RESULTS OF THE FIRST 150 DAYS OF THE NTS-1 SOLAR CELL EXPERIMENTS

Richard L. Statler
Naval Research Laboratory

ABSTRACT

Twelve solar cell experiments were on the Naval Research Laboratory NTS-1 satellite launched on 14 July 1974, into a 13,620 km circular orbit at an inclination of 125°. The experiment comprises: 2 ohm-cm n/p, lithium-diffused p/n, violet n/p, p^+ back-surface field, and ultra-thin wrap-around contact cells. The short-circuit current of the experiments ranged from 2 to 12 percent higher in space than under solar simulators. During the 5 year life of the satellite, the experiments will be exposed to radiation equivalent to 2 x 10^{15} 1-MeV electron cm^{-2} and to nearly 5500 thermal cycles.

INTRODUCTION

The NTS-1 satellite is a forerunner of the NAVSTAR Global Positioning System being developed to provide extremely accurate world-wide navigational capability for ships, aircraft, and ground forces. Two earlier TIMATION satellites have proven this concept of passive and accurate position-fixing, and demonstrated through a joint British - U. S. experiment in 1972 that the system is ideal for transferring precise time around the world.

The payload also contains twelve solar cell experiments from the Royal Aircraft Establishment, Comsat Laboratories, and the Naval Research Laboratory.

The satellite viewed from the top (Fig. 1) is an octagon with a 48 inch diameter (122 cm) and is 22 inches high (56 cm). The solar array consists of 4 paddles made up of 2 x 4 cm n/p solar cells of 2 ohm-cm resistivity, placed on both sides. Each side has 10 strings of 81 cells in series connection. The coverslips are 12 mil (0.030 cm) Corning 7940 fused silica with blue-filters, cemented to the cells with Sylgard R6-3489 adhesive. Interconnects are 2 mil (0.005 cm) silver-plated molybdenum attached by reflow soldering.

OBJECTIVES OF THE SOLAR CELL EXPERIMENTS

The NRL and COMSAT Experiments are designed to compare the performance and degradation in time of various types of experimental solar cells with the reference experiment consisting of conventional cells of the same type used in the main array. The NTS-1 orbit is in a severe radiation environment which is equivalent to a 1-MeV electron fluence of 4×10^{14} electron cm^{-2} $year^{-1}$ incident on a solar cell shielded by 12 mils (0.030 cm) of fused silica. The specific objectives of these experiments are:

(1) To compare performance and radiation resistance of the Comsat and Centralab violet cells manufactured in 1973 to a reference cell.

(2) To compare the performance and radiation resistance of the Spectrolab "Helios" cell to a reference cell.

(3) To observe radiation resistance of lithium-diffused cells in orbit at temperatures near 50°C where annealing can occur.

(4) To observe performance and radiation degradation of a very thin solar cell (100 μm) having a p^+ diffused layer at the back contact.

The RAE experiment on the satellite represents a further stage in the process of proving and demonstrating the spaceworthiness of British components and techniques for the construction of advanced lightweight deployable arrays of thin silicon solar cells. The first flight experiments, embodying the thin cells, coverslips and flexible panel assembly techniques, were flown on the Prospero (X3) technological satellite and are still working satisfactorily after nearly three years in orbit (1). Miranda (X4) launched earlier this year, demonstrated the soundness of the fold-up stowage and telescopic deployment systems which have been developed for such arrays (2).

The aims of the present experiment are:

(1) To demonstrate the spaceworthiness of Ferranti 125 μm wrap-around solar cells of the latest 24-finger design, solder interconnected and mounted without cement on a flexible substrate.

(2) To compare Czochralski (CZ) and float zone (FZ) cells of the same type, with particular reference to any photon-induced degradation.

(3) To compare the performance and radiation resistance of 1 and 10 ohm-cm thin cells.

(4) To check initial performance and radiation damage predictions.

(5) To compare integral and discrete coverslips.

DESCRIPTION OF EXPERIMENTS

The experiments consist of the 12 types shown in Table 1. Fig. 2 is a photograph of experiments 1 through 4. The Helios cell experiment is shown in Fig. 3 and the reference array is shown in Fig. 4. The NRL and Comsat experiments are all series-wired patches, for which I-V curves are obtained from the telemetered data in orbit. The I-V curve is produced by the electrical circuit shown in Fig. 5. A ramp voltage with a time length of 30 seconds is applied to each experiment in sequence through a clock operated switching gate, and data is recorded at intervals of 2.56 seconds, yielding about 12 points of the IV curve during each sampling period.

All of the experiments are fixed to the satellite through thermally insulating stand-off legs. As a result of this and because the NTS-1 will be a three-axis stabilized spacecraft, the solar cell patches are calculated to reach temperatures of 70°C for the NRL and Comsat experiments, and 90°C for the RAE experiment. A Fenwall Type GB35P52T5 thermistor is attached to the rear surface of one cell on each of the NRL and Comsat experiments to measure temperature.

CALIBRATION OF EXPERIMENTS

Measurement of the NRL panels under solar simulator conditions was performed in part at the following locations: Air Force Aero Propulsion Laboratory, Hughes Aircraft Company, Jet Propulsion Laboratory, NASA Goddard Space Flight Center, and the Naval Research Laboratory. The calibration of the Comsat experiment was performed by Comsat Laboratories, and the RAE experiment was calibrated with the RAE Large Area Pulsed Solar Simulator (LAPSS).

Also, temperature coefficients for the experimental patches were determined at NRL and the Air Force Aero Propulsion Laboratory.

The short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and maximum power (P_{max}) obtained from the solar-simulator measurements are shown in Table I.

CALCULATION OF SPACE RADIATION FLUENCE

The effect of the natural trapped radiation environment was calculated from data available from the National Space Science Data Center, NASA (5,6). Computerized calculations were made of solar cell I-V curves as a function of temperature and coverslip thickness, using a program developed for NASA Goddard Space Flight Center (7).

The electron spectrum flux was calculated to be equivalent to 3×10^{14}

1-MeV e $cm^{-2}yr^{-1}$, while the proton spectrum flux was 1 x 10^{14} 1-MeV e $cm^{-2}yr^{-1}$, for a solar cell array with 0.030 cm of fused silica shielding at a circular orbit of 7500 n.m. (13,900 km). In a total radiation fluence of 4 x 10^{14} 1-MeV e cm^{-2} yr^{-1} the 2 ohm-cm solar cells in the main array will lose 19 percent of their maximum power in one year, and 35 percent after 5 years.

MEASUREMENT IN ORBIT

NTS-1 was launched on 14 July 1974 at 04:55:00 hours GMT. The four solar paddles of the main array were commanded to deploy in the first revolution; two of them indicated positive latch-up during Rev 1, the other two latched into final position during Rev 18 and Rev 19 after 6 days in orbit. During this time the spin rate of the satellite was slowed down to about 18 minutes per revolution. After Rev 20, high quality data was received from the solar cell experiments, with sun aspect angle varying from 0 to 15 degrees from normal incidence. The orbital period is 468.73 minutes, resulting in slightly more than 3 revolutions per day. The perigee is 12,193 km and the apogee is 13,606 km. The inclination is 125.11 degrees. Solar cell experiment data is recorded in real-time during a 2½ hour period as the satellite is in view of the Naval Research Laboratory Satellite Tracking Facility at Blossom Point, Maryland, located 50 km south of Washington, D.C.

The experiments are mounted on the top surface of the satellite, from which extends an 18.3 m gravity-gradient boom and a 56 cm magnetic boom. Thus, at certain solar aspect angle and rotation angle it is possible for partial shading to occur on the experiments. A computer program is being prepared which will predict the shading and reject data from shaded panels during processing. In the meantime, shading effects are obvious when the entire I-V curve is measured.

The temperature of the NRL experiments ranged from -13°C to +32°C during the first weeks while the spacecraft is rotating. The Comsat panel temperature ranged from -16°C to +19°C. The RAE patches are operating at temperatures somewhat higher than these. After several months the NRL and Comsat solar panel temperatures went as high as 60°C.

The results of measurements during Rev 30 (tenth day in orbit) are shown in Table 1. The I_{sc}, V_{oc}, and P_{max} have been corrected to a cell temperature of 25°C. The pre-launch solar simulator data are shown in this table for comparison.

A general observation of the space data shows that the short-circuit current (I_{sc}) of all the NRL and Comsat experiments is higher in space than under the solar simulators. Of the two lithium-doped cell experiments, the Centralab cell indicated a loss in P_{max} of 7 percent from ground to space. The power loss of four of the experiments is shown in Fig. 6 as a function of time in orbit for the first 5 months. No data is available prior to the tenth day because of the unfavorable sun angles during maneuvers to achieve final flight configuration and orientation. The reference panel is performing as predicted. The high efficiency arrays also degraded as expected for the first 100 days; from that point to 150 days the degradation rate for the Comsat violet was much more than had been predicted from electron accelerator experiments. The Helios panel is performing as expected. The lithium-diffused silicon panel improved slightly in power output between the third and fifth month. This annealing of radiation damage can be accounted for since the solar cell average temperatures increased during this period to as much as 50° Centigrade for many hours. This is sufficient to anneal some of the radiation damage from the first few months, as well as to reduce the present rate of damage below that for the other types of cells.

CONCLUSIONS

The NTS-1 solar cell experiments are operating very successfully; good quality data in the form of twelve-point IV curves is being obtained from the NRL and Comsat experiments. The results indicate higher initial output for all experiments than had been measured under solar simulators. The cells having the highest P_{max} are, in descending order: (1) Comsat violet, (2) Centralab violet, and (3) Heliotek "Helios" solar cells. Because of the orbital constraints, data will be obtained at semiannual periods lasting for 20 to 30 days. A shadowing program will be completed to assist in data reduction.

The NTS-1 experiment is of significant importance, because it permits the continuing evaluation of several types of high-efficiency solar cells and lithium-doped cells in a hard radiation environment with a direct comparison to a flight-quality conventional solar cell.

ACKNOWLEDGEMENT

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REFERENCES

1. F. C. Treble, "The Prospero Solar Cell Experiments", 10th IEEE Photovoltaic Specialists Conference, Palo Alto, CA, Nov. 1973.

2. B. Collins, "Power Generation for the X4 Spacecraft, A Step in the Development of a High Power to Weight Ratio 1-2 kW Hybrid Solar

Array System", Int. Conf. on Photovoltaic Power Generation, Hamburg, Sept. 1974.

3. A. A. Dollery, "Type Approval Tests on PPE Ceria-Stabilized Solar Cell Coverslips", RAE Tech Memo Space 172, Oct. 1971.

4. G. Brackley, K. Lawson, D. W. Stachell, "Integral Covers for Silicon Solar Cells", 9th IEEE Photovoltaic Specialists Conference, Silver Spring, Md., May 1972.

5. M. J. Teague and J. Stein, "The Use of the Inner Zone Electron Model AE-5 and Associated Computer Programs", NASA NSSDC 72-11, Nov. 1972.

6. J. P. Lavine and J. I. Vette, "Models of the Trapped Radiation Environment. Volume V: Inner Belt Protons", NASA SP-3024, 1969.

7. "The Revised Solar Array Synthesis Computer Program", RCA Final Report, NAS-5-11669 for NASA Goddard Space Flight Center, 1 Feb. 1970.

Table 1

PHOTOVOLTAIC MEASUREMENTS OF THE NRL AND COMSAT EXPERIMENTS

Experiment No.	Cell Type	Cell Size (cm)	Coverslip (cm)	Measured AMO performance per cell at 25° C					
				Solar Simulator			Rev 30 in Orbit		
				I_{sc} mA	V_{oc} mV	P_{max} mW	I_{sc} mA	V_{oc} mV	P_{max} mW
1	CEN Radial Grid n/p, 10 ohm-cm	2 X 2 X .01	Fused silica .015	141	576	61.1	151	558	55.5
2	CEN Violet n/p	2 X 2 X .03	Fused silica .015	157	582	68.1	169	574	73.0
3	HEL Lithium p/n	2 X 2 X .02	Fused silica .015	131	600	60.5	143	587	63.2
4	CEN Lithium p/n	2 X 2 X .02	Fused silica .015	125	606	57.0	144	589	56.0
5	CEN Violet n/p	2 X 2 X .03	Fused silica .030	149	570	65.6	172	569	73.3
6	HEL Helios n/p, 10 ohm-cm	2 X 2 X .03	Fused silica .030	159[1]	581[1]	69.7[1]	168	562	68.6
7	CEN n/p 2 ohm-cm	2 X 4 X .03	Fused silica .030	250	591	115	282	573	122.2
8	Comsat Violet	2 X 2	Ceria glass .015	162[2]	594[2]	74.3[2]	185	578	83.3

[1]Measured by Spectralab.
[2]Measured by Comsat Laboratories. All other measurements by Naval Research Laboratory.

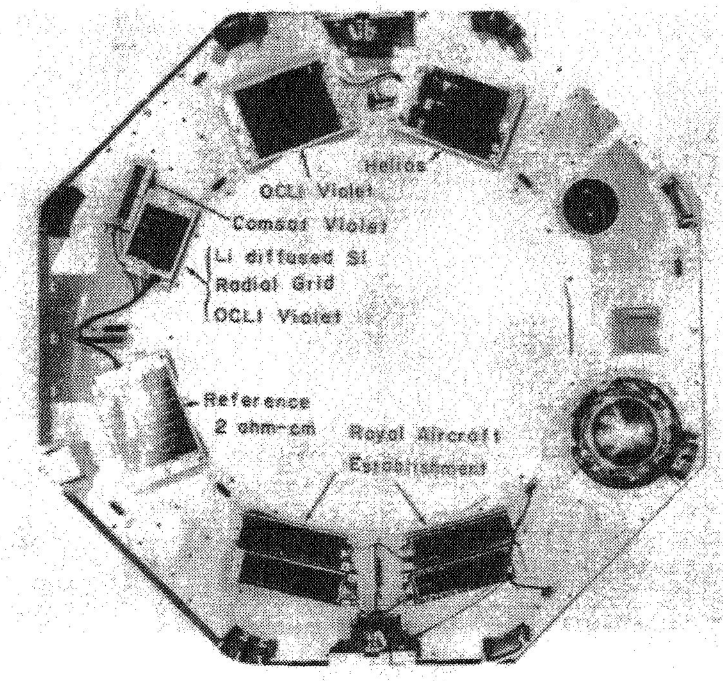

Fig. 1 Solar cell experiments on the top deck of NTS-1.

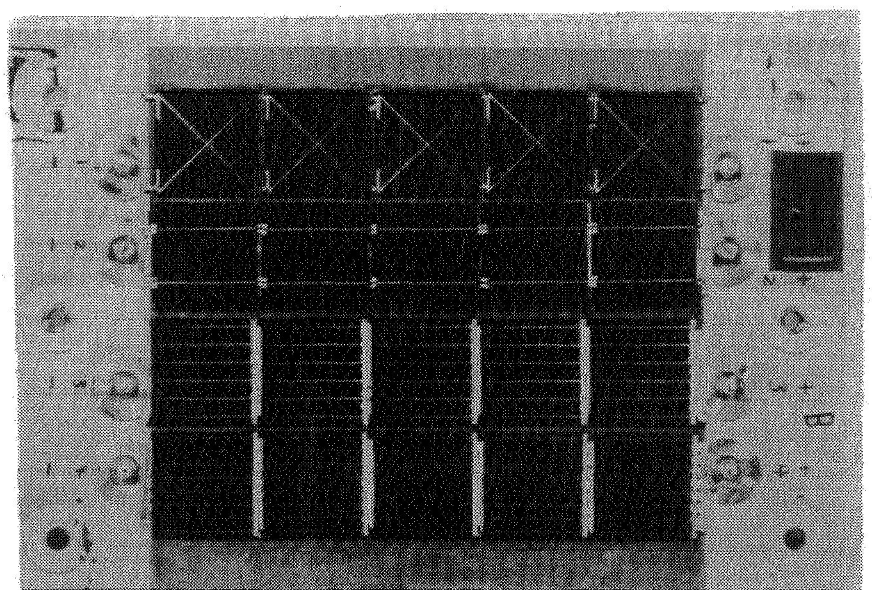

Fig. 2 Solar cell panel containing experiments 1 through 4.

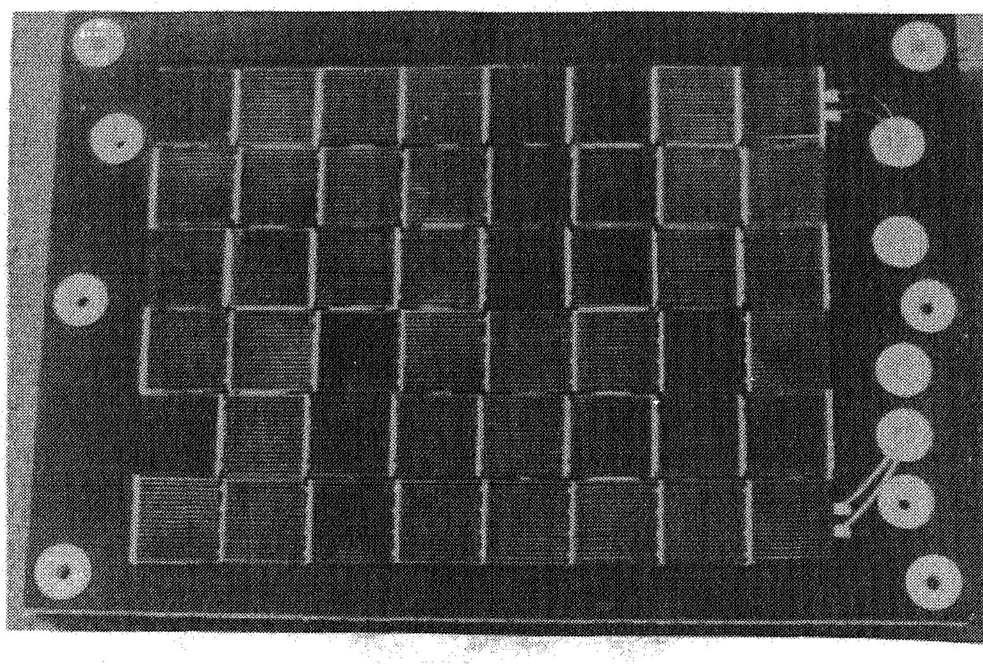

Fig. 3 The Spectrolab "Helios" solar cell experiment on NTS-1.

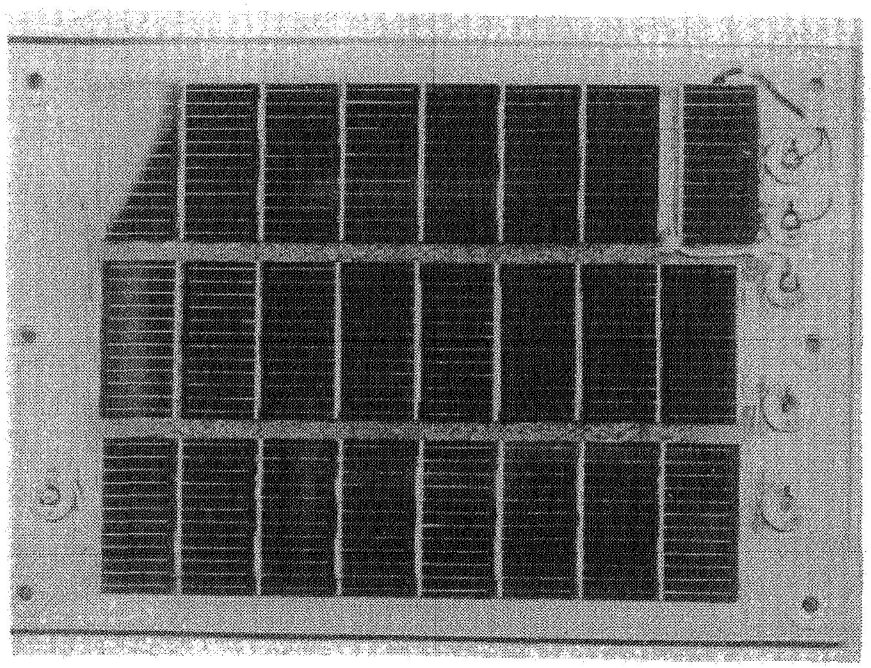

Fig. 4 The reference solar cell panel containing 2 ohm-cm N-on-P cells.

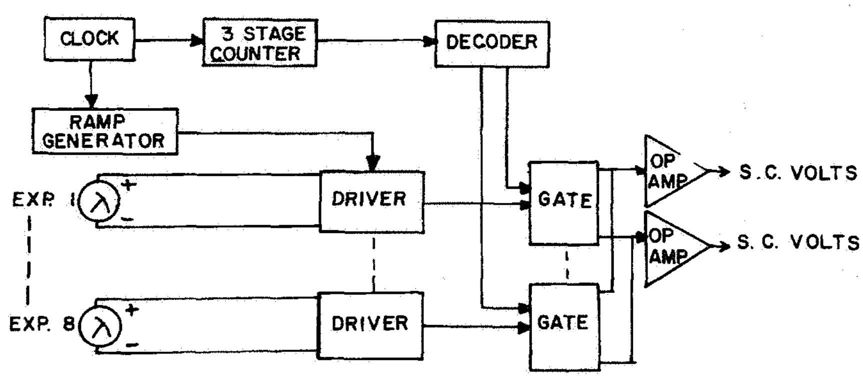

Fig. 5 The photovoltaic current-voltage measuring circuit on NTS-1.

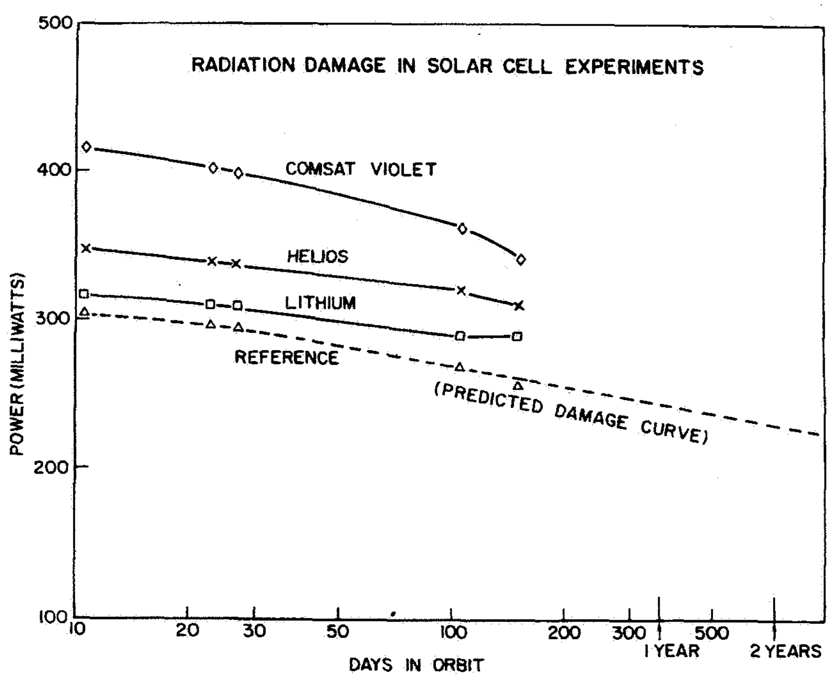

Fig. 6 The effect of trapped radiation damage on the maximum power output of the solar cell experiments on NTS-1.