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PASP PLUS: AN EXPERIMENT TO MEASURE SPACE-ENVIRONMENT EFFECTS ON PHOTOVOLTAIC POWER SUBSYSTEMS

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Abstract: The Photovoltaic Array Space Power Plus Diagnostics experiment (PASP Plus, for short) has been accepted as part of the APEX mission payload aboard a Pegastar satellite to be orbited by a Pegasus launch vehicle in late 1992. The mission's elliptical orbit (190 nmi perigee, 1000 nmi apogee, nominal) will allow us to investigate both space plasma and space radiation effects. PASP Plus will have eleven types of solar arrays and a full complement of environmental and interactions diagnostic sensors. Measurements of space-plasma interactions on the various solar arrays will be made at large negative voltages (to investigate arcing parameters) and at large positive voltages (to investigate leakage currents) by biasing the arrays to various levels up to -500 and +500 Volts. The long-term deterioration in solar array performance caused by exposure to space radiation will also be investigated; radiation dosage will be measured by an electron/proton dosimeter included in the environmental sensor complement. Experimental results from PASP Plus will help establish cause-and-effect relationships and lead to improved design guidelines and test standards for new-technology solar arrays.

INTRODUCTION

Future space system operations will require higher powered photovoltaic subsystems to carry out more ambitious missions. Standard planar-array power sources using small *silicon* solar cells in low-voltage configurations (not much above 28 Volts) could be superseded by larger cells (to reduce array costs), different materials (with higher efficiencies), and higher voltage levels (to minimize cable losses or reduce cable weight). However, before any space-system designers will commit to using new technologies or configurations, systematic investigations of the effects of the space environment on the performance of advanced solar arrays must be made. The Photovoltaic Array Space Power Plus Diagnostics (PASP Plus) experiment provides a means for carrying out the needed investigations.

Originally, as described in a SOAR '89 paper (Ref. 1), the objectives of the PASP Plus experiment were limited to the investigation of the effects of space-plasma interactions on high-voltage solar array operations at low altitudes. However, in early 1990 the Space Test Program of Space Systems Division (SSD) offered the PASP Plus experiment a flight on a Pegastar satellite boosted into orbit by a Pegasus launch vehicle. PASP Plus became part of the APEX (Advanced Photovoltaic and Electronics Experiments) mission set up to fly PASP Plus and two small "radiation effects on electronics" experiments, CRUX/CREDO and FERRO. A Spaceflight Plan for APEX was approved by Hq USAF on 3 October 1990. Because of the enhanced opportunity provided by APEX—an elliptical [350 km by 1850 km] near-polar [i = 70°] orbit with a one to three year lifetime, it was decided to broaden the scope of PASP Plus to include the investigation of the effects of space radiation dose on long-term solar array performance. We also added diagnostic instruments appropriate to PASP Plus's new scope and mission profile. This paper is intended to describe the features of the new PASP Plus experiment.

PASP PLUS OBJECTIVES

The objectives of the expanded-scope PASP Plus experiment are:

a. To measure the plasma "leakage" current for many different arrays subjected to positive biasing levels up to +500 V, simulating array operation at high positive voltages.

b. To measure the arcing parameters for many different arrays subjected to negative biasing levels up to -500 V, simulating array operation at high negative voltages.

c. To measure the long-term deterioration in the electrical performance of many different types of solar arrays exposed to space radiation.

d. To provide an opportunity to test various new photovoltaic technologies (new materials and/or designs) in the real space environment.

e. To establish cause-and-effect relationships between array performance and environmental conditions.

PASP PLUS INSTRUMENTATION

The experiment consists of four kinds of equipment:

a. a set of test arrays, several of which are divided into biased and unbiased segments.

b. experiment-control instrumentation capable of creating *array* or *spacecraft* conditions under which measurable environmental interactions will occur.

c. interactions-measuring instrumentation that will quantify what happens when the ambient or created conditions impact the performance of the test arrays.

d. diagnostic sensors to measure the ambient space-environment conditions affecting array performance.

Solar Array Complement To maximize the applicability of the experiment, a variety of conventional and advanced-concept solar arrays were included in the PASP Plus array complement. As shown in Table I, eleven different solar arrays will be investigated on PASP Plus. Other than array #1 (which serves as a standard), the decisions on array selection made for PASP Plus were based on the array's potential utilization on future DoD or NASA spacecraft missions.

TABLE I. PASP PLUS SOLAR ARRAYS

ARRAY	CELL TYPE	DESCRIPTION	SIZE (in x in)	BIASED SEGMENTS
1	Si	2cm x 2cm, BSF	10 x 20	2 of 3
2	Si	8cm x 8cm, 8-mil WTC (for Space Station)	8 x 9.5	1 of 1
3	GaAs/Ge	4cm x 4cm, 3.5-mil	10 x 20	2 of 3
4	GaAs/Ge	4cm x 4cm, 7-mil	5 x 10	1 of 1
5	GaAs/Ge	4cm x 4cm, 7-mil, WTC	5 x 10	1 of 1
6	GaAs/Ge	4cm x 4cm, 3.5-mil,w/ICG	4 x 4.5	1 of 1
7	InP	2cm x 2cm	4 x 5.5	0 of 1
8	AlGaAs/GaAs	2cm x 2cm, monolithic MBG	3 x 6	0 of 1
9	$GaAs/CuInSe_2$	2cm x 2cm, mech-aligned MBG	6 x 6	0 of 2
10	GaAs	SLATS Concentrator	11 x 13.5	1 of 1
11	GaAs/GaSb	Mini-Dome Fresnel Lens Concentrator, MBG	4.5 x 7.5	1 of 1

BSF = Back-Surface Field
WTC = Wrap-Through Contact
ICG = Integral Coverglass
MBG = Multi-Bandgap

The second solar array in Table I consists of 8 cm × 8 cm silicon cells with wrap-through contacts; these cells are baselined to fly on NASA's Space Station Freedom. The next four arrays (#3 through 6) use the same size GaAs on Ge cells, but differ in electrical or mechanical configuration. The next three arrays (#7 through 9) utilize small (2 cm × 2 cm) new-material cells; the InP cells have high radiation resistance, while the AlGaAs/GaAs and $GaAs/CuInSe_2$ cells are dual junction types having high conversion efficiencies. The final two arrays (#10 and 11) are concentrator designs. SLATS, using venetian-blind like metal mirrors, focuses light onto linear strings of GaAs solar cells mounted on the backs of adjacent mirrors (see Figure 1). This design enhances its survivability against man-made threats such as high-powered lasers. The second concentrator (array #11) is the mini-dome fresnel-lens GaAs/GaSb design which has demonstrated extremely high conversion efficiencies through the use of its dual-junction mechanically stacked GaAs and GaSb solar cells and its prismatic coverglass. See Figure 2.

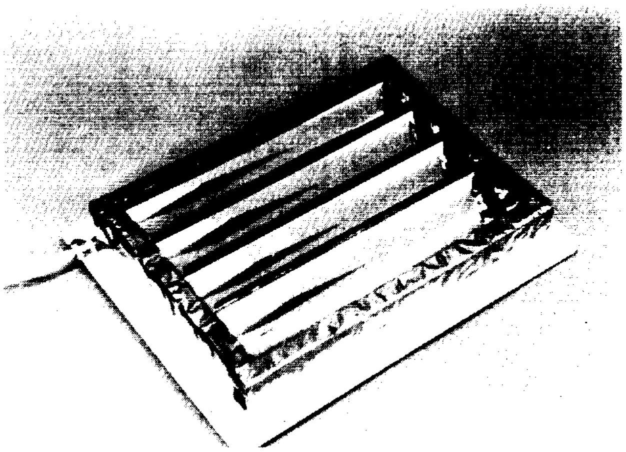

Figure 1. SLATS Concentrator Array.

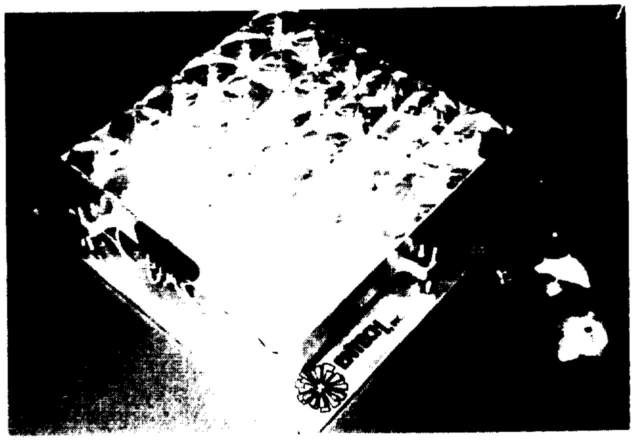

Figure 2. Mini-Dome Fresnel-Lens Dual-Junction GaAs/GaSb Concentrator Array.

The last column of Table I indicates which arrays will be subjected to high-voltage biasing. In some cases, biasing will be applied to only part of an array and not the remaining part. We can thereby investigate long-term radiation damage to array performance for portions (individual "modules") of the array subjected to and not subjected to biasing. High-voltage biasing, besides causing deterioration itself (detectable at the time of the bias measurements), can also increase the susceptibility of the biased array or module to later (or longer-term) contamination or radiation damage. Instrumentation included in PASP Plus will help us to distinguish between different damage effects.

Experiment-Control Instrumentation To simulate a large space-power subsystem operating at high positive or negative voltage levels, PASP Plus instrumentation must provide a multi-step high voltage generator to bias our relatively small test arrays. Some of the eleven arrays will be partitioned into two or three sections, resulting in 16 electrically isolated, individual modules. Ten of the 16 segments will be biased. The high-voltage biasing sequences for each module (one at a time) will consist of four all-positive or all-negative steps (each about 20 sec long) of successively greater voltage levels. The range of bias values (positive or negative) is 50 to 500 Volts. The minimum difference between step values is 10 volts.

In order that positive biasing of a test array can properly simulate actual high-positive-voltage operation of a large array, PASP Plus must provide an additional experiment-control device: an electron emitter. Pegastar's power arrays operate at about +32 Volts with respect to spacecraft ground; however, with respect to the space plasma, the positive side of Pegastar's power arrays will be only a few Volts positive while its frame will float to a potential of around -25 V. Because of the lower mobility of ions, greater highly-negative vehicle surface area is needed to collect the required incoming ion current to balance the incoming current of highly mobile electrons. When (during biasing) a high positive voltage is applied to a small PASP Plus test array, the vehicle frame will be driven further negative, possibly to as much as several hundred Volts depending on array size, bias level, and vehicle metallic surface area (for ion collection). Besides the frame being at a large negative potential, negative-potential contours around the vehicle would limit the accessibility of the plasma's thermal electrons to our positively biased test array except for those directly over it. The incoming-electron acceptance cone for the biased array would be narrowed by the spacecraft's negative-potential contours, artificially lessening the electron current that would otherwise be collected. The plasma "leakage" current measured in our experiment would not be properly representative of the current for a large array operating at a high positive voltage level.

If PASP Plus's electron emitter can produce enough outgoing electrons so as to better balance incoming electrons, Pegastar's frame potential will not swing so highly negative. The ensuing negative-potential contours would not be so obtrusive so as to significantly obstruct the plasma "leakage" electrons on their way to our positively biased test array. Therefore, the PASP Plus measurement of leakage current will be more representative (proportionally) of what will happen to large arrays operating at high positive voltage levels.

Interactions-Measuring Instrumentation To measure the characteristics of the arc pulses produced by negative biasing of the experiment's test arrays or array modules, PASP Plus makes use of several electrical transient sensors (ETSs) connected to a Transient Pulse Monitor (TPM). Several E-field sensors at various locations on the surfaces to which the test arrays are mounted are used to measure the parameters of radiated emission from arcs on the test arrays. A current-loop ETS is used to measure arc parameters of emission conducted down the high-voltage power line from the arcing arrays. The pulse characteristics obtained are amplitude, derivative, integral, and number of pulses per time interval.

To measure the plasma "leakage" current produced by positive biasing of the test arrays or array modules, PASP Plus uses an electrometer covering the range of roughly 1 μA to 20 mA. This range should be sufficient to measure from the lowest current of interest up to the largest expected leakage current (i.e., where "snapover" has occurred for our largest array module at the highest bias level [+500 V] and highest plasma density [1×10^6 cm^{-3}] in the nominal APEX mission orbit).

To determine how various environmental interactions affect the arrays, the electrical performance of each of the 16 array modules, whether biased or not, is monitored by taking numerous current-voltage measurements (I-V curves) of the module over the course of mission lifetime. The I-V curves for each module are obtained from the rapid application of dynamically varying resistance values between $R = \infty$ to $R = 0$ (corresponding to open-circuit voltage V_{OC} and short-circuit current I_{SC}) to the sun-illuminated array module. Thirty-two digitized measurements of current and voltage are recorded (all within about two sec) for each array module.

Diagnostic Sensors To allow us to investigate fully the linkage between environmental interactions and their performance deteriorating effects, a suite of relevant environmental diagnostics sensors is provided as part of the PASP Plus experiment. These sensors include:

a. a Langmuir probe (LP) to measure low-energy plasma density and temperature.

b. an electrostatic analyzer (ESA) to measure 10 eV - 30 keV electron and ion spectra and detect the passage of Pegastar through an auroral region.

c. an electron/proton radiation dosimeter to measure the high-energy charged particle radiation that damages solar cells, causing the deterioration in array performance measured by the I-V curves. The design of one of the four detection domes of this dosimeter has been specially modified to facilitate the measurement of the 5-10 MeV proton radiation that is an important source of solar-cell degradation (Ref. 2). See Figure 3.

d. contamination monitors to measure the amount of effluents deposited on array surfaces (leading to decreased sunlight collection and array output power). Contamination sensors will include quartz crystal microbalances (QCMs) and calorimeters. The information from these sensors will allow us to differentiate array performance degradation caused by radiation dosage from that caused by contamination.

e. a PASP Plus sun incidence-angle sensor to assure us of the alignment of the arrays to the incident solar energy; this alignment is critically important for the concentrator arrays. To meet PASP Plus requirements the Pegastar satellite, using its own sun incidence-angle sensor to provide inputs to the vehicle's magnetic-torque attitude control subsystem, will point its sun-viewing upper-deck honeycomb panel (on which both of our concentrator arrays will be mounted) to within ±0.5° of the sun.

Instrument Layout on Pegastar The various photovoltaic test arrays, the Pegastar and PASP-Plus sun incidence-angle sensors, and the PASP Plus interactions-measuring and diagnostic sensor "heads" separated from their control boxes will be mounted on the hexagon-shaped upper-deck payload shelf and one deployable payload panel, as shown in Figure 4. The other three deployable panels of the satellite will be used for mounting the Pegastar solar arrays used to provide vehicle (and experiment) power. The PASP Plus electronics boxes and those of the other two small experiments (FERRO and CRUX/CREDO) also selected for flight on the APEX mission are mounted on the lower-deck avionics payload panel.

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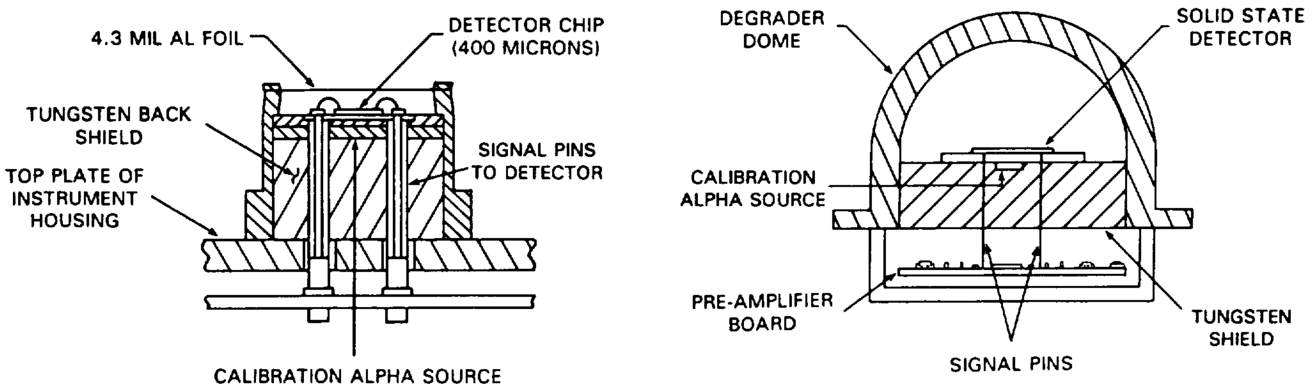

Figure 3. Domes of PASP Plus Dosimeter. Customary design for higher-energy particles is shown at right. Modified design to measure 5-10 MeV protons is shown at left.

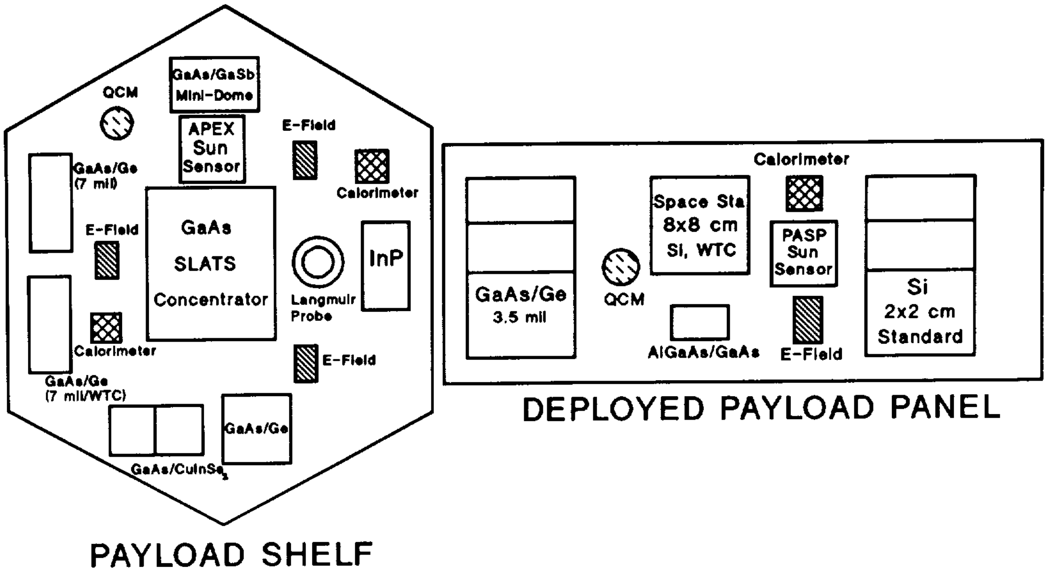

Figure 4. PASP Plus Arrays and Instruments on Pegastar's Upper-Deck Payload Shelf and Deployed Payload Panel.

PEGASTAR/APEX OPERATIONS

The Pegastar satellite characteristics and the expected PASP Plus flight-profile parameters are given in Table II below.

TABLE II. NOMINAL SATELLITE AND FLIGHT-PROFILE PARAMETERS

a. Pegastar Satellite Parameters

SATELLITE BUS: 44 inch diam hexagon ≈60 inch height

WEIGHT TO ORBIT: ≈820 lb

STABILIZATION: three-axis stabilized sun-pointing to ± 0.5°

ELECTRICAL POWER: 320 - 380 Watts

b. Expected PASP Plus Flight Profile

LAUNCH: Pegasus, Western Test Range, Late 1992

APOGEE: 1850 km (2000 km preferable)

PERIGEE: 350 km **INCLINATION:** 70°

LIFETIME: One to Three Years

The high-voltage plasma interactions objectives of PASP Plus will be achieved while Pegastar is near perigee passing through the ionospheric F-region and/or through auroral regions. The radiation degradation objectives of PASP Plus will be achieved while the vehicle is near apogee in the *equatorial* regions (Pegastar's line of apsides will rotate about 1.5° a day in its orbital plane).

EXPERIMENT STATUS

The functional baseline of the upgraded PASP Plus experiment was established at a meeting of scientists from Phillips Laboratory, Wright Laboratory, Aerospace Corp., Naval Research Laboratory, and NASA Lewis Research Center held at Wright-Patterson AFB in October, 1990. All the basic instruments of the experiment have been designed. Some have been breadboarded; in a few instances, flight-unit construction has begun. In some cases (e.g., the Transient Pulse Monitor and our sun incidence-angle sensor), we have the flight units on hand. Several of the test arrays are on hand; the rest will be delivered by mid-July 1991. Subsequently, they will be tested and mounted on the upper-deck payload shelf and deployable payload panel at the NASA Lewis Research Center. The APEX-mission contractor has begun its design work on the Pegastar satellite; a Preliminary Design Review (PDR) was held in March 1991.

EXPECTED RESULTS

Many investigations of high-voltage interactions have been carried out by the NASA Lewis Research Center, including laboratory and flight-test work (Ref. 3, 4, 5). Various explanations of the causes of arcing from high negative voltage operation have been offered (Ref. 6, 7). The arcing rate (beyond a threshold voltage) appears to be roughly proportional to plasma density, but has a large power-law dependence on voltage level (Ref. 8). For high positive voltage operation, available array power is reduced by electron currents flowing between the array and the surrounding space plasma (Ref. 9). This "leakage" current will depend on the operating voltage, plasma density, exposure of the interconnects, and the geometry of the sheath surrounding the array; various computer simulations have been used to investigate the problem (Ref. 10). Data from the PASP Plus experiment should be very helpful in determining the relationships between various parameters.

APEX's 350 km nominal perigee will provide the greatest electron density (in the order of 10^5 to 10^6 cm^{-3}) at around perigee and allow investigation of space-plasma induced effects over the largest useful range of electron density variations. After several months of flight, a large data base on arc-pulse parameters (negative biasing) and leakage current parameters (positive biasing) as functions of bias levels and types of array will be collected over the mission-achievable ranges of the controlling parameters: plasma density (perigee through apogee), auroral passage, and velocity-vector orientation. This large data base will permit examination of the correlations between all the linkable variables and lead to the establishment of cause-and-effect relationships for high-voltage interactions effects. These relationships will then be available for analytic study, modeling, and code development.

APEX's nominal 70° inclination and 1850 km apogee will allow passage of Pegastar through the lower portion of the inner radiation belt only when apogee occurs near equatorial geomagnetic latitudes. The line of apsides (the perigee-apogee line in the orbital plane) continuously rotates about 1.5° per day throughout the mission. On a long-term basis, Pegastar's apogee will pass through the radiation belt at equatorial latitudes about one-quarter of the time. A higher apogee (up to 2000 or 2200 km) would increase the dosage (or lessen the time to reach a specific dose accumulation), but there are limitations in the Pegasus-Pegastar boosting capability. With some modest improvement in apogee, we expect to obtain sufficient radiation dosage in one year to see array performance degradation in Si cells in the order of 8 to 12 percent. For the more radiation-hard materials (GaAs and especially InP) and the concentrators, the degradation may be only a few percent. Information from the contamination sensors (QCMs and calorimeters) will be used to separate contamination effects from radiation effects. The radiation-induced performance degradation data for all the PASP Plus test arrays will be correlated with the radiation dosage data from our dosimeter to establish cause-and-effect relationships.

Within the first year after a successful PASP Plus flight, correlated PASP Plus data would be made available to the space-power communities in DoD and NASA. Phillips Laboratory, together with Wright Laboratory and NASA's Lewis Research Center, will conduct a series of workshops which will be targeted to major topics of interest such as high-voltage operation and EMI-generation effects. As data on array performance degradation from radiation effects becomes available (1-3 years, depending on flight apogee), additional workshops will be held on radiation effects on new cell technologies and concentrator arrays. Results from these workshops will be directed towards upgrading space-power design guidelines and test standards.

CONCLUSIONS

Because of the APEX-mission orbit, the upgraded PASP Plus experiment now has the opportunity to investigate both space plasma effects on high-voltage operation and long-term array performance degradation due to space radiation. PASP Plus data on environmental interactions will be given over to the space-system development community so it can capitalize on our results and begin utilizing new-technology photovoltaic arrays on future space systems.

ACKNOWLEDGEMENTS

The support of other Air Force and NASA organizations in the development and future flight of the PASP Plus experiment is gratefully acknowledged. SSD's Space Test Program provides direction and funding of the APEX mission utilizing the Pegastar satellite. Wright Laboratory specified and made arrangements to obtain the PASP Plus test arrays. NASA Lewis Research Center will mount the test arrays on the payload panels and conduct/support testing of the arrays throughout experiment integration.

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