SOLAR ARRAY SAILS:
POSSIBLE SPACE PLASMA ENVIRONMENTAL EFFECTS

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An examination of the interactions between proposed "solar sail" propulsion systems with photovoltaic energy generation capabilities and the space plasma environments. Major areas of interactions are: Arcing from high voltage arrays, ram and wake effects, V x B current loops and EMI. Preliminary analysis indicates that arcing will be a major risk factor for voltages > 300V. Electron temperature enhancement in the wake will produce noise that can be transmitted via the wake echo process. In addition, V x B induced potential will generate sheath voltages with potential tether like breakage effects in the thin film sails. Advocacy of further attention to these processes is emphasized so that plasma environmental mitigation will be instituted in photovoltaic sail design.

INTRODUCTION:

NASA New Millenium Program has promoted the development of advanced propulsion technologies to enable less expensive future space exploration (1). Solar sailing as a mean of space propulsion is one system under consideration. The range of potential missions with this technology is only limited by the solar flux.

ENVIRONMENTS	FLUX
LEO/MEO/GEO	1368 $Js^{-1}m^{-2}$
JUPITER	55 $Js^{-1}m^{-2}$

Solar sailing essentially involves utilizing the radiation pressure of the sun to accelerate a spacecraft to its desired mission. There are however several variant of the sail concepts under consideration by NASA (2). The variations differ primary in the source of the propulsive power.

PROPULSIVE SOURCES
Solar Photons
Solar Wind
Lasers
Microwaves

The major design considerations for all sail types are mass, stability of the sail, temperature control and optimizing reflectivity (3). Possible plasma interactions with sail technologies are usually given secondary consideration in the quest for peak sail accelerations. However, experience with spacecraft charging in LEO and GEO and the projected increase particle and UV radiation due to Solar Cycle 23 warrants investigation of environmental compatibility as an ongoing design factor.

SAIL ACCELERATION:

A solar sail of area A, a few micron thick and mass m will in the near earth environment experienced an acceleration of

$$a_s = \frac{2A_s P}{m_s}\eta \approx few\ mm\, s^{-2}$$

where η is the efficiency factor due to the sail imperfect optical properties, structural billowing and P is the local solar radiation pressure (4). Sail area, mass and optical attributes are the key design elements. Mass reduction as in all spacecraft design is the major cost driver. In the case of solar sails, the mass reduction is critical to achieving the highest possible accelerations. Mass reduction in sail design is achieved by the use of polymer such as Kapton[R], a mainstay substrate of solar array power systems. Environmental mitigation is well established for array substrates and may readily transfer to sail technologies (5). Lets examine some possible environmental effects associated with the design factors unique to sail technologies.

SAIL AREA

In order to achieve significant accelerations, sail lengths will be .1-10km. Sail area then becomes the dominant region of environmental interactions. Three environmental effects must be considered in the design: V x B, wake and ram effects.

V x B

An electric field will be induced along the sail as it crosses planetary, galactic and solar magnetic fields. In LEO orbits this induced field has a value of E = .22 V/m. This induced field will effect the dynamics of plasma currents to the sail and consequently sheath formation. For this case, a key intrinsic environmental design consideration is that the sail is restricted to a diameter of less than a km since the plasma environment will induce voltage breakdown near 200 volts on exposed conductors at attitudes less than 1000 km.(Fig 1). Alven wave generation in the kHz region will be transmitted if the induced field supports a current through the sail (6). Radiation induced drag will then represent a loss mechanism to the sail acceleration (7).

If the induced current within the sail structures form a loop then a magnetic dipole moment given by M = IA will be produced. For a current loop in the plane of the sail, the magnet dipole moment will be perpendicular to the sail area normal. The magnetic dipole moment will tend to orient itself parallel to the ambient B field in the position of minimum potential energy. Mission specifics will determine whether this torque is a source of drag and station keeping power loss. However it does point to a possible interesting application in solar cycle trapped radiation physics as a means of measuring particle flux coupled with secular variations in the ambient magnetic field.

WAKE AND RAM

The front and rear surfaces of the sail will experience different particle and radiation flux. Photoelectron generation from solar UV and space plasma absorption will produce differential voltages between the ram and wake surfaces. The required micron thinness of the sail material and substrate may be subject to up to kilo voltage stress which will lead to arcing (8). Arcing can then lead to tearing of the sail materials and ultimately failure. This differential-charging problem is not restricted to the LEO-GEO environments. The solar wind is a plasma and the sunspot maximum for solar cycle 23 will mean an increase in solar wind density and solar UV throughout the solar – interplanetary region. Models of the 11-year solar cycle lack real time density capabilities thereby elevating differential charging as a critical sail design factor. Mitigation of the potential threat of differential charging can be achieved by grounding all conductive surfaces to the same potential thereby severely complicating the sail design. However sail designs that include solar arrays as an additional power source either within the sail or on the spacecraft body will increase the possibility of differential charging and thereby the potential for arcing.

OPTICAL PROPERTIES

Solar sails require a reflective surface in order to achieve optimal accelerations. A metallic coating which is vapor deposited on a Kapton^{R} substrate is the typical sail design (9). Reflectivity across the entire solar spectrum is desired. In practice, UV transparency and thermal absorption are key design boundaries. Research at the NASA Glenn Research Center has indicated that whenever there is a conductor–dielectric junction in a plasma there exist a potential arc site (10). The metallic reflective coating and dielectric design of solar sails is a conductor dielectric junction and therefore arcing mitigation should then be a initial design priority.

Combining the reflective and photovoltaic potential of the sail coating may optimize the optical properties of the sail. Terrestrial photovoltaic manufacturers are experimenting with spray deposition of photovoltaic material. Given the size of sail structures the low efficiency spray deposition array may enable sail designs with smaller diameters thereby reducing area related environmental effects. Grounding and arc mitigation would still be the major plasma environmental consideration.

SUMMARY

Solar sails can provide an alternate means of increasing access to space. The size and power requirement of sail technologies will require consideration of environmental effects such as arcing and radiation drag in order to optimize sail design. Sail area is a major benefit and detriment to sail technologies. A combined reflective and photovoltaic sail coating may reduce the negative environmental impacts of sail area.

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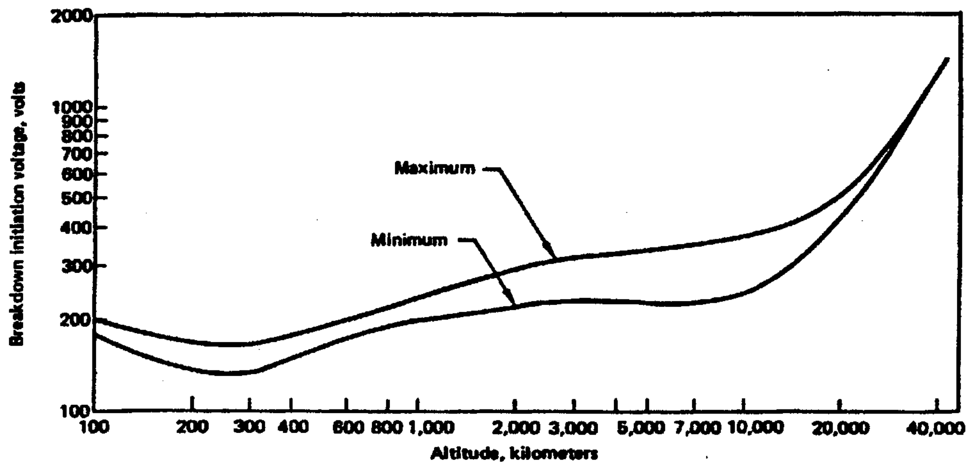
Figures From Space Power Design Course, LaunchSpace, M. Patel. 1999

MAXIMUM VOLTAGE Vs. ORBIT ALTITUDE



Effects of Plasma on Exposed Bare Conductors

ORBIT PARAMETERS INFLUENCING THE VOLTAGE SELECTION