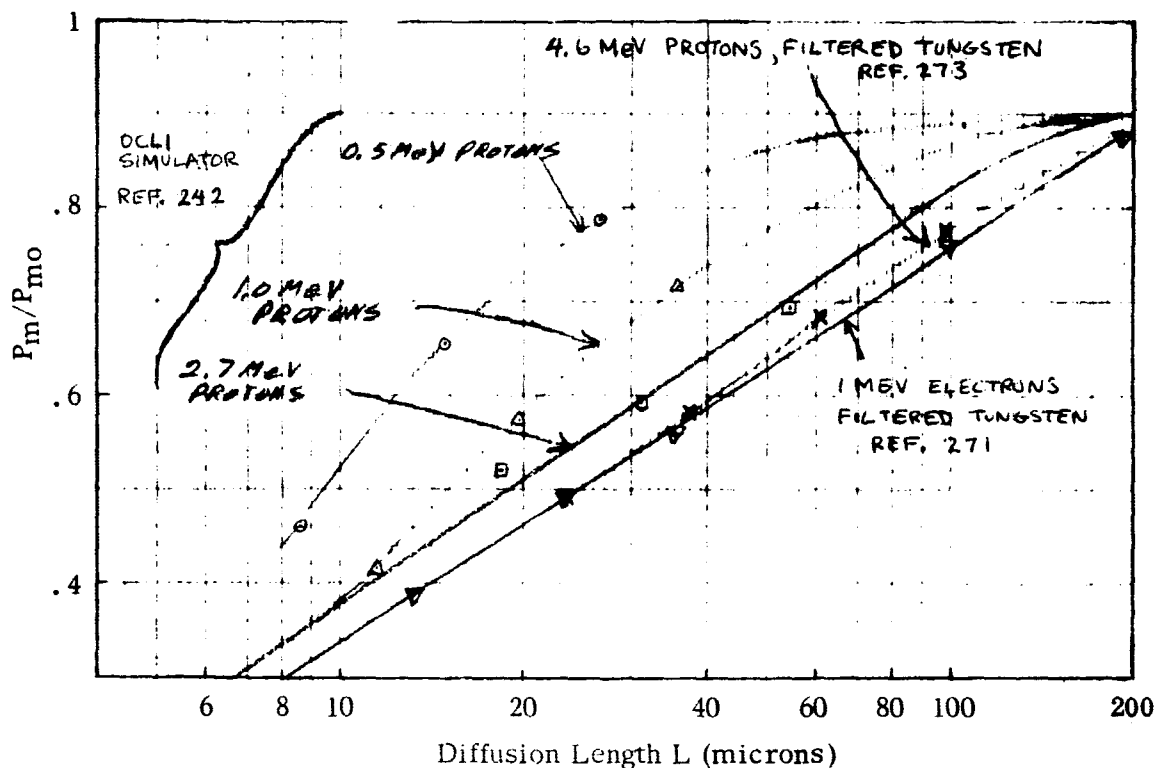


Figure IV-21. Maximum Power Ratio, P_M/P_{MO} VS. L Under OCLI Simulator and Varying Electron Energies for One and 10 ohm-cm N/P Silicon Cells

6. Maximum Power Ratio Under Various Light Sources

An attempt has been made to correlate maximum power ratio for one ohm-cm and 10 ohm-cm n/p silicon cells with the dimensionless ratio of diffusion length, L , to effective photon attenuation length, λ_e , using values of λ_e which were shown to correlate short circuit current data in figure IV-20. Figures IV-25 and IV-26 show the data for 10 ohm-cm and one ohm-cm cells, respectively. The data for 4.6 MeV proton irradiated cells in figure IV-25 do not correlate very well with the electron-irradiated cells, possibly because of an inaccurate injection level correction for L . Also, the data for blue n/p one ohm-cm cells in figure IV-26 which were obtained in 1962 (ref. 251) do not match the data for the cells tested by Reynard (ref. 242) in 1965. This may be caused by cell construction differences or by inaccurate selection of the values of λ_e for the two light sources.



Note: K_p values for sunlight injection level extrapolated to energies below 6.7 MeV.
 L values from ref. 273 corrected upward for injection level dependence by factor $\sqrt{1.5}$ for 4.6 MeV protons.

Figure IV-22. Maximum Power Ratio vs. L for 10 Ohm-cm n/p Silicon Cells Under OCLI Simulator and Filtered Tungsten Spectra

However, it appears that for production cells of a given type, the maximum power data under various light sources can be correlated approximately with the dimensionless ratio L/λ_e , for the range of maximum power ratios less than 0.8.

7. Open Circuit Voltage

The open circuit voltage ratio for 10 ohm-cm n/p silicon cells is plotted against diffusion length in the damaged base region in figure IV-27. The data for penetrating electrons and 2.7 MeV protons plot as a single line. The 0.5 and 1.0 MeV protons have less effect on open circuit voltage at a given value of L than the more penetrating radiations. Similar data for one ohm-cm n/p cells can be derived from results reported by Reynard (ref. 242).

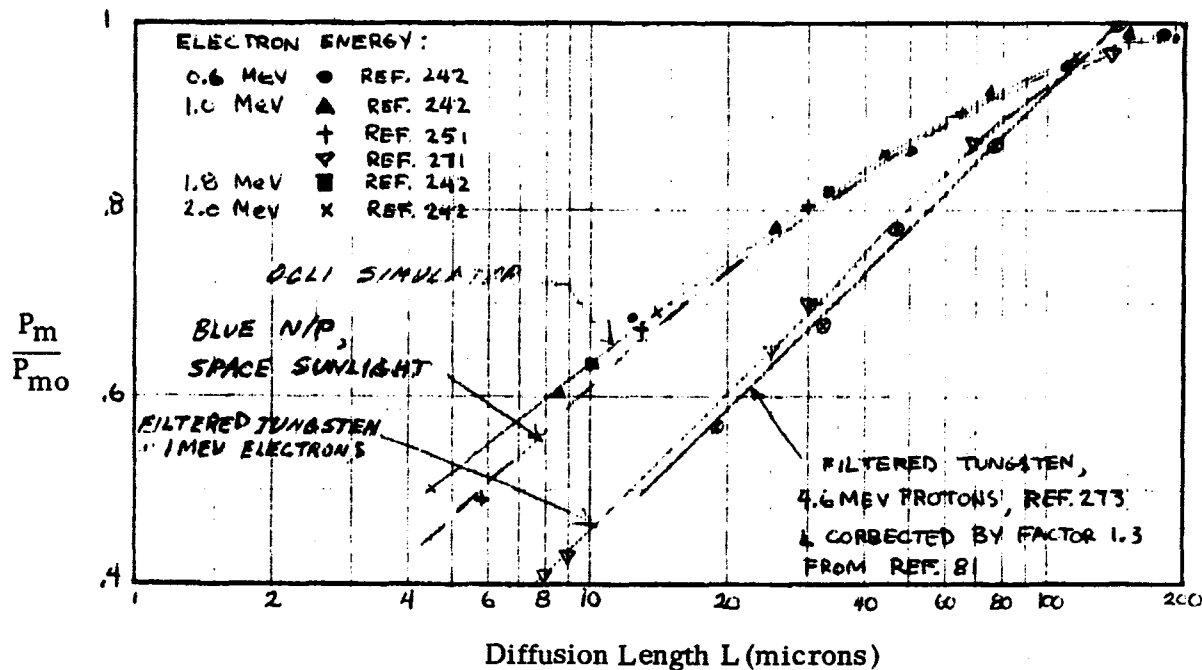


Figure IV-23. Maximum Power Ratio vs. L for one ohm-cm n/p Silicon Cells Under Various Light Sources

8. Effect of Solar Cell Temperature on Maximum Power

The maximum power obtainable from a solar cell tends to decrease as its temperature increases. Figure IV-28 shows a plot of maximum power, referenced to initial power at 77°F, for various temperatures and base diffusion lengths, for 10 ohm-cm n/p cells. These data were obtained using an OCLI Solar Simulator (ref. 242), and L was computed on the basis of equation IV-4, with the initial value L_0 assumed to be 200 microns. The curves are seen to be of the form given by equation IV-9, with the numerical parameters dependent on temperature. Additional data for 10 and one ohm-cm n/p cells are shown in figures IV-29, IV-30, IV-31, and IV-32.

It should be noted that solar cell thickness will affect the temperature coefficients of at least the current and power from the cells.

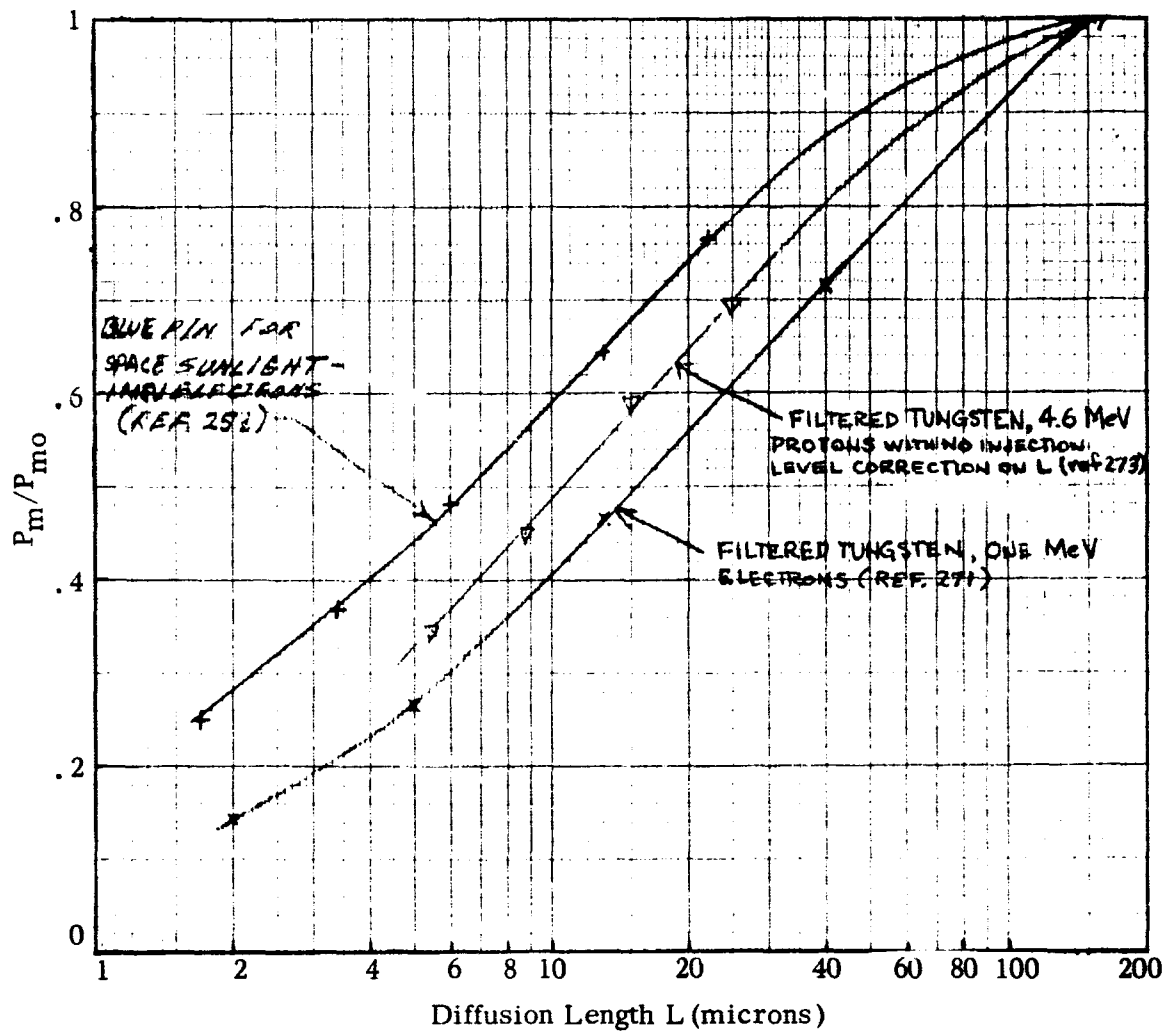


Figure IV-24. Maximum Power Ratio vs. L for One Ohm-cm p/n Silicon Cells Under Various Light Sources

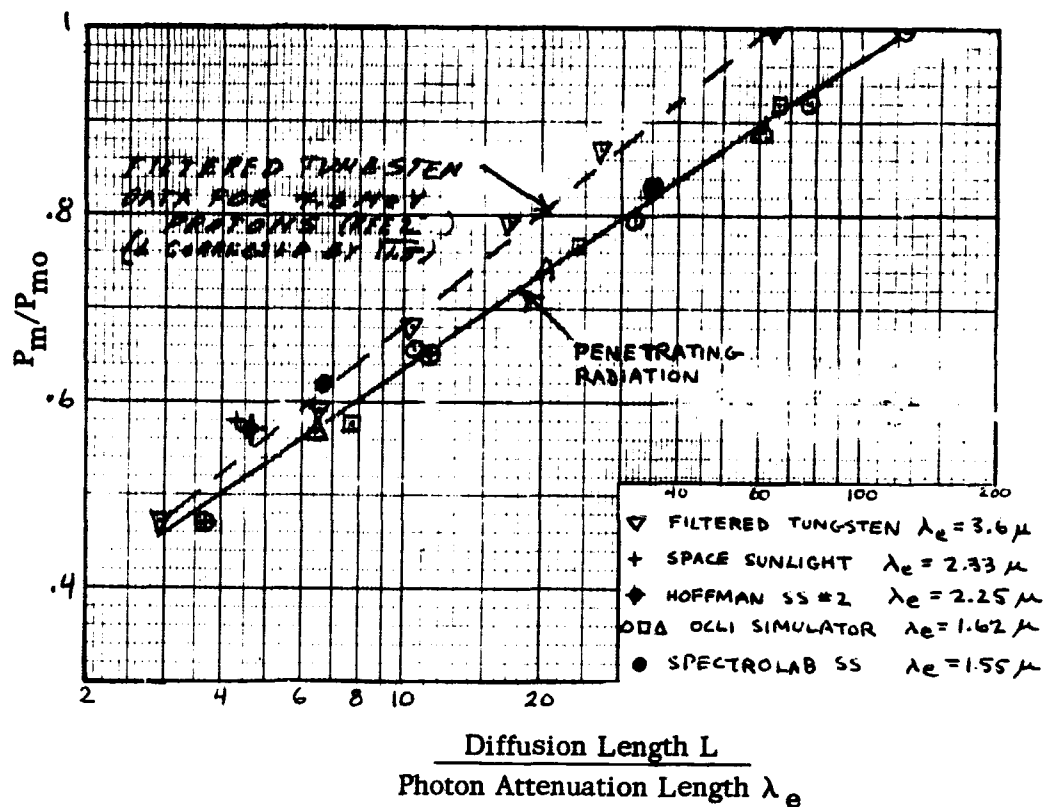


Figure IV-25. Correlation of Maximum Power Ratios Measured under Various Light Sources for 10 Ohm-cm n/p Silicon Cells

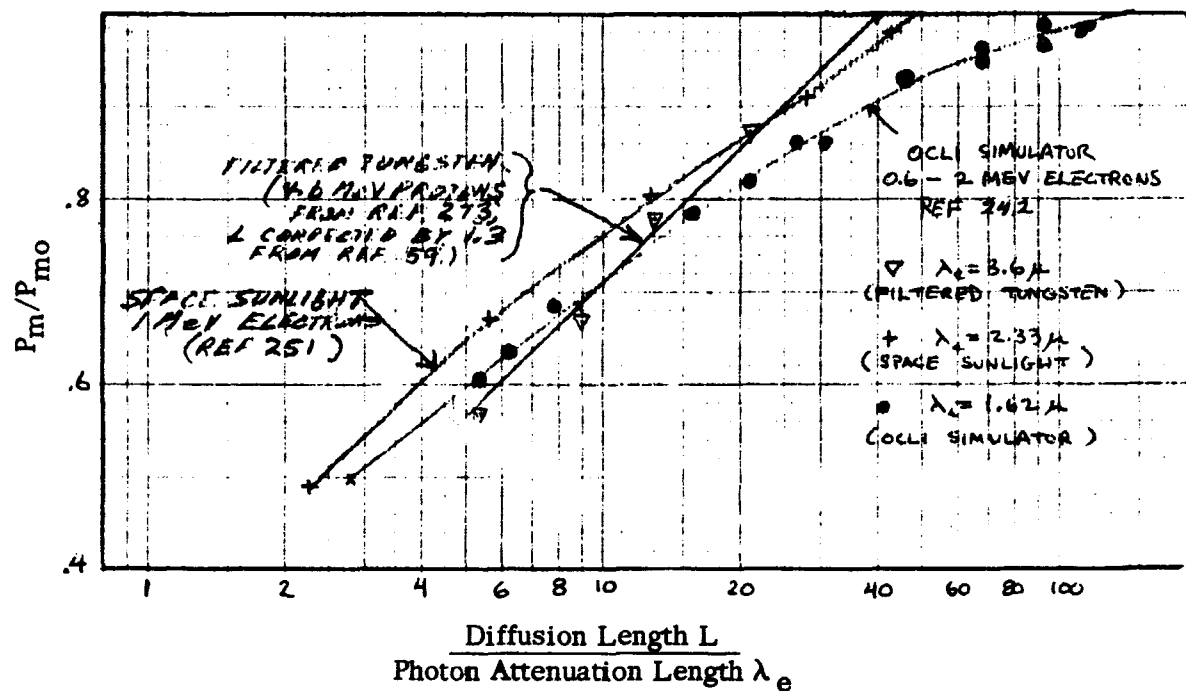


Figure IV-26. Correlation of Maximum Power Ratios Measured Under Various Light Sources for One Ohm-cm n/p Silicon Cells (K_E Values from ref. 287)

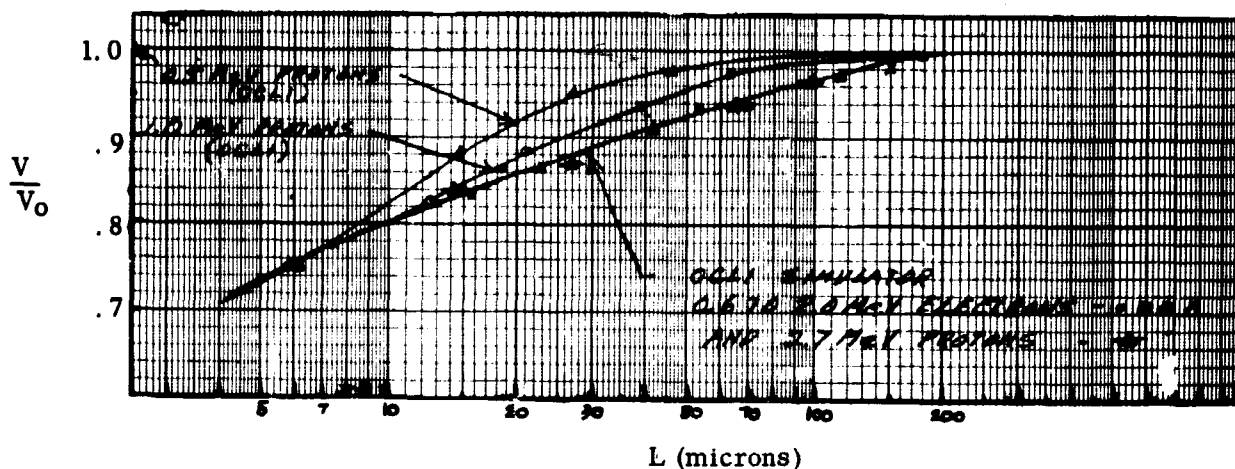


Figure IV-27. Open Circuit Voltage Ratio vs. L , under OCLI Simulator for 10 Ohm-cm n/p Silicon Cells at 77° F

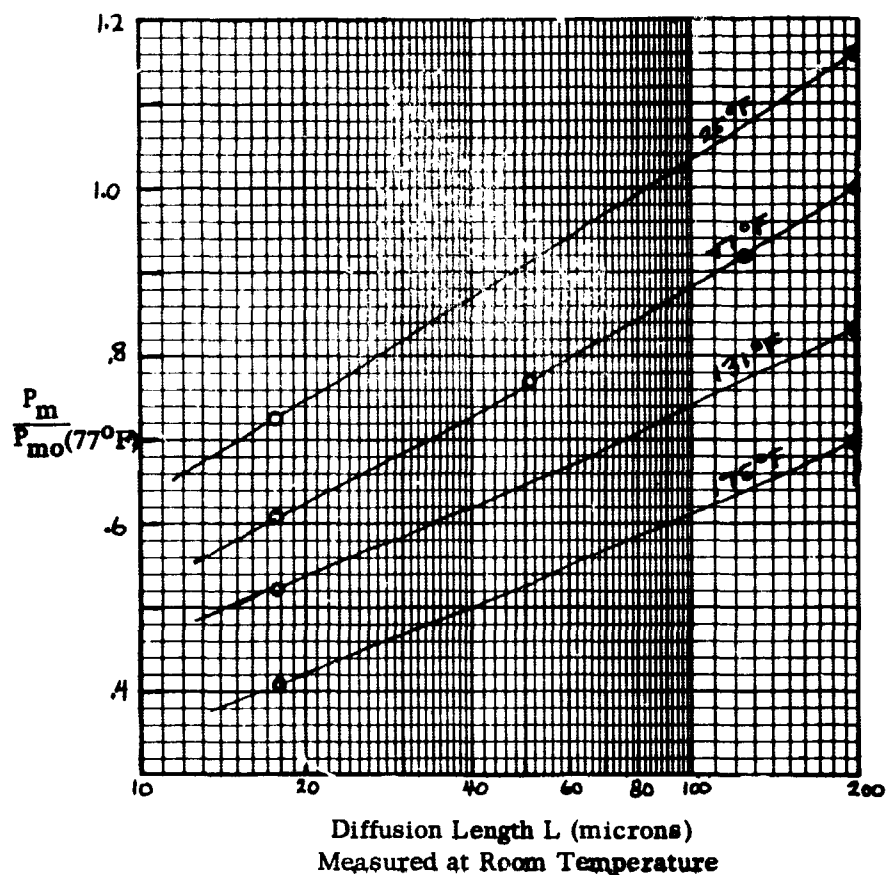


Figure IV-28. Maximum Power Ratio vs. L for Hoffman 10 Ohm-cm Silicon Cells under OCLI Simulator and Penetrating Radiation of One MeV Electrons at Various Cell Temperatures (ref. 242)

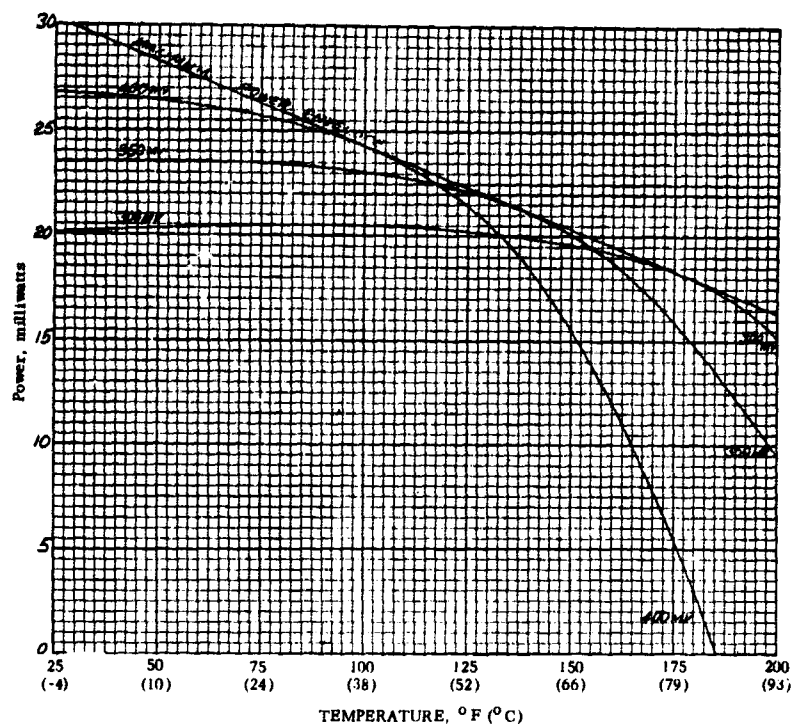


Figure IV-29. Power vs. Temperature, HEC 10 Ohm-cm n/p Silicon Cells, Unirradiated

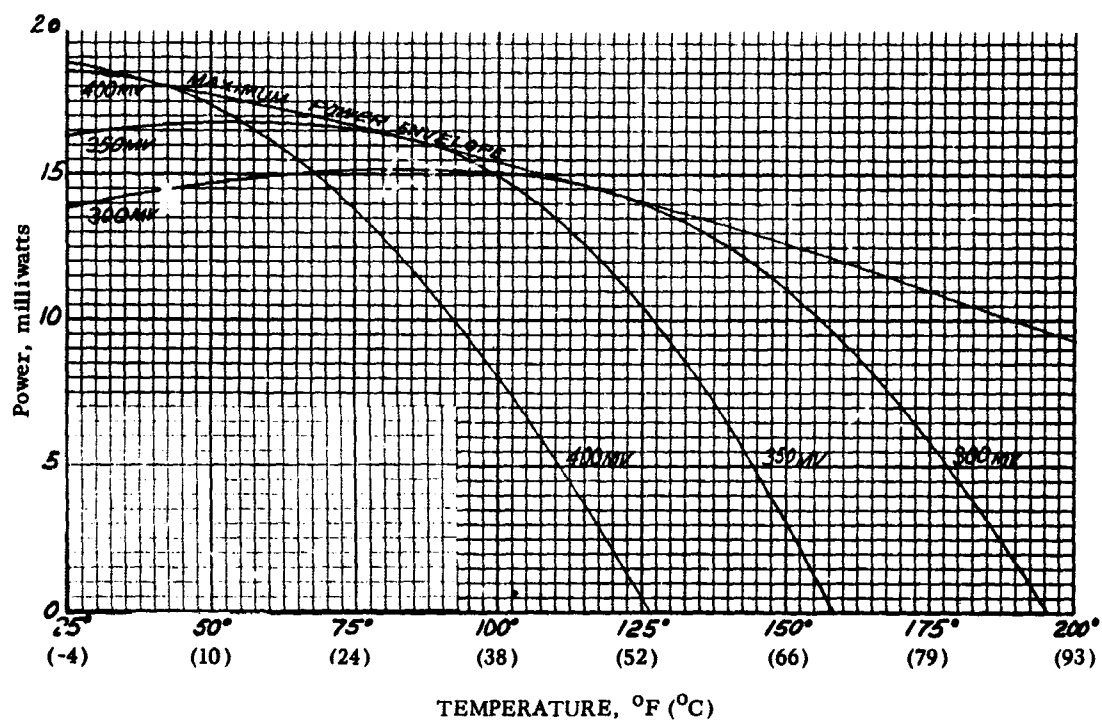


Figure IV-30. Power vs. Temperature, HEC 10 Ohm-cm n/p Silicon Cells, Irradiated at 5.2×10^{15} one-MeV Electrons per cm^2

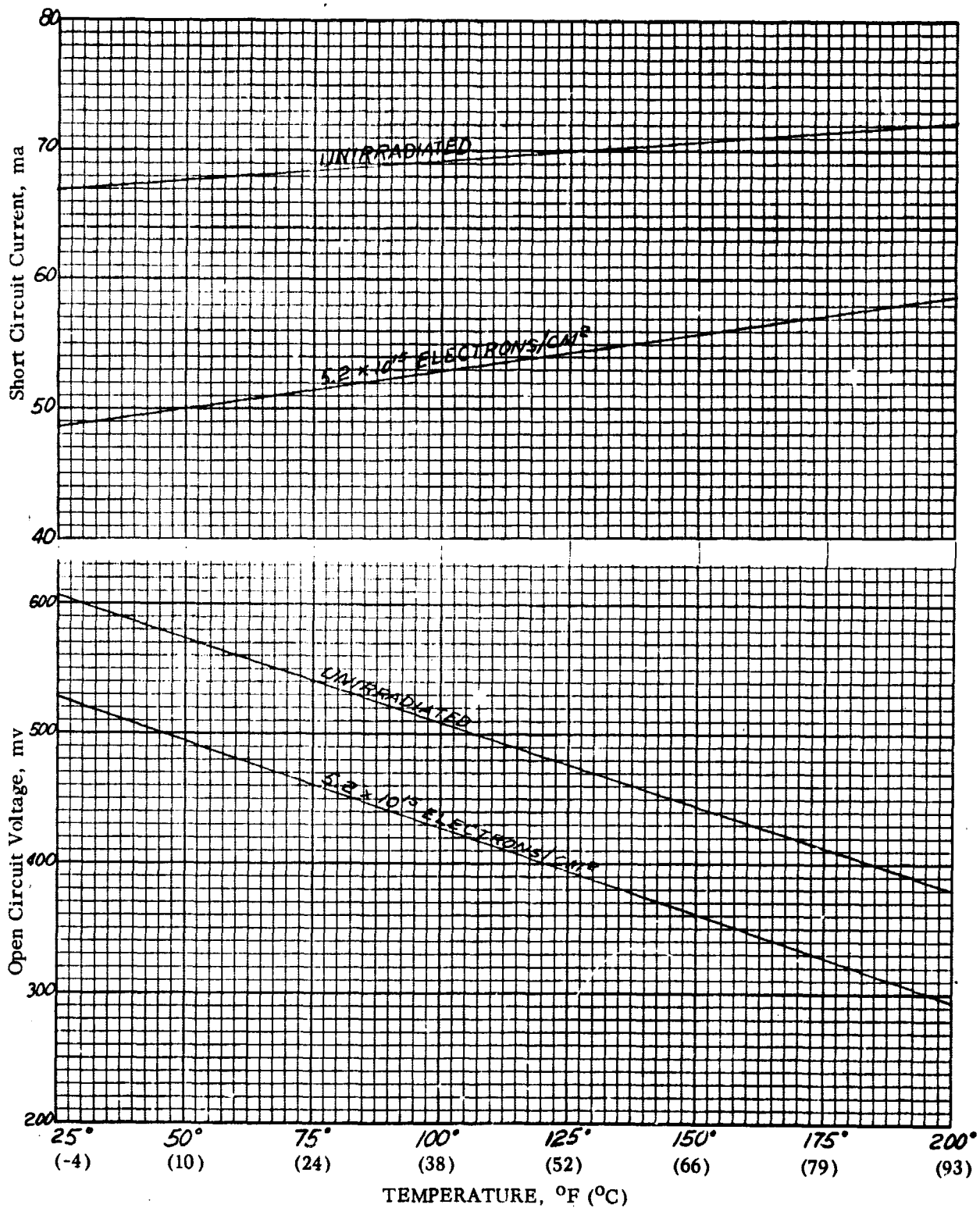


Figure IV-31. Short Circuit Current and Open Circuit Voltage vs. Temperature for HEC 10 Ohm-cm n/p Silicon Cells, with and without Radiation Effects

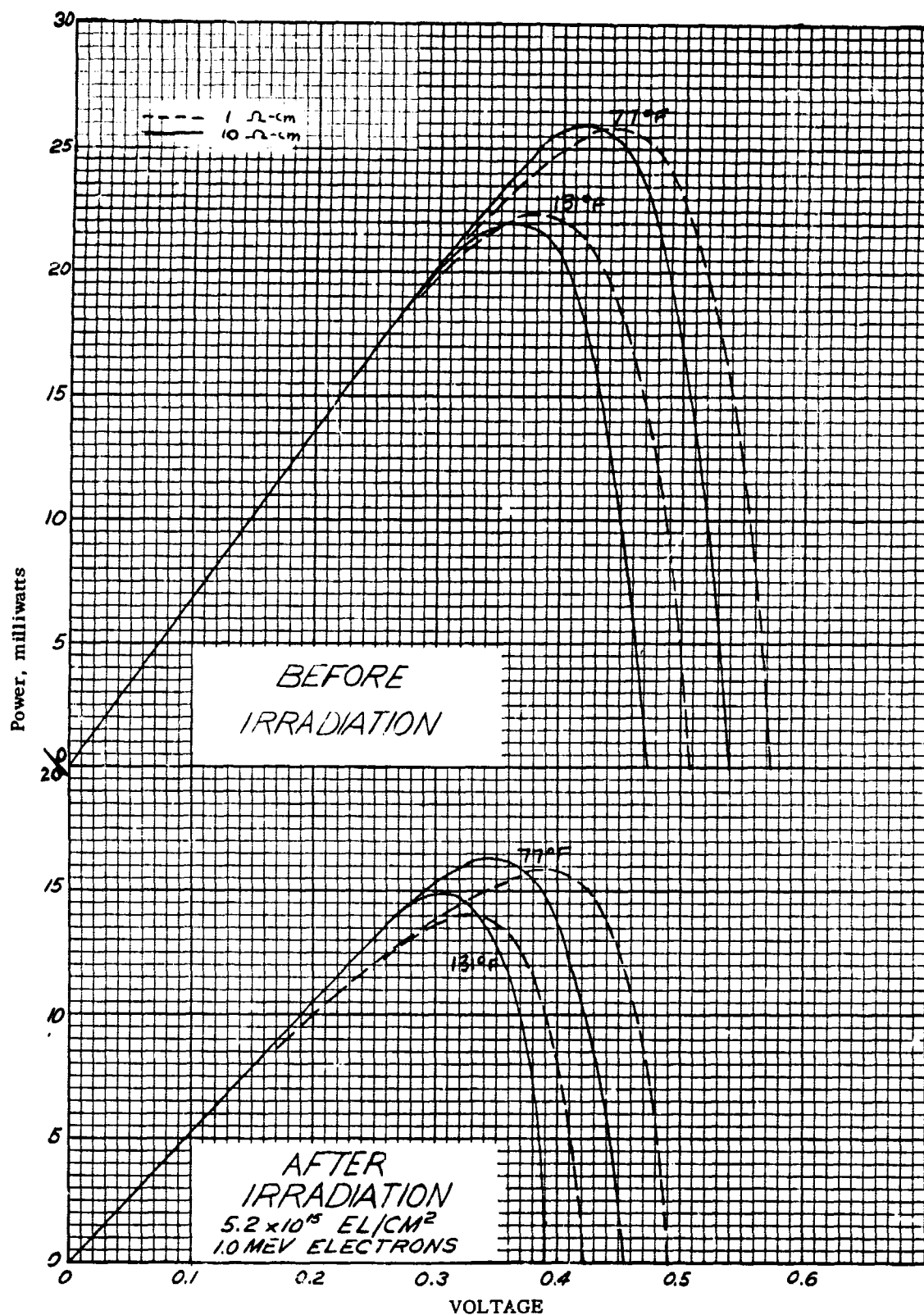


Figure IV-32. Power vs. Voltage for One and 10 Ohm-cm n/p Silicon Cells Before and After Irradiation

V. THE SPACE RADIATION ENVIRONMENT

A. PARTICLE TRAPPING IN THE GEOMAGNETIC FIELD

Electrons and protons, in close orbits in Earth's magnetic field beyond the atmosphere, were postulated by Stormer (ref. 277) and first discovered by Van Allen (ref. 291) in 1958. An understanding of the trapped particle orbits requires a knowledge of the geomagnetic field.

To a first approximation, the geomagnetic field is that of a simple dipole offset about 436 kilometers from the center of the Earth on a line toward the point at 150.9° E, 15.6° N. The axis of the dipole is tilted about 10° so that it penetrates the Earth's surface at 81.0° N, 84.7° W and 75.0° S, 120.4° E (ref. 221). In spherical R- θ coordinates, the radial and tangential components of the magnetic field are

$$B_R = (\mu_0 m / 4\pi R^3) 2 \cos \theta \quad (V-1)$$

$$B_\theta = (\mu_0 m / 4\pi R^3) \sin \theta \quad (V-2)$$

For B_R and B_θ measured in gauss and R measured in Earth radii of 6371.2 kilometers (3440 nautical miles), then $(\mu_0 m / 4\pi)$ equals 0.310 gauss, the strength of the earth's field at sea level on the magnetic equator (ref. 132). Vector addition gives the field intensity at any point (R, θ) for the dipole approximation:

$$B = (0.31/R^3) (4 - 3 \sin^2 \theta)^{1/2} \text{ gauss} \quad (V-3)$$

where θ is the magnetic colatitude. The force on a charged particle in this field leads to curved orbits which can be circular or helical.

The convergence of the field near the poles reduces the pitch of the helical orbit of a particle. Zero pitch marks the "mirror point" for a given particle and the orbit

then moves back toward the equator, as pictured in figure V-1. The radius of the helix is, according to classical physics, $m v (\sin\alpha) c / e B$, where m is particle mass, $v (\sin\alpha)$ the velocity perpendicular to the field B , c the speed of light, and e the particle charge.

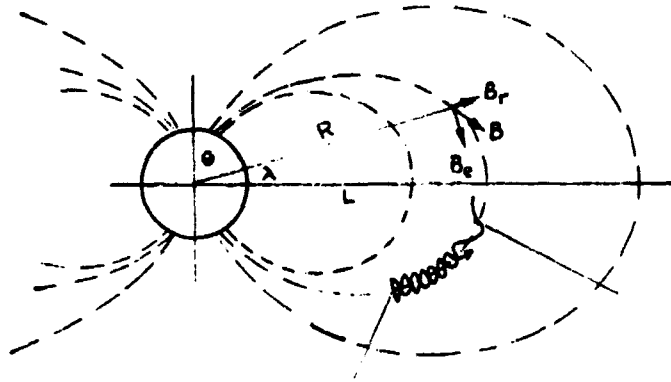


Figure V-1. Magnetic lines of force, showing relationship of R , θ , L , B , B_R , and B_θ . A possible trapped particle orbit is shown.

In the figure, the lines of force indicate the direction of the vector B . At the magnetic equator, a given line has a distance L from the dipole center; this is used to identify the line. In three dimensions, each line forms an L shell. At a colatitude θ or a latitude λ , the distance of an L shell from the dipole is

$$R = L \sin^2 \theta = L \cos^2 \lambda \quad (V-4)$$

Combining with eq. (V-3), we have

$$B = (0.31/R^3) (4-3R/L)^{1/2} \quad (V-5)$$

This relation, plotted in figure V-2, is a first approximation of the geomagnetic field. The path of a trapped particle in this mapping is represented as a straight vertical line on the graph from the magnetic equator to the mirror point; the actual orbit is a helix about this line, such that the instantaneous angle of the particle velocity with the line of force is given by

$$\sin^2 \alpha = \frac{(B)}{B_0} \sin^2 \alpha_0 \quad (V-6)$$

where B_0 and α_0 are measured for the particle crossing the magnetic equator. The pitch angle goes to 90° when $B \sin^2 \alpha_0$ equals B_0 ; the particle can not progress further along the line of force and is mirrored back to the equator. Trapped particles typically travel along field lines (with a rotation period on the order of 10^{-4} seconds), from north to south mirror points, with about a second or more between reflections. Also, there is an azimuthal drift, eastward by electrons and westward by protons, circling the earth with periods ranging from minutes to hours.

This stable motion of the trapped particles ends in one of two ways. At lower altitudes, a particle may collide with an atmospheric molecule, transferring energy and entering a new orbit or being neutralized to escape the magnetic field. The second mechanism for redistribution and loss of particles is a temporal variation of the magnetic field, such as the superposition of a magnetic "storm". This mechanism leads to large fluctuations in the local particle flux above about 3 Earth radii.

Since the particle dynamics in the quiet field depend on B and L , it is desirable to record flux distributions in this two dimensional coordinate system rather than in three geographical coordinates such as height R' , colatitude θ' , and east longitude φ . A transformation is then required to related R' , θ' , and φ to B and L . Using orthonormal Legendre polynomials, this transformation can be written as

$$U = R_0 \sum_{n=1}^{\infty} \sum_{m=0}^n (R_0/R')^{n+1} \left[g_n^m \cos m \varphi + h_n^m \sin m \varphi \right] P_n^m \cos \theta' \quad (V-7)$$

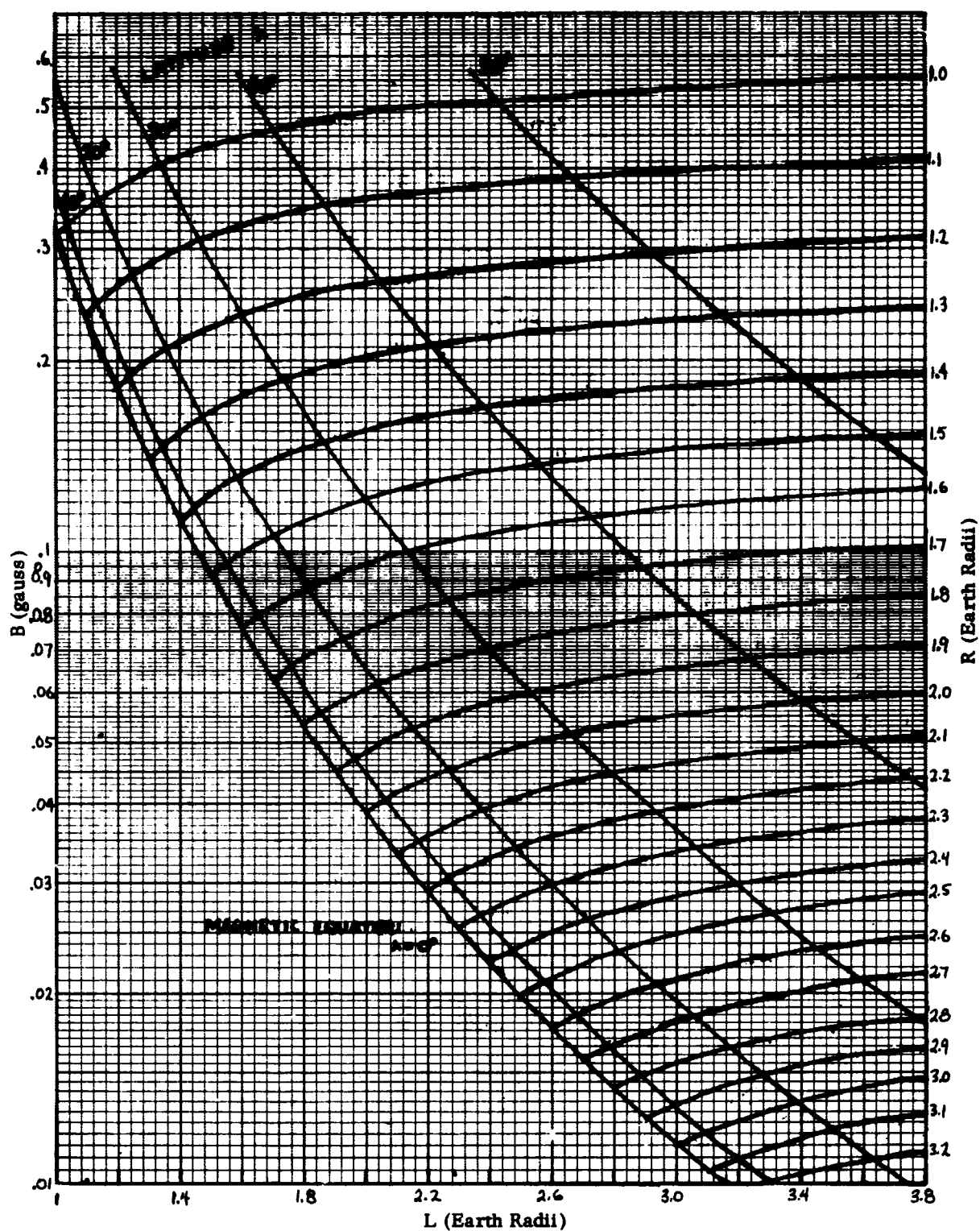


Figure V-2. Dipole Relations Between the Magnetic Coordinates (B, L) and the Spatial Coordinates (R, λ) .

where U is the magnetic potential at the position R', θ', φ , with R_0 the radius of the earth. The fit constants, g_n^m and h_n^m , are called Gaussian coefficients, and are obtained by measuring the field over some closed surface such as the ground level. Hendricks and Cain (ref. 132) have generated the most recent expansion for the Gaussian coefficients. The vector B is obtained as the gradient of U , while L is defined by McIlwain (ref. 197) in terms of an integral invariant. Frequently in the literature, the magnetic coordinates (B, L) are calculated by these equations from the geographical coordinates (R', θ', φ) and then related to the dipole coordinates (R, λ) by equations (V-4) and (V-5). This approach allows a simplified study of radiation belts and generates an apparent distortion of the earth's surface, which will vary in the (R, λ) plot by as much as ten percent from the unit circle.

An interesting chart produced with the aid of a computer program (ref. 244) Figure V-3, shows how the magnetic field varies as a function of latitude and longitude. The displacement of the field causes a dip of the magnetic shells off the coast of Brazil. This is the well-known South Atlantic Anomaly, important in that trapped particles drifting into this area will go to low altitudes, experiencing an increase in atmosphere density, and more collisions to remove them from orbit. Satellites in low orbits (below 1000 kilometers altitude) will accumulate most of their radiation fluence while passing through this region.

The geomagnetic field (decreasing as the inverse cube of R) is abruptly terminated by interaction with a more or less steady emission of solar particles. This is the "solar wind", consisting of about 10^8 protons/cm²-sec., an equal number of electrons and much smaller quantities of heavier nuclei. The zone of interaction is a surface known as the magnetopause, containing the geomagnetic field on the inside and deflecting the solar wind on the outside. The surface is spherical on the sunward side, at a distance of about 10 Earth radii and stretches out on the night side in a long, almost cylindrical shape, with a diameter of 35-40 Earth radii and an unknown length (fig. V-4).

As a result of this interaction, the total magnetic field, which is the sum of the geomagnetic field and that induced by the solar wind, is severely distorted above the

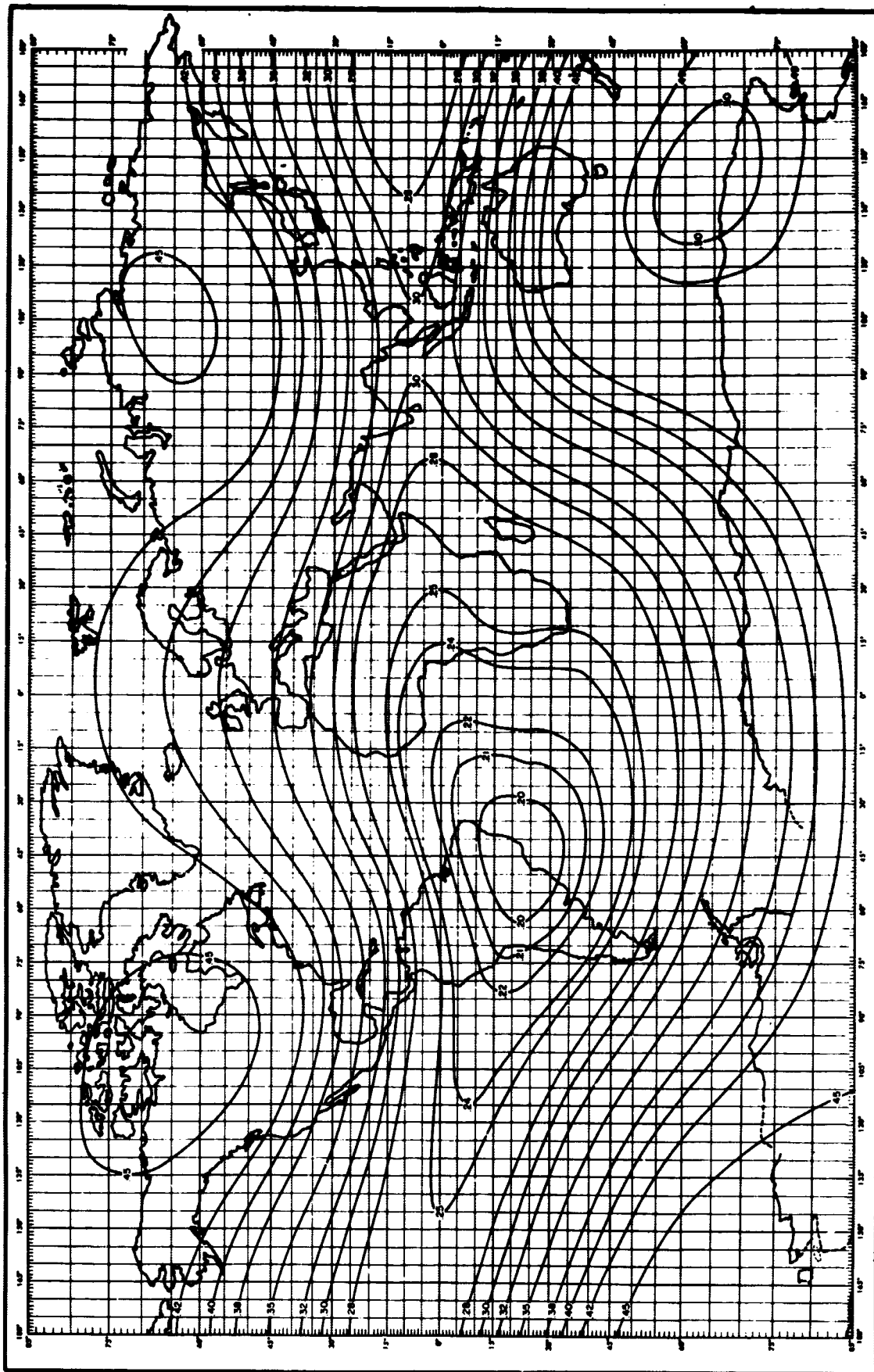


Figure V-3. Lines of Constant Magnetic Intensity B at Altitude of 600 Kilometers (Ref. 297). These Would Be All Straight Lines if the Earth's Field Were Dipolar and the Magnetic Equator Coincided with 0° Latitude.

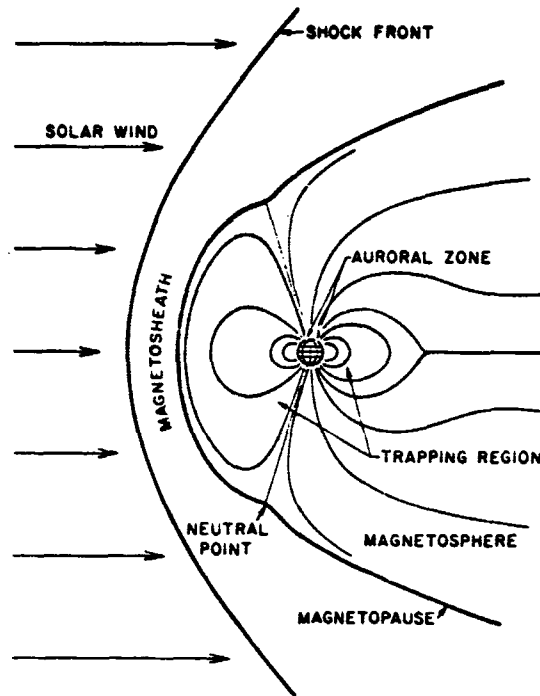


Figure V-4. Cross Section of Magnetosphere Taken Through Noon-Midnight Meridian. (Ref. 114)

L=5 shell. Particles trapped above this shell would move at altitudes that are strongly dependent on the direction of the sun and the prevailing intensity of the solar wind.

B. TRAPPED PROTONS

Protons trapped in the earth's magnetic field have energy and space distributions affected by magnetic disturbances, solar activity, and other gain and loss mechanisms. Generally, there is a fairly stable inner zone from 600 miles to 5000 miles altitude between 45° north and south geomagnetic latitudes, with a peak omnidirectional flux over the magnetic equator at 2200 statute miles altitude of about $10^4/\text{cm}^2\text{-sec}$ having energies greater than 40 Me V. Beyond the inner zone lies a zone of relatively low energy protons extending from the L=3 shell. This outer energy zone extends to the magnetopause

and has intensities that vary with time of day (ref. 64). In figure V-5, it can be seen that the low energy protons actually span both "zones".

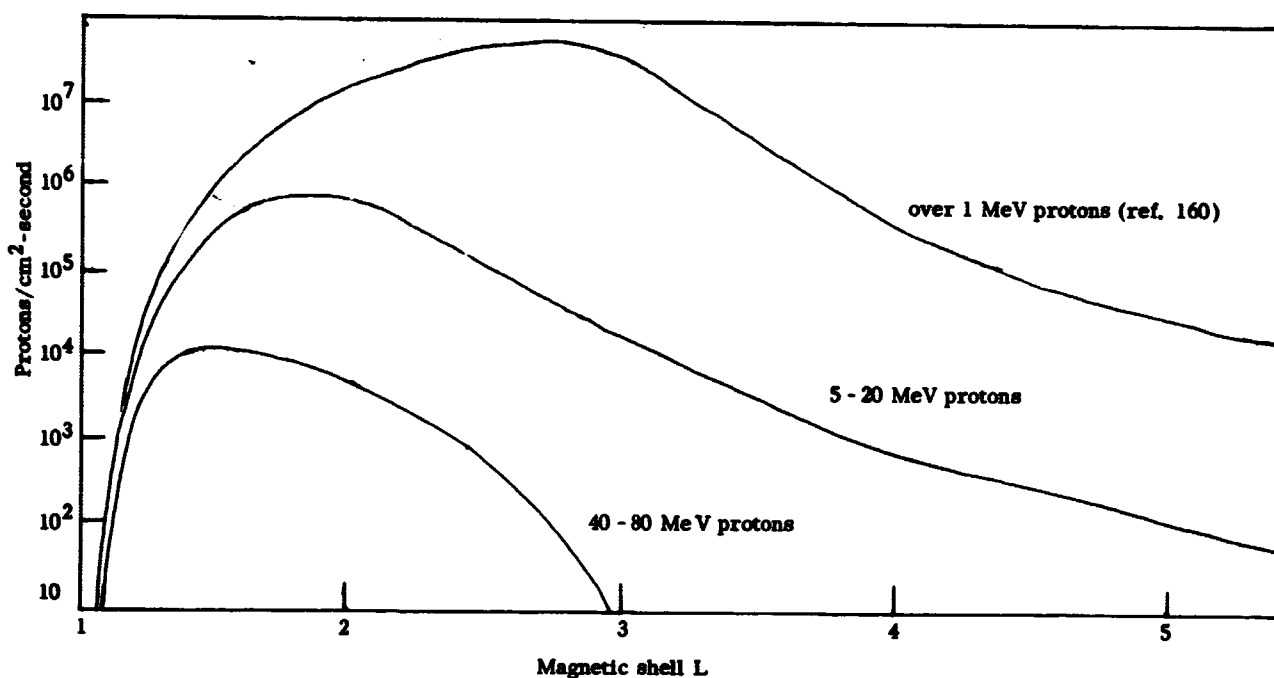


Figure V-5. Proton Fluxes on the Magnetic Equator. Replotted From Ref. 18 and Ref. 160

In the inner zone, the proton spectrum has an exponential appearance. Fits have been made, with exponentials, to the integral energy spectrum in the form (ref. 297).

$$J(>E, B, L) = F(B, L) \exp \left[\frac{E_1 - E}{E_0(B, L)} \right] \quad (V-8)$$

where $F(B, L)$ equals $J(E_1, B, L)$, the flux of protons of energies greater than the low energy cutoff E_1 above which the equation applies*. The dependence of F and the characteristic energy E_0 on the coordinates B and L is generally weak but becomes strong

*It has become conventional to present flux data as the integral energy spectrum. Thus, equation V-8 gives the flux of protons of energies greater than E . To obtain the differential energy spectrum for mathematical operations, it is necessary merely to differentiate with respect to $(-E)$.

in regions where the flux changes rapidly and the spectrum deviates from the exponential form. Four mappings span the data for the inner radiation belt. These are

Proton Map AP1 for 30 to 50 MeV

Proton Map AP2 for 15 to 30 MeV

Proton Map AP3 for E greater than 50 MeV

Proton Map AP4 for 4 to 15 MeV

F and E_0 are reproduced here as Figures V-6 to V-13 for the four maps.

For a satellite in a circular orbit, an integration of these data has been performed to obtain figures V-14 through V-17. From these figures, one can reconstruct an energy histogram of the time-averaged proton flux in this special case.

Some general observations on the proton spectra in the inner zone can be made. The integral spectra, on the magnetic equator, based on Relay I data, are seen in figure V-18. These give the maximum intensity on their respective L shell, since all particles travel orbits that are bisected by the equator. The intensity, as one moves away from this point, falls off about as B^{-n} , where n varies from 3.5 to 4 for protons in the range up to 14 MeV, and drops to 3 for the highest range (35-63 MeV) measured. Beyond about 30° to 45° , the drop is more gradual, until the mirror points start to enter the atmosphere and the intensity drops suddenly (ref. 104)

In the outer zone, the proton flux drops off and the spectrum becomes less energetic (figure V-5). At 19,300 nautical miles, the altitude of synchronous orbit, the proton flux is about $1.49 \times 10^{13} \exp(-E/0.11)$ per cm^2 - day-MeV. King has recently published a mapping of the integral proton flux (ref. 160), presented here as figure V-19. The theoretical work of Nakada and Mead (ref. 207) states that the spectral index E_0 , of equation (V-8), which is 0.11 MeV at synchronous orbit (L equal 6.6), should vary such that $E_0 L^3$ remains constant. While this does not seem to reproduce the data precisely (ref. 200) it does provide a rough estimate of the hardening of the proton spectrum with decreasing altitude.

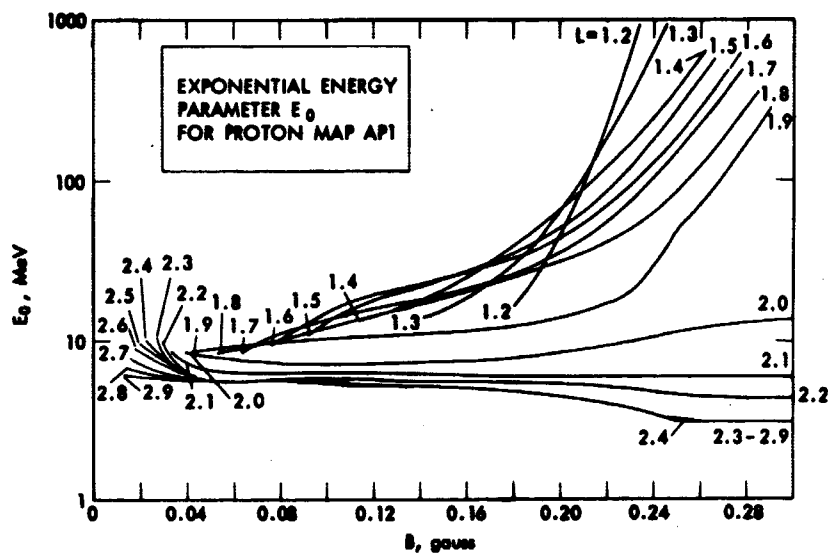


Figure V-6. The Energy Spectral Parameter, E_0 , for Proton Map AP1. This Function is to be Used Over the Energy Range 30-50 Me V.

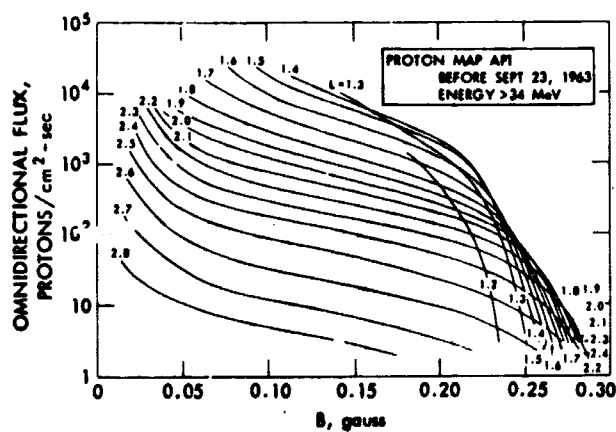


Figure V-7. The Flux Versus B Plot of AP1, $E > 34$ Me V.

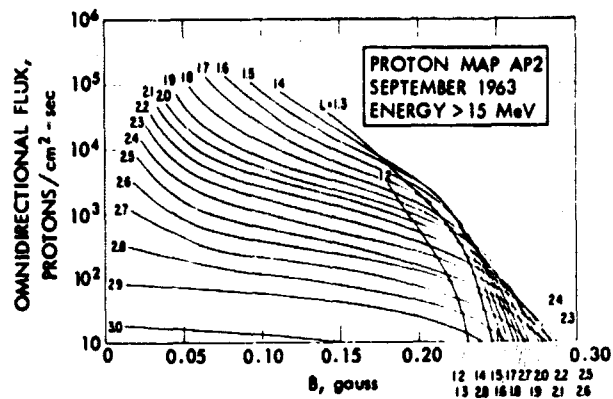


Figure V-8. The Flux Versus B Plot of AP2, $E > 15$ MeV.

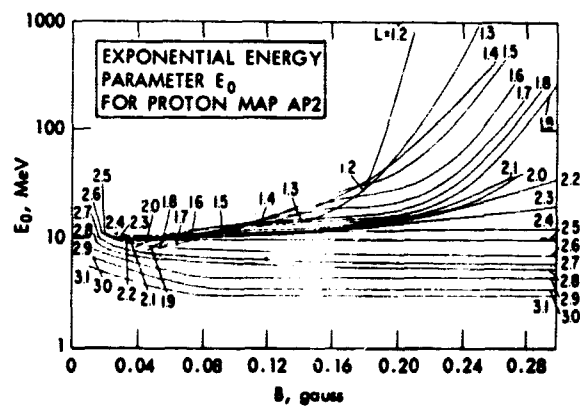


Figure V-9. The Energy Spectral Parameter, E_0 , for Proton Map AP2. This Function is to be Used Over the Energy Range 15 - 30 MeV.

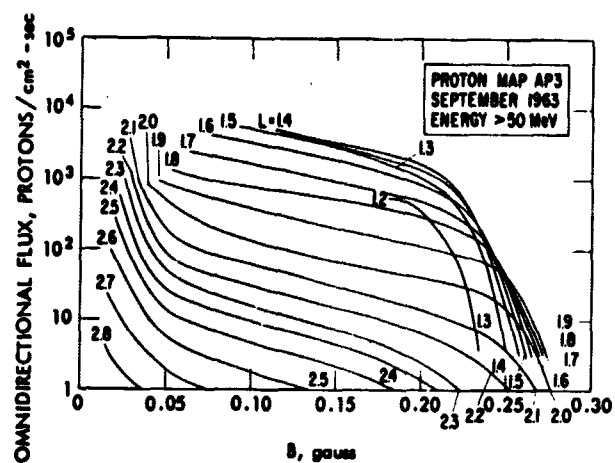


Figure V-10. The Flux Versus B Plot of AP3, $E > \text{MeV}$.

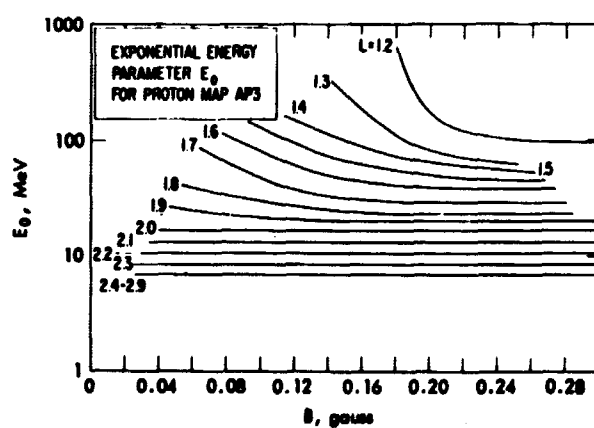


Figure V-11. The Energy Spectral Parameter, E_0 , for Proton Map AP3. This Function is to be Used for Energies Greater than 50 MeV.

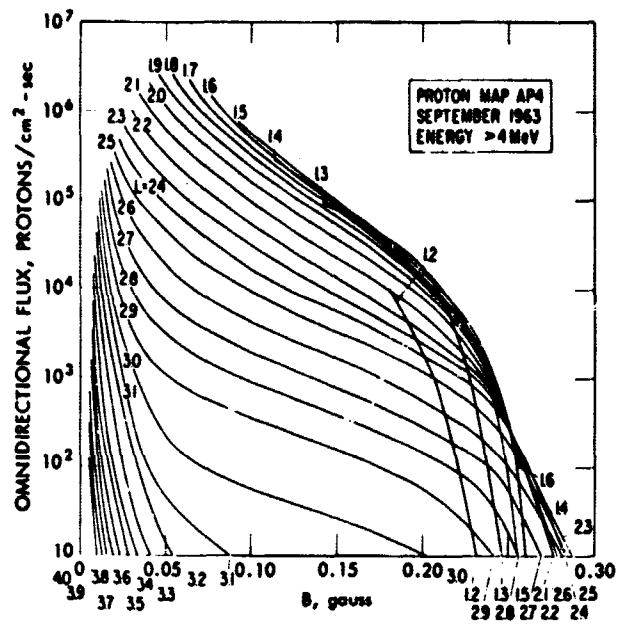


Figure V-12. The Flux Versus B Plot of AP4, $E > 4$ MeV.

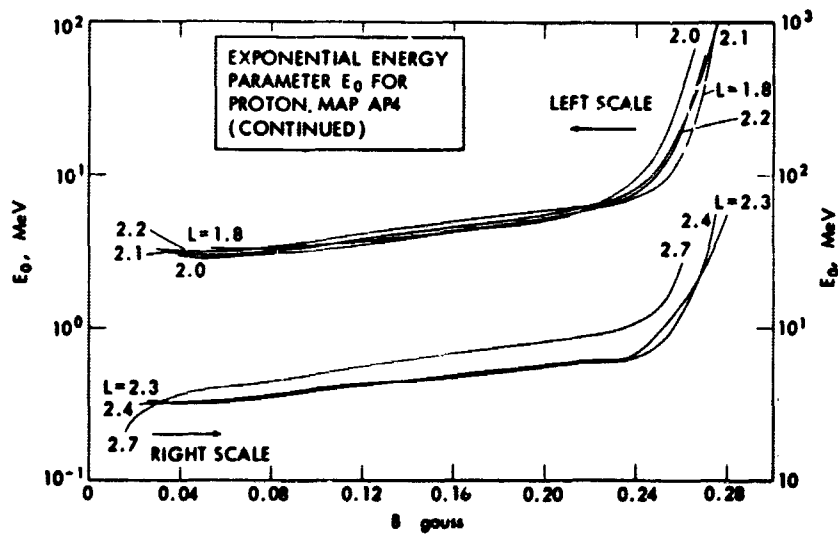


Figure V-13. The Energy Spectral Parameter, E_0 , for Proton Map AP4. This Function is to be Used Over the Energy Range 4 - 15 MeV.

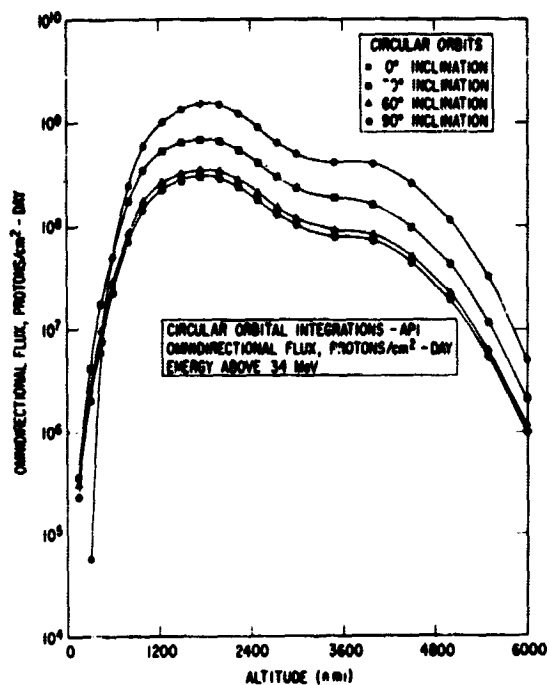


Figure V-14. Orbital Integrations With Proton Map AP1.

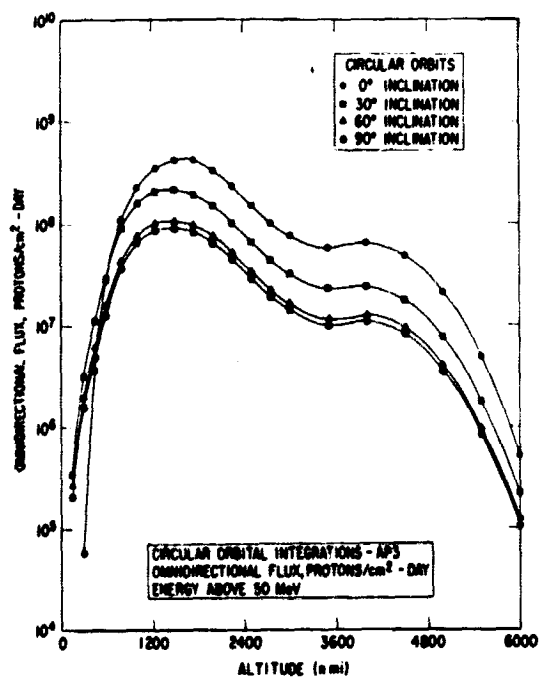


Figure V-15. Orbital Integrations With Proton Map AP3.

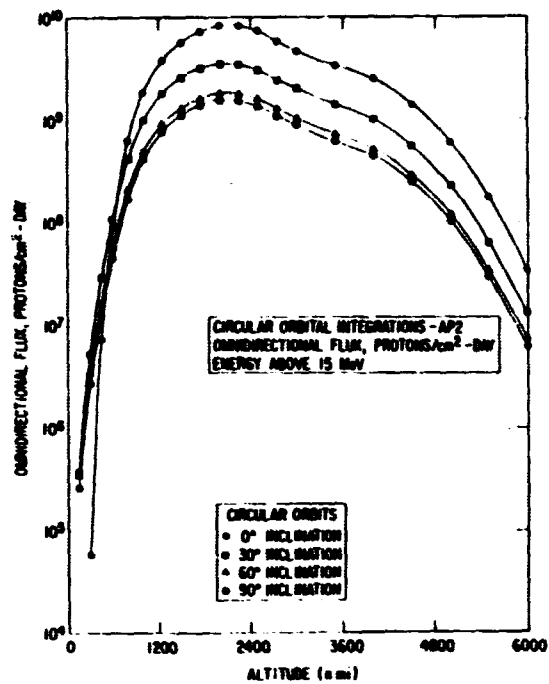


Figure V-16. Orbital Integrations With Proton Map AP2.

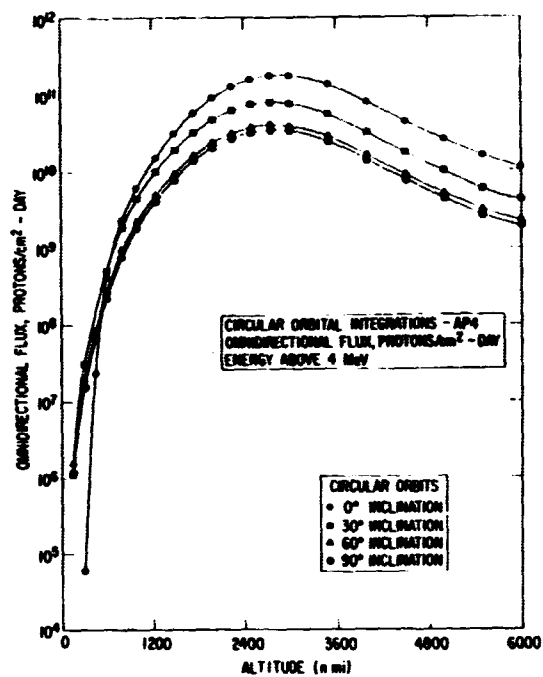


Figure V-17. Orbital Integrations With Proton Map AP4.

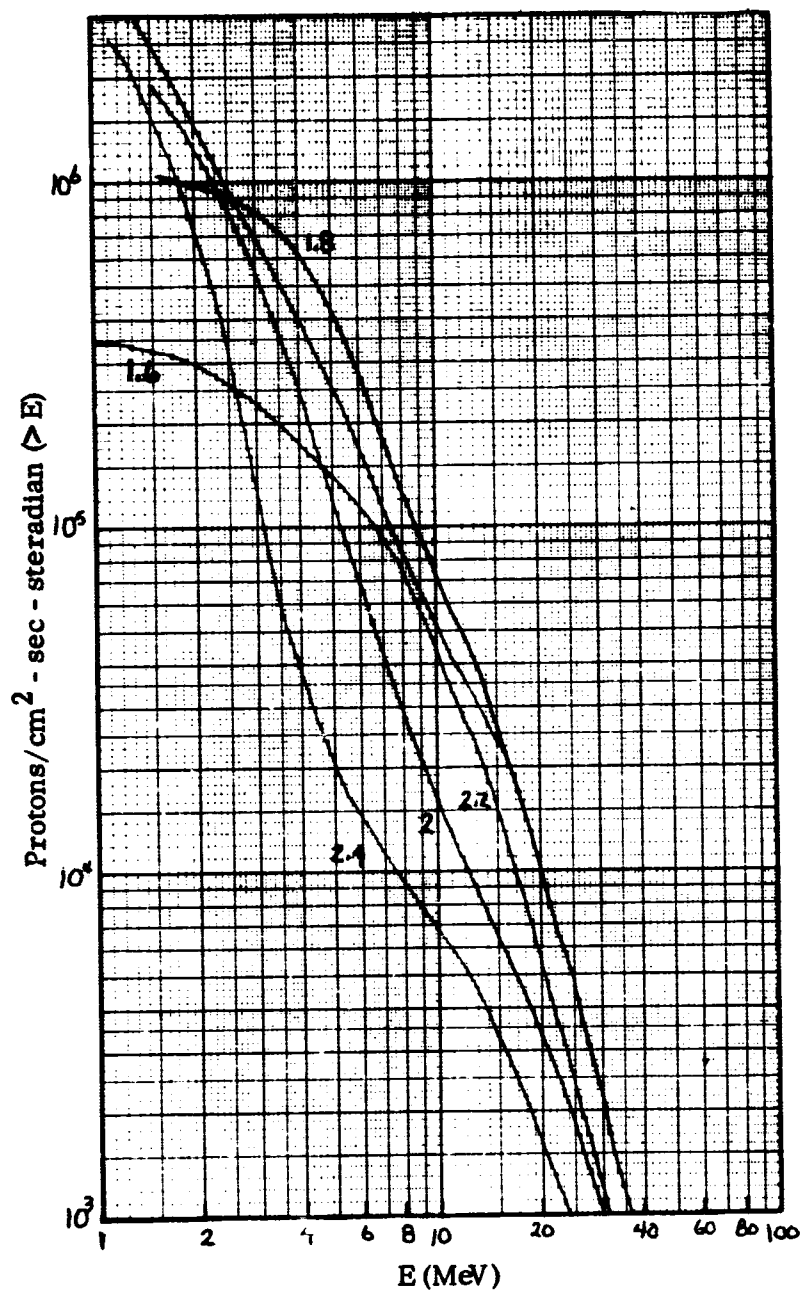


Figure V-18. Integral Proton Fluxes (protons/cm²-sec-steradian) of Energy Greater Than E , vs. Energy at Various Values of L on the Equator.

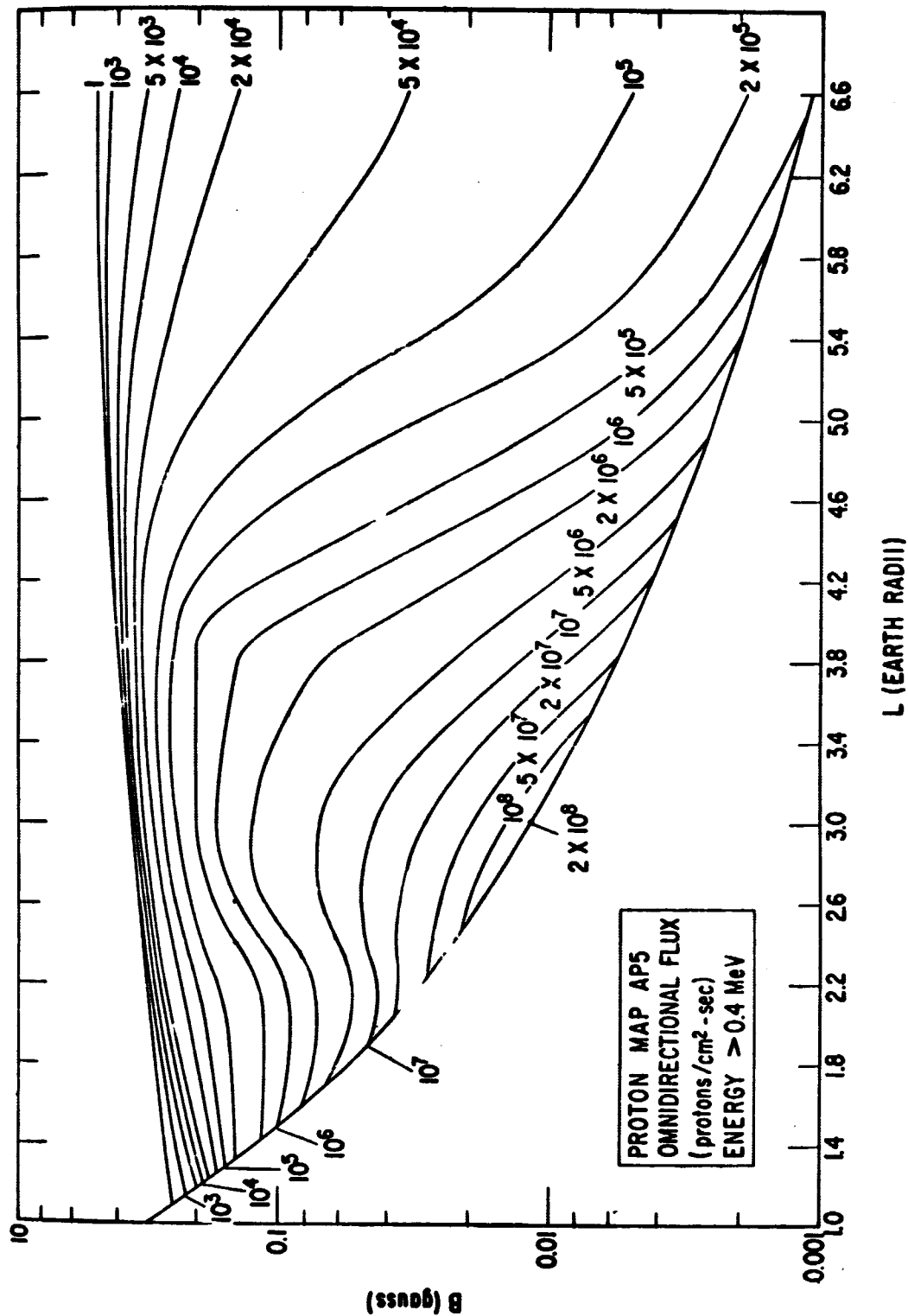


Figure V-19. Protons of Energies Greater Than 0.4 MeV in the Earth's Magnetic Field.

C. TRAPPED ELECTRONS

Superimposed on the natural belt of electrons in the inner zone is a flux due to the beta decay of radioisotopes injected in the magnetosphere by high altitude nuclear explosions. At present, only the electrons due to the 1.4 megaton "Starfish" explosion 250 miles above Johnston Island in the Pacific on July 8, 1962 are in evidence. These are lingering in the L shells around 1.2-1.7, with a mean lifetime on the order of 150-500 days in accordance with Table V-1.

TABLE V-1. MEAN LIFETIME FOR ELECTRONS WITH ENERGIES OVER 1.2 MeV (REF. 37).

L	T (days)
1.20	120
1.30	235
1.40	390
1.50	460
1.60	360

The decay of this fission electron flux, together with the injection of electrons into the outer zone during the present period of increased solar activity (1968-1971) is leading to a shift in the relative intensities of electrons in the inner and outer zones. The electron flux typically peaks at 2,500 kilometers and around 15,000 kilometers above the equator, in a distribution that is spoken of as the "inner" and "outer" electron zones. Intensities and profiles of the zones vary greatly with phase of the solar cycle; this is especially noticeable in the outer zone. Compilations of flux data gathered during one phase of the most recent solar cycle should be considered only as rough guides to estimate future flux levels.

The outer zone, peaking around the L = 7 shell, is characterized by variable intensities (a factor of 10), energies extending to a few MeV, and a strong day-night dependence, as seen in figure V-4 (ref 111).

Vette (ref. 297) has prepared detailed maps of the spatial and spectral distributions of the electron belt in the formalism described above for the proton belt. The spectrum,

a slowly-varying function of B and L, is strongly exponential above one MeV. Below one MeV, especially in the inner zone, the decrease in flux with energy is much steeper (the spectrum is "softer"). Orbital integrations for circular orbits in the inner zone are given in Table V-2.

In the outer zone, the electron flux is highly variable, changing by orders of magnitude in periods of a few weeks. Averaging over these variations, Vette arrives at an electron flux for the synchronous satellite orbit. Averaged over daily as well as longer variations, this is

$$J = 2.2 \times 10^8 \exp(-4.65 E) / \text{cm}^2 \text{-sec-MeV} \quad (\text{V-9})$$

on the magnetic equator, according to measurements taken at the minimum of the solar cycle. At solar maximum, an increased solar wind is expected to compress the magnetosphere, pushing the charged particle population inward. There is evidence to suggest that J for synchronous altitude will decrease by a factor of two during solar maximum (1969) as a result of this compression.

D. SOLAR PROTONS

The continual "solar wind", discussed above, is characterized by a proton spectrum with average energy on the order of one keV (ref. 213). The electrons which must be present for neutrality are presumed to have the same velocity and hence an energy so small as to escape detection. The low energy of the solar wind would cause negligible damage to solar cells in all presently conceivable situations.

In addition to this low energy, low intensity emission, there occur large sporadic bursts of particles, primarily protons, with a typically steep spectrum ranging from less than 10 MeV to a few BeV. These protons originate in spectacular solar flares and diffuse outward through the solar magnetic field. Particles arrive in a wide band of directions at the Earth a few minutes after the burst and continue to arrive more and more isotropically for hours to days with the spectrum gradually softening as the event subsides. Over the entire flare, the differential energy spectrum above 30 MeV that is

TABLE V-2. AVERAGE ELECTRON FLUENCE, PER $\text{cm}^2\text{-day}$, OF ELECTRONS ABOVE AN ENERGY E, INCIDENT ON A SATELLITE IN AN EQUATORIAL ORBIT IN 1968. LAST TWO DIGITS FOR EACH ENTRY INDICATE THE EXPONENT OF 10 (EG. READ 2.67×10^5 for 2.67 05). (REF 297)

LOWER ENERGY CUTOFF E						
Altitude (Naut. Miles)	0.5 MeV	1 MeV	1.5 MeV	2 MeV	2.5 MeV	3.5 MeV
150	0	0	0	0	0	0
300	2.67 05	1.58 04	1.06 03	5.31 02	2.66 02	6.67 01
450	4.91 08	2.61 07	2.05 06	1.20 06	7.48 05	3.29 05
600	2.51 10	1.15 09	1.12 08	7.77 07	7.75 07	3.39 07
800	2.17 11	8.02 09	1.08 09	8.69 08	7.18 08	5.01 08
1000	8.22 11	2.59 10	4.48 09	3.81 09	3.28 09	2.45 09
1250	2.32 12	5.88 10	1.46 10	1.29 10	1.16 10	9.23 09
1500	3.57 12	7.65 10	2.51 10	2.28 10	2.07 10	1.72 10
1750	3.03 11	5.88 10	2.40 10	2.22 10	2.06 10	1.77 10
2000	1.17 12	2.43 10	1.02 10	9.33 09	8.53 09	7.13 09
2250	4.18 11	1.13 10	5.24 09	4.56 09	3.98 09	3.03 09
2500	1.79 11	4.98 09	2.40 09	2.08 09	1.79 09	1.35 09
2750	1.10 11	3.36 09	1.78 09	1.53 09	1.26 09	9.08 08
3000	8.31 10	2.74 09	1.55 09	1.28 09	1.04 09	7.07 08
3500	7.21 10	3.16 09	1.97 09	1.48 09	1.13 09	6.72 08
4000	1.07 11	6.35 09	3.89 09	2.66 09	1.94 09	1.06 09
4500	1.94 11	1.99 10	1.00 10	6.15 09	3.92 09	1.69 09
5000	3.59 11	5.75 10	2.57 10	1.45 10	8.24 09	2.73 09
5500	5.95 11	1.40 11	5.79 10	3.02 10	1.57 10	4.81 09
6000	9.04 11	2.71 11	1.11 11	5.43 10	2.55 10	6.43 09
7000	1.60 12	6.23 11	2.69 11	1.13 11	4.80 10	8.47 09
8000	2.07 12	8.39 11	3.54 11	1.39 11	5.54 10	8.62 09
9000	2.10 12	7.98 11	3.03 11	1.16 11	4.42 10	6.54 09
10000	2.00 12	6.25 11	2.04 11	6.63 10	2.16 10	2.30 09
12000	1.54 12	3.74 11	9.08 10	2.22 10	5.39 09	3.20 08
14000	1.05 12	1.79 11	3.12 10	5.49 09	9.72 08	3.08 07
16000	6.42 11	7.15 10	8.16 09	9.48 08	1.13 08	1.67 06
18000	6.89 10	6.54 09	6.21 08	5.90 07	5.61 06	5.06 04

accumulated is often proportional to E^{-n} , where n may vary from about 3.5 to 5.0 in a given event (ref. 149), and a typical flare will result in a proton fluence of about $10^5 - 10^8/\text{cm}^2$ near the earth.

The nearly isotropic* arrival of solar flare protons at the Earth distance suggests a diffusion process. A number of investigators have been able to corroborate this, fitting the data by a formula (ref. 138)

$$I = Nv (4\pi Dt)^{-3/2} \exp (-r^2/4Dt) \quad (\text{V-10})$$

where N is the instantaneous source strength, v the proton velocity, D a diffusion coefficient of the order of $5-6 \times 10^{21} \text{ cm}^2/\text{sec}$, and I the flux intensity at time t after the burst and at a distance r from the sun. Thus, an assumption of a $1/r^2$ dependence of proton intensity with solar distance can lead to erroneous results.

One or two days after a solar flare is observed on the sun, a geomagnetic storm may occur, indicating a large flux of low energy particles interacting with the magnetosphere. The magnetic field is momentarily perturbed by the flux, leading to such spectacular effects as aurorae, ionospheric changes disrupting radio communication, and apparent decreases in galactic cosmic ray intensity at ground level (Forbush decreases).

The sporadic occurrence of solar flares makes prediction of their damage effects difficult. Table V-3 lists the yearly integrated fluences for 1956-1961 and, for comparison, the yearly integrated fluences of galactic cosmic rays.

Bailey (ref. 16) has analyzed the spectra of the large flares and developed a time-dependent representative model. This may be integrated over time to provide an integral spectrum which is piecewise fitted by the expression

$$\begin{aligned} J(>E) &= 2.6 \times 10^{10} E^{-1.33} & 5 < E < 100 \\ &= 1.97 \times 10^{17} E^{-4.77} & 100 < E \end{aligned} \quad (\text{V-11})$$

*Anisotropy measurements have shown that current from the direction of the Sun is somewhat higher than from the anti-Sun direction for at least a small flare (ref. 17).

TABLE V-3. SOLAR FLARE DATA (REF 103)

Year	No. Flares	Fluence for Year (E > 30 MeV)	Cosmic Ray Fluence
1956	2	8×10^9	1×10^8
1957	4-5	4×10^8	7×10^7
1958	6	1×10^9	6×10^7
1959	4	7×10^9	6×10^7
1960	8	5×10^9	8×10^7
1961	5	2.7×10^8	1×10^8

This fit corresponds to a fluence of 2.8×10^8 protons/cm²-flare, with energies E greater than 30 MeV. For individual events, the spectrum can deviate considerably from this, as was discussed above. The Bailey spectrum is useful in predictions of future activity. In connection with this, the probability that the solar flare fluence will be N protons (of energies greater than 30 MeV), in a period of T weeks, is given in figure V-20 (ref. 205).

There is a preference for the use of a spectral representation based on magnetic rigidity*. In this form, introduced by Frier and Webber (ref. 116), the spectrum of the solar flare is presented in the form

$$\frac{dJ}{dP} = \frac{J_0}{P_0} e^{-P/P_0} \quad (V-12)$$

where P is the magnetic rigidity and P₀ and J₀ are constants for the particular flare. There appears to be a better fit of known flare spectra to this rigidity spectrum than that obtainable with equation V-10. The relationship between the rigidity P of a particle and its energy E is given by

$$ZP = [E^2 + 2 Mc^2 E]^{1/2} \quad (V-13)$$

*Magnetic rigidity of a charged particle is its radius of curvature in a magnetic field, times the field strength. (See Ref. 100, p. 892)

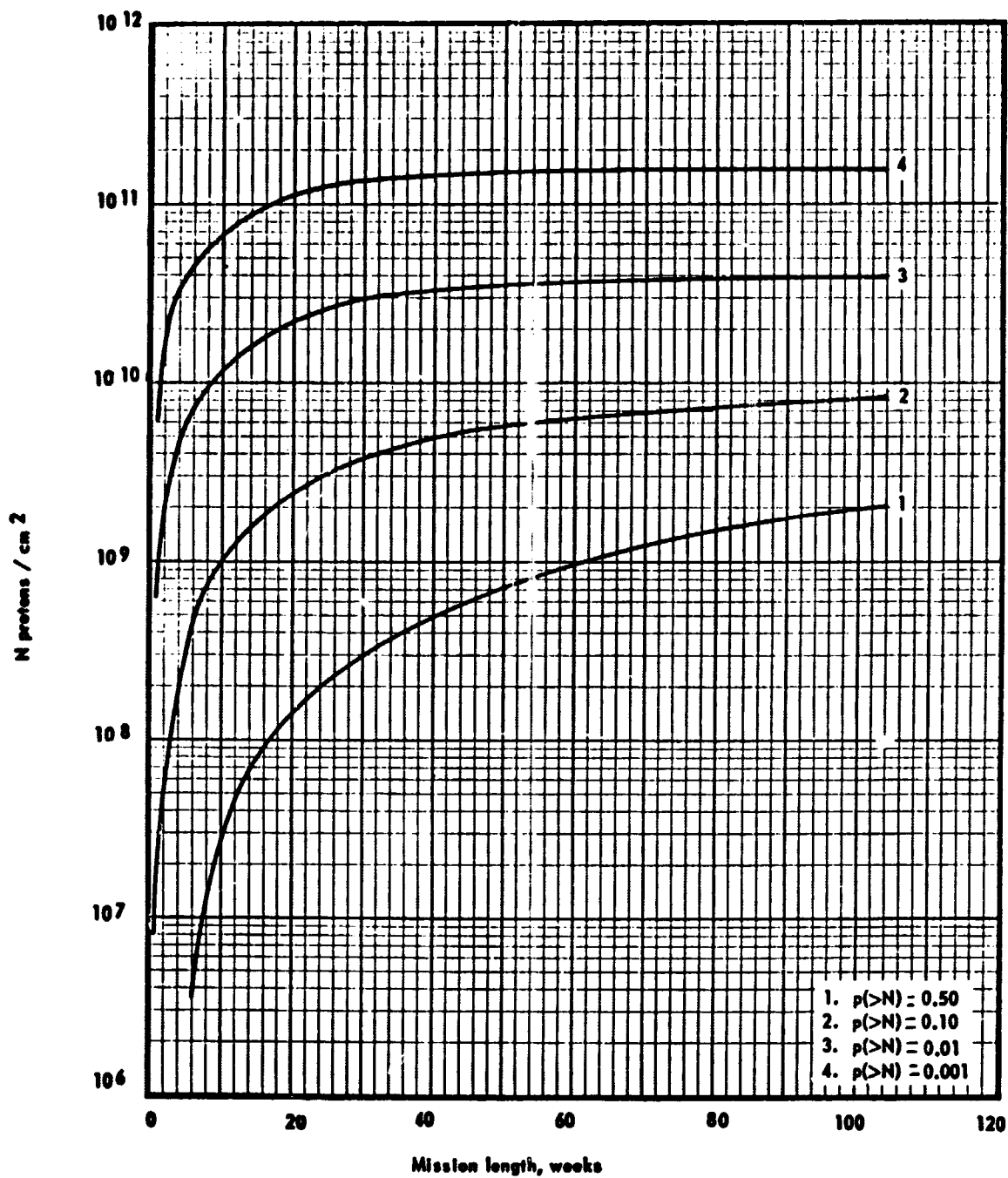


Figure V-20. Probability of a Fluence, Outside the Magnetosphere 1 AU from the Sun, of More Than N Solar Flare Protons for a Given Mission Duration

where Z is the electronic charge of the particle (unity for protons), P the rigidity in MV, E the kinetic energy in MeV, and Mc^2 the rest mass in MeV (931 for protons).

For a satellite orbiting within the geomagnetic field, a calculation of solar flare-induced radiation damage requires an evaluation of the shielding effect of the field. The effect is the complete exclusion of flare protons below some minimum rigidity which is determined by the geomagnetic latitude and longitude and the complete transmission of flare protons above some maximum rigidity. These have been calculated theoretically (ref. 7) to be, in the dipole approximation,

$$P \text{ (min, max)} = \frac{5.94 \times 10^4 Z k \cos^4 \lambda}{R^2 \left[1 + (1 \pm \cos^3 \lambda)^{1/2} \right]^2} \quad (V-14)$$

for a point at the dipole coordinates (R, λ) . The constant k is unity in the dipole field but 0.38 experimentally for P (min), partially explainable by a cancelling of the field by a ring current of the trapped particles (ref. 1). Furthermore, P (min, max) can vary greatly from this dipole approximation equation, for the field fluctuates unpredictably when a magnetic storm accompanies the solar protons.

Between these rigidity limits, the solar flare particles strike the spacecraft from directions in a cone opening to the west from zero steradians for protons of P (min) to 4π steradians for P (max). Where the cone intercepts the Earth's horizon, a portion of the flux is blocked by the solid Earth. At the earth's surface, the intensity is decreased in this way by 50%; Higher up, the blocked fraction of particles with rigidities greater than P (max) is 0.35 at 200 miles and 0.10 at 2700 miles (ref. 163).

A determination of the blockage by the earth and the shielding by the magnetic field is obviously difficult for satellites in orbit. A computer program for this calculation is listed in Table VI-1.

E. COSMIC RAYS

The cosmic rays, mentioned above, are a relatively constant background of high energy particles, about 94% protons, 5% alpha particles, the remainder being nuclei of heavier atoms with the lighter species predominating. The particle energies are high, with all but a negligible portion being over 100 MeV in energy, and the fluence is (as seen in table V-3) fairly low (ref. 149). Thus, cosmic rays are responsible for a minor portion of the radiation damage to spacecraft solar power systems, and may generally be neglected in damage studies.

VI. RADIATION SHIELDING OF SOLAR CELLS

A. GENERAL CONSIDERATIONS

Silicon solar cells are typically shielded with fused silica, glass, or sapphire as a coverslide of 0.006 to 0.10 in. thickness. Two requirements significant to solar cell efficiency and reliability are accommodated by coverslides. Thermal emissivity is increased by the coverslide so that the cell can run cooler and more efficiently. Secondly, the optical reflectivity of glass is about 2%, while it is about 30% for silicon. While modern solar cells have a thin coating of SiO₂ to improve the light transmission, the coating of such a cell in space would be subject to micrometeoroid erosion. A thin glass coating of 0.001 inch thickness or more suffices for these two requirements.

The interaction of radiation and coverslides is complex. Ultra violet radiation can darken certain materials, notably the adhesive between coverslide and silicon. Electrons and protons can also darken the coverslide, as discussed in section VII.

It would appear that all these considerations, taken together, would lead to an "optimum" coverslide design. In this section, radiation shielding by coverslides is discussed and a method outlined by which the shield thickness can be selected for a particular mission. The formulation is similar to the general approach of Weiner (ref 304), who optimizes for a minimum weight with an allowed loss in power, and of Zoutendyk (ref 322), who optimizes for a minimum loss in power for a given solar cell. To provide a basis for the analysis, it is first appropriate to discuss the basic mechanisms by which protons and electrons interact with the coverslide.

B. PROTON SHIELDING

As discussed in the previous section, proton flux in the space environment typically has a spectrum in the one to 100 MeV energy interval. Protons in this interval display very little nuclear interaction with materials of low atomic number, such as glass. The

proton travels through such material in a straight line, losing energy primarily by ionization and excitation of the neighboring atoms until it comes to rest and captures an electron to form a hydrogen atom. The distance of travel is known as the range (R , in centimeters) or mass-range (density times range (ρR , in grams/cm^2), which is related to the energy of the incident proton as shown in figure VI-1.

The data for protons in fused silica (Si O_2) may be approximated by a range $R_0 E^n \text{ gm/cm}^2$, where E is the proton energy in MeV, R_0 is 2.72×10^{-3} , and n is 1.75. Protons with ranges less than the thickness of the coverslide are unable to penetrate it and therefore do not damage the solar cell. If a proton should enter a coverslide of thickness τ at angle θ to the normal, then its path to the solar cell is slanted and the initial energy it must have to penetrate the coverslide must correspond to a range of at least $\tau / \cos \theta$.

In most situations, the time-averaged proton flux can be considered to be isotropic. The effect of a coverslide in such a situation is: (1) to remove those protons with energies E_0 and incident angles θ with the normal such that their range R is less than the slant path through the coverslide of thickness τ .

$$R(E_0) < t / \cos \theta \quad (\text{VI-1})$$

and (2) to reduce the energy of a proton which is transmitted to the cell, to an energy E given by

$$E = \left[E_0^{1.75} - t / R_0 \cos \theta \right]^{.572} \quad (\text{VI-2})$$

Protons arriving at an angle θ to the normal have a longer path in the sensitive region of the solar cell by a factor $1 / \cos \theta$ and therefore, produce a larger number of defects in this region. However, the number of protons which enter the cell per unit surface area from an angle θ is reduced by the term $\cos \theta$, due to the projection of the cell, which just compensates for the larger proton range in the sensitive region. (Another way of stating this is that a volume element of silicon has a rate of defect production per unit volume that is directly proportional to the omnidirectional flux, which is uniform at all angles of incidence.) No correction for incidence angle is needed to predict defect production rate or the change in diffusion length of the material. This is true so long

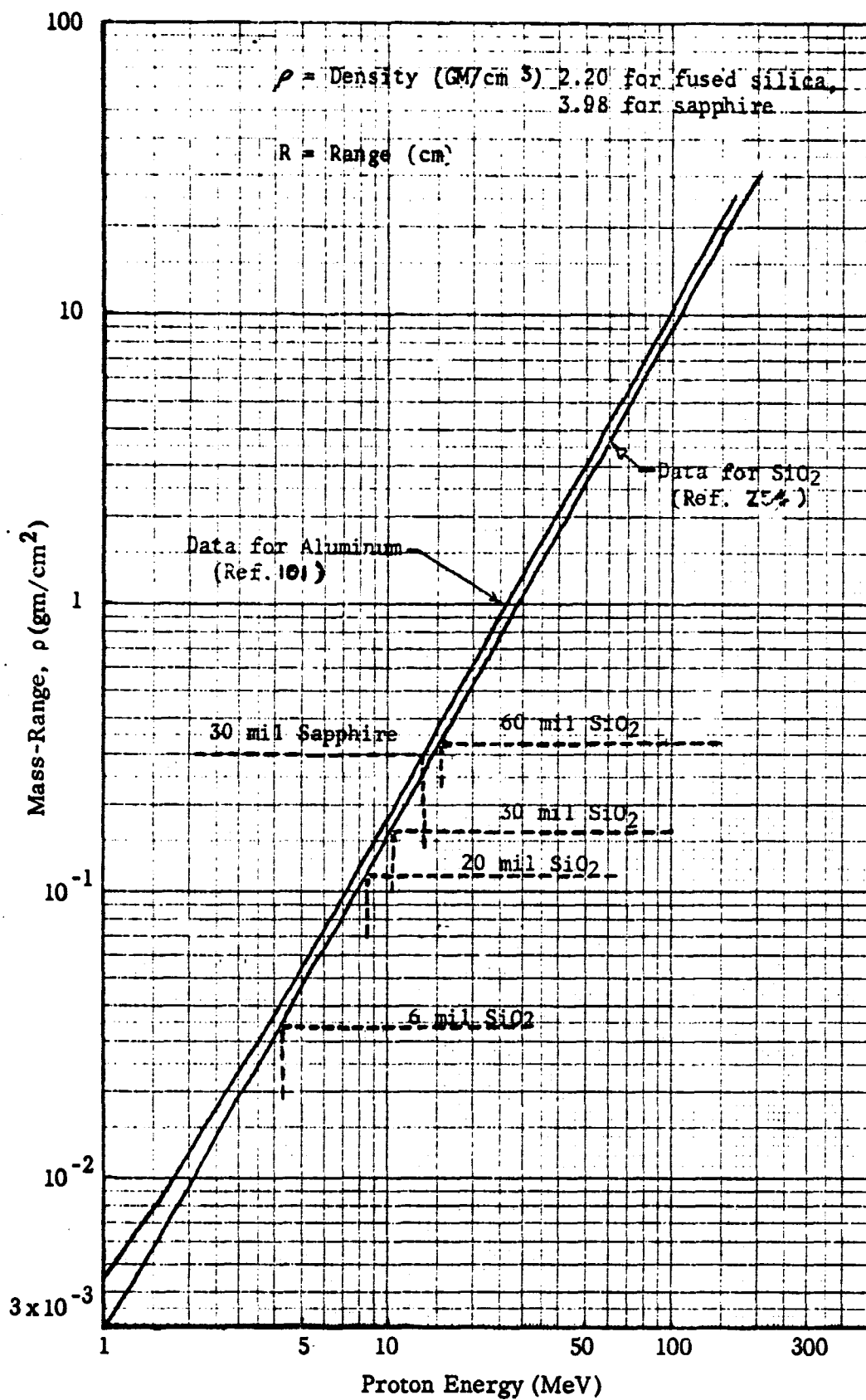


Figure VI-1. Mass-Range for Protons Through Coverslide Materials

as the range of the protons is sufficient to pass through the sensitive layer of the cell. At low proton energies, below about 5 MeV, this approximation breaks down (ref 43).

Although the shield reduces the proton energy, thereby raising its damage coefficient, protons with non-normal incidence are reduced in number by the path length in the shield. Therefore, an omnidirectional flux of protons generally produces less damage to the coverslide shielded cell's average diffusion length than is produced in bare cells under unidirectional flux. This result has been calculated by Rosenzweig as shown in figure VI-2. His calculated results show that an omnidirectional average proton of 10 to 40 MeV produces slightly more damage than a unidirectional proton for a shield thickness of 0.05 gm/cm^2 . At larger shield thicknesses, the shielding always helps for protons exceeding the shield cutoff energy.

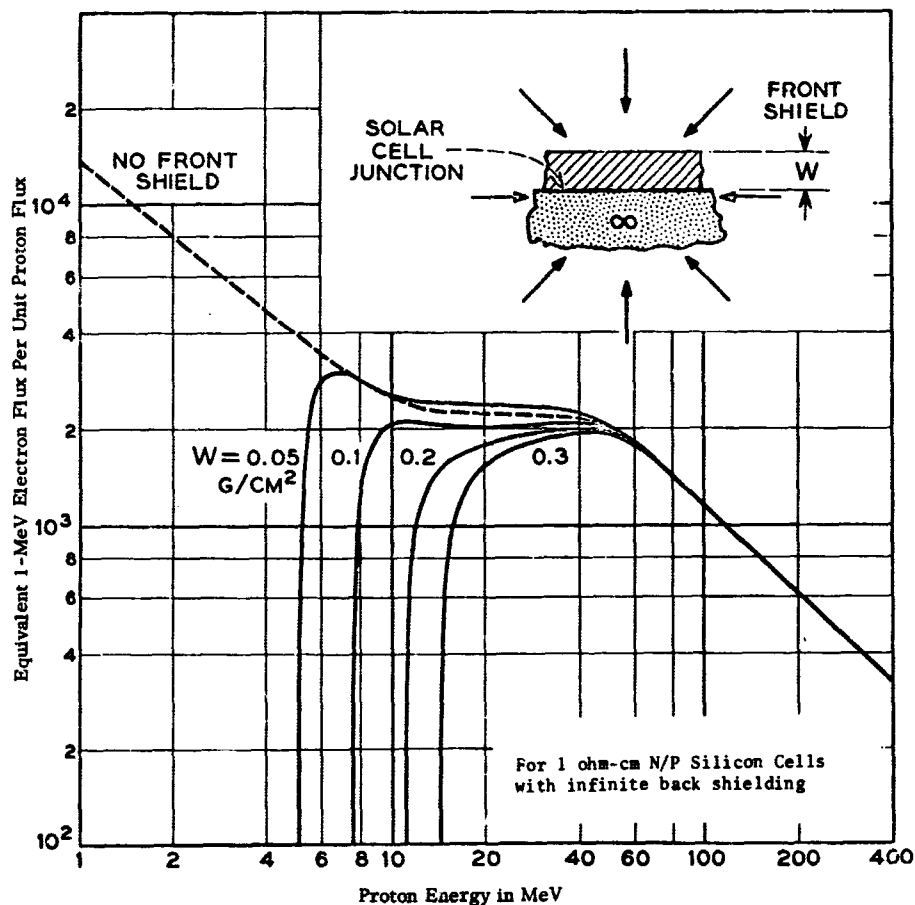


Figure VI-2. Equivalent Damage for Monoenergetic Isotropic Protons on Shielded 1 ohm-cm N/P Silicon Solar Cells (From Ref. 43)

in the figure. However, a counterbalancing effect in the loss, from an incident isotropic flux, of those protons which strike the coverslide at angles such that the slant distance to the solar cell is greater than their range. In conclusion, those protons which can just penetrate the shield to the solar cell will have low energies and consequently inflict damage in a nonuniform way, as discussed briefly in section IV-E-3. Nonuniform damage creates effects that can not be simply superimposed on uniform damage effects; this is an outstanding problem in the physics of solar cell damage.

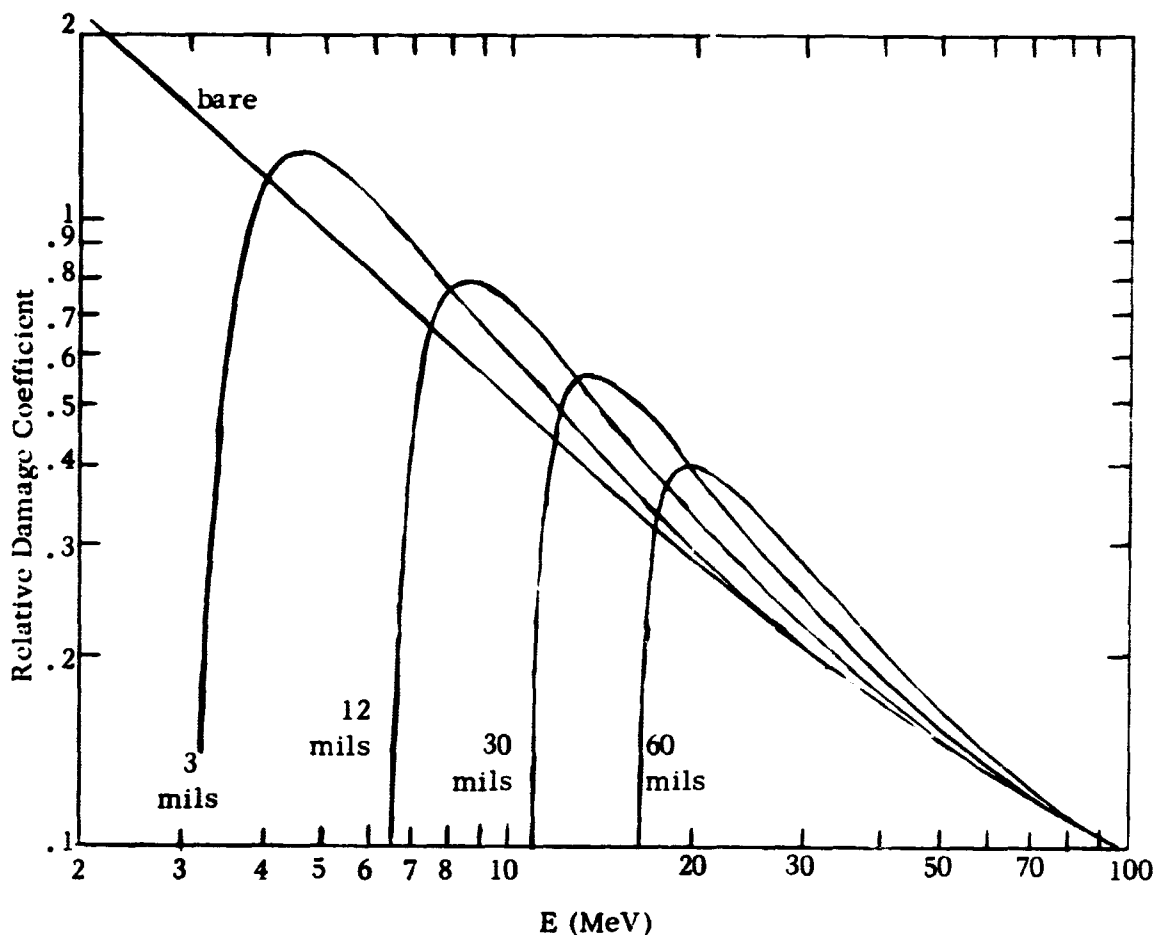


Figure VI-2. Relative Damage for Monoenergetic Isotropic Protons on 10 ohm-cm N/P Silicon Solar Cells Shielded with SiO_2

A more detailed analysis of proton shielding would be useful where thin coverslides are considered, such that the proton damage becomes of significant magnitude that it can not be treated by the above approximations. In such a case, the proton flux spectrum striking the solar cell due to a monoenergetic, unit flux incident isotropically on the coverslide must be computed. This can be obtained by differentiation of Eq. VI-2 to give

$$dE = \frac{-1}{n} \left(\frac{t}{R_o} \right) \left[E_o^n - \frac{t}{R_o \cos \theta} \right]^{1/n-1} \frac{\sin \theta d\theta}{\cos^2 \theta} \quad (VI-3)$$

In this result, all the terms are positive numbers, and the negative sign indicates that the greater the angle at which the proton strikes the coverslide, the less will be its energy after penetration.

The energy spectrum of the proton flux after penetrating the coverslide is spread out due to the spread in angle of entry. Relating these variables,

$$\Phi(E) = -\Phi_o(\theta) \frac{d\theta}{dE} \quad (VI-4)$$

where $\Phi(E)$ is the differential proton flux spectrum and $\Phi_o(\theta)$ is the differential in angle of the incident monoenergetic flux, and is simply given by $\sin \theta$ for isotropic unit flux incident on the coverslide. Combining this with the result above yields

$$\Phi(E) = \frac{R_o}{t} \left[E_c^n - \frac{t}{R_o \cos \theta} \right]^{1-1/n} \cos^2 \theta \quad (VI-5)$$

and, since

$$\cos \theta = \frac{t}{R_o (E_o^n - E^n)} \quad (VI-6)$$

we can simplify this expression to

$$\Phi(E) = \frac{nt E^{n-1}}{R_o (E_o^n - E^n)^2} \quad (VI-7)$$

A straight forward extension of this result will yield the space proton spectrum as modified by the coverslide.

C. ELECTRON SHIELDING

In contrast with the straight-line path of a proton, the path of an electron through matter will have sharp turns due to Rutherford scattering (elastic collisions with nuclei, transferring large amounts of momentum). Secondary electrons and bremsstrahlung radiation are also produced. These effects will cause a spread, both in energy and angle distribution, of electrons penetrating a coverslide. For a monoenergetic, normally-incident beam, the number of electrons penetrating the shield continually decreases as the shield thickness increases. As a result, there is no clear-cut electron range analogous to the proton range.

The effective range, R , for electrons of a given energy is that thickness of material for which the linear decrease in the beam intensity extrapolates to zero. At this range, however, it is found that the beam does not vanish, but a small number of electrons "straggle" to greater distances. The effective range, R , shown in figure VI-3, therefore allows only an estimate of the low-energy cutoff for electrons in space, penetrating a given coverslide, to cause significant damage to a solar cell.

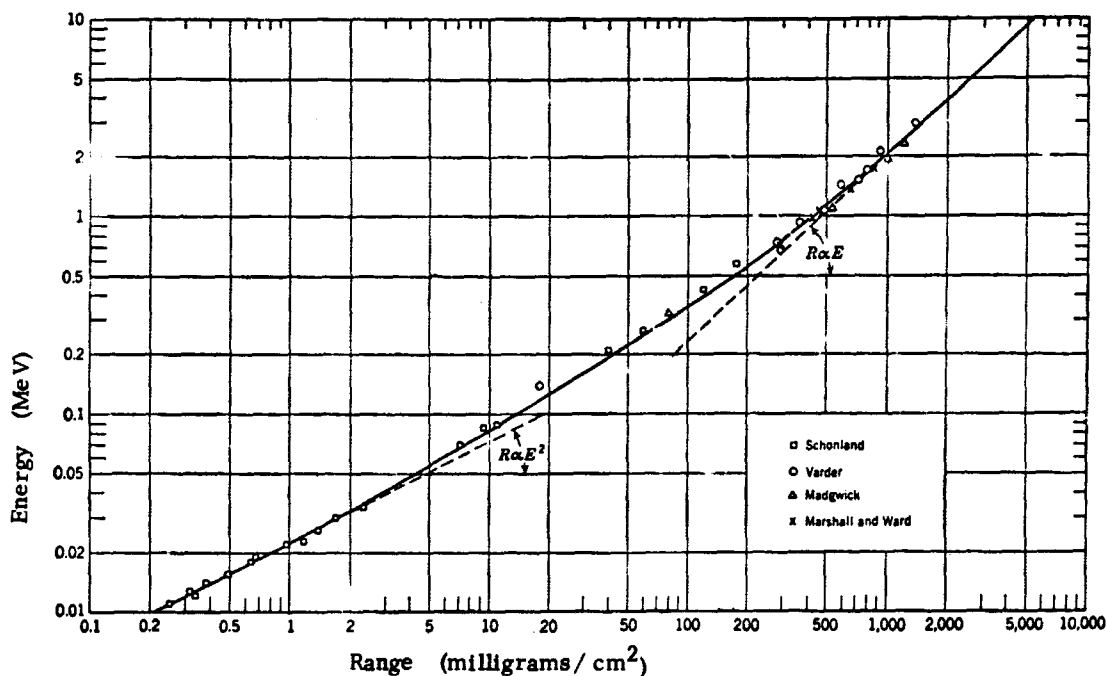


Figure VI-3. Range-energy relationship for monoenergetic electrons normally incident on an aluminum-equivalent shield. (Ref. 100)

A basis for predicting electron shielding effects on solar cells is derived from experimental data of Rosenzweig, Gummel and Smits (ref 251), as reproduced in figure VI-4. This figure is developed by an extrapolation of measurements of damage to one ohm-cm n/p silicon cells by electrons up to 3 Me V at several different angles of incidence and thicknesses of shielding.

The calculation of solar cell diffusion length is given by

$$\left(\frac{1}{L^2} - \frac{1}{L_o^2} \right) = \int_{E_c}^{\infty} \theta(E) K_L(E) \varphi_e(E) dE \quad (VI-8)$$

where θ , K_L and the spectral flux $\varphi_e(E)$ are all functions of electron energy. The evaluation of this integral must be done graphically or by a tabular calculation.

Using the energy spectrum of electrons of initial energy E after penetrating a distance τ , a reduction can be computed for the damage caused. This shield factor, θ , is defined by

$$\theta(\tau, E) = \frac{\sum n(E_1, \tau) K_L(E_1)}{K_L(E)} \quad (VI-9)$$

where $K_L(E_1)$ is the damage coefficient for electrons of energy E_1 , as given in section IV. Monte Carlo calculations provide $n(E_1, \tau)$, the fraction of the incident electron flux which falls in the interval selected about the energy E_1 , after penetration to the depth τ . Then the damage, i.e., the change in minority carrier diffusion length L^2 , is reduced by a factor $\theta(\tau, E)$ as a result of coverslide shielding.

Results of a Monte Carlo code devised by Berger and Seltzer (27) combine with the Denney and Downing (ref 287) experimental values for K_L in 10 ohm-cm p-type silicon to yield the values of $K_L(E) \theta(\tau, E)$ graphed in figure VI-5. The angular distribution

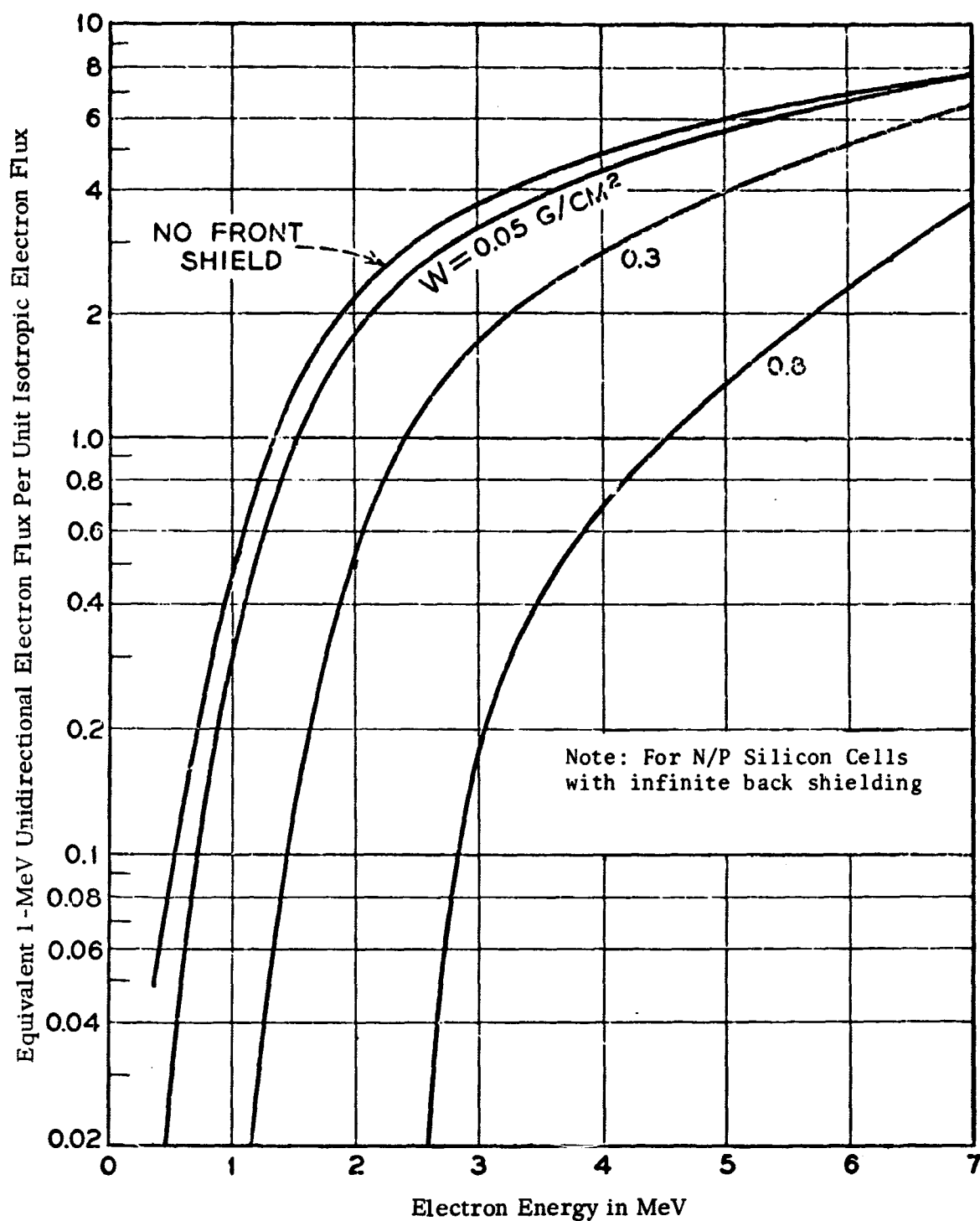


Figure VI-4. Equivalent Damage for Monoenergetic Isotropic Electrons on Shielded N/P Silicon Solar Cells (From Ref. 40)

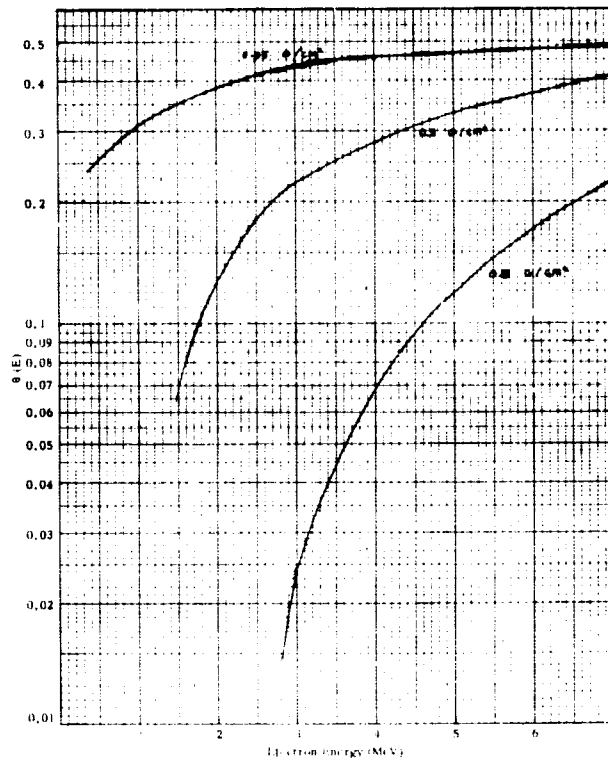


Figure VI-5. The Shield Factor θ for Decrease in Effective Damage Coefficient (applicable for monoenergetic electrons of energy E incident isotropically on solar cells, with infinite backshielding and a cover-slide of various areal densities).

assumed for the incident electrons is isotropic over a hemisphere. For an isotropic flux, and a solar cell with thick back-shielding, these results would be multiplied by 0.5. Over most of the range of the electron, a good approximation is

$$\theta(\tau, E) = \exp(-10\tau/E^{1.5}) \quad (\text{VI-10})$$

where τ is in grams/cm^2 of cover-slide, and E is the incident electron energy in MeV. As seen in figure VI-5, this exponential form holds true for values of τ up to about half the range of the electron. $\theta(\tau, E)$ must go to zero at the range of the electron; indeed it must vanish at a depth where the electrons of energy E all have degraded to energies below the threshold for atomic displacement (about 145 kev). The evaluation of the

effect of a shield which is slightly less than the range of the electron incident on it must await more precise data on the energy and number distribution of the penetrating electrons and on the behavior of $K_L(E)$ near the displacement threshold.

Similar results for p/n cells have not been generated. Because $K_L(E)$ does not have such a rapid variation with energy for these cells, the expected magnitude of $\theta(\tau, E)$ would not be as small.

D. OPTIMIZATION OF SHIELD THICKNESS

Since a thin shield results in large exposure and large degradation of solar cell power, requiring a large area array for a given power at the end of a mission, and a thick shield increases the weight per unit area, there is usually an optimum shield thickness which minimizes the power system weight for a given mission. A method of optimizing the shielding has been reported by Weiner (ref 304) and applied to the Advance Orbiting Solar Observatory. If the solar cell shielding material darkens appreciably under particle radiation, then the optimum shielding thickness shifts to a lower value.

There is evidence from flight test results on satellite 1963 38C that the solar cell current on N/P cells actually degraded faster under a 0.125-in. fused silica shield than under 0.020 in. of fused silica or 0.006 in. of glass. This effect is attributed to discoloration of the thick coverslide (ref 109). The flight test data suggested an optimum shield thickness between 0.020 in. and 0.125 in. of fused silica for maximum power per unit area after 500 days in this polar orbit at an altitude of 1070 to 1120 kilometers.

For concentrating solar cell arrays using V-shaped ridges to reflect light onto the cells, the shielding effect of the metal ridges in an isotropic flux can double the life of bare solar cells (ref 162).

A compilation of computer programs to aid in shield design and optimization is presented in table VI-1.

**TABLE VI-1. A COMPILATION OF COMPUTER PROGRAMS FOR SOLAR CELL
RADIATION EFFECTS AND SHIELD DESIGN CALCULATION**

Code, Machine	Originator	Reference	Problem	Availability
INVAR IBM 7090	C. McIlwain U. Cal, San Diego	J. Geophys Res. 66, 3681 (1961)	Calculate (B, L) From Space Coordinates	Nat. Space Sci. Ctr, Goddard
ORBITAL FLUX (MP1) IBM 7094, IBM 360	E. Stassinopoulos Goddard	NASA SP 3024	24 hr. protons and electrons in orbit	Author
CARSTEP IBM 7094	Northrop	NSL 63-63R-1	Protons, electrons in orbit, lunar trajectory	RSIC (Oak Ridge, Tenn.)
TAEC, SPARES, IBM 7094 CDC 1604	Boeing	WL-TDR-64-71, D2-90864-1,	Protons, electrons in orbit	RSIC, Author
LMFC IBM 7094	Lockheed Nuclear	ER 6643	Protons, electrons in orbit	Author
DECAY IBM 6094	E. Stassinopoulos Goddard	NASA TN D-2874	Artificial electron decay factors	Part of MP1
LPPC IBM 7094	Lockheed Nuclear	ER 6643	Proton dose, spectra through slabs	Author
PROP IBM 7094 CDC 1604	Boeing	WL-TDR-64-71	Proton dose, spectra through slabs	RSIC
(NONE) IBM 7094	M. Berger Nat. Bus. Stand.	NASA SP-71, NASA SP-3008	Electrons through slabs (Monte Carlo)	Author
CHARGE	W. Yucker, J. Lilley Douglas	Douglas Paper 3415, N65-24738	Electrons, protons through slabs	Author
ADVENT IBM 1620	Gen. Electric	PIR 9742-026 PIR 9742-022	Damage integral	Author
(NONE) IBM 7090	F. Roth, L. Kossa Martin	NASA SP-71, TID 7652	Protons in orbit, shielded damage integral	Author
(NONE) IBM 7094	E. Kuhn, F. Schwamb, W. T. Payne Republic	NASA SP-71,	Flare proton shielding by geo- magnetic field	Author
COMPOSER Philco 2000	W. T. Picciano Philco-Ford	-	Proton, electron shielding I-V array	Author

VII. RADIATION EFFECTS ON COVERSLIDES, ADHESIVES AND OPTICAL FILTERS

A. INTRODUCTION

The typical silicon solar cell assembly is shown in figure VII-1. The coverslide is usually coated on the outer surface with an anti-reflection coating to increase the amount of light transmitted to the cell, and is coated on the inner surface with a selectively reflecting filter. The doubly coated coverslide is bonded to the surface of the solar cell with a thin layer of transparent adhesive. The inner reflective coating reflects the ultraviolet which would not photo-activate the solar cell and would heat it excessively and decrease its efficiency. It also protects the adhesive against darkening by ultraviolet degradation. The inner reflective coating may also be designed to reflect the infrared beyond 1.1 microns which does not photo-activate the cell.

Reviews of the radiation damage to coverslides, adhesives and filters have been prepared by Cambell (refs. 53, 56).

B. DARKENING OF COVERSLIDES

Haynes and Miller (ref 129) have reported an extensive study on coverslide materials. The decrease in transmittance of coverslides under electron and proton radiation is greatest in the ultraviolet and visible region of the spectrum. Figure VII-2 shows an example of the degradation of 0.006 in. Corning 0211 microsheet glass under 10^{16} one-MeV electrons/cm² (ref. 53). Data by Campbell on the transmission loss of various materials at three wavelengths is given in table VII-1. A summary of the "wide-band" transmittance loss is given in table VII-2. These measurements were made with a silicon solar cell at room temperature illuminated with a 2800° K tungsten light at an intensity of 100 mw/cm². "Wide-band transmission" was calculated as the ratio of short circuit current of the cell when covered with the sample glass to that of the bare cell.

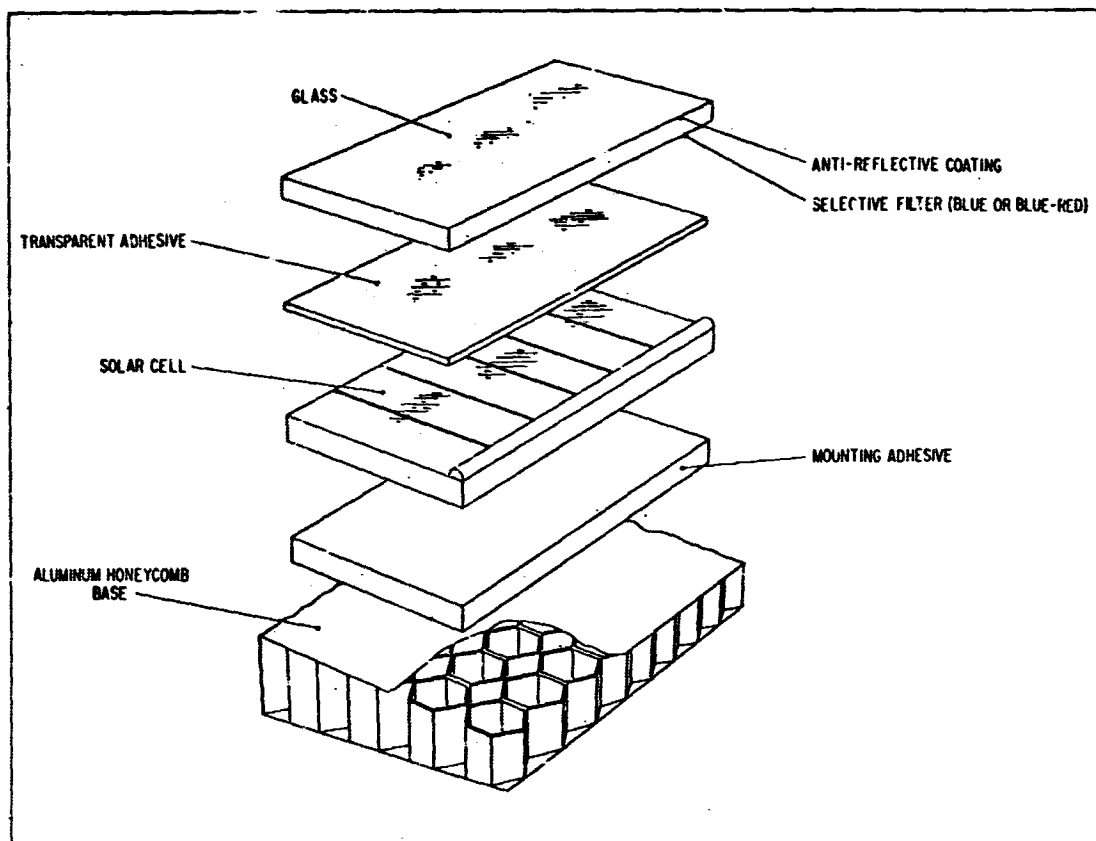


Figure VII-1. Solar Panel Construction

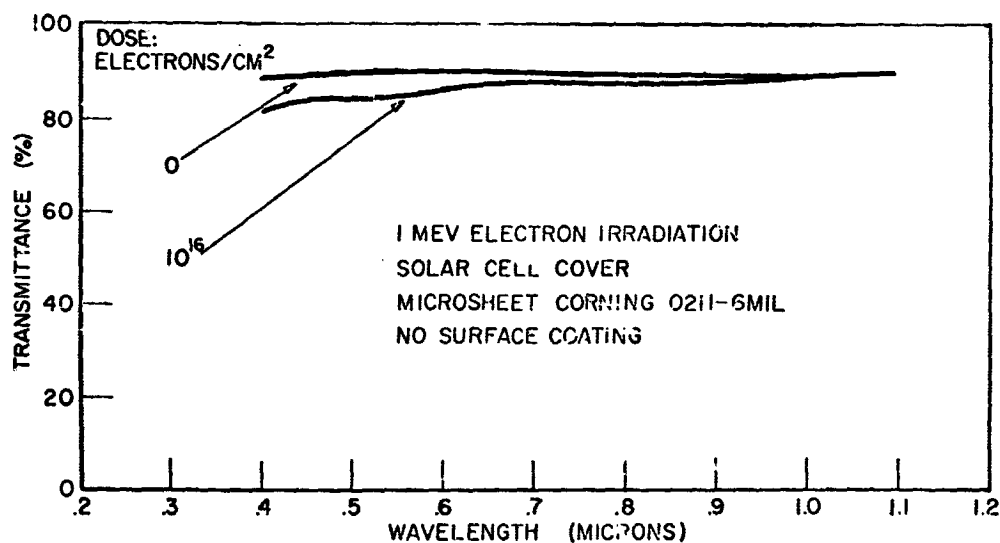


Figure VII-2. Effect of 10^{16} one-MeV Electrons Per cm² Irradiation on Transmittance of Solar Cell Cover (Microsheet Corning 0211-6 mil) without Surface Coating

TABLE VII-1. EFFECTS OF ELECTRONS AND PROTONS ON SPECTRAL TRANSMITTANCE OF SOLAR CELL COVER MATERIALS (REF. 53)

Material Description	% Change in Transmittance at Wavelengths (microns)		
	0.5	0.6	0.7
A. 1 MeV Electrons — Total Dose of 10^{16}e/cm^2			
1. Microsheet (6 mil) Corning 0211	5.6	3.3	2.2
2. Same as (1) + A-R coating + "blue" filter	7.3	5.1	4.2
3. Same as (1) + A-R coating + "blue-red" filter	9.9	8.6	6.9
4. 3-mil microsheet + A-R coating + "blue" filter	3.7	2.1	
5. Fused silica (66 mil) Corning 7940	1.7	2.2	1.1
6. Fused silica-Corning 7940 (20 mil) + A-R coating + "blue" filter	1.1	2.2	1.1
7. Adhesive ES-10 (Spectrolab)	1.7	1.7	1.1
8. Adhesive 15-E (Furane)	24	13	12
9. Adhesive DER-332 (Dow)	8.6	9.1	4.5
10. Non-browning Lime glass (Corning 8365) density 2.7 (60 mil)		See Note	
11. Non-browning Lead glass (Corning 8362) density 3.3 (60 mil)		See Note	
12. High density Lead glass (Corning 8363) density 6.2 (60 mil)	7.1	3.5	1.2
Note: Radiation caused internal crazing in these specimens.			
B. 4.6 MeV Protons — Total Dose of $4 \times 10^{11} \text{p/cm}^2$			
1. Microsheet (6 mil) Corning 0211	3.4	1.1	1.1
2. Same as (1) + A-R coating + "blue" filter	5.2	2.1	1.1
3. Fused silica (30 mil) Corning 7940		No Change	
4. Fused silica (20 mil) + A-R coating + "blue" filter		No Change	

TABLE VII-2. EFFECTS OF ELECTRON IRRADIATION ON "WIDE-BAND" TRANSMITTANCE OF VARIOUS TRANSPARENT MATERIALS

Electron Energy = 1.2 MeV
Integrated Flux = $2.7 \times 10^{15} \text{e/cm}^2$

Material, Thickness	Manufacturer	% Loss in "Wide-Band" Transmittance
Linde sapphire, 80 mil	Linde Co. , Division of Union Carbide Corp.	0
Corning 7940, 125 mil (fused silica)	Corning Glass Works	0
Fused Quartz 62.5 mil (optical grade)	Engelhard Inc. (Amersil Quartz Div.)	1.8
GE 104 (fused quartz) 94 mil	General Electric Co.	0.8
GE 105 (fused quartz) 94 mil	General Electric Co.	30.0
Natural crystal quartz 292 mil	—	26.8
Corning 8362, 62.5 mil (non-browning lead glass)	Corning Glass Works	2.4
Corning 8363, 62.5 mil (High-density lead glass)	Corning Glass Works	0
Corning 8365, 62.5 mil (non-browning lead glass)	Corning Glass Works	0
Corning 0211, 26 mil (micro-sheet)	Corning Glass Works	7.6
Solex, 250 mil	Pittsburgh Plate Glass Co.	2.7
Soda-lime plate glass, 250 mil	—	26.0
Feurex, 250 (heat-resistant borosilicate glass)	Blue Ridge Glass Corp.	25.2

The materials which are most resistant to "wide-band transmission" loss are synthetic fused sapphire, synthetic fused silica and some of the high density radiation shielding glasses.

C. FILTERS

Data on ultraviolet degradation of filters have been reported by Mauri (ref. 192). Table VII-3 summarizes the data on transmittance loss of "blue" and "blue-red" filters. The "blue-red" filters suffer the greater degradation. Tests by Reynard (ref. 239) indicate that a blue filter is effective in reducing the transmission loss due to darkening of an epoxy adhesive by a factor of five.

TABLE VII-3. (REF. 11) EFFECTS OF ULTRAVIOLET RADIATION ON TRANSMITTANCE OF REFLECTIVE FILTERS DEPOSITED ON CORNING 7940 FUSED SILICA

Filter	Ultraviolet Exposure, sun-hours	Ave. Initial Transmittance % (500-1100 m μ)	Ave. Final Transmittance % (500-1100 m μ)	Ave. Change in Transmittance % (500-1100 m μ)
none	703	93.3	92.0	-1.4
"blue-red"	590	93.3	87.3	-6.4
"blue"	735	93.0	91.0	-2.2

D. ADHESIVES

Coverslides are bonded to solar cells for good optical and thermal contact. Normally a clear silicone RTV rubber is used, which is less susceptible to ultraviolet and charged particle darkening than epoxy. General Electric RTV-602 or 615 is typically used, without a primer, and has sufficient bonding strength although the coverslide can be removed for replacement of broken or chipped units. Dow Corning makes an especially pure version of Sylgard 182 which is resistant to darkening but has a low bond strength and usually requires a primer if the coverslide is to be thicker than 10 mils. When a primer is used, the bond strength increases so that the coverslide is difficult to remove for repair work, (ref. 276) and the primer may exhibit darkening.

The degradation of silicone adhesives under ultraviolet is shown in the following table.

TABLE VII-4. (REF. 198) EFFECTS OF ULTRAVIOLET RADIATION ON SILICONE ADHESIVES WITH AND WITHOUT THE USE OF PRIMERS

Adhesive	Primer	Ave. % change in Transmittance (500-900 mμ) after indicated sun-hours of exposure	
		500	2000
XR63488 (Sylgard 182)	no	0	0
XR63488 (Sylgard 182)	yes	1.1	1.2
RTV - 602	no	1.1	0.6
RTV - 602	yes	0.6	2.9

E. EXPERIMENTS ON COMPOSITE ASSEMBLIES

Reynard (ref. 242) irradiated 10 ohm-cm n/p silicon cells with shields and filters as shown in figure VII-3. The adhesive was RTV-602 silicone. The tests showed considerable degradation of power using 0.026 in. 0211 microsheet as compared to 0.026 in. 7940 fused silica.

Campbell and Lambert (ref. 57) showed that the radiation darkening of 0.006 in. of microsheet with a "blue" reflective filter and Furane 15 E epoxy adhesive results in a decrease in spectral response of p/n cells as shown in figure VII-4.

Haynes (ref. 130) concluded from experiments by Campbell that 7940 fused silica is preferable to microsheet glass and that Sylgard 182 adhesive was most suitable for the S-3C Satellite Solar Cell Experiment.

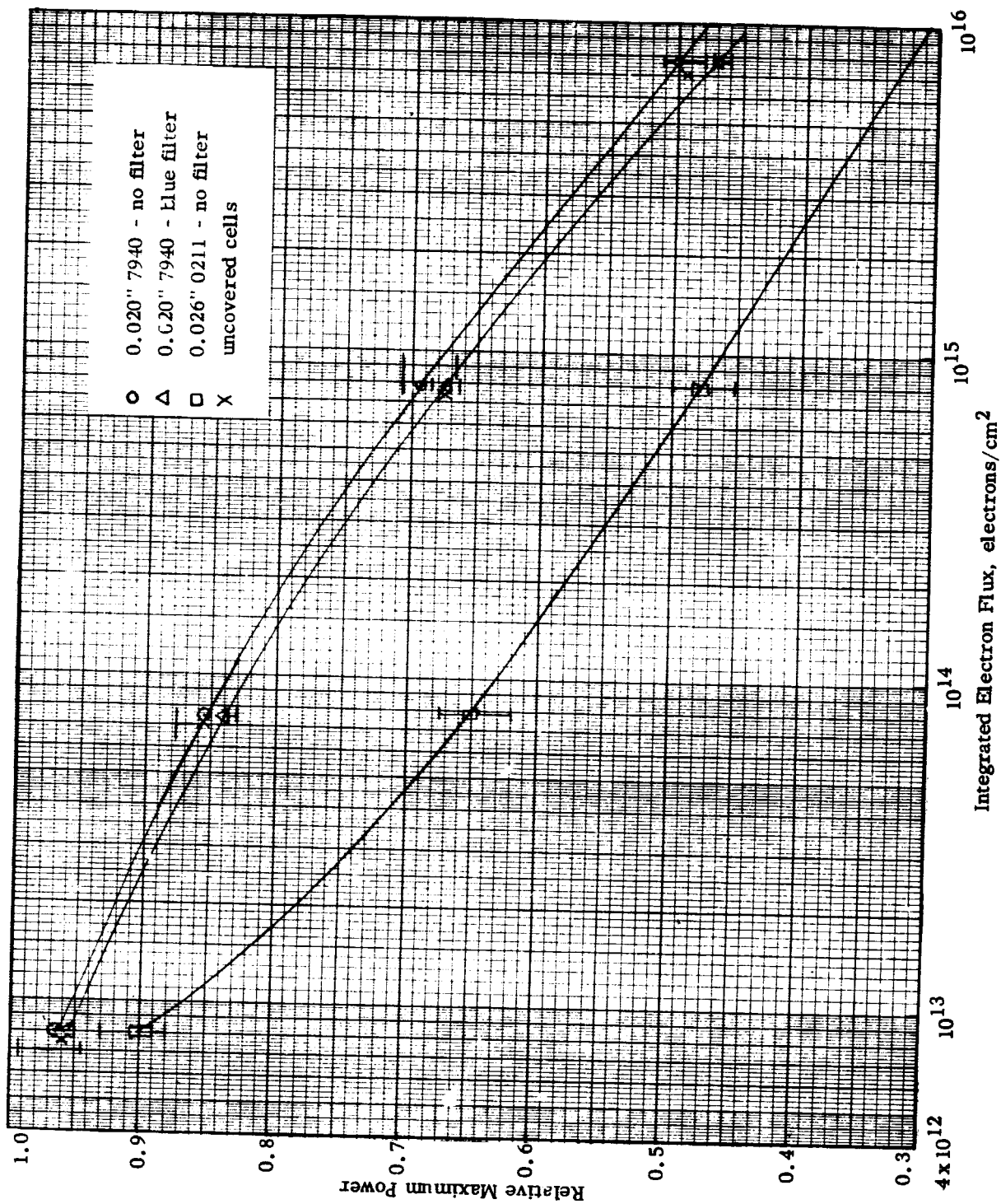


Figure VII-3. Relative Maximum Power vs. Integrated Flux, 2.0 MeV Electrons, for Hoffman 10 ohm-cm n/p Silicon Solar Cells

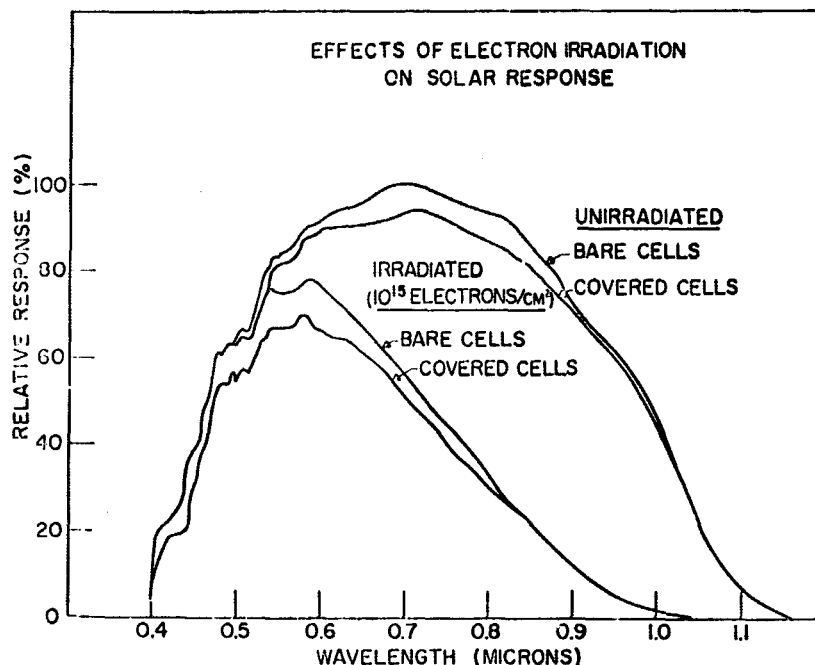


Figure VII-4. Effects of Electron Irradiation on Solar Response

F. THIN COATINGS

The thinnest separate coverslide that can be handled conveniently without breakage is about 0.006 in. In order to avoid the expense and complexity of separate coverslides with optical coatings and filters or to obtain thinner coverslides, there is research underway on thin integral coatings. Iles (ref. 146) has reported tests of integral fused-glass coatings about 0.001 in. thick which showed no additional damage to cell performance under 2×10^{15} one-MeV electrons/cm².

Marks (ref. 188) has tested organometallic coatings about 0.002 in. thick which can be sprayed, brushed, or rolled onto solar cells. The coatings show some damage under ultraviolet light but very little under electrons. The coated cells under ultraviolet and electron irradiation showed about the same degradation of short circuit current (11%) as for cells protected by 0.020 in. fused silica with blue filters. Further development of thin coatings could result in cost savings in production of solar power systems.

G. CONCLUSIONS

- 1. Sapphire and synthetic fused silica are the most resistant glasses under ultraviolet and electron degradation.**
- 2. Silicone adhesives are more stable than epoxies under ultraviolet light.**
- 3. The broad-band transmittance of reflective filters is decreased slightly by ultraviolet and electron irradiation.**
- 4. Thin glass coatings show promise for future applications.**

VIII. RADIATION EFFECTS ON POWER CONVERSION AND REGULATION EQUIPMENT

A. DESIGN REQUIREMENTS

Since power system components other than solar cells and blocking diodes are usually located inside the spacecraft, they are not directly affected by meteoroid effects. However, certain components, particularly transistors, may be insufficiently shielded against penetrating radiation. Therefore, careful selection of components and/or provision of radiation shielding may be required.

The purposes served by the power conversion and regulation equipment may include:

1. Matching the solar array output voltage and current to the variable power demand and battery charging requirements, allowing for periods of eclipse, misorientation of the solar cell arrays, gradual degradation of array performance, and changes in operating temperature.
2. Controlling the operating point of the solar cell array to deliver the maximum power available near the end of operational life.
3. Providing the regulated dc or ac outputs required by the various loads.

B. PROBLEM AREAS

An important problem area is that of radiation effects on power transistors, which are comparable in radiation sensitivity to solar cells, and diodes which are much less sensitive. Non-semiconductor components such as resistors, capacitors, and batteries are not appreciably affected by the space radiation environment.

C. DEGRADATION OF TRANSISTORS

Other than solar cells, the most radiation sensitive semiconductor devices are junction transistors. Only silicon types will be discussed here, since these predominate

in the space industry. The emitter-collector current in passing through the transistor base region in the form of a minority carrier current, encounters radiation-induced recombination centers. This decreases the observed gain of the device.

Specifically, a radiation-induced change in lifetime τ of minority carriers in the bulk material of the transistor base results in a change in the common emitter dc current gain β (or H_{FE} in hybrid terminology). The two changes are related (ref. 45) when the radiation damage is not excessive by the expression

$$\Delta \left[\frac{1}{\beta} \right] = t \Delta \left[\frac{1}{\tau} \right] = K_{\beta} \Phi \quad (\text{VIII-1})$$

where t is the base transit time for minority carriers and K_{β} is the gain damage coefficient per unit fluence Φ . The base transit time is often simply related to construction parameters. The relation is

$$t = W^2/2D \text{ for a uniform base transistor} \quad (\text{VIII-2a})$$

$$t = W^2/4D \text{ for a linear graded base transistor} \quad (\text{VIII-2b})$$

where W is the base width in centimeters and D is the diffusion constant for the minority carriers in the base material.

In addition, radiation can induce states on the surface of the transistor which also affect the recombination of minority carriers, and hence the gain β . The production of these states is dependent on the amount of bias on the transistor being irradiated, and also has a tendency to saturate. A modification of eq. (8.1a) to account for this effect is (ref. 51)

$$\begin{aligned} \Delta (1/\beta) &= K_{\beta} \Phi + K_s \Phi^n \quad (\Phi < \Phi_0) \\ \Delta (1/\beta) &= K_{\beta} \Phi + K_s \Phi_0 \quad (\Phi > \Phi_0) \end{aligned} \quad (\text{VIII-1b})$$

where K_g is a surface damage constant dependent on device and operating conditions. Since generalized expressions for K_g , Φ_0 , and n are not presently available, they must be determined experimentally for the case on hand. Generally speaking, surface effects saturate at doses under 10^7 rad and tend to disappear (anneal) when the transistor has no bias applied (ref. 204).

The gain damage coefficient is related to the diffusion length damage coefficient by

$$K_\beta = tDK_L \quad (\text{VIII-3})$$

As an example, consider a Fairchild 2N1613 transistor. This is an n-p-n silicon transistor. Measurements of gain decreases with 2 MeV electrons give a value of 4×10^{-17} for K_β (ref. 45). An independent measure of t is 1.7 nanoseconds (ref. 112). Using the value of $38 \text{ cm}^2/\text{sec}$ for D , we obtain

$$K_L = 4 \times 10^{-17} / 1.7 \times 10^{-9} \times 38 = 6.2 \times 10^{-10} \quad (\text{VIII-4})$$

which agrees with a point for p-type silicon of resistivity of about 2 ohm-centimeters, as plotted in figure IV-2.

Since the base transit time varies inversely with the alpha cutoff frequency, use of a transistor with a high cutoff frequency would decrease the unit's radiation sensitivity. Power handling considerations of available transistors may, however, set an upper limit of the alpha cutoff frequency. Table VIII-I lists some of the parameters of available silicon power transistors.

An obvious approach to protection of transistors from radiation is to locate them inside the spacecraft and take advantage of the shell and payload as shielding, although this shielding may not be sufficient. For example in Telstar I, the power regulator was mounted on a board acting as a heat sink, located inside the outer shell, and additional shielding of 0.125 inch thick aluminum was placed around all transistors (ref. 9). Special shields are particularly useful when a power handling transistor

**TABLE VIII-1. AVAILABLE SILICON HIGH FREQUENCY POWER TRANSISTORS
(AFTER REF. 92)**

MFR	Type	Power	Gain β	Cutoff Frequency f
BEN	2N3016	5W	80	300 mc
SSPI	2N2849	5W	100	80 mc
M-H	MHT2001	5W	1,000	50 mc
TI	TIK3036	10W	30	20 mc
BEN	2N3017	10W	30	300 mc
TI	2N2986	15W	20	10 mc
MOT	2N3297	25W	2.5	200 mc
MOT	2N3026	25W	50	100 mc
RCA	2N3231	25W	20,000	40 mc
BEN	2N3018	25W	40	300 mc
TI	2N2151	30W	40	10 mc
FAIR	2N2893	30W	40	20 mc
M-H	2N2880	30W	40	50 mc
M-H	MHT6016	40W	100	30 mc
M-H	2N2814	40W	40	30 mc
TI	TIK211	40W	20	50 mc
TI	2N1725	50W	50	10 mc
TI	2N1722A	50W	20	10 mc
RCA	2N3263	80W	25	20 mc
M-H	MHT8302	100W	10	25 mc
M-H	MHT8003	100W	40	40 mc
WEST	130-08	120W	15	1 mc
PSI	2N1902	125W	25	—
TI	2N1937	150W	10	18 mc

cannot be placed inside the spacecraft because of heat dissipation requirements. Thus, on Relay I, the power regulating transistors were mounted on the spacecraft mounting collar to radiate heat directly into space, and a shielding cap of stainless steel was bonded to each transistor. An alternative approach is to make the system relatively insensitive to decrease in transistor gain. Design methods, such as the use of feedback networks, are available for this purpose.

D. DEGRADATION OF DIODES

It is generally observed that semiconductor diodes are about 2 orders of magnitude less sensitive to radiation than are transistors (ref. 140). The diode equation can be written (ref. 284) as

$$I = qAn (D/\tau)^{1/2} [\exp (qV/kT) - 1] \quad (\text{VIII-5})$$

where q is the electron charge, A is the junction area, D is the diffusion constant of electrons in the base material, n is the minority-carrier density, τ is the minority-carrier lifetime in the base material, V is the applied voltage and kT the temperature in electron volts. Radiation affects the minority carrier lifetime τ , since τ equals L^2 divided by the diffusion coefficient D . Thus, combination of equations II-1, IV-4, and VIII-5 yields an approximate formula

$$I = qAn D \left[\frac{1}{L_o^2} + K_L \Phi \right] [\exp (qV/kT) - 1] \quad (\text{VIII-6})$$

for the current I through a diode exposed to a fluence corresponding to the damage integral $K_L \Phi$.

E. DEGRADATION OF MICROCIRCUITS AND MOS DEVICES

The effects of radiation on the performance of microcircuits can frequently be predicted in terms of the individual components in the microcircuit. Where transistors

are present, the most significant effect on the circuit is via the damage mechanisms discussed in Section VIII-C above. Transistors gain and base transit time are usually the significant factors. Passive microcircuits, without transistors, are less sensitive to radiation, their sensitivity depending first on the semiconductors (diodes) present, and then on the remaining parts to a lesser degree. Microcircuit damage can generally be related to the mechanisms previously discussed, primarily through the decrease in minority carrier lifetime.

With the rapid development in microcircuit design and the complex nature of the radiation effects studies which have been reported, it is not possible to generalize experimental results here. In one test, (ref. 20) 80 microcircuits of 16 types were irradiated with 3 MeV electrons. Failure occurred after a fluence of 7×10^{14} to 2×10^{16} e/cm². This indicates that similar microcircuits would be about as sensitive to radiation as solar cells. Their radiation damage can be reduced greatly by a design where they are provided with a reasonable amount of shielding by the spacecraft skin and internal components.

The effects of radiation on metal oxide semiconductor devices are also difficult to correlate. Here, ionization and surface effects are more significant than the bulk effects discussed above, and there is as a result no energy threshold. This suggests that thin shielding is not very effective for these devices; the reduction of electron energy in penetrating a thin shield does not significantly reduce the observed damage (ref. 142). Prediction of radiation effects is best accomplished by radiation tests of MOS devices from the same lot as the units for flight.

F. CIRCUIT HARDENING

Since electronic circuit components such as resistors, capacitors and insulators are orders of magnitude less sensitive to irradiation than semiconductor devices, it is reasonable to assume that the maximum radiation level at which a circuit will operate satisfactorily is determined by the degradation of its semiconductor components.

Therefore, useful prediction of electronic system performance can be made based upon expected performance of such components and knowledge of the behavior of the system as a function of component changes.

Rogers (ref. 245) has described both analytical and experimental methods for evaluating the effects of radiation-induced component changes on electronic circuits. The experimental technique consists of introducing groups of pre-irradiated transistors into circuits and then measuring circuit performance. Repetitions of this procedure using groups of transistors which have been subjected to progressively higher radiation levels provides for identifying the "worst case" failure level. It is particularly useful for screening circuits or subsystems to identify areas most sensitive to irradiation.

In the analytical approach to circuit evaluation, "worst case" transistor parameters, determined from prior testing of representative samples or the devices should be used to simplify the analysis. Design criteria based upon "worst case" component performance have been found reasonable for spacecraft systems (refs. 8, 217, 245).

The combination of circuit design techniques and availability of semiconductor devices with increased resistance to radiation damage, provides established means for obtaining circuits that are little affected by the radiation environment of space.

IX. THE EFFECT OF METEOROIDS ON SOLAR CELL ARRAYS

(This Section was prepared by Robert G. Lyle.)

Particle debris in space presents a hazard to solar cell arrays because impingements by these particles may result in erosion, penetration and/or puncture.

A. THE METEOROID ENVIRONMENT

Meteoroid is a term which applies to any of a vast population of particulate matter travelling in space outside the atmospheres of the sun, planets and moons. Frequently a distinction is made between meteoroids and micrometeoroids, the latter being microscopic particles, i.e., with mass less than a microgram (ref. 72). Most meteoroids (90 percent or more) are thought to be porous, fragile, low density debris from comets, with the remainder attributed to debris from collisions among asteroids. The particles emanating from these collisions are hard, dense, and take up solar orbits in the ecliptic plane; meteoroids associated with comets have velocity and direction related to their common orbits. The debris is distributed throughout interplanetary space by means of dispersive forces including gravitational attraction of the larger bodies in the solar system, solar radiation pressure, and interactions with solar corpuscular radiation. Meteoroids which intercept Earth's atmosphere, if relatively large and dense, experience a burning passage as meteors. Others which have a large surface area to mass ratio can pass through the atmosphere without significant ablation or physical changes. Meteoroids which survive passage through Earth's atmosphere and impact the surface are known as meteorites.

The present understanding of the meteoroid environment stems from studies of:

- (1) The solar Fraunhofer-corona and zodiacal light, due to reflection and refraction of sunlight by particles ranging in size from about 0.2 micron to 300 microns in diameter and located between Earth and Sun, and gegenschein, a similar light phenomenon due to particles in the solar system beyond the orbit of Earth;

- (2) ground-based observations of particles entering the upper atmosphere (meteors);
- (3) meteorites and micrometeorites recovered from many different areas on Earth and collected at high altitudes in the atmosphere; and
- (4) direct measurements obtained in recent years with particle-flux sensors on rocket probes and earth satellites, particularly in the Explorer, Mariner, and Pegasus flights.

The meteoroid population has a mass range extending from cosmic dust particles of the order of 10^{-15} gm or less to asteroids in excess of 10^{10} kg. Analyses of recovered meteorites indicate that the main-body composition of asteroidal meteoroids is iron, nickel and stone. Some are almost entirely iron and others mostly stone, with the majority being a combination of the three ingredients. Densities of these meteoroids thus range from approximately 3.5 gm/cm^3 (stone) to approximately 7.8 gm/cm^3 (iron).

Cometary debris is characterized by a conglomerate structure of mineral particles with low bulk density and high porosity except for the smaller sizes (below the minimum size that can include voids) which have bulk density appropriate to the mixtures of the heavier elements present. Spectral analysis has shown the presence of Al, Si, Fe, Ni, Ti, Ca, Mg, and Cu. On the basis of analyses of vast amounts of data from terrestrial observations, Whipple (ref. 308) has placed the average meteoroid density at 0.44 gm/cm^3 with a cautionary note that the range of densities may extend to an order of magnitude either side of the value.

Related to the afore-mentioned structures and range of bulk densities for meteoroids, are expected crushing strengths of about 10^4 dynes/cm^2 for small meteoroids and micrometeoroids increasing to the order of 10^9 dynes/cm^2 for large stoney meteoroids.

The geocentric velocities range from 11 to 73 km/sec. The lower limit corresponds to Earth's escape velocity (the minimum velocity that a particle near Earth's atmosphere can have without being pulled into Earth by gravitational attraction.) The

upper limit is the sum of Earth's orbital velocity (approximately 29.70 km/sec) and the parabolic heliocentric velocity for a particle at Earth's distance (1 a.u.) from the Sun (approximately 43 km/sec). Velocities relative to a space vehicle will, of course, depend on the velocity of the vehicle relative to Earth. An Earth-orbiting vehicle or a spacecraft in direct solar orbit near one a.u. will encounter meteoroids with an average velocity known to be close to 30 km/sec.

In the vicinity of Venus, the maximum relative velocity of meteoroids would be approximately 84 km/sec: 35 km/sec orbital velocity plus 49 km/sec for the parabolic heliocentric velocity for a particle at Venus' distance from the Sun, [McCoy (ref. 195)].

B. THE SOLID PARTICLE ENVIRONMENT IN SPACE

1. Dynamic Equilibrium of the Environment.

The most influential force experienced by debris in interplanetary space is that due to gravitational attraction of the larger bodies in the solar system (Sun, Jupiter, Earth, etc.). There are other lesser forces acting on the debris which tend to further distribute it throughout interplanetary space, the most important of which is probably solar radiation pressure.

Sunlight exerts a radiation pressure on meteoroids, creating a radial force and a drag force. The radial force acts against the solar gravitational attraction; the drag force results from a slight relativistic aberration and causes the particle to spiral gradually toward the Sun. These effects can be understood by considering the absorption of light from the Sun by the meteoroid, and its subsequent emission isotropically.

Poynting and Robertson have developed expressions (ref. 21) for the resulting meteoroid motion. Before the meteoroid on its inward spiral reaches the Sun, it would shrink from vaporization. At some point the outward radiation pressure, proportional to the area of the meteoroid, would exceed the inward gravitational pull, proportional to the mass. The meteoroid is then pushed out of the solar system by solar radiation pressure.

The critical limit to the radius of a meteoroid below which it is repelled at 1 a.u. by solar radiation pressure, is $0.6/\rho$ microns, assuming a completely absorbing particle of density ρ gms/cm³. However, the solar wind discussed in Section V adds to the radial pressure so that the critical limit becomes about $1.2/\rho$ microns (ref. 21). The solar wind also erodes meteoroids, combining with the Poynting-Robertson effect to reduce the size of particles to the critical limit.

There is a continuous input of small particles which acts against the reduction of micrometeoroid population by the sweep-out mechanisms described above. Whipple (ref. 308) has estimated that 30 tons of grit and cobwebby material is injected into the solar system each second by comets alone. Such a quantity is sufficient to account for the large number of particles indicated by the zodiacal light, satellite measurements and meteor observations. It is reasonable to consider that, in the asteroidal belt, collisional breakup and subsequent planetary gravitational perturbations of asteroidal fragments are sufficient to account for the number observed as meteors and recovered on Earth as meteorites.

It is not surprising, in view of the recognized sources of particle debris and the complex of forces acting on such particles, that the distribution of meteoroids in the solar system is not uniform. It is convenient therefore to consider the environment as divided into three regions: (1) near Earth, (2) near the Moon, and (3) the solar system external to cislunar space.

2. Meteoroids Near Earth

The distribution of meteoroids in the plane of planetary motion is not homogeneous. During a meteor "shower," the Earth intercepts the common orbit of a swarm of meteoroids. The flux at such a time may range up to 10^5 times the normal sporadic background, although this is rare, and 10 times or less is more typical. With time, these showers are thought to spread and become part of the normal background.

Comparison of solar corona, zodiacal light, and direct meteoroid measurements by satellites indicates that the density within 10^5 kilometers of Earth is much greater

than in interplanetary space. There appears to be, from numerous determinations (ref. 72), a "dust cloud" of meteoroids in orbits around Earth.

A collection by Moroz of satellite measurements indicate that the near-Earth flux of particles with mass greater than 10^{-8} grams drops exponentially from about one per square meter per second at 100 kilometers to about $10^{-5}/\text{m}^2\text{-sec}$ at 10^5 kilometers, which is the level of flux in deep space deduced by zodiacal light measurements (ref. 72).

When the frequency of puncture is of interest, the flux of meteoroids must be related to their masses and velocities, or direct observations must be used. Microphone experiments aboard Explorer VIII were analyzed by Alexander (ref. 2) to obtain the distribution in mass over the range 10^{-10} to 10^{-7} gm of the impacting meteoroids. The microphonic pulse was presumed to be proportional to momentum, and an average meteoroid velocity of 25 km/sec was assumed. The data fit the expression

$$N(m) = 10^{-17}/m^{1.7} \text{ per m}^2\text{-sec} \quad (\text{IX-1})$$

where $N(m)$ is the number of hits (flux) per $\text{m}^2\text{-sec}$, of meteoroids of masses greater than m grams. The data were multiplied by 2 to remove the effect of the Earth's shadow. If we take m equal 10^{-8} grams, we find N equal to twice $2 \times 10^{-4}/\text{m}^2\text{-sec}$. Since the orbit of Explorer VIII is from 425 to 2300 kilometers, this is in rough agreement with the collected data of Moroz (fig. IX-1).

A more useful expression for the meteoroid flux would be in terms of the flux differentiated with respect to penetration capability, rather than mass. The ability of a meteoroid to produce a hole in a sheet is a function of the meteoroid mass and velocity. Whipple (ref. 309) made early estimates of the flux, $N(T)$, of meteoroids capable of penetrating T centimeters of aluminum. His "best" estimate predicts

$$N(T) = 4.7 \times 10^{-14}/T^{4.02} \text{ per m}^2\text{-sec} \quad (\text{IX-2})$$

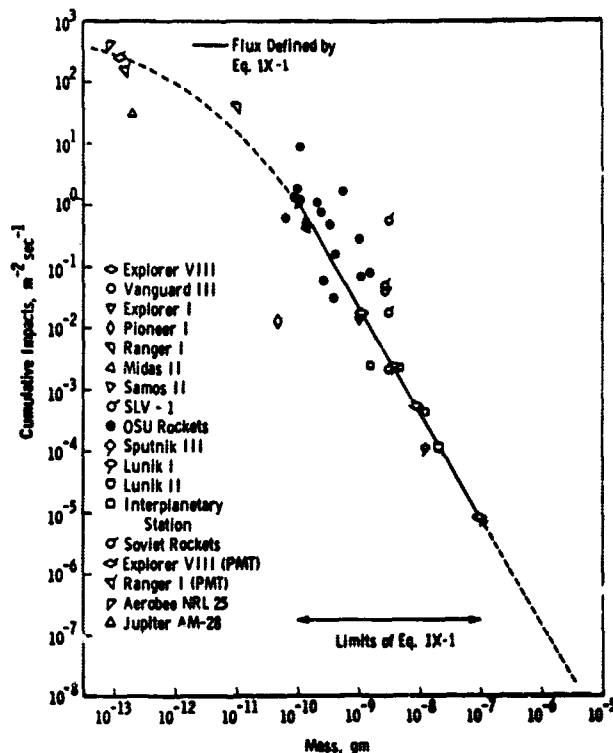


Figure IX-1. Measured Near-Earth Micrometeoroid Flux Distribution (ref. 72)

The Pegasus series of satellites, in orbits at altitudes 500-750 kilometers, have measured meteoroid fluxes penetrating aluminum sheets as follows (ref. 208): $2 \times 10^{-6}/m^2\text{-sec}$ through 0.04 mm; $2 \times 10^{-7}/m^2\text{-sec}$ through 0.2; and $3 \times 10^{-8}/m^2\text{-sec}$ through 0.4 mm.

These data can be interpolated for other thicknesses, or scaled by the fluxes presented above, for an estimate of the puncture rate for a given thickness at a given altitude. Comparison of the Pegasus results with values calculated by equation IX-2 indicates that the equation overestimates by about an order of magnitude the puncture rate for T less than 0.01 centimeters (ref. 90).

A detailed study of the meteoroid environment by Naumann (ref. 211), using data from Explorer XVI, Explorer XXIII, Pegasus I, II, and III as well as from radar and photographic techniques resulted in the estimated frequency of penetration in various thickness of aluminum (2024-T3) backed with foam as shown in figure IX-2. The curves

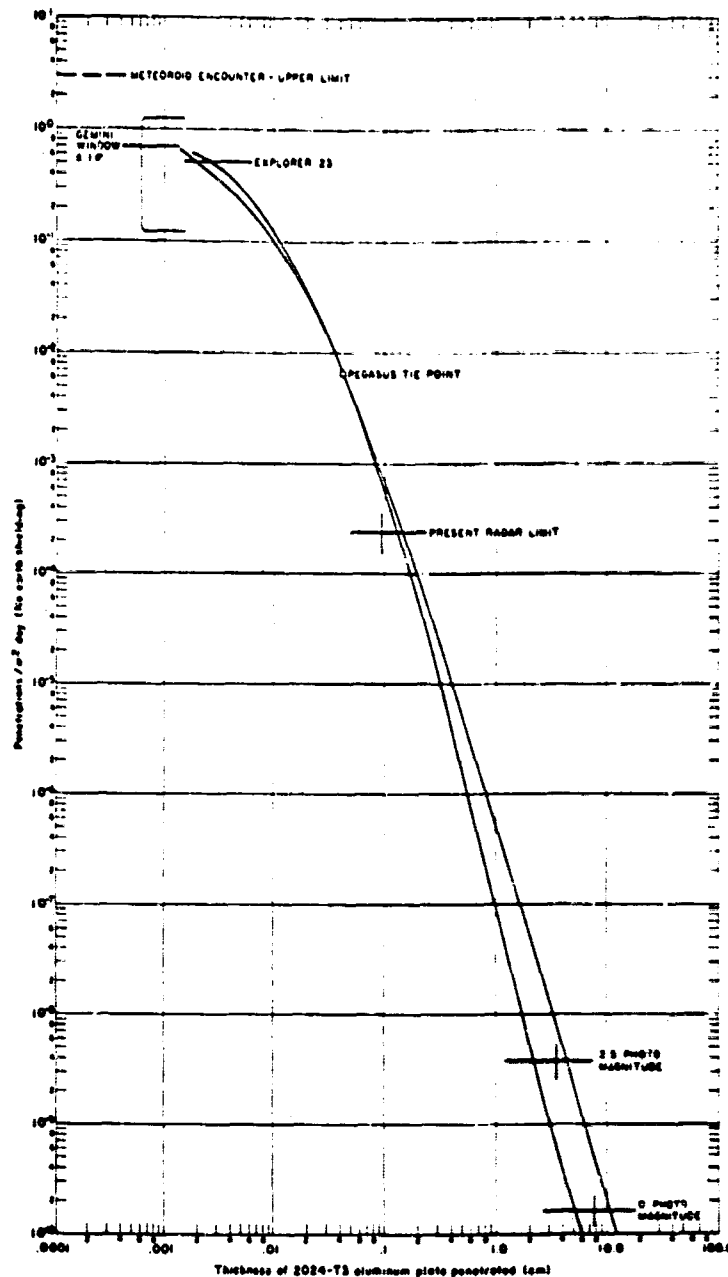


Figure IX-2. Estimated penetration frequency in various thicknesses of 2024-T3 Al. The envelope represents limits of combined uncertainties in mass dependence and form of functional fits. The indicated measurements are penetration rates estimated on the basis of the calculated characteristic mass for each measurement. (ref. 211).

may be used for other materials by establishing an equivalent thickness of 2024-T3 by laboratory impact tests. It is further shown in this study that the available data suggests an upper limit on the number of meteoroid encounters of the order of $3/\text{m}^2\text{-day}$ regardless of particle size. There is considerable disagreement between this recent evaluation based on satellite penetration data together with radar and photographic observations of meteors and the environment (mass flux relation) described by equation IX-1. An example of the order of magnitude of this discrepancy is that the puncture rate experienced by Explorer XVI 0.0025 cm pressure cells is almost four orders of magnitude lower than expected according to the earlier model.

The "dust cloud" mentioned above may be related to an additional large population of particles concentrated near Earth which do not penetrate materials as thin as 0.01 mm aluminum. However, even if such is the case, it will not contribute significantly to the meteoroid penetration hazard.

Particles which do not puncture a surface can still erode it. Thus, an estimate that is based in part on data from penetration of very thin layers, is of particular interest. For the thin-walled cans (0.0025 and 0.0050 cm thick beryllium-copper) on Explorer XVI, Hastings has matched puncture rates (ref. 128) by

$$N(T) = 1.95 \times 10^{-14} / T^{1.35} \text{ per m}^2\text{-sec} \quad (\text{IX-3})$$

for T in centimeters. Orrok (ref. 219) compared such expressions as these and concluded that a piecewise-linear relationship is suitable to relate $\log N(T)$ with $\log T$. Table IX-1 gives this relationship. One sees that the dependence on T decreases as the wall becomes thinner, but the table gives no indication of the fractional area cratered by meteoroids which penetrate less than a micron into the surface.

Since the slope falls off with smaller T, a log-normal distribution is suggested. Head (ref. 131) has analyzed puncture data from Explorers XVI and XXIII and Pegasus I and II to see if such a distribution is possible. The available hypervelocity impact information was subjected to dimensional analysis and correlation in order to relate

TABLE IX-1. METEOROID PENETRATIONS/METER²-SECOND VERSUS THICKNESS OF ALUMINUM IN CENTIMETERS

log T(cm)	log N(T)
-4 to -1.36	- 8.31 -1.35 log T
to - .24	-10.14 -2.68 log T
to + .09	-10.98 -6 log T
to + .70	-10.37 -4.02 log T

sheet thickness which a meteoroid will just perforate with target density ρ and Brinell hardness H by

$$T = 12.4C [100/\rho (H + 7)]^{1/3} \quad (\text{IX-4})$$

where C, the mass concentration or meteoroid perforation capability, is 2/3 the product of meteoroid characteristic dimension (diameter in the case of sphere) and density. In this work the assumed statistical average values for meteoroid density and velocity are 1 gm/cm³ and 30 km/sec respectively. Figure IX-3 shows that the data fit the expression

$$\log N = 14.96 -4.16 \log C -0.38 (\log C)^2 \quad (\text{IX-5})$$

over the entire range of observations. Further, it fits the data on meteors, so that N may be computed for the range of sizes from C equal 5×10^{-4} gm/cm². The Poynting-Robertson effect limits C to values over 10^{-4} gm/cm².

The relation between the flux N(T) that penetrates a thickness T, and the flux N(m) greater than mass m involves, as indicated by equation IX-4, particle density and target characteristics. Velocity is also important, and in his work Head employed the average of 30 km/sec with a nearly equal probability of travel in any direction. Although orbits are not possible for motion directly radially into or away from the sun, a solar-oriented surface could receive near-normal collisions due to meteoroid perturbations associated with Earth's gravity.

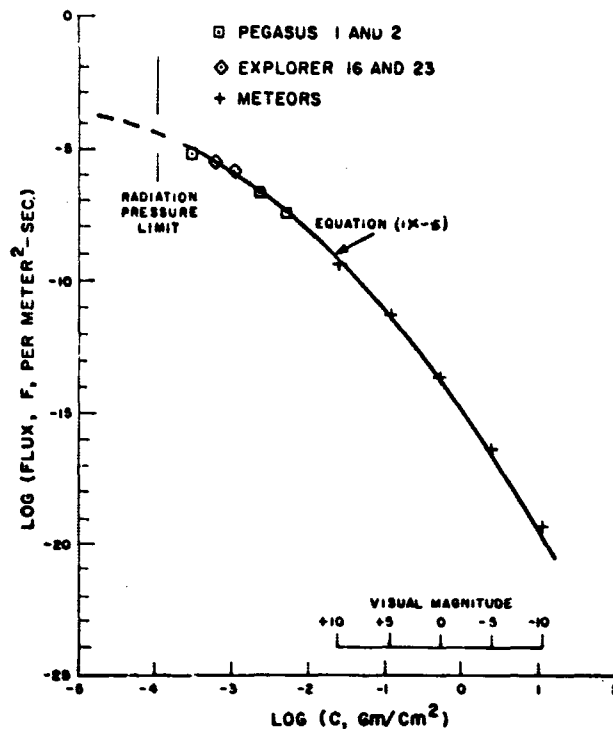


Figure IX-3. Annual Average Meteoroid Flux (Cumulative, $> c$) at one A.U. (ref. 131)

3. Meteoroids Near the Moon

Nazarova (ref. 72) reports that the meteoroid flux near the moon, as measured at a height of 355 km by Luna 10, is about $4 \times 10^{-3}/\text{m}^2\text{-sec}$. This is greater, by two orders of magnitude, than that encountered in space and suggests that there is a cloud of meteoroids around the moon, similar to that around the earth but less intense. Gault et al (ref. 118) estimate such an increase in flux as being ejecta from the moon, due to meteoroid impacts, and thus comprised of particles having low velocities (maximum of 2.4 km/sec and average velocity of 200 meters/sec). Under reasonable assumptions about the kinetic energy distribution of secondary fragments, the penetration rate can not be as great as twice the near-Earth rate (ref. 219). As an upper limit, therefore, one might double the rate given by equation IX-3 for rough calculations of penetration rates near the moon.

4. Outside the "dust cloud" surrounding Earth, described in section IX-B-2, the deep space density of meteoroids is about two orders of magnitude less than described by equations IX-1 and IX-2. This, however, is the background density. Streams and sporadic fluxes of meteoroids are encountered. The most important of the meteor streams have been tabulated by McKinley and are reproduced here in table IX-2. Most of the streams are seen to be associated with comets.

Concentrations of meteoroids also probably occur in the asteroid belt and near planets, similar to that observed for Earth. The concentration of meteoroids is also greater in the plane of the ecliptic than it is outside the plane. This is evidenced by solar corona observations, where the halo around the Sun, due to light reflection by meteoroids, extends farther in the plane of the planets. The halo indicates a density of about 10^{-5} particles/cm³ at 1 a.u. in the ecliptic. Measurements of zodiacal light (the faint sky light noticeable after twilight, concentrated in the plane of the ecliptic) agree with this estimate (ref. 72).

C. EFFECTS OF METEOROIDS

The effects of meteoroid bombardment of solar cells are surface erosion by the micrometeoroids and occasional puncture by the larger particles. Erosion consists of cratering, where the bombarding particle vaporizes a small volume of the surface, and cracking, which for brittle materials as glass or plastic, occurs in a small area around each crater, and several times the crater diameter. On the basis of conservative (pessimistic) estimates, the number of craters increases from one per few cm²/year far from Earth to 10 per cm²/year at low altitudes (ref. 72). Punctures by the larger particles are much less frequent but can cause mechanical difficulty, such as open circuits, with a low but finite probability which can be computed with the aid of equations IX-4 and IX-5. One should remember that the effect of a puncture of a solar cell may not be limited to a corresponding loss of photovoltaic material, but also may involve destruction of a portion of the surface collecting grid.

Mirtich and Mark (ref. 203) have experimentally explored the effect of micrometeoroids on optical surfaces. They find that the reflectance of a polished metal surface is

TABLE IX-2. ORBITAL ELEMENTS OF THE MOST IMPORTANT METEOR STREAMS AND THEIR ASSOCIATED COMETS

Source: McKinley, David. Meteor Science and Engineering, McGraw-Hill, 1961

Meteor Stream and Comet	P, * Years	q, * au	e*	ω , * deg	Ω , * deg	i, * deg
Lyrids	161	0.92	0.97	214	32	80
1861	415	0.921	0.983	213.4	29.9	79.8
Eta Aquarids	8	0.70	0.83	109	44	158
Orionids	21	0.54	0.93	87	30	163
1910 II (Halley)	76.0	0.587	0.967	111.7	57.3	162.2
Beta Taurids (D)	3.3	0.34	0.85	246	276	6
Southern Taurids	3.5	0.37	0.84	112	45	5
Northern Taurids	3.1	0.32	0.85	298	222	3
1954 IX (Encke)	3.30	0.338	0.847	185.2	334.7	12.4
Alpha Capricornids	4.1	0.57	0.78	271	133	4
1954 III (Honda-Mrkos-Pajdušáková)	5.22	0.559	0.814	184.0	233.1	13.2
Perseids	95	0.94	0.96	151	138	114
1862 III (Swift-Tuttle)	119.6	0.963	0.960	152.8	137.5	113.6
Giacobinids (October Draconids)	6.59	0.996	0.717	171.8	196.2	30.7
1946 V (Giacobini-Zinner)	6.59	0.996	0.717	171.8	196.2	30.7
Bielids (Andromedids)	6.	0.75	0.78	242	224	6
1852 III (Biela)	6.62	0.861	0.756	223.3	245.9	12.6
Leonids	45	0.97	0.92	174	235	163
1866 I (Tempel)	33.2	0.977	0.905	171.0	231.4	162.7
Ursids	14	0.92	0.85	212	265	53
1939 X (Tuttle)	13.6	1.022	0.821	207.0	269.8	54.7
Meteor Stream						
Quadrantids	6.3	0.97	0.72	168	283	74
Arietids (D)	2.0	0.09	0.94	29	77	21
Zeta Perseids (D)	2.0	0.35	0.79	60	78	0
Southern Delta Aquarids	4.2	0.06	0.976	154	302	29
Northern Delta Aquarids	4.2	0.07	0.973	333	139	20
Southern Iota Aquarids	4.9	0.23	0.92	128	311	6
Northern Iota Aquarids	2.3	0.27	0.84	303	151	5
Kappa Cygnids	8.3	0.97	0.75	204	144	37
Geminids	1.64	0.140	0.900	324.3	261.2	23.9
*P=period (years); q=perihelion (au); e=eccentricity; ω =angle between q and Earth's orbit; Ω =angle between sun, vernal equinox and intersection of stream and Earth orbital planes; i=inclination of plane of stream orbit with plane of Earth orbit.						

degraded as shown in figure IX-4, with the accumulated kinetic energy of the bombarding flux. The change in optical property is the result of cratering in the reflective surface of the metal. Comparable damage to surfaces of transparent materials will degrade transmittance particularly in cases of brittle materials where reflections and interactions of induced pressure waves cause subsurface damage. Such effects in glass and cast, transparent methyl methacrylate, in both 1/8 and 1/4 inch thick specimens were observed in the experimental work of Diedrich and Stepka (ref. 91). These investigators studied the individual effects of target size, shape, internal boundaries, internal reinforcement, and materials contacting the external boundaries. They conclude that: Primary fractures due to initial impact (e.g., crater and radial dilatation fractures) are unique occurrences for a particular target shape, material, and set of impact condition and cannot be controlled or diminished; secondary fractures (e.g., spalling, dilatation and internal cracks due to interactions between reflected components of the incident stress values) are dependent on the proximity of free edges in the target and adjacent materials in contact with the free edges and therefore are controllable in both location and severity; geometrical discontinuities act as stress raisers and induce secondary fractures; the placement of a material having higher acoustic impedance than the target on the free surfaces of a brittle target is the most effective method of controlling secondary fractures; flat plates having filled internal voids (or internal steel wire reinforcement) consistently exhibit greater secondary damage than do homogeneous targets of the same material; in thin targets which are perforated by a projectile, total damage decreases with decreasing plate thickness. (In this case adjacent material with higher acoustic impedance can increase damage.)

While a small probability exists for a solar cell array to be catastrophically damaged or at least perforated by meteoroids, the more common hazard is due to micrometeoroid impingement resulting in erosion of the coverslide and reduced transmission of solar radiation to the cell. The effects of coverslide surface erosion on cell performance was investigated and reported by Ross (ref. 254). Silicon n/p solar cells equipped with coverslides were sandblasted with 220 grit silicon carbide resulting in an average diameter of craters of 30 microns. Short circuit current degradation

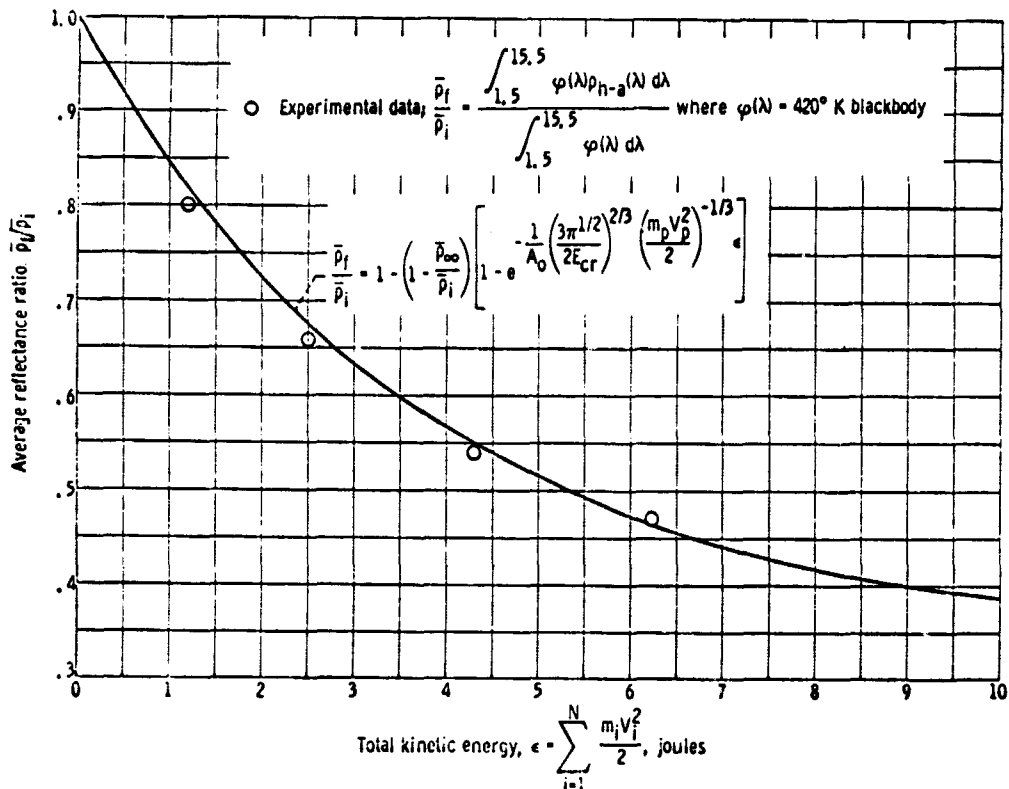


Figure IX-4. Plot of reflectance ratio as function of kinetic energy of 6-micron diameter silicon carbide particles falling on an aluminum disk 15/16 inch in diameter. Total effective reflectance for area damaged by crater, ρ_∞ , 0.34; total initial reflectance of area A_0 before exposure, ρ_i , 0.991; disk area, A_0 , $\pi(15/32 \text{ in.})^2$; cratering energy density, E_{cr} , 1.65×10^{10} erg per cm.^3 ; particle mass, m_p , 3.62×10^{-10} gram; particle velocity, V_p , 8200 ft. per sec. (ref. 203).

ranged from less than one percent at 10^3 craters/ cm^2 to a maximum of 12 percent at 10^6 craters/ cm^2 . The exposed surface of the coverslide was completely roughened at 10^6 craters/ cm^2 and the craters were extensively overlapping. Sandblasting caused damage to cell edges causing significant increase in leakage current with the result that power degradation was considerably more serious, ranging from 11 percent at 10^3 craters/ cm^2 to 60 percent at 10^6 craters/ cm^2 .

The performance of both uncovered and covered n/p silicon cells and encapsulated CdS solar cells in simulated near-Earth micrometeoroid environment has been studied experimentally by Mirtich and Bowman (ref. 202). The environment was simulated by

clouds of 6- μ diameter SiC particles accelerated to hypervelocities (2.65 km/sec) in a shock tube. Figure IX-5 shows the ratio of final to initial short-circuit current (measured at one solar constant) as a function of total kinetic energy of bombarding particles. The unprotected n/p silicon cells suffered an exponential decrease which can be approximated by $I_{sc} = I_{sc0} e^{-9.3\epsilon}$ where ϵ is the cumulative flux energy in joules: For silicon solar cells protected by coverslides of 6 mil microsheet, 21 mil quartz, 62 mil quartz and 60 mil sapphire exposed to the same kinetic energy of particles the decrease in short circuit current is relatively small, and can be approximated by $I_{sc} = I_{sc0} e^{-0.22\epsilon}$. Conversion of laboratory exposure to equivalent time in space was based upon scaling of the total kinetic energy of the cloud of particles impinging upon the 1 x 2 centimeter solar cells in accordance with mass ranges and flux distribution functions for different meteoroid environment models according to Alexander and Loeffler (see ref. 202). According to the mass distribution model of Alexander the total kinetic energy of particles in the mass interval of 10^{-8} to 10^{-12} gm striking a 1 x 2 cm solar cell in one year near Earth is 4.9 joules; the comparable value for the model according to Loeffler is 0.225 joule. [As a further example of the order of magnitude of disagreement existing among models of the environment, the total energy of particles striking a 1 x 2 cm solar cell in one year near Earth would be about 0.0029 joule according to the penetrating flux model of Naumann (ref. 211). It was pointed out earlier that this model does not include a near-Earth concentration of very small particles (dust cloud) which are non-penetrating to 0.01 mm aluminum.]

Using the above-mentioned time laboratory kinetic energy conversion, Mirtich and Bowman conclude that, even in the case of the lower kinetic energy meteoroid flux distribution according to Loeffler, an unprotected n/p silicon solar cell will degrade excessively in a few weeks for any near-Earth space mission. Coverslide protected n/p silicon solar cells in the same environment would suffer very little damage by erosion (about one percent reduction in short circuit current in 55 days) from micrometeoroids. Results of this study also indicate that equivalent protection against simulated micrometeoroid bombardment was achieved irrespective of coverslide material (glass, quartz or sapphire) or thickness in the range of six to 60 mils.

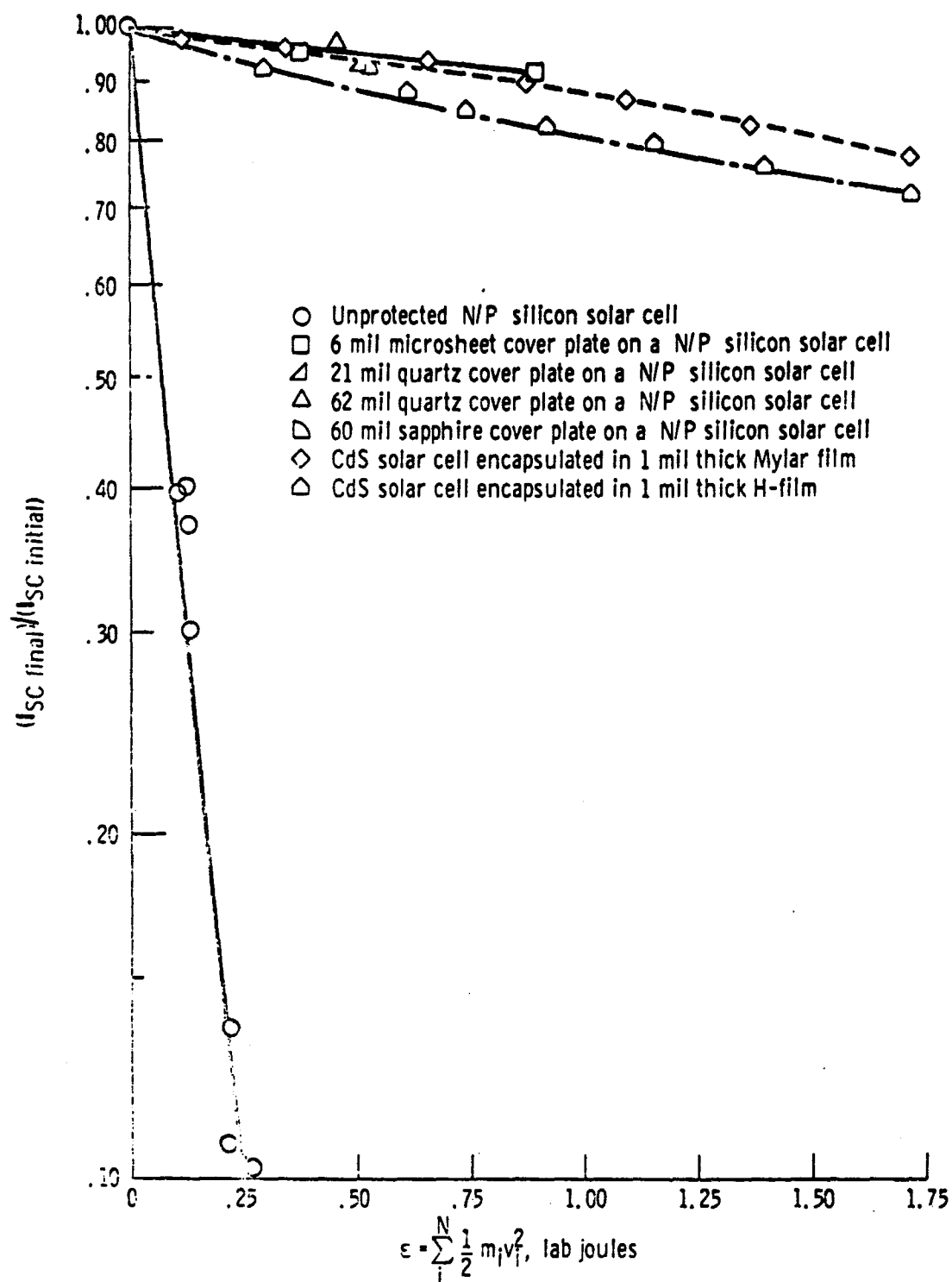


Figure IX-5. Ratio of final to initial short circuit current for 1 x 2 cm silicon and CdS solar cells versus kinetic energy or cloud of impinging 6-micron SiC particles at 2.65 km/sec. (ref. 202).

It was also found that CdS solar cells encapsulated in mylar, one mil thick, will perform as well as n/p silicon solar cells covered by 6 mil microsheet when bombarded by the simulated micrometeoroid flux.

Considering that the experimental work discussed above did not involve complete perforations of solar cells but was limited to surface effects, then the reduction in short circuit current is due to a loss in effective light intensity. This loss is given by the factor $e^{-0.073t}$ where t is time in orbit, in years, assuming a meteoroid flux of 0.225 joules per year. No such loss has been observed at synchronous altitude (ref. 298), where, however, the meteoroid flux would be much lower than the near-Earth value.

According to an evaluation by Whipple (ref. 309), the etching of optical or other surfaces of deep space probes is negligible over periods of several years (less than 10^{-6} cm/year). As for the near-Earth environment, observations of the balloon satellite, Echo I, show that surface erosion is not particularly rapid since the satellite's loss of reflectivity has not exceeded 0.6 percent per year. Harder, more brittle surfaces than the aluminum-coated (less than 1μ) mylar film of ECHO I, may be degraded more readily. However, experience with Earth-orbiting vehicles does not warrant an expectation of extensive surface erosion over periods less than three or four years.

The uncertainties which persist concerning the meteoroid environment involve many orders of magnitude due to difficulties in defining the masses of particle debris and the flux-size distribution functions, as well as interpretations of observations and data from a variety of sensors employed in both Earth-based and spacecraft studies. However, it is concluded that surface erosion, the most probable degradation of solar cells due to micrometeoroids, can be significantly retarded by the use of appropriately designed coverslides. Protection against the less likely event of extensive damage due to hypervelocity impact of a particle of mass sufficient to deeply crater or perforate a solar cell array involves penalties in weight and/or design complexity. Protective techniques include redundant solar cell circuits as well as transparent shielding or bumpers. (A summary of such protective concepts is presented by Cosby and Lyle in reference 72.)

D. SUMMARY

Recent work concerned with the meteoroid environment has resulted in revised estimates of damaging flux particularly in the near-Earth region of space. The revisions have consistently tended to reduce the expected number of impacts which would damage spacecraft surfaces by erosion, cratering, and the perforation of thin sheet materials.

Since our concern is with degradation of solar cell performance, evaluations of the meteoroid environment based upon the Explorer and Pegasus perforating flux are of particular interest. The results of recent work by Naumann (ref. 211) and Head (ref. 131) discussed earlier in this section are in reasonable agreement with the distribution deduced by Bjork et al and shown in figure IX-6 (See also figs. IX-2 and IX-3). The earlier discussion of Naumann's work pointed out that he evaluates that the flux of particles, of any size, striking a spacecraft has an upper limit of approximately $3/\text{m}^2\text{-day}$. Comparable limits for particles capable of inflicting impact damage according to the meteoroid flux models of Bjork and Head are greater but within a factor of 2. Both Whipple (ref. 309) and Naumann (ref. 211) indicate that perforation rates in deep space should not be expected to be much reduced, if any, from those observed near Earth. In the vicinity of the Moon, secondary particles (lunar surface ejecta) increase the particle flux, however, the velocity of such particles is relatively low. Therefore, the impact damage hazard is not expected to be significantly increased.

Since the variation of penetration hazard among the near-Earth, near-Moon, and deep space regions is thought to be small, and in view of the magnitude of uncertainty associated with even the latest models of meteoroid flux, it is reasonable to use a single model for estimating the problem. It is important to recognize that the meteoroid flux models discussed in this section represent averages over considerable periods of time and are appropriate for missions of a year or more in duration. In cases of very short missions consideration must be given to meteoroid streams and their individual deviations in velocity, flux, and duration. The annual average combined flux of sporadic and stream meteoroids at 1 a.u. in terms of perforation capability is shown in figure IX-3 and characterized by the equation

$$\log N = -14.96 - 4.16 \log C - 0.38 (\log C)^2 \quad (\text{IX-5})$$

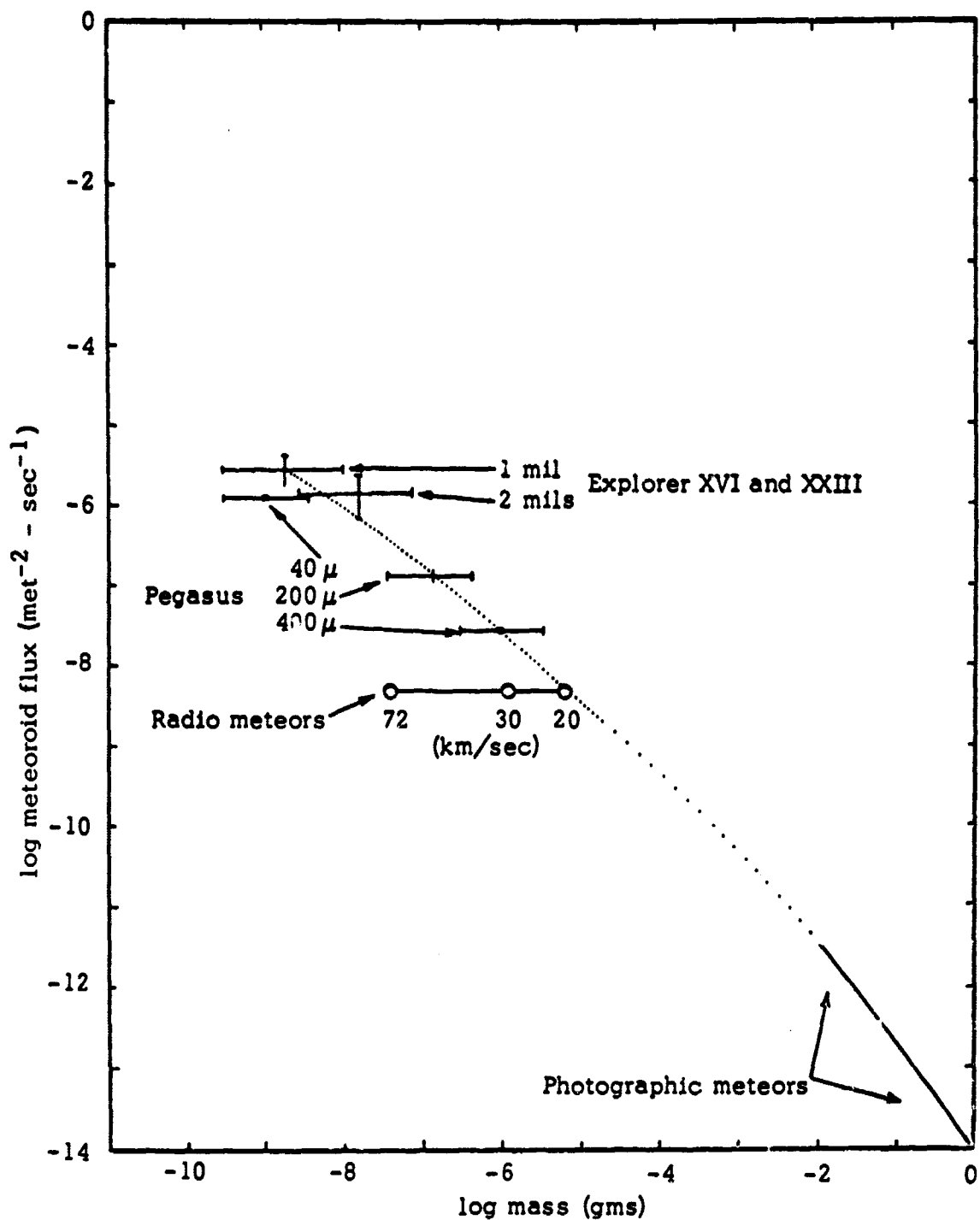


Figure IX-6. Meteoroid Mass Flux Near Earth (Bjork, R. L. et al, Analytical Study of Impact Effects Applied to the Meteoroid Hazard, NASA-CR-757)

In terms of meteoroid mass, this flux is represented by the curve of figure IX-6; of more direct significance is the flux in terms of thickness of aluminum sheet penetrated as shown in figure IX-2.

Properties of the coverslides are accommodated in equation IX-5. When the penetration frequency for aluminum sheet is to be applied, scaling to other materials is accomplished by establishing an equivalent thickness of 2024-T3 aluminum for those materials by laboratory impact tests.

X. FLIGHT TEST DATA ON SOLAR CELLS

A. SOURCES OF FLIGHT TEST DATA

The effect of the space radiation environment on solar cells has been measured by telemetry from special experiments and from the power systems of satellites. The interpretation of flight data is hindered in many cases by the lack of complete data to define the I-V curve, temperature and solar aspect angle for each measurement.

Typical data on power systems are limited to measurement of current output at a fixed voltage on the short circuit side of the peak power point of the I-V curve. In specially designed experiments, the use of a low load resistance permits measurement of a current very close to the short circuit value. In some cases, the use of a load resistance of more than 5 ohms per cell resulted in measurements of current values in the vicinity of the peak power point.

Some of the more useful radiation damage experiments have been reported by Waddel on the Relay I and II, (refs. 300, 301, 302) and ATS-1 (ref. 298), by Brown on the Telstar I and II, (refs. 43, 48, 50) by Fischell on Anna I-B and other satellites, (refs. 105, 109) by Reynard on Midas III and IV (ref. 241) by TRW Systems on the Tetrahedral Research Satellites (ref. 286) and by Slifer on Explorer XXVI (ref. 264).

B. SUMMARY OF FLIGHT EXPERIMENTS AND RESULTS

A summary of the design parameters for silicon solar cell flight experiments are included in table X-1. In most cases, the shielded solar cells have a coverslide which is adhesive-bonded to the cell. However, the Telstar cells had sapphire coverslides mounted in platinum retaining frames, without adhesive. Figure X-1 shows a plot of areal density (density times thickness) vs. thickness for various coverslide materials.

TABLE X-1. DESIGN PARAMETERS OF SILICON SOLAR CELL FLIGHT EXPERIMENTS

Experiment Identifier (a)	R. E. Fischell, J. H. Martin, W. E. Allen and W. E. Radford, Johns Hopkins Applied Physics Laboratory									
Experiment Identifier										
Specimen Name(s)	1981 01	1981 07	1981 07	1981 07	1981 07	1981 07	1981 07	1981 07	1981 07	1981 07
Launch Date	7/29/61	7/29/61	7/29/61	7/29/61	7/29/61	7/29/61	7/29/61	7/29/61	7/29/61	7/29/61
Altitude at Apogee	1146 Km	1111 Km	1111 Km	1111 Km	1111 Km	1111 Km	1111 Km	1111 Km	1111 Km	1111 Km
Altitude at Apogee	618 NM	609 NM	609 NM	609 NM	609 NM	609 NM	609 NM	609 NM	609 NM	609 NM
Altitude at Apogee	943 Km	943 Km	943 Km	943 Km	943 Km	943 Km	943 Km	943 Km	943 Km	943 Km
Ballistics (pressure)	67"	32.4"	32.4"	32.4"	32.4"	32.4"	32.4"	32.4"	32.4"	32.4"
Period										
Solar Cell Type	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N
Solar Cell Manufacturer	20 Series	20 Series	20 Series	20 Series	20 Series	20 Series	20 Series	20 Series	20 Series	20 Series
Number of Cells for Each	Cells	Cells	Cells	Cells	Cells	Cells	Cells	Cells	Cells	Cells
Type of Coverlip	1 x 1 cm	1 x 2 cm	1 x 2 cm	1 x 2 cm	1 x 2 cm	1 x 2 cm	1 x 2 cm	1 x 2 cm	1 x 2 cm	1 x 2 cm
Solar Cell Bias										
Solar Cell Active Area										
Grid Arrangement										
Base Resistivity										
Base Resistance										
Diffusion Depth	Deep	Shallow	Shallow	Shallow	Shallow	Shallow	Shallow	Shallow	Shallow	Shallow
Diffusion Material										
Coverlip Thickness & Material	6 Mil Corning 0211	6 Mil Corning 0211	6 Mil Corning 0211	6 Mil Corning 0211	6 Mil Corning 0211	6 Mil Corning 0211	6 Mil Corning 0211	6 Mil Corning 0211	6 Mil Corning 0211	6 Mil Corning 0211
Type of Reflective Filter	U.V.	U.V.	U.V.	U.V.	U.V.	U.V.	U.V.	U.V.	U.V.	U.V.
Activator	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Coverlip Adhesive or Application Technique	Purmo 15-E	Purmo 15-E	Purmo 15-E	Purmo 15-E	Purmo 15-E	Purmo 15-E	Purmo 15-E	Purmo 15-E	Purmo 15-E	Purmo 15-E
Lead Resistance per 1 x 2 cm	1.87 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q
Solar Cell	1.87 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q	3.75 Q
Measured Parameter	750	750	750	750	750	750	750	750	750	750
Stops	Stopped 7/15/61	Stopped 7/12/63	Stopped 7/12/63	Stopped 7/12/63	Stopped 7/12/63	Stopped 7/12/63	Stopped 7/12/63	Stopped 7/12/63	Stopped 7/12/63	Stopped 7/12/63
*Four Separate Panels Were Flown										

TABLE X-1. DESIGN PARAMETERS OF SILICON SOLAR CELL FLIGHT EXPERIMENTS (CONTINUED)

Experiment Initiator(s) Experiment Fabricator		D. L. Raynard, LMSC				W. L. Brown, W. Rosenzweig H. K. Gansel, K. D. Smith B. T. L.			
Spacecraft Name(s)		Midas III				Explorer XV			
Launch Date		7/12/61				10/27/62			
Altitude at Apogee		3802 Km				17,600 Km			
Altitude at Perigee		1850 NM				9,500 NM			
Declination (Degrees)		3425 Km				315 Km			
Period		91.2"				167 NM			
		141.5 Min				44.8"			
		164.9 Min				5.3 Hrs			
Solar Cell Type		P/N				P/N			
Solar Cell Manufacturer		IR				Hoffman			
Number of Cells for Each		30 Series				30 Series			
Type of Coverlip		Cells				Cells			
Solar Cell Size		1 x 2 cm				1 x 2 cm			
Grid Arrangement		Ungridded				3 Grids			
Base Resistivity		3 Grids				3 Grids			
Sheet Resistance		Deep				Deep			
Diffusion Depth		Deep				Shallow			
Diffusion Material		Deep				Deep			
		Deep				Phosphorus			
		Deep				Phosphorus			
Overship Thickness & Material		6 Mil 0211 40 Mil 7940 80 Mil 7940				40 Mil 7940 80 Mil 7940			
Type of Reflective Filler		6 Mil 0211 40 Mil 7940 80 Mil 0211				40 Mil 7940 80 Mil 7940			
Antireflective Filler		Fused Silica				Fused Silica			
Overship Adhesive or Application Technique									
Load Resistance per 1 x 2 cm		6.66Ω				6.66Ω			
Solar Cell		Voltage across 200Ω				Voltage across 200Ω			
Measured Parameter		Operated 19 Days				Voltage across 2136 Ohms			
Status		Days				1.5Ω			
						Voltage across 1.5Ω			
						Telstar Type*			
						Telstar Type*			
						1.5Ω			
						Voltage across 2136 Ohms			
						1.5Ω			

TABLE X-1. DESIGN PARAMETERS OF SILICON SOLAR CELL FLIGHT EXPERIMENTS (CONTINUED)

Experiment Identifier(s) Experiment Fabricator	Dr. Raymond Waddell, G. S. F. C. Spectrolab		G. W. Longmeyer, G. S. F. C. and Luther Riller, G. S. F. C. Spectrolab		Luther Riller, G. S. F. C. G. S. F. C.
Spacecraft Name(s)	Relay I	Relay II	Explorer XIV	Explorer XXVI	
Launch Date	Dec. 13, 1962	Jan. 21, 1964	Aug. 15, 1961	October 2, 1962	December 21, 1964
Altitude at Apogee	7439 Km	7415 Km	77,000 Km	99,000 Km	26,191 Km
	6014 NM	4001 NM	41,500 NM	53,400 NM	14,134 NM
Altitude at Perigee	1321 Km	2009 Km	304 Km	278 Km	316 Km
	713 NM	1126 NM	144 NM	150 NM	170.5 NM
Inclination (Degrees)	47.5°	46.3°	33°	33°	20°
Period	106.1 Min	104 Min	24.5 Hrs	36.5 Hrs	7.6 Hrs
Solar Cell Type	P/N	N/P	P/N	P/N	N/P
Solar Cell Manufacturer	Hoffman	Texas Inst.	Hoffman	Hoffman	Hoffman
Number of Cells for Each Type	3 Individual	3 Individual	10 Series	10 Series	10 Series
Type of Coverglass	cells	cells	cells	cells	cells
Solar Cell Size	1 x 2 cm	1 x 2 cm	1 x 2 cm	1 x 2 cm	1 x 2 cm
Solar Cell Active Area	1.8 cm ²	1.8 cm ²	1.8 cm ²	1.8 cm ²	1.8 cm ²
Grid Arrangement	3 Grids	3 Grids	No Grids	No Grids	5 Grids
Base Rectifier	10-cm	10-cm	10-cm	10-cm	10-cm
Diffusion Depth	Shallow	Shallow	Shallow	Shallow	Shallow
Diffusion Material	Boron	Phosphorous	Boron	Phosphorous	Boron
Coverglass Thickness & Material	0.30, 60 Mil Corning 7840	0.30, 60 Mil Corning 7840	0.30, 60 Mil Corning 7840	0.30, 60 Mil Corning 8211	0.30, 60 Mil Corning 8211
Type of Backactive Filter	U.V.	U.V.	U.V.	U.V.	U.V.
Anti-reflective Filter	BIO	BIO	BIO	BIO	BIO
Manufacturer who Applied Filters	O. C. L. I.	O. C. L. I.	O. C. L. I.	O. C. L. I.	O. C. L. I.
Coverglass Adhesive or Application Technique	ES-10	ES-10	ES-10	ES-10	ES-10
Lead Resistance per 1 x 2 cm Solar Cell	10.6Ω	10.6Ω	10.6Ω	10.6Ω	10.6Ω
Measured Parameter	10.6Ω	10.6Ω	10.6Ω	10.6Ω	10.6Ω

TABLE X-1. DESIGN PARAMETERS OF SILICON SOLAR CELL FLIGHT EXPERIMENTS (CONTINUED)

Experiment Initiator(s) Experiment Fabricator	J. Denney, T. R. W. Space Technology Laboratories			
Spectrograph Name(s)	Tetrahedral Res. Sat. 1963-14B		Tetrahedral Res. Sat. 1963-14C	
Launch Date	5/9/63		7/19/63	
Altitude at Apogee				
Altitude at Perigee				
Inclination (Degrees)				
Period				
Solar Cell Type	N/P	P/N	N/P	P/N
Solar Cell Manufacturer	West. Elec.	Hoffman	West. Elec.	Hoffman
Number of Cells for Each Type	4 Cells in Parallel	4 Cells in Parallel	4 Cells in Parallel	4 Cells in Parallel
Area of Coverglass	1 x 1 cm	1 x 1 cm	1 x 1 cm	1 x 1 cm
Solar Cell Size	1 x 1 cm	Boron	Phosphorous	Boron
Diffusion Material	Phosphorous	Boron	Phosphorous	Boron
Coverglass Thickness & Material	0 and 40 Mil Quartz	20 Mil CeO ₂ 20 Mil Q	0 20 Mil CeO ₂ 20 Mil Quartz	6 Mil Q211 60 Mil Quartz 20 Mil CeO ₂
Type of Reflective Filter				
Antireflective Filter				
Coverglass Adhesive or Application Technique	None	None for Quartz EPDX-74 for CeO ₂	None for Quartz EPDX-74 for CeO ₂	None EPDX-74
Load Resistance per 1 x 2 cm Solar Cell	3.0Ω ^a Voltage across 6Ω	3.0Ω ^a Voltage across 6Ω	3.0Ω ^a Voltage across 6Ω	3.0Ω ^a Voltage across 6Ω
Measured Parameter				
*Based upon 1 Solar Cell. Since each of the four parallel cells is mounted on a separate face of the tetrahedron, only one cell can be fully illuminated at any given time.				

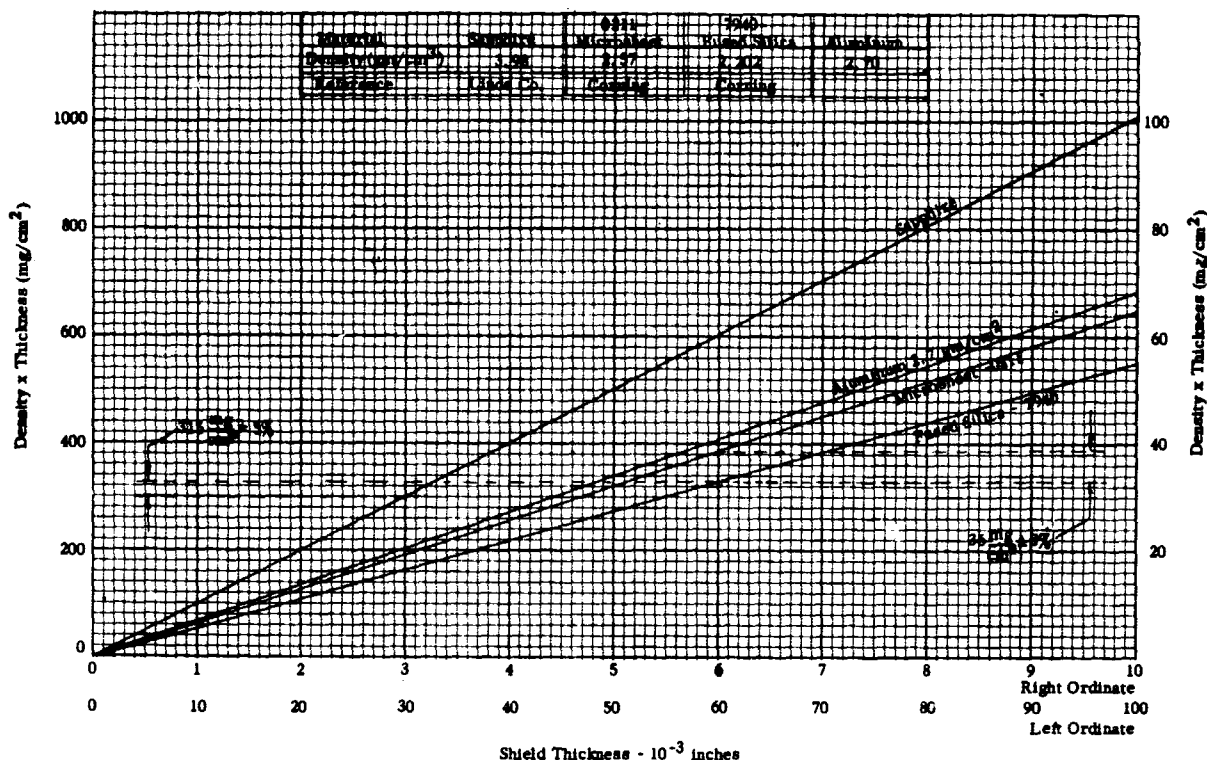


Figure X-1. Density x Thickness vs. Thickness For Various Shield Materials

Data on the time for 25% current degradation of n/p and p/n silicon cells vs. shield thickness on various satellites is shown in figures X-2 and X-3. The solid curves are for load resistances less than 4.5 ohms per cell which approximate short circuit current. The dotted curves are for load resistances of more than 6.5 ohms per cell which are closer to the current at maximum power from the cells.

The data on Relay I experiments have been plotted in figure X-4 in terms of the base diffusion length of silicon cells vs. time in orbit. Values of L were determined by assuming that one ohm-cm silicon cells in space sunlight follow the curves of short circuit current ratio (I_{SC}/I_{SCO}) vs. L as given in figures IV-18 and IV-19 for n/p and p/n cells, respectively. It is seen that a dependence of L on the inverse square root of time in orbit is closely approximated after an initial period of about 80 days, during which the cyclic flux variations due to orbital precession are prominent. Results of the

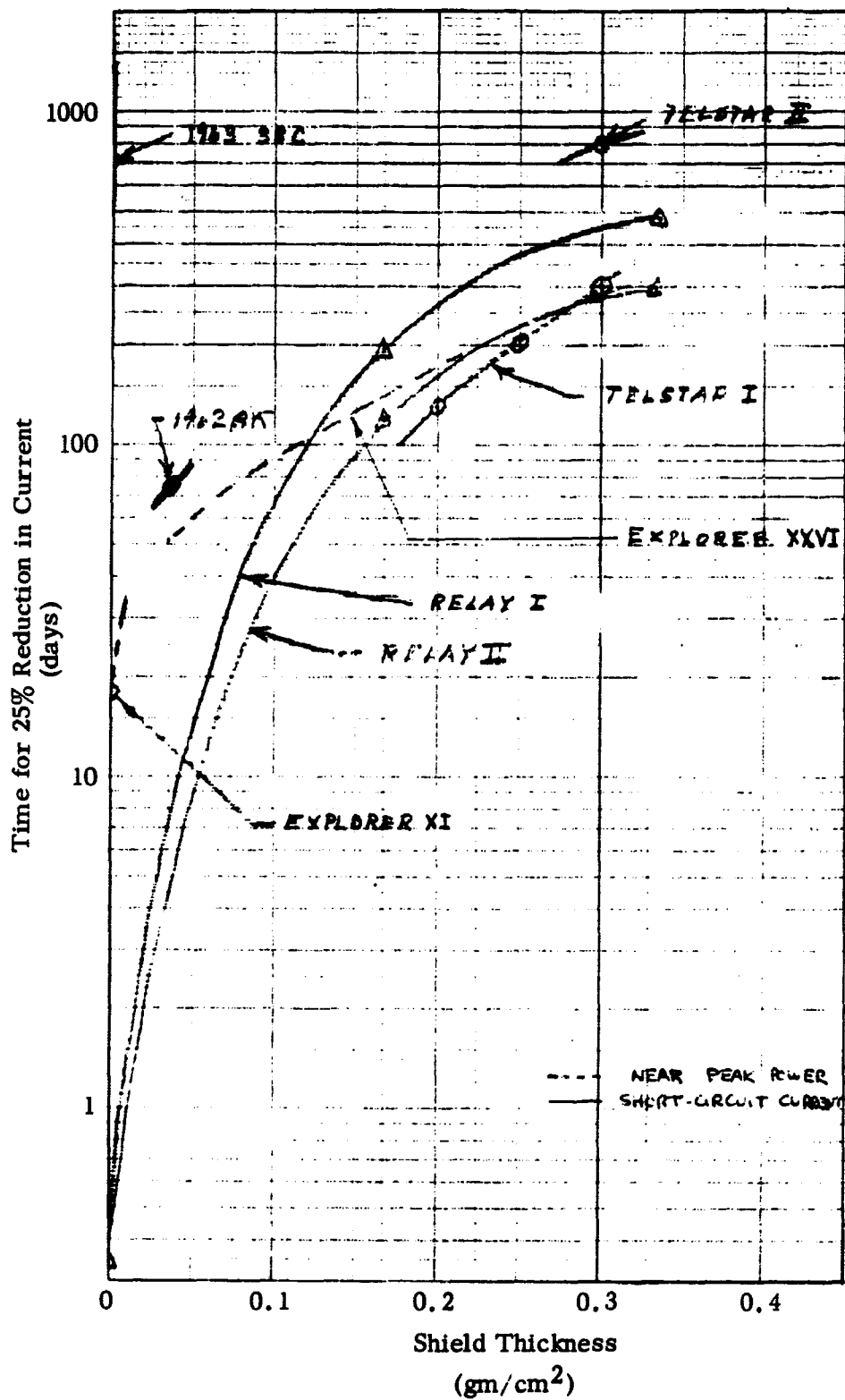


Figure X-2. Time to 25 Percent Degradation vs. Shield Thickness for N/P One ohm cm. Silicon Solar Cells

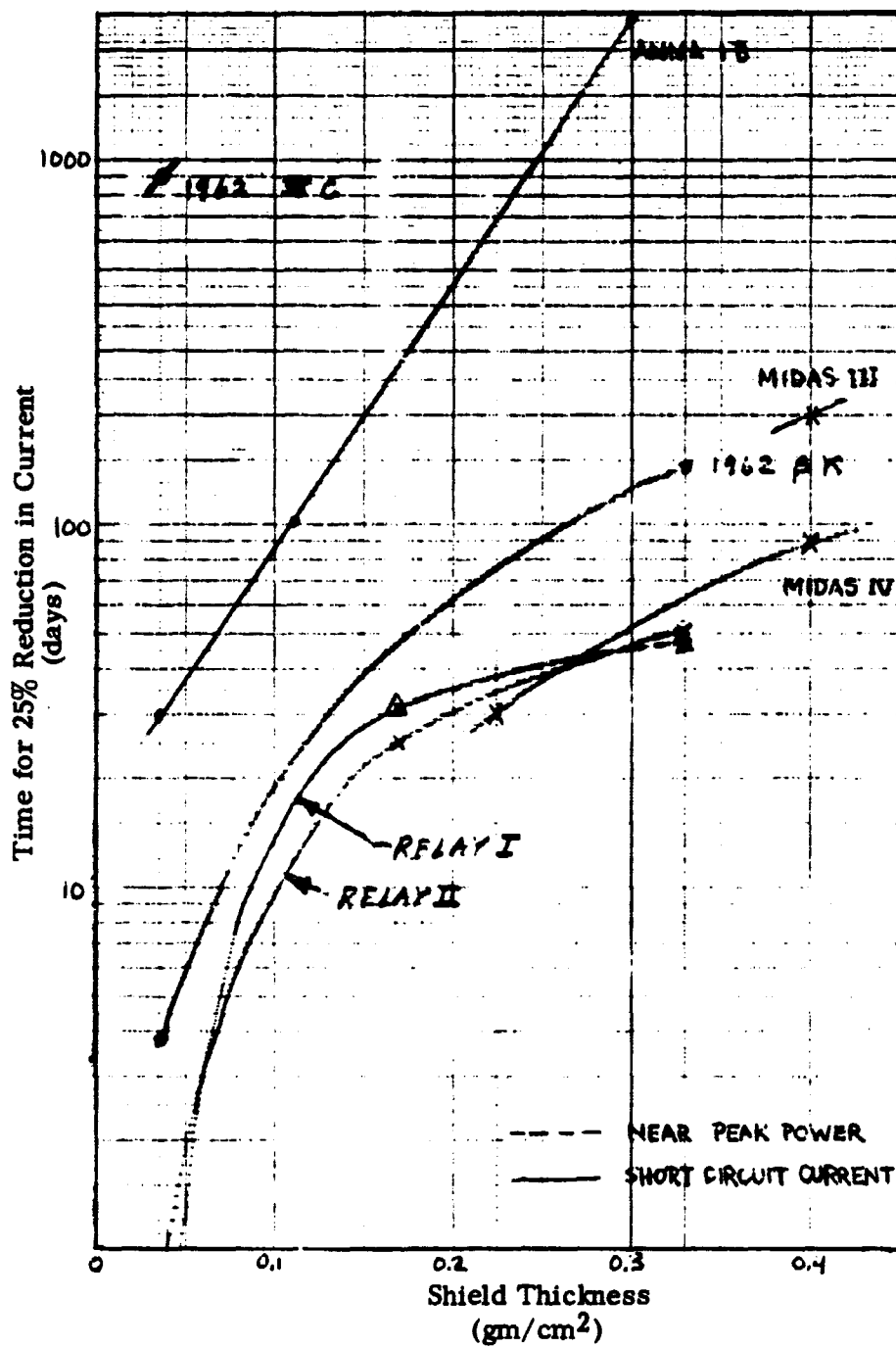


Figure X-3. Time to 25 Percent Degradation vs. Shield Thickness for P/N One ohm-cm. Silicon Solar Cells

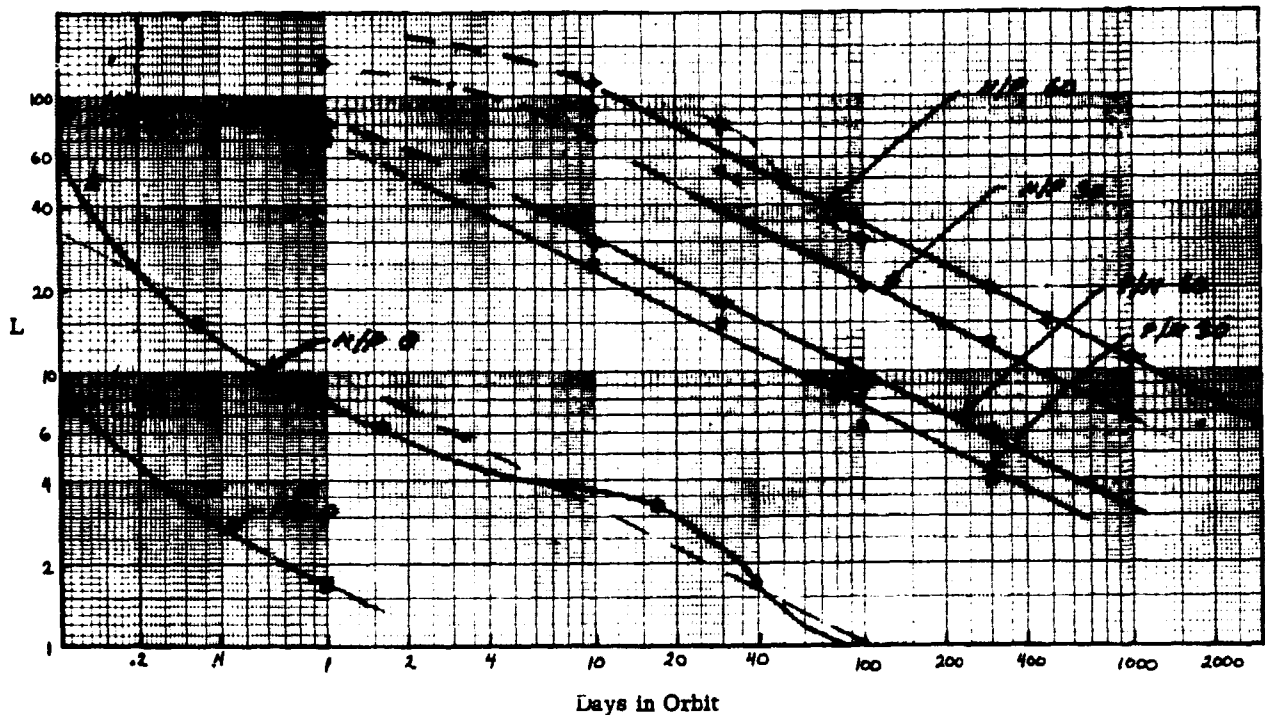


Figure X-4. Base Diffusion Length VS. Time in Orbit for Relay I Solar Cell Experiments, Unshielded and with Fused Silica Shields (Corning 7940).
(Developed using I_{SC}/I_{SC0} VS. L Data from Figures IV-18 and IV-19.)

Relay I experiments showed that the n/p cells with 0.060 in shields took 10 to 12 times longer to degrade to 75% short circuit current ratio ($L = 15$ microns) than similarly shielded p/n cells. For the 0.030 in shielded cells, the comparable time ratio was about 6 to 7.

It is believed that data on diffusion length vs. time as in figure X-4 provides a more sound basis for extrapolating performance of solar cells to long times than the typical plot of short circuit current ratio vs. time. There is a good theoretical basis for the variation of L with the inverse square root of time at a constant flux, whereas short circuit current does not vary linearly with the logarithm of time under space sunlight illumination.

Figure X-5 shows the current degradation of Telstar I and II vs. actual number of days in orbit (ref. 46). Figure X-6 shows the current degradation for Telstar II, converted to equivalent days in orbit at the average flux over a several month period. The equivalent unidirectional one-MeV electron fluxes on unshielded cells which give the same degradations of current and diffusion length as observed in space under 0.030 in of sapphire shielding are 6×10^{12} electrons/cm² -day for Telstar I and 2.3×10^{12} electrons/cm² -day for Telstar II. A sample calculation is given in table X-2.

TABLE X-2. COMPARISON OF TELSTAR 1 DATA WITH CALCULATION

From figure IV-2, $K = 2.5 \times 10^{-10}$

$$D/t = K \Phi = 2.5 \times 10^{-10} \times 6 \times 10^{12} = 1.5 \times 10^3 / \text{cm}^2 - \text{day}$$

t (days)	D cm ⁻²	L* (microns)	(Isc/Isc0)**	Observed Ratio
1	$.15 \times 10^4$	158 u	.98	1
10	1.5×10^4	75.5	.935	.96
40	6×10^4	40	.88	.88
100	15×10^4	25.5	.82	.84
400	60×10^4	13.9	.72	.71
1000	150×10^4	8.13	.65	.65
$* \frac{1}{L^2} = \left[\frac{1}{4 \times 10^{-4}} + D \right] \text{cm}^{-2}, \text{ Eq. IV-1. } ** \text{From figure IV-18.}$				

Brown (ref. 46) has also predicted the equivalent one-MeV flux by using measured electron and proton fluxes and energy spectra and analyzing the shielding and damage coefficient effects. His predictions give equivalent one-MeV fluxes of 7.9×10^{12} and 2.9×10^{12} electrons/cm² - day for Telstar I and II respectively, which are only

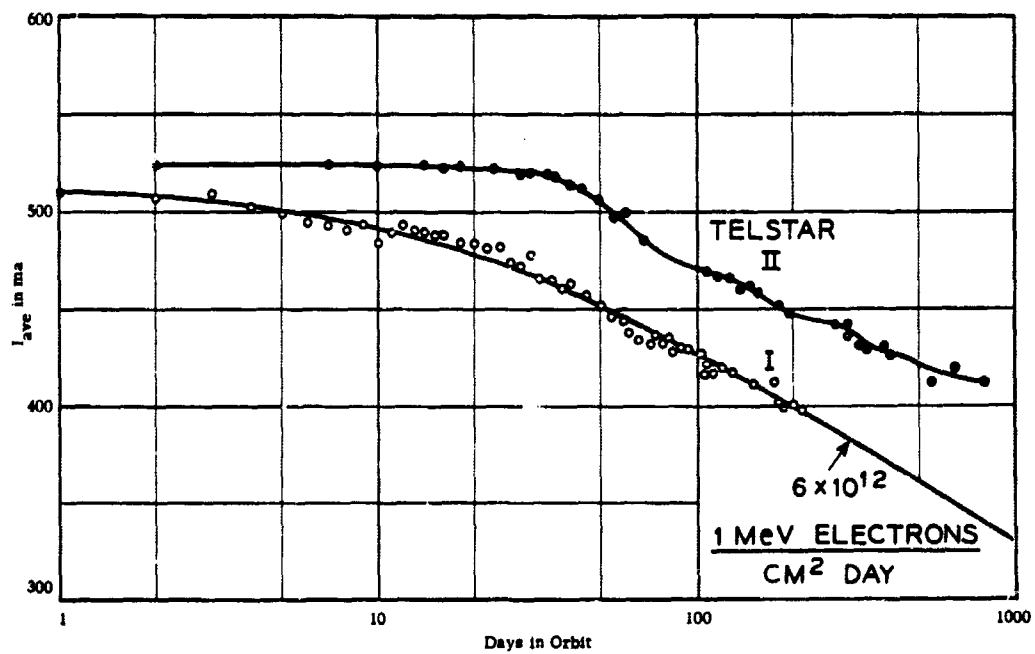


Figure X-5. Current VS. Days in Orbit for Telstar I and II

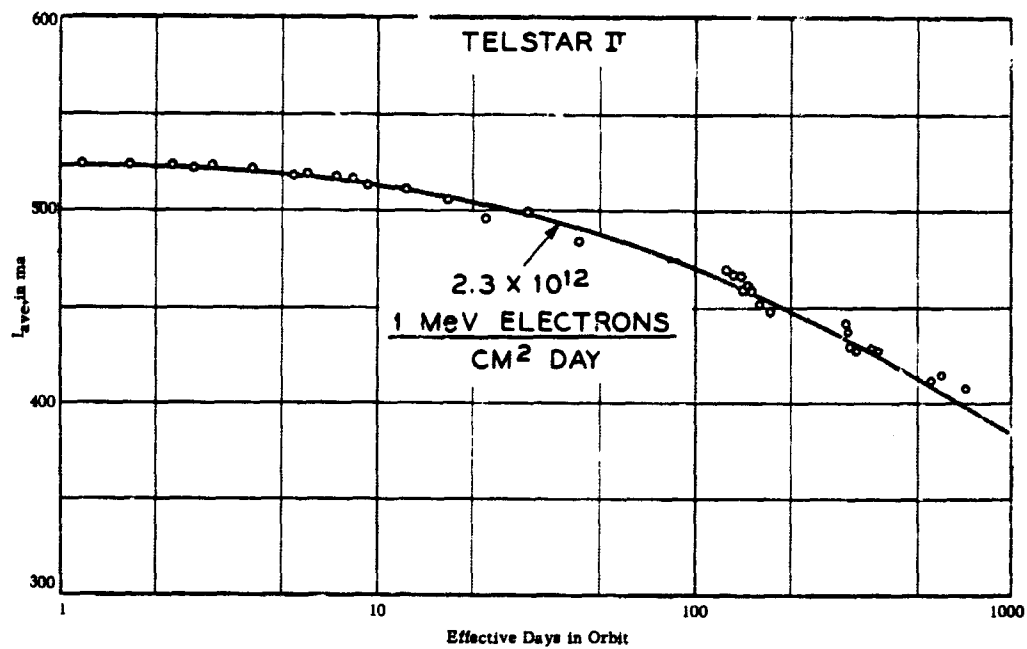


Figure X-6. Current VS. Effective Days in Orbit for Telstar II

32 percent and 26 percent higher than observed on the basis of current degradation of the power supply. This is surprisingly good agreement, considering the approximations which were made and the uncertainties in the radiation fluxes and energy spectra. Also, his analysis made no allowance for an increase of diffusion length with injection level under proton bombardment, which could cause a less rapid degradation of current than predicted.

A long term experiment with one ohm-centimeter cells continued for five years on the ANNA-1B satellite, launched October 31, 1962 into an orbit with 584 nautical mile perigee, 635 nautical mile apogee and 50° inclination. In this low orbit the radiation exposure occurs chiefly as the satellite passes through the region of the South Atlantic Anomaly. Nevertheless, degradation in short circuit current over the long term was fairly smooth, as seen in figure X-7. One sees the superior resistance to radiation effects of n/p cells in comparison to p/n cells. Further, the value of coverslides as shielding is apparent; the cells with the thicker coverslides were less affected than the ones with the thinner coverslides.

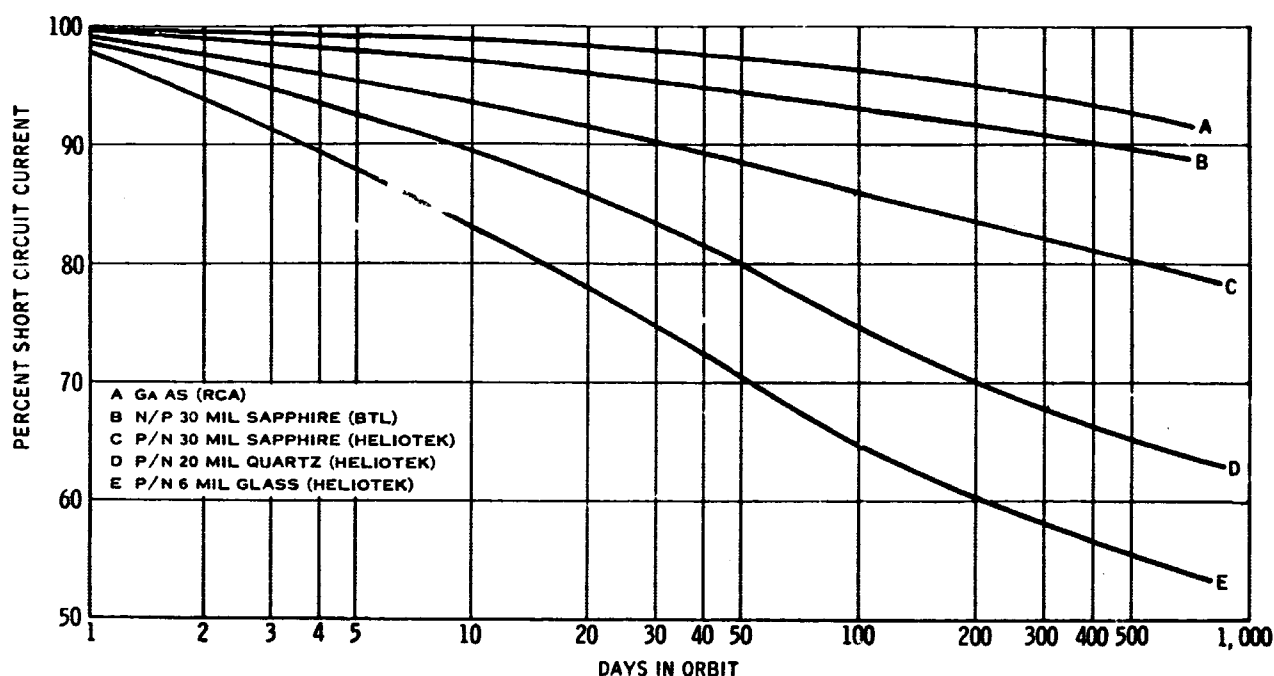


Figure X-7. Results of Solar Cell Experiment on ANNA I-B Satellite, Launched Oct. 31, 1962. Orbit: APOGEE 1130 KM, PERIGEE 1075 KM, Inclination 50.1 degrees.

XI. DESIGN METHODS FOR SOLAR CELL POWER SYSTEMS

A. SELECTION OF TYPE OF SOLAR CELLS

If a proposed satellite is to spend an appreciable time at altitudes between 1000 km and 10,000 km, the effects of radiation become prominent. In this case, n/p silicon solar cells will be preferable over p/n cells. The radiation resistance of the cell increases as its base resistivity increases, as shown in section IV-D and E. The widely-used 10 ohm-cm cells are therefore generally preferred in this regard over the earlier 1 ohm-cm cells. P/N cells may eventually turn out to be the most resistant to radiation if they are lithium-doped and can be developed to meet stability and manufacturing requirements. Recent experimental work looks promising, but has not as yet resulted in production quantities of reliable cells.

The thickness of the solar cell also affects its radiation resistance, as discussed in section IV-F. Since radiation affects primarily the current production from the deep layers of the cell, thinner cells have a smaller percentage drop in power, at the expense of a reduced initial efficiency.

Generally, solar cells have an area of 2 x 2 cm. Sizes such as 1 x 2, 2 x 6 and 3 cm squares are also available. There is no significant relation between radiation resistance and cell area, but lower cost of manufacture and assembly favors the larger cells.

B. CONSTRUCTION OF SOLAR ARRAY

The I-V curve typical of a solar cell, as depicted in section III, figure 1, indicates that for maximum power output, a cell should be operated across a load resistance that permits operation at an optimum output voltage. Cells are connected in series to provide the desired output voltage and strings are connected in parallel to provide the required current. Reliability of the resulting array is improved by interconnecting leads between the rows of cells in parallel strings. To prevent any loss of power through a

solar cell array that is shadowed from the sun, a reverse current blocking diode may be placed in series with each section of the cell array having a different orientation.

The resulting current loops in a spacecraft generate a magnetic field. This can interact with the geomagnetic field, discussed in section V, and provide a torque that disturbs the attitude of the spacecraft or affects magnetic instruments. An array configuration should be developed to reduce the magnetic field to an acceptable level.

As the space environment reduces the output of each cell, the array power production drops by the same percentage. The optimum voltage also shifts. It may be desirable, especially for large loads, that a power conversion unit be provided between the array and load so that the point of maximum power can be followed by the effective load resistance. In any case, it is desirable to design the array to operate near the maximum power point at the end of life, taking into account the highest expected operating temperature of the cells.

C. PROCEDURE FOR CALCULATING SOLAR CELL DEGRADATION IN ARBITRARY ORBITS

The calculation of solar cell performance after prolonged exposure can be a rather complex problem, particularly for orbits which traverse widely varying flux regions of the magnetosphere. The extension of this calculation to the performance of the power system involves additional effects that further complicate the calculation. The effects of cover-slide darkening, erosion by micrometeoroids, adhesive deterioration, power conversion system deterioration, temperature changes, thermal cycling, variation of battery parameters and variations in light intensity all can lead to a performance that is best analyzed by computer. These effects accumulate into a significant addition to the degradation, but it is generally observed that the dominant effect is radiation deterioration of the solar cells.

A simple approximate method for estimating the degradation of short circuit current, maximum power, and open circuit voltage in an arbitrary orbit is given below.

The main steps are:

1. Calculate the radiation exposure and the diffusion length L in base silicon having the resistivity desired for a time in orbit equal to the desired mission life (see procedure in part D below).

2. Using this diffusion length value, enter figures IV-21, IV-23 or IV-24 to determine the maximum power ratio at the end of the mission.
3. Refer to figure IV-28 to estimate the temperature dependence of power at the end of the mission.
4. If data on short circuit current are desired, use figures IV-15, IV-18, or IV-19.
5. If data on open circuit voltage are desired (for 10 ohm-cm n/p cells) use figure IV-27.

D. CALCULATION OF DIFFUSION LENGTH DEGRADATION

The procedure for estimating diffusion length of silicon vs. time in orbit is outlined below:

1. Assume a solar cell coverslide thickness in gm/cm^2 and determine the minimum proton energy (E_C) which will penetrate, using figure VI-1.
2. For the orbit of interest, the flux and energy distribution of protons and electrons to be encountered on the average per day in orbit should be determined by use of Vette's flux maps in section V. The differential proton energy spectrum may be approximated for the energy interval of interest above the shield cutoff energy E_C by the expression,

$$\frac{d\Phi_p}{dE} = I_o e^{-E/E_o} \quad (\text{XI-1})$$

where E_o depends on the range of values of the McIlwain parameter L which will be covered by the orbit, and is presented in figures V-7, V-9, V-11, and V-13.

3. Approximate the proton damage coefficient K_p applicable to the solar cell base material under sunlight injection level by assuming a $1/E$ dependence:

$$K_p = A/E \quad (\text{XI-2})$$

where A is a constant which is determined from figure IV-7 for n/p cells or from figure IV-8 for pn cells. For example, if the curves are matched in the region one to 60 MeV:

$$A = 3 \times 10^{-6} \text{ for } 10 \text{ ohm-cm n/p}$$

$$A = 1.5 \times 10^{-5} \text{ for one ohm-cm n/p}$$

$$A = 6 \times 10^{-5} \text{ for one ohm-cm p/n}$$

4. Form the proton damage rate integral, per day in orbit. This is

$$d_p = \frac{d(1/L^2)}{dt} = \theta \int_{E_c}^{\infty} K_p(E) \left(\frac{d\Phi_p}{dE} \right) dE \quad (\text{XI-3})$$

where E_c is the energy cutoff due to the coverslide, and θ is the fractional correction for back shielding, taken as $1/2$ for infinite back shielding and omnidirectional protons. The integral can be approximated by substitution of the simple expressions described above for the proton flux and the damage coefficient.

$$d_p = \theta A \left\{ I_{oa} \int_{E_c}^{E_2} \frac{e^{-E/E_{oa}} dE}{E} + I_{ob} \int_{E_2}^{E_3} \frac{e^{-E/E_{ob}} dE}{E} + \dots \right\} \quad (\text{XI-4})$$

Each integral represents a segment of the proton spectrum which has been fitted by a formula of the form of equation XI-1. The flux intensity constants I_o can be derived from the piecewise-integrations of the flux, as shown in figures V-14 to V-17. The value of I_o for each interval is

$$I_o = \frac{\Delta \Phi_p}{E_o \left[e^{-E_1/E_o} - e^{-E_2/E_o} \right]} \quad (\text{XI-5})$$

where $\Delta \Phi_p$ is the daily flux for the energy interval, which is readily found for circular orbits as the difference in the integral values for the two energies as plotted in figures V-14 to V-17. In most cases, only the first integral in equation XI-4 need be considered because most of the damage by

protons is produced by the lowest energy group that penetrates to the solar cell. The integral is of the form of the exponential integral

$$F(X) = \int_X^{\infty} \frac{e^{-u}}{u} du \quad (XI-6)$$

This function is plotted as figure XI-1. Therefore, considering only the first term of equation XI-4 yields

$$d_p = \theta A I_{oa} [F(X_c) - F(X_2)] \quad (XI-7)$$

Each succeeding term is of the same form and produces a small correction to this first term approximation.

where

$$X_c = E_c/E_o$$

$$X_2 = E_2/E_o$$

The values of $F(X)$ are read from figure XI-1 at the values of X_c and X_2 which are appropriate.

5. The electron damage rate integral is based on equation VI-1, with shield factors, θ , from figure VI-4, electron damage coefficients, K_E , from figure IV-2, and electron spectral flux values, $\Phi(E)$, from section V, particularly table V-2. The integral can be approximated by a tabular calculation for various energy groups:

$$d_E = \sum_{i=1}^n \theta_E K_E \Delta \Phi_E \quad (XI-7)$$

When the energy groups are sufficiently narrow, θ_E and K_E can be taken from figures VI-5 and IV-2 for the upper energy limit of each group. This provides a conservative estimate of d_E , which becomes more accurate as the spectrum is divided into smaller groups.

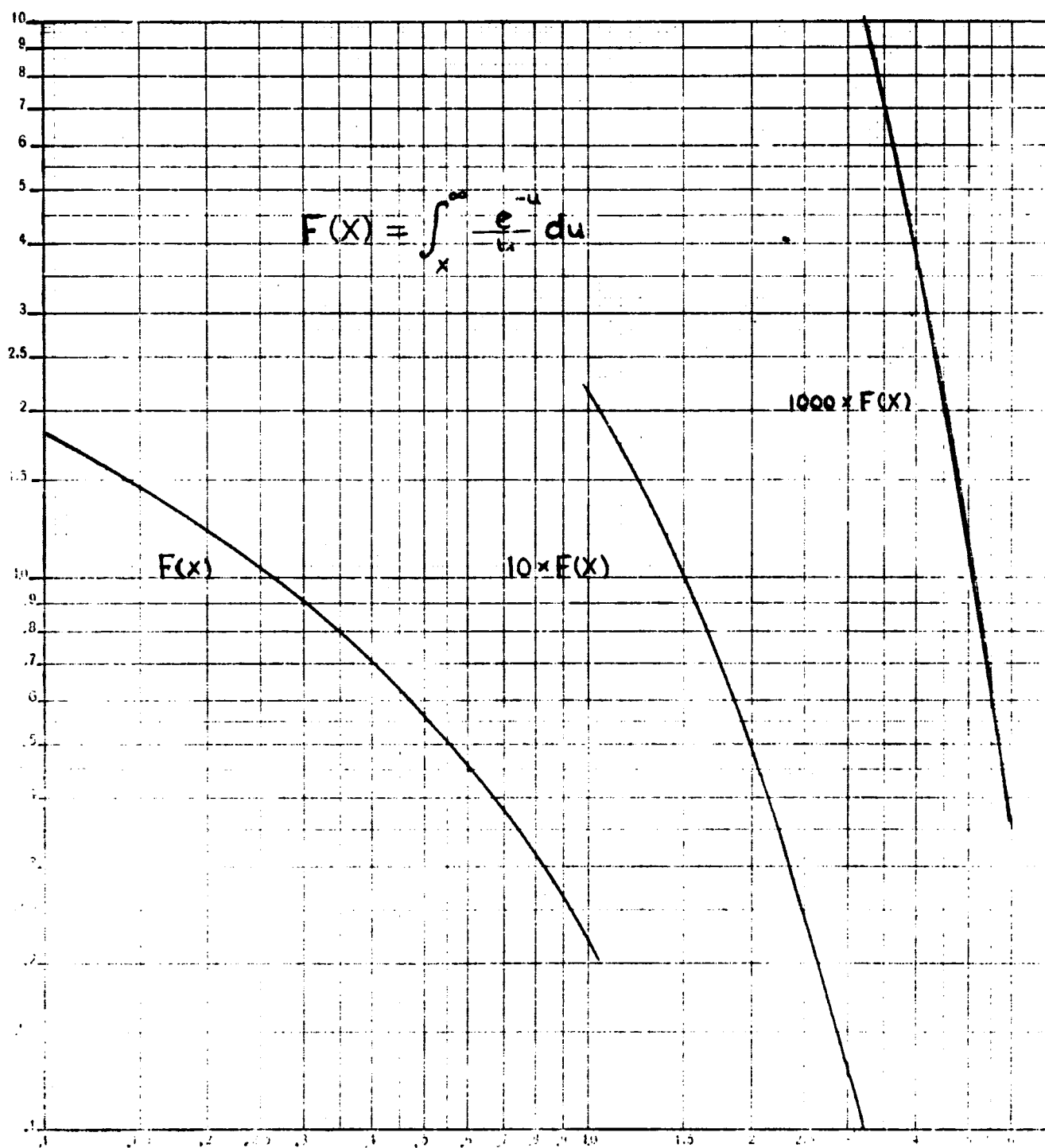


Figure XI-1. The Exponential Integral $F(X)$, for use in Evaluating the Proton Damage Integral

6. The total damage rate per day is the sum of the trapped proton damage rate (step 4, equation XI-7), the electron damage rate (step 5, equation XI-7), and the solar flare proton damage (discussed in part F of this section),

$$d_T = d_p + d_E + d_F \quad (\text{XI-8})$$

The portion due to solar flares for low orbit satellites may often be neglected unless the satellite is in a polar orbit that may expose it to solar flares twice per orbit (near the north and south magnetic poles).

7. The final value of diffusion length, L , in the cells is found from:

$$\frac{1}{L^2} = \frac{1}{L_o^2} + d_T t \quad (\text{XI-9})$$

or,

$$L = \left[\frac{1}{L_o^2} + d_T t \right]^{-1/2} \quad (\text{XI-10})$$

where t is the number of days the spacecraft has been in orbit and L_o is initial diffusion length in cm (1 micron = 10^{-4} cm). Typically, solar cells are manufactured with an L_o of about 150 to 200 microns.

8. The value of L is used with the curves of section IV to determine solar cell performance parameters after a mission life of t days. See part C above for details of the procedure (steps 2 thru 5).

E. CALCULATION FOR A CIRCULAR EQUATORIAL ORBIT AT 2600 MILES

As an example, consider 10 ohm-cm n/p silicon cells having an initial diffusion length of 200 microns and a coverslide shield of 0.3 gm/cm^2 in a circular equatorial orbit at 2250 nautical miles (2600 miles) altitude. This is a fairly thick coverslide, but the orbit goes through a dense radiation region.

1. The proton energy cutoff is at about 14 MeV for a shield of 0.3 gm/cm^2 from figure VI-1. We assume this cutoff is at 15 MeV in order to use Vette's proton data for the energy range 15 to 34 MeV.

2. The proton flux from 15 to 34 MeV at $L = 1.5$ on the equator can be approximated from figure V-9 by:

$$\Delta\Phi_p = I_o e^{-E/E_o},$$

where

$$E_o = 10 \text{ MeV},$$

and from equation XI-5:

$$I_o = \frac{\Delta\Phi_p}{E_o [e^{-X_c} - e^{-X_2}]} = \frac{9.0 \times 10^9 - 1.5 \times 10^9}{10 [e^{-1.5} - e^{-3.4}]} = 3.95 \times 10^9$$

3. The proton damage coefficient for 10 ohm-cm n/p cells from equation XI-2 is

$$K_p = A/E$$

where

$$A = 3 \times 10^{-6} \text{ cm}^{-2}, \text{ MeV}.$$

4. We use only one energy interval as in equation XI-7. The values of X are

$$X_c = E_c/E_o = 15/10 = 1.5$$

$$X_2 = E_2/E_o = 34/10 = 3.4$$

Evaluating $F(X_c)$ and $F(X_2)$ from figure XI-1, we get

$$\begin{aligned} d_p &= \theta A I_o [F(X_c) - F(X_2)] \\ &= (1/2) (3 \times 10^{-6}) (3.95 \times 10^9) [1.0 \times 10^{-1} - 8 \times 10^{-3}] \\ &= 5.93 \times 10^2 \text{ cm}^{-2} \text{ day}^{-1}. \end{aligned}$$

The proton damage rate is later combined with the electron damage rate from step 5 below.

5. By using shield factors from figure VI-5, electron damage coefficients for 10 ohm-cm n/p cells from figure IV-2 and deriving electron fluxes from table V-2, calculate the electron damage using six energy groups as follows:

$E_{\min} - E_{\max}$	$\Phi_e > E_{\min}^*$	$\Delta\Phi_e$	$\theta(E)^{**}$	K_e^{***}
0.5 - 1 MeV	4.18×10^{11}	4.07×10^{11}	.01	9×10^{-11}
1 - 1.5 MeV	1.13×10^{10}	6.06×10^9	.07	1.8×10^{-10}
1.5 - 2 MeV	5.24×10^9	6.80×10^9	.12	2.7×10^{-10}
2 - 2.5 MeV	4.56×10^9	5.80×10^8	.18	4.4×10^{-10}
2.5 - 3.5 MeV	3.98×10^9	9.50×10^8	.25	5.3×10^{-10}
3.5 MeV up	3.03×10^9	3.03×10^9	.4	2×10^{-9}
*from table V-2 **from figure VI-5 ***from figure IV-2; maximum value in interval is used.				

The sum of the products of $K_e \theta(E)$ in the above table is the electron damage integral. This gives

$$d_e = 4.4 \text{ cm}^{-2} \text{ day}^{-1},$$

a contribution significantly lower than the proton damage integral calculated above.

6. The total damage rate, from equation XI-8, is (neglecting solar flares):

$$d_T = d_p + d_e = 593 + 4.4 = 597/\text{cm}^2\text{-day}$$

7. After one year in orbit, the diffusion length L , assuming an initial diffusion length of 200 microns (0.02 cm), is given by equation XI-10 as,

$$\frac{1}{L^2} = \frac{1}{(2 \times 10^{-2})^2} + 597 \times 365$$

$$L = 0.00213 \text{ cm} = 21.3 \text{ microns}$$

8. The degraded solar cell parameters are determined from steps 2 through 5 of the procedure in part C, above. From figure IV-15, the short circuit current in space sunlight drops by a fraction

$$I_{sc}/I_{sc0} = 0.805.$$

Lacking suitable curves for space sunlight, we may assume that the OCLI simulator results approximate the maximum power ratio and the open circuit voltage ratio for the degraded cells. Figure IV-21 gives

$$P_m/P_o = 0.66$$

as the fraction of the initial maximum power output remaining, and figure IV-27 gives

$$V_{oc}/V_{oco} = 0.86$$

as the fractional reduction of the cell's open-circuit voltage.

The dependence of the maximum power on temperature can be determined from figure IV-28. The distance from the Earth to the Sun varies through the year, causing a small sinusoidal variation in solar cell power output. Finally, effects of degradation of cover slides and filters (section VII) and of power conversion and regulation equipment (section VIII) should be considered for a complete picture of the change in the power available to the spacecraft.

F. SAMPLE CALCULATION FOR A SOLAR FLARE EVENT

We will consider for this calculation a solar flare proton fluence at the Earth's orbit of about 10^6 protons/cm², of energies greater than 30 MeV, and with a spectrum of the form E^{-n} . The exponent n generally lies between 3.5 and 6.

To calculate the damage to a solar cell due to a single solar flare, one must determine a representation of the proton spectrum, and with it evaluate the proton damage integral.

Since proton damage increases as the proton energy decreases, a value of 6 used for the exponent n leads to a more damaging spectrum for a given fluence. The requirements that the fluence over 30 MeV total 10^6 means that the spectrum must be

$$\frac{d\phi}{dE} = 1.22 \times 10^{14} E^{-6} \text{ protons/cm}^2, \text{ MeV}$$

for the flare of this size that is most damaging to the solar cell.

The proton damage coefficient varies as A/E up to about 60 MeV. For energies above this, it is conservatively assumed to be roughly constant. Using this behavior, the damage integral is

$$d_p = \theta \int_{E_c}^{60} \frac{d\Phi_f}{dE} \left(\frac{A}{E} \right) dE + \frac{A\theta}{60} \int_{60}^{\infty} \frac{d\Phi_f}{dE} dE$$

where E_c is the minimum energy proton that can penetrate to the sensitive area of the solar cell. θ is the shield factor, which will be assumed to be $1/2$

In the general case where the proton spectrum is $N_o E^{-n}$, this integral has the solution

$$d_p = \frac{\theta A N_o}{n} \left[E_c^{-n} + \frac{(60)^{-n}}{n-1} \right]$$

For the flare under consideration, with a one ohm-cm n/p cell ($A=1.5 \times 10^{-5}$) and a coverslide providing an energy cutoff of 10 MeV, the numerical solution becomes

$$d_p = \frac{1.5 \times 10^{-5} \times 1.22 \times 10^{14}}{2 \times 6} \left[10^{-6} + \frac{(60)^{-6}}{5} \right]$$

$$d_p = 153 \text{ cm}^{-2}/\text{typical flare}$$

and, by comparison with the results of part E, it is seen that such a simple solar flare produces small damage to a 30-mil silica shielded solar cell. However, there is a wide variation in the characteristics and number of solar flares per year. Averaged over the year 1960, for example, the solar flare proton fluence in the vicinity of the Earth was, from table V-2, $5 \times 10^9/\text{cm}^2$. This could provide a damage integral of 7×10^5 , as seen by scaling the above results. A solar cell with an initial diffusion length

L_0 of 150 microns, after spending the year 1960 in orbit outside the radiation belts, would have a diffusion length given by

$$\frac{1}{L^2} = \frac{1}{(1.50 \times 10^{-2})^2} + 7 \times 10^5$$

$$L = 12 \text{ microns.}$$

From figure IV-23, the maximum power ratio is 65 percent for $L = 12$ microns under space sunlight.

One sees that the radiation damage to solar cells by solar flares may be significant, depending particularly on cell shielding, solar activity, and solar flare spectrum.

Solar flare proton damage is a significant consideration for satellites in synchronous orbits. As was discussed in section V-D, magnetic disturbances often accompany solar flares. At synchronous altitudes, such a disturbance can distort the geomagnetic field so that it is essentially ineffective in shielding from solar flare protons of energy down to 4 - 5 MeV.

G. CALCULATION FOR A CIRCULAR POLAR ORBIT COMPARED WITH EXPERIMENT

Consider 10 ohm-cm n/p silicon cells with three different thicknesses of coverslide shielding: bare, with 30 mil sapphire, and with 125 mil fused silica, all on a satellite in a circular polar orbit at 600 nautical miles, in 1964.

The methods described in part E, above, are still applicable although some of the data must now be estimated. The proton fluence is given by figures V-14 through V-17.

E_i (Minimum)	$\Phi_p > E_i$	$\Delta\Phi_p$	$\Delta\Phi_p / \Delta E$
4	25×10^7	17×10^7	1.55×10^7
15	8×10^7	6×10^7	4×10^6
34	2×10^7	5×10^6	3.15×10^5
50	1.5×10^7	1.5×10^7	

The proton energy spectrum is assumed, as before, to follow the shape e^{-E/E_0} (eq. XI-1). The value of E_0 , however, must be estimated either from the above data or from a judicious use of figure V-7. This figure indicates that E_0 , for the 4 to 15 MeV interval, varies from 3 gradually to 6 as B increases to 0.24 gauss, and rapidly climbs thereafter. But figure V-6 indicates that the flux is heavily concentrated in the lower values of B. Physically this is to be expected; the belt is densest near the equator. Our estimate is therefore that $E_0 = 3$ for this situation.

The calculation proceeds as in the previous section. The bare cell is considered first. Here, the proton energy interval 4 to 15 MeV provides the largest damage of the intervals considered. The steps yield the following results:

$$X_c = 4/3 = 1.33$$

$$X_2 = 15/3 = 5$$

$$F(X_c) = 1.30$$

$$F(X_2) = .0012$$

$$e^{-X_c} = 0.264$$

$$e^{-X_2} = 0.007$$

$$I_o = \Delta\Phi_p / E_o (e^{-X_c} - e^{-X_2}) = 22.1 \times 10^7$$

$$\theta A = 0.5 \times 3 \times 10^{-6}$$

$$d_p = \theta A I_o [F(X_c) - F(X_2)] = 374/\text{cm}^2 - \text{day}$$

The proton energy interval 13-34 MeV predominates for the cell with a 30 mil sapphire coverslide. (Figure VI-1 shows that protons with energies less than 13 MeV cannot penetrate the coverslide.) Two energy intervals, 13-15 MeV and 15-34 MeV, from the tabulated spectrum dominate the proton damage. For the first interval, the damage is simply

$$d_p(13-15) = \theta A I_o [F(13/3) - F(15/3)] = 0.50/\text{cm}^2 - \text{day}$$

For the second interval, proceeding as before,

$$d_p(15-34) = \theta A (3 \times 10^9) (1.2 \times 10^{-3} - 10^{-6}) = 5.4/\text{cm}^2 - \text{day}$$

The lowest energy a proton may have and penetrate the 125 mil quartz coverslide is, from figure VI-1, seen to be 24 MeV. Again, this cutoff energy falls inside a proton energy interval, and the damage integral for two groups, here the 24-34 MeV and the 34-50 MeV intervals, are about equally important. I_o is calculated for each group using its end points with equation XI-5, and the 24 MeV cutoff energy enters the calculation only through $F(X_c)$.

The results are

$$d_p(24-34) = \theta A (3 \times 10^9) (4.2 \times 10^{-5} - 0.1 \times 10^{-5}) = 0.18$$

$$d_p(34-50) = \theta A (1.33 \times 10^{11}) (1.06 \times 10^{-6} - 10^{-8}) = 0.21$$

The proton damage integrals for each of the three n/p solar cells considered are the sums of the partial values, d_p , for the allowed proton energies. Thus,

$$d_p \text{ (bare cell)} = 374 + 5.4 + 0.21 = 379.6/\text{cm}^2\text{-day}$$

$$d_p \text{ (30 mil sapphire)} = 0.50 + 5.4 + 0.21 = 6.1$$

$$d_p \text{ (125 mil)} = 0.18 + 0.21 = 0.39$$

Turning now to the component of the damage integral generated by electrons in the radiation belt, we form a table as in part E of this section. Orbital integration of the electron fluence for a polar orbit for the belt as measured in 1964 results in fluences that are tabulated in reference 297a. These will be used, rather than the tables of Section V, since the electron flux decreased considerably between 1964 and 1968.

E	$\Phi_e > E$	$\Delta\Phi_e$	K_e
.5	3.51×10^8	2.11×10^8	9×10^{-11}
1	1.40×10^8	7.32×10^7	1.8×10^{-10}
1.5	6.68×10^7	3.27×10^7	2.7×10^{-10}
2	3.41×10^7	1.59×10^7	4.4×10^{-10}
2.5	1.82×10^7	1.35×10^7	5.3×10^{-10}
3.5	5.72×10^6	5.72×10^6	2×10^{-9}

From figure VI-4, the factor q for equivalence between shielded cells in an isotropic flux and bare cells in a normally incident flux is:

E	θ (30 mil sapphire)	θ (125 mil quartz)
.5	.01	.005
1	.07	.01
1.5	.12	.01
2	.18	.015
2.5	.25	.02
3.5	.4	.10

For the bare cell, θ is 0.5 for all electron energies. The electron damage integral is the sum over all energy groups of the products $\theta K_e \Phi_e$. This is added to the above-computed proton damage integrals to obtain the totals:

$$d_T (\text{bare cell}) = 379.6 + .03 \approx 380/\text{cm}^2\text{-day}$$

$$d_T (30 \text{ mil sapphire}) = 6.1 + .0088 \approx 6.1/\text{cm}^2\text{-day}$$

$$d_T (125 \text{ mil quartz}) = 0.39 + .0017 \approx 0.39/\text{cm}^2\text{-day}$$

The remainder of the calculation proceeds as before. The value of L after t days is given by

$$\frac{1}{L^2} = \frac{1}{L_o^2} + d_T t$$

where L_o , the initial diffusion length, is taken as 200 microns. The short circuit current drops to a fraction of its initial value as given by figure IV-18, depending on L .

Some results are plotted for the bare cell and the 30 mil sapphire-covered cell in figure XI-2 as circles. The lines represent measurements taken on satellite 1963 38C, in a polar orbit at a height of 600 n. mi, with solar cells of the three coverslide thickness used in this calculation (ref. 109). There is reasonable agreement between the

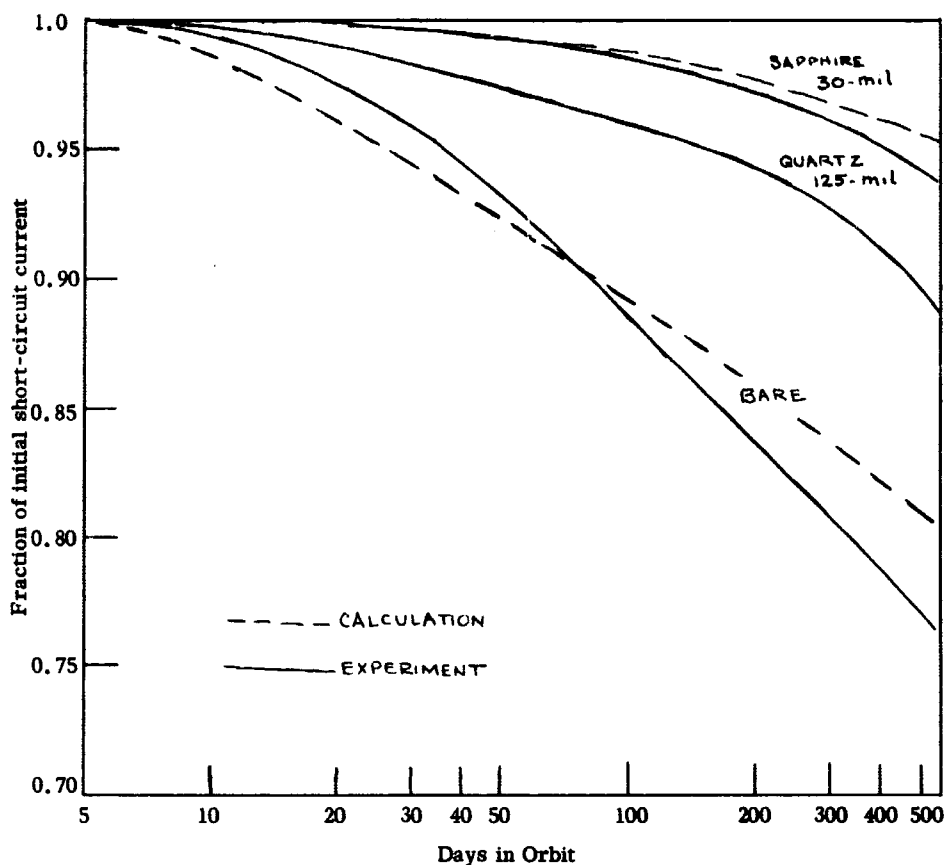


Figure XI-2. Some Results of Solar Cell Experiments on Satellite 1963 38C. This is in a Nearly Circular Polar Orbit at 594 n. mi. The Results are for 10 ohm-cm n/p cells; the Dashes Represent Calculations Detailed in the Text for a 600 n. mi. Polar Orbit.

calculation and the flight results. The theoretical results, for the 125 mil quartz-covered cell, are not shown. These results predict not more than a 1 percent drop in short-circuit current. The actual drop is seen to be much greater. In fact, this cell receives more damage than the one covered with only 30 mils of sapphire. It has been suggested that this anomaly is due to coverslide darkening and (or) adhesive darkening (c.f. Table VII-2).

H. CALCULATIONS OF SOLAR CELL DEGRADATION IN LOW ALTITUDE INCLINED ORBITS

Let us consider typical solar cells, of 10 ohm-cm n/p construction, with 6 mil fused silica coverslides, on satellites in circular orbits at 200 and 300 nautical miles.

Orbital inclination to the equator is assumed to be 30 degrees in each case. The cell output after one year is to be estimated using flux values for 1968.

Section VII presents data to show that fused silica coverslides are highly resistant to radiation darkening. Therefore, and because the coverslide is thin, we shall omit coverslide darkening from this estimate.

1. A compilation of the incident fluences is accomplished with the aid of figure V-15 through 18 for trapped protons, and Table V-2 for trapped electrons. At these low altitudes, the solar flare fluence is blocked by the planet and shielded by the geomagnetic field and is assumed to be negligible.

The omnidirectional proton fluence, of energies above E , at these altitudes is given by figures V-15 to V-18 and is:

E	$\Phi_p(>E)$ at 200 n. mi.	$\Phi_p(>E)$ at 300 n. mi.
4	6×10^6	3×10^7
15	1.5×10^6	5×10^6
34	8×10^5	4×10^6
50	7×10^5	3×10^6

in p/cm^2 -day.

The omnidirectional electron fluence of energies above E is given by the data of reference 297a and is, for a circular orbit inclined 30° to the equator,

E	$\Phi_e(>E)$ at 200 n. mi.	$\Phi_e(>E)$ at 300 n. mi.
.5	1.4×10^8	1.69×10^9
1	3.6×10^6	5.09×10^7
1.5	7.8×10^5	1.00×10^7
2	6.5×10^5	8.56×10^6
2.5	5.8×10^5	7.46×10^6
3.5	4.3×10^5	5.76×10^6

in e/cm^2 -day, where the 200 n. mi. values are simple interpolations.

2. The proton damage integral is formed by the technique of part D above. Estimates of E_0 are obtained from figures V-6 through V-13. For the first two energy groups, at 200 n. miles,

$$I_{oa} = \frac{(6 - 1.5) 10^6}{4 [e^{-4/4} - e^{-15/4}]} = 3.26 \times 10^6$$

$$I_{ob} = \frac{(1.5 - .8) 10^6}{10 [e^{-15/10} - e^{-34/10}]} = 3.69 \times 10^5$$

The contributions by higher energy groups can be computed in a similar manner. They contribute negligibly to the proton damage integral. From figure XI-1,

$$F(4/4) = 0.23$$

$$F(15/4) = 5 \times 10^{-3}$$

$$F(15/10) = 0.10$$

$$F(34/10) = 8 \times 10^{-3}$$

and, from Eq. XI-7, with θ approximated as $1/2$,

$$\begin{aligned} d_p &= (0.5) (3 \times 10^{-6}) (3.26 \times 10^6) [0.23 - 5 \times 10^{-3}] \\ &\quad + (0.5) (3 \times 10^{-6}) (3.69 \times 10^5) [0.10 - 8 \times 10^{-3}] + \dots \end{aligned}$$

$$d_p \approx 1.51/\text{cm}^2\text{-day at 200 n. mi.}$$

In a similar calculation, we obtain

$$d_p \approx 6.9/\text{cm}^2\text{-day at 300 n. mi.}$$

3. The electron damage integral follows from Eq. XI-7, where

$E_{\min} - E_{\max}$	θ_E	$K_E(E_{\max})$	$\Delta\Phi_E$ at 200 n. mi.	$\Delta\Phi_E$ at 300 n. mi.
.5 - 1 MeV	0.30	9×10^{-11}	1.4×10^8	1.64×10^9
1 - 1.5 MeV	0.35	1.8×10^{-10}	2.8×10^6	4.09×10^7
1.5 - 2 MeV	0.40	2.7×10^{-10}	1.3×10^5	1.44×10^6
2 - 2.5 MeV	0.43	4.4×10^{-10}	7×10^4	1.1×10^6
2.5 - 3.5 MeV	0.45	5.3×10^{-10}	1.5×10^5	1.7×10^6
3.5 MeV up	0.46	2×10^{-9}	4.3×10^5	5.76×10^6

Summed over all energy groups, the damage integral due to electrons is,

$$d_E = \sum \theta K_E \Delta\theta_E$$

$$d_E = \begin{cases} .0044/\text{cm}^2\text{-day at 200 n. mi.} \\ .053/\text{cm}^2\text{-day at 300 n. mi.} \end{cases}$$

The total damage integral is the sum of d_p and d_E . Solar flare protons may be neglected for these orbits.

$$200 \text{ n. mi.: } d_T = 1.514/\text{cm}^2\text{-day, or } 553/\text{cm}^2\text{-year}$$

$$300 \text{ n. mi.: } d_T = 6.95/\text{cm}^2\text{-day, or } 2540/\text{cm}^2\text{-year}$$

4. The diffusion length drops in one year from 150 microns to a value L given by

$$\frac{1}{L^2} = \frac{1}{(1.5 \times 10^{-2})^2} + d_T$$

$$L = \begin{cases} 1.41 \times 10^{-2} \text{ cm (141 microns) for 200 n. mi.} \\ 1.195 \times 10^{-2} \text{ cm (119.5 microns) for 300 n. mi.} \end{cases}$$

5. The resulting loss of power capability by the solar cell can be found with the aid of figure IV-21. After one year,

$$\frac{P_m}{P_{mo}} = \begin{cases} 97\% \text{ at } 200 \text{ n. mi.} \\ 93\% \text{ at } 300 \text{ n. mi.} \end{cases}$$

Either of these may be acceptable for the mission at hand. The result indicates, however, a significant advantage for the lower orbit.

Another observation to be made on the basis of this calculation is that almost all the radiation damage to the solar cell is due to protons. Further, step 1 indicates that most of the proton damage is due to protons below 15 MeV. Since protons are stopped by relatively thin shields (as compared with electrons), increasing the coverslide thickness from 6 mils might be advantageous.

I. CALCULATION OF SOLAR CELL DEGRADATION IN SYNCHRONOUS ORBITS

As a final example of an application of the methods outlined above, consider a 10 ohm-cm n/p silicon solar cell in an equatorial 24 hour synchronous orbit with and without a 6 mil fused silica coverslide. With such a thin coverslide being considered we will again neglect the effects of coverslide darkening.

For comparison, an exposure period of 120 days will be assumed. The experiment that is to be compared is aboard the ATS-1 satellite which has been in synchronous orbit since December 1966. After 120 days, bare cells of the above description dropped to 52 percent of their initial short-circuit current, and 56.2 percent of their initial open-circuit voltage. The cells with 6 mil fused silica coverslides dropped to 95.6 percent of their initial short-circuit current and 98.2 percent of their initial open-circuit voltage.

In Section V, analytical forms for the radiation environment at synchronous altitude were given. Both proton and electron fluxes are characterized by lower mean energies than are typical of the previous examples:

$$\frac{d\Phi_P}{dE} = 5 \times 10^5 \exp\left(-\frac{E-0.4}{0.11}\right) / \text{cm}^2\text{-sec-MeV}$$

$$\frac{d\Phi_e}{dE} = 2.2 \times 10^8 \exp(-4.65E) / \text{cm}^2\text{-sec-MeV}$$

The mean energies of protons and electrons at this altitude are both below one MeV. As a result, the energy groupings useful in the previous examples are not appropriate here. Since the fluxes are presented in analytical form, an analytical rather than a numerical evaluation will be demonstrated.

For the proton damage integral, we evaluate Φ_P for one year to be

$$\frac{d\Phi_P}{dE} = 1.65 \times 10^{15} e^{-E/0.11} \text{ p/cm}^2\text{-year-}2\pi \text{ steradians-MeV,}$$

and set the proton damage coefficients to be

$$K_P = \left(\frac{2.2 \times 10^{-6}}{E} \right)$$

(This is somewhat lower than the value assumed earlier in step D-3).

The lower limit, E_{cp} , of proton energies which can penetrate the half-micron surface layer of the solar cell is about 0.17 MeV. The proton damage integral can be integrated with these approximate expressions.

$$\begin{aligned}
\int_{0.17}^{\infty} \left(\frac{2.2 \times 10^{-6}}{E} \right) 1.65 \times 10^{15} e^{-E/0.11} dE &= 3.62 \times 10^9 E_1 (0.17/0.11) \\
&= 3.62 \times 10^9 \times .0957 \\
(K\Phi)_{\text{protons}} &= 3.46 \times 10^8 \text{ per cm}^2\text{-year}
\end{aligned}$$

Similarly, the electron fluence is

$$\Phi_e = 3.3 \times 10^{15} e^{-4.65E} / \text{cm}^2\text{-year} \cdot 2\pi \text{ steradians}$$

The graph of K_e presented in section IV does not allow a simple, approximate calculation of the electron damage integral, but does indicate that when the significant portion of the electron spectrum is below 1 MeV, the damage coefficient can be fitted approximately by the equation

$$K_e = (.922E^2 - .058) 10^{-10}$$

With this expression, the integral can be carried out analytically, with an effective lower limit of 0.25 MeV:

$$\begin{aligned}
\int_{.25}^{\infty} K_e \Phi_e dE &= \frac{.922 \times 3.3 \times 10^{15}}{4.65} \left[(.25)^2 + \frac{2}{(4.65)^2} (4.65 \times .25 + 1) \right] e^{-1.14} \\
&\quad - \left[\frac{.058 \times 3.3 \times 10^{15}}{4.65} \right] e^{-1.14}
\end{aligned}$$

$$(K\Phi)_{\text{electrons}} = 4.15 \times 10^3 \text{ per cm}^2\text{-year}$$

For a one year fluence of solar flares, we take

$$\Phi_f = 9.2 \times 10^{10} E^{-2.33}$$

based on figure V-20 and equation V-11.

The low energy proton cutoff due to geomagnetic shielding is considered to be 5 MeV. Using the same proton damage coefficient as before, the integral becomes

$$\int_5^{\infty} \left(\frac{2.2 \times 10^{-6}}{E} \right) 9.2 \times 10^{10} E^{-2.33} dE = 2.02 \times 10^5 \left(\frac{5^{-2.33}}{2.33} \right)$$

$$(K\Phi)_{\text{flares}} = 2040 \text{ per cm}^2\text{-year for bare cells}$$

Comparison of the three portions of the damage integral indicates that the flare protons produce not quite half as much damage as the trapped electron damage, and both of these are negligible as compared with the trapped proton damage. For the bare cell, the minority carrier diffusion length after one year is given by

$$\frac{1}{L^2} = \frac{1}{(150)^2} + 3.46$$

$$\frac{1}{L^2} = 4.45 \times 10^{-5} + 3.46$$

$$L = 0.537 \text{ microns,}$$

and after 120 days is given by

$$\frac{1}{L^2} = 4.45 \times 10^{-5} + 1.14$$

$$L = 0.94 \text{ microns.}$$

The short-circuit current is then given, assuming negligible temperature change, by extrapolation from figure IV-15 as,

$$\frac{I_{sc}}{I_{sco}} = 0.32 \quad \text{at 120 days}$$

and the open-circuit voltage is estimated from figure IV-27 to be half of the initial value.

$$\frac{V_{oc}}{V_{oco}} = 0.5 \quad \text{at 120 days}$$

These results only approximate the corresponding percentages observed. Part of the difference may be ascribed to the non-uniform damage due to low energy protons. The damage calculated is that to be anticipated near the solar cell junction. The back of the cell is not degraded so greatly, so that the bare cell results of this model are expected to be conservative.

A 6-mil coverslide shields the solar cell from trapped protons. The lowest energy proton which can penetrate a 6-mil coverslide has an energy of 4.2 MeV. Neglecting slowing down and absorption of the higher energy protons, the proton damage integral due to protons above 4.2 MeV is given by

$$\int_{4.2}^{\infty} \left(\frac{2.2 \times 10^{-6}}{E} \right) 1.65 \times 10^{15} e^{-E/0.11} dE = 3.62 \times 10^9 E_1 \left(\frac{4.2}{.11} \right)$$

$$= 3.62 \times 10^9 \times 10^{-20}$$

$$(K\Phi)_{\text{protons}} \approx 10^{-11}$$

which is negligible.

An electron of 0.18 MeV can penetrate a 6-mil coverslide. Thus the 6-mil coverslide reduces electron energies, but does not significantly reduce the number striking the cell. The resulting reduction in the damage integral can be found by lengthy, or machine-aided, calculations. Here, a simple approximation will be used. This is based upon the observation from section VI that a 6 mil shield reduces the damage by 0.5 MeV electrons by a factor of two. With the assumption that this is typical of the electron spectrum considered, the damage integral becomes

$$\begin{array}{rcl} (K\Phi) \text{ electrons} & = & 4150 \times 1/2 = 2075 \\ (K\Phi) \text{ flares} & = & \frac{2040}{4115} \\ (K\Phi) \text{ total} & = & \end{array}$$

After 120 days, this total damage integral for the 6-mil covered cell reduces L according to

$$\frac{1}{L^2} = 4.45 \times 10^{-5} + 4.12 \times 10^{-5} \times \frac{120}{365}$$

$$L = 131 \text{ microns}$$

The short circuit current drop can be estimated from figure IV-15. The ratio to the initial value is

$$I_{sc}/I_{sco} = 0.97$$

as compared to the experimental value of 0.956. (Measured values were adjusted to equal light intensity.)

The open-circuit voltage drops by a fraction

$$V_{oc}/V_{oco} = 0.98$$

according to figure IV-27 as compared to the experimental value of 0.982.

These numbers calculated for a relatively short exposure time deviate somewhat from the measured values. Part of this deviation can be ascribed to the measured increase of 3.7°C in the cell temperatures, but more elaborate calculations would have to include a more precise fitting to the energy dependence of the coverslide shielding effect, the damage coefficients, and the relation of the cell parameters to the diffusion length L . Recent work along this line has been reported by Rasmussen*

J. ALTERNATE CALCULATION METHOD USING EQUIVALENT ONE MeV ELECTRON FLUX

It has become the practice by many organizations to compute solar cell damage by converting all penetrating space radiation fluxes to an equivalent one MeV electron flux. Specifically, the damage to a solar cell with a particular shield thickness by an omnidirectional flux of fast protons and electrons, can be equated to damage by an equivalent unidirectional flux of one MeV electrons impinging on bare cells. This method is satisfactory if laboratory data are available to permit prediction of current, voltage and power of the specific solar cells as a function of one MeV electron exposure when illuminated by space sunlight or an equivalent light source. In this case, the use of equivalent one MeV flux as the independent variable to characterize the damaged state of the cell is fully as adequate as the use of base diffusion length (L) which has been done in this handbook.

Conversion from one basis to the other is possible if experimental data are available to correlate the base diffusion length with the equivalent one MeV electron fluence for the cells of interest. The diffusion length, L , has been used in this handbook because it is a measurable property of the damaged cell and is independent of the type or energy of penetrating radiation which may have been used in laboratory experiments. However, it must be noted that low energy protons, below about 5 MeV produce non-uniform damage with depth in the cell and therefore neither the concept of diffusion length nor equivalent one MeV electron fluence as the single independent parameter is valid. (See figures IV-17 and IV-27).

*Rasmussen, R. Conference Record of the 6th Photovoltaics Specialists Conference, Vol. II, p. 209. March 1967.

XII. REFERENCES AND BIBLIOGRAPHY

1. Akasofu, S.-I., W.C. Lin, and J.A. Van Allen. The Anomalous Entry of Low-Rigidity Solar Cosmic Rays into the Geomagnetic Field. *J. Geophys. Res.* 68:19. Oct. 1963.
2. Alexander, W.M., et al. Review of Direct Measurements of Interplanetary Dust from Satellites and Probes. NASA. Goddard Space Flight Center, Greenbelt, Md. NASA Preprint X-613-62-25. 40 p. (n.d.) (Paper presented at the COSPAR meeting, May 1962.)
3. Allen, L., Jr., et al. Project Jason Measurement of Trapped Electrons from a Nuclear Device by Sounding Rockets. (Symposium on Scientific Effects of Artificially Introduced Radiations at High Altitudes) *J. Geophys. Res.* 64:893-907. Aug. 1959.
4. Allen, W. Experience with Sunlight Simulators. Fourth Photovoltaic Specialists Conference, Proc. Vol. II. June 1964.
5. Almeleh, N., B. Goldstein, Y. Shaham, and J.J. Wysocki. Radiation Damage in Silicon. Radio Corporation of America, Princeton, N.J., First Semi-annual Report on Contract NAS5-3788. 29 p. May 1964.
6. Almeleh, N., B. Goldstein, and J.J. Wysocki. Radiation Damage in Silicon. Radio Corporation of America, Princeton, N.J., Final Report on Contract NAS5-3788. Dec. 1964.
7. Alpher, R.A. Theoretical Geomagnetic Effects in Cosmic Radiation. *J. Geophys. Res.* 55:437-471. 1950.
8. American Society for Testing and Materials, Philadelphia, Pa. Committee E-10 on Radioisotopes and Radiation Effects. Space Radiation Effects on Materials. ASTM Special Tech. Publ. No. 330. Oct. 1962. (See p. 43)
9. Anderson, R.E.D., E.A. Hake, and D. Feldman. Telstar Satellite Power System. Paper presented at the Am. Rocket Soc. Space Power Systems Conference, Santa Monica, Calif., Sept. 25-28, 1962. (ARS Paper No. 2503-62)
10. Anderson, R.E.D., G.W. Meszaros, and D.F. Ciccolella. The Satellite Power System. (Bell Laboratories) Record 41:142-150. April 1963.

11. Anstead, R.J. Measurements of Minority-Carrier Lifetime in N-Type Diffused Skin. Harry Diamond Labs., Washington, D.C., Technical Report. TR-1320. 25 p. Spring 1966. (AD-633 955)
12. Baicker, J.A., and B.W. Faughnan. Radiation Damage to Silicon Solar Cells. Radio Corporation of America, Princeton, N.J., Summary Report on Contract NAS5-457. July 1961.
13. Baicker, J.A., and B.W. Faughnan. Radiation-Induced Changes in Silicon Photovoltaic Cells. J. Appl. Phys. 33:3271. 1962.
14. Baicker, J.A., B.W. Faughnan, and J.J. Wysocki. Radiation Damage to Silicon. Radio Corporation of America, Princeton, N.J., 3rd Semiannual Report on Contract NAS5-457. April 1963.
15. Baicker, J.A., and P. Rappaport. Radiation Damage to Solar Cells. U.S. Atomic Energy Commission Report TID-7652, p. 118-135. Nov. 1962.
16. Bailey, D.K. Time Variations of the Energy Spectrum of Solar Cosmic Rays in Relation to the Radiation Hazard in Space. J. Geophys. Res. 67:1. Jan. 1962.
17. Bartley, W.C., et al. Anisotropic Cosmic Radiation Fluxes of Solar Origin. J. Geophys. Res. 71. 1966.
18. Barton, J.A., editor. Symposium on Space Radiation Environment and Shielding Codes. Boeing Co., Seattle, Wash., Document #D2-90684-1. May 1965.
19. Baruch, P. Radiation Damage in Semiconductors. July 1965. (AD-621 049)
20. Battelle Memorial Inst., Columbus, Ohio. Radiation Effects Info. Center. Radiation-Effects State of the Art 1964-1965. REIC Report No. 38. June 1965. (AD-473 472)
21. Beard, David B. Comets and Cometary Debris in the Solar System. Revs. Geophys. 1:211-229. May 1963.
22. Beatty, M.E., and G.F. Hill. Effect of 40-MeV Protons on Semiconductors as Determined with an Improved Method of Measuring Diffusion Length of Minority Carriers. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-2817. June 1965.
23. Bedwell, Theodore C., Jr., et al, editors. Bioastronautics and the Exploration of Space, The Proceedings of the Third International Symposium on. . . 642 p. Dec. 1965. (AD-627 686)

24. Bell Telephone Laboratories, Inc., New York. NEEP Nuclear Electronic Effects Program. Fifth Triannual Tech. Note on Contract AF33(616)-6235. WADD Technical Note 61-17. Nov. 1960. (AD-254 479 L)
25. Bell Telephone Laboratories, New York. Project SERB. Study on the Enhanced Radiation Belts. Final Report of Experiments on Explorer XV on Contract NAS5-3058. June 1964.
26. Bemski, G. IRE, Proc. 46:990. 1958.
27. Berger, Martin J., and Stephen M. Seltzer. Energy Spectra and Angular Distributions of Electrons Transmitted Through Sapphire (Al_2O_3) Foils. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Special Publication 3008. 1964.
28. Berman, Paul. Radiation Damage in Silicon Solar Cells Using 750 KeV and MeV Electrons. Presented at the meeting on Radiation Damage to Semiconductors by High Energy Protons, U.S. National Aeronautics and Space Administration, Washington, D.C., Oct. 20, 1960.
29. Berry, L.A., et al. Radiation Effects on Silicon. General Dynamics, San Diego, Calif. John Jay Hopkins Lab. for Pure and Applied Sci., Third Quarterly Progress Report on Contract NAS7-289. GACD-6249. March 1965.
30. Bertolotti, Mario. Radiation Damage on Diodes and Transistors. Part I. Alta Frequenza 31:104-115. Feb. 1962.
31. Bilinski, J.R., and R. Merrill. Selecting Transistors for Radiation Environments. Electronics. p. 38-40. Dec. 25, 1959.
32. Bilinski, J.R., et al. Proton-Neutron Damage Correlation in Semiconductors. General Electric Co., Syracuse, New York, Final Report on Contract NAS 1-1595. June 1962.
33. Billington, D.S., and H. Crawford, Jr. Radiation Damage in Solids. Princeton University Press, 1961.
34. Blair, John. Impurity Photovoltaic Effect in Cadmium Sulfide. In Proceedings of the 5th Photovoltaic Specialists Conference, Vol. I, Section B-3. Dec. 1965. (Published by the Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6)
35. Bobone, R., and B.W. Merchant. Predicting Damage to Silicon Solar Cells Subject to Complex Radiation Spectra. AIEE Conference Paper 62-1279. 1962.

36. Bomberger, D.C., et al. The Spacecraft Power Supply System. Bell System Tech. J. 42:943-972. July 1963.
37. Bostrom, C.O., and D.J. Williams. Time Decay of the Artificial Radiation Belt. J. Geophys. Res. 70:240-242. Jan. 1965.
38. Brancato, E.L. The Effects of Space Radiation on Solar Cells and Components. Paper presented at the Fall National Symposium of the Society of Aerospace Material and Process Engineers, Seattle, Washington, Nov. 18-20, 1963.
39. Brancato, E.L. Determination of Significant Differences in Solar Cell Experiments. In Transcript of the Third Photovoltaic Specialists Conference, Vol. I, Section B-5. July 1963. (Published by the Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
40. Brandhorst, H.W., Jr. Airplane Testing of Solar Cells. Presented at the Fourth Photovoltaic Specialists Conference, Cleveland, Ohio, June 1964.
41. Brandhorst, H.W., Jr. Calibration of Solar Cells using High-Altitude Aircraft. In Proceedings of the 5th Photovoltaic Specialists Conference, Vol. III, Section E-1. Jan. 1966. (Published by the Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.2)
42. Brandhorst, H.W., Jr., and R.E. Hart, Jr. Radiation Damage to Cadmium Sulfide Solar Cells. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-2932. July 1965.
43. Brown, W.L., J.D. Gabbe, and W. Rosenzweig. Results of the Telstar Radiation Experiments. Bell System Tech. J. 42:1505-1561. July 1963.
44. Brown, R.R. Natural Space Radiation Effects to Sensitive Space System Components and Materials. Vol. 1 Space Radiation Environment. Boeing Co., Seattle, Wash., Document #D2-90037-1. (1963)
45. Brown, R.R. Proton and Electron Permanent Damage in Silicon Semiconductor Devices. In Radiation Effects in Electronics, Am. Soc. for Testing and Materials, Philadelphia, Pa. ASTM Special Tech. Publ. No. 384. May 1965.
46. Brown, W.L. Damage to Semiconductors from Space Radiation. Presented at the Am. Rocket Soc. Space Nuclear Conference, Gatlinburg, Tenn., May 3, 1961.
47. Brown, W.L. Personal Communication, July 15, 1963.

48. Brown, W.L. Radiation Damage Effects on Telstar and Serb. In Transcript of the Third Photovoltaic Specialists Conference, Vol. I, Section B-7. April 1963. (Published by the Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
49. Brown, W.L. Studies of Trapped Radiation by the Telstar I and Explorer XV Satellites. In Proc. Plasma Space Sci. Symposium, edited by Chang & Huang.
50. Brown, W.L., et al. Final Report on Bell Telephone Laboratories Experiments on Explorer XII, Project SERB (Study on the Enhanced Radiation Belts). NASA Contract NAS 5-3058, June 30, 1964.
51. Brucker, G., W. Dennehy, and A. Holmes-Siedle. High-Energy Radiation Damage in Silicon Transistors. IEEE Trans. on Nuclear Sci. NS-12(5):69-77. Oct. 1965.
52. Burrill, J.T. Ion Implantation as a Production Technique. In Proceedings of the 5th Photovoltaic Specialists Conference, Vol. I, Section B-1. Dec. 1965. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6)
53. Campbell, F.J. Effects of Radiation on Transmittance of Glasses and Adhesives. Presented at the 17th Annual Power Sources Conference, May 21-23. 1963. (Sponsored by NASA and the Dept. of the Navy)
54. Campbell, F.J. Effects of Space Radiation on Solar Cell Cover Materials. In Transcript of the Photovoltaic Specialists Conference, Vol. II, Section D-2. July 1963. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3.1)
55. Campbell, F.J. Personal Communication, June 1963.
56. Campbell, F.J. Status of Solar Cell Cover Material Radiation Damage. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. II, Section D-2.1. Jan. 1966. (Published by Power Info. Center Philadelphia, Pa. PIC-SOL 209/6.1)
57. Campbell, F.J., and R.J. Lambert. Effects of Shielding on Electron Damage to Solar Cells. In Proc. 4th Photovoltaic Specialists Conference. Aug. 1964. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/5)
58. Carter, J.R., Jr. Radiation Damage in Lithium Doped Silicon. Paper presented at the IEEE Annual Conference on Nuclear and Space Radiation Effects, Columbus, Ohio July 1967.

59. Carter, J.R., and R.G. Downing. Charged Particle Radiation Damage in Semiconductors, XI: Effects of Low Energy Protons and High Energy Electrons on Silicon. TRW Space Technology Laboratories, Redondo Beach, Calif., Interim Tech. Final Report on Contract NAS5-3805. TRW 4161-6012-RU-000. May 4, 1965.
60. Carter, J.R., and R.G. Downing. Charged Particle Radiation Damage in Semiconductors, VII: Energy Levels of Defect Centers in Electron and Proton Bombarded Silicon. TRW Space Technology Labs., Redondo Beach, Calif., Report on Contract NAS5-1851. TRW 8652-6021-KU-000. Feb. 15, 1963.
61. Carter, J.R., and R.G. Downing. Effects of Low Energy Protons and High Energy Electrons on Silicon. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Contract Report 404. March 1966.
62. Carter, J.R., R.G. Downing, and H. Flicker. Charged Particle Radiation Damage in Semiconductors, XII: Effects of High Energy Electrons in Silicon Solar Cells. TRW Space Technology Labs., Redondo Beach, Calif., Final Tech. Report on Contract NAS5-3805. TRW 4161-6023-R0000. May 25, 1966.
63. Chapin, W.E., et al. Space-Radiation Damage to Electronic Components and Materials. Radiation Effects Information Center, Columbus, Ohio Report No. 32. Oct. 1963.
64. Chapman, M.C., and M.R. Morrison. A Summary of Natural Particulate Radiation in Space. Northrop Space Labs., Hawthorne, Calif., Progress Report on Contract AF33(657)-7851. Technical Documentary Report ASD-EDR-62-606. Jan. 1963.
65. Cherry, William R. (NASA, Goddard Space Flight Center, Greenbelt, Md.) Solar Cell Radiation Damage with 1 MeV Electrons. (Includes Specification No. 63-106 - . . . for Determining Relative 1 MeV Electron Radiation Damage Resistance for Silicon Solar Cells, Oct. 31, 1962) n.d.
66. Cherry, William R., and Luther W. Slifer. Solar Cell Radiation Damage Studies with 1 MeV Electrons and 4.6 MeV Protons. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-2098. Feb. 1964.
67. Cheslow, M., and S. Kaye. Feasibility Study Toward Development of Radiation Resistant Solar Cell. Electro-Optical Systems, Inc., Pasadena, Calif. Final Report on Contract NAS7-92. EOS Report No. 2080-Final. Feb. 1963.
68. Clark, J.W. Effects of Radiation on Semiconductors. Electronic Industries 16(8):80. 1957.

69. Clark, J.W., H.L. Wiser, and M.D. Petroff. Radiation Effects on Silicon Diodes. IRE-Wescon Convention Record Vol. 1, No. 43. 1957.
70. Clifton, Sturat, and Robert Naumann. Pegasus Satellite Measurements of Meteoroid Penetration (Feb. 16 - Dec. 31, 1965). U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Memorandum X-1316. Dec. 1966.
71. Corelli, J.C., and H.B. Huntington. Radiation Damage to Semiconductors by High-Energy Electron and Proton Radiation. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Contract Report 62. July 1964.
72. Cosby, William A., and Robert G. Lyle. The Meteoroid Environment and its Effects on Materials and Equipment. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Special Publications 78. 1965.
73. Cunningham, B.T., and E. Moss. Post Irradiation Room Temperature Electrical Characteristics of N/P Silicon Solar Cells. NASA. Goddard Space Flight Center, Greenbelt, Md. NASA Preprint X-636-64-253. Aug. 1964.
74. Cunningham, B.T., R.L. Sharp, and L.W. Slifer. The Electrical Characteristics of Irradiated Silicon Solar Cells as a Function of Temperature. NASA, Goddard Space Flight Center, Greenbelt, Md. NASA Preprint X-636-64-135. March 1964.
75. Curtis, O.L., Jr. Effects of Oxygen and Dopant on Lifetime in Neutron-Irradiated Silicon. IEEE Trans. on Nuclear Sci. NS-13(6):33-40. Dec. 1966.
76. Dash, W.C., and R. Newman. Intrinsic Optical Absorption in Single-Crystal Germanium and Silicon at 77°K and 300°K. Phys. Rev. 99(4):1151-1155. Aug. 1955.
77. Davis, Don D. Space Environment and Its Effect on Materials. In Proc. of NASA - Univ. Conference on the Science and Technology of Space Exploration. Vol. 2, p. 439-449. Nov. 1962.
78. Davis, Leo R., and J.M. Williamson. Low-Energy Trapped Protons. NASA Goddard Space Flight Center, Greenbelt, Md. NASA Preprint X-611-62-89. 1962.
79. Dawson, K.M., G.C. Cleven, and C.D. Fredrickson. Reliability Considerations in the Design, Assembly, and Testing of the Mariner IV Power System. U.S. National Aeronautics and Space Administration. Washington, D.C. NASA Contract Report 63807. July 1965.

80. Denney, J.M., and R.G. Downing. Charged Particle Radiation Damage in Semiconductors, VIII: The Electron Energy Dependence of Radiation Damage in Photovoltaic Devices. TRW Space Technology Labs., Redondo Beach, Calif., Report on Contract NAS5-1851. TRW 8653-6025-KU-000. July 1963.
81. Denney, J.M., and R.G. Downing. Charged Particle Radiation Damage in Semiconductors, IX: Proton Radiation Damage in Silicon Solar Cells. TRW Space Technology Labs., Redondo Beach, Calif., Final Report on Contract NAS5-1851. TRW 8653-6026-KU-000. Aug. 1963.
82. Denney, J.M., and R.G. Downing. Final Report, Charged Particle Radiation Damage in Semiconductors, I: Experimental Proton Irradiation of Solar Cells. TRW Space Technology Labs., Los Angeles, Calif., Report on Contract NAS5-613. TRW 8987-0001-RU-000. Sept. 1961.
83. Denney, J.M., et al. Charged Particle Radiation Damage in Semiconductors, IV: High Energy Proton Radiation Damage in Solar Cells. TRW Space Technology Labs., Redondo Beach, Calif., Report on Contract NAS5-1851. TRW 8653-6017-KU-000. Jan. 1963.
84. Denney, J.M., R.G. Downing, S.R. Lackman, and J.W. Oliver. Estimate of Space Radiation Effects on Satellite Solar Cell Power Supplies. TRW Space Technology Labs., Los Angeles, Calif., Report EM 10-21 MR-13. Oct. 20, 1961.
85. Denney, J.M., R.B. Downing, and G.W. Simon. Revision of Charged Particle Radiation Damage in Semiconductors, III: The Energy Dependence of Proton Damage in Silicon. TRW Space Technology Labs., Redondo Beach, Calif., Report on Contract NAS5-1851. TRW 8653-6005-KU-001. Feb. 1963.
86. Denney, J.M., R.G. Downing, W.I. Hoffnung, and W.K. Van Atta. Charged Particle Radiation Damage in Semiconductors, V: Effect of 1 MeV Electron Bombardment on Solar Cells. TRW Space Technology Labs., Redondo Beach, Calif., Report on Contract NAS5-1851. TRW 8653-6018-KU-000. Feb. 11, 1963.
87. Denney, J.M., and D. Pomeroy. Radiation Damage and Transistor Life in Satellites. IRE, Proc. 48(5):950-2. May 1960.
88. Denney, J.M., et al. Charged Particle Radiation Damage in Semiconductors, VI: The Electron Energy Dependence of Radiation Damage in Silicon Solar Cells. TRW Space Technology Labs., Redondo Beach, Calif., Report on Contract NAS5-1815. TRW 8653-6019-KU-000. Feb. 13, 1963.

89. Denney, J.M., et al. Preliminary Flight Report No. 2, Tetrahedral Research Satellite No. 1. Space Technology Labs., Inc., Los Angeles, Calif. Report 8685-6002-KU-000. Nov. 19, 1962.
90. Dessler, A.J. Penetrating Radiation. In Satellite Environment Handbook, edited by F.C. Johnson. Dec. 1960.
91. Diedrich, James H., and Francis S. Stepka. Investigation of Damage to Brittle Materials by Impact with High-Velocity Projectiles into Glass and Lucite. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-2720. March 1965.
92. Donner, R. Nondissipative DC to DC Regulator-Converter Study. United Aircraft Corp., Broad Brook, Conn. First Quartly. Rept. on Contract NAS 5-3921. HSER 3037. Sept. 1964.
93. Downing, R.G. Low Energy Proton Degradation in Silicon Solar Cells. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. II, Section D-7. Jan. 1966. (Published by the Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.1)
94. Downing, R.G. STL Radiation Damage Experiments. In Transcript of the Photovoltaic Specialists Conference, Vol. I, Section B-3. July 1963. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
95. Downing, R.G., and J.M. Denney. Lifetime Dependence in Proton Bombarded Silicon on Minority Carrier Density. TRW Space Technology Labs., Redondo Beach, Calif., Report on Contract NAS5-1851. TRW 8653-6016-KU-000. Jan. 18, 1963.
96. Drennan, J.F., and D.J. Hamman. Space Radiation Damage to Electronic Components and Materials. Radiation Effects Info. Center, Columbus, Ohio. REIC Report No. 39. Jan. 1966.
97. Duncan, C., et al. Solar Simulation Research. NASA, Goddard Space Flight Center, Greenbelt, Md. NASA Preprint X-633-65-332. 1965.
98. Dungey, J.W. In Planetary Space Sci. 11:591. 1963.
99. Easley, J.W., and J.A. Dooley. On the Neutron Bombardment Reduction of Transistor Current Gain. J. Appl. Phys. 31:1024-1028. June 1960.
100. Evans, R.D. The Atomic Nucleus, McGraw Hill, 1955. (p. 624.)

101. Evans, R.D. Principles for the Calculation of Radiation Dose Rates in Space Vehicles. Arthur D. Little, Inc., Cambridge, Mass., Report 63270-05-01. July 1961.
102. Fairbanks, J.W. The Feasibility of a Programmed Heat Shield for Solar Cell Performance Control. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. III, Section E-8. Jan. 1966. (Published by the Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.2)
103. Fichtel, C.F., et al. Solar Proton Manual. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Report R-169. Dec. 1963.
104. Fillius, R. Walker. Trapped Protons of the Inner Radiation Belt. J. Geophys. Res. 71:97-123. Jan. 1966.
105. Fischell, R.E. Anna 1-B Solar Cell Damage Experience. In Transcript of the Photovoltaic Specialists Conference, Vol. I, Section B-8. July 1963. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
106. Fischell, R.E. Effect of the Artificial Radiation Belt on Solar Power Systems. APL Tech. Digest 2(2):8-13. Nov.-Dec. 1962.
107. Fischell, R.E. Solar Cell Performance in the Artificial Radiation Belt. Presented at the ARS Space Power Systems Conference, Santa Monica, Calif., Sept. 1962. (ARS Paper 2578-62)
108. Fischell, R.E. Solar Cell Power Systems for APL Satellites. In Conf. Record of the 6th Photovoltaics Specialists Conference, Vol. II, p. 32-53. 1967.
109. Fischell, R.E., and J.H. Martin. Radiation Damage to Orbiting Solar Cells and Transistors. In Radiation Trapped in the Earth's Magnetic Field, Reidel Publ. Co., Holland, 1966.
110. Foster, J.V., et al. A Comparison of Gallium Arsenide and Silicon Cells for a Solar Mission. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. III, Section E-5. Jan. 1966. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.2)
111. Frank, L.A., J.A. Van Allen and E. Macagno. Charged-Particle Observations in the Earth's Outer Magnetosphere. J. Geophys. Res. 68:3543-3554. June 1963.
112. Frank, M., and F. Larin. Effect of Operating Conditions and Transistor Parameters in Gain Degradation. IEEE Trans. on Nuclear Sci. NS-12(5):126-133. Oct. 1965.

113. **Freden, S.C., and R.S. White. Particle Fluxes in the Inner Radiation Belt. J. Geophys. Res. 65:1377-1383. May 1960.**
114. **Freeman, J.W., Jr. The Geomagnetically Trapped Radiation. In Second Symposium on Protection Against Radiations in Space, Gatlinburg, Tenn., Oct. 1964. NASA Special Publication 71.**
115. **Freidman, A., et al. The Effect of Reactor Radiation and Temperature on Silicon Junction Diodes. General Electric, Cincinnati, Ohio. Contract Report on AF 33(600)-38062. Report APEX 462. Feb. 1959.**
116. **Freier, P.S., and W.R. Webber. Exponential Rigidity Spectrums for Solar-Flare Cosmic Rays. J. Geophys. Res. 68:1605-1629. March 1963.**
117. **Gardner, L.B. Semiconductors and Space Radiation. Solid State Design 3(4):42-46. April 1962.**
118. **Gault, Donald E., E.M. Shoemaker, and H.J. Moore. Spray Ejected from the Lunar Surface by Meteoroid Impact. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-1767. April 1963.**
119. **Gibson, D.W., and J. Weinard. Absolute Spectral Energy Distribution of Light Sources. In Proc. of the Solar Working Group Conference, Vol. II, p. 27-28. Feb. 1962.**
120. **Goddard Space Flight Center Contributions to the COSPAR Meeting, May 1962. NASA Technical Note D-1669. 1962.**
121. **Goetzol, C.G., and J.B. Singletary. Space Materials Handbook. Lockheed Missiles and Space Co., Sunnyvale, Calif. Jan. 1962.**
122. **Gonshery, Marvin E. Pulsed Nuclear Radiation Effects on Optical Materials, Presented at the Fall Meeting of the Optical Soc. of America, Los Angeles, Calif. Oct. 1961.**
123. **Gorchyakov, E.V. Disposition of the Inner Radiation Belt and Magnetic Field of the Earth. AIAA Journal 1(2):520-521. Feb. 1963.**
124. **Gremmelmaier, R. Irradiation of P-N Junctions with Gamma Rays: A Method for Measuring Diffusion Lengths. IRE, Proc. 46(6):1045-1049. June 1958.**
125. **Gummel, H.K., and F.M. Smits. Evaluation of Solar Cells by Means of Spectral Analysis. Bell System Tech. J. 43:1103-1121. 1964.**

126. Hammel, R. L. Low Energy Radiation Damage to Surfaces. Report of the TRW Space Technology Labs., Redondo Beach, Calif. n.d.
127. Hammel, R. L., M.E. Kirkpatrick, and E.E. Luedke. Observations on Vacuum Ultraviolet Materials Studies. Space Technology Labs., Redondo Beach, Calif. Report 9869-6001-KU-000, MR 24. Nov. 26, 1962.
128. Hastings, E.C., Jr. The Explorer XVI Micrometeoroid Satellite - Supplement I, Preliminary Results for the Period Jan. 14, 1963 - March 2, 1963. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Memorandum X-824. April 1963.
129. Haynes, G.A., and W.E. Miller. Effects of 1.2 and 0.30 MeV Electrons on the Optical Transmission Properties of Several Transparent Materials. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-2620. March 1965.
130. Haynos, J.G. Investigation of Resinous Materials for Use as Solar Cell Cover Glass Adhesive. NASA, Goddard Space Flight Center, Greenbelt, Md. NASA Preprint X-716-65-369. Sept. 1965.
131. Head, Victor P. Correlation of Meteoroid Environments in the Solar System. AIAA Journal 5:1976-1984. Nov. 1967.
132. Hendricks, S.J., and J.C. Cain. Magnetic Field Data for Trapped-Particle Evaluation. J. Geophys. Res. 71:346-347. 1966.
133. Hesketh, R.U. Photon Creation and Destruction of F Centres. Phil. Mag. (8th Series) 4:114-125. 1959.
134. Hess, W.N. The Bomb-Produced Radiation Belt. IEEE Trans. on Nuclear Sci. NS-10(1):8-11. Jan. 1963.
135. Hess, W.N. Neutrons in Space. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-1696. Feb. 1963.
136. Hess, W.N. The Artificial Radiation Belt Made on July 9, 1962. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-1687. April 1963.
137. Hoffman Electronics Corp., El Monte, Calif. Design Study of Solar Energy Measurement Techniques. ASD-TDR-62-8882. Nov. 9, 1962.
138. Hofmann, D.J., and J.R. Winckler. Simultaneous Balloon Observations. J. Geophys. Res. 68:2067-2098. April 1963.

139. Hollister, William L., compiler. Radiation Effects on Electronic Components: An Annotated Bibliography. Lockheed Missiles & Space Co., Sunnyvale, Calif., Contract AF 04(647)840. Special Bibliography-62-13. April 1962.
140. Holmes-Siedle, A.G. Space Radiation. Its Influence on Satellite Design. Radio Corp. of America, Princeton, N.J. Paper PE-239. 1965.
141. Honaker, W.C., and F.R. Bryant. Irradiation Effects of 40 and 440 MeV Protons on Transistors. U.S. National Aeronautics and Space Administration. Washington, D.C. NASA Technical Note D-1490. Jan. 1963.
142. Hughes, H.L., and P.A. Giroux. Space Radiation versus MOS Devices and Circuits. Paper presented at the 12th East Coast Conference on Aerospace and Navigational Electronics, Baltimore, Md. Oct. 1965.
143. Hulten, W.C., W.C. Honaker, and J.L. Patterson. Irradiation Effects of 22 and 240 MeV Protons on Several Transistors and Solar Cells. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-718. April 1961.
144. Hunter, L.P. Handbook of Semiconductor Electronics. 2nd ed. McGraw-Hill, New York. 1962. (Section 3.6)
145. Huth, G.C. Study Directed Toward Improving the Radiation Tolerance of Silicon Diodes. In Proc. of the 2nd AGET Conference on Nuclear Radiation Effects on Semiconductor Devices, Materials and Circuits, Cowan Publ., Sept. 1959.
146. Iles, P.A. Integral Glass Coating for Solar Cells. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. I, Section B-4. Dec. 1965. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6)
147. Institute of Radio Engineers, New York. IRE Third Annual Seminar: Reliability of Space Vehicles. Held in Los Angeles, Calif., Oct. 1962.
148. Jaffe, L.D., and J.B. Rittenhouse. Behavior of Materials in Space Environments. Presented at the Am. Rocket Soc. Space Flight Report to the Nation, New York, Oct. 9-15, 1961. ARS Paper 2033-61.
149. Johnson, F.S., editor. Satellite Environment Handbook. Lockheed Aircraft Corp., Sunnyvale, Calif., Missiles and Space Division. LMSD-895006 (Technical Report: Physics). Dec. 1960. (AD-249 473)
150. Johnson, F.S. The Solar Constant. J. Meteorology 2(6):431. 1954.
151. Jones, D.C. TREE (Transient Radiation Effects on Electronics) Handbook. DASA 1420. Feb. 26, 1965.

152. Junga, A., and G.M. Enslow. Radiation Effects on Silicon Solar Cells. IRE Trans. on Nuclear Sci. June 1959.
153. Kallander, J.W., and J.F. Weller. Radiation Behavior of Electrical Materials and Components for Space Vehicles. Paper presented at the 5th Navy Science Symposium, Annapolis, Md., April 18, 1961.
154. Katz, L., and A.S. Penfold. Range-Energy Relationships for Electrons and the Determination of Beta-Ray and End Point Energies by Absorption. Rev. Modern Phys. 24:28. 1952.
155. Kaye, S. Drift Field Solar Cells. In Transcript of the Photovoltaic Specialists Conference, Vol. I, Section B-11. July 1963. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
156. Kaye, S. Feasibility Study Toward Development of Radiation Resistant Solar Cell. Electro-Optical Systems, Inc., Pasadena, Calif., Interim Engr. Report on Contract NAS7-92. Nov. 30, 1962. EOS Report 2080-IR-2.
157. Kaye, S. Status of Advanced Solar Cells at Electro-Optical Systems, Inc. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. I, Section A-4. Dec. 1965. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6)
158. Keister, G.L., and H.V. Stewart. The Effect of Radiation on Selected Semiconductor Devices. In Proc. of the I.R.E. 45:931-937. 1957.
159. Keller, J.W., R.D. Shelton, R.A. Potter, and L. Lacy. A Study of the Effect of Geomagnetically Trapped Radiation on Unprotected Solar Cells. Proc. IRE 50(11):2320-2327. Nov. 1962.
160. King, J.H. Models of the Trapped Radiation Environment. Volume IV: Low Energy Protons. U.S. Aeronautics and Space Administration, Washington, D.C. NASA Special Publication 3024. 1967.
161. Kleinman, D.A. Considerations on the Solar Cell. Bell System Tech. J. 40:85-115. Jan. 1961.
162. Krause, A.J., and R.R. Ferber. Enhanced Radiation Resistance of Concentrator Solar Cell Panels. Solar Energy 10(2). April 1966.
163. Kuhn, E., F.E. Schwamb, and W.T. Payne. Solar Flare Hazard to Earth-Orbiting Vehicles. In Second Symposium on Protection Against Radiations in Space, Gatlinburg, Tenn., Oct. 1964. NASA Special Publication 71.

164. Lambert, R.J. Instrumentation for the Direct Measurement of Outer Space Short Circuit Current of Solar Cells. *Rev. Sci. Instruments* 36:1713-1719. Dec. 1965.
165. Lamond, P., and B. Dale. Lifetime Evaluation in P-N Junctions by the Use of Spectral Response Curves. *In Colloque International sur les Dispositifs a Semiconducteurs*, Editions Chiron, Paris. 1961.
166. Lamorte, M.F., and G.W. McIver. Development of Improved Solar Energy Converters from Gallium Arsenide. Radio Corp. of America, Somerville, N.J. Report on Contract AF33(616)-6615. Sept. 1962. Issued as Technical Documentary Report no. ASD-TDR-62-639.
167. Latil, J.P. Carbon Arc Solar Radiation Simulators. *In Proc. of the Solar Working Group Conference*, Vol. II, p. 27-28. Feb. 1962.
168. Lehr, S.N., L.J. Martire, and V.J. Tronolone. Equipment Design Considerations for Space Environment. TRW Space Technology Labs., Redondo Beach, Calif. Report TRW 9990-6032-RU 000. Feb. 1962. (Ad-288 341)
169. Lehr, S.N., and V.J. Tronolone. The Space Environment and Its Effect on Materials and Component Parts. *IRE Trans. on Reliability and Quality Control* RQC-10(2):24-37. Aug. 1961.
170. Lenchek, A.M., and S.F. Singer. Geomagnetically Trapped Protons from Cosmic-Ray Albedo Neutrons. *J. Geophys. Res.* 67:1263-1287. April 1962.
171. Levy, G., R.R. Touse, and S.V. Castner. The Effects of Nuclear Radiation on Some Selected Semiconductor Devices. *In Proc. of the 2nd AGET Conference on Nuclear Radiation Effects on Semiconductor Devices, Materials and Circuits*, Cowan Publ. Corp., Sept. 1959.
172. Lodi, Edward. Lockheed Low-Energy Proton Damage Experiments. *In Transcript of the Photovoltaic Specialists Conference*, Vol. I, Section B-4. July 1963. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
173. Loferski, J.J. Analysis of the Effect on Nuclear Radiation on Transistors. *J. Applied Phys.* 29:35-40. Jan. 1958.
174. Loferski, J.J., and P. Rappaport. *Phys. Rev.* 111:432. 1958.
175. Loferski, J.J., and P. Rappaport. Electron Voltaic Study of Electron Bombardment Damage and Its Threshold in Germanium and Silicon. *Phys. Rev.* 98:1861. 1955.

176. Loferski, J.J., and J. Scott-Monck. Radiation Damage to Silicon Solar Cells. Radio Corp. of America, Princeton, N.J. Quarterly Report No. 1 on Contract NAS5-457. Oct. 15, 1960.
177. Loferski, J.J., and J.J. Wysocki. Spectral Response of Photovoltaic Cells. RCA Rev. 22:38-55. March 1961.
178. Long, William G. Testing Electrical Components for the Snap Environment. Presented at the 1965 Annual Technical Meeting of the Institute of Environmental Sciences. 1965.
179. Longanecker, G.W. Solar Cell Damage on Explorer Vehicles. In Transcript of the Photovoltaic Specialists Conference, Vol. I, Section B-9. July 1963. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
180. Madey, R. Solar Cell Degradation by Protons in Space. U.S. Atomic Energy Commission Report TID-7652, Book I, p. 243-259. Nov. 1962.
181. Magee, R.M. Radiation Effects Parameters in NAP Applications. U.S. Air Force, Kirtland AFB, New Mexico. AFWL Technical Documentary Report WL-TDR-64-97. Nov. 1964.
182. Mandelkorn, G., et al. A New Radiation-Resistant, High-Efficiency Solar Cell. USASRDL Technical Report 2162.
183. Mandelkorn, J. A Filter Wheel Simulator. In Proc. of the 4th Photovoltaic Specialists Conference, held in Cleveland, Ohio, June 1964.
184. Mandelkorn, J., J.H. Lamneck, and R.P. Ulman. Behavior of Bombarded Solar Cells Made From Various Silicon Materials. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. II, Section B-5. Jan. 1966. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.1)
185. Mandelkorn, J., et al. Effects of Impurities on Radiation Damage of Silicon Solar Cells. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Memorandum X-52007. n.d.
186. Mann, A.E. and F. Benning. Reaching for the Sun. Environ. Quarterly 9(3):16-18, 20-21, 30-31. Sept. 1963.
187. Mar, B.W. An Electron Shielding Analysis for Space Vehicles. Nuclear Sci. and Engr. 24:2. Feb. 1966.
188. Marks, B.S. Solar Cell Coatings. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. I, Section B-5. Dec. 1965. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6)

189. Marquardt Corp., Van Nuys, Calif. Aircraft Nuclear Propulsion Systems, Project Pluto. Report 3002, Vol. 3 on Contract AF 33(616)-6214. Nov. 1959. (Also issued as WADC-TN-59-365)
190. Martin, J.H., R.L. Statler, and E.L. Ralph. Radiation Damage to Thin Silicon Solar Cells. In Advances in Energy Conversion Engineering, A.S.M.E., New York, 1967. (See p. 289-296)
191. Martin, J.H., J.W. Teener, and E.L. Ralph. Some Effects of Electron Irradiation and Temperature on Solar Cell Performance. Johns Hopkins Univ., Applied Physics Lab. Paper CF-3028. May 15, 1963.
192. Mauri, R.E. Evaluation of Optical Properties and Environmental Stability of Solar Cell Adhesives. Lockheed Aircraft Corp., Sunnyvale, Calif., Missiles & Space Co. Report LMSC AO 34229. April 1964.
193. Maxwell, K.H. Solar Cells from Exptaxial Gallium Arsenide on Germanium. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. I, Section B-2. Dec. 1965. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6)
194. Mayo, J.S., et al. The Command System Malfunction of the Telstar Satellite. Bell System Tech. J. 42:1631-1657. July 1963.
195. McCoy, T.M. Hyperenvironment Simulation. Part I. Definition and Effects of Space Vehicle Environment Natural and Induced. Issued by U.S. Wright Air Development Division, Ohio, WADD Technical Report 60-785, Part I. Jan. 1961.
196. McHendry, F.J., H.W. Kuzminski, and C.P. Hadley. Comparison of Flight and Terrestrial Solar Measurements on Silicon Cells. (Discussion of the Paper) Paper presented at the 4th Photovoltaic Specialists Conference, Cleveland, Ohio, June 1964
197. McIlwain, C.E. Coordinates for Mapping the Distribution of Magnetically Trapped Particles. J. Geophys. Res. 66:3681-3691. Nov. 1961.
198. McIlwain, C.E., and G. Pizzella. On the Energy Spectrum of Protons Trapped in the Earth's Inner Van Allen Zone. J. Geophys. Res. 68:1811-1823. April 1963.
199. McKenzie, D.F. Some Considerations on Estimating the Life of Electronic Equipment During Orbit. North American/Autonetics. June 9, 1964.
200. Mihalov, J.D., and R.S. White. Low Energy Proton Radiation Belts. J. Geophys. Res. 71:2207-2216. May 1966.

201. Miller, W., K. Bewig, and B. Salzberg. Note on the Reduction of Carrier Lifetime in PN Junction Diodes by Electron Bombardment. *J. of Appl. Phys.* 27:1524. 1956.
202. Mirtich, M.J., and R.L. Bowman. The Performance of N/P Silicon and CdS Solar Cells as Affected by Simulated Micrometeoroid Exposure. *In Conference Record of the 6th Photovoltaic Specialists Conference, Vol. III*, p. 64-74. March 1967.
203. Mirtich, M.J., and M. Herman. Feasibility of Accelerating Micron-Size Particles in Shock-Tube Flows for Hypervelocity Degradation of Reflective Surfaces. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-3187. Jan. 1966.
204. Mitchell, F.P., and D.K. Wilson. A Summary of Surface Effects of Radiation on Semiconductor Devices. Report on Contract AF 19(628)-4157. Dec. 1, 1965. AFCRL 65-898.
205. Modisette, J.L., T.M. Vinson, and A.C. Hardy. Model Solar Proton Environments for Manned Spacecraft Design. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-2746. April 1965.
206. Moll, J.C., and I.M. Ross. The Dependence of Transistor Parameters on the Distribution of Base Layer Resistivity. *IRE, Proc.* 44. Jan. 1956.
207. Nakada, M.P., and G.D. Mead. Diffusion of Protons in the Outer Radiation Belt. *J. Geophys. Res.* 70:4777-4791. 1965.
208. NASA. George C. Marshall Space Flight Center, Huntsville, Ala. The Meteoroid Satellite Project Pegasus. First Summary Report. NASA Technical Note D-3505. Nov. 1966.
209. Naugle, J.E., and D.A. Kniffen. The Flux and Energy Spectra of the Protons in the Inner Van Allen Belt. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-412. n.d.
210. Naugle, J.E., and D.A. Kniffen. Variations of the Proton Energy Spectrum with Position in the Inner Van Allen Belt. NASA, Goddard Space Flight Center, Greenbelt, Md. NASA Preprint X-611-63-35. 1962.
211. Naumann, R.J. The Near-Earth Meteoroid Environment. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-3717. Nov. 1966.

212. Nelms, A.T. Energy Loss and Range of Electrons and Positrons. National Bur. Standards Circular No. 477, and Supplement. 1956 and 1958.
213. Ness, Norman F. The Magnetosphere and Its Boundary Layer. In Second Symposium on Protection Against Radiations in Space, Gatlinburg, Tenn. Oct. 1964. (Issued as NASA Special Publication 71. (p. 31))
214. O'Brien, B.J. A Large Diurnal Variation of the Geomagnetically Trapped Radiation. J. Geophys. Res. 68:989-995. Feb. 1963.
215. O'Brien, B.J. Radiation Belts. Sci. American 208(5):84-96. May 1963.
216. O'Brien, B.J. Review of Studies of Trapped Radiation with Satellite-Borne Apparatus. Space Sci. Rev. 1:415-484. 1963.
217. Olesen, H.L. Radiation Effects on Electronic Systems. Plenum Press, New York, 1966.
218. Oliver, J.W. Charged Particle Radiation Damage in Semiconductors, II: Minority Carrier Diffusion Analysis in Photovoltaic Devices. TRW Space Technology Labs., Los Angeles, Calif. Report 8987-0001-RU-001. Feb. 19, 1962
219. Orrok, G.T. The Meteoroid Environment of Project Appolo, 2nd edition. Bellcomm, Inc., Washington, D.C. NASA Contract Report 68189. Feb. 20, 1964.
220. Palmer, J.M., Centralab Semiconductor. Private Communication.
221. Parkinson and Cleary. In Satellite Environment Handbook. Lockheed Aircraft Corp., Sunnyvale, Calif. LMSD-895006, Dec. 1960. (A 1958 quote) (AD-249 473)
222. Patterson, J.L., and G.A. Haynes. Effect of High Energy Electron Radiation on Solar Cell Shields. Private Communication, May 1963.
223. Patterson, J.L., and W.E. Miller. Artificial Electron-Belt Radiation Protection for the Explorer SVI Solar Cell Power Supply. AIAA Paper 63-186. June 1963.
224. Paulkovich, J., Goddard Space Flight Center. Private Communication.
225. Paulkovich, J. Slope Detection as a Method of Determining the Peak Power Point of Solar Arrays. NASA, Goddard Space Flight Center, Greenbelt, Md. NASA Preprint X-636-64-282. Oct. 1964. (Also issued as NASA TMX-55137)

226. Peck, D.S., R.R. Blair, W.L. Brown, and F.M. Smits. Surface Effects of Radiation on Transistors. *Bell System Tech. J.* 42:95-129. Jan. 1963. (Also in AEC Report TID-7652, Book 1, p. 136-200. Nov. 1962)
227. Piaseczny, I.J., Jr. Designing for the Space Radiation Environment. Sanders Associates, Inc., Nashua, N.H. Report 1-1611-487. March 17, 1964. (AD-475 651)
228. Pieper, G.F. The Artificial Radiation Belt. *APL Tech. Digest* 2(2):3-7. Nov.-Dec. 1962.
229. Potter, A.E. Behavior of Bombarded Solar Cells Made from Various Silicon Materials. *In Proc. of the 5th Photovoltaic Specialists Conference, Vol. II, Section D-5.* Jan. 1966. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.1)
230. Prince, M.B. Drift Mobilities in Semiconductors - II. Silicon. *Phys. Rev.* 93:1204-1206. March 1954.
231. Ralph, E. L. Performance of Very Thin Silicon Solar Cells. *In Conference Record of the 6th Photovoltaics Specialists Conference, Vol. I,* p. 98. March 1967.
232. Ralph, E. L. Preflight Calibration and Matching of Solar Cells for a Band-Pass Filter Experiment. *In Proc. of the 5th Photovoltaic Specialists Conference, Vol. III, Section E-3.* Jan. 1966. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.2)
233. Ralph, E. L., and M. Wolf. Effect of Antireflection Coatings and Coverglasses on Silicon Solar Cell Performance. Paper presented at the 4th Photovoltaic Specialists Conference, Cleveland, Ohio, June 1964.
234. Ratcheson, W.I. A Fifty KW, Twenty Watt Per Pound Solar Cell Array Feasibility Study. *In Proc. of the 5th Photovoltaic Specialists Conference, Vol. III, Section E-7.* Jan. 1966. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.2)
235. Ray, K.A. Recent Developments in Large Area Solar Cell Arrays. *In Proc. of the 5th Photovoltaic Specialists Conference, Vol. III, Section E-6.* Jan. 1966. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.2)
236. Raymond, J., and W. Chang. Study for Generalized Model for Semiconductor Radiation Response Prediction. Northrop Corp., Newbury Park, Calif., Report No. 1 on Contract DA-28-043-AMC-00423(E). March 1965. (Available from DDC)

237. Reid, F.J. The Effect of Nuclear Radiation on Semiconductor Devices. Radiation Effects Info. Center, Columbus, Ohio. REIC Report No. 10. April 1960.
238. Reid, F.J., J.W. Moody, and R.K. Willardson. The Effect of Nuclear Radiation on Semiconductor Materials. Radiation Effects Info. Center, Columbus, Ohio Report on Contract AF 33(616)-5171. n.d.
239. Reynard, D.L. Irradiation of Solar Cell Cover Slides and Adhesives with 1.5 MeV Electrons. Lockheed Aircraft Corp., Sunnyvale, Calif., Report LMSC 3-56-64-5. Aug. 1964.
240. Reynard, D.L. Irradiation of Solar Cell Sub-Panels with 0.8 MeV Electrons. Lockheed Aircraft Corp., Sunnyvale, Calif., Report LMSC 3-56-64-8. Nov. 1964.
241. Reynard, D.L. Measurements of Silicon Solar Cell Degradation in the Van Allen Radiation Environment. Lockheed Aircraft Corp., Sunnyvale, Calif., Report LMSC A0 73668. Feb. 27, 1962.
242. Reynard, D.L. Proton and Electron Irradiation of N/P Silicon Solar Cells, Lockheed Aircraft Corp., Sunnyvale, Calif., Report LMSC 3-56-65-4. April 12, 1965.
243. Reynard, D.L. Solar Cell and Solar Cell Module Test Facility. March 1, 1966
244. Roederer, J.G., W.N. Hess, and E.G. Stassinopoulos. Conjugate Intersects to Selected Geophysical Stations. NASA, Goodard Space Flight Center, Greenbelt, Md. NASA Preprint X-642-65-182. April 1965.
245. Rogers, S.C. Radiation Damage to Satellite Electronic Systems. IEEE Trans. Nuclear Sci. NS-10:97-105. Jan. 1963.
246. Rohrbach, E.J., and H.S. Goldstein. Radiation vs. Electronic Components. Machine Design, 35:101-104. Jan. 1963.
247. Rolik, G.P. Development of an Improved Radiation Resistant Solar Cell. Electro-Optical Systems, Inc., Pasadena, Calif., Final Report on Contract NAS5-3560. Dec. 27, 1964.
248. Rosen, A., et al. A Comprehensive Map of the Space Radiation Environment. TRW Space Technology Labs., Redondo Beach, Calif. Report no. 8644-6002-RU-000.
249. Rosenzweig, W. Diffusion Length Measurement by Means of Ionizing Radiation. Bell System Tech. 41:1573-1588. Sept. 1962.

250. Rosenzweig, W. Radiation Damage Studies. In Photovoltaic Specialists Conference Transcript, Vol. I, Section B-2. July 1963. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
251. Rosenzweig, W., H.K. Gummel, and F.M. Smits. Solar Cell Degradation Under 1-MeV Electron Bombardment. Bell System Tech. 42:399-414. March 1963.
252. Rosenzweig, W., F.M. Smits, and W.L. Brown. Energy Dependence of Proton Irradiation Damage in Silicon. J. Appl. Phys. 35:2707-2711. Sept. 1964.
253. Ross, B. Estimation of Solar Cell Degradation in Space Sunlight Under 1 MeV Electron Bombardment. In Transcript of the Photovoltaic Specialists Conference, Vol. I, Section B-13. July 1963.
254. Ross, Bernd. Design Criteria for Satellite Power Supplies Using Radiation Resistant Solar Cells. Presented at ASME Aviation and Space, Hydraulic and Gas Turbine Conference, Los Angeles, Calif., Mar. 1963.
255. Rosser, W.G.V. Changes in the Structure of the Outer Radiation Zone Associated with the Magnetic Storm of Sept. 30, 1961. Geophys. Res. 68:3131-3148, 1963.
256. Runyan, W.R. Development of Epitaxial Structures for Radiation Resistant Silicon Solar Cells. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. I., Section A-2. Dec. 1965. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6)
257. Schulte, H.J. Models for Space Environmental Hazards: Radiation. Bellcomm, Inc., Washington, D.C. Jan. 1963.
258. Seitz, F. Color Centers in Alkali Halide Crystals, II. Rev. Mod. Phys. 26:7-94. 1954.
259. Seitz, F., and J.S. Koehler. Solid State Physics. Academic Press, New York, 1956.
260. Sherman, C.H. Indirect Displacement of Atoms in Solids by Knock-on Impurity Atoms. March 1965.
261. Shirland, F.A., et al. Development of Cadmium Sulfide Thin Film Photovoltaic Cells. U. S. National Aeronautics and Space Administration, Washington, D. C. NASA Contract Report 54806.
262. Shockley, W. Electrons and Holes in Semiconductors. Van Nostrand, Inc., New York, 1954. (p. 309-315)

263. Singer, S.F. Trapped Albedo Theory of the Radiation Belt. *Phys. Rev. Letters* 1(5):181-183. Sept. 1958.
264. Slifer, L.W. Preliminary Results of the Explorer XXVI Solar Cell Experiment. *In Proc. of the 5th Photovoltaic Specialists Conference, Vol. II, Section D-3.* Jan. 1966. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.1)
265. Smith, A.B., and J.W. Blue. A Comparison of Solar Cell Damage by Alpha Particles and Protons. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-3427. May 1966.
266. Smith, K.D., et al. The Solar Cells and Their Mounting. *Bell System Tech.* 42:1765-1816. July 1963.
267. Smits, F.M. The Degradation of Solar Cells Under Van Allen Radiation. Sandia Corp., Albuquerque, New Mexico.
268. Smits, F.M. The Degradation of Solar Cells Under Van Allen Radiation. *IEEE Trans. Nuclear Sci.* NS-10:88-96. Jan. 1963.
269. Smits, F.M., K.D. Smith, and W.L. Brown. Solar Cells for Communication Satellites in the Van Allen Belt. *J. of the British IRE*, pp. 161-169. Aug. 1961.
270. Statler, R.L. The Effect of Illumination on the Performance of Irradiated Solar Cells. *In Transcript of the Photovoltaic Specialists Conference, Vol. I, Section B-6.* July 1963. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
271. Statler, R.L. Electron-Bombardment Damage in Silicon Solar Cells. U.S. Naval Research Lab., Washington, D.C. NRL Report 6091. Oct. 7, 1964.
272. Statler, R.L. One MeV Electron Damage in Silicon Solar Cells. Presented at the IEEE Photovoltaic Specialists Meeting, Washington, D.C., April 10-11 1963.
273. Statler, R.L. Radiation Damage in Silicon Solar Cells From 4.6-MeV Proton Bombardment. U.S. Naval Research Lab., Washington, D.C. NRL Report 6333. Nov. 15, 1965.
274. Statler, R.L. Solar Cell Radiation Damage with 4.6 MeV Protons. U.S. Naval Research Lab., Preliminary Report, May 1, 1963.
275. Statler, R.L. Status of Silicon Solar Cell Radiation Damage. *In Proc. of the 5th Photovoltaic Specialists Conference, Vol. II, Section D-2.* Jan. 1966. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.1)

276. Stofel, E.J. Solar Cell Power Systems for Air Force Satellites. In Conference Record of the 6th Photovoltaics Specialists Conference, Vol. II, p. 54. March 1967.
277. Stormer, C. The Polar Aurora. Clarendon Press, Oxford, 1955.
278. Sullivan, R. Johns Hopkins Applied Physics Laboratory. Private Communication.
279. Tada, H.Y. A Theoretical Model for Low-Energy Proton Irradiated Silicon Solar Cells. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. II, Section D-8. Jan. 1966. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.1)
280. Tarneja, K.S., editor. Dendritic Solar Cell and Array Investigation. Air Force Aero Propulsion Lab., Wright-Patterson AFB, Ohio, AFAPL-TR-65-92. 1965.
281. Tarneja, K.S. Drift Field Dendritic Silicon Solar Cells. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. I, Section A-3. Dec. 1965. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6)
282. Texas Instruments, Inc., Dallas, Texas. Development of Expitaxial Structures for Radiation Resistant Silicon Solar Cells.
283. Textron Electronics, Inc., Sylmar, Calif. Heliotek Division. Heliotek Information and Silicon Solar Cell Data Book. March 28, 1966.
284. Thatcher, R.K., et al. The Effect of Nuclear Radiation on Electronic Components, Including Semiconductors. Radiation Effects Info. Center, Columbus, Ohio. REIC Report No. 36. Oct. 1964.
285. Thelen, A. Solar Simulator. Proc. of the Solar Working Group Conference, Vol. II, 27-28 Feb. 1962.
286. Thompson Ramo Wooldridge, Inc., Redondo Beach, Calif. Space Technology Labs. Final Flight Report: Tetrahedral Research Satellites 1963-14B-1963-14C-1963-30B Volume II: Experiments and Results. Report 8685-6006-RU-000. On Contract AF 04(695)-128. Feb. 15, 1964.
287. Thompson Ramo Wooldridge, Inc., Redondo Beach, Calif. Space Technology Labs. Charged Particle Radiation Damage in Semiconductors, X: The Energy Dependence of Electron Damage in Silicon, Report 4161-6004-KU-000. On Contract No. NAS5-3805. Sept. 3, 1964.

288. Toole, J.M. Wrap-Around Contact Solar Cells. In Proc. of the 5th Photo-voltaic Specialists Conference, Vol. I, Section A-1. Dec. 1965. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6)
289. Univ. of Pennsylvania. Power Information Center. Proc. of the Solar Working Group Conference. Vol. I: Radiation Damage to Semiconductor Solar Devices. Report PIC-SOL 209/2. April 1962.
290. Van Allen, J.A. Spatial Distribution and Time Decay of the Intensities of Geomagnetically Trapped Electrons from the High Altitude Nuclear Burst of July 1962. Univ. of Iowa, Research Report No. 63-11. May 1963.
291. Van Allen, J.A., et al. Some Preliminary Reports of Experiments in Satellites 1958 Alpha and Gamma. IGY Satellite Report Series No. 3, 73-92. (National Academy of Sciences)
292. Van Allen, J.A., C.E. McIlwain, and G. Ludwig. Satellite Observations of Electrons Artificially Injected into the Geomagnetic Field. Symposium on Scientific Effects on Artificially Introduced Radiations at High Altitudes, J. Geophys. Res. 64:872-891. Aug. 1959.
293. Van Lint, V.A.J., J.W. Harrity, D.K. Nichols, and D.P. Snowden. Radiation Effects on Silicon Solar Cells. General Dynamics, San Diego, Calif., General Atomic Division Report GA-4797. Division Report GA-4797. Dec. 4, 1963.
294. Van Lint, V.A.J., and E.B. Willmer. Correlation of Radiation Types with Radiation Effects. IEEE Trans. on Nuclear Sci. NS-10:80-87. Jan. 1963.
295. Van Lint, V.A.J., et al. Radiation Effects on Silicon Solar Cells. General Dynamics, San Diego, Calif., General Atomic Division. Report GA-3872. Feb. 15, 1963.
296. Vavilov, Viktor S. Effects of Radiation on Semiconductors. Translated by A. Tybulewicz, Consultants Bureau, New York, 1965.
297. Vette, J.I. Models of the Trapped Radiation Environment. Volume I: Inner Zone Protons and Electrons. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Special Publication 3024. 1966.
- 297a. Vette, J.I., A.B. Lucero, and J.A. Wright. Models of the Trapped Radiation Environment. Volume II: Inner and Outer Zone Electrons. NASA SP-3024. 1966.
- 297b. Vette, J.I., and A.B. Lucero. Models of the Trapped Radiation Environment. Volume III: Electrons at Synchronous Altitudes. NASA SP-3024. 1967.

298. Waddel, Ramond C. ATS-1 Solar Cell Radiation Damage Experiment, First 120 Days. NASA Preprint X-710-67-412. Aug. 1967.
299. Waddel, R.C. Goddard Space Flight Center. Personal Communication, June 1963.
300. Waddel, R.C. Radiation Damage Experiments on Relay. In Transcript of the Photovoltaic Specialists Conference, Vol. I, Section B-10. July 1963. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
301. Waddel, R.C. Radiation Damage to Solar Cells on Relay I and Relay II. IEEE Trans. on Nuclear Sci., p. 60-68. Nov. 1964.
302. Waddel, R.C. The Relay I Radiation Effects Experiment. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Special Publication 76. 1965. (p. 449-463)
303. Walt, M., G.E. Crane, and W.M. McDonald. Analysis of Atmospheric Scattering Rates for Geomagnetically Trapped Electrons. Presented at the 44th Annual Meeting of American Geophysical Union, Washington, D.C. April 17-20, 1963.
304. Weiner, H. Optimum Solar Cell Shielding for the Advanced Orbiting Solar Observatory. In Second Symposium on Protection Against Radiations in Space. NASA Special Publication 71. 1965. (p. 377)
305. Weller, J.F. Proton Damage to Silicon Solar Cells. In Report on NRL Progress, Jan. 1963. (p. 1-6)
306. Weller, J.F., and R.L. Statler. Low Energy Proton Damage to Solar Cells, Presented at the IEEE Summer General Meeting, Toronto, Canada, June 19, 1963. (Conference Paper CP 63-1184)
307. Wikner, E.G., and H. Horiye. Study of n-and p-Type Silicon Exposed to Highly Energetic Radiation. General Dynamics, San Diego, Calif., General Atomic Division. Report GA-7280. July 13, 1966.
308. Whipple, F.L. Dust and Meteorites. Paper Presented at the American Rocket Society Space Flight Report to the Nation, New York, Oct. 1961. (ARS Paper 2253-61)
309. Whipple, F.L. On Meteoroids and Penetration. J. Geophys. Res. 68:4929-4939. Sept. 1963. (Also issued as a Report of the Smithsonian Astrophysical and Harvard College Observatories, Cambridge, Mass.)
310. Wolf, M. Drift Fields in Photovoltaic Solar Energy Converter Cells. IEEE, Proc. 51(5). May 1963.

311. Wolf, M. The Effects of a Drift Field on Solar Cells. In Transcript of the Photovoltaic Specialists Conference, Vol. I, Section B-12. July 1963. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
312. Wolf, M. Limitations and Possibilities for Improvement of Photovoltaic Solar Energy Converters. IRE, Proc. 48:1246-1263. 1960.
313. Wolf, M., and M.B. Prince. New Developments in Silicon Photovoltaic Devices and Their Application to Electronics. Solid State Phys. (Semiconductors, Part 2):1180-1196. 1960.
314. Wolf, Martin, and Hans Rauschenbach. Series Resistance Effects on Solar Cell Measurements. Advanced Energy Conversion 3:455-479. 1963.
315. Wyatt, M. E., and V.A.J. Van Lint. Correlation of Displacement Damage Produced by Electrons and Protons. Paper presented at the IEEE Annual Conference on Nuclear and Space Radiation Effects, Ann Arbor, Michigan, 1965.
316. Wysocki, J.J. The Effect of Lithium on Radiation Damage in Silicon Solar Cell Devices. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. II, Section D-6. Jan. 1966. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/6.1)
317. Wysocki, J.J. The Effect of Series Resistance on Photovoltaic Solar Energy Converters. RCA Review, p. 57-70. March 1961.
318. Wysocki, J.J. Lithium-Doped Radiation-Resistant Solar Cells. IEEE Trans. on Nuclear Sci. NS-13(6):168-173. Dec. 1966.
319. Wysocki, J.J. Radiation Damage in Solar Cells. In Transcript of the Photovoltaic Specialists Conference, Vol. I, Section B-1. July 1963. (Published by Power Info. Center, Philadelphia, Pa. PIC-SOL 209/3)
320. Wysocki, J.J. Self-Healing Radiation-Resistant Silicon Solar Cells. In Conference Record of the 6th Photovoltaics Specialists Conference, Vol. III, p. 96-109. March 1967.
321. Xavier, M.A. The Performance of Some Zener Reference Elements During Exposure to Nuclear Radiation. Presented at the Third Semiannual Radiation Effects Symposium, Atlanta, Ga., Oct. 1958.
322. Zoutendyk, J.A. The Effect of Solar Cosmic Radiation on Solar Cell Power Sources in Interplanetary Space. Jet Propulsion Lab. Engineering Memo No. 342-55. June 7, 1965.
323. Zoutendyk, J.A. Solar Cell Power Systems. Jet Propulsion Lab. Technical Report 32-354. Dec. 1962.
324. Zoutendyk, J.A. The Space Calibration of Standard Solar Cells Using High-Altitude Balloon Flights. Presented at the 4th Photovoltaic Specialists Conference, Cleveland, Ohio, June 1964.

APPENDIX A

THE EFFECTS OF PLANETARY ENVIRONMENTS ON SOLAR CELL POWER SYSTEMS

Solar cell power systems have been used and are being developed for deep space missions. Silicon solar cells powered the Mariner flybys of Mars and Venus; they are planned for the Voyager mission and could possibly be used as far from the sun as the asteroids and Jupiter. As the solar radiation energy decreases as the inverse square of the distance from the sun, the required area of the solar cells must increase and the resulting increase in size, weight and cost will put some limit beyond which other power sources, such as nuclear, will gain the advantage. The increase in area required, however, is not as the square of the distance to the sun, for the photovoltaic efficiency rises as the solar cell illumination drops and the cells operate at lower temperature. Table A-1 gives planetary data, including solar constants, for the planets of the solar system. Further consideration of the planets beyond Jupiter will be omitted, in view of the extremely small sunlight intensity.

In interplanetary space, radiation hazards are related to the solar wind, sporadic bursts of solar flare protons, and cosmic rays. These have been discussed in section V. The meteoroid hazards discussed in section IX are also present. In this appendix is discussed the planetary environments associated with Mercury, Venus, Mars and Jupiter. The presence or absence of trapped radiation belts such as those of Earth, the measured surface temperature and its distribution, the existence of an atmosphere and its nature, are all significant factors affecting the design of the solar cell power system for a planetary orbiter or lander. The available evidences, concerning these factors are summarized here; where evidence is not available, contemporary theory is included.

TABLE A-1. SOLAR CONSTANT IN PLANETARY ORBITS

Planet	Relative Mass	Radius	Mean Orbital Radius (AU)	Solar Constant (mw/cm²)
Mercury	.055	0.38	.367	920
Venus	.813	.955	.724	270
Earth	1.000	1.00	1.000	137.4
Mars	.107	.523	1.524	60
Jupiter	316.7	11.2	5.203	5
Saturn	94.7	9.48	9.54	1.5
Uranus	14.6	3.90	19.19	0.37
Neptune	17.0	4.16	30.07	0.15
Pluto	0.1?	0.45?	39.46	.087

MERCURY

Missions to investigate the planet Mercury or to approach nearer to the sun, will require careful design for thermal considerations. The intense solar energy, nearly one watt per square centimeter, makes the use of solar cells attractive, but the resultant heating of the cells will lower their efficiency.

Mercury is not well known. The difficulty in observing a planet so close in the sky to the sun is obvious. Optical measurements indicate its rotational period is the same as its 88 Earth-day period of revolution around the sun. Because of its small mass, little if any atmosphere would be expected. From table 1 it may be computed that the density of Mercury is about that of Earth, and hence the planet could be of similar material, and even be magnetic. With negligible atmosphere, a possible magnetic field, and a close source of particles, Mercury is a good candidate for possessing a radiation belt. This would be greatly compressed by the solar wind on the sunward side, with a long tail on the dark side. The thin atmosphere would allow it to reach

almost to the surface of the planet. Such a belt would be detected with difficulty from the Earth, however, it could help clear up some of the apparent discrepancies in telescopic observations.

For one, there is conflicting evidence regarding the rotational period (ref. 1). A rotation of about 59 days has been measured by radar experiments. This could be reconciled to the optical result of an 88 day rotation by assuming a circulating atmosphere; one figure would represent the atmospheric rotation and the other would represent the planet's rotation. Unfortunately, the relative motion of the two results in a wind speed that is unreasonably high. Various sources indicate an atmosphere, possibly carbon dioxide, of 3-4 millibars.

The sunside temperature, about 613°K, agrees well with a theoretical model based on a planet with no circulating atmosphere and one side always facing the sun. But this model would indicate a nightside temperature of absolute zero, and measurements (ref. 2) of the average temperature across the disk of the planet indicate the nightside temperature is well above this figure. Further, the measurements give similar results over a wavelength range of one to 11 centimeters. There is no evidence of nonthermal radiation, such as that of very energetic electrons in a magnetosphere (ref. 1).

Mercury appears to have a tenuous atmosphere, high winds, and a rotation period of 59 days. Its density and its proximity to the sun indicate the possibility of a magnetic field, highly distorted, and well-supplied with protons and electrons of low energies by the solar wind.

VENUS

The planet Venus is remarkably like Earth in density, size, and distance from the sun. It has a dense atmosphere composed mostly of carbon dioxide with traces of oxygen and water, pressure at the planet's surface that appears to be ten to twenty times that on Earth, dense clouds, and temperatures ranging from 550°K near the

surface to 300°K at the top of the atmosphere (ref. 3). These temperatures and the opacity of the clouds indicate solar cells would not be practical for a lander spacecraft. Also, the Venusian rotation period, as long as 250 Earth days, would present a requirement for a large energy storage device in conjunction with a solar power system.

There appears to be no radiation belt. Earth's belt extends about 65,000 kilometers on the sunward side but the Venus flyby spacecraft Mariner II, passing on the sunside of Venus at 41,000 kilometers, could measure no increase in radiation density characteristic of a similar belt for Venus. This means that the magnetic dipole moment of Venus can be no more than 0.1 that of Earth (ref. 4) despite other similarities of the planets. Venus probably has no trapped electrons and protons.

MARS

Mars, a small cratered planet with density about 3/4 that of Earth, also appears to lack a trapped radiation belt. Mariner IV, passing within 13,200 kilometers of the planet, detected no belt. Although the result was obscured by the coincidental measurement of a solar proton event, the sequence of counts was unlike that to be expected from a spacecraft penetrating a belt-like distribution. The absence of electron counts further indicated the absence of a Martian belt. This result limits the possible dipole moment of Mars to less than 0.0005 that of Earth (ref. 4). The radiation environment of Mars is probably similar to that in outer space: solar wind with occasional solar proton flares, and with a cosmic ray background. If Mars has an atmosphere, it would shield the surface of the planet from the less energetic particles of this environment. A slight atmospheric shielding, plus a geometric blockage of the space radiation would be the only effects observed.

The possible presence of sand storms on Mars makes the choice of solar cells for a lander spacecraft questionable until the environment can be studied directly.

JUPITER

Jupiter possesses a strong magnetic field and a well populated, large and complicated radiation belt. Decimeter wavelength radiation from the planet has been identified as a synchrotron radiation from energetic electrons in the belt. The orbit of a small, low moon, Io, inside the belt, causes a turbulence in the magnetic field that results in bursts of decameter wavelength radiation.

As indicated in Table A-1, Jupiter has a radius, R_J , of 71,500 kilometers. The inner Jovian belt appears to be centered at $2R_J$ and the outer Jovian belt centered at $3.5 R_J$ (ref. 5). The synchrotron radiation spectrum observed is flat (constant in intensity along a broad band of wavelengths), which would be produced by an electron spectrum of the form E^{-1} . The rocking of the plane of polarization of this radiation indicates that the magnetic poles are inclined about 10° to the rotation axis (ref. 6), and it further appears that the dipole is considerably displaced off the planet center. The model proposed by Warwick for the radiation belts is shown in figure A-1. The field at the magnetic equator is about 10 gauss.

Two quantitative expressions have been derived assuming a centered dipole field, for the electron spectrum in the field as a function of pitch angle and energy (ref. 7). They are,

$$N(E, \alpha) = \left(\frac{2.2 \times 10^{-4}}{B_0 \Delta R} \right) \frac{\sin^3 \alpha}{E} \text{ per cm}^3 - \text{MeV}$$

$$N(E, \alpha) = \left(\frac{1.2 \times 10^{-4}}{B_0 \Delta R} \right) \frac{\sin^2 \alpha + 2 \sin^4 \alpha}{E} \text{ per cm}^3 - \text{MeV}$$

where B_0 is the field in gauss at $3R_J$, and ΔR is the width of the belt in Jovian radii. The first expression could be expected to hold for low energy electrons while the second holds at the upper end of the spectrum. Integrated over pitch angle α , the

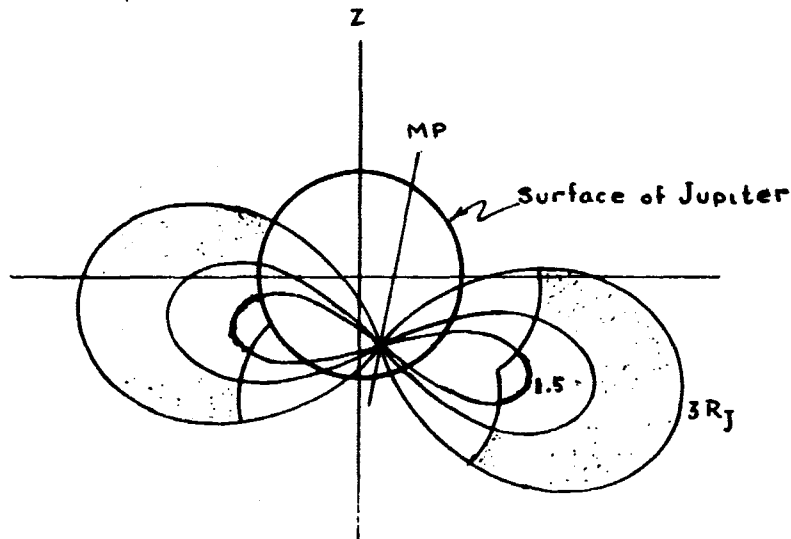


Figure A-1. Possible Model of Jupiter Radiation Belts (ref. 11)

electron density is approximately $(2.4 \pm 1) \times 10^{-4} (B_0 \Delta R E)^{-1}$ per $\text{cm}^3 - \text{MeV}$ from these expressions; $B_0 \Delta R$ may be taken as 15. This gives a density of $(1.6 \times 10^{-4}/E)$; the corresponding flux is obtained by the product of the density and the relativistic velocity:

$$\phi(E) = N(E) v(E) = 4.8 \times 10^6 / E$$

The radial distance of the magnetopause for Jupiter has been estimated by Ellis to be as much as 35 times the planet's radius, R_J (ref. 8). He suggests that planetary rotation could greatly reduce this value, but it is greater than $6 R_J$. The moon Io, at this altitude, creates a turbulence in the magnetosphere emitting detectable bursts of decameter radiation (ref. 9). The radiation belt centered at $3.5 R_J$ presumably extends out this far, but not as far as $9 R_J$, since the moon Europa at that distance does not appear to generate such a turbulence (ref. 10).

While a lander for Jupiter is not presently contemplated in view of the dense atmosphere and the large planetary mass, an orbiter for the planet or a lander on one of the Jovian moons could use a solar cell power system. The anticipated radiation effects in the radiation belt are not expected to be prohibitive.

REFERENCES

APPENDIX A

1. Kellermann, K.I. "The Thermal Radio Emission from Mercury, Venus, Mars, Saturn, and Uranus". *Icarus* 5:478-490, Sept. 1966.
2. Barrett, A.H. "Passive Radio Observations of Mercury, Venus, Mars, Saturn, and Uranus". *Radio Sci.* 69D, Dec. 1965.
3. Davydov, V.D. "New View of Venus", *Sci. & Tech.*, No. 73, Jan. 1968.
4. Van Allen, J.A. "Absence of Martian Radiation Belts and Implications Thereof". Univ. of Iowa Report 65-30, Aug. 1965.
5. Roberts, J.A., and M.M. Komesaroff. "Observations of Jupiter's Radio Spectrum and Polarization in the Range from 6 cm to 100 cm". *Icarus* 4:127-156. 1965.
6. Morris, D. and G.L. Berge, "Measurements of the Polarization and Angular Extent of the Decimeter Radiation from Jupiter", *Astrophysics J.* 136:276-289. 1962.
7. Thorne, K.S. "Dependence of Jupiter's Decimeter Radiation on the Electron Distribution in Its Van Allen Belts". *Radio Sci.* 69D. Dec. 1965.
8. Ellis, G.R.A. "The Decametric Radio Emissions of Jupiter", *Radio Sci.* 69D. Dec. 1965.
9. Bigg, E.K. "Influence of the Satellite Io on Jupiter's Decametric Emission". *Nature* 203. 1964.
10. Melrose, D.B., "Rotational Effects on the Distribution of Thermal Plasma in the Magnetosphere of Jupiter". *Planetary and Space Sci.* 15:2. Feb. 1967.
11. Warwick, J.J. "Mechanisms of Decameter Radiation". Air Force Cambridge Research Labs., Bedford, Mass. AFCRL-64-774. Sept. 1964.

APPENDIX B

GLOSSARY OF SYMBOLS, BASIC CONSTANTS AND CONVERSION FACTORS

1. Glossary of Symbols

A	=	junction parameter (dimensionless)
B	=	magnetic field strength (gauss)
D	=	diffusion constant (cm^2/sec)
E	=	particle energy (MeV) or electric field (volts/cm)
E_c	=	minimum energy needed to penetrate a given shield
F	=	flux greater than a given energy E (particles/ $\text{cm}^2\text{-sec}$)
$F(x)$	=	exponential integral
G	=	carrier generation rate (carriers/ $\text{cm}^3\text{-sec}$)
I	=	current (amperes or milliamperes)
I_L	=	photovoltaic current (amperes or milliamperes)
I_{sc}	=	short-circuit current (milliamperes)
J	=	current density (milliamperes/ cm^2)
K	=	damage coefficient (dimensionless)
L	=	magnetic coordinate (Earth radii)
L	=	minority carrier diffusion length (microns or cm)
M	=	atomic mass
m	=	electron mass
P	=	power (watts)
P	=	magnetic rigidity
q	=	electron charge (coulombs)
R	=	particle range (gm/ cm^2)
R	=	resistance (ohms)
R_E	=	distance (Earth radius)
R_J	=	distance (Jovian radius)
S_0	=	specific ionization (charges/cm-particle)
T	=	temperature ($^{\circ}\text{F}$ or $^{\circ}\text{C}$)
U	=	magnetic potential
V	=	potential (volts)
V_{oc}	=	open-circuit voltage (volts)
α	=	pitch angle (degrees)
θ	=	colatitude (degrees)
θ	=	shield reduction factor (dimensionless)
ρ	=	density
λ	=	wavelength of light (cm)

μ = charge mobility ($\text{cm}^2/\text{volt-sec}$)
 τ = depth of particle penetration (gms/cm^2)
 τ = minority carrier lifetime (seconds)
 Φ = particle fluence ($\text{particles}/\text{cm}^2$)
 Ω = bulk resistivity (ohm-cm)

2. Basic Constants

Astronomical Unit (a. u.) = earth's mean distance from sun = 8.07×10^7 nautical miles
 = 1.5×10^8 kilometers

Boltzmann's constant $k = 1.38 \times 10^{-23}$ joules/ $^\circ\text{K}$

Earth radius (R_E) = 3437.87 n. mi.
 = 6371.23 KM.

Planck's constant $h = 6.625 \times 10^{-27}$ erg seconds

Rest mass of electron $mc^2 = 0.511$ MeV

Rest mass of proton $Mc^2 = 931$ MeV

3. Conversion Factors

Area

Square centimeter (cm^2) = 0.155 square inch (in. ²)
 Square meter (m^2) = 10.76 square feet (ft. ²)

Energy

Joule = 10^7 ergs
 = 1 watt-second
 MeV = 10^6 electron volts
 = 1.6×10^{-13} joules

Length

Centimeter (cm) = 0.3937 inches (in.)
 = 393.7 mils
 = 10^4 microns (μ)
 Micron (μ) = 10^{-4} cm
 = 3.937×10^{-2} mils
 Mil = 0.001 inch (in.)
 = 2.54×10^{-3} centimeter (cm.)
 Kilometer (km.) = 3,281 feet (ft)
 = 0.6214 mile (mi.)
 Nautical mile (n. mi.) = 1.853 Kilometers (km)
 = 1.152 miles (mi), statute

Mass

Pound = 453.6 Grams

Power:

Watt = 10^7 ergs/sec
= 3.413 Btu/hr

Temperature:

(° C) = $5/9$ (° F - 32)
degree Centigrade (° C) = degree Kelvin (° K) - 273
degree Fahrenheit (° F) = $9/5$ (° C) + 32
degree Kelvin (° K) = ° C + 273

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