Exploring PV on the Red Planet:
Mars Array Technology Experiment and Dust Accumulation and Removal Technology

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Abstract

The environment on the surface of Mars is different in several critical ways from the orbital environment in which space solar arrays normally operate. Some important differences are:

(1) low intensity, low temperature operation

(2) spectrum modified by atmospheric dust, varies with time

(3) indirect sunlight

(4) possibility of dust storms at some times of year

(5) deposited dust

(6) wind

(7) peroxide-rich reactive soil

We are developing two experiments to test operation of solar arrays on the surface of Mars, to be flown on the 2001 Surveyor Lander mission. The Mars Array Technology Experiment (MATE) will test the operation of several types of solar cells under Mars conditions, and determine the direct and scattered solar spectrum at the surface. The Dust Accumulation and Removal Technology (DART) experiment will monitor the amount of dust deposition on a target solar cell, measure the characteristics of the dust, and test the feasibility of dust removal.

1. Introduction

Over the next ten years, Earth is launching an assault on the planet Mars. Starting with Pathfinder [1] and Mars Global Surveyor, which arrive at Mars this year, there will be at least two spacecraft sent to explore the Red Planet during each launch opportunity for the next decade, leading, perhaps, toward a human mission early in the next century.

The single most important resource required for operation of robotic and human spacecraft on Mars is energy. Power is required for all phases of a mission, for scientific instrumentation, communication, transportation, life-support (for human missions), and for propellant production (for missions manufacturing propellant from Mars resources), including atmospheric collection and compression, thermal and electrical requirements for processing, and requirements for liquefaction and storage of cryogenic fuels.

For proposed missions in the next decade, the power source will be solar arrays. The power system will be the major constraint on the landing site latitude, on how much propellant can be produced, and on how long during each day and during which Mars seasons propellant can be produced. For this reason, it is important to use advanced, high-efficiency/low-mass solar array technology. However, issues related to the operation of advanced solar array technology on the surface of Mars have to be resolved.

Operation of solar arrays on the surface of Mars has been a research area at NASA Lewis for the last eight years. A result of initial studies of solar array operation on Mars [2-7] which determined that solar power systems are, in fact, feasible on the surface of Mars, solar arrays were chosen for the Pathfinder [1] lander and rover mission, which will be the first mission to operate on solar power on the surface of Mars.

The Pathfinder mission includes an instrument to measure the deposition rate of dust onto the Rover [8-10]. This will give us our first look at the effect of dust deposition on solar arrays on Mars.

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There are major unknowns about the operation of solar arrays on Mars due to the lack of "ground truth" information. Long-term performance of advanced photovoltaic cell and array hardware in the hostile Mars environment is not known, and cannot be adequately tested on Earth.

To answer these questions, we have designed two experiment packages to fly on the Mars-2001 Surveyor Lander. This mission, to launch in April 2001, will arrive on Mars in January 2002. The primary science mission is to deliver a rover vehicle to the surface of Mars; after this science objective is accomplished, the mission will be devoted to technology experiments. One of these technology objectives is to test technologies required for production of rocket propellant using the Martian atmosphere as a resource; this will be tested with the MIP (Mars In-Situ Propellant) package. The MATE and DART experiments will be flown part of the MIP package.

A conceptual rendering of the spacecraft is shown in figure 1.

The MATE experiment (Mars Array Technology Experiment) is designed to test performance of advanced solar cells under Mars conditions, verify solar-cell operation after long-term exposure to the Mars environmental conditions, in order to qualify solar arrays for Mars, and obtain measurements of parameters of the Mars solar environment most important to solar cell performance, in order to reduce the uncertainty in solar array performance prediction.

The DART experiment (Dust Accumulation and Removal Technology) is designed to quantify dust deposition from the Mars atmosphere, measure the properties of settled dust, and test a method of clearing the dust from the array.

Figure 1: Conceptual design of the Mars-2001 Surveyor Lander spacecraft, featuring foldable circular solar arrays. The MATE and DART experiment packages will be in the "MIP" box on the surface of the lander.

2. Solar Cell Operation on Mars

The Mars environment is different in several critical ways from the orbital environment in which space solar arrays normally operate. Some important differences are:

(1) low intensity, low temperature operation
(2) spectrum modified by dust; spectrum may change with time of day and year
(3) indirect sunlight (i.e., scattered light)
(4) presence of dust storms at some times of year
(5) deposited dust
(6) wind
(7) peroxide-rich reactive soil

1. Low Temperature

Orbital solar arrays typically operate at temperatures between 50 and 100 Celsius. For this reason, a cell technology is usually selected to have a low coefficient of temperature degradation. On Mars, however, the temperature is lower than the standard test temperature, rather than higher. This means that a high temperature coefficient is desirable, since this actually leads to higher efficiency at Mars temperatures than at test temperature. This shifts the technology choice toward lower bandgap materials and away from higher bandgap materials.

Temperature coefficients are also highly dependent on spectrum, and depend on the detailed shape of the spectrum near the energy bandgap of the material. They are almost impossible to measure with simulated sunlight.

The combination of low intensity and low temperature is a condition known as "LILT", which can lead to anomalous degradation of cell efficiency. It is important to verify that the technology chosen is tested against LILT phenomena.

2. Spectrum

The solar spectrum on the surface of Mars is modified by the atmospheric dust, making it blue-deficient, and enriched in red and IR compared to the orbital ("Air Mass Zero") spectrum. This will change the technology choice to make materials which respond most to the red and IR more desirable than cells responding to the blue end of the spectrum. The spectrum modification is minimum when the dust thickness is lowest, at high sun angles (mid-day, low latitude operation), and for low atmospheric dust content (northern hemisphere summer). The spectrum modification is maximum when dust thickness is highest, at low sun angles (early and late in the day, operation at high latitudes) and when the atmospheric dust is high (northern hemisphere winter). It is most important to have high efficiency when the solar intensity is low. Many systems, for example, are limited not by the average power, but have an operational limit determined by how soon after sunrise the power reaches high enough levels to begin operation. Thus, spectral shifting is more important than average power level numbers might suggest.

Another difficulty is that future high-efficiency cells will use tandem junctions, which require a current matching of several sub-cells of different materials. This matching is highly dependent on details of the spectrum. The variation of the spectrum with time of day and time of year may result in unacceptable degradation due to current mismatch; this is very difficult to predict based on laboratory tests, since it is very sensitive to the details of the spectrum. For example, a high-efficiency GaAs/Ge tandem cell developed in 1987 turned out to be unusable because of current mismatch. The test results were excellent under simulated sunlight, but the performance was poor when test conditions approached actual AMO conditions.

These two effects imply that a critical measurement for determining solar performance on Mars is the operational performance of cells of different bandgaps. It would be desirable to measure this as a function of temperature, sun angle, and atmospheric dust content.

Unfortunately, the Pathfinder and Surveyor-98 landers use only a single type of solar cell, GaAs. The Pathfinder operational lifetime is also too short to make the required measurements, especially as it lands well before perihelion, and probably won't see high-dust loadings. Surveyor-98 lander lands in very high latitudes (inside the Martian antarctic circle) and never sees high sun angles or increased temperatures. Thus, the solar operational information we get from these two missions will be important in that it will verify operation of solar arrays on Mars, but will not be badly insufficient to use for design of future large power systems which will operate for long periods on the Martian surface.

A selection of technologies chosen to specifically generate this information would be single-junction cells of a range of bandgaps It would also be desirable to add dual-junction and triple-junction cells to directly determine the operation of tandem cells on Mars. In principle the performance of dual and triple junction cells can be analyzed by determining the performance of the individual semiconductor elements, but it is desirable for qualification of the full array to be able to reference results from tests of a complete tandem stack.

3. Indirect sunlight.

Since the sky of Mars scatters light, the sunlight comes from a range of angles, rather than in a straight line from the sun. The primary implication of this for solar cell technology is that it means that concentration technologies (such as mirrors or lenses) will be much less effective than planar technologies which accept light from a wide range of angles, and the efficiency of concentration devices will be worst at the highest dust loadings, when efficiency is most critical. It also means that physical spectrum-splitting devices, such as prisms or gratings, will probably be not be effective on Mars, since they generally require collimated light to function.

The indirect sunlight also has implications for array design, choice of tracking, fixed-tilt, or horizontal array orientation, and fresnel reflection from the coverglass.

These effects are known. While it is important in selection of technology, information from Viking, Pathfinder, and Surveyor are likely to be sufficient. Given limited resources; we do not expect to require an experiment on the MIP experiment to test these effects.

4. Dust Storms

The seasonal dust storms are discussed earlier in terms of their effect on the solar spectrum. We believe that it is a very important to measure power production during a global storm for cells of different materials, since we expect that the best materials for producing power during a global storm may be considerably different from the technology best suited for operation during clear periods. Thus, we would very much like the experiment to have a duration at least to perihelion (northern winter).

5. Settled Dust

The atmosphere of Mars contains a considerable load of suspended dust. This dust deposits out of the atmosphere and onto any flat surface; the time scale for this settling has been measured to be on the order of 100 days. For example, observations by the Viking lander showed dark-colored surfaces being coated with a covering of dust, attributed to particles deposited from dust storms, over a time-scale of a hundred days to a few hundred days [11,12].

This is potentially the major lifetime limiting factor for a solar power system on any Mars mission which is required to last for longer than a 100 day mission, unless a technique is developed to periodically remove the dust. The issue of dust settling has been analyzed in detail by Landis [13,14], based on a review of the available evidence from Viking and Mariner [the Viking lander [15], with a RTG (nuclear) power system, was not subject to this limitation, however, future missions are not projected to use RTG power systems.] Table 1 shows the predicted dust deposition, based on the best available models of Mars dust settling.

The worst-case scenario is that the lander is in the settling phase of a global dust storm. There can be one, and possibly two, global dust storms per Martian year, typically occurring near perihelion (southern summer). However, in some years there are no global storms.

As can be seen, except for the case of a probe landing during a dust storm, the obscuration is not too bad for a short mission. It can be catastrophic for a long mission, unless dust removal is effected. It will be necessary to have a means to remove dust if a long-duration stay on the surface is to be achieved. Preferably, the dust removal should require little or no EVA activity by astronauts, since, even for a human mission, a Mars propellant plant will probably be operated as an unmanned vehicle launched two years before the piloted launch. A technique that requires no moving parts and is as simple as just pressing a button would be most desirable.

Case:	obscuration (30 day mission)	obscuration (2 yr mission)
Baseline	6.6%	77%
Best	0.5%	22%
Worst	52.2%	89%

Table 1: dust obscuration for short and long duration missions to Mars

6. Wind

Wind is an array design issue. In fact, the low atmospheric density (less than 1% of Earth pressure) on Mars means that dynamic pressures are low, which makes wind far less of a problem on Mars than on Earth. However, typical array designs for space are not designed for wind loads at all, and this must be taken as an additional array design factor. Viking measured an average wind of 2 meters per second, with a velocity of 17 meters per second exceeded less than 1% of the time.

7. Mars Soil Oxidant

Experiments on Viking [15] indicate that the soil of Mars (and presumably the dust as well) apparently contains a highly energetic oxidant, presumably produced by the action of ultraviolet light on the soil. The Viking experiments found the oxidant active in the presence of moisture. Quoting from reference 15: "The evolution of O_2 on humidification of the Martian surface samples was clearly a chemical reaction involving one or more reactive species such as ozonides, superoxides and peroxides," and later in the same reference: "The spontaneous evolution of O_2 when the Martian surface samples were humidified... suggested that the superoxides were modified by the water vapor available." Based on the fact that water was required for the oxidant to become active, since liquid water is absent on the surface of Mars we do not expect oxidant attack to be a difficulty. It would be useful to monitor long-term operation of different technologies on Mars to verify this supposition.

The atmosphere of Mars is expected to also have some presence of reactive radicals, produced by the action of ultraviolet.

In order to have good confidence in Mars array operation, we will want long-term exposure on the Mars surface to look for degradation with time. This will show that there is no unexpected synergy of operating conditions produces a degradation mechanism in the actual environment that was not predicted from lab tests. There is no substitute for operation in the actual environment.

8. Radiation environment

The radiation environment includes ultraviolet (UV) and particulate radiation (primarily high-energy protons and electrons).

The radiation environment of Mars is actually quite benign compared to the ordinary environment, since the Mars has no trapped radiation belts, and the Mars atmosphere serves as a mass shield against coronal mass-ejection ("solar flare") events. The shielding provided by the Mars atmosphere is, in fact, sufficient that we could consider flying a solar array without the conventional coverglass used for protection against radiation.

3. MATE Experiment Package

The MATE experiment (Mars Array Technology Experiment) is designed to (1) test performance of advanced solar cells under Mars conditions, (2) verify solar-cell operation after long-term exposure to the Mars environmental conditions, in order to qualify solar arrays for Mars, and (3) obtain measurements of parameters of the Mars solar environment most important to solar cell performance, in order to reduce the uncertainty in solar array performance prediction. Due to limited area and budget, only a limited set of cell types will be tested. Primary considerations in selection of cell types to test will be (1) commercial availability in the 2005+ time frame, (2) potential for high performance and/or low mass under Mars conditions, and (3) generation of information which will be widely applicable to general predictions of array performance on Mars.

MATE will be designed as a fixed flat plate with cells and instruments on surface, plus a separate electronics package. The plate will be a lightweight rigid substrate commonly used for arrays and spacecraft, either aluminum honeycomb with woven Kevlar or graphite epoxy face sheets. All sensors and diagnostics will be made in the plane of the plate, with no solar tracking. (Sun tracking would be costly and most proposed arrays for Mars do not employ this technique.) MATE's primary function is passive diagnostics, i.e. measure the performance of solar cells, light, and temperature on Mars.

A conceptual diagram of MATE is shown in figure 2.

1. Test of Individual Cells

The baseline MATE package will test two samples each of 5 different cell types. There are two samples of each type of cell for intercomparison and redundancy

Full IV curves will be run on each cell. To do this, all the cells require 4 wire connections, a front and back pair for both voltage and current. The cells can share common grounds. Based on the Mars insolation and cell sizes, currents will range from 0 to 60 mA and voltages range from 0 to 2.5 V.

These photodiodes arrays complicate the electronics package for MATE. They require start/stop and reset pulses from a computer along with a sequential timing pulses to read each element voltage. They are an off-the-shelf component. Two proposed photodiode arrays are Hamamatsu S3904 (Si) and G6890. The S3904 is currently used in a wide range of spectrometers.

Sun Position Sensor (will be part of DART package). This sun position sensor will consist of a lens mounted over a CCD array with a solar filter. The same sensor will be used to determine optical depth.

4. DART experiment package

The utility of dust removal technique on Mars may depend on the detailed properties of the surface dust, including composition, binding strength, particle size distribution, native charge, and surface chemical state. These properties cannot be adequately simulated in an Earth environment, but must be tested with actual Mars dust. It would also be desirable to demonstrate operation in the actual temperature, UV radiation, dry, low-pressure mixed-gas atmosphere (primary components: CO_2, N_2, and Ar) environment of Mars.

A survey of dust removal techniques on Mars is given by Landis [16]. The DART package is flight demonstration program to gather engineering data about the deposition rate and properties of the dust, data important to the future exploration of Mars (as well as of fundamental scientific interest), and to demonstrate the removal of dust.

The flight experiment will measure the dust deposition rate, the dust optical opacity, the solar constant on Mars and the portion of the spectrum which is important to the operation of solar cells. By improving knowledge of the operating conditions of solar cells on Mars, the uncertainty in power output for future Mars missions can be reduced. This result is quite important in selecting a site, since the amount of power available is often the limiting factor in what latitudes can be reached.

The flight demonstration package, shown in schematic in figure 3, consists of five portions.

Integrated onto the upward-facing surface of the spacecraft:

(1) Solar cells. This will include one control and two experimental solar cells.

(2) diagnostic sensors to measure the amount of dust

(3) plasma breakdown electrodes

In the MIP warm-electronics box:

(4) RS-422 programmable high-voltage power supply

(5) electronics to support sensors; spacecraft interface.

This is shown in schematic in figure 2.

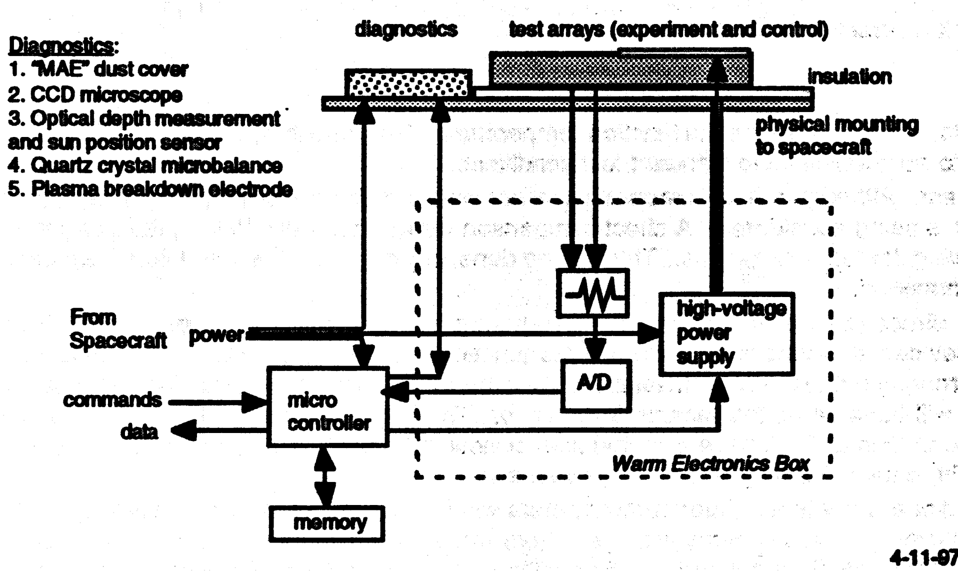

Figure 3: DART experiment package block diagram

The diagnostic sensor set will be based on the "CADO" package [17] under development at Lewis, and uses heritage from the Pathfinder "MAE" experiment [8,9]. It will also measure the amount of dust deposited, its optical opacity, and particle size, and will include an electrode set to measure the breakdown potential of the Mars

In addition to measuring the IV curve, there are three cell temperature sensors. The temperature sensor is an resistance temperature device or RTD. An RTD is a resistive device that varies linearly with temperature, it typically is 100 Ω at 0° C. These are mounted under three of the ten cells. The temperatures will be used to extrapolate the temperatures of all 10 cells. All temperature sensors can share a common ground.

2. Test of Strings

MATE will test two strings of cells, of two different cell technologies. The strings will require a full IV curve. The test will not only detect changes in the cells but evaluate the integrity of the related interconnect technology. Interconnects between cells are highly affected by thermal stresses and related fatigue. The cell types and interconnects will be based on the best viable technology of the time, and presumably one standard cell string, one thin-film string. Each string will require a 4 wire connection and can share common grounds.

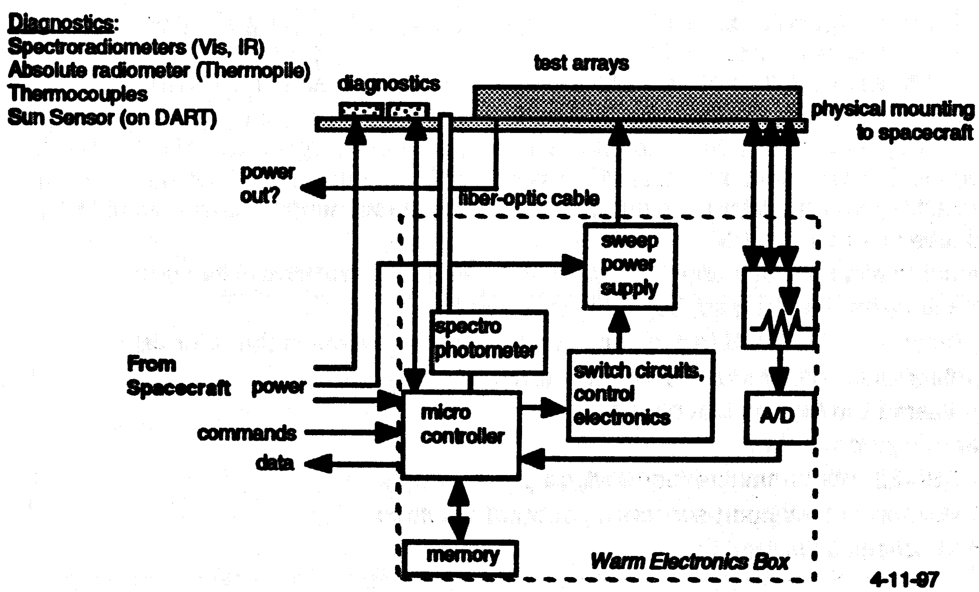

Figure 2: Conceptual block diagram of MATE components

3. Diagnostic Sensors

Temperature measurements. We will measure the junction temperature of representative cells. This is required to allow the cell performance to be normalized to standard test conditions.

Air temperature measurement. Although the air temperature is not critical to the performance of solar cells, an air temperature measurement is being considered. A direct comparison between the cell temperature and the air temperature may aid in modeling for future programs. This will be done using an RTD with additional absorptive and emissive materials as determined.

Radiometers (global and direct (as close as possible)) requiring some temperature correction. These radiometers are thermopile devices and consist of thermocouple junctions on a thin substrate. The radiometers generate a voltage which is proportional to the solar insolation. As a thermal device, the radiometers are sensitive to temperature and each unit will have an added temperature sensor. The two radiometers are used to measure both direct and global insulation. One unit will have a limited field of view to measure the direct light, the other will be shielded from direct sunlight to measure only surrounding irradiance.

Spectroradiometers (photodiode array type). Spectroradiometers will include UV/Vis/NIR and NIR to cover 300 nm to 1800 nm or more as feasible. These devices are made from three separate components. The first is the fore-optics which take in the light, this will be a fiber optic tube with a direct view of the sun from the plane of the cells and <25° field of view. Second will be a grating which splits the sunlight into its spectral components (as a prism). Third will be a photodiode array of ~ 512 elements. These three components will be used to generate a high resolution (<5 nm) spectral energy plot of the Mars sunlight. Two spectroradiometers are required because of the limitations of the gratings and photodiode array. One array will consist of Si elements which respond to 300-1100 nm light, a second array will consist of InGaAs elements and respond to 900-1800 nm. The grating and photodiode array do not need to be located on the cell plate and could be housed beneath it.

atmosphere. The diagnostic instrument set comprises:

1. "MAE" commandable dust cover (similar to the Mars Pathfinder instrument [8,9])
2. Quartz crystal microbalance (similar to the Mars Pathfinder instrument [8,9])
3. CCD microscope based on TC-255 CCD array or other focal plane detector as specified [17]
4. Optical depth measurement and sun position sensor, also based on TC-255
5. Plasma breakdown electrode

5. Conclusions

The first solar-powered spacecraft to operate on the surface of Mars are on their way to the red planet, and will land on July 4th of this year. The environment in which solar arrays will operate on Mars is quite different from the operating environment of other spacecraft power systems, and it would be valuable to characterize the operating environment, measure the operation of solar cells on Mars, and test whether deposited dust will be a problem for the long-term operation. Two experiments on the Mars-2001 Surveyor Lander, MATE and DART, are designed to accomplish these goals.

6. References

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Workshop III - Arcs, Sparks & Spacecraft Charging

Issues:

What levels of arcs are acceptable?

In particular what level of arc currents/time scale can Ga/As or Multijunction cells tolerate?

How do Arc Characteristics scale with Array Size?

Capacitance? Stored Energy? Finite discharge area?

Past testing has been performed on small array samples of 10's cm dimensions. We need to understand how to extrapolate observations to flight systems. Some hypotheses have been advanced on how to do this but we need to verify or modify these hypotheses.

Effects of New Materials?

Cell material, new solvents, new adhesives, conductive cover slides, new coatings, etc.

Test Methods: Cannot simply put a grounded array in an electron beam and assume this represents flight conditions. We know more about arc's than we did 10 years ago. Need to reproduce correct potential distributions, and approximate floating conditions of a satellite in space.

Effects of High voltage arrays?

LEO grounding issues, Kapton pyralization (LEO and Geo)? Other?

Who should lead/fund these efforts?

Government? *Open data, reluctance to do commercial research, under-funded.*

Flight Programs? *Cost Conscious, Off-the-shelf systems, proprietary data.*

Consortiums?

Workshop III - Arcs, Sparks & Spacecraft Charging

What charging/arcing issues are specifically of concern to solar array designers? (summary of short tutorial)

EMI characteristics are determined by size of arrays, and conductivity of array structure, and bus. Dimensions contribute to frequency spectrum. High Impedance permits high Voltages, Low Impedance permits high currents.

Also large solar cell arrays present the highest capacitance to space, so they will contribute a significant Displacement Current, to a voltage transient elsewhere on the spacecraft.

As transients propagate, additional arcs may occur.

Effects of Arcs may be mitigated by doing things spread out the pulse. Introduce Inductance to ground and DC bus lines?

Conductive Black Kapton (Warning: not all black Kaptons are conductive) alleviates many charging problems of thermal blankets.

High Voltage arrays (100V) in Low Earth Orbit can control structure potentials, and lead to arcing elsewhere on the spacecraft. Solutions are positive or floating ground for Array power bus, large exposed conductive areas at spacecraft ground or active control techniques such as a plasma contactor (will be used for ISSA).