THREE-YEAR PERFORMANCE OF THE NTS-2 SOLAR CELL EXPERIMENT*

R. L. Statler and D. H. Walker
Naval Research Laboratory

SUMMARY

Twelve different solar cell modules from the NTS-2 experiment are functioning after more than three years in a severe trapped radiation orbit of 20,367 km (10,990 nm) circular, 63° inclination. The rate of maximum power (P_M) degradation may be fit to a predicted rate which is based on twice the value of 1-MeV electron equivalent damage fluence calculated from the space electron model AEI-7. The photovoltaic parameters of the cells are compared to their original values to demonstrate rank order of performance.

INTRODUCTION

Solar cell experiments on satellites can, in principle, provide the most reliable information for evaluating actual operating efficiency, degradation effects from the space environment, and synergystic effects of combined space environmental factors. It is obviously infeasible to duplicate in the laboratory the long term exposures to radiation spectrums, ultra-violet photons, high vacuum, and temperature cycling which are continuously present during a satellite experiment. There are, however, certain experimental difficulties which have impaired many space solar cell experiments, for example, a non-stabilized spacecraft, electronics failure, unknown error voltages sometimes attributed to ground loops, etc. The NTS-2 solar cell experiments have been fortunate to avoid these problems, having a stabilized spacecraft with the test panels favorably located to send data when the sun is within 3° of the zenith to the panel surface. The data acquisition system has functioned without any problems.

SYMBOLS

I-V curve	photovoltaic current-voltage curve
I_{sc}	short-circuit current, mA
P_M	maximum power point, mW
V_{oc}	open circuit voltage, mV
BOL	beginning of life

*This work is partially supported by the Aero Propulsion Laboratory, AFWAL; and by the Space Division, AFSC.

DENI	damage equivalent normally incident
P/Po	relative maximum power
X_j	p/n junction depth

OBJECTIVES OF THE EXPERIMENT

The objectives of the experiment may be listed as follows:

- Compare radiation damage among advanced silicon cells utilizing textured surfaces, shallow junctions, and back surface fields.
- Study space environment degradation damage in an aluminum-gallium-arsenide cell (AlGaAs/GaAs) having a junction depth of 1 μm.
- Compare space degradation in a conventional deep-junction cell (0.3-0.5 μm) using an adhesively bonded coverslip vs. the cell using an electrostatically bonded coverslip.
- Compare degradation in the Comsat nonreflecting cell using a conventional fused silica coverslip with an ultraviolet cutoff filter vs. a coverslip without a filter.
- Study the performance of the vertical junction cell developed by Solarex for the Air Force Aero Propulsion Laboratory.
- Compare space degradation in a textured shallow junction cell having an adhesively bonded fused silica coverslip vs. the cell having an FEP Teflon bonded fused silica coverslip.
- Compare performance of lithium-doped p/n cells on NTS-2 with similar cells on NTS-1.
- Study the performance of a 1 x 2 cm planar blocking diode developed by Spectrolab for the Air Force Aero Propulsion Laboratory.
- Compare the values of solar cell parameters measured with a solar simulator to those obtained in space.
- Evaluate the accuracy of space degradation predictions based on trapped radiation models.

DESCRIPTION OF EXPERIMENTAL PANELS

The experimental hardware consists of two solar panels and an electronics subsystem. The panels each have 7 modules of five cells connected in series. The cells individually measure 2 cm x 2 cm. The modules are mounted on two 0.64-cm-thick aluminum honeycomb panels. There is also an experimental blocking diode which is a 1 x 2 cm planar device with a polished aluminized surface. This diode, in series with the lithium-doped cells of module #11, comprise the experiment designated Experiment 12 in Table 1. The panels are thermally isolated from the spacecraft structure; therefore, in order to allow for heat dissipation which can only be accomplished by thermal radiation from the front panel surface, the modules were evenly spaced on the panel and the intervening regions were coated with a white thermal control coating, Dow Corning 92007, which covers 52 percent of the panel surface. Temperatures are monitored at the rear surface of four cells by means of three thermistors and one wire resistance thermometer. The thermistors are accurate to within $\pm$ 3 degrees C up to 100 degrees C, and the wire thermometer is accurate to within $\pm$ 2 degrees C to above 120 degrees C.

The experimental panels are continuously illuminated by the sun (except during the biannual eclipse season of 25 days). The experiment is mounted on the satellite surface which faces the direction of travel about the earth, and twice during each orbit the satellite is rotated 180 degrees in yaw so that the paddles (and experiment) face the sun. Table 1 gives a brief description of the experiments showing the type and thickness of the solar cell, the type and thickness of the coverslip, the type of coverslip bonding, the interconnect material, and the beginning-of-life (BOL) cell efficiency.

EXPERIMENTAL RESULTS

Data were recorded at weekly intervals during the first 6 months, then at monthly intervals thereafter. The data shown here extend from the first day to day 1116. It should be pointed out that day one is designated as the day the main solar paddles were deployed. Although the spacecraft was launched on 23 June 1977, the main paddles remained folded over the experiment panels until NTS-2 was on station and despun on 7 July 1977. At that time the main solar paddles were unfolded, and the experimental panels were exposed to the total space environment.

The current-voltage characteristics of the solar cell arrays are telemetered in real time as the satellite passes over the tracking station at Blossom Point, Maryland. The electronic circuit measures the I-V curve for each module in sequence reading out current-voltage values for evenly-spaced points from I_{SC} to V_{OC}. Each cell module is short-circuited except when it is being stepped through the I-V curve. The average value of I_{SC} measured in space on the first day of exposure agreed with the solar simulator values to 1.41 $\pm$ 0.99 percent. The agreement between V_{OC} on initial space exposure and the solar simulator values was 1.24 $\pm$ 2.02 percent. The values of I_{SC}, V_{OC} and P_M measured on the first day in orbit are listed in Table 2.

Module Failures

Three experiments have ceased to function: on day 69, the Solarex space cell (Exp. 8) failed; on day 729 the Solarex vertical junction cell (Exp. 7) failed; on day 783 the Spectrolab Textured Helios Reflector cell (Exp. 9) failed. After analyzing the data acquisition electronics it was decided that these failures were not caused by faults in the data processor but were the result of open circuits occurring in the cell modules. These failure modes are discussed in references 1 and 2.

Radiation Environment

The observed degradation rates of the NTS-2 solar cell experiments were utilized to estimate equivalent 1 MeV electron fluence in the 11,000 nm circular orbit. Prior to launch, an estimation of the equivalent fluence based on the AEI-7 LO electron model (ref. 3) from the National Space Science Data Center gave a value of 2×10^{14} DENI 1-MeV e/cm^2-yr for a solar cell with a 0.030 cm fused silica coverglass. An earlier estimate based on the values published in reference 4 gave a lesser value of 3.3×10^{13} 1-MeV electron annual fluence. This result is obtained using the electron environment models designated as AE 3, AE 4, and AE 5. These models have been superseded by the more accurate AEI 7 model. We have attempted to fit the observed degradation rates in several of the silicon cell experiments to degradation curves in reference 4 which were obtained by irradiating similar types of solar cells with electron accelerators. For this purpose we have used the space data from experiments 1, 2, 3, 4, 10, and 13. It is to be noted that the proton fluence at this orbit is defined by the proton models AP5, AP6, and AP7 to be negligible with respect to the electron damage environment (at least three orders of magnitude less). Solar flare proton events since launch have been weak enough to be ignored. The results of fitting power degradation rates from space data to the reference 4 curves indicate that the equivalent 1-MeV electron annual fluence is approximately 3.5×10^{14} e/cm^2-year. Although this is nearly twice the value obtained from the AEI 7 model, it is not large compared to the stated intrinsic uncertainties in the space flux data from which the models are generated. These uncertainties range from x2 to x10 (ref. 4).

Gallium Arsenide Solar Cell

An (AlGa)As-GaAs solar cell covered with 12 mil 7490 fused silica and DC93-500 comprises Exp. 15. This module, which was made by the Hughes Research Laboratory, had an efficiency of 13.6 percent. These cells have a junction depth of 1 micon, and are interconnected by a metal-filled epoxy. This experiment behaved in a very unusual manner during the first 3 months. The GaAs cells sustained a sharp drop in power output as measured on the first orbit and throughout the next 28 days as shown in figure 1. The P_M gradually increased to its peak value on the 100th day, then the normal rate of radiation degradation became evident. The behavior during the early days has not been positively explained; it may be related to the epoxy interconnect material for lack of other identifiable mechanisms in the cell.

The maximum power degradation of the gallium arsenide cell is shown in figure 1 along with that of the highest output cell, which was the Comsat nonreflective cell, and with the Spectrolab Helios cell, referred to also as "K-6." The Helios cell is a shallow junction, polished surface, back surface field cell. The fourth cell on the figure is a p/n lithium-doped cell from the 1972 period when there was a concerted effort to develop a radiation hardened solar cell. Lithium was observed to enhance room temperature annealing of radiation induced defects in p/n silicon cells. The annealing was observed to be more prominent in the case for proton damage than for electron damage. Hence the NTS-2 results shown here are somewhat surprising, in that the power output of this cell is nearly as high as the power of the Helios cell after 1116 days (equivalent to 1.1 x 10^{15} 1-MeV e/cm^2). This behavior leads to the speculation that the reason for the increased radiation environment, which is about twice that predicted from the trapped radiation models, may be ascribed to an enhanced proton environment at this altitude.

Another example of simultaneous annealing occurring during the radiation damage process is illustrated in the case of the gallium arsenide cell in fig. 2. This figure shows the relative power (power remaining after radiation divided by the initial power) reported by Loo, Kamath, and Knetchli (ref. 5) for aluminum-gallium/gallium arsenide solar cells with junction depths of 1.0 μm and 0.5 μm, obtained after electron accelerator measurements at near room temperature. The NTS-2 gallium arsenide cells are known to have junction depths of 1.0 μm. The relative power of these cells is plotted at 1, 2, and 3 years, assuming an annual fluence of 3.5 x 10^{14} 1-MeV e/cm^2-year. After 3 years, the cells which have been at temperatures near 100°C almost continuously while being irradiated have 50 percent greater power than those in accelerator tests. This behavior suggests the possibility of annealing of primary radiation defects during the time at which radiation lattice displacements are being made.

Effect of Junction Depth

One source of improvement in cell efficiency has been to reduce the depth of the diffused p/n junction in silicon cells. Shallow junction cells are more efficient converters of ultraviolet energy. One cell type, module #1, the OCLI conventional, was included as a baseline to show the improvements in the advanced cells. The OCLI conventional is a typical "deep-junction" 10 ohm-cm cell, in which the diffused junction is about 0.5 μm deep. More advanced cells have junctions in the range of 0.15 to 0.30 μm. Figure 3 clearly shows the gain in power afforded by the newer cells, such as the OCLI Violet, the HESP, and the Spectrolab Textured Hybrid. At 1116 days the power output of the advanced cells was higher by 22 to 31 percent. Figure 3 also shows the interesting fact that the slope of the power degradation curve of the Textured Hybrid cell is much less than that for the other cells. This Hybrid cell module is the one utilizing FEP Teflon as the coverslip bonding medium, while the other modules shown here use an adhesive system. These results suggest that the adhesive bonded cells undergo additional power loss attributed to radiation and/or ultraviolet darkening of the adhesive. These conclusions are presented in more detail in reference 1.

CONCLUSIONS

The power output at beginning of life and after 1116 days are compared in the bar graph in fig. 4. All data have been corrected to cell temperatures of 50°C. The temperature coefficients used are discussed in ref. 6. Table 3 is a listing of the percentage changes in I_{sc}, V_{oc}, and P_M for all experiments after three years.

The following conclusions may be stated after observing three years of orbital performance:

(1) The effect of the trapped electron environment at 11,000 nm, 63° inclination orbit on silicon solar cells can be fairly well predicted by multiplying the equivalent 1-MeV fluence obtained from the NASA AEI-7 model by a factor of two. The harder environment may be due to higher fluxes of trapped protons.

(2) The total loss in P_M for production type silicon cells varies from a high of 35.0 percent in a 10.7 percent conventional two ohm-cm cell with adhesive bonded 12 mil silica cover to 21.1 percent loss in a 11.1 percent textured shallow junction cell with an FEP bonded 6 mil silica cover.

(3) The (AlGa)As-GaAs cell with a 1 micron junction depth retains good power output at 44.0 mW. being surpassed only by the Comsat Nonreflecting cell (Exp. 6) at 49.4 mW and the OCLI violet cell at 46.6 mW.

REFERENCES

1. Statler, R.L.; Walker, D.H.; and Faraday, B.J.: Performance of the Solar Cell Experiment on the NTS-2 Satellite. Photovoltaic Generators in Space Symposium. ESA SP-147. June 1980, pp. 167-176.

2. Statler, R.L.; and Walker, D.H.: NTS-2 Solar Cell Experiment After Two Years in Orbit. Fourteenth Photovoltatic Specialists Conference, Institute of Electrical and Electronics Engineers, Inc., 1980, pp. 1234-1239.

3. Stassinopoulos, E.G.: Charged Particle Radiation Environment for NTS-2 and NTS-3 Satellites. NASA Goddard Space Flight Center. X-601-80-1, December 1979.

4. Tada, H.Y; and Carter, J.R.: Solar Cell Radiation Handbook. Jet Propulsion Laboratory, JPL Publication 77-56.1 November 1977.

5. Loo, R.; Kamath, G.S.; and Knechtli, R.C.: Radiation Damage in GaAs Solar Cells. Fourteenth Photovoltaic Specialists Conference, Institute of Electrical and Electronics Engineers, Inc., 1980, pp. 1090-1097.

6. Statler, R.L.; and Walker, D.H.: The NTS-2 Satellite Solar Cell Experiment. Proceedings of the Thirteenth Intersociety Energy Conversion Engineering Conference. 1978, pp. 97-104.

Table 1

Exp. No.	Cell Type	Thickness (cm)	Coverslip (cm)	Coverslip Bond (cm)	Interconnect	Efficiency 28°C (%)
1	OCLI Conventional, 2 ohm-cm	0.025	Corning 7940, AR and UV, (0.030)	R63-489	Cu/Ag	10.7
2	Spectrolab "Helios" p^+ 15-45 ohm-cm	0.0228	Ceria microsheet w/o AR, (0.025)	DC 93-500	Moly/Ag (.0025)	11.5
3	Spectrolab Hybrid Sculptured 7-14 ohm-cm	0.020	Corning 7940, AR and UV, (0.0152)	DC 93-500	Moly/Ag (.0025)	10.5
4	Spectrolab Hybrid Sculptured 7-14 ohm-cm	0.020	Corning 7940, w/o AR or UV, (0.0152)	FEP Teflon (0.0051)	Moly/Ag (.0025)	11.1
5	Comsat Non-Reflecting, p^+ Textured, 1.8 ohm-cm	0.025	Corning 7940, AR, w/o UV (.030)	R63-489	Ag, thermo-compression bonding	14.5
6	Comsat Non-Reflecting, p^+ Textured, 1.8 ohm-cm	0.025	Corning 7940, AR and UV (.030)	R63-489	Ag; thermo-compression bonding	14.6
7	Solarex Vertical Junction, p^+, 1.5 ohm-cm	0.030	Ceria microsheet w/o AR (.0152)	Sylgard 182	Ag mesh	13.0
8	Solarex Space Cell, p^+ 2 ohm-cm	0.025	Ceria microsheet w/o AR (0.0152)	Sylgard 182	Ag mesh	12.8
9	Spectrolab "Helios" p^+ Sculptured, BSR, 10 ohm-cm	0.030	Corning 7940 (.030) w/o AR or UV	FEP teflon (.003)	Ag mesh (.003)	14.2
10	OCLI Violet, 2 ohm-cm	0.025	Corning 7940 (.030) AR and UV	R63-489	Cu/Ag	13.5
11	Spectrolab P/N Li-doped 15-30 ohm-cm, Al contacts	0.020	Corning 7940, AR and UV, (0.015)	Silicone	Aluminum (.0025) Ultra-sonic welding	10.8
12	Spectrolab Planar Diode in series with Exp. 11	NA	NA	NA	NA	NA
13	OCLI Conventional, 2 ohm-cm	0.025	Corning 7070 (.028)	Electrostatic bonding	Cu/Ag	10.2
14	Spectrolab HESP, no p^+, Sculptured, 2 ohm-cm	0.030	Corning 7940, AR and UV (0.0305)	R63-489	Moly/Ag (.0025)	13.6
15	Hughes Gallium-Aluminum Arsenide	0.0305	Corning 7940, AR and UV, (0.0305)	DC 93-500	Aluminum GPD (.0025), epoxy	13.6

Table 2

NTS-2 SOLAR CELL EXPERIMENTS

EXPERIMENT NO.	CELL TYPE	FIRST DAY IN ORBIT		
		V_{OC}(MV)	I_{SC}(MA)	P_M (MW)
1	OCLI CONV. 2 OHM-CM	549	136.5	56.3
2	SPECTROLAB HELIOS (NTS-2)	546	155.5	60.6
3	SPECTROLAB TEXT. HYBR., F.S.	508	154.0	53.5
4	SPECTROLAB TEXT. HYBR., FEP, F.S. W/O FILTER	505	149.6	55.4
5	COMSTAT TEXT. F.S., W/O FILTER	555	180.4	74.7
6	COMSAT TEXT., F.S.	549	178.7	72.0
7	SOLAREX VERT. JUNC.	521	160.5	62.2
8	SOLAREX SPACE CELL	541	158.8	63.1
9	SPECTROLAB TEXT. HELIOS REFLECTOR	545	175.8	70.0
10	OCLI VIOLET, F.S.	552	164.3	66.6
11	SPECTROLAB HASP W/O DIODE	559	132.6	55.8
12	SPECTROLAB HASP W/DIODE	523	132.4	42.1
13	OCLI CONV., ESB	490	146.1	46.8
14	SPECTROLAB HESP	528	165.8	63.8
15	HRL AlGaAs	895	100.6	61.4

*THESE DATA HAVE BEEN CORRECTED TO 50°C AT ONE-SUN AND AIR MASS ZERO (AM0)

Table 3

NTS-2 SOLAR CELL EXPERIMENTS

SUMMARY OF CHANGES IN PHOTOVOLTAIC PARAMETERS*

EXPERIMENT NO.	CELL TYPE	PERCENT LOSS DAY 1 TO DAY 1116		
		MAXIMUM POWER	SHORT-CIRCUIT CURRENT	OPEN-CIRCUIT VOLTAGE
1	OCLI CONV. 2 OHM-CM	35.0	30.0	7.3
2	SPECTROLAB HELIOS (NTS-2)	33.2	25.3	11.5
3	SPECTROLAB TEXT. HYBR., F.S.	28.0	23.2	5.3
4	SPECTROLAB TEXT. HYBR., FEP, F.S. W/O FILTER	21.1	15.1	4.8
5	COMSAT TEXT. F.S., W/O FILTER	55.3	49.2	9.7
6	COMSAT TEXT., F.S.	31.3	28.4	7.1
7	SOLAREX VERT. JUNC.	(MODULE FAILED ON DAY 759)		
8	SOLAREX SPACE CELL	(MODULE FAILED ON DAY 69)		
9	SPECTROLAB TEXT. HELIOS REFLECTOR	(MODULE FAILED ON DAY 783)		
10	OCLI VIOLET, F.S.	30.0	24.7	6.0
11	SPECTROLAB HASP W/O DIODE	29.7	19.0	7.2
12	SPECTROLAB HASP W/DIODE	35.7	19.3	8.6
13	OCLI CONV., ESB	23.9	15.7	7.1
14	SPECTROLAB HESP	32.1	25.3	10.2
15	HRL AlGaAs	28.3	28.9	4.6

* THESE DATA HAVE BEEN CORRECTED TO 50°C AT ONE-SUN AND AIR MASS ZERO (AM0)

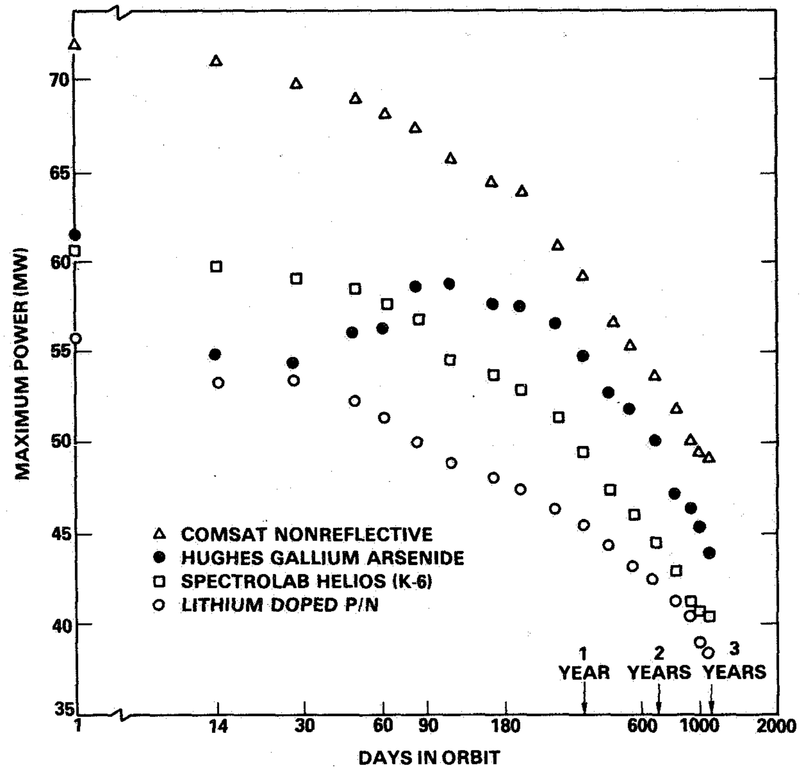

Fig. 1. Maximum power degradation of four cell types: Exps. 2, 6, 11, and 15.

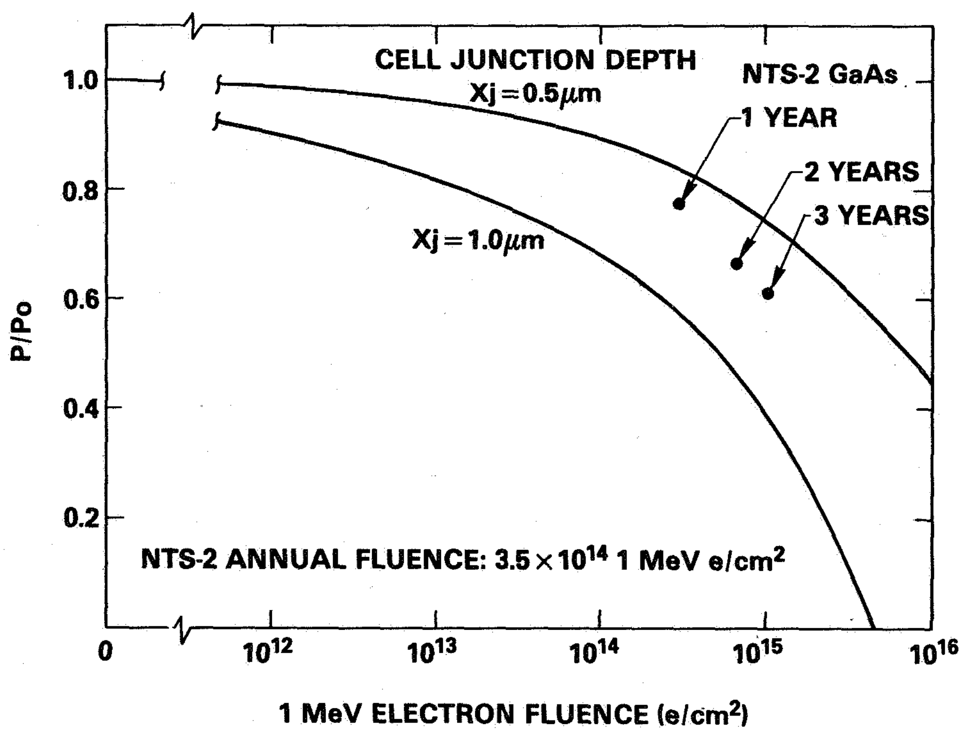

Fig. 2. Comparison of NTS-2 gallium arsenide with electron accelerator degradation (ref. 5)

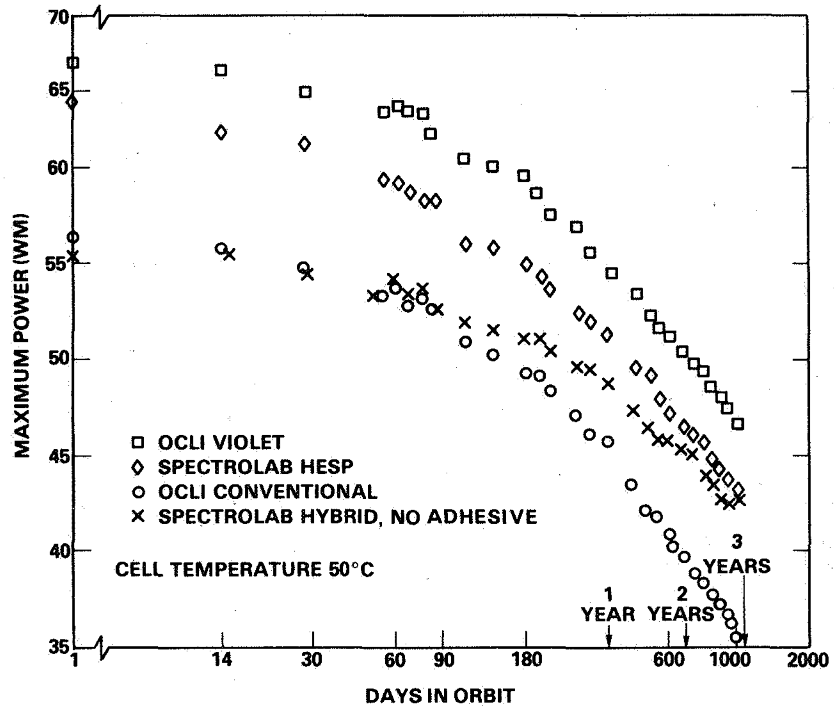

Fig. 3. Maximum power degradation of four cell types: Exps. 1, 4, 10, and 14.

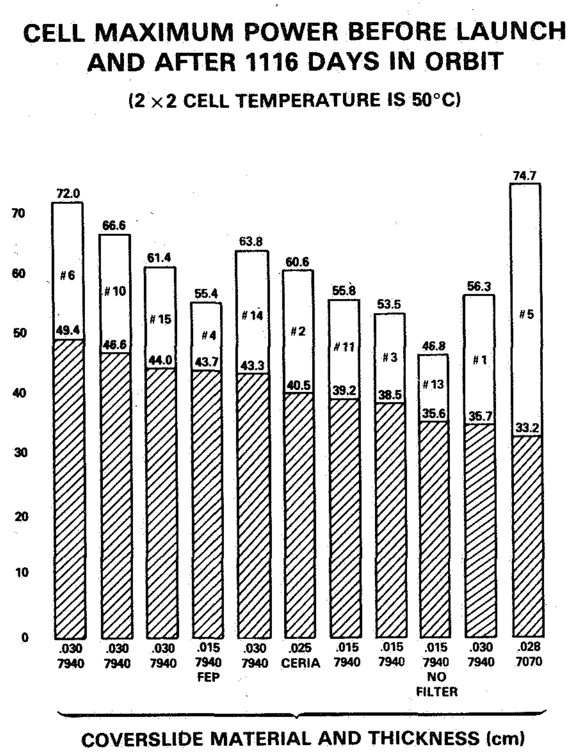

Fig. 4. Maximum output before launch and after 1116 days .