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Space Environment Testing of Photovoltaic Array Systems

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Introduction

To successfully operate a photovoltaic (PV) array system in space requires planning and testing to account for the effects of the space environment. It is critical to understand space environment interactions not only on the PV components, but also the array substrate materials, wiring harnesses, connectors, and protection circuitry.

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Space Environments

The space environment varies dramatically across our solar system. The following environments represent a wide cross-section in terms of the environment characteristics; however they constitute the most popular environments with respect to qualification testing needs and number of spacecraft deployed to those regions of space.

- Geosynchronous Earth Orbit (GEO)
- Low Earth Orbit (LEO)
- Solar Wind Environments

GEO Environment

The most common orbit for communication satellites, some of the key features include:

- A low density plasma environment with streaming electrons in the 1 keV to 30 keV range
- Long thermal cycle times
- Solar intensity of one sun (AM0)
- High energy radiation events – solar storm events

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LEO Environment

Commonly occupied by Earth-observing satellites, manned missions, CubeSats, and NanoSats, LEO is characterized by:

- High density Oxygen plasma with up to 10^6 particles/cm^3
- 90 minute thermal cycle times
- Solar intensity of one sun (AM0)
- Neutral atomic Oxygen

Solar Wind Environment

This is a broad environment category that refers to regions well outside of Earth orbit, such as interplanetary environments and lunar orbits. The solar wind is a continuous stream of charged particles generated by the Sun. The solar wind environments can be generally characterized as:

- Low density plasma with only 6-10 particles/cm^3
- Minimal thermal cycles
- Solar intensities ranging from a fraction of one sun for outer planets, to several hundred suns for missions inside of Mercury's orbit

Test Environments

MSFC space environment test capabilities are far ranging. They cover from the solar corona to the outer planets, with a particular focus on Earth orbit environments. Led by experienced personnel in the Environmental Effects Branch, test programs are tailored to the customer's needs, and can range from a fully integrated test program that uses all of the test systems described below, to focused tests that employ a single capability.

- Ultraviolet (UV) Exposure
- Charged Particle Radiation (Electron and Proton)
- Thermal Cycling
- Plasma and Beam Environments

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UV Exposure

MSFC's Environmental Effects Branch has developed an Ultraviolet (UV) Radiation capability to cover both materials and PV array tests. Five different UV test facilities comprise the capability, and provide R&D engineers with a means to screen new materials, or for systems engineers to qualify solar arrays in compliance with the AIAA standard.

Fig. 1. Solar cell samples undergoing combined ultraviolet radiation exposure tests (VUV and NUV).

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UV Exposure

As indicated in Table 1, many of the UV sources are capable of delivering intensities greater than 1 sun at the sample location. Operation at higher intensity levels can significantly reduce the overall sample test time – which reduces costs and increase schedule margin.

TABLE I
UV SOURCES OPERATED BY MSFC'S ENVIRONMENTAL EFFECTS BRANCH

Source	Wavelength Range	Features
Spectrolab X-25	250 – 3000 nm	Full solar spectrum from NUV through short wavelength IR. Filters included to better match the AM0 spectrum
Deuterium Lamp	115 – 200 nm	Vacuum Ultraviolet (VUV); Capable of 2 – 4 equivalent VUV suns intensity
Enhanced NUV	230 – 580 nm	Provides strong NUV radiation without heating the sample (IR wavelengths are filtered-out). Intensities as high as 4 – 5 equivalent NUV suns are achievable.
HISET	250 – 3000 nm	Capable of extremely high intensities: 500 equivalent suns over a 10 cm spot. Configurable to produce 1 sun intensity over a large (60 cm diameter) spot size. Full solar spectrum coverage.

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Charged Particle Radiation

It is well known that charged particle radiation degrades the performance of photovoltaic devices. For spacecraft operating in environments subjected to high energy electron and proton radiation, the degradation of PV cells translates to reduced power levels over the mission lifetime.

Fig. 2. The High Energy Charged Particle Radiation facility. The electron accelerator is visible on the left side (blue chamber) and the sample chamber is visible on the right side (silver chamber). The proton accelerator is not visible in this picture.

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Charged Particle Radiation

The Environmental Effects Branch operates two linear accelerators to provide high energy charged particle radiation. The accelerators are connected, via vacuum beam lines, to a cylindrical sample chamber with 0.8 m diameter. The accelerators can be operated individually or at the same time. Beam energy and flux levels can be adjusted to meet the customer's requirements, as well as minimize the total test time required to achieve full fluence.

TABLE II
HIGH ENERGY CHARGED PARTICLE RADIATION FACILITY SPECIFICATIONS

Device	Energy Range (MeV)	Flux Range (nA/cm^2)	Maximum Beam Diameter (cm)
Electron Accelerator	0.2 – 2.5	0.03 – 10	40
Proton Accelerator	0.04 – 0.7	1 – 10	40

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Thermal Cycling

Spacecraft in Earth orbit are subjected to temperature extremes ranging from +150 C when fully exposed to the Sun, to -180 C when in eclipse. The continual cycling of temperatures on spacecraft materials and components stresses systems due to thermal expansion and contraction.

Fig. 3. Solar array wire coupons being heated in the V3 thermal cycle chamber. Samples are translated between the heated zone at the bottom of the chamber and the cold zone at the top of the chamber.

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Plasma and Beam Environments

Given the dynamic range of space environments across the solar system, the MSFC Environmental Effects Branch has maintained a full complement of plasma and beam sources that can be deployed in a wide variety of combinations to meet the needs of the most demanding missions.

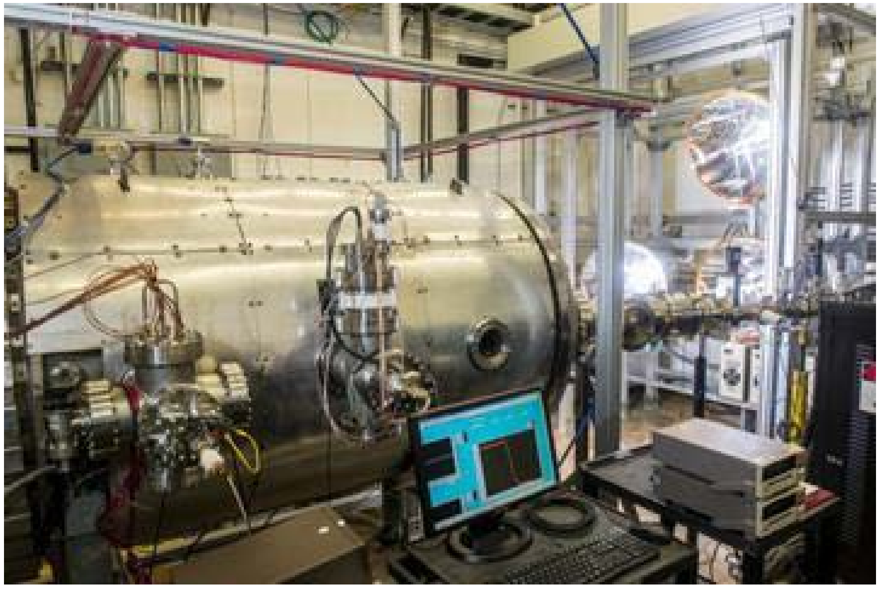

Fig. 4. HISET facility at MSFC. The facility is equipped with both broad beam and narrow beam electron and ion sources, as well as high intensity solar simulator lamps.

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Evaluation Capabilities

In order to quantify the effects of the space environment on a given sample or system, MSFC has developed a number of measurement and evaluation capabilities:

- Electrostatic Discharge (ESD) Screening
- Large Area Pulsed Solar Simulator (LAPSS) PV Power Output
- Optical / Electrical Inspection

ESD Screening

As plasma and charged particle environments exist throughout the solar system, spacecraft charging is ubiquitous. The magnitude and impact of spacecraft charging is dependent on the mission environments and spacecraft design features.

Fig. 5. ESD arc site formation on a 4-cell PV array coupon. The coupon was tested under GEO environment conditions.

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ESD Screening

MSFC’s Environmental Effects Branch has conducted hundreds of ESD screening tests using a broad range test capability first developed in 2002 to evaluate high voltage array designs. The ESD test capability has been continually updated as the technology has changed over time. Having helped to develop an international test standard, the MSFC ESD Test system is capable of performing ESD screening tests compliant with the ISO-11221 standard.

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LAPSS PV Power Output

The MSFC Power System Test Facility provides the capability to illuminate solar cells and panels as large as 1.1 m^2 (12 ft^2). This facility is equipped with a Spectrolab Large Area Pulsed Solar Simulator (LAPSS) that contains its own data acquisition and control system.

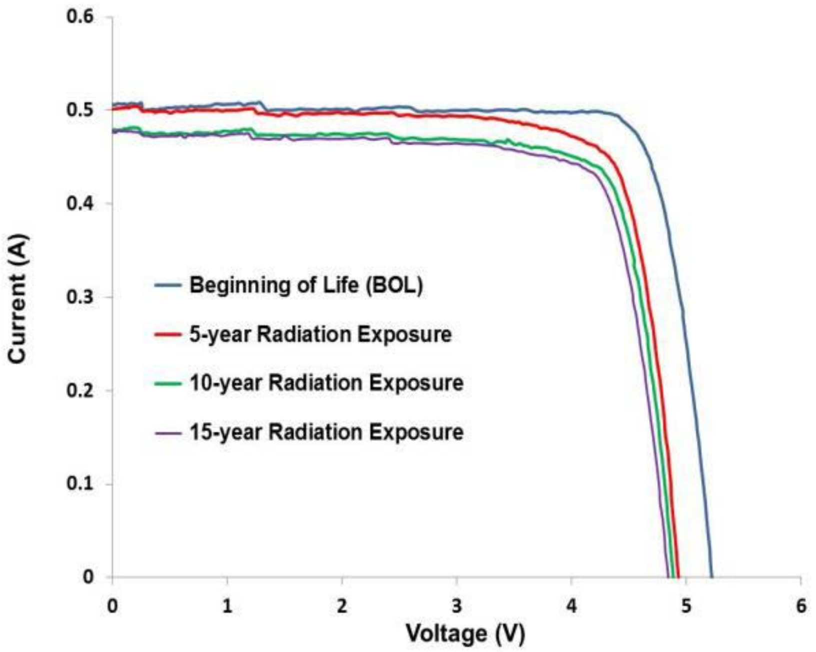

Fig. 6. Current versus Voltage (I-V) curves generated using the LAPSS system at MSFC. The test sample was a 2-cell string that was part of a fully integrated PV array coupon.

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Optical / Electrical Inspection

Given that space environment exposures of PV array coupons and material samples often results in changes in optical properties, the Environmental Effects Branch utilizes the following techniques to document the changes.

- Optical Microscopy – Leica Digital Microscope – up to 30X magnification, annotated high resolution TIFF images
- Hemispherical Emissivity Measurement – AZ Technology Temp 2000 – integrated emissivity
- Solar Absorptance – AZ Technology LPSR 3000 – outputs curve over the range of 250 nm to 2800 nm

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Capability Summary

Comparing Fig. 7 with Fig. 8, one can see the effect of UV radiation on the white wires as they turn to a yellow/brown color. The samples are representative of a sun-facing PV array wiring harness used on a GEO satellite to transfer power from the PV array strings to the satellite power distribution system.

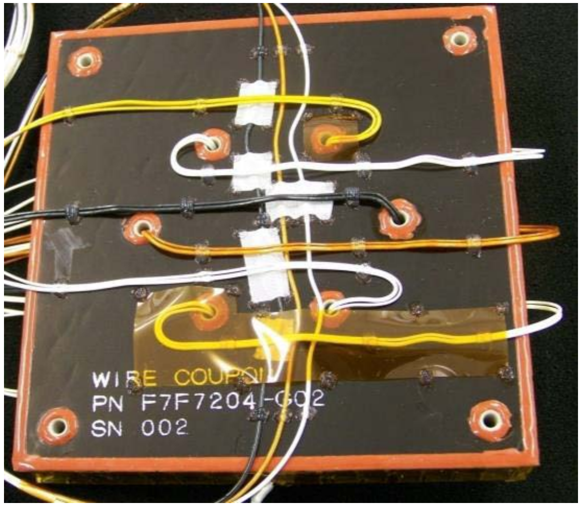

Fig. 7. Solar array wire coupon at Beginning of Life (BOL). The insulated wires are characteristic of those used on the sun-facing side of the array

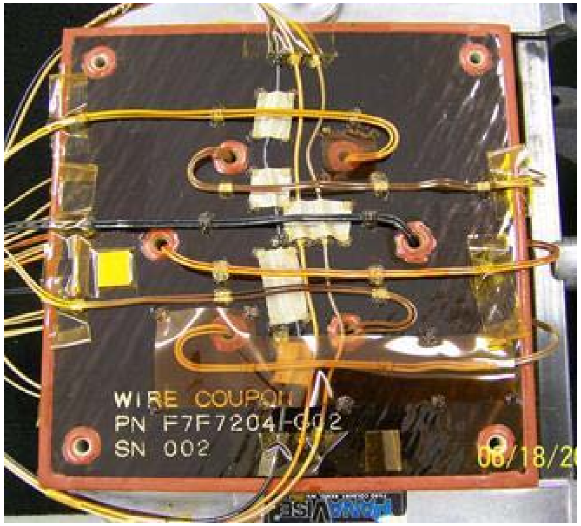

Fig. 8. Solar array wire coupon after 15 year equivalent of on-orbit UV exposure. Notice the darkening of the wire insulation compared to the BOL coupon in Fig. 7.

Capability Summary

The space environment is a demanding environment and can take its toll on PV array system materials and components. On-orbit degradation of these components can, in some cases, jeopardize spacecraft power production. To avoid on-orbit failures, it is best to test PV array systems in realistic space environments recreated in the laboratory.

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