TG–886

MARCH 1967

Copy No. 2

Technical Memorandum

RADIATION DAMAGE TO ORBITING SOLAR CELLS AND TRANSISTORS

R. E. FISCHELL

J. H. MARTIN

W. E. RADFORD

W. E. ALLEN

THE JOHNS HOPKINS UNIVERSITY ■ APPLIED PHYSICS LABORATORY

33

TG--886
MARCH 1967

Technical Memorandum

RADIATION DAMAGE TO ORBITING SOLAR CELLS AND TRANSISTORS

R. E. FISCHELL
J. H. MARTIN
W. E. RADFORD
W. E. ALLEN

THE JOHNS HOPKINS UNIVERSITY ▫ APPLIED PHYSICS LABORATORY
8621 Georgia Avenue, Silver S... , Maryland 20910

Operating under Contract NOw 62-0604 with the Department of the Navy

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
SILVER SPRING, MARYLAND

ABSTRACT

The Applied Physics Laboratory began in-flight solar cell degradation studies with the launching of the 1961-o1 satellite on June 29, 1961. Similar experiments were flown on the 1961-$\alpha\eta$1 and 1961-$\alpha\eta$2 satellites. Data obtained from these satellites cover a time period both before and after Operation Starfish on July 9, 1962. Subsequently, the Applied Physics Laboratory has flown solar-cell and electronic-component experiments on satellites 1962-$\beta\eta$, ANNA I-B, 1963-38C and 1964-83C. The data indicate that the damage to solar cells in a 1000-km orbit during the early months after Operation Starfish may not have been mostly a result of fission spectrum electrons. Although many energetic electrons were introduced into the inner belt, it is indicated that some high energy (>4.5 mev) protons were redistributed to altitudes including 1000 km. The results of flight experiments indicate that optimum power-to-weight-ratio solar arrays will be obtained by the use of N-on-P solar cells with 6-mil glass covers.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. DESCRIPTION OF EXPERIMENTS

Table I lists all satellites on which Applied Physics Laboratory solar cell and transistor experiments have been flown until August 1965. Launch dates, orbital parameters, the status as of August 1965, and basic circuit descriptions are included in the table. An experimental panel consisting of 20 series-connected P-on-N, 1 x 1 cm, solar cells was flown on 1961-o1. A similar panel consisting of 20 series-connected 1 x 2 cm "blue sensitive" P-on-N solar cells was flown on 1961-$\alpha\eta$1. Four separate solar panels were flown on the 1961-$\alpha\eta$2 satellite. Each of these panels consisted of two series-connected 1 x 2 cm P-on-N solar cells. The solar cells in each of the experiments described above were loaded at approximately 0.2 volt per cell, thereby providing a voltage measurement essentially proportional to short-circuit current. Six-mil-thick cover glasses with blue reflecting filters and antireflecting coatings were attached to the solar cells. Furane 15-E adhesive was used to attach cover slides for the 1961-o1 and 1961-$\alpha\eta$2 experiments while Spectrolab ES-10 adhesive was employed for the 1961-$\alpha\eta$1 cover slides.

The remainder of the Applied Physics Laboratory's degradation experiments are outlined in Tables II through V. Two by two mm solar cells were employed on satellite 1962-$\beta\kappa$ solar cell experiments while all other experimental solar cells were 1 x 2 cm. In each experiment the short-circuit current was monitored. Furane 15-E adhesive was used to attach cover slides on the 1962-$\beta\kappa$ and ANNA experiments with exception of ANNA experiment number 6 which employed the Telstar cover slide attachment technique (see Ref. 1). RTV-602 was used to attach most of

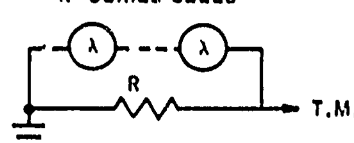
Table I

Satellites on Which Solar Cell and Transistor Experiments Were Flown

SATELLITE	1961-o1	1961-αη1	1961-αη2	1962-βκ	ANNA I-B	1963-38C	1964-83C
DATE OF LAUNCH	29 JUN 1961	15 NOV 1961	15 NOV 1961	26 OCT 1962	31 OCT 1962	28 SEPT 1963	12 DEC 1964
APOGEE, KM	1146	1111	1111	6335	1180	1120	1070
PERIGEE, KM	983	950	950	220	1075	1070	1027
INCLINATION, DEGREES	67	32.4	22.4	71.4	50.1	89.9	89.99
TELEMETRY ACCURACY	± 1%	± 1%	± 1%	±1%	± 1%	± 1%	± 1%
ATTITUDE CONTROL SYSTEM	MAGNETIC	MAGNETIC	NONE	SPIN	MAGNETIC	MAGNETIC	MAGNETIC
CIRCUIT FOR SOLAR CELL EXPERIMENTS	A N = 20 R = 75Ω	A N = 20 R = 75Ω	A N = 2 R = 7.5Ω	B N = 4 R = 909Ω	B N = 2 ** R = 4Ω **	B N = 4 *** R = 1Ω ***	B N = 4 *** R = 1Ω
CIRCUIT FOR TRANSISTOR EXPERIMENTS	NONE FLOWN	NONE FLOWN	NONE FLOWN	C	C	SEE TABLE IV	SEE TABLES IV AND V
CONDITION	T.M. FAILED 15 JULY 1961	CEASED TRANSMITTING 2 AUG 1962	CEASED TRANSMITTING 12 AUG 1962	CEASED TRANSMITTING 13 DEC 1962	STILL TRANSMITTING	STILL TRANSMITTING	STILL TRANSMITTING

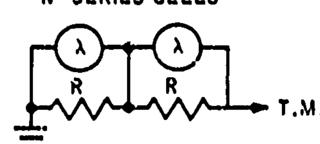
** THE GaAs EXPERIMENT CONSISTED OF ONE CELL OPERATING INTO A 7-OHM RESISTOR.
*** THE 135 MIL FUSED SILICA EXPERIMENT CONSISTED OF ONE CELL OPERATING INTO A 1-OHM RESISTOR.

"N" SERIES CELLS

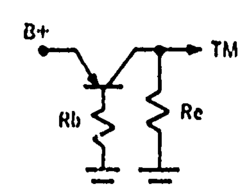


CIRCUIT A

"N" SERIES CELLS



CIRCUIT B



CIRCUIT C

Table II

1962-βκ Degradation Experiments

EXPERIMENT	DEVICE	SHIELDING	
		TYPE	GRAMS/CM^2
1	P-ON-N SOLAR CELLS (4)	6 MIL GLASS	0.037
2	N-ON-P SOLAR CELLS (4)	6 MIL GLASS	0.037
3	P-ON-N SOLAR CELLS (4)	60 MIL QUARTZ	0.336
4	N-ON-P SOLAR CELLS (4)	60 MIL QUARTZ	0.336
5	2N327A TRANSISTOR	BARE	
6	2N327A TRANSISTOR	ALUMINUM	0.4
7	2N327A TRANSISTOR	ALUMINUM	0.8

Table III

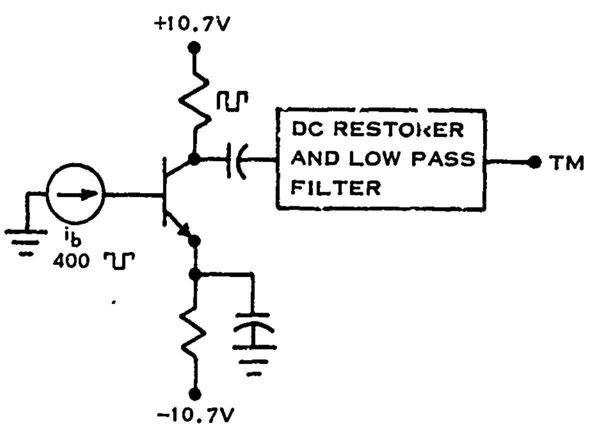
ANNA I-B Degradation Experiments

EXPERIMENT	DEVICE	SHIELDING	
		TYPE	GRAMS/CM^2
1	P-ON-N SOLAR CELLS (2)	6 MIL GLASS	0.037
2	N-ON-P SOLAR CELL (1) (AZIMUTH DETECTOR)	6 MIL GLASS	0.037
3	N-ON-P PRE-IRRADIATED SOLAR CELLS (2)	6 MIL GLASS	0.037
4	P-ON-N SOLAR CELLS (2)	20 MIL QUARTZ	0.112
5	P-ON-N SOLAR CELLS (2)	30 MIL SAPPHIRE	0.302
6	N-ON-P SOLAR CELLS (2)	30 MIL SAPPHIRE	0.302
7	GALLIUM ARSENIDE SOLAR CELL (1)	6 MIL GLASS	0.037
8	2N327A TRANSISTOR	10 MIL KOVAR	0.203
9	2N327A TRANSISTOR	10 MIL KOVAR + 57 MIL ALUMINUM	0.609
10	2N327A TRANSISTOR	10 MIL KOVAR + 250 MIL ALUMINUM	1.960

Table IV

1963-38C Degradation Experiments

EXPERIMENT	DEVICE	SHIELDING	
		TYPE	GRAMS/CM²
1	N-ON-P SOLAR CELLS (4)	NONE	
2	N-ON-P SOLAR CELLS (4)	1-MIL QUARTZ	0.006
3	N-ON-P SOLAR CELLS (4)	3-MIL QUARTZ	0.017
4	N-ON-P SOLAR CELLS (4)	6-MIL GLASS	0.037
5	N-ON-P SOLAR CELLS (4)	20-MIL QUARTZ	0.112
6	N-ON-P SOLAR CELLS (4)	30-MIL SAPPHIRE	0.302
7	N-ON-P SOLAR CELL (1)	125-MIL QUARTZ	0.700
8	P-ON-N SOLAR CELLS (4)	6-MIL GLASS	0.037
9	TRANSISTORS 2N1711 (4)	EPOGLASS COATED HONEYCOMB	0.280
10	TRANSISTORS 2N1711 (2) (CASES PUNCTURED)	EPOGLASS COATED HONEYCOMB	0.280



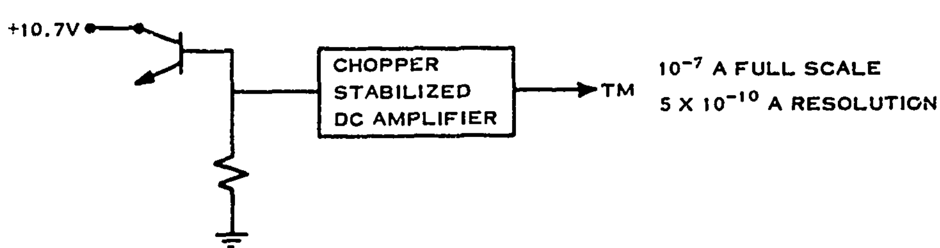
CIRCUIT FOR TRANSISTOR
BETA EXPERIMENTS

Table V

1964-83C Degradation Experiments

EXPERIMENT	DEVICE	SHIELDING	
		TYPE	GRAMS/CM^2
1 (BETA)	2N2222 TRANSISTORS (2)	NONE	
2 (BETA)	2N2586 TRANSISTORS (2)	NONE	
3 (BETA)	2N2222 TRANSISTOR (1)	0.1"Al	0.685
4 (BETA)	2N2586 TRANSISTOR (1)	0.1"Al	0.685
5 (BETA)	2N2222 TRANSISTOR (1)	0.3"Al	2.057
6 (BETA)	2N2586 TRANSISTOR (1)	0.3"Al	2.057
7 (BETA)	2N2907-A TRANSISTORS (2)	NONE	
8 (BETA)	2N2907-A TRANSISTOR (1)	0.1"Al	0.685
9 (BETA)	2N2907-A TRANSISTOR (1)	0.3"Al	2.057
10 (LEAKAGE)	2N2222 TRANSISTORS (2)	NONE	
11 (LEAKAGE)	2N2586 TRANSISTORS (2)	NONE	
12 (LEAKAGE)	2N2907-A TRANSISTORS (2)	NONE	
13 (LEAKAGE)	2N2222 TRANSISTOR (1)	0.1"Al	0.685
14 (LEAKAGE)	2N2586 TRANSISTOR (1)	0.1"Al	0.685
15 (LEAKAGE)	2N2907-A TRANSISTOR (1)	0.1"Al	0.685
16 (LEAKAGE)	2N2222 TRANSISTOR (1)	0.3"Al	2.057
17 (LEAKAGE)	2N2586 TRANSISTOR (1)	0.3"Al	2.057
18 (LEAKAGE)	2N2907-A TRANSISTOR (1)	0.3"Al	2.057
19 (LEAKAGE)	100 μf, 20 wv, 150D CAPACITORS (2)	NONE	
20 (SHORT)	39 μf, 10 wv, 350D CAPACITOR V=11 VOLTS	NONE	
21 (SHORT)	39 μf, 10 wv, 350D CAPACITOR V=12 VOLTS	NONE	
22 (SHORT)	39 μf, 10 wv, 350D CAPACITOR V=14 VOLTS	NONE	
23 (SHORT)	39 μf, 10 wv, 350D CAPACITOR V=16 VOLTS	NONE	

NOTE: SOLAR CELL EXPERIMENTS WERE SIMILAR TO THOSE ON 1963-38C.



the cover slides for the satellites 1963-38C and 1964-83C. For those satellites the 125 mil quartz shielding was mounted just above the solar cell with no adhesive in between.

The transistor experiments on 1962-$\beta\varkappa$ and ANNA were mounted on the solar cell test panels. A basic diagram for these experiments is given as part of Table I. The test transistors on 1963-38C satellite were placed inside the satellite's outer skin and directly behind an aluminum support brace. There was no other shielding except for the case of the transistors. The circuit diagram for the 400-cps beta (gain) experiment is shown on Table IV. All of the electronic component experiments on the 1963-83C satellite had the shielding listed in Table V in addition to transistor cases. Components shielded by 0. 3 inch aluminum are reference standards. The circuit diagram for the 400-cycle beta experiments is basically the same as that for the 1963-38C satellite transistor experiment. All beta measurements were made with 0.5 ma bias currents and were therefore not "worse-case" measurements. Transistors that are irradiated while they are biased "off" experience channeling damage. This type of degradation does not occur when the transistors are conducting.

II. RESULTS OF SATELLITE EXPERIMENTS

Meaningful data were not obtained from several experiments owing to various problems; only pertinent data are presented below. The telemetry system used in APL satellites gives accuracies better than ±1 percent. Data were read when the solar cell experiments were near normal incidence to the sun and were corrected by dividing by the cosine of the angle of incidence. All such data were then normalized for sun intensity at the mean solar distance, i.e. 140 mv/cm^2. Next, these data were plotted as a function of measured temperature for several consecutive passes. The intersection of the straight line fit of these data points with the 50°F temperature line was considered to be the fully corrected output of the cell. Temperature measurements were not made on the 1961-o1, 1961-$\alpha\eta$1, and 1961-$\alpha\eta$2 panels. However, since all readings were at nearly the same angle of incidence, temperature variations for these satellites were assumed to contribute less than two percent error.

Results of experiments on satellites 1961-$\alpha\eta$1 and 1961-$\alpha\eta$2 are presented in Fig. 1. The satellite 1962-$\beta\kappa$ experimental results are shown in Fig. 2. Figure 3 is a presentation of the ANNA I-B solar cell data. A decrease in the slope of curves D and E indicates that during the period January through May 1963 the radiation intensity in the Van Allen belts had decreased slightly. Results of the 1963-38C solar cell experiments are given in Fig. 4.

Figure 5 gives a comparison of results of similar experiments on the ANNA I-B and 1963-38C satellites. Rapid initial degradation was noted

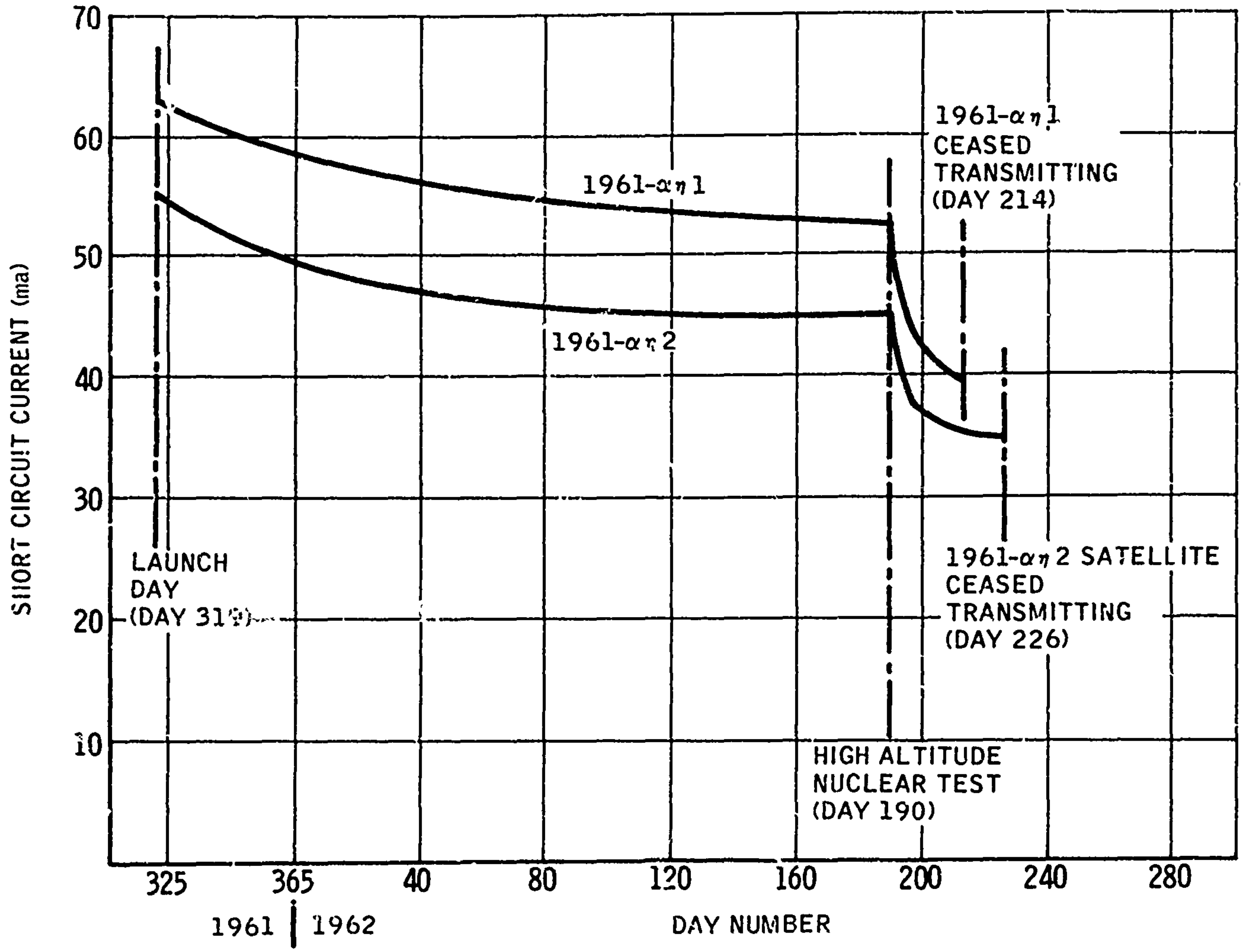


Fig. 1 Solar Cell Output as a Function of Time for 1961-$\alpha\eta$1 and 1961-$\alpha\eta$2. Orbit: Apogee 1111 km, Perigee 950 km, Inclination 32.4°

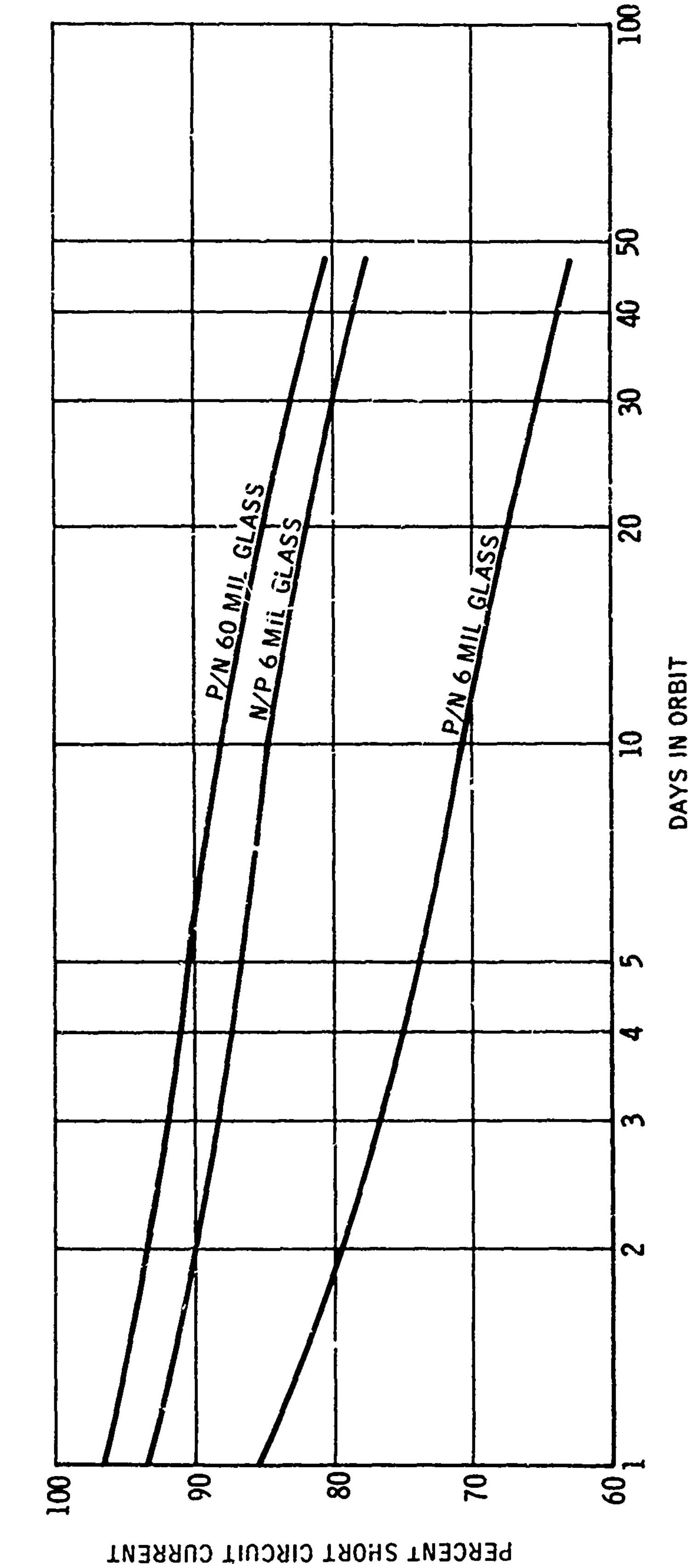


Fig. 2 Results of Solar Cell Experiments on Satellite 1962-*βκ* Launched 26 Oct., 1962.
Orbit: Perigee 220 km, Apogee 6335 km, Inclination 71.4°

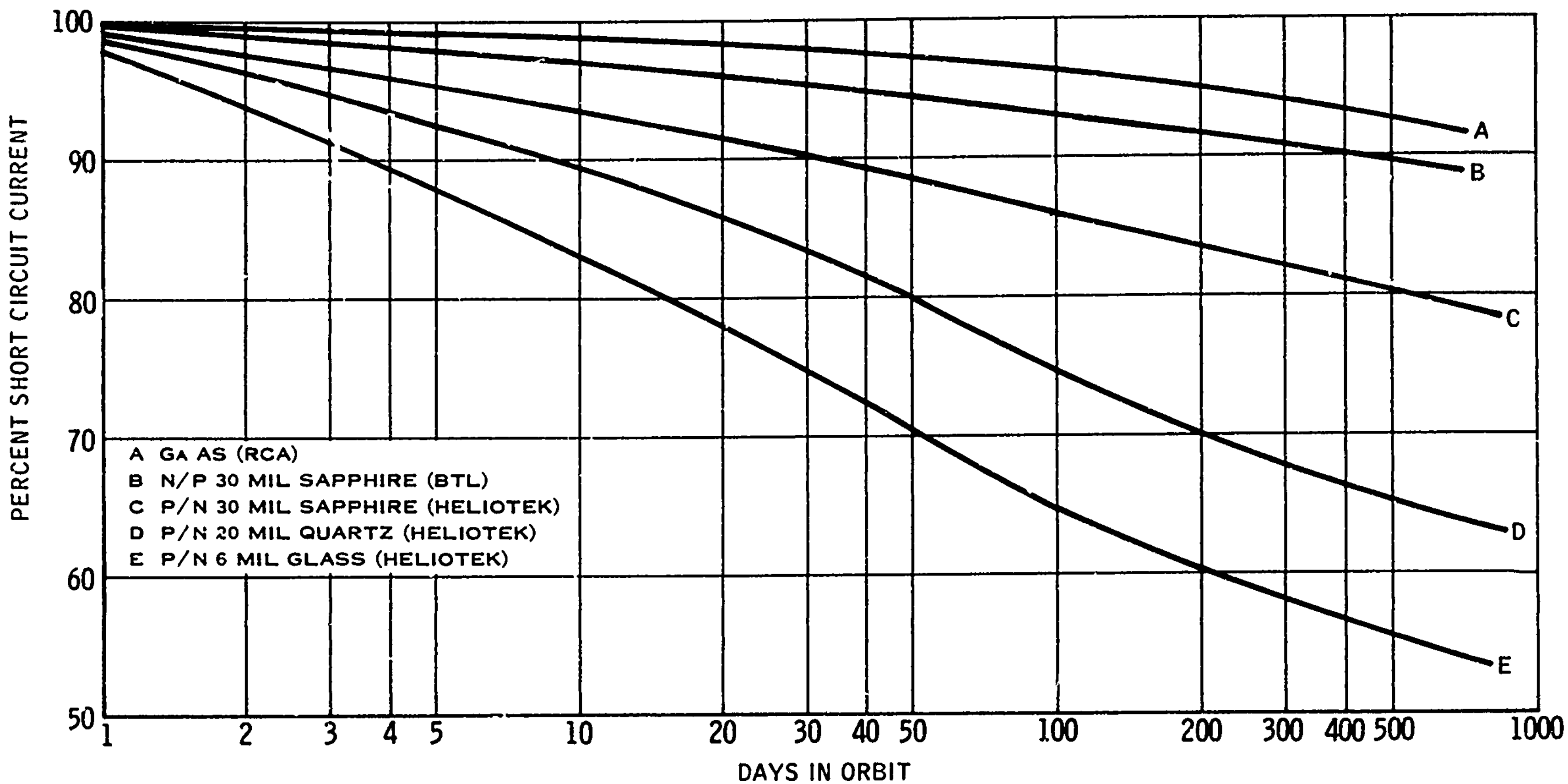


Fig. 3 Results of Solar Cell Experiments on ANNA I-B Satellite Launched 31 Oct., 1962
Orbit: Apogee 1180 km, Perigee 1075 km, Inclination 50.1°

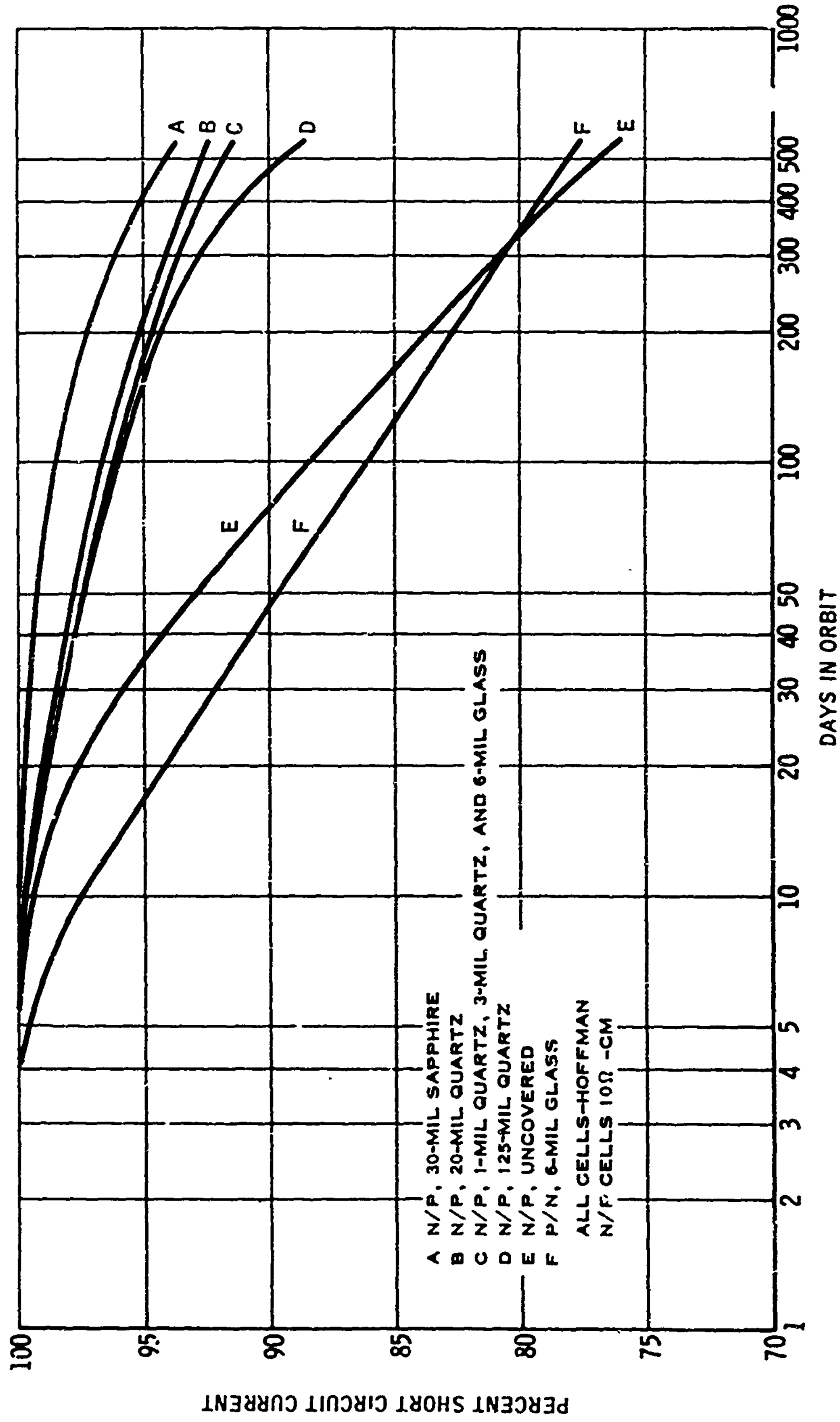


Fig. 4 Results of Solar Cell Experiments on Satellite 1963-38C Launched 28 Sept., 1963.
Orbit: Apogee 1120 km, Perigee 1070 km, Inclination 89.9°

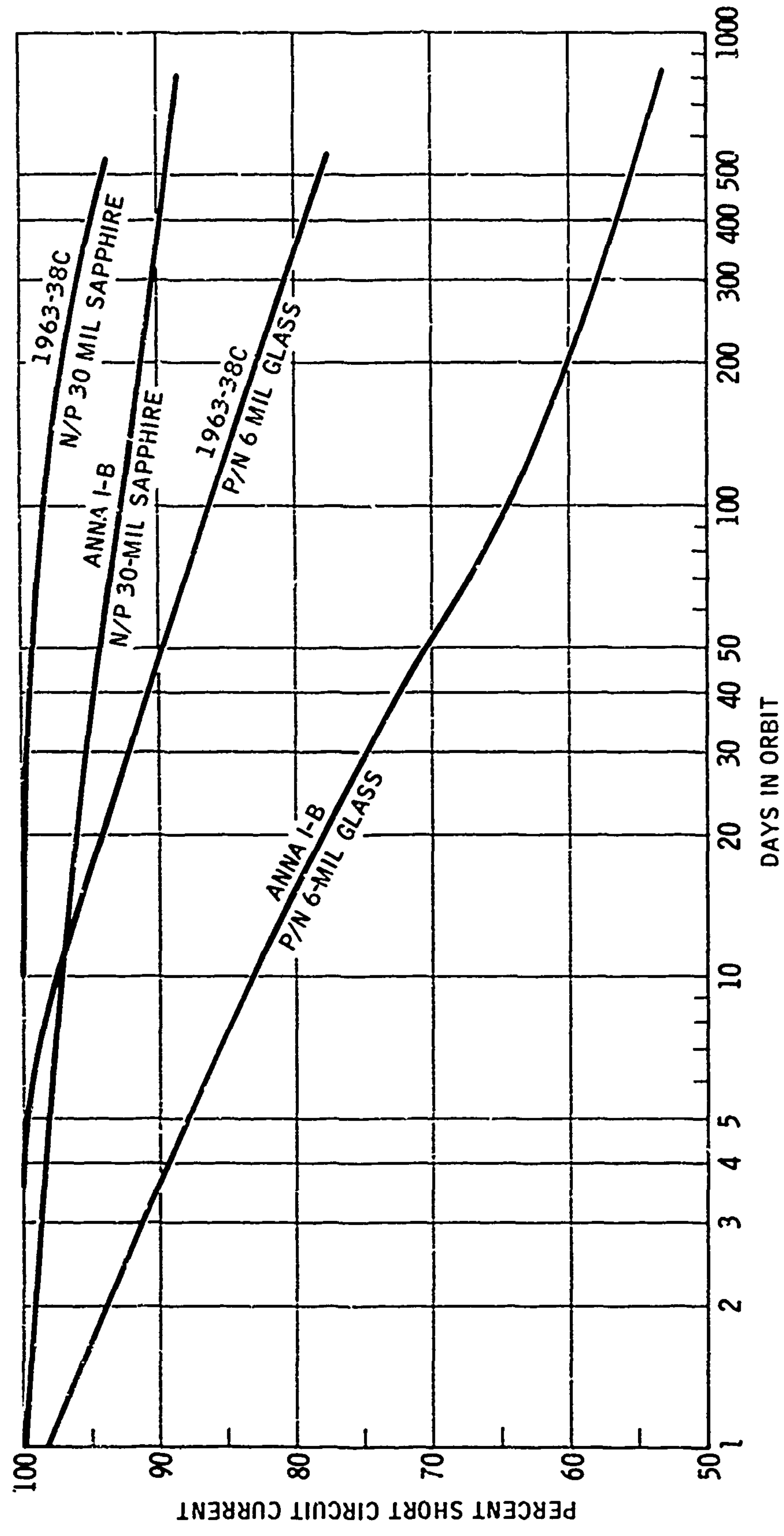


Fig. 5 Comparison of ANNA I-B and Satellite 1963-38C Solar Cell Experiment Data

on the ANNA experiments; however, five days passed before the first noticeable degradation occurred on the 1963-38C experiments. This indicates a significant decrease in radiation belt intensity which occurred prior to launch of the 1963-38C satellite in September 1963.

The ANNA transistor experiments (circuit C, Table I) were devised on the premise that bulk damage would be predominant. Because the output is a function of collector to base leakage as well as gain, telemetered data from these experiments would not be an accurate measure of either. Hogrefe (Ref. 2) concluded that since an initial increase in output was followed by a decrease in output, a substantial increase in leakage did occur.

Data received from the satellite 1963-38C transistor experiments were corrected for variations in temperature by normalizing to 90°F and for variations in power supply voltage by normalizing to +10.7 volts. Curve A of Fig. 6 is a plot of beta as a function of time for one of the transistors with a punctured case. Curve B is a plot of the time variation of the average beta of four unaltered transistors. The gain-bandwidth product of these transistors was 60 mc before flight. Ionization of gases in the case of the unaltered transistors has caused surface damage which, coupled with bulk damage, has resulted in rapid degradation of these components. The single gasless transistor appears to be less affected by surface damage. A decrease in the rate of degradation of both types of transistor is noted to coincide with the decrease in solar cell degradation.

Data received from the electronic component tests on 1964-83C indicates no capacitor degradation had occurred at the time (August 1965). Transistor data were corrected as follows: The transistors shielded by

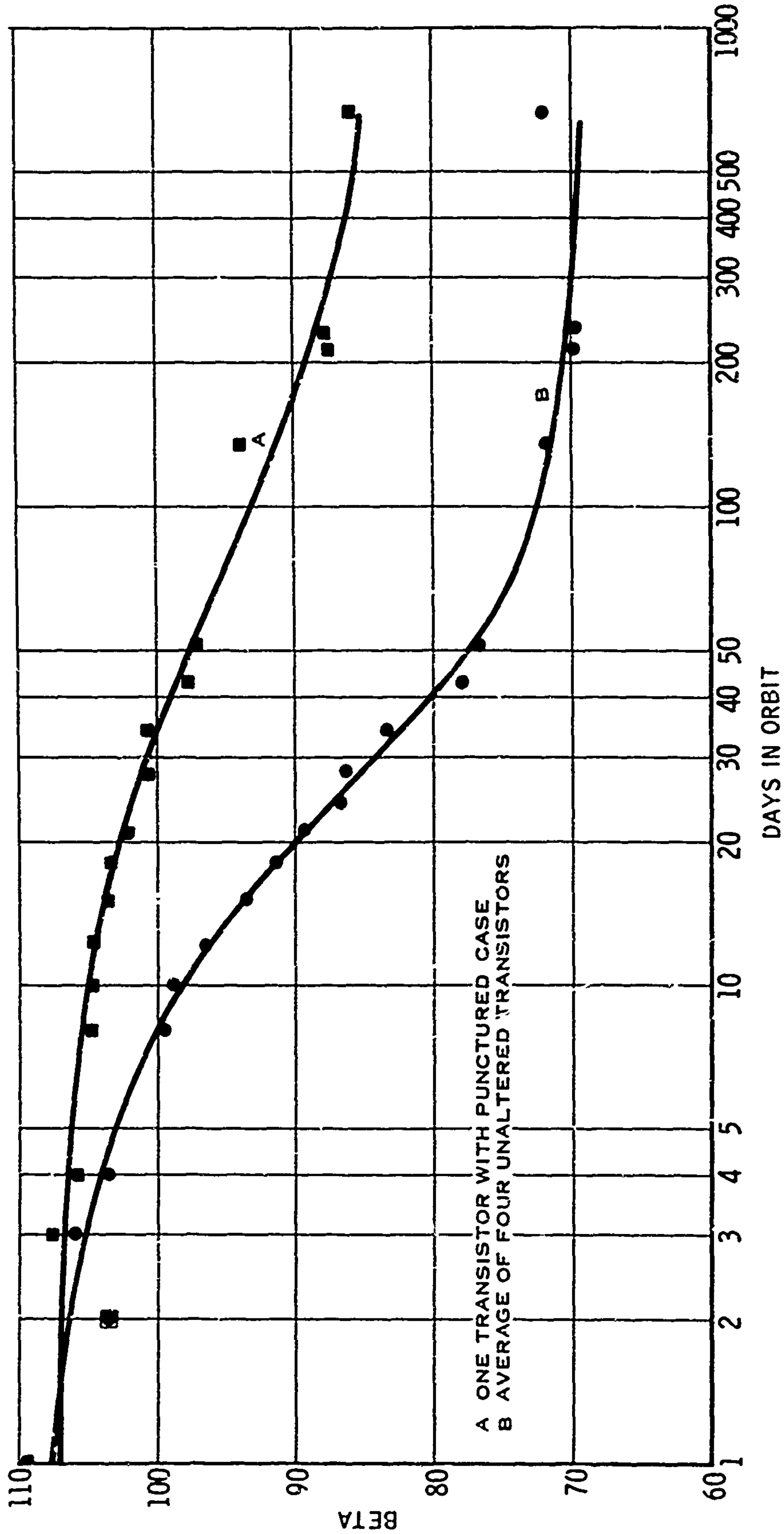


Fig. 6 Beta versus Time for Fairchild 2N1711 NPN Planar Transistors Flown on 1963-38C Satellite

0.3 inch of aluminum, one of each type, are controlled and are considered to be undegraded by radiation. The telemetered gain of each control transistor is normalized to its preflight value for each set of readings. The appropriate normalizing factor is then used to correct the test transistors for temperature and line voltage variations. Thus far, base-to-collector leakage has been found to be less than one nanoampere above preflight values. The beta experiments presented in Fig. 7 show that both the shielded and unshielded 2N2907-A -PNP bandguard transistors degraded approximately one percent in 250 days, while the unshielded NPN transistors degraded approximately 27 percent in the same period. Preflight gain bandwidth products are as follows: 2N2222, 200 mc; 2N2586, 45 mc; 2N2907-A, 200 mc.

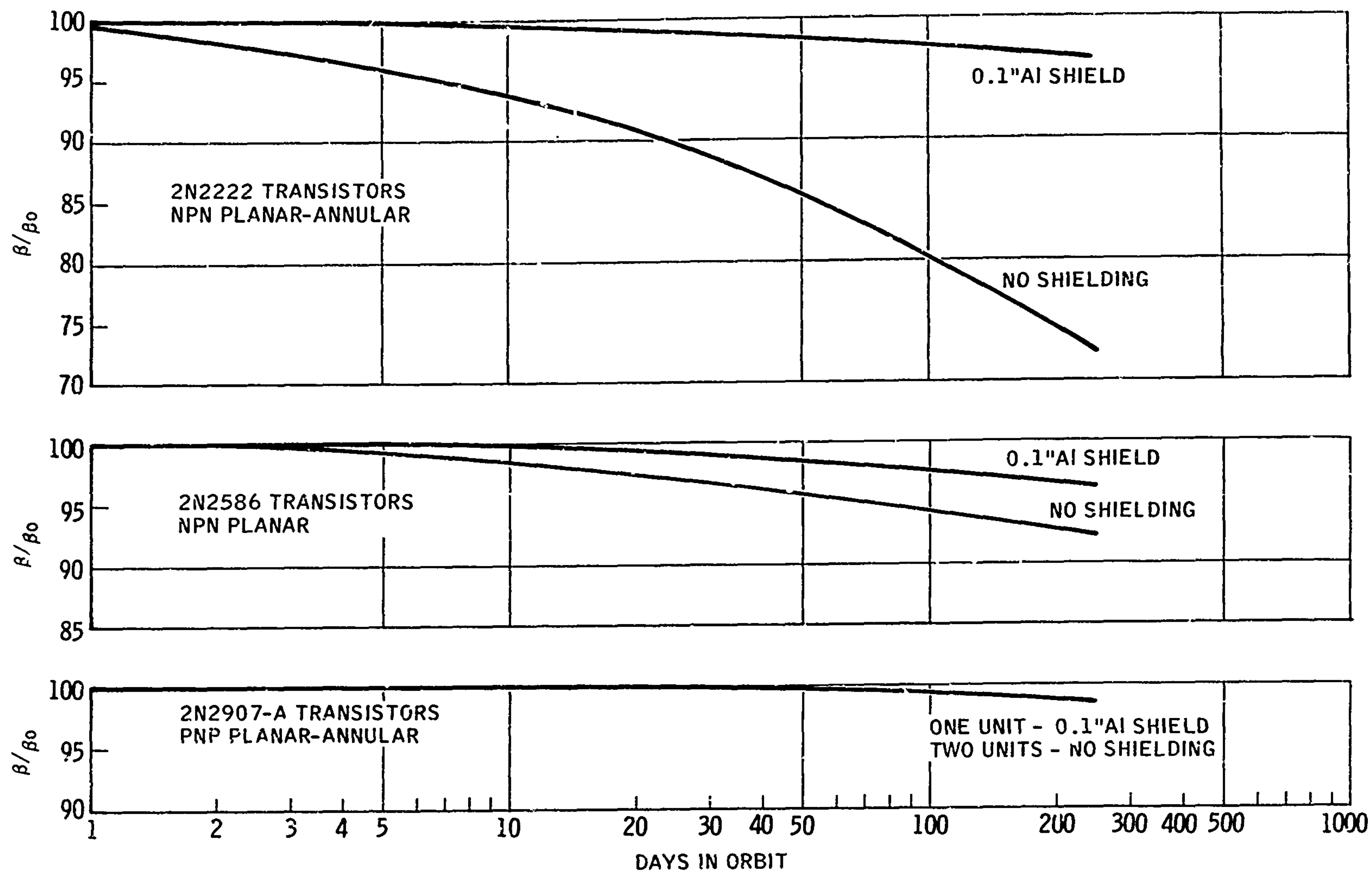


Fig. 7 Results of Transistor Reliability Experiment Flown on Satellite 1964-83C. Orbit: Apogee 1070 km, Perigee 1027 km, Inclination 89.9°

III. ANALYSIS OF RESULTS

Figure 1 shows that during the 236-day period prior to Operation Starfish, the 1961-$\alpha\eta$1 solar cells degraded by 16 percent and the 1961-$\alpha\eta$2 solar cells degraded by 18 percent. In a 20-day period immediately following the high-altitude nuclear test, the 1961-$\alpha\eta$1 solar cells were degraded by an additional 22 percent. The 1961-$\alpha\eta$2 solar cells were degraded by an additional 22 percent in 28 days after the test.

The Applied Physics Laboratory conducted an investigation of the degradation of "blue-sensitive" P-on-N and 10 ohm-cm N-on-P solar cells in a normal incident 1 mev electron environment (Ref. 3). Data obtained from this investigation were plotted as relative output of the solar cells as a function of time-integrated 1 mev flux in electrons/cm^2. Rosenzweig computed the damage to N-on-P and P-on-N solar cells protected by various shield thicknesses in a radiation environment consisting of an omnidirectional U^{235} fission electron flux. These results were related to equivalent damage by 1 mev normal incident electron flux, and were presented as equivalent 1 mev electron flux as a function of shield thickness for omidirectional fission electrons incident on the solar cells with infinite back shielding (Ref. 4).

By measuring solar cell degradation in orbit and using the laboratory-determined degradation rate as a function of 1 mev electron flux, one can compute the equivalent 1 mev electron flux encountered by an orbiting solar cell. This was done using the experimental data from the satellites 1961-$\alpha\eta$1 and 1962-$\beta\kappa$ and the results are presented in Table VI.

Table VI

Comparison of P-on-N Solar Cell Degradation for Periods Before and After the Operation Starfish High Altitude Nuclear Test

EXPERIMENT	PERIOD	PERCENT DEGRADATION	EQUIVALENT 1 MEV ELECTRONS PER CM^2 PER DAY INCIDENT ON BARE P-ON-N SOLAR CELLS
1961-$\alpha\eta$1			
P-ON-N SOLAR CELL DEGRADATION EXPERIMENT	236 DAYS PRIOR TO OPERATION STARFISH	16	39.4g
SAME	20 DAYS AFTER OPERATION STARFISH	22	8,550g
SATELLITE 1962 $\beta\kappa$			
P-ON-N SOLAR CELLS 60 MIL GLASS COVERS	47 DAYS-BEGINNING 109 DAYS AFTER STARFISH	19.4	320g
P-ON-N SOLAR CELLS 6 MIL GLASS COVERS	47 DAYS-BEGINNING 109 DAYS AFTER STARFISH	37.0	3,340g

NOTE: A SOLAR CELL ATTITUDE DETECTOR ON THE 1961 $\alpha\eta$2 SATELLITE DEGRADED LESS THAN 7.8 PERCENT FROM DAY 95 TO DAY 195. THIS DETECTOR WAS SHIELDED BY A 125 MIL QUARTZ WINDOW.

Results from the 1961-$\alpha\eta$1 satellite indicate that particle flux effective in damaging solar cells protected by 6-mil-thick glass increased by a factor of 217 after Starfish. Results of the satellite 1962-$\beta\kappa$ experiments indicate that during the period from late October through early December 1962 the P-on-N cells protected by 6-mil glass were subjected to 10.5 times as much damaging particle flux as were cells protected by 60-mil-thick glass.

Table VII shows a comparison of the P-on-N solar cell degradation on ANNA I-B during the first 120 days in orbit. The equivalent 1 mev electron flux values were computed by relating the in-orbit degradations to laboratory data. Correlation of these values with Rosenzweig's curves yielded the omnidirectional integrated fission electron flux. Had the damaging particles been fission electrons, the fission electron flux would have been approximately equal for all three experiments. However, the solar cells with 6-mil-thick glass had nearly seven times the fission flux value as compared to the solar cells with 30-mil-thick sapphire.

Filz and Yagoda (Ref. 5) measured an increase in 55 mev protons at altitudes from 367 to 514 km after Starfish and after the Soviet test of 1962. After July 9, 1962 they observed an increase in 55 mev protons by a factor of six. This was followed by a decay to approximately a factor of four above the pre-Starfish value just prior to the Soviet tests when the proton flux was increased to a factor of five over the normal level. As late as March 1963 they measured 55 mev proton levels about 3.5 times the level they were before the high-altitude nuclear tests. It may be assumed that protons at other energy levels were also added to the radiation belts at these comparatively low altitudes as a result of these tests. Protons with $E > 4.5$ mev will penetrate 6-mil-thick glass while those with

Table VII

Comparison of P-on-N Solar Cell Degradation on ANNA I-B Satellite; 120 Day Period Beginning 114 Days After Operation Starfish

EXPERIMENT	PERCENT DEGRADATION	EQUIVALENT 1 MEV ELECTRONS PER CM^2 PER DAY INCIDENT ON BARE P-ON-N SOLAR CELLS	OMNIDIRECTIONAL INTEGRATED FISSION ELECTRONS PER CM^2 PER DAY ON COVERED CELLS
P-ON-N SOLAR CELLS 30 MIL SAPPHIRE COVERS	14.8	63g	0.42 T
P-ON-N SOLAR CELLS 20 MIL QUARTZ COVERS	26.9	358g	1.1 T
P-ON-N SOLAR CELLS 6 MIL GLASS COVERS	36.7	1,250g	2.8 T

ALL EXPERIMENTS HAD INFINITE BACK SHIELDING

$E \geq 9.3$ mev will penetrate 20 mils of quartz. Thirty-mil sapphire covers will shield against protons with $E < 14$ mev (Ref. 6). Therefore, it is postulated that the high-altitude nuclear test caused a significant increase in the number of protons ($E > 4.5$ mev) to be redistributed, at least to an altitude range between 400 and 1,200 km.

Earlier mention was made that the radiation intensity decreased during the period January to May 1963. This is indicated on curves D and E of Fig. 3. By use of curve E, P-on-N solar cells with 6-mil cover slides, one finds that after 50 days in orbit those cells have degraded by 29.7 percent. Had the radiation intensity remained constant, the cells under question would have degraded by 46.4 percent at the end of 500 days. However, the cells degraded by 44.6 percent during that period. By the same analysis, the P-on-N solar cells with 20-mil quartz cover slides degraded 34.8 percent at the end of 500 days while they would have degraded by 36.5 percent in the same period had the intensity level not decreased.

An interesting comparison of the effects of radiation environment is given in Fig. 5. The P-on-N solar cells with 6-mil glass covers on ANNA I-B had experienced 1 mev radiation flux equivalent to 850 G electrons/cm^2/day during the first 500 days in orbit while the equivalent experimental solar cells on satellite 1963-38C had experienced an equivalent 1 mev radiation flux of only 44 G electrons/cm^2/day, a factor of 19.3 lower. This is explained by the fact that ANNA I-B was launched while the radiation intensity was higher than when the satellite 1963-38C was launched.

Figure 4 shows that heavy cover slides may not, in themselves, be the solution to the problem of solar cell degradation in the radiation environment. The N-on-P solar cell with 125-mil quartz cover window, curve D, degraded by 10.5 percent in 500 days while the N-on-P solar cells with 6-mil glass degraded by only 8 percent in the same time. This difference is attributed to discoloration of the thick cover slide.

To determine the power-to-weight-ratio of a solar array after one year in an orbit similar to that of the 1963-38C satellite, one must consider the number of solar cells required to deliver the required power after one year and the cover slide thickness to be used. Thus, if n solar cells with 6-mil glass covers are required, reference to curves C, B, and A of Fig. 4 shows that 0.92 n cells with 20-mil quartz covers or 0.69 n cells with 30-mil sapphire will be required to deliver the same power after one year. However, when one considers the relative mass of cover slides compared to the weight of (15-mil-thick) solar cells, the power-to-weight-ratio is significantly increased by using 6-mil cover slides. To use Figs. 3 and 4 for power systems analysis one must assume operation toward the short-circuit side of the solar array IV curve.

IV. CONCLUSIONS

A review of the data analysis presented above indicates that the damage to solar cells in a 1,000 km orbit during the early months after Operation Starfish may not necessarily have been mostly a result of fission spectrum electrons. Although many energetic electrons were introduced into the inner belt, it is concluded that some high energy (> 4.5 mev) protons were redistributed to altitudes including 1,000 km. The results of flight experiments indicate optimum power-to-weight-ratio for a solar cell power supply and one year life expectancy may be obtained by use of N-on-P solar cells with 6-mil glass covers. By projection of curve C, Fig. 4, one may predict the degradation of optimum solar power supply for several years in a 1,000 km polar orbit. Thus, the optimum power-to-weight-design should degrade by 7 percent in one year and by 11 percent in three years. Orbital data obtained thus far indicate high reliability (against radiation damage) electronic circuits may be designed for operation in the radiation belts by use of the 2N2907-A transistors with minimal shielding or by use of 2N2586 and 2N2222 transistors with 0.60 gram/cm^2 of shielding.

ACKNOWLEDGMENTS

The authors wish to acknowledge the significant contributions of Mr. A. F. Hogrefe without which this paper would have been incomplete. His efforts made possible presentation of all the transistor and capacitor data included and his technical advice in this area was most valuable. The technical discussions with Dr. A. J. Zmuda were most helpful.

REFERENCES

1. K. D. Smith, H. K. Gummel, J. D. Bode, D. B. Cuttriss, R. J. Nielsen, and W. Rosenzweig, "The Solar Cells and Their Mounting," Bell System Technical Journal, July 1963.

2. A. F. Hogrefe, "Near Earth Ionizing Radiation and Electronic Circuitry," Appendix D, TG-510, The Johns Hopkins University, Applied Physics Laboratory, July 1963.

3. J. H. Martin, "Solar Cell Characteristics Determined as Function of Electron Irradiation and Temperature on Table Mountain," Fourth Annual Photovoltaic Specialists Conference, Cleveland, Ohio, June 1964.

4. W. L. Brown, J. D. Gabbe, and W. Rosenzweig, "Results of the Telstar Radiation Experiments," Bell System Technical Journal, July 1963.

5. R. Filz, and H. Yagoda, "Observations on Trapped Protons in Emulsions Recovered from Satellite Orbits," Proc. Space Research IV, 1963.

6. B. Ross, "Design Criteria for Satellite Power Supplies Using Radiation Resistant Solar Cells," ASME Aviation and Space Hydraulic and Gas Turbine Conference, Los Angeles, California, March 1963.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) The Johns Hopkins Univ., Applied Physics Lab. 8621 Georgia Avenue Silver Spring, Maryland	**2a. REPORT SECURITY CLASSIFICATION** Unclassified **2b. GROUP** na

3. REPORT TITLE

Radiation Damage to Orbiting Solar Cells and Transistors

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Technical Memorandum

5. AUTHOR(S) *(Last name, first name, initial)*

R. E. Fischell, J. H. Martin, W. E. Radford, W. E. Allen

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1967	25	6

8a. CONTRACT OR GRANT NO. NOw 62-0604-c **b. PROJECT NO.** Task Assignment Y1SB **c.** **d.**	**9a. ORIGINATOR'S REPORT NUMBER(S)** TG-886 **9b. OTHER REPORT NO(S)** *(Any other numbers that may be assigned this report)*

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Naval Air Systems Command and Special Projects Office SP-2403

13. ABSTRACT

The Applied Physics Laboratory, The Johns Hopkins University began in-flight solar cell degradation studies with the launching of the 1961-01 satellite on June 29, 1961. Similar experiments were flown on the 1961-οη1 and 1961-οη2 satellites. Data obtained from these satellites cover a time period both before and after Operation Starfish on July 9, 1962. Subsequently ~~the Applied Physics Laboratory has flown~~ solar cell and electronic experiments on satellites 1962-βη, ANNA I-B, 1963- 38C, and 1964-83C. The data indicate that the damage to solar cells in a 1000 km orbit during the early months after Operation Starfish may not have been mostly a result of fission spectrum electrons. Although many energetic electrons were introduced into the inner belt, it is indicated that some high energy (>4.5 mev) protons were redistributed to altitudes including 1000 km. The results of flight experiments indicate that optimum power-to-weight ratio solar arrays will be obtained by use of N-on-P solar cells with 6 mil glass covers.

DD FORM 1 JAN 64 1473

UNCLASSIFIED
Security Classification

14. KEY WORDS

Radiation belt
Radiation damage
Solar cells
Transistors
Satellites
Component degradacion