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On-Orbit Study of Primary Arc Effects on Solar Cell Performance

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Outline

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- Background
- Overview of flight experiment
  - Goals and objectives
  - Design and construction
- Schedule
- Summary

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Overview of Plasma Interactions

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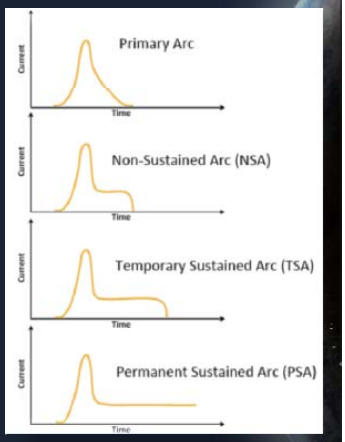
- Spacecraft operating in near earth orbit and subjected to potential detrimental interactions with plasma environment
  - These interactions are widely studied
- The undesirable effects of plasma / charging induced ElectroStatic Discharges (ESD) on solar arrays have also been widely studied
  - Space solar arrays operating in high density plasma (LEO) may be subject to parasitic current loss and discharges
  - Space solar arrays operating in low temperature GEO plasma may be subject to surface charging / flashover induced discharges
  - Space solar arrays on vehicles which employ electric propulsion system may also be subjected to plasma plumes during periods of thruster operation



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An Industry Wide Challenge

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- The complex principle of solar array operation in a plasma environment affects all spacecraft, spacecraft manufacturers, spacecraft operators, and insurers
- This topic is of critical concern to all parties
  - Solar arrays often represents sole power generator for near earth spacecraft
  - Increased need for high reliability / interruption free operation
    - There is continuing desire to push spacecraft design lifetimes beyond >15 yr
    - Higher operating voltages and more technically complex cells exacerbate the challenges
  - Arcing induced failure of solar array can be catastrophic for a mission

Review of 9th SCTC Proceedings (Tsukuba 2005)

ALCATEL	CNES	EADS ASTRIUM	ESA	JAXA	NASA	ONERA	Other*

*Universities (notably KIT), Aerospace, AFRL, BSS, JPL, LMC, SS/L, …

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Motivation / Background

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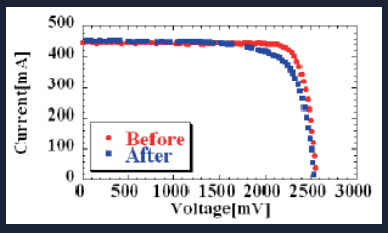
- Ground testing suggests that under appropriate conditions primary arc contains sufficient energy / power to result in damage to solar cell
- Primary arc characteristics
  - 20 A to 40 A via blow off for ~500 nF and -400 V conditions
  - Duration of ~20 μs
  - On order of 1-10 mJ energy



- Limitations of ground testing make “combined effects” or “long term” characterization difficult and / or cumbersome
  - Si and TJ GaAs tested as part of NEDO / ISO testing
  - Flight opportunity enables “long term” testing in *in situ* environment that includes such effects
- The Primary Arcing effects on Solar Cells At LEO (PASCAL) experiment conceived and designed to address these topics

Natural / Artificial Combined Plasma Environment

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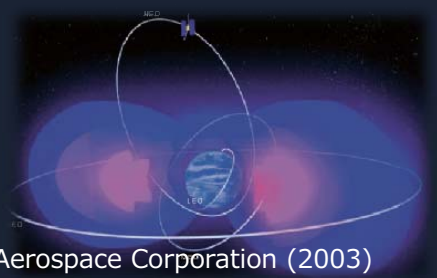
- Natural environment
  - Low Earth Orbit (LEO)
    - Plasma densities of 10^5-10^6 cm^{-3}
    - Electron energies of <1eV
  - Geosynchronous Earth Orbit (GEO)
    - Plasma densities of 10^1-10^2 cm^{-3}
    - Electron energies of 1-100 keV
    - Tenuous with large diurnal variations



Aerospace Corporation (2003)

- Spacecraft generated (artificial)
  - Primary source is propulsion system
  - Hall Current Thrusters (HCT)
    - n_e » 10^6-10^9 cm^{-3} / T_e » 10-100 eV (and more)
  - Arcjet Thrusters (AJT)
    - n_e » 10^5-10^6 cm^{-3} / T_e » 0.1-1.0 eV
  - Ion Thrusters including Xenon Ion Propulsion Systems (XIPS)
    - n_e » 10^6-10^9 cm^{-3} / T_e » 10-100 eV
- During SK maneuvers a GEO spacecraft can be temporarily subjected to LEO type plasma conditions

Likar, et al (2006)

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On-Orbit Observations

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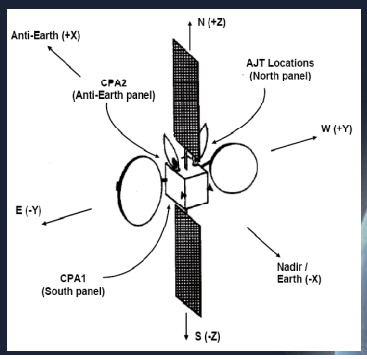
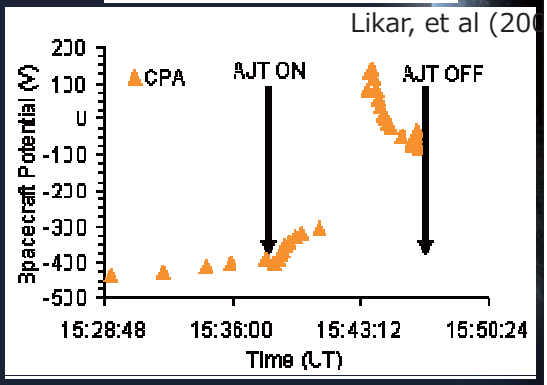
Likar, et al (2009)

- Charge Plate Assembly (CPA) measures the potential difference between a surface sample and the spacecraft frame
  - More than 6 instruments on-orbit (GEO) on board numerous LM built commercial telecommunications spacecraft
  - Previously correlated with LANL MPA instruments
- Charging plate on spacecraft exterior exposed directly to space environment
  - Associated electronics inside the spacecraft
- On-orbit observations suggest that arcjet firing acts to neutralize spacecraft
  - During such process vehicle is negatively charged (biased) during plume environment



Likar, et al (200



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Biased Solar Array in Arcjet Environment

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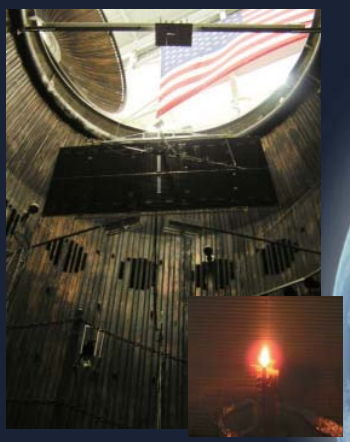

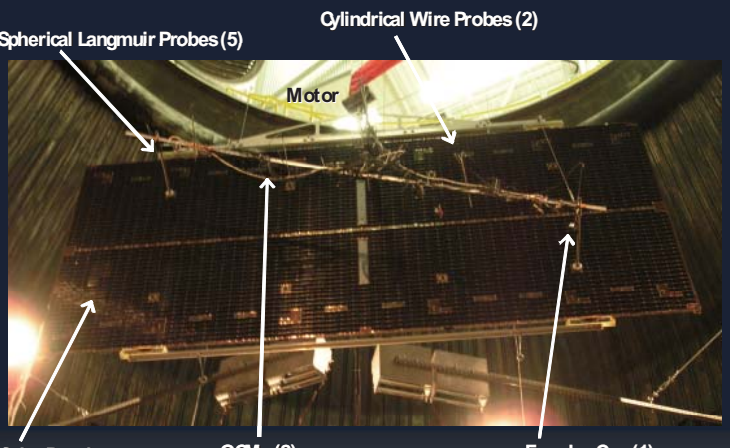

NASA GRC Plum Brook Station B-2 Spacecraft Propulsion Facility

- 80 ft x 40 ft approximate chamber dimensions
- Used for upper stage firings

Likar, et al (2006)

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MISSE Background

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- The Materials International Space Station Experiment (MISSE), is a series of experiments mounted externally on the International Space Station (ISS)
  - Purpose is to investigate the effects of long-term exposure to space environment
  - Enables characterization of synergistic effects of the complex space environment
  - Generate on-orbit data to validate models / ground test results
- Sample return enables post-flight material characterization
- "Suitcase" style carrier attaches to ISS exterior
- MISSE history
  - MISSE-1 / 2 (AFRL/ML)
    - Launched 2001; retrieved 2005
  - MISSE-3 /4 (AFRL/ML)
    - Launched 2006; retrieved 2007
  - MISSE-5 (NRL)
    - Launched August 2005; retrieved 2006
  - MISSE-6 (AFOSR)
    - Launched March 2008; retrieved 2009
  - MISSE-7 (NRL)
    - Launch Fall 2009; return Summer 2010


MISSE-3 (NASA)


MISSE-1 (NASA)

PRELSE / MISSE-8 Background

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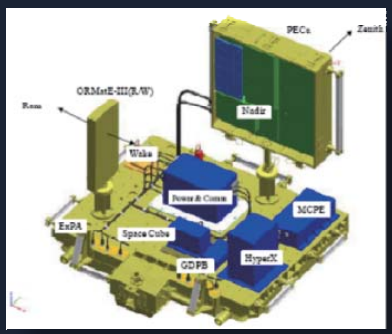

- PASCAL is included on the United States Naval Research Laboratory (NRL) developed Platform for Retrievable Experiments in a LEO Space Environment (PRELSE) platform
  - Also known as MISSE-8
    - Launch via STS-134 and deployed via Extra Vehicular Activity (EVA)
  - Will reuse MISSE-7 infrastructure
  - ISS accommodations on ELC2 top deck
    - Installed into MISSE-7 PECa pedestal
    - PASCAL on zenith facing surface
  - Uses ISS power and communications / telemetry

PASCAL and PEC Mechanical Overview

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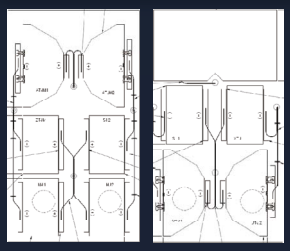

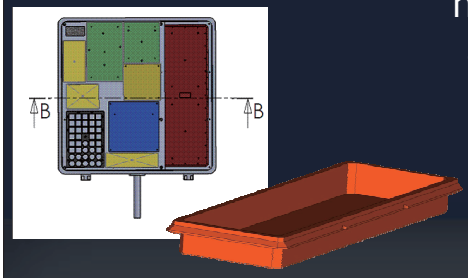

- All MISSE experiments housed within Passive Experiment Container (PEC)
  - Approximately 60 cm x 60 cm x 15 cm metal box (2 ft x 2 ft x 0.5 ft)
  - Experiment is mounted on trays are placed in the PEC
  - The PEC is attached to the ISS and opened on orbit to expose materials to space
  - At the end of the mission the PEC is closed and retuned to Earth
- PASCAL consists of two solar array coupons mounted to electronics assembly
  - Occupies approximately 1/3 of zenith facing portion of PEC

Methodology

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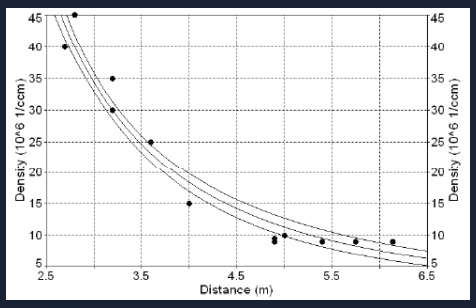
Wright, et al. (2008)



Vayner, et al. (2006)

- ISS plasma environment offers adequate conditions for characterizing solar array plasma interactions
  - Typically
    - $5x10^4$ cm^{-3} $<n_e<$ $5x10^5$ cm^{-3}
    - 0.05 eV $< T_e <$ 0.5 eV
- MISSE accommodations enable continuous characterization during exposure to space environmental conditions
- Experiment shall vary primary arc energy via variations in capacitance and negative bias
- Experiment shall characterize performance via repeated IV curve “delta” measurements
  - Comparison to ground test data
- Plasma condition monitoring and beta (sun) angle monitoring via ISS / NASA collaborations
- Degradation mechanisms can be studied in detail upon sample return

Technical Objectives

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- PASCAL to characterize, *in situ*, the effects of cumulative primary arcs on solar cell performance
  1. Characterize solar cell performance (degradation) after repeated primary arcing in space
  2. Characterize solar cell performance (degradation) after repeated primary arcing in space for multiple typical solar cell types
  3. Determine primary arc inception voltage in space for various typical solar cell types
  4. Characterize solar cell performance (degradation) after repeated primary arcing, at various energies, in space
- Value of PASCAL science offers multi-fold benefits for many end-users
  - Provide data valuable in development of future space solar arrays operating in environment in which plasma interactions may be present
  - Provide data valuable in assessing on-orbit operations of spacecraft / space solar arrays operating in environments in which plasma interactions may be present
  - Experiment results offers benefits to spacecraft / space solar array designers and manufacturers, customers, insurers, and academia

PASCAL Team

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- PASCAL team includes
  - Lockheed Martin
    - Project PI, programmatic responsibilities, systems engineering, and definition of technical objectives
    - Solar array coupon design, fabrication, and test
    - Ground station design and operation
  - KIT
    - Definition of technical objectives
    - Flight readiness of control / measurement electronics
      - Operational / environmental testing and performance validation
  - JAXA
    - Control / measurement electronics assembly design and fabrication
  - NRL
    - AI&T, MISSE-8 level interface, and flight operations interface
  - NASA and AFRL
    - ISS / flight operations, technical and operations oversight, scientific advisory

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Equivalent Bias Circuit

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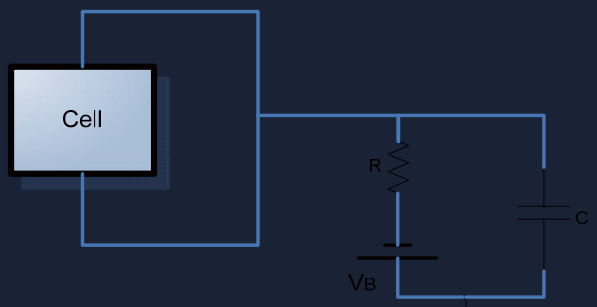
- Equivalent bias circuit is designed using well validated ground test methodology best documented by the ISO standard for ESD Test of Space Solar Array

Equivalent bias circuit



R, C, and V_B sized to simulate energy of arcs occurring on-orbit
C and V_B variable

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Overview of On-Orbit ConOps

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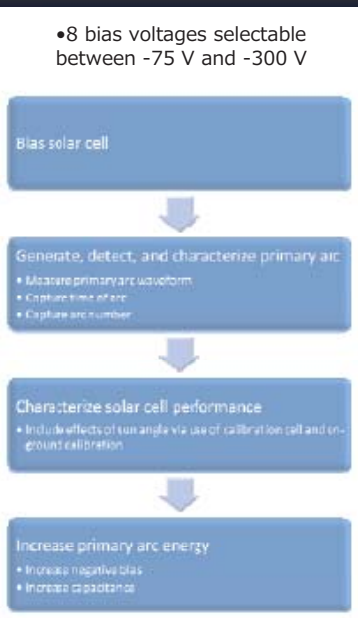
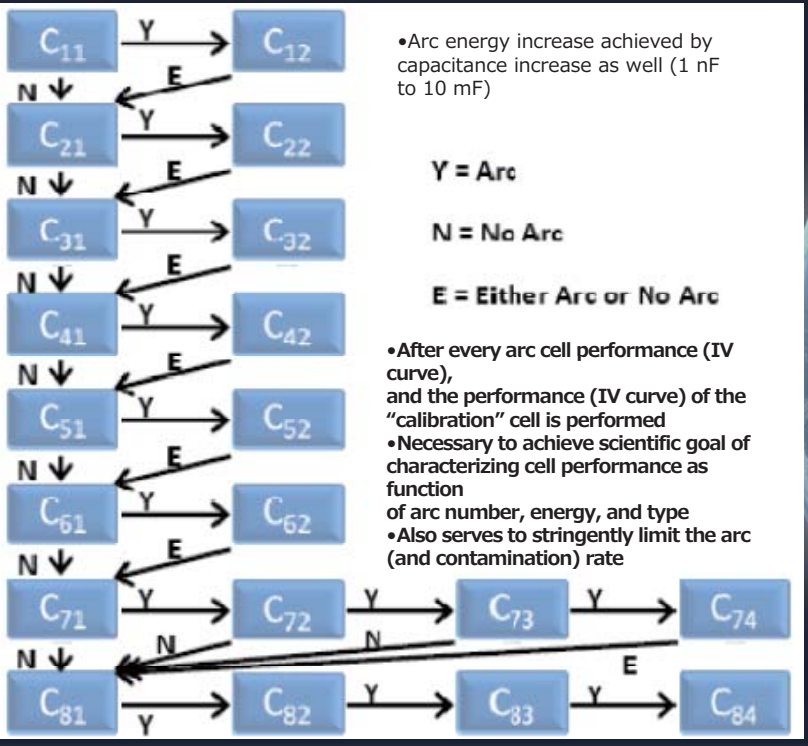
•8 bias voltages selectable between -75 V and -300 V





•Arc energy increase achieved by capacitance increase as well (1 nF to 10 mF)

Y = Arc

N = No Arc

E = Either Arc or No Arc

•After every arc cell performance (IV curve),
and the performance (IV curve) of the "calibration" cell is performed
•Necessary to achieve scientific goal of characterizing cell performance as function
of arc number, energy, and type
•Also serves to stringently limit the arc (and contamination) rate

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High Level Schedule

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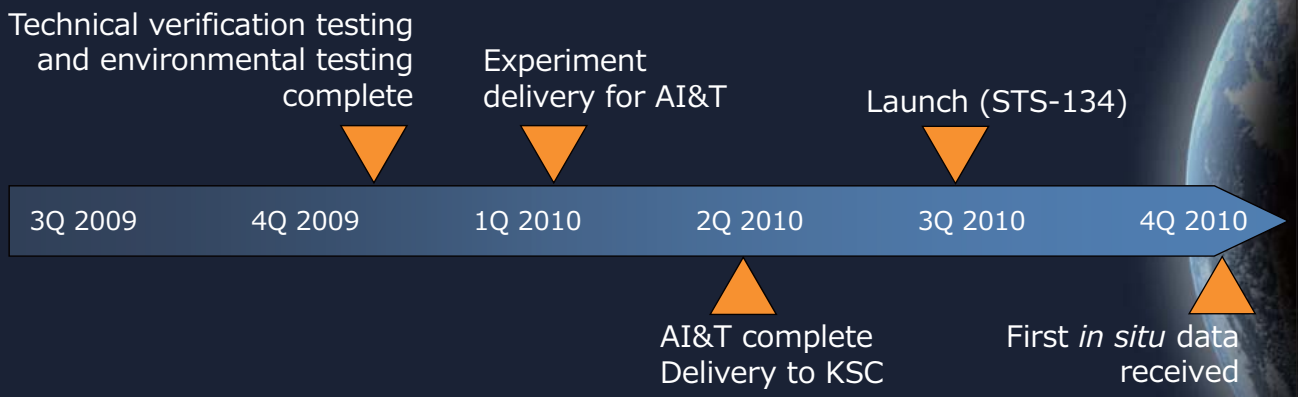

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Summary

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- Ground testing suggests that under appropriate conditions primary arc contains sufficient energy / power to result in damage to solar cell
- MISSE-8 / PRELSE flight opportunity enables long duration characterization of these effects under continuous space environment exposure
  - Multiple solar cell types and primary arc energies
  - Data return real-time
  - Sample return after several years
- Results should be of value to spacecraft designers, operators, insurers, and academia

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