

## EARLY RESULTS FROM THE PASP PLUS FLIGHT EXPERIMENT

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### ABSTRACT

Early results from the PASP Plus experiment, launched on Aug. 3, 1994, are given. The experiment consists of sixteen individual solar cell modules on twelve different panels. A wide variety of solar cell types are included. Two of the modules are concentrators. The orbit is 363x2552 km inclined at 70 degrees. There are two main purposes of PASP Plus, 1) to determine the interactions between the space plasma and solar arrays biased to plus or minus 500 volts, and 2) to determine the long term radiation performance of a wide variety of new solar cell types.

### INTRODUCTION

The PASP Plus (Photovoltaic Array Space Power Plus Diagnostics) program is a photovoltaic experiment which is flying on the Air Force satellite APEX (Advanced Photovoltaic and Electronics Experiments). The satellite was launched on Aug. 3, 1994 with a Pegasus low cost launch vehicle. There are two other small experiments on APEX, however PASP Plus is the largest, uses the most power, and accounts for the largest portion of the data requirements. The satellite is in an elliptical orbit with an apogee of 2552 km and a perigee of 363 km. The inclination is 70 degrees. The orbit was chosen to put the spacecraft into a wide variety of plasma environments as well as be high enough to receive a radiation dose which would degrade the PASP Plus modules during the life of the flight.

The two main purposes of the PASP Plus experiment are to determine the interactions between high voltage arrays and the space plasma and to determine the radiation damage characteristics of a variety of solar cells. Several of the individual modules are biased at various voltages up to plus or minus 500 volts at various times. Arcing rates and leakage currents are then measured. Radiation damage characteristics are obtained by continuous monitoring of I-V data for all solar cell modules.

The purpose of this paper is to present some of the early data from the first three months of the PASP Plus flight. Cell performance and module thermal performance will be discussed as well as some very preliminary leakage current data.

### PASP PLUS DESCRIPTION

The PASP Plus experiment consists of twelve photovoltaic panels containing a total of sixteen separate cell modules. Two of the modules are concentrator modules, while the rest are planar. Table I lists the different solar cell modules. There are several different solar cell types flying on PASP Plus including silicon, GaAs on germanium substrates, InP, amorphous silicon, and three multi-bandgap cells, AlGaAs/GaAs, GaAs/GaSb, and GaAs/CIS.

As noted in Table I, not all of the individual solar cell modules will be biased for the plasma interaction tests. Six of the sixteen individual modules will never be biased and only their radiation degradation will be observed. There are three panels with two or three individual modules. Numbers 0, 1, and 2 are all 2x4 cm silicon cell modules on the same panel, while numbers 4 and 6 are GaAs modules on one panel. The other panel with two modules is the GaAs/CIS panel with two (#'s 12 and 13) mechanically stacked multi-bandgap cell modules. Eight of the individual modules are on a deployed spacecraft panel (#'s 0-7), while the other eight are on the top payload shelf of the APEX spacecraft. Both the deployed panel and payload shelf are pointed toward the sun.

Two of the modules are samples of flexible arrays, Space Station and APSA. Both of these modules are mounted on the deployed panel over a corresponding opening in the panel. This allows these two modules to operate not only with the top surface of the array exposed to the environment, but with the back side also open to space. The APSA module is designed to operate in a GEO orbit, hence a thin layer of germanium was applied to the thin film substrate of the module for atomic oxygen protection. The Space Station array is already designed for LEO operations and the atomic oxygen environment.

In addition to the photovoltaic modules, PASP Plus has several diagnostic instruments to measure the environment through which the spacecraft is flying or help determine the plasma interactions with the biased arrays. A Langmuir probe is used to measure plasma properties; a dosimeter measures the radiation environment in several energy bands; and a set of quartz crystal micro-balances and calorimeters are used to determine the contamination effects. A transient pulse monitor, an electrostatic

Table I PASP Plus Individual Cell Panels

<u>PASP+ #</u>	<u>Cell Type</u>	<u>Array Type</u>	<u>Bias</u>	<u>Cells</u>
0	Silicon 2x4 cm	Planar	No	20
1	Silicon 2x4 cm	Planar	Yes	20
2	Silicon 2x4 cm	Planar	Yes	60
3	Silicon 8x8 cm	Space Station	Yes	4
5	Silicon 2.6x5 cm	APSA	Yes	12
4	GaAs 4x4 cm	Planar	Yes	20
6	GaAs 4x4 cm	Planar	Yes	12
8	GaAs 4x4 cm WT	Planar	Yes	4
11	GaAs 4x4 cm	Planar	Yes	8
9	Amorphous Si 4x4 cm	Planar	No	1
10	InP 2x2 cm	Planar	No	10
7	AlGaAs/GaAs	Planar	No	20
12	GaAs/CIS 2x2 cm	Planar	No	9
13	GaAs/CIS 2x4 cm	Planar	No	3
14	GaAs concentrator	Cassegrainian	Yes	8
15	GaAs/GaSb	Mini-Dome Concentrator	Yes	12

analyzer and an electron emitter are used in the plasma interaction portions of the experiment

The last major portion of the PASP Plus experiment is the controller, which measures all the I-V curves, controls the bias voltages to the arrays, and in general runs the experiment. All data from PASP Plus except for the dosimeter data is collected by the controller. The dosimeter operates with its own controller.

### EARLY RESULTS

Three hours after the APEX spacecraft was launched, the PASP Plus experiment was turned on. The experiment is set up such that one module has an IV curve taken each 30 seconds. Hence after eight minutes, all 16 separate modules have been sampled. The process then repeats itself. If the controller were left on for an entire year, we would have 1.05 million IV curves. The data collection process is somewhat complex and delayed in time by a few months. However to monitor early PASP Plus performance and to obtain data for this paper, the experiment was monitored at the Air Force Base which controls technical spacecraft (Onizuka AFB in Sunnyvale CA). Therefore we have available continuous data from launch (Aug. 3, 1994) to Sep. 4; scattered data from Sep. 4 to Oct. 9; and complete data from Oct. 9 to Oct. 25. This gives us data during times when the spacecraft is going through eclipses (Aug. 18 to Oct. 5) and during non-eclipse times caused by the high inclination orbit.

### Albedo Effects

The first thing we noticed about the individual module performances was the variation in Isc with time. This was

much more than could be explained by temperature effects. Figure 1 shows the Isc for five different modules for the first five hours of data. (The currents for some of the modules were multiplied by a constant so all five would fit on the same graph.) Note that the currents for the four planar modules show a variation with time with a period equal to the PASP Plus orbit period of 115 minutes. The variation is about 6% maximum to minimum. The high current occurs at perigee and the lower current at apogee. The one module with a constant Isc is the Mini-dome concentrator module. The concentrator "sees" incoming light only within a few degrees of normal while the planar modules view an entire hemisphere. Hence there is no albedo effect on the concentrator module. The 6% spread in Isc (and Pmax) leads to some difficulty in analyzing the PASP Plus data. We are in the process of changing the data gathering software to tag those IV curves taken when there is no view of the earth by the PASP Plus modules. For this paper we will use daily averages which will be discussed later.

### Experiment Module Heating

During the first 80 days of PASP Plus, we noticed a gentle increase in the operating temperatures of the modules. This is best seen in Figure 2 which shows the temperature of the silicon panel with cell modules 0, 1, and 2. About two and a half orbits of temperature vs. time are shown for three different dates. High temperatures are at perigee and low temperatures are at apogee. The spacecraft is in continuous sunlight (no eclipse) for all three dates. Aug. 3 is right after launch; Aug. 15 is twelve days later and still without an eclipse; and Oct. 22 is 17 days after the most recent eclipse. There is a definite trend of increasing temperature with time in orbit. One possible cause of the

temperature rise is a change in the properties of the white paint (Z-93) on the APEX panels. The temperatures will continue to be monitored over the next several months.

#### PASP Plus Module Performance Data

As mentioned earlier each individual module is measured once every eight minutes. However to keep the amount of analyzed data to a reasonable level, we only used IV data sampled every two hours. (An exception to this was the first five hours of flight where we used data every eight minutes to obtain an initial level.) We then corrected the  $I_{sc}$  and  $P_{max}$  values to AM0 by using the earth-sun distance. This correction varies from zero to plus or minus 3.3% over a full year. We then made a second correction for temperature using coefficients obtained as PASP Plus came out of an eclipse. (The controller has the option of taking all sixteen IV curves within one minute upon ground command. By repeating this every three minutes, we obtained data to calculate temperature coefficients.) Each individual module was corrected to its average measured temperature taken during IV data collection

After the temperature correction we still have a spread in data due to the albedo from the earth. For this paper, we took all data for any one day and averaged it to a daily value of  $I_{sc}$ ,  $V_{oc}$ , and  $P_{max}$ . The following plots then show the averaged values normalized to the first day (Aug. 3). For future data analysis, we are changing the data software to tag those IV curves where the PASP Plus experiment has no view of the Earth.

The PASP Plus experiment has a highly variable radiation flux due to the elliptical nature of the orbit. The flux changes over a factor of ten as the latitude of the apogee moves around the orbit. Preliminary calculations [1] indicate the 1 MeV equivalent fluence for silicon cells with 6 mil covers and 60 mil backs is  $7.95E13$  electrons/cm squared after 30 days, and  $1.72E14$  after 90 days. Future work will compare the PASP Plus dosimeter with calculated radiation environments.

#### Mini-Dome Concentrator

Figure 3 shows the normalized values of  $I_{sc}$ ,  $V_{oc}$ , and  $P_{max}$  for the mini-dome refractive concentrator module. Boeing made this twelve element module with GaAs/GaSb multi-junction cells and ENTECH lenses. After 83 days in orbit there is about a 1% drop in  $I_{sc}$  and a 2% drop in  $P_{max}$ . These are the smallest degradations of any of the 16 PASP Plus modules. At the present time, we have not determined if the small degradation is due to radiation, contamination, or statistical variations.

A secondary purpose of the PASP Plus experiment is to determine the off-pointing performance of concentrator arrays in space. However the APEX spacecraft is maintaining its orientation towards the sun so well that we

do not have enough data as yet to make such an analysis. When we look at all the data rather than just the every two hour sampling, we probably will be able to look at some off-pointing.

#### Comparison of InP, Si, and GaAs

Figure 4 shows  $P_{max}$  for three different cell types, InP, silicon, and GaAs. They all have 6 mil covers and very thick back shielding. In a proton dominated orbit, the InP is showing much less degradation than either the GaAs or silicon. If this trend continues, it will further enhance the potential use of InP cells in high radiation applications.

The slight rise after 72 days in orbit is not explained but most likely due to statistical variation due to the averaging of the albedo effects. The operational temperatures of 40C to 60C are probably too low to have any annealing effects.

#### Flexible Array Modules

Two of the PASP Plus modules are made using the flexible array design. There are the Space Station module and an APSA module. Both of these modules are mounted over cutouts in the deployed panel. Hence their rear surfaces are open to the space environment as they would be in an actual array. Figure 5 shows the  $I_{sc}$ ,  $V_{oc}$ , and  $P_{max}$  of the Space Station module. The  $P_{max}$  has dropped to about 88% of its original value. Although this drop may seem somewhat large, several items must be noted. The Space Station module is made using thick (8 mil) silicon cells with essentially no shielding on the back. PASP Plus is in a proton dominated orbit while the Space Station array is **designed to operate in a LEO orbit** with a much smaller proton environment. Hence the PASP Plus radiation degradation results for this particular module do not directly relate to projected performance in its proper orbit.

#### Array Interactions

The main objective of the PASP Plus experiment is to determine the interactions with the space environment of arrays biased to plus or minus 500 volts. At the present time the data analysis of this area is just beginning and there is little to report in this paper. It should be noted that at bias voltages up to 500 volts, there is no leakage current from either the Cassegrainian or Mini-dome concentrator modules. This is as expected based on ground tests.

#### Concluding Remarks

The PASP Plus experiment on board the APEX satellite is operating successfully. Albedo effects are on the order of 6% and effect the data. The modules are showing a slow warming trend. We are seeing some radiation damage

even after only 83 days in the proton dominated orbit. InP cells compare favorably with Si and GaAs cells. There appears to be little or no contamination on the PASP Plus modules.

## References

[1] D. Marvin, private communication, Aerospace corp., Phillips Lab, Albuquerque NM.

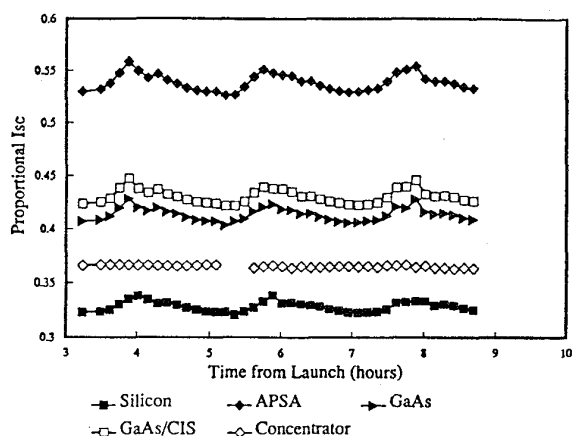


Fig. 1. Effect of Earth albedo on short-circuit current.

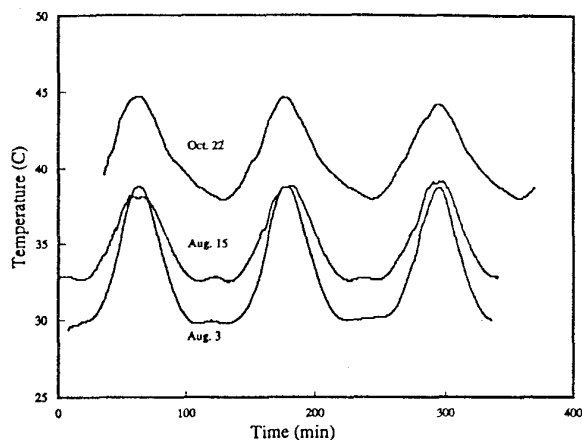


Fig. 2. Temperature of silicon modules 0, 1, and 2.

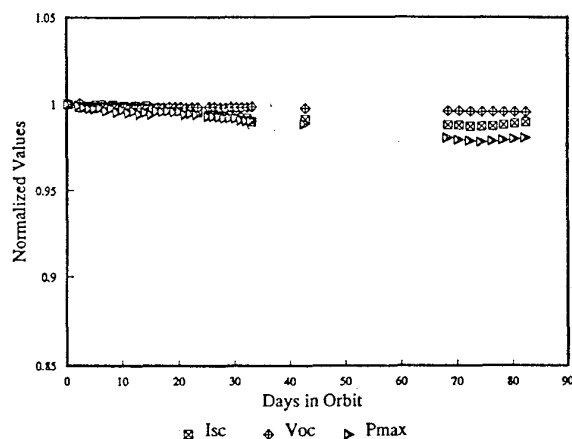


Fig. 3 Performance of Mini-dome concentrator (48.3C).

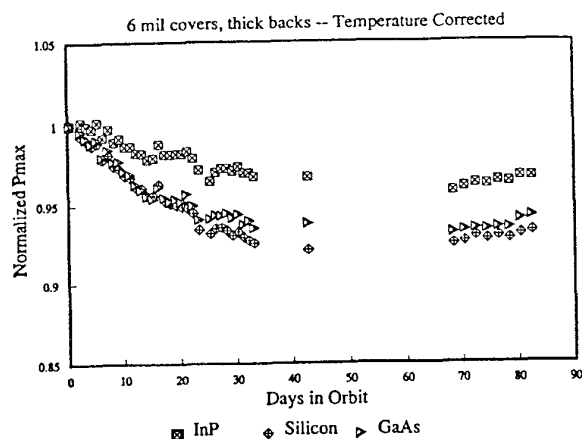


Fig. 4. Performance of three different cell types, InP (44.6C), GaAs (54.3C), and silicon (32.9C).

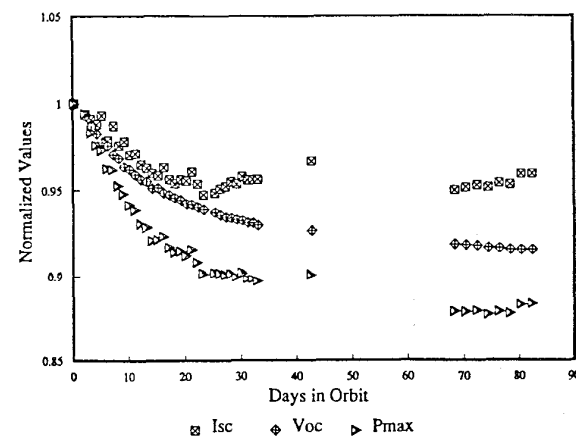


Fig. 5 Performance of Space Station module (50.7C).