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INTRODUCTION

Solar cells are solid-state devices capable of directly converting sunlight to electric power with an efficiency of the order of ten percent. They may be made by crystallizing a proper semiconductor material, such as silicon, with a controlled amount of acceptor (p) impurity. A donor (n) impurity may then be diffused into one surface of a thin slab of the crystal material. The result, after adding electrodes, is a large-area solid state diode of n-on-p (n/p) construction. When the thin diffused n layer is illuminated hole and electron carrier pairs are generated within the cell by photon absorption. The diffusion of the carriers, assisted by the electric field at the diode interface, causes charge separation. This makes electric power available at the terminals.

Solar cells are fairly light, rugged, and efficient. They have been widely used to furnish electric power for unmanned scientific spacecraft. However, they suffer damage under irradiation by the trapped electrons and protons in the Van Allen radiation belts. The damage is caused by the particles creating crystal defects. These in turn assist the undesired recombination of the hole-electron pairs created by photon absorption. The defects can be said to shorten the diffusion length and the lifetime of the minority carriers.

To minimize the damage one can choose optimum materials and then cover the cell with a shield which is transparent to light but which stops the electrons and protons.

While much valuable information on cell radiation damage can be obtained in the laboratory, using electron and proton accelerators, it is impossible to fully simulate the complex environment of space, with its wide range of electron and proton energies at relatively low intensities.

The solar cell radiation damage studies on Relay I and Relay II were therefore designed to study, in orbit, the characteristics of several different kinds of solar cells, shielded to various degrees.

ORBITS

The results of the experiments here reported necessarily reflect the character of the spacecraft orbits. Orbit parameters are shown in Table I. It is seen that perigee and apogee bracket the "inner" Van Allen belt whose center is at an altitude of about 3000 km above the equator. Thus, the Relay spacecraft spent considerable time in heavily damaging regions of space.

The results here reported are characteristic of the electron and proton energies and intensities associated with these similar orbits. However, comparisons between cells and shields can be safely made and it was hoped that some useful generalities might be inferred.

APPARATUS

The apparatus used in these solar cell radiation damage experiments on Relay I and Relay II were identical, except for the selection of solar cells and shields.

In each experiment thirty 1 cm by 2 cm solar cells were mounted on the surface of an aluminum damage panel whose dimensions were 10.2 cm by 13.5 cm by 0.318 cm thick. Each cell was loaded by a resistor of a few ohms and therefore operated in, substantially, a short circuit condition. This condition of observation has been widely used in solar cell damage studies. The voltages developed across the load resistors were telemetered, and then recorded by ground stations as continuously as possible. Also telemetered were the cell temperature, the solar aspect angle (from which the angle of incidence of the illumination of the solar cells may be determined), and carrier-lifetime signals derived from six diodes mounted on the damage panel. These diodes were of a commercial power rectifier type (1N645), selected for long minority carrier lifetime (initially from 11.5 to 16.5 microseconds). The technique used was that of carrier injection-extraction[1].

The solar cells of these experiments are listed in Table II. It is seen that Si p/n, Si n/p, GaAs p/n and special Si REV p/n cells, with various shields, were investigated. While silicon is the most widely used solar cell material, gallium arsenide has some theoretical advantages. It should have a high efficiency because its band-gap appears near optimum for sunlight and it should be highly damage resistant. The Si, REV cells were of special construction, aimed at providing some cells that were very sensitive to radiation damage. To do this the front (illuminated) diode portion was made abnormally thick, presumably about one diffusion length in extent. Theoretically, while undamaged these cells should have a moderate efficiency, which was the case. Since irradiation causes a decrease in diffusion length it was expected that carrier pairs, created by photon absorption near the surface, to then find themselves at distances greater than a diffusion length from the junction, with consequent rapid loss of cell efficiency.

The base resistivity of the normal Si n/p and Si p/n cells was about 1 ohm-cm.

The stopping powers of 19.1, 76.5, 168, and 336 mg/cm^2 shields are, for electrons, about 0.13, 0.29, 0.53, and 0.90 MeV, respectively; and, for protons, they are 3.2, 7.0, 11.0, and 16.5 MeV, respectively.

RESULTS, RELAY I

In Fig. 1 the results of about 400 days of observations of Relay I are shown. These are for the normal silicon cells and the unshielded gallium arsenide cells.

The short circuit currents, shown here and later, have been normalized with respect to initial, undamaged values. They have also been corrected to 20°C temperature, normal angle of illumination, and to mean earth-sun distance. Results for a given cell type and shield have been averaged. From 12 to 18 observations, taken over an interval of a few minutes, were used in calculating each data point. In general, smooth curves can be passed within 1 percent of each data point.

In the laboratory, if a solar cell is irradiated at a constant rate with a given type and energy of particle, and the results are plotted in the semi-log manner of Fig. 1 the graph shows a constant initial level, then a smooth downward curve which straightens out to a final section of near constant slope. The departures of the curves of Fig. 1 from the above ideal reflect the changing irradiation rate encountered during this experiment. In the four upper curves there is a prominent plateau of low damage rate at about 100 days. Beyond this point all of these curves have a slope of about 17 percent per decade (factor of 10) of time.

It is evident that the silicon n/p cells were more damage resistant than the silicon p/n cells. Also, the shields were partly successful in excluding damaging particles.

Figure 2 shows some of the same data as Fig. 1, plotted to a linear time base, with closer adherence to the data points. It appears here that the irradiation was not only variable, but tended to occur in heavy doses, separated by intervals of little damage. The damage periodicity is about 70 days. In the upper part of Fig. 2 is shown the latitude of perigee of Relay I as a function of time. A generality is apparent. The high damage rates experienced by the solar cells occured slightly before latitude of perigee was a positive maximum, zero, or a negative maximum. The period of the precession of latitude of perigee was 296 days, one-fourth of which is 74 days. There is thus a strong suggestion that the Relay I orbit, together with the spatial and energy distributions of the trapped particles in the inner belt, were such that precession of the latitude of perigee periodically carried the spacecraft through highly damaging regions of space. Further, any attempt to predict radiation damage can not be based on analysis of a few random orbits, but must anticipate the long term fluctuations here observed.

It was considered instructive, to attempt to calculate the degradation of certain of the experimental cells on Relay I and to compare the predicted and observed damage.

The Mathematics and Computing Branch of the Theoretical Division of Goddard Space Flight Center has compiled a description of the spatial and energy distributions of electrons and protons trapped in the earth's magnetic field. These "grids" allow computer calculation of the cumulative fluxes of particles encountered during given orbits. Such calculations were made and the fluxes obtained were used, together with laboratory solar cell damage information obtained by W. R. Cherry and L. W. Slifer[2], to predict the damage suffered by the heavily shielded normal silicon solar cells. The results are summarized in Table III.

It is seen that the predicted responses after considering either electron or proton damage in orbit are less than those observed; that is, the predicted damage is somewhat greater than that observed. It is now believed that the electron fluxes present were actually less than those calculated, because of decay. Also, the laboratory damage information had been evaluated using incandesent lamps, which tended to exaggerate the damage. It appears probable, however, that the orbital damage suffered by the heavily shielded silicon cells in Relay I was caused by both electrons and protons. The effort to predict this damage was moderately successful.

To return to Fig. 1, the unshielded cells show several interesting characteristics. Most evident is the fact that unshielded cells are very highly vulnerable to radiation damage. Their currents fall to 75 percent in a few tenths of a day, compared to tens or hundreds of days for the shielded cells. Further, their damage, initially, occurs in steps a few hours apart. The orbital period is 3.08 hours or 0.128 days. Thus we see here the damage involved in single orbital passages through some highly damaging region of space. Other peculiarities are the crossing of the curves for (Si, n/p, 0), (Si, p/n, 0), and (GaAs, p/n, 0) cells, and the steep fall of (Si, n/p, 0) cells near 130 days. It is evident that the unshielded gallium arsenide cells are inferior to the unshielded (Si, n/p, 0) cells, but all bare cells deteriorate so rapidly as to be useless in this orbit.

It has been established by laboratory experiments that the effectiveness of protons in causing damage to bare silicon solar cells is approximately inversely proportional to energy, down to a few hundred Kev. It was therefore logical to attempt to account for the rapid early degradation of the unshielded silicon cells on Relay I by considering such low energy protons. Davis and Williamson[3] have reported a large flux of protons of energies above 100 Kev centering about an equatorial altitude of about 2.5 earth radii. The early Relay I orbit penetrates parts of this distribution.

L. Davis[4] calculated the cumulative flux of protons of energy greater than 0.5 Mev encountered by Relay I in its first 12 hours of flight. Calculations using this flux and the solar cell damage information of Cherry and Slifer[2] lead to predicted damage for the (Si, p/n, 0) cells as shown in Fig. 3. The predicted damage occured in orbital steps each time the spacecraft passed through a region at about 30 degrees south latitude and at an altitude of about 6,100 km. It is seen that the observed damage points agree fairly well with the calculated damage curve.

Figure 4 shows a similar comparison of predicted and observed damage for the (Si, n/p, 0) cells. Again the agreement is fair. It is thus highly probable that the severe damage to the unshielded silicon cells was caused by low energy protons.

It is apparent from Fig. 1 that the (GaAs, p/n, 0) cells are also highly vulnerable, their response being near zero after a few hundred days. Since gallium arsenide has a very high optical absorption only a very thin front layer is effective in generating power. The rapid failure after about one day is probably due to junction damage.

The results for the special REV (for "reversed") silicon cells are shown in Fig. 5. These cells did not perform as expected. Instead of rapidly deteriorating, as intended, all of these low efficiency cells initially improved in their response. Their performance suggests that some aspect of their environment caused an "annealing" action which was finally overcome by a damage mechanism. The details are still a subject of speculation.

The silicon p/n diodes, whose minority carrier lifetime was monitored, were enclosed in their commercial glass capsules. These furnished a shield of about 115 mg/cm^2. Figure 6 shows how the normalized carrier lifetimes changed with time. Responses of (Si, p/n, 336) and (Si, p/n, 0) cells are also included. While the diode data is limited in amount and in dynamic range the degradation is intermediate between that of the two types of solar cells and appears to occur in similar steps. Thus we obtain in dependent confirmation that the observed solar cell degradation was due to the proposed mechanism of shortened minority carrier lifetime, and not by shield darkening telemetry defects, or other effects.

RESULTS, RELAY II

Since the orbits of Relay I and Relay II were similar it may be expected that solar cell damage to given types of cells would be similar. Figure 7 shows some results which may be compared with those from Relay I in Fig. 1. There are striking resemblances. The 900 days of observation of Relay II indicate again that silicon n/p cells are longer-lived than silicon p/n cells. The curves for the four shielded types of cells have an average final slope of about 15 percent per decade. Those for the unshielded cells cross each other in much the same manner as in Relay I, confirming the validity of these complex results.

There is a well-defined increase in output of the (Si, n/p, 0) cells near 10 days. In Relay I there is only a plateau in this region but the data there were sparse between one and twelve days and a maximum may have been present. There is a plateau followed by a rapid fall for the (Si, n/p, 0) cells in both Figures 1 and 7 near 100 days. Since these effects are absent in the other cells they are believed to be peculiar to the damage mechanism of severely degraded silicon n/p cells, rather than indicating unusual changes in the irradiation rate. Again, the unshielded gallium arsenide cells are inferior to the silicon n/p cells.

It is believed that the irradiation rate of Relay II fluctuated with precession of perigee in much the same way as it did for Relay I, as was shown in Fig. 2. However, in Relay II it was not possible to compensate for temperature variations as well as in Relay I, and the resultant irregularities in the data obscured the precession effect.

The results for the gallium arsenide cells on Relay II are shown in Fig. 8. To avoid confusion the initial levels for the various cells have been displaced 5 percent. It is apparent that shielding is very effective in extending the life of these cells. While the bare cells fall to 75 percent in a few tenths of a day those shielded with only 19.1 mg/cm^2 last 190 days. The fact that the 76.5 mg/cm^2 shielded cells last little longer is peculiar. It indicates either that the energy spectrum of the damaging particles had a strong discontinuity, or, perhaps, that the degradation of the 19.1 and 76.5 mg/cm^2 shielded cells was due to shield darkening. The shields for these two types of cells were made of Corning number 0211 "microsheet," a kind of glass, whereas all other shields were of quartz. Figure 8 indicates that the gallium arsenide cells with 168 and 336 mg/cm^2 shields last much longer than either the silicon p/n or n/p cells with similar shields, which were shown in Fig. 7. However, it must be mentioned that the initial efficiency of the gallium arsenide cells was considerably below that of the silicon cells, so that the superiority of the former is only true on the normalized current basis used here. Further, both laboratory damage studies on gallium arsenide and the 19.1 and 76.5 mg/cm^2 shield curves of Fig. 8 (if valid) show that the final damage slopes for these cells are much steeper than those for silicon cells. Finally, the cost of both raw materials and fabrication of the gallium arsenide cells was much greater than of those made of silicon. Thus, while further development may raise the efficiency and lower the cost of the gallium arsenide cells they can not now compete with silicon cells in spacecraft power supplies. Certain high temperature missions involving close approach to the sun might justify their use, because they will function at higher temperatures than will silicon.

CONCLUSIONS

A numerical summary of the results of the solar cell radiation damage studies carried on spacecraft Relay I and Relay II is given in Table IV. These are in terms of the times in orbit required for given types of cells to degrade to given percent of their initial short circuit currents. Since the irradiation rate fluctuated, time in orbit is not an exact measure of amount of radiation received. Nevertheless, it is believed that these data correctly indicate the relative merit of the various cells and shields and provide spacecraft power supply designers with useful numerical information.

Certain conclusions may be drawn from the results of these experiments.

(a) The results from the Relay I and Relay II damage experiments, where comparable, were similar.

(b) Unshielded silicon and gallium arsenide solar cells degraded, in these orbits, to the 75 percent initial short circuit current response level in less than one day.

(c) Shields of 19.1 mg/cm^2 extended time to 75 percent initial response by a factor of at least 100.

(d) Silicon n/p cells with 336 mg/cm^2 shields lasted (at the 75 percent level) about nine times as long as similarly shielded silicon p/n cells.

(e) Silicon n/p cells with 336 mg/cm^2 shields lasted about 2.6 times as long as similar cells with 168 mg/cm^2 shields.

(f) The degradation rate of the shielded silicon cells was about 16 percent per decade (factor of ten) of time, in the severe damage region.

(g) Unshielded cells showed early damage steps associated with individual orbital passages through a highly damaging region of space.

(h) The above damage steps were caused by protons whose energies were a few hundred KeV and above.

(i) The damage to shielded cells was caused by both high energy protons and electrons.

(j) The precession of the latitude of perigee of the Relay orbits, together with the energy spectra of the electrons and protons and their spatial distributions caused the damage to the shielded cells to occur in four steps per cycle of latitude of perigee.

(k) Attempts to predict the damage to shielded and unshielded cells were fairly successful.

(l) While unshielded gallium arsenide cells were very susceptible to radiation damage, shielding extended their lives to values greater than those for silicon cells, when performance was judged by short circuit currents normalized to initial values.

(m) The lower efficiency and higher cost of gallium arsenide solar cells at present make them inferior to silicon n/p solar cells from a practical stand-point.

(n) The unshielded silicon n/p cells showed several anamolies probably associated with details of the radiation damage mechanism.

(o) The supposedly highly damage susceptible "reversed" silicon cells did not degrade as expected, but exhibited an initial increase in sensitivity before final degradation.

ACKNOWLEDGMENTS

The author acknowledges the invaluable assistance of Luther Slifer in procuring the solar cell damage panel and in calibrating the cells for solar aspect angle. Also James Albus designed and provided the solar aspect sensor. Justin Schaffert designed the diode carrier lifetime circuitry. Daniel Brown provided liaison with the Relay Project Group. Joseph Bourne gave valuable aid in computer processing the data for these experiments.

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

(2) Cherry, W. R., and Slifer, W. W., "Solar Cell Radiation Damage Studies with 1 Mev Electrons and 4.6 Mev Protons," National Aeronautics and Space Administration Technical Note NASA TN D-2098, of February, 1964.

(3) Davis, Leo R. and Williamson, James M., "Low Energy Trapped Protons," National Aeronautics and Space Administration Document X-611-62-89, of May, 1962.

(4) Davis, Leo R., of Goddard Space Flight Center, private communication.

TABLE I
ORBIT PARAMETERS

PARAMETER	RELAY I	RELAY II
APOGEE (Km)	7439	7414
PERIGEE (Km)	1321	2088
PERIOD (MIN)	185.1	194
ZERO TIME (GMT)	1962 YR, 347 DAY, 23 HR, 49 MIN, 06 SEC	1964 YR, 21 DAY, 21 HR , 42 MIN, 00 SEC

TABLE II

SOLAR CELLS AND SHIELDS

CELLTYPE	SHIELD MATERIAL	SHIELD THICKNESS mg/cm²	NO. CELLS ON RELAY I	NO. CELLS ON RELAY II
Si, p/n	0	0	3	3
Si, p/n	A	168	3	3
Si, p/n	A	336	3	3
Si, n/p	0	0	3	3
Si, n/p	A	168	3	3
Si, n/p	A	336	3	3
Si, REV	0	0	3	0
Si, REV	A	168	3	0
Si, REV	A	336	3	0
GaAs, p/n	0	0	3	2
GaAs, p/n	B	19.1	0	2
GaAs, p/n	B	76.5	0	4
GaAs, p/n	A	168	0	2
GaAs, p/n	A	336	0	2

MATERIAL A = CORNING 7940 CLEAR FUSED QUARTZ

MATERIAL B = CORNING 0211 MICROSHEET GLASS

TABLE III

PREDICTED AND OBSERVED SOLAR CELL RADIATION DAMAGE AFTER 300 DAYS IN ORBIT, RELAY I

CELLTYPE	SHIELD mg/cm^2, MATERIAL	RADIATION INFORMATION SOURCE	PREDICTED RESPONSE (% INITIAL)	OBSERVED RESPONSE (% INITIAL)
Si, p/n	336, A	GSFC PI PROTON GRID	56	60
Si, n/p	336, A	GSFC PI PROTON GRID	75	79
Si, p/n	336, A	GSFC E8 ELECTRON GRID	47	60
Si, n/p	336, A	GSFC E8 ELECTRON GRID	75	79

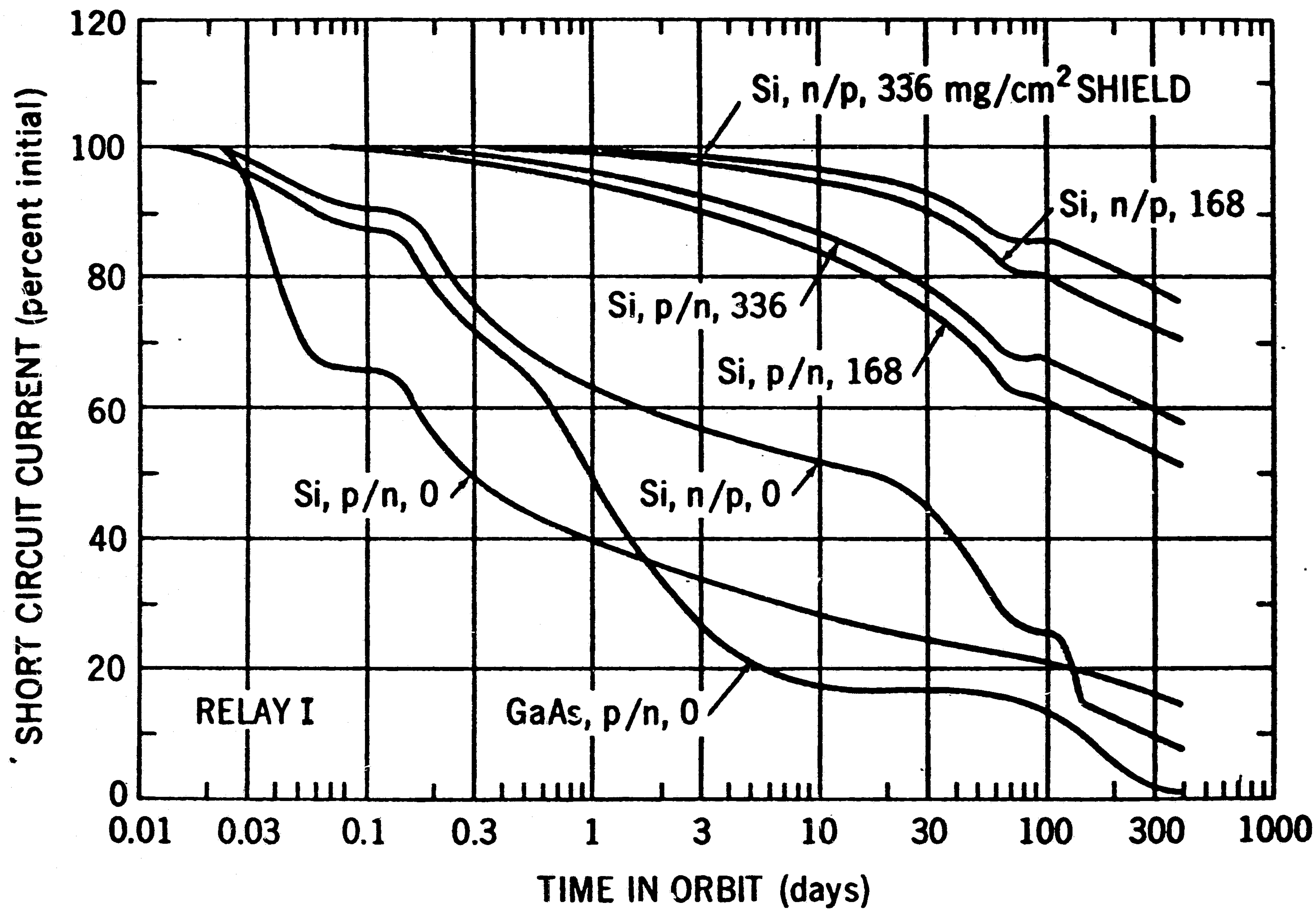
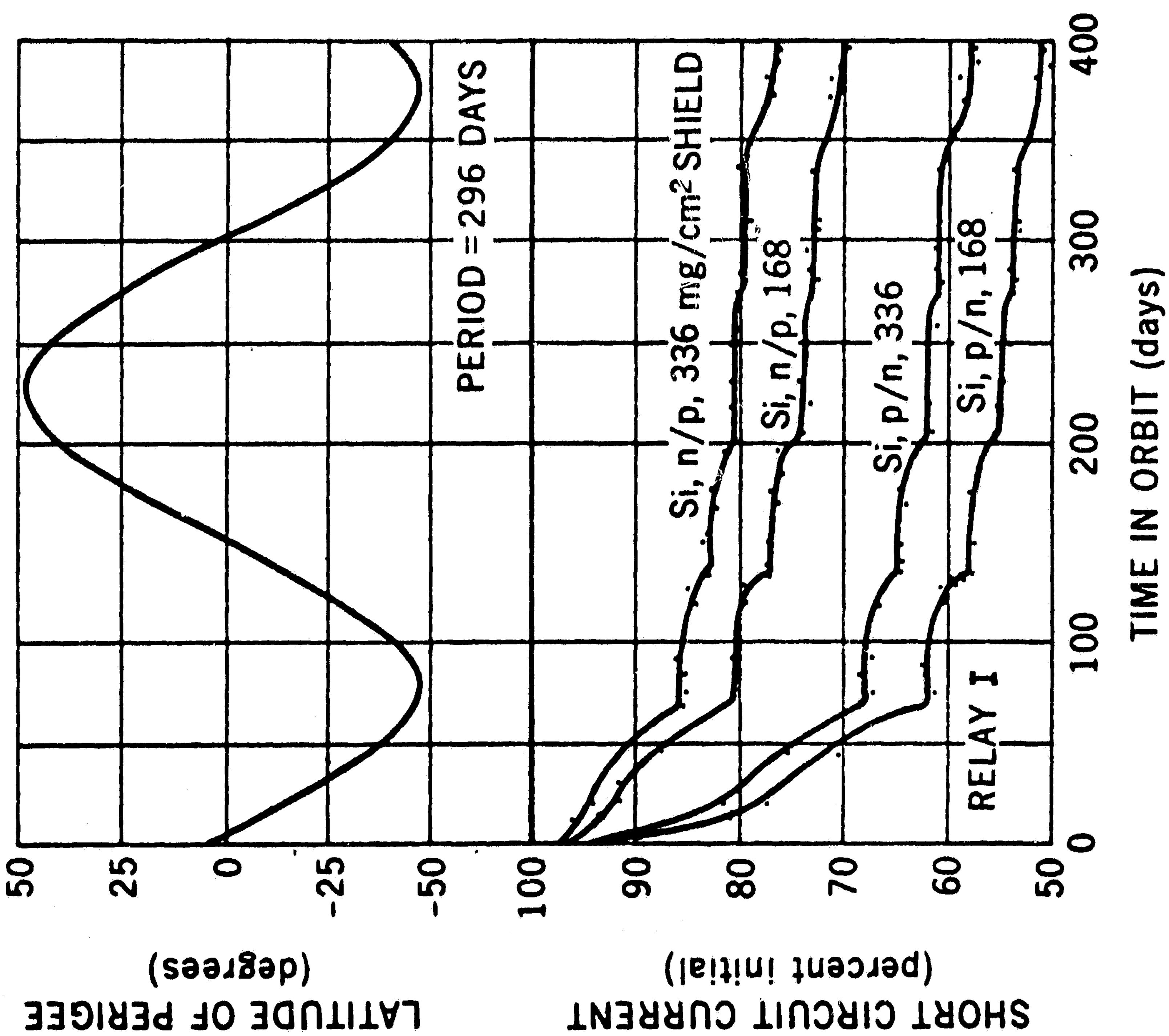


Figure 1. Degradation of the Silicon Solar Cells on Relay I

Figure 2   Upper: Precession of Latitude of Perigee of Relay I.

Lower: Degradation of Silicon Solar Cells



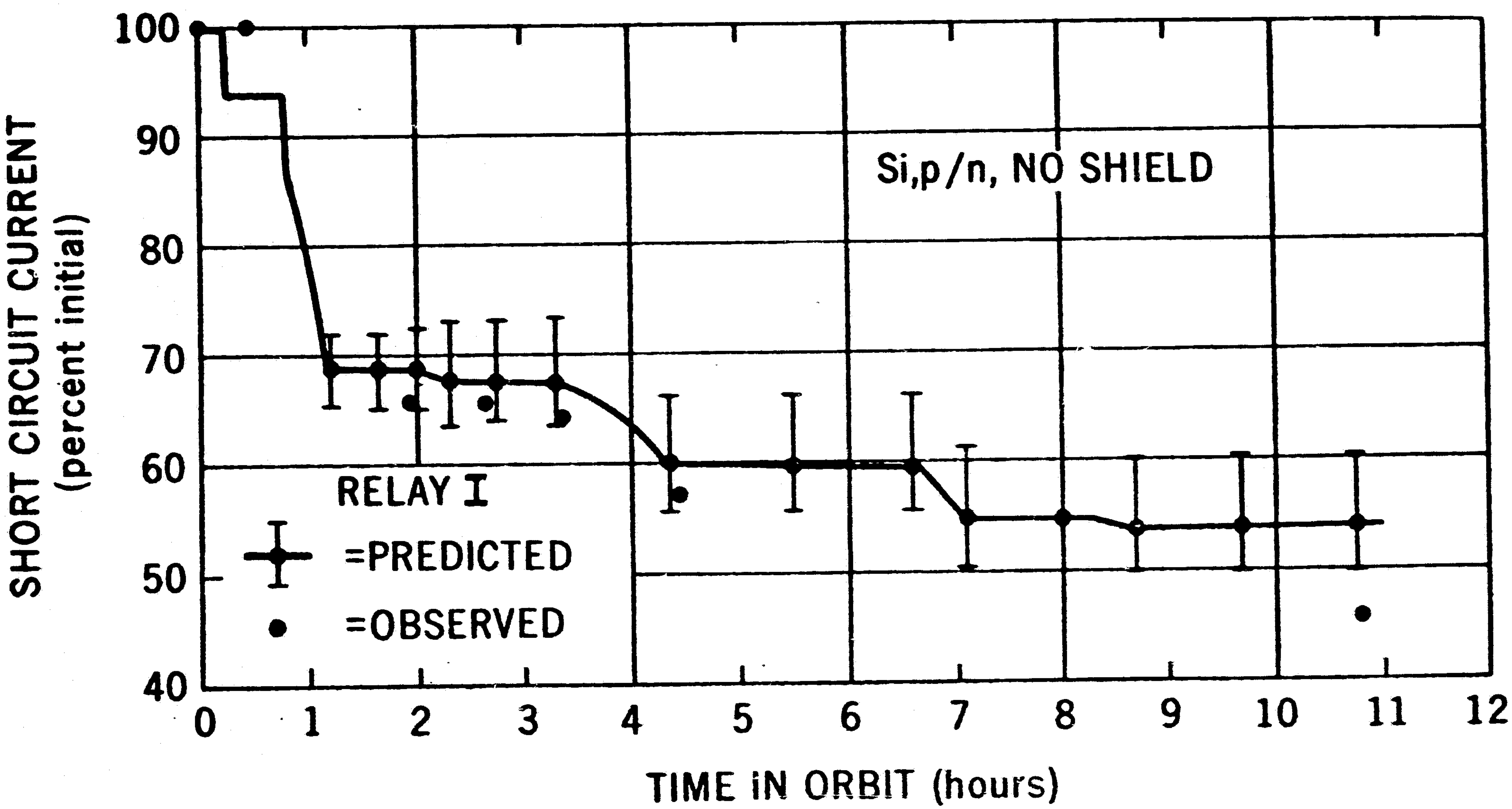


Figure 3 Predicted and Observed Degradation of the Unshielded p/n Solar Cells on Relay I

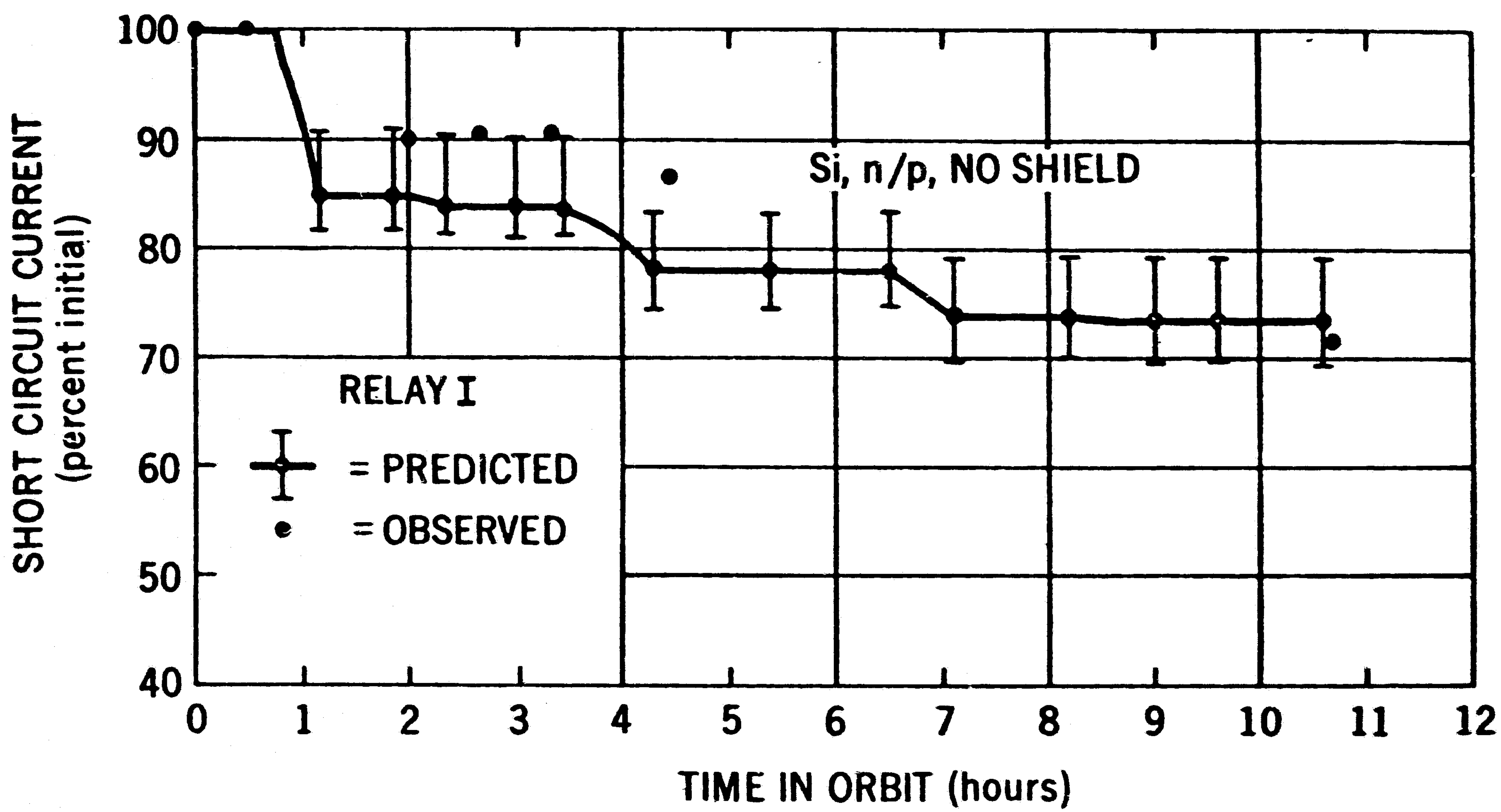


Figure 4 Predicted and Observed Degradation of the Unshielded n/p Solar Cells on Relay I

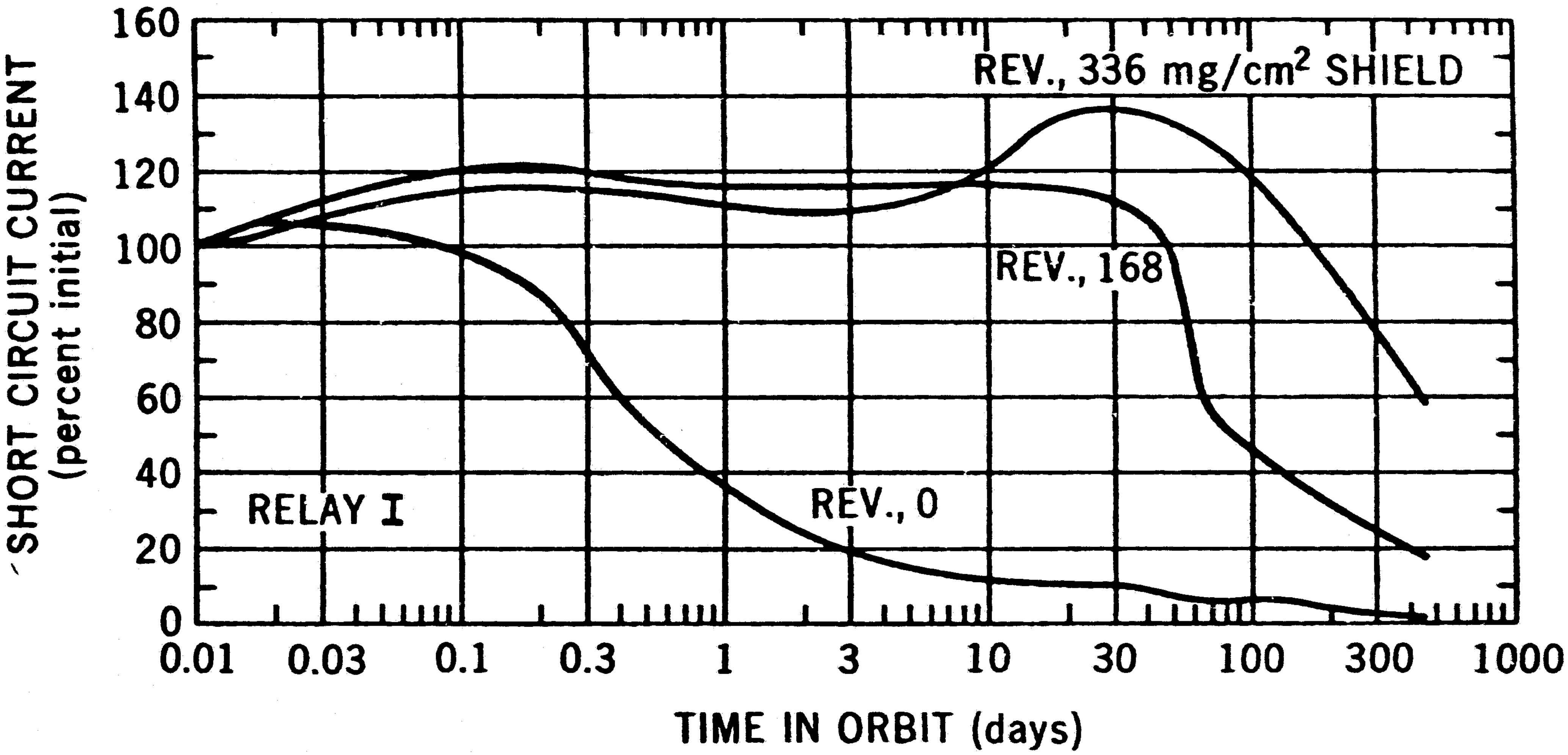
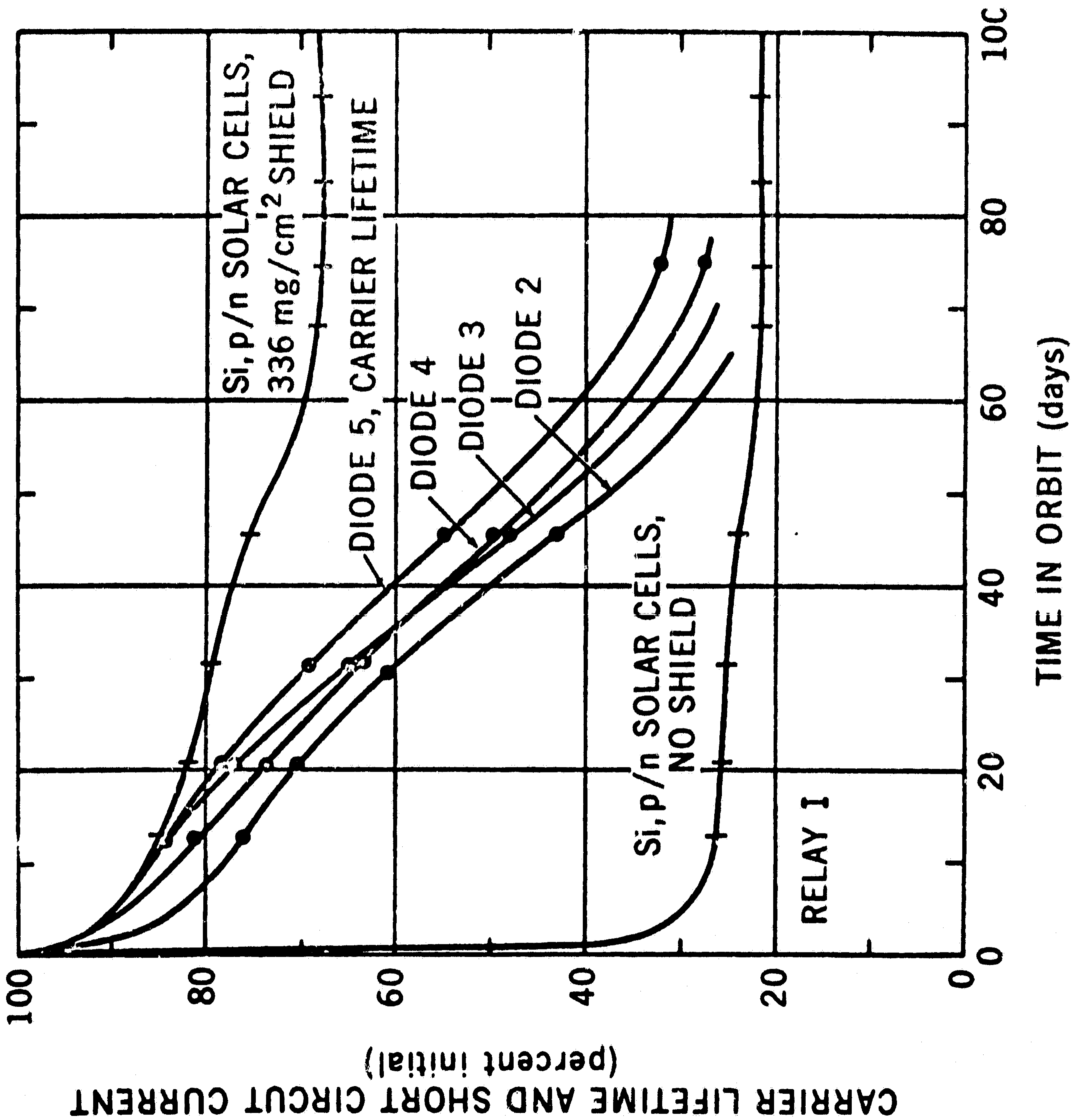


Figure 5 **Response of the "Reversed" Solar Cells on Relay I**

Figure 6 Changes of Minority Carrier Lifetime of 1N645 Diodes, and of the Currents from Some Silicon p/n Solar Cells



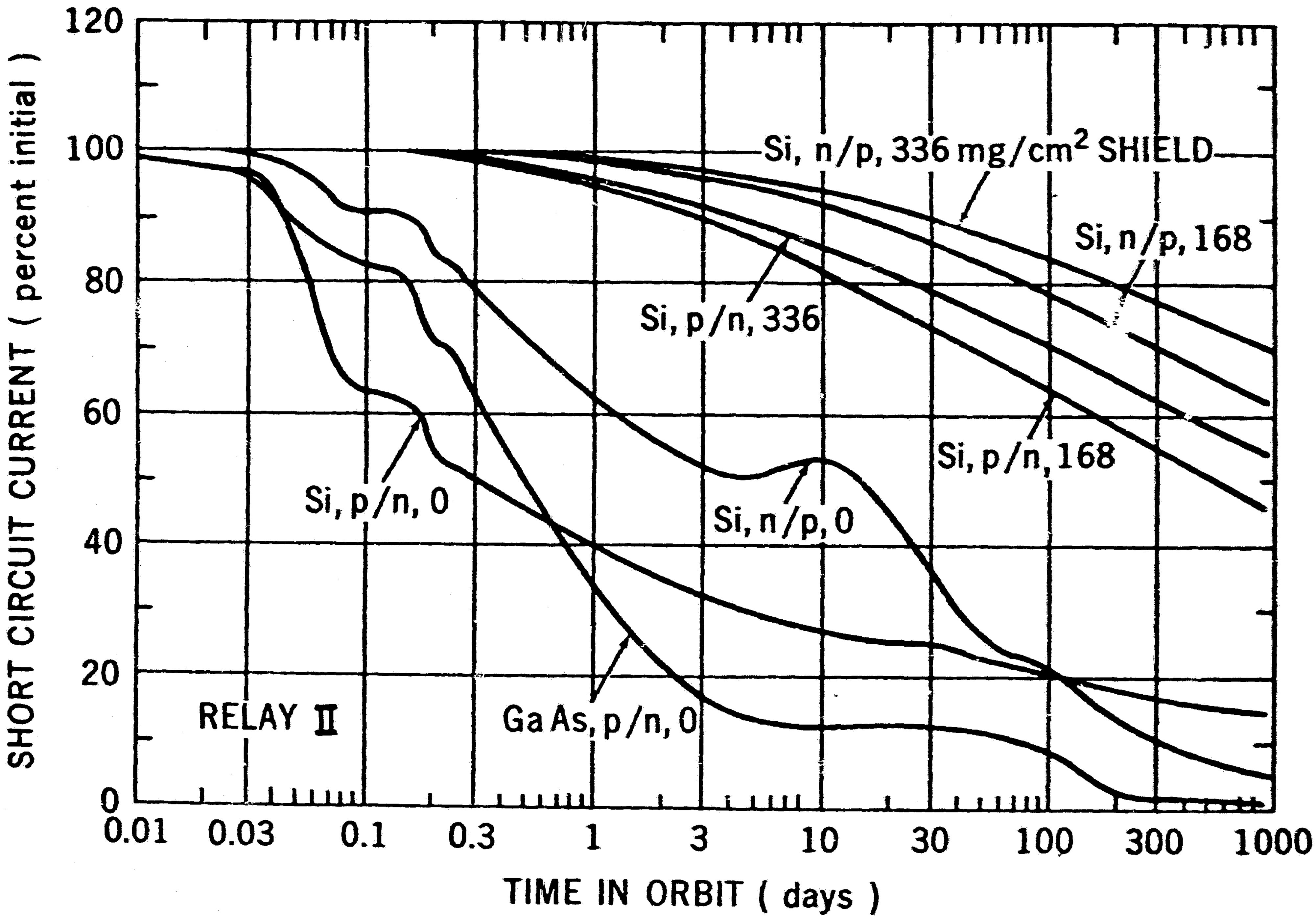
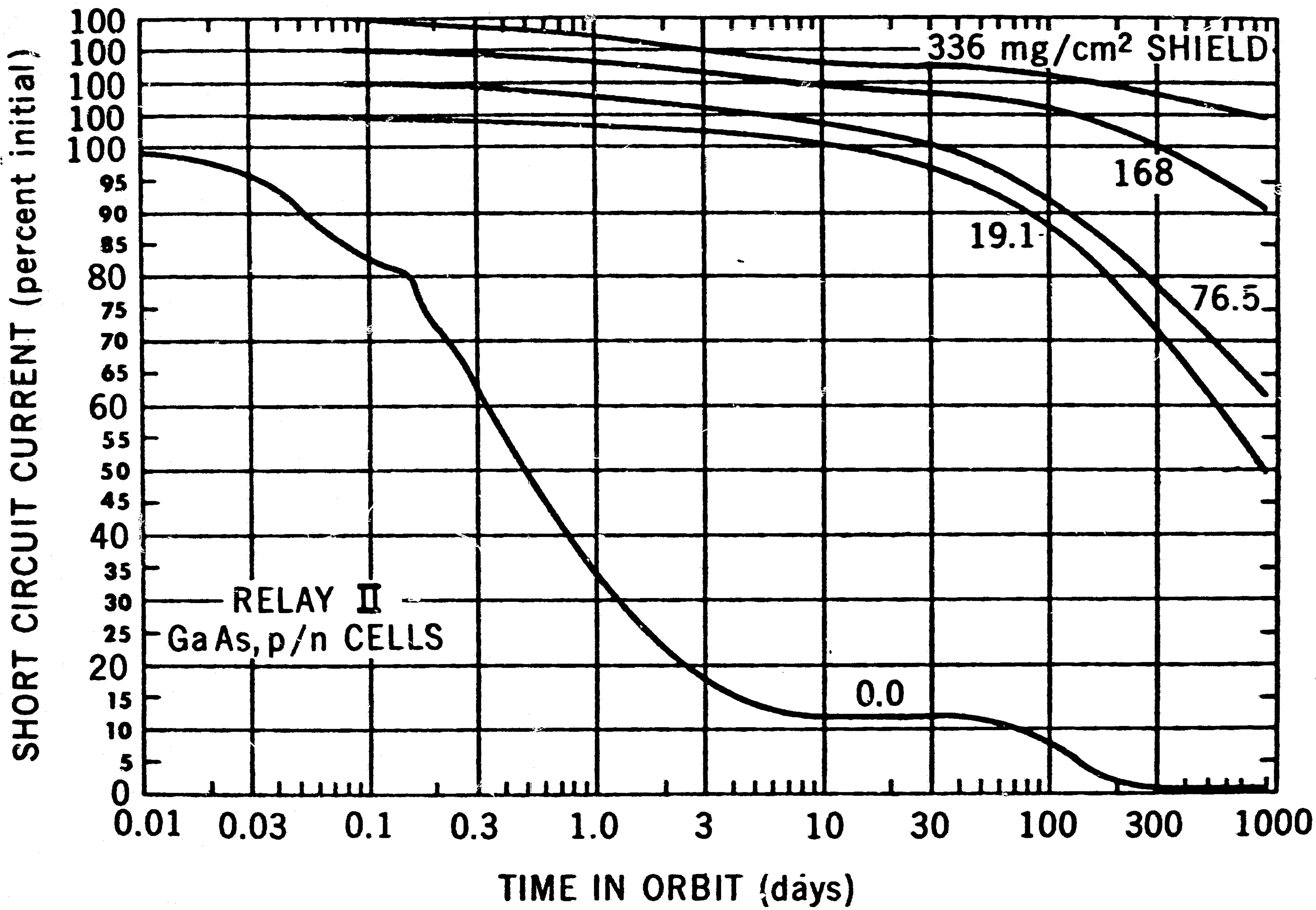


Figure 7   Degradation of the Silicon Solar Cells on Relay II



120

Figure 8 Degradation of the Gallium Arsenide Solar Cells on Relay II. Note that Initial Levels of Various Cells Have Been Displaced 5 Percent.