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THE RELAY I RADIATION EFFECTS EXPERIMENT

by Ramond C. Waddel

Goddard Space Flight Center

Greenbelt, Md.

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ABSTRACT

Solar cells on Relay I were monitored for radiation damage by measurement of short circuit current. The orbit was 1321 km perigee, 7439 km apogee, 47.5 degrees inclination. Unshielded N/P, P/N, and gallium arsenide cells degraded in 10 days to 52, 28, and 18 percent, respectively. This damage is ascribed to low energy protons. At 300 days, silicon N/P and P/N cells, shielded with 30 mils of fused silica, had degraded to 73 and 53 percent respectively. At 300 days, silicon N/P and P/N cells, shielded with 60 mils of fused silica, had degraded to 80 and 61 percent, respectively. Available space flux maps predicted somewhat greater damage to the heavily shielded cells, from either electrons or high energy protons, than that observed. The minority carrier lifetime of some 1N645 silicon diodes declined to 50 percent in about 45 days.

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INTRODUCTION

Objectives

Numerous experiments have shown the presence of energetic electrons and protons trapped by the earth's magnetic field at high altitudes. The center of the "inner belt" of such particles is at an altitude of about 0.5 earth radii, over the magnetic equator. These electrons and protons damage semiconductor devices directly, and through the x-rays generated when the electrons are decelerated. Solar cells, widely used on spacecraft to convert sunlight to electric power, are particularly vulnerable. To function they must be situated in exposed positions and they can be shielded by only moderate amounts of transparent materials.

It is, therefore, of considerable interest to observe the radiation damage sustained by various types of solar cells with various shields, on an orbiting body. Such experiments provide direct empirical engineering information, useful in the design of solar power supplies for satellites with similar orbits. Further, they allow a test of the state-of-the-art through comparison of the damage observed and that predicted from laboratory studies and a knowledge of the character of the trapped particles.

It is the purpose of this report to describe such a satellite radiation damage experiment, and to compare the results with predictions based on various information sources and with other satellite damage experiments.

Orbit Parameters

The Relay satellite was launched from Cape Kennedy on 1962^y, 347^d, 23^h, 30^m, 01^s GMT. It carried wideband relay communications equipment, radiation measuring devices, and the radiation effects experiment herein reported. Final stage burnout and nominal

*The material in this technical note was previously published as Chapter 8 in "Final Report on the Relay I Program," NASA SP-76.

Table 1

Orbit Parameters of Relay I.

Apogee	7439 KM 4001 NM 1.17 R_e
Perigee	1321 KM 713 NM 0.21 R_e
Inclination Period	47.5 degrees 185.1 minutes 3.085 hours
Eccentricity Maximum latitude	0.285 47.62 degrees

injection in orbit occurred on 1962^y, 347^d, 23^h, 49^m, 06^s GMT. For convenience in this report, the zero for "time in orbit" has been taken as 1962^y, 348^d, 00^h, 00^m, 00^s. It is believed that no significant radiation damage effects occurred before this time.

Table 1 shows some of the orbit characteristics. It is seen that perigee and apogee are such that the spacecraft is subjected to the radiations of the "inner belt."

APPARATUS

The satellite devices concerned with the radiation effects experiment are the radiation damage panel, the radiation effects circuitry box, and the solar aspect indicator.

Radiation Damage Panel

The devices subjected to radiation damage are listed in Table 2. They were mounted on the surface of a "damage panel" attached to the skin of the satellite. The panel "looked" perpendicularly to the spin axis.

For types of solar cells bearing shields of three thicknesses were used. Also, measurements were made in triplicate.

Table 2

Radiation Damage Sensors.

Device	No.	Type	Shield Thickness (units)
Solar Cell	3	P/N	0
Solar Cell	3	P/N	30
Solar Cell	3	P/N	60
Solar Cell	3	N/P	0
Solar Cell	3	N/P	30
Solar Cell	3	N/P	60
Solar Cell	3	REV	0
Solar Cell	3	REV	30
Solar Cell	3	REV	60
Solar Cell	3	GaAs	0
Diode	6	1N645	0

The diodes used were 1N645 silicon diodes, manufactured by the Texas Instrument Company. They were diffused power rectifiers with a peak inverse rating of 225 volts and an average forward current of 400 ma. The glass envelope constitutes a shield of about 20 mils thickness. This diode type has been widely used in exposed positions on solar panels as a reverse current blocking device. It also happens to have a relatively long minority carrier lifetime, which simplified the associated circuitry. The diodes used were selected for long carrier lifetime, which ranged, initially, from 11.5 to 16.5 microseconds.

As shown in Figure 1, the solar cells and diodes were mounted on a 4.0-inch by 5.3-inch by 1/8-inch aluminum panel, for temperature uniformity. Eight thermistors were imbedded in the panel for temperature determination, since both solar cell and diode responses were temperature sensitive. An enclosure attached to the back of the panel carried the solar cell load resistors and circuitry for energizing the thermistors, and for providing a mid-scale calibration signal of 100 mv.

The solar cells were insulated from the panel. The shields were of Corning Type 7940, clear fused silica, of density 2.20 grams per cm^2. This shield material, and the proprietary transparent adhesive, are very resistant to darkening under irradiation.

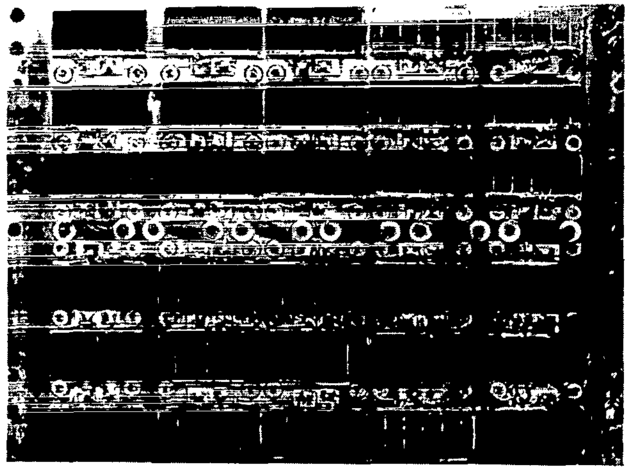

Figure 1—Radiation damage panel, front.

Silicon solar cells of the P/N (P on N) and N/P types carried on the damage panel have been widely used in satellite solar power supplies. The gallium arsenide cells are not considered commerically available yet, but on a theoretical basis, have shown promise of high efficiency and high radiation damage resistance.

The REV (reversed) cells of Table 2 were devised and included in order to have some cells on board that were particularly susceptible to radiation damage, since an uncertainty of several orders of magnitude existed in the damage effects to be expected in orbit. These cells were of silicon, with a front (illuminated) layer about one diffusion length thick. On theoretical grounds, such a cell, while of low efficiency, should be susceptible to damage. This is because radiation damage shortens minority carrier lifetime and diffusion length, leaving carrier pairs generated near the surface (by photon absorption) at a distance from the junction greater than a diffusion length, and therefore unavailable externally.

In order to be uniform in characteristics, cells of a given type were cut from the same crystal ingot and processed together. They were then further selected for uniformity on a basis of spectral response and efficiency. It is believed that the silicon P/N and N/P cells used are representative of the central part of the distribution of commercial cells of these types. Both were of nominal 1 ohm-cm base resistivity.

The condition of the solar cells was judged by noting the currents furnished to low resistance loads. The use of a short circuit current in evaluating radiation damage is common. However, some laboratory damage experiments have shown that such a measurement does not always accurately reflect the power generating capability of some types of cells after damage by low energy radiations.

The load resistors were individually adjusted for each cell to give an expected output of 160 mv under normal space illumination.

The damage panel weighed 1.02 pounds, occupied 15.7 cubic inches, and required 0.54 watts.

Radiation Effects Circuitry

Figure 2 shows a block diagram of the circuitry used in determining the minority carrier lifetime of 1N645 diodes by the "injection-extraction" method (Reference 1). Radiation damage to a semi-conductor diode reduces this lifetime and causes an associated deterioration in both forward and reverse conduction characteristics. As indicated by the waveform in Figure 2, the circuitry periodically establishes forward conduction at 1.3 ma in the diodes. This is followed by the application of a reverse voltage of such value and at such impedance level that the characteristic flat-topped reverse current transient is also 1.3 ma. The duration of the flat-topped pulse is proportional to minority carrier lifetime. When forward and reverse currents are equal, the lifetime is very nearly four times the pulse duration. As indicated by Figure 2, the diode circuitry, after supplying the forward and reverse conduction conditions, provides an analog telemetry signal proportional to the pulse duration. This circuitry weighed 1.4 pounds, occupied 67.5 cubic inches, and required 1.15 watts.

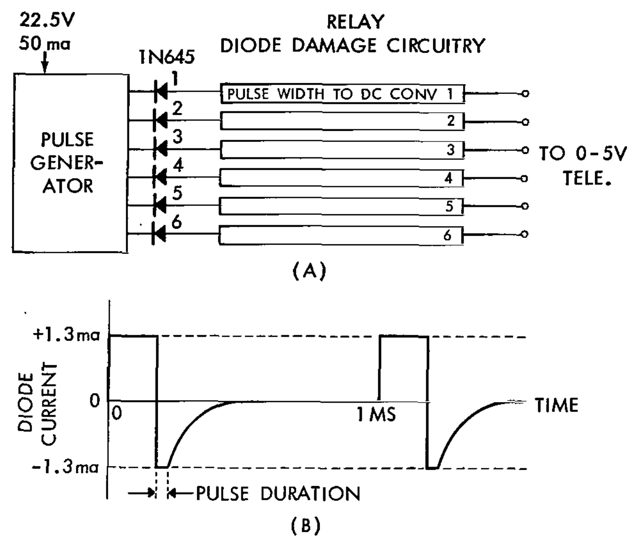

Figure 2—Radiation effects circuitry.

Solar Aspect Indicator

The condition of the experimental solar cells is judged by measuring their short circuit current under some standard environmental condition. The standard illumination source here is the Sun, at normal incidence and at its mean distance from the Earth. The actual angle of incidence is measured by a solar aspect indicator, whose readings are later used to correct the outputs from the solar cells to normal illumination, using correction data determined in the laboratory. In obtaining this aspect calibration information, the Sun was used as a source, sky-light being excluded by a 6-foot collimator.

A photograph of the aspect sensor is shown as Figure 3. In principle, it consisted of an arrangement of narrow slits and associated light

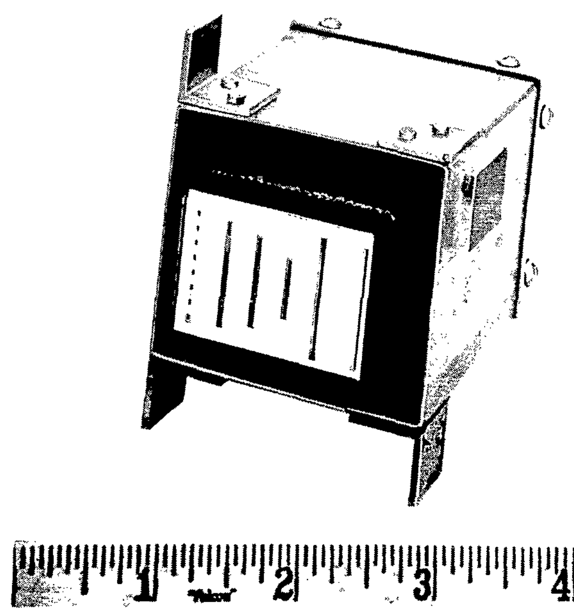

Figure 3—Solar aspect indicator.

sensitive photo-resistors. At a given angle of illumination, a unique combination of photo-resistors was energized (Reference 2). These controlled six flip-flops whose states indicated, through a six-bit binary word in the Gray code, the solar aspect angle. The angular resolution was about 3 degrees, and the range was from plus 80 to minus 80 degrees. The weight was 0.52 pounds, the volume was 16.8 cubic inches, and the power requirement was 0.075 watts.

RESULTS

Telemetry and Data Processing

The data concerning the radiation effects apparatus and other satellite-borne devices were transmitted to ground by a 9-bit word PCM telemetry system that would accept digital inputs (as from the aspect sensor), zero to 5 volt analog signals (as from the thermistors), and zero to 200 millivolt analog signals (as from the solar cells). The word rate was 128 per second. This allowed 100 successive samplings of a given solar cell in 100/128 second. Because of the satellite spin rate, at least two maxima in the solar cell output were observable in this interval. These maxima, when corrected to zero solar aspect angle, to mean solar distance, and to 25°C, indicated the condition of the solar cell.

The aspect angle variations are shown in Figure 4. This angle never exceeded 11 degrees. The associated solar cell corrections were not greater than 2 percent. Temperatures at times when data were taken ranged from 2°C to 28°C. The maximum associated cell correction was less than 3 percent for most of the cells. The maximum correction for solar distance was about 3.5 percent.

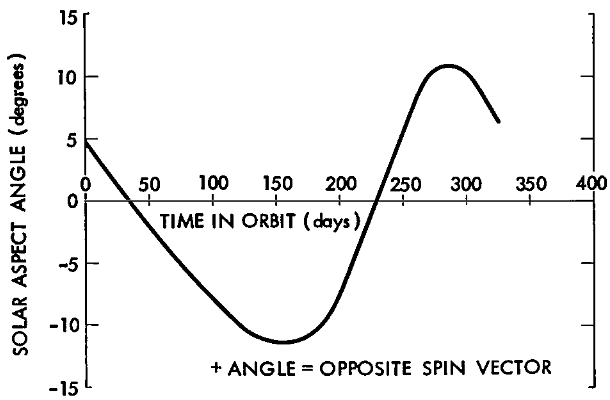

Figure 4—Relay I solar aspect vs. time.

A suitable computer program selected the maximum value (during spacecraft spin) of a cell output from the telemetry recording, and corrected it for telemetry zero shift, telemetry gain change, cell temperature, aspect angle, and solar distance. Six such responses of a given cell were read from the printed record, normalized with respect to the initial undamaged value, averaged, and then averaged with the results from the other two cells of the same type and shield. Thus, each final data point for a given cell type at a given time represents 18 observations.

The telemetered voltage signals from the six diodes on the damage panel were corrected for telemetry and temperature effects, converted to pulse length through a somewhat nonlinear calibration function, and normalized with respect to initial undamaged values.

Solar Cell Damage

Tables 3, 4, and 5 show relatively raw data from some of the solar cells to indicate the consistency of the results. It is evident that the three cells of a given type and shield deteriorated, in general, in a similar way. Exceptions are the N/P, 60 (N on P, 60 mils shield) cell 17 which suffered a catastrophic drop in output, between 45 and 49 days in orbit. The data from this cell were not used in computing the average behavior of the N/P, 60 cells after this sudden change in characteristics. The gallium arsenide cell 29 had a low initial output, but degraded in a regular manner.

Figure 5 shows the normalized, corrected short circuit current signals from the silicon and gallium arsenide cells as a function of time in the log-linear coordinates often used in this field. The uncertainty bars are plus and minus one percent of full scale in length, and the curves, in general, can be passed through the bars without effort. Certain features invite comment.

Table 3

P/N Silicon Solar Cell Load Voltages for Various Times.

Orbit Time (days)	Cell 1 P/N, 0 (mv)	Cell 2 P/N, 0 (mv)	Cell 3 P/N, 0 (mv)	Cell 7 P/N, 60 (mv)	Cell 8 P/N, 60 (mv)	Cell 9 P/N, 60 (mv)
0.020	164	158	157	161	160	159
0.083	107	103	103	159	158	158
0.185	94	89	90	157	157	157
0.448	72	72	72	160	161	161
0.860	68	65	65	159	159	159
12.8	43	41	42	133	136	136
45.5	39	37	38	117	122	121
93.0	36	34	34	106	111	109
148.0	33	31	31	101	104	103
312.0	26	24	25	93	98	96

Table 4

N/P Silicon Solar Cell Load Voltages for Various Times.

Orbit Time (days)	Cell 10 N/P, 0 (mv)	Cell 11 N/P, 0 (mv)	Cell 12 N/P, 0 (mv)	Cell 16 N/P, 60 (mv)	Cell 17 N/P, 60 (mv)	Cell 18 N/P, 60 (mv)
0.020	160	163	174	166	163	169
0.083	148	146	157	165	161	167
0.185	142	140	150	164	161	166
0.448	117	115	124	162	160	164
0.860	106	103	111	161	156	163
12.8	85	80	88	158	155	161
45.5	59	62	65	152	149	153
93.0	42	46	47	143	8	145
148.0	25	28	27	139	7	140
312.0	13	15	17	131	3	134

Table 5

Gallium Arsenide Solar Cell Load Voltages for Various Times.

Orbit Time (days)	Cell 28 GaAs, 0 (mv)	Cell 29 GaAs, 0 (mv)	Cell 30 GaAs, 0 (mv)
0.020	160	95	159
0.083	144	87	137
0.185	130	82	121
0.448	111	73	102
0.860	85	63	71
12.8	22	26	20
45.5	25	24	21
93.0	22	18	16
148.0	16	13	12
312.0	2	2	2

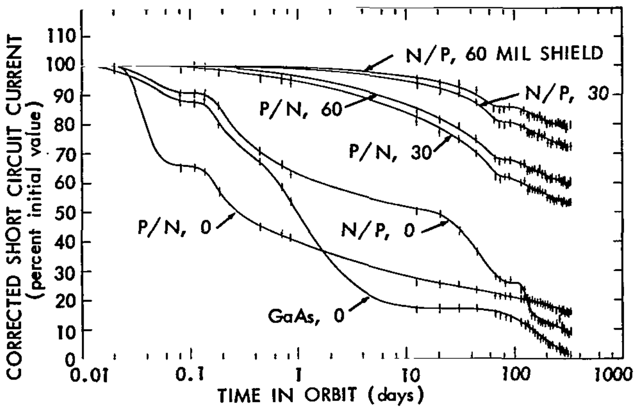

Figure 5—Response of silicon and gallium arsenide cells vs. log time.

The damage plateaus shown by the shielded cells from about 70 to 100 days are very probably real. The steep drop in the N/P, 0 cells around 135 days was present in all three cells of this type, and must be real. The early data for the unshielded cells show that they suffered large damage during the first orbit (an orbit is about 0.13 days). Gaps in the data are due to the satellite being out of range of the ground stations, or the experiment not being commanded ON. The gap between 1 and 12 days is due to satellite malfunction. Lacking data, the curves between 0.02 and 0.08 days, and between 0.9 days and 13 days, are simply drawn in a smooth, but arbitrary, manner.

Figure 6 shows the same information as Figure 5, but on a linear time scale. The curves of this figure are drawn closer to the data points than they were in Figure 5. There is a strong suggestion of damage steps for the shielded cells near 130 days, confirmed by the additional data for the P/N, 30 cells near this time. Another apparent step occurs near 200 days. A non-uniform irradiation rate is indicated, with high intensities at intervals of about 70 days.

Table 6 shows numerical values of the relative responses from the silicon and gallium arsenide cells at various times. Some interpolation and extrapolation here is necessary. Values less certain are in parentheses.

Table 7 shows the orbit times at which various types of cells fell to given response levels. Again parentheses indicate less certain values. The 75 percent level is of particular interest, since the associated particle fluxes or orbit times have been widely used in comparing solar cells. In any event, the non-uniform irradiation rates make time only an approximate measure of total irradiation, especially for the bare cells during the first day. However,

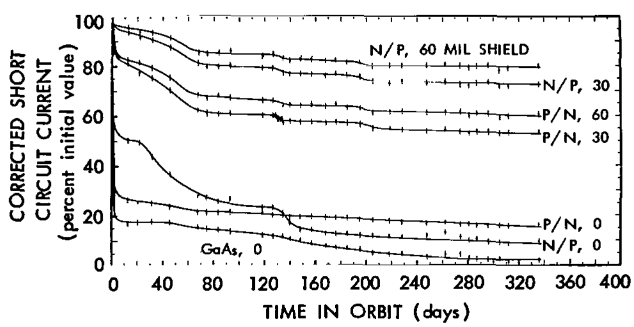

Figure 6—Response of silicon and gallium arsenide cells vs. time.

Table 6

Percent Initial Short Circuit Current for Various Solar Cells at Given Times.

Orbit Time (days)	P/N, 0 (%)	P/N, 30 (%)	P/N, 60 (%)	N/P, 0 (%)	N/P, 30 (%)	N/P, 60 (%)	GaAs, 0 (%)
0.01	100	100	100	100	100	100	100
0.03	95	100	100	98	100	100	96
0.1	66	100	100	91	100	100	98
0.3	(49)	98	99	(76)	100	100	(72)
1.0	40	95	96	63	99	99	50
3.0	(34)	(90)	(93)	(57)	(97)	(98)	(27)
10.0	28	84	87	52	95	96	18
30.0	25	76	79	45	91	94	18
100.0	21	61	67	25	80	85	15
300.0	16	53	61	9	73	70	2
1000.0	(9)	(45)	(51)	(0)	(66)	(70)	(0)

Table 7

Times in Orbit at Which Various Solar Cells Fell to Given Percent Initial Values.

Output (%)	P/N, 0 (days)	P/N, 30 (days)	P/N, 60 (days)	N/P, 0 (days)	N/P, 30 (days)	N/P, 60 (days)	GaAs, 0 (days)
90	(0.033)	(3.2)	(5.7)	0.14	34	50	(0.06)
75	(0.044)	32	47	0.33	197	(480)	0.25
60	0.17	128	300	(1.6)	(1800)	(4000)	0.66
50	(0.28)	(470)	(1200)	17	(7200)	(18000)	1

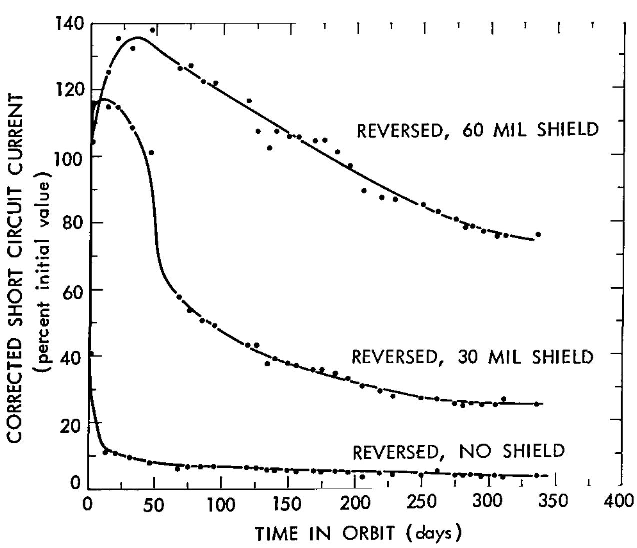

Figure 7—Response of reversed cells vs. time.

all cells were subjected to the same flux with a high degree of uniformity, so that cells can be compared at given times with considerable confidence, especially if the observation is made at or near a data-taking time.

Figure 7 shows the results obtained from the "reversed," presumably highly susceptible, solar cells. Their behavior is obviously anomalous. They show initial increases in relative response before they eventually fall. The responses suggest that there is an "annealing" action by some aspect of the environment which is finally overpowered by a damage mechanism which is retarded, as shown, by the shields of increasing thickness. In any event, these cells hardly served their intended purpose.

Diodes

The normalized diode pulse length (or minority carrier lifetime) versus time is shown in Figure 8 for several of the diodes, together with the responses from the P/N, 0 and P/N, 60 solar cells. Curves for several of the diodes are not shown because they are practically identical with those given in Figure 8. While the diode data are limited in amount and in dynamic range, an initial steep damage rate, intermediate between the P/N, 0 and P/N, 60 solar cells, is evident.

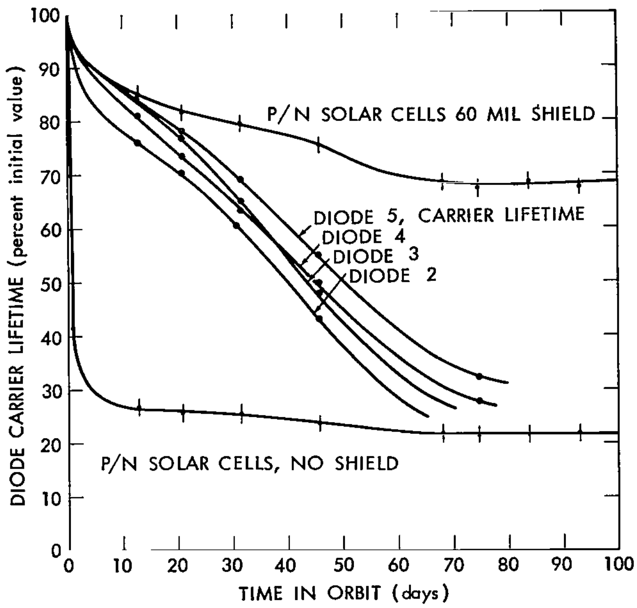

Figure 8—Diode carrier lifetime vs. time.

DISCUSSION

Merits of Various Cell Types

Figures 5 and 6 indicate that the order of merit of the shielded cells is N/P, higher, and P/N, lower. The unshielded cells, judged while their relative responses are above 50 percent, have the order N/P, GaAs, and P/N. It must be remembered that this comparison, and others to follow, is influenced by the character of the radiations present in the Relay orbit.

It may be determined from Figures 5 and 6 that the N/P, 60 cells last 10 times longer than the P/N, 60 cells, when judged at the 75 percent level. Further, the N/P, 30 cells last 5.9 times longer than the P/N, 30 cells. The degradation of the bare cells is so rapid, and the early irradiation rate is so non-uniform, that making numerical comparisons among them is scarcely meaningful. It is apparent that the N/P, 0 and the GaAs, 0 cells behave quite similarly down to the 70 percent level, with several odd changes in order of merit among the bare cells at large degradations. The GaAs cells do not show the expected superiority over silicon cells under the conditions of this experiment, using bare cells and short circuit current as a measure of merit.

Merits of Shields

Figures 5 and 6 show, at the 75 percent response level, that the N/P, 60 cells last about 2.3 times longer than the N/P, 30 cells. The P/N, 60 cells last about 1.4 times longer than the P/N, 30. Thus, for both types, doubling the weight of shield material (which contributes materially to the total spacecraft weight) only extends life (at the 75 percent level) by about 2 times. This same life extension could be attained by using an additional 5 percent of the less heavily shielded cells.

The useful lifetime of the unshielded cells is so short as to prohibit their use in spacecraft in this type of orbit. It is apparent that even a 30 mil shield increases the useful lifetime of the bare silicon cells by a factor of about 600.

Solar Cell Damage Predictions

Prediction Methods

Damage to solar cells by trapped radiations may be predicted by various methods. The empirical approach is to examine the literature to find a spacecraft whose orbit is similar to the one of interest, and to determine the radiation damage it sustained, either in its main solar cell power supply or in some damage experiment like that reported here. This method is necessarily approximate.

Another approach that might be attempted would be to fully determine the character of the semiconductor materials of the type of solar cell of interest, the nature of any shield, and the character of the radiations to be encountered in orbit. The damage contributed by each component of the radiation would then be calculated from fundamental physical principles, and the power output at, say, the end of a given time in orbit would be determined.

This method would require a detailed space map of particle type, intensity, energy distribution, and angular distribution, with allowance for possible variations with time. Such maps are being built up, but the accuracy claims are still very modest. Also required would be a method of calculating how the shield material alters the radiation in intensity, energy, and angular distribution. These matters cannot yet be calculated easily or accurately.

The composition and structure of the solar cell must be known, and the number and nature of the lattice defects caused by the various components of incident radiation calculated, together with their influence on the efficiency of the cell. These matters involve the frontiers of solid state physics.

The above academic approach, while desirable, is not yet practicable.

Of several approaches, intermediate between the extremes noted above, the following was chosen.

Bare silicon cells similar to the ones used in this experiment have been subjected to well controlled radiation damage, using 1 Mev electrons and 4.6 Mev protons from accelerators, by W. R. Cherry and L. W. Slifer (Reference 3). The short circuit current was monitored, with the cells illuminated by a 2800°K tungsten source, filtered by 3 cm. of distilled water. The intensity was comparable with sunlight.

The above information on damage susceptibility will be combined with the available knowledge of the electron and proton intensity (and, to some extent, energy) distribution in space. This information will come from several sources, but will not include data obtained by the radiation measuring instruments on Relay. A suitable computer program will, in effect, carry the experiment through the trapped particles, computing the accumulated doses for a number of Relay orbits. This radiation information will be modified to account for the effect of the shielding. The result of combining the laboratory-determined damage susceptibilities with the radiation information will permit prediction of cell damage.

This approach has its weaknesses. The cells measured in the laboratory are similar to, but not identical with, those used in orbit. The light source used to evaluate the laboratory damage is different in spectral energy distribution from sunlight. This causes apparent damage different from that obtained in orbit. This effect depends on cell type, and nature and energy of the particle that did the damage. It is being investigated further. The laboratory damage studies directed beams of particles perpendicularly to the cell surface and the effect of oblique irradiation, which occurs in space, can only be estimated. Interpolation and extrapolation of the laboratory damage data will be required.

Concerning the space maps of particle distribution, these are being assembled and modified as more information becomes available. Data on energy distribution are incomplete. Finally, the maps are subject to change with time as a result of natural and man-made disturbances. In view of the above, approximate prediction of damage is all that can be expected.

Unshielded Silicon Cells

It has been shown that bare silicon solar cells are damaged by either electrons or protons whose energy exceeds a few hundred kev. A cursory review of approximate doses of the particle fluxes along the Relay orbit indicated that low energy protons would probably be the predominant cause of damage to bare silicon cells. Davis and Williamson have reported a large flux of protons of energies above 100 kev centering about an equatorial altitude of about 2.5 earth radii (Reference 4). The measurements were made on Explorer XII. The Relay orbit penetrates high latitude parts of this distribution.

Davis has organized this data into a space map of protons of energies above 100 kev, 500 kev, and 1000 kev, and integrated the fluxes over the first eleven hours of the Relay path, using 1-minute steps. The resulting plots are shown in Figure 9. Major damage steps at about three-hour (one orbit) intervals are evident. An accuracy of plus or minus fifty percent is quoted.

The susceptibility of silicon solar cells to proton damage is known to be relatively small at both very high and very low energies. Baicker, Faughnan, and Wysocki have shown that the susceptibility is a maximum around 1 Mev, falling rapidly below 0.2 Mev and slowly above 1 Mev, when judged by maximum power output under sunlight illumination (Reference 5). It will be assumed here that the damage susceptibility to protons is zero up to 0.5 Mev, where it has a maximum value, and above which it falls inversely with energy. The latter characteristic is indicated by both theory and experiment, for energies up to about 100 Mev. Thus, the Figure 9 curve for proton energies

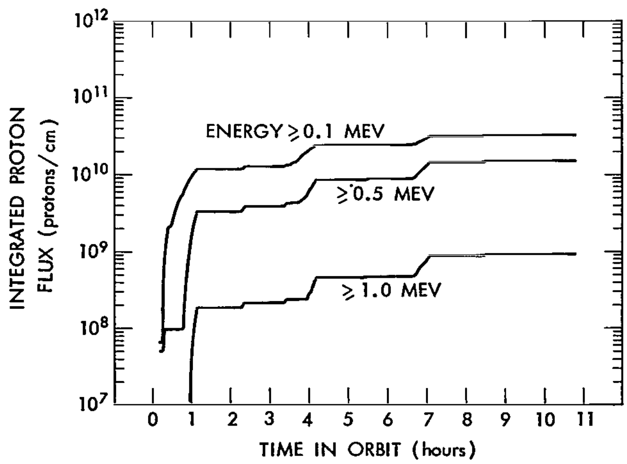

Figure 9—Low energy proton flux vs. time.

equal to or greater than 0.5 Mev is of interest. The figure indicates that the proton population falls rapidly with energy. It is estimated that the "energy center" of the protons whose energy is above 0.5 Mev is at 0.7 Mev. Using the assumption that the damage susceptibility is inverse with energy, we then multiply the ordinates of the 0.5 Mev curve of Figure 9 by 4.6/0.7 to obtain the number of equivalent 4.6 Mev protons per cm^2 as a function of time. We then use the Cherry and Slifer 4.6 Mev proton damage data of Figure 10 to convert the above predicted equivalent 4.6 Mev orbital proton fluxes to solar cell damage values. The result, for silicon P/N cells, is shown in Figure 11, together with data obtained from the relay radiation damage experiment.

It is evident that the predicted values of short circuit current are in fair agreement with the observed values, most of which fall within the error limits associated with the 50 percent uncertainty in orbital fluxes. The predicted values are systematically higher than the observed ones.

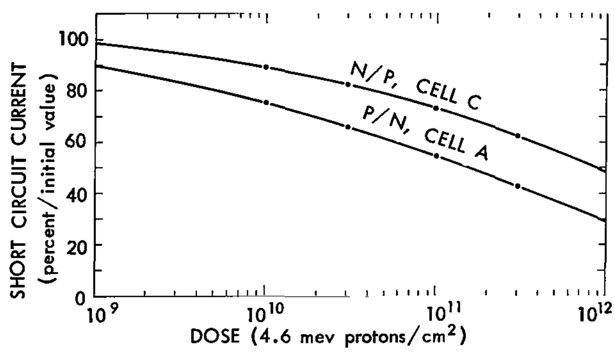

Figure 10—Response of silicon solar cells vs. flux of protons.

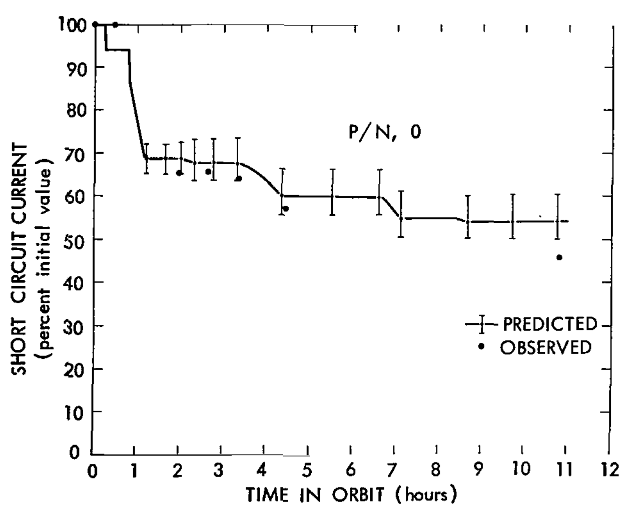

Figure 11—Predicted and observed damage to P/N cells.

The time structure of the observed damage is correctly predicted, with the indication that a damage step probably occurred near seven hours, but was not observed. It may be mentioned that damage predictions based on high energy protons and on electrons failed to account for the magnitude of the damage to these unshielded cells, and the predicted damage steps occurred at the wrong times.

Figure 12 shows a plot of the first six hours of orbit in the B, L coordinates devised by

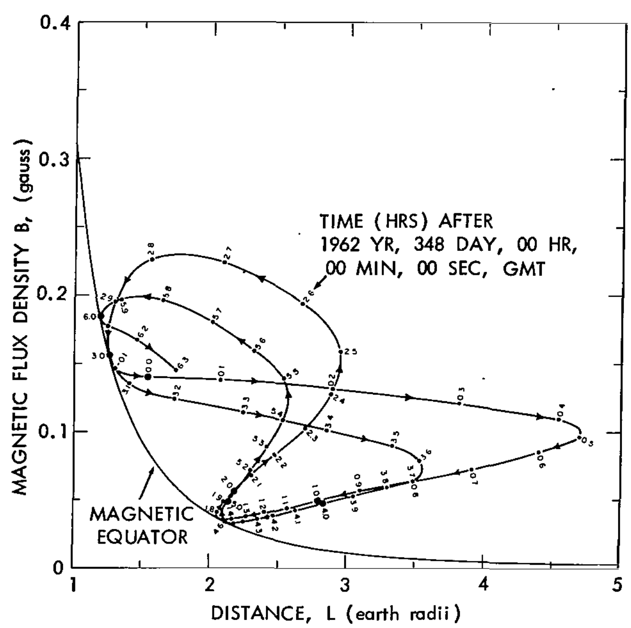

Figure 12—Orbit plot in B vs. L coordinates.

McIlwain (Reference 6). The predicted damage steps centering at 0.8, 3.9, and 6.9 hours in Figure 11 have B, L coordinates of (0.064, 3.46), (0.053, 3.04), and (0.049, 2.67), respectively. These all lie at about 30 degrees south latitude, at an altitude of about 6,100 km.

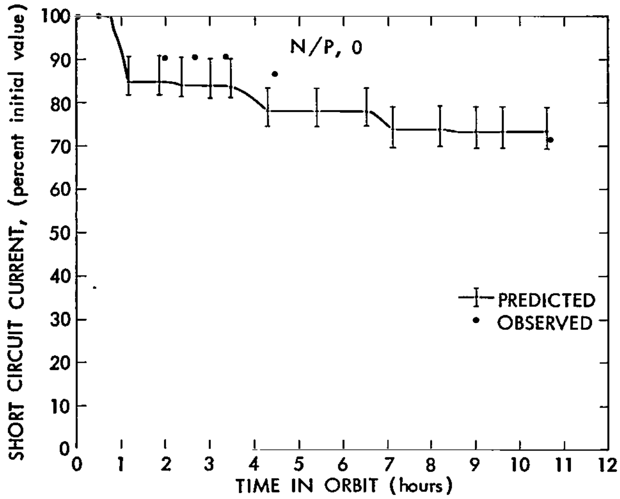

Figure 13—Predicted and observed damage to N/P cells.

The result of the above damage prediction procedure when applied to the N/P silicon solar cells is shown in Figure 13. The Cherry and Slifer laboratory damage data of Figure 10 were again employed. The observed damage points in Figure 13 fall near the upper error limits of the predicted values, a systematic difference of sign opposite to that of Figure 11 being evident. The predicted time variation is in agreement with that observed. The desirability of more frequent and complete data in observing orbital damage is obvious.

Since laboratory proton damage studies on gallium arsenide equivalent to those of Figures 10 and 14 are not available, the above type of prediction of gallium arsenide damage cannot be attempted. Baicker et al. (Reference 7), have considered the unexpectedly rapid deterioration of the gallium arsenide cells on Relay and attribute it to a relatively high damage susceptibility to protons of energies below a few hundred kev. This is related to the fact that the useful volume of a gallium arsenide solar cell is located in a much thinner front layer than is the case for silicon. A shield of even 1 mil of fused silica would stop all low energy protons up to 1.5 Mev, and presumably allow the gallium arsenide cells to exhibit the high radiation damage resistance indicated by theory and by laboratory damage studies when protons above approximately 2 Mev are used.

Proton Damage to Shielded Cells

We will here attempt to predict the damage suffered by silicon P/N and N/P cells, shielded by 60 mils (0.336 grams per cm^2) of clear fused silica (Corning 7940). Since the damage per orbit was too small to be resolved, only long time damage effects will be considered.

A fused silica shield of 60 mils thickness will, nominally, stop a 16.5 Mev proton and a 0.90 Mev electron. The large flux of low energy protons which evidently damaged the unshielded cells is therefore excluded.

The Mathematics and Computing Branch of the Theoretical Division of GSFC calculated fluxes of high energy protons and electrons over intervals of Relay flight. These predictions covered five two-day intervals. Fourteen second steps were used. The cumulative flux of protons of energy above 30 Mev involved use of the P_1 proton grid, or space particle distribution map.

Electron fluxes were made with the E8U and E8L electron grids, giving upper and lower limits. This information is summarized in Table 8. The fluxes are omni-directional.

Table 8

Predicted Omnidirectional Proton and Electron Fluxes.

Days in orbit	Proton Flux (Protons/cm²-day)	Electron Flux upper (Electrons/cm²-day)	Electron Flux lower (Electrons/cm²-day)
0 to 2	0.254 (9)	2.87 (12)	1.58 (12)
14 to 16	0.305 (9)	3.74 (12)	1.85 (12)
45 to 47	10.5 (9)	8.72 (12)	5.78 (12)
83 to 85	17.4 (9)	14.1 (12)	6.92 (12)
194 to 196	10.5 (9)	8.17 (12)	4.58 (12)
	Mean = 8.79 (8)	Mean = 7.52 (12)	Mean = 4.14 (12)
		Mean = 5.83 (12) ± 30% electrons/cm²-day	

Proton energies are equal to or greater than 30 Mev.
Electron energies are equal to or greater than 0.5 Mev.

The mean proton flux of Table 8 refers to protons of energy above 30 Mev. It is necessary to move the cut-off energy downward from 30 Mev to 16.5 Mev. According to McIlwain and Pizella (Reference 8), the ratio of the proton fluxes Q_1 and Q_2 having energy cutoffs at E_1 and E_2, respectively, is given by

$$\frac{Q_1}{Q_2} = \exp \frac{E_2 - E_1}{E_0} , \tag{1}$$

where

$$E_0 = 360\, L^{-5.2} . \tag{2}$$

Assuming that the major cell damage occurred near equatorial crossings, an average equatorial L value of 1.7 was determined from orbit predictions. This, with Equation (2), gives a value of E_0 of 19.45 Mev. When this is entered in Equation (1), together with the energy cut-off values of 30 and 16.5 Mev, the flux extension factor is found to be 2.0. Other factors to be applied to the mean proton flux value of 8.79×10^8 protons/cm²-day are estimated as: 1/2 (for infinite rear shielding), 1/3 (for oblique incidence) and 1 (to get 4.6 Mev equivalence). The latter is roughly estimated as follows: the steeply falling incident integral proton spectrum is considered cut off below 16.5 Mev. Increasing numbers of protons of initial energies greater than this value penetrate the shield, with exit energies rising from zero. The rise is estimated to terminate in a few Mev, after which a fall dictated by the shape of the initial spectrum occurs. The maximum is probably at a few Mev. Since laboratory damage information on these types of cells was available at 4.6 Mev, this same energy equivalent of the protons penetrating the shield is assumed, lacking a more precise determination. The straggling of protons in shields is very severe.

The overall factor deduced above is 1/3, giving a predicted 4.6 Mev normal incidence proton flux of $1/3 \times 8.79 \times 10^8$ or 2.93×10^8 protons/cm^2-day, or 8.8×10^{10} protons/cm^2 over 300 days. Using this value with the damage curves of Figure 10 gives cell responses of 56 percent for the P/N, 60 cells and 75 percent for the N/P, 60 cells. These are to be compared with the observed values of 60 and 79 percent. The agreement is fair.

Electron Damage to Shielded Cells

Table 8 indicates a predicted average omni-directional electron flux of 5.83×10^{12} electrons/cm^2-day. We will assume they have a fission spectrum and utilize a function (Reference 9) to convert this value to equivalent normal incidence 1 Mev electrons after passage through shielding material. The result is, for the P/N, 60 cells, a factor of 0.14, and, for the N/P, 60, a factor of 0.31. Thus the predicted equivalent 1 Mev electron flux per cm^2-day becomes 8.16×10^{11} electrons/cm^2-day, or 2.45×10^{14} electrons/cm^2 over 300 days, for the P/N, 60 cells. Using the appropriate damage curve of Figure 14, we obtain a predicted cell response of 47 percent. This is considerably smaller than the observed value of 59.8 percent. Similarly, for N/P, 60 cells the predicted flux per cm^2 over 300 days is 5.4×10^{14} equivalent 1 Mev electrons, giving a predicted response of 75 percent, versus an observed 79 percent, which is fair agreement.

Thus, the predicted damage by both electrons and protons on heavily shielded silicon cells exceeds that observed. This nature of disagreement can be partly attributed to the use of tungsten light in evaluating the laboratory damage curves of Figures 10 and 14. This tends to exaggerate damage, as compared with that demonstrated in orbit with sunlight illumination. The electron damage prediction also neglected a decrease in electron intensities, which is known to have occurred during the experiment.

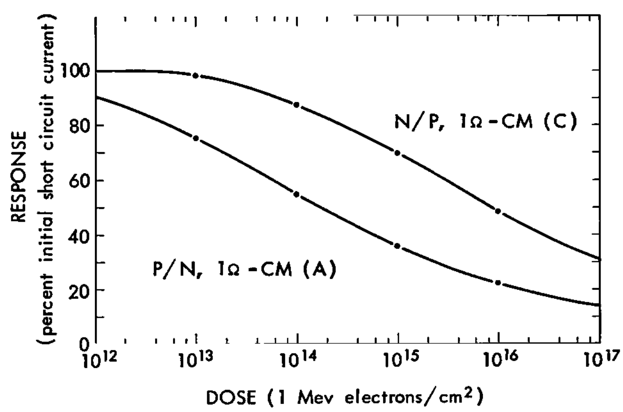

Figure 14—Response to silicon solar cells vs. flux of electrons.

Comparison with Other Orbital Damage Experiments

Table 9 shows the orbit parameters of some other satellites which have carried radiation damage experiments, together with cells, shields, and times estimated for cell responses to fall to 75 percent of their original values. These data are largely taken from Cooley et al, (Reference 10).

Some comparison may be made. Midas III has a circular polar orbit at about the same mean altitudes as Telstar I and Relay I. They all carry N/P cells with about the same effective shields. Their "lifetimes" in orbit are 1000, 400, and 480 days, respectively. The fact that Midas III was at the altitude of the "inner belt" is evidently compensated by the fact that it spends a large part of its time in low damage regions near the poles.

Table 9

Orbital Radiation Damage Experiments.

No.	Satellite	Perigee (km)	Apogee (km)	Inclination (deg)	Launch Date	Cell Type	Shield Thickness (mils)	$T_{0.75}$ (days)
1	Explorer XI	491	1799	28.8	4/27/61	N/P	0	70
2	Midas III	3450	3510	91.2	7/12/61	P/N	40, silica	100
						P/N	80, silica	250
						N/P	60, silica	1000
3	Explorer XII	304	77000	33.0	8/16/61	P/N	3, glass	1000
						P/N	0	1 orbit
4	Midas IV	3530	3760	95.9	10/21/61	P/N	40, silica	53
						P/N	80, silica	110
5	Telstar I	952	5660	45.0	7/26/62	N/P	30, sapp.	400
6	Alouette	1004	1029	90.0	9/29/62	P/N	12, glass	30
7	Explorer XIV	278	99000	33.0	10/21/62	P/N	0	1 orbit
8	1962-BK	191	5550	71.0	10/26/62	P/N	6, glass	4
						P/N	60, glass	100
						N/P	6, glass	50
9	ANNA 1B	1090	1180	50.0	10/31/62	P/N	6, glass	40
						P/N	20, silica	90
						P/N	30, sapp.	400
						N/P	30, sapp.	1400
10	Relay 1	1321	7439	47.5	12/13/62	P/N	0	1 orbit
						P/N	30, silica	32
						P/N	60, silica	47
						N/P	0	0.33
						N/P	30, silica	197
						N/P	60, silica	480
						GaAs	0	0.06

The Explorer XII and Explorer XIV P/N, 0 cells and the Relay I P/N, 0 cells, although in greatly different orbits, agree in that they were all very severely damaged in one orbit. The fact that the Explorer XII (P/N, 3 glass) cells had such a long lifetime compared to that of the unshielded cells strongly indicates damage by low energy protons, to which the damage to the unshielded cells on Relay has been quantitatively ascribed.

The (P/N, 60 glass) cells on 1962 BK and the (P/N, 60 silica) cells on Relay had roughly the same mean altitudes, and their critical times of 100 and 47 days, respectively, are comparable.

Although not shown in Table 9, ANNA 1B carried a gallium arsenide cell with a 6 mil glass shield. This appeared more damage resistant than any of the much more heavily shielded silicon cells up to 80 days in orbit, when it apparently began to degrade rapidly. Although its orbit is quite different from that of Relay, the long lifetime compared to the unshielded gallium arsenide cells on the latter spacecraft (0.06 days) suggests again that low energy protons were the damaging agent.

A review of Table 9 strongly indicates that N/P silicon solar cells, shielded with the equivalent of 60 mils of Corning Type 7940 transparent, fused silica would probably have a lifetime (75 percent point) of about one year, if in the most damaging orbit. This presumably would be an equatorial one at an altitude of about 3000 km.

In view of the approximations now required in the prediction of the lifetime of solar cell power supplies in orbit, it is obviously prudent to check such predictions against empirical information of the kind indicated in Table 9.

CONCLUSIONS

The radiation effects experiment carried on Relay has shown, by virtue of observations taken over about one year, that silicon N/P solar cells shielded with 60 mils of Type 7940 silica last about 10 times longer than similarly shielded P/N cells, when judged by short circuit current at the 75 percent initial value level.

Silicon N/P cells with 30 mil shields last about six times longer than similar P/N cells.

Silicon N/P cells with 60 mil shields last about 480 days; silicon N/P cells with 30 mil shields last 197 days, all at the 75 percent level.

Unshielded silicon N/P, P/N, and gallium arsenide cells all last less than one day.

The use of 60 mil shields approximately doubles the life of a silicon cell, as compared to one using a 30 mil shield.

Fluctuations in the degradation rates were apparent. Early effects were attributable to successive passes through highly damaging regions of space.

Early damage to unshielded P/N and N/P cells was approximately accounted for, in magnitude and in time, by predictions based on a space map of low energy protons, to which unshielded cells, particularly those of gallium arsenide, are very sensitive.

The long term degradation of the shielded silicon cells was predicted, approximately, by consideration of the effects of protons of energy greater than 16.5 Mev, using the GSFC P1 proton grid.

However, a consideration of the damage caused by electrons of energy greater than 0.5 Mev, using the GSFC E8 grid, also approximately predicted the observed damage. This prediction ignored a decrease in electron intensities which is known to have occurred during this flight.

It thus appears that protons were the principal cause of damage to the heavily shielded cells. Also, the particle information, the data on laboratory radiation damage, or approximations in the calculations, have tended to an over-prediction of damage to shielded cells.

The radiation damage observed on Relay is similar to damage occurring on Midas III and Telstar I. This is reasonable when the orbits are considered. The empirical information indicates that for a solar cell-powered spacecraft to last one year in an equatorial orbit of about 3000 km altitude, N/P silicon cells shielded with at least 60 mils of fused silica would be required if the performance were not to fall below the 75 percent initial value.

It would be of great value if future satellite solar cell damage experiments were such that the maximum power from the cells were measured, instead of short circuit current, which is known to be only a poor measure of power under some conditions. The use of gallium arsenide cells with a variety of shields may allow this material to demonstrate its potential. More complete and accurate space maps of the trapped radiations are highly desirable, together with improved laboratory damage studies on solar cells. Damage studies using high energy electrons and protons on shielded cells would remove some of the uncertainties now involved in calculating shielding effects, particularly if the damage were evaluated in sunlight.

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REFERENCES

1. Lax, Benjamin, and Neustadter, S. F., "Transient Response of a p-n Junction," *J. Applied Physics* 25(9):1148-1154, September, 1954.

2. Albus, J. S., and Schaefer, D. H., "Satellite Attitude Determination: Digital Sensing and On-Board Processing," GSFC Document X-631-63-133, July, 1963.

3. Cherry, W. R., and Slifer, W. W., "Solar Cell Radiation Damage Studies with 1 Mev Electrons and 4.6 Mev Protons," GSFC Document X-636-63-110, May 27, 1963.

4. Davis, Leo R. and Williamson, James M., "Low Energy Trapped Protons," GSFC Document X-611-62-89, May, 1962.

5. Baicker, J. A., Faughnan, B. W., and Wysocki, J. J., "Radiation Damage to Silicon," Third Semi-Annual Report on Contract NAS 5-457, April 15, 1962.

6. McIlwain, C. E., "Coordinates for Mapping the Distribution of Magnetically Trapped Particles," *J. Geophys. Res.* 66, 3681-3691, 1961.

7. Baicker, J. A., Faughnan, B. W., and Wysocki, J. J., "Radiation Damage to Silicon," Third Semi-Annual Report on Contract NAS5-457, April 15, 1962.

8. McIlwain, C. E., and Pizzella, G., "On the Energy Spectrum of Protons Trapped in the Earth's Inner Van Allen Zone," *J. Geophys. Res.* 68(7):1811-23, April 1, 1963.

9. Rosenzweig, W., "Radiation Damage Studies," IEEE Photovoltaic Specialists Conference, Washington, D. C., April 10-11, 1963.

10. Cooley, William C., Janda, Robert J., and Shivanandan, Kandiah, "Handbook on Space Radiation Effects to Solar Cell Power Systems," Contract NASw-598, July 22, 1963.

NASA-Langley, 1966

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