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ISSA/TSS POWER PRELIMINARY DESIGN

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Introduction A projected power shortfall during the initial utilization flights of the International Space Station Alpha (ISSA) has prompted an inquiry into the use of the Tethered Satellite System (TSS) to provide station power. The prelimary design of the combined ISSA/TSS system is currently underway in the Preliminary Design Office at the Marshall Space Flight Center. This document focusses on the justification for using a tether system on space station, the physical principles behind such a system, and how it might be operated to best utilize its capabilities.

Concept The basic components of a simple DC generator are a magnet of some type and a conductive wire. Moving the wire through the magnetic field causes forces to be applied to the electric charges in the conductor, and thus current is induced to flow. This simple concept is the idea behind generating power with space-borne tether systems. The function of the magnet is performed by the earth's magnetic field, and orbiting a conductive tether about the earth effectively moves the tether through the field.

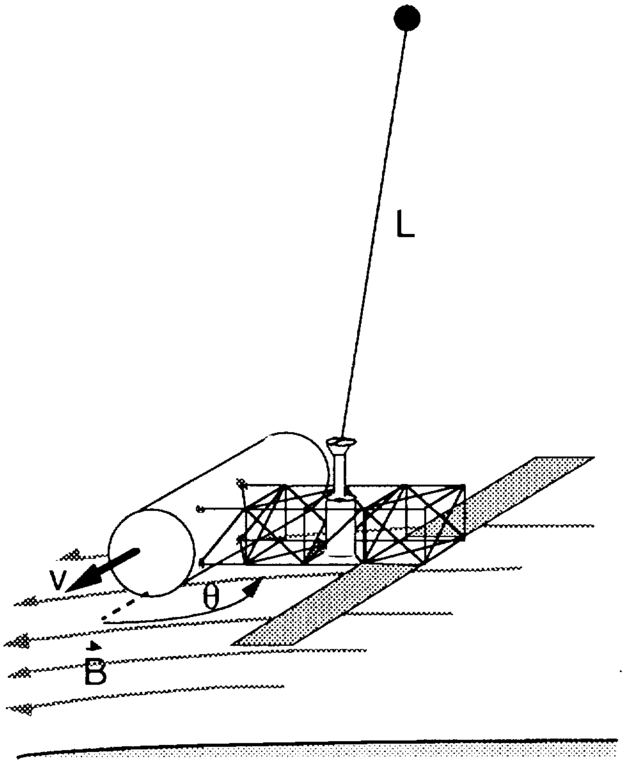

Figure 1. Generation of a potential difference in a tether moving through the earth's magnetic field.

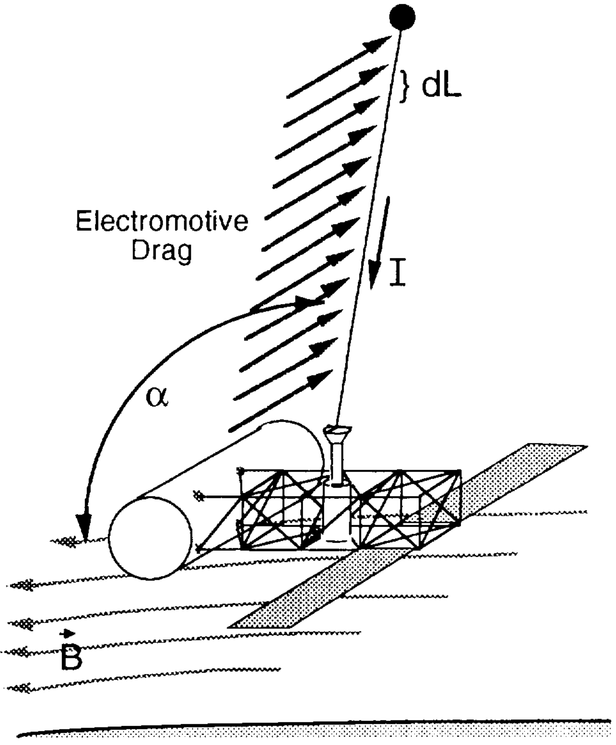

Figure 2. The electromotive drag due to generation of power with a tether.

Dragging a conductor through a magnetic field will create a potential in the conductor according to[1]

$$\vec{V} = \left(\vec{v} \times \vec{B}\right) \bullet \vec{L} \qquad (1)$$

where V is the electric potential generated, v is the velocity of the tether, B the magnetic field vector, and L the tether length vector.

It is fairly reasonable in the case of a near-equatorial, low-earth, circular orbit to assume that B and L are mutually perpindicular. In this case equation (1) simplifies to

$$V = vBL\sin(\theta) \tag{2}$$

where θ is the angle between the B-field and the velocity vector.

Assuming nominal values for orbit altitudes, velocities, and magnetic fields in low earth orbit a potential of approximately 200 V/km can be generated in a conductive tether.[2] This value can vary widely due to variations in the earth's magnetic field, however, so potentials as high as 250 V/km and as low as 75 V/km should be expected in any given orbit.

The laws of thermodynamics state that you do not get something for nothing, and that is as true here as anywhere. The energy that is being extracted from the tether as electric power must come from somewhere, and it turns out that electric power extracted from an orbiting tether will cause a net drag on the tether, thus slowing the orbital velocity and lowering kinetic energy.

This drag force is directly proportional to the amount of current flowing through the tether according to

$$\vec{F} = I\int d\vec{L} \times \vec{B} \tag{3}$$

where F is the total drag force on the tether and I is the current flow.

In the case of a straight tether equation (3) simplifies to

$$F = ILB\sin(\alpha) \tag{4}$$

where α is the angle between the B-field and the tether vector.

It is interesting to note in equation (3) that the direction of the force is dependent upon the direction of the current. This emphasizes one of the unique capabilities of space-borne tether systems: if power is being generated from the tether, then, logically, the drag force acts to slow the system, but if current is pumped through the tether in the opposite direction, an accelerating force is applied. This means that a conductive tether is not just a generating system. Its true function is as an energy exchange mechanism between electic power and system kinetic energy. An application of this exchange mechanism would be in a system where there was an additional power generation capability, say solar panels. In periods when the solar panels cannot supply the needed power to the orbiting spacecraft the tether could be used in generating mode to fill the gap, thus decelerating the spacecraft. When the solar panels are generating excess power, power that would otherwise be burned up and radiated to space, that power would instead be pumped through the tether and used to accelerate the spacecraft. Use of a tether system in this fashion could reduce overall propellant requirements for reboosting the space station, decrease the amount of heat that must be rejected from a primary power source, and increase the overall efficiency of the primary power source since excess power is stored as kinetic energy, not wasted.

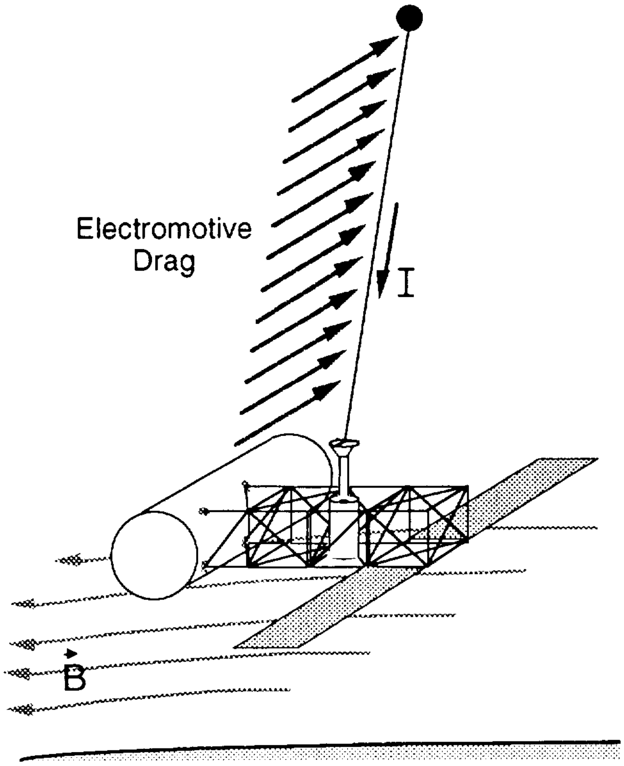

Figure 3. Current flow direction during power generation produces a net drag.

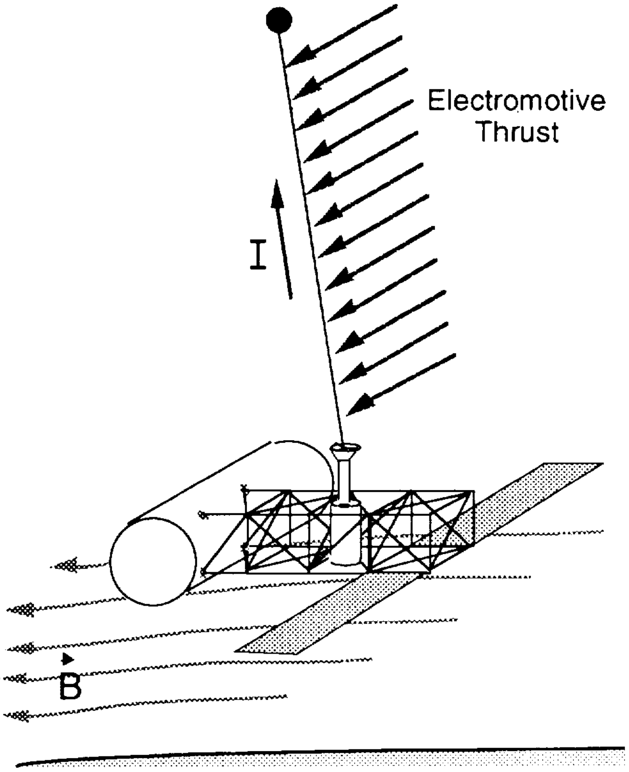

Figure 4. Pumping current in the reverse direction will produce an accelerating force.

Performance Predictions The current design of the ISSA tether power system calls for a 5 km #6 aluminum tether which will have a 250 kg endmass that includes a plasma contactor. A 5 km tether in LEO would be expected to generate a nominal potential difference of approximately 1 kV, with voltages ranging between 380 V and 1.25 kV.

Losses in the system will come from electrical resistance in the tether, plasma contactor losses, and conversion losses. It is unlear at this point what the conversion losses will be, as those will be very method dependent. A 5 km #6 aluminum wire has a resistance of approximately 10Ω, so if 5 amps are flowing the tether losses would amount to 50 V. Budgeting an additional loss of 15 volts to the plasma contactor leaves 935 V nominal left for station use. At 5 amps this amounts to a 4.7 kW power supply!

Of course, this power generation will induce a drag force on the station that will have to be countered with additional reboost if the thrusting capability of the tether is not utilized. Assuming a nominal field strength for earth at LEO of 30×10^{-6} Tesla, the force acting on the tether due to the generation of 4.7 kW of power is

$$F_{Elec} = (5\text{amps})(5\text{km})\left(30\text{x}10^{-6}\text{Tesla}\right) = 0.750\text{N} \tag{5}$$

where F_{Elec} is an electromotive drag in this case. An additional drag of 0.04 N will also be present with this tether design due to aerodynamic drag.[3] Unlike the electromotive forces, this will always be a decelerating force.

The electromotive drag force (F_{Elec}) at 4.7 kW represents an impulse loss to the station of 2700 N-s/hr, but only while the power system is running. Assuming the reboost propellant is hydrazine (I_{sp}=300 s) this will necessitate burning 0.918 kg of extra fuel for every hour the system is in operation. The aerodynamic forces, on the other hand, will be present whenever the tether is reeled out. The aerodynamic force represents an impulse loss of 144 N-s/hr, which results in a fuel requirement of 0.05 kg/hr.

Figures 5 and 6 are included to aid in the calculation of the extra fuel required for a given mission. Figure 5 shows the extra fuel needed as a function of the length of time the tether will be reeled out, and Figure 6 shows the extra fuel necessary as a function of the length of time the power system is running at nominal. Adding these two values will yield the total extra fuel required for a given mission.

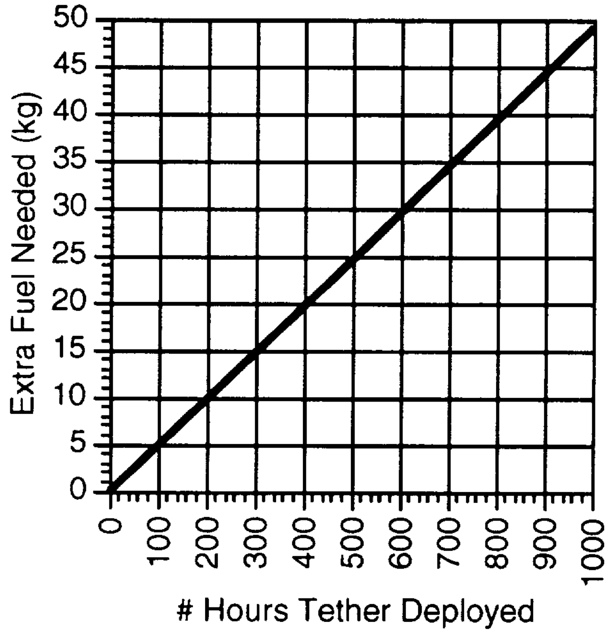

Figure 5. Extra fuel required as a function of tether depoyment time.

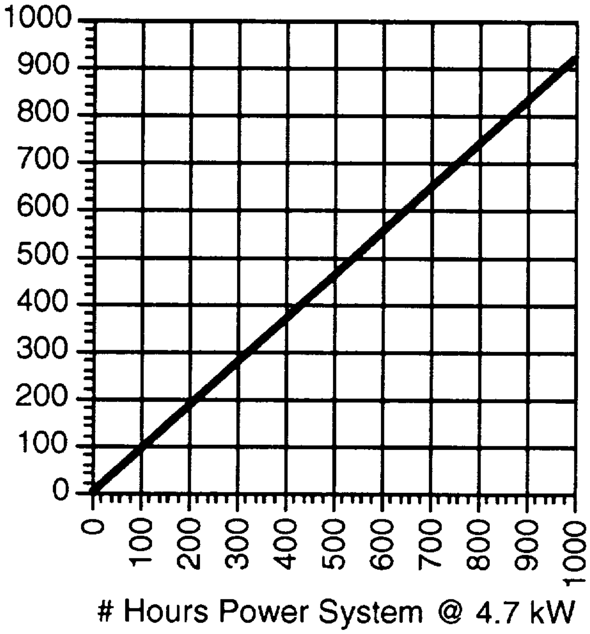

Figure 6. Extra fuel required as a function of the duration of power system operation.

Fuel Cell Trade An important point to address in this study is whether or not there is another available system that can abate the temporary power shortfall in the ISSA faster/better/cheaper than the TSS tether system. One possible alternative for providing this kind of temporary power is a hydrogen-oxygen fuel cell. Table 1 shows a trade study comparing the cost and fuel requirements of the TSS power sysem as compared to a fuel cell capable of providing the same level of power (4.7 kW nominal).

The cost of the TSS system modified to generate power on the space station is TBD. The deployer hardware is available from the TSS-1 mission, but the electrical interface exists only in concept at this time. The cost of an orbiter fuel cell, basically the only one available, comes in at about $8 million.[4]

The fuel weight for the required for the TSS power system is calculated from the results of the previous section. Note that it assumes that excess power is not pumped through the tether to reboost the station. The mass of hydrogen and oxygen required (0.372 kg/kW-hr) to run an equivalent fuel cell is based on a fuel cell efficiency of 75%.[5] Note that, by weight, the fuel requirement for the tether system is about half that required by an equivalent fuel cell. This ratio will become even more favorable if excess power is pumped through the tether to reboost the station.

Table 1. Tether Power - Fuel Cell Trade.

Tether - Fuel Cell Trade

Power Source	EquipmentCost	Fuel Requirement Running at 4.7 kW
5 km #6 AL Tether	Cost of Tether & Power Conditioner (TBD)	0.968 kg/hr (hydrazine)
Orbiter Fuel Cell	~$8 Million	1.748 kg/hr (hydrogen/oxygen)

Additional Benefits Perhaps the greatest benefit of using the TSS tether system to generate power would come after the power generation phase were over. The ISSA would then have an absolutely unique facility for atmospheric research. The possibities for a downward deployed tether are extremely exciting and include 3-D mapping of the upper atmosphere, two-body dynamics and control experiments, examination of auroral structure, controlling µ-gravity on station for materials experiments, and examining antenna behavior in the magnetoplasma. These applications alone justify the addition of a tether facility to the ISSA, the added benefit here is that the system can be used to abate an already serious station power shortage.

Conclusions This short report represents a very top-level look at the possiblity of using a tether on the ISSA to abate the projected power shortfall. No showstoppers were encountered, although the treatment of the design is admittedly very shallow and the amount of extra fuel needed does become large as the power generation time rises. The results of this study indicate that there are strong reasons for including a tether facility like TSS on the ISSA both for power generation and general science. The fact that both of these issues can be addressed with one facility makes the case for pursuing this concept very strong.

Acknowledgments The author gratefully acknowledges the assistance of a number of individuals in Program Development at the Marshall Space Flight Center, some of whom are noted in the reference section. In addition, Chris Rupp of MSFC provided valuable insight and much of the material that this study is based upon.

References

1. Tethers in Space Handbook, Second Edition.
2. Presentation by J. McCoy, Johnson Space Flight Center, at the Marshall Space Flight Center, 6/15/95.
3. Conversation with Jim McCarter, Marshall Space Flight Center.
4. Conversation with Don Williams, Marshall Space Flight Center.
5. Batteries and Energy Systems, C.L. Mantell, Second Edition, McGraw-Hill.