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PRELIMINARY ASSESSMENT OF POWER-GENERATING TETHERS IN SPACE AND OF PROPULSION FOR THEIR ORBIT MAINTENANCE

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The concept of generating power in space by means of a conducting tether deployed from a spacecraft was studied. Using hydrogen and oxygen as the rocket propellant to overcome the drag of such a power-generating tether would yield more benefit than if used in a fuel cell. The mass consumption would be 25 percent less than the reactant consumption of fuel cells. Residual hydrogen and oxygen in the external tank and in the orbiter could be used very effectively for this purpose. Many other materials (such as waste from life support) could be used as the propellant. Electric propulsion using tether-generated power can compensate for the drag of a power-generating tether, half the power going to the useful load and the rest for electric propulsion. In addition, the spacecraft's orbital energy is a large energy reservoir that permits load leveling and a ratio of peak to average power equal to 2. Critical technologies to be explored before a power-generating tether can be used in space are delineated.

INTRODUCTION

Tethered spacecraft are a topic of considerable and growing interest (ref. 1). Among the features they offer is the possibility of power generation from an electrically conducting tether trailed through the Earth's magnetic field. Such a tether would be acted on by forces from the gravity gradient, from aerodynamic drag, and from electrodynamic interaction with the Earth's magnetic field; the tether would thus trail in a generally radial direction, either up or down, rather than directly behind the spacecraft as the word "trail" might indicate.

This paper describes a broad, general study of such power-generating tethers that explored their potential value and their problems. The following topics were studied: (1) the conditions of power generation, the drag imposed on the spacecraft, and the resulting orbit decay; (2) the use of chemical propulsion to compensate for this drag; and (3) the use of some of the generated power in electric propulsion to compensate for this drag. Finally, questions of feasibility were considered. These topics define a technology program to be completed before any application of such power-generating tethers in space.

THE POWER-GENERATING PROCESS

A spacecraft in low Earth orbit that trails an electric conductor that is, say, 100 km long (fig. 1) will produce an electric potential in that conductor as a result of its motion through the Earth's magnetic field. The voltage results from the familiar $\underline{v} \times \underline{B}$. For an orbital velocity of 7600 m/s, the potential generated by such a tether might be 15 to 20 kV. For an electric current to flow, electrons must be discharged at one end of the tether. Figure 1 shows an electron gun for this purpose. Electrons, being very mobile, are expected to provide the major flow of current.

For collection of the electrons at the tether's opposite end, an electron collector of large surface area is required. Although figure 1 shows a sphere for the collector, almost any surface would be suitable. Reference 2, for example, suggests a plane surface aligned with the spacecraft's orbit path as a way to decrease the aerodynamic drag from this large area.

Current through the conducting tether will impose a drag on the spacecraft from the familiar $\underline{i} \times \underline{B}$ interaction. Aerodynamic drag on the tether will also extract energy from the spacecraft. Rocket propulsion could compensate for these drags and permit the spacecraft to maintain a stable flightpath.

The useful power output would, of course, be the product of the current flow and the generated voltage. Inasmuch as generated voltages of tens of kilovolts are somewhat of a problem in their own right, the lower voltages produced by shorter tethers might at first appear attractive. For a given power output, however, the voltage reduction must be compensated for by an increase in current flow. At the higher current a larger surface is required for collecting the electrons.

Plasma interactions will also impede electron flow. In a perfect vacuum, the geomagnetic field would force the electrons to move along paths that are roughly helical, that surround given lines of the magnetic field, and that would thereby generally prevent the emitted electrons from reaching the electron-collecting surface. In an actual plasma, collisions of the electrons with ions and neutral particles as well as with other electrons will randomize the electron motions and permit their gradual diffusion toward the electron-collecting surface. Both the plasma impedance from these collisions and the space charge near the electron-collecting surface will restrict the flow of electrons. The regions of space having the highest plasma density may permit high currents of electrons, but these high densities may also impose severe aerodynamic drag. Data to permit optimization of altitude, these conflicting requirements being considered, are not available. Thus the conservative approach at this time requires the assumption of low current flow and, concomitantly, acceptance of the difficulties associated with the high voltages. This will, in turn, require a tether of length sufficient to generate the voltage required. For that reason, the generated voltage in figure 2 was taken as 17.5 kV. The tabulated inputs, outputs, and losses resulted in a projected generator efficiency of 0.73 for the conducting tether, with a useful power output of 70 kW.

The total drag (aerodynamic and electromagnetic) imposed by the tether power generator is about 13 N in this example, with a corresponding energy decay from the tether of 96 kW. In the absence of propulsion to overcome this drag, the orbit altitude would decrease about 20 km each day if the 96 kW were extracted from the orbital energy of a 100-ton space station. Although such energy extraction would markedly shorten the life of a space station if continued for a long time, this power could be extracted for perhaps a week in an emergency. Spacecraft propulsion could, of course, compensate for this drag and thereby sustain orbit altitude. Both chemical and electric propulsion are likely candidates.

CHEMICAL PROPULSION FOR ORBIT MAINTENANCE

For 70 kW of useful power to be generated by a conducting tether, an average thrust of about 13 N is required to overcome tether drag (fig. 2). In principle, this thrust could be steady or in brief bursts of higher thrust. For a specific impulse of 400 s (already exceeded by hydrogen-oxygen rockets), propellant consumption would average 3 g/s, or 280 kg/day. In turn, propellant consumption would be 0.17 kg/kWh of electric energy. To some in the space-power field, this is a startingly low value of reactant consumption, for it is only 43 percent of the reactant flow required by hydrogen-oxygen fuel cells. In fact, it is also only 58 percent of the reactant consumption of an ideal fuel cell, operating reversibly. How is this possible? The critical factor is the large amount of kinetic energy possessed by the reactants by virtue of their being in low Earth orbit, about 29 MJ/kg. In contrast, the Gibbs free energy for combining hydrogen and oxygen into water is only 13 MJ/kg, the theoretical limit on fuel-cell output per unit mass of hydrogen and oxygen consumed.

What are the various contributions to energy generation by a chemically propelled space station generating electric power via a conducting tether? A rocket having a specific impulse of 400 s can supply 3923 N-s of impulse to the space station for each kilogram of propellant expelled, corresponding to an exhaust velocity of 3923 m/s. For an orbital velocity of 7612 m/s, the rocket's energy addition to the space station would be 29.86 MJ/kg of propellant. What are the constituents of this energy addition? First, the kinetic energy with which the propellant would be discharged from the space station is 7.69 MJ/kg. The propellant-discharge velocity of 3923 m/s relative to the space station would reduce propellant velocity in Earth-centered coordinates from 7612 to 3689 m/s; in turn, its kinetic energy would be reduced by 22.17 MJ/kg. The sum of these two terms equals the 29.86 MJ/kg added to the space station in the paragraph above. The energy account thus balances.

On theoretical ground, the combination of rocket propulsion and a conducting tether can generate 2.3 times the electric energy that a fuel cell can. Although losses with the tether power generator will decrease this advantage, the gain in performance may still be substantial.

An important problem for a space station is to effectively use the residual propellants from the orbiter and the external tank. Readily recoverable amounts of hydrogen and oxygen might average 1000 and 1400 kg, respectively, for each flight of a fully loaded shuttle. On any given flight however, the recoverable residuals might vary substantially from these values, even for a fully loaded shuttle. For many flights, the shuttle's payload will be limited by volume rather than by a mass constraint, and in that event, the amounts of residual propellants would be substantially greater. For example, if the payload mass were 80 percent of the rate value, the propellant residuals might average 1800 and 5400 kg of hydrogen and oxygen, respectively, totaling over 7000 kg. In either case, the proportion of hydrogen and oxygen would be far from the stoichiometric proportion of 1/8. A rocket-sustained power-generating tether can make more effective use of such nonstoichiometric residuals than can fuel cells for three reasons:

(1) Inasmuch as the reactant consumption of fuel cells is 200 to 250 percent of that of the power-generating tether, the tether can produce from a given stoichiometric supply of reactants 2 to 2.5 times as much beneficial product (kilowatt-hours of electric energy).

(2) Because the fuel cell requires a stoichiometric proportion of hydrogen and oxygen, any excess of either would be wasted. In contrast with this, a chemical rocket can readily accept imbalances in the proportions of hydrogen and oxygen.

(3) Contaminating gases such as helium in the propellant-grade hydrogen and oxygen will accumulate in fuel cells unless they are frequently purged to vent the contaminants, a factor increasing the reactant consumption above theoretical values.

Scavenging 7000 kg of hydrogen and oxygen from just a single shuttle flight is sufficient to provide 4.7 kW of power from a rocket-sustained power-generating tether for an entire year. The potential of using these residual reactants is thus clear. On the other hand, the long-term potential of the power-generating tether to supply power to a space station is very sensitive to the level of power required, to the frequency of the shuttle flights to the station, and to the mass of residual hydrogen and oxygen recoverable from the orbiter and the external tank. Consider, for example, the 70-kW power source discussed earlier. Even the rocket-sustained power-generating tether would require 100 tons of hydrogen and oxygen a year, or 1000 tons over 10 years. Either a solar or a nuclear power supply would require far less mass in order to provide the same baseload power. For long-term applications the rocket-sustained power-generating tether is utterly dependent on a supply of "free" propellant. This type of power-generating tether is thus an effective competitor only of other reactant-consuming, chemical power systems such as fuel cells, these power systems being generally limited to missions of modest duration.

ELECTRIC PROPULSION FOR ORBIT MAINTENANCE

The high propellant consumption of the rocket-sustained power-generating tether raises the question, Might this propellant consumption be reduced by switching to electric propulsion, which can attain very high specific impulse Because it can use a variety of propellants, electric propulsion also offers a second interesting possibility: perhaps the residual hydrogen and oxygen could be used for other purposes, such as generating power in fuel cells, and then the product water used as propellant for electric propulsion. In fact, the propellant might be almost any supply of material otherwise wasted. The power source for the electric propulsion could be either the conducting tether itself or an independent power supply; both will be considered. The electric propulsion device might be either an electrothermal jet, an arcjet, an electroplasma-dynamic thruster, or an ion thruster (this list being in order of increasing specific impulse). Thus an entire spectrum of specific impulse is available for consideration.

Not all of the concepts to be explored will be found valuable, but at this stage in the study of tethers, some coarse screening of concepts such as this is worthwhile.

Using Tether-Generated Power

Although electric propulsion with its high specific impulse offers the possibility of lower propellant consumption than chemical propulsion, generating power for the electric propulsion itself will impose an added drag on the tether. Concomitantly, this added drag will increase propellant consumption. Let us briefly investigate how these two factors balance, one increasing and the other decreasing propellant consumption.

For the fiducial case of power generation compensated by chemical rocket propulsion,

$$P_0 = \eta_e D_0 V \tag{1}$$

$$-\dot{m}_0 = \frac{F_0}{I_0 g_0} \tag{2}$$

where

P_0	useful power generated
η_e	overall efficiency of power generation (0.73)
D_0	drag of tether
V	spacecraft velocity (7612 m/s)
$-\dot{m}_0$	propellant flow rate
F_0	propulsive thrust of chemical rocket
g_0	standard gravitational acceleration (9.80665 m/s^2)
I_0	specific impulse of chemical rocket (400 s)

For steady operation, the thrust F_0 must balance the drag D_0, the required propellant flow then being 4.6×10^{-8} kg/J of electric energy.

When electric propulsion is used, the power generated P must be increased by P_f, the power required to produce the thrust, that is,

$$P = P_0 + P_f \tag{3}$$

and

$$P_f = \frac{F I g_0}{2 \eta_f} \tag{4}$$

where

F	thrust
I	specific impulse
η_f	thruster efficiency

As before, the drag D on the tether for this increased power is

$$D = \frac{P}{\eta_e V} \tag{5}$$

Propellant flow rate $-\dot{m}$ is

$$-\dot{m} = \frac{F}{I g_0} \tag{6}$$

For thrust F balancing drag D, combining equations (1) to (6) yields

$$\frac{\dot{m}}{\dot{m}_0} = \frac{I_0}{I\left(1 - \frac{I g_0}{2\eta_e \eta_f V}\right)} \tag{7}$$

Representative values of propellant flow ratio $\dot{m}/\dot{m}_0$ from equation (7) are given in table I for a thruster efficiency η_f of 0.8 and for various values of specific impulse. In each case, the propellant flow rate $\dot{m}$ or $\dot{m}_0$ is that required to produce the same amount of useful power P_0. As specific impulse approaches 907 s, the propellant flow ratio goes to infinity; that is, all the generated power would be consumed for electric propulsion, and none would be left for the useful load.

The minimum propellant flow rate was determined by equating the derivative of equation (7) to zero:

$$I^* = \frac{\eta_e \eta_f V}{g_0} \tag{8}$$

where I^* is the optimum specific impulse. For the nominal conditions assumed herein, this optimum specific impulse is 453 s, the value that for a given useful power P_0 minimizes propellant flow or, for a given propellant flow, maximizes the useful power P_0. For this value of specific impulse, half the generated power is consumed in providing thrust; the remaining half is available to the useful load.

The propellant flow ratio in equation (7) is then 1.76; that is, the propellant flow rate is 76 percent above that for chemical propulsion by a hydrogen-oxygen rocket. From equations (1) to (6), the net useful power P_0 per unit mass flow rate can be expressed as

$$\frac{P_0}{-\dot{m}} = I g_0 \eta_e V \left(1 - \frac{I g_0}{2\eta_e \eta_f V}\right) \tag{9}$$

Substituting equation (8) into this gives

$$\left(\frac{P_0}{-\dot{m}}\right)^* = \frac{\eta_e^2 \eta_f V^2}{2} \tag{10}$$

for the optimum specific impulse. The energy generated is then 12.3 MJ/kg of propellant, corresponding to a propellant flow of 0.29 kg/kWh. This value of propellant flow is 25 percent less than that required by hydrogen-oxygen fuel cells. In addition, hydrogen and oxygen are not required, only any material that can be electrically accelerated to 4400 m/s, corresponding to a specific impulse of 453 s.

The amount of useful power that can be generated in this way depends, of course, on the amount of material available as propellant. Some estimates of consumables to be supplied to the space station early in its evolution run as high as 1 kg/h for each astronaut. Using that quantity of propellant could then produce 3.4 kW of useful power per astronaut, or 27 kW for a crew of 8. On the other hand, an alternative use of that same mass of consumables could provide even more power. Consider, for example, a space station having aboard a powerplant of either the solar or the nuclear type. Not only would such powerplants impose less drag than the power-generating tether, but also substantially higher specific impulse would be practical. Thus that same mass of expended consumables could compensate for the drag of a powerplant of much higher power than would be practical with a power-generating tether.

The electrically propelled power-generating tether offers an interesting opportunity for load leveling. If, for example, the tether power generator were capable of delivering 100 kW of total power, the analysis herein suggests that this would normally be divided into two halves: one for the useful load and the other for propulsion. But that need not always be so. At times of high power demand, the entire output of 100 kW could be used by the useful load. During this time the orbit altitude of the spacecraft would decrease, but only slowly if the spacecraft were fairly massive. At times of below-average power demand, the extra power could augment spacecraft propulsion for reboosting the orbit to its nominal altitude. The average power demand must, of course, be low enough for sustaining the orbit altitude or the spacecraft would gradually descend into the Earth's atmosphere. The spacecraft's orbital energy would constitute the reservoir for storage and extraction of energy, and it is quite a large reservoir. For example, if the orbit altitude of a 100-ton spacecraft were to decrease only 10 km, 850 kWh of electric energy would be made available - the power-generating efficiency being taken as 0.73, as before. Without propulsion to compensate for the tether's drag, this reservoir of 850 kWh would sustain the 100 kW of generated power for 8.5 h.

The characteristics of the concept of electrically propelling a power-generating tether can be summarized as follows:

(1) Useful power can be generated in excess of that required for electric propulsion, maximum power for a given propellant flow being generated in low Earth orbit if the specific impulse is about 450 s.

(2) Almost any supply of propellant can be used, provided only that it can be electrically accelerated to about 400 m/s.

(3) The required flow of propellant is 25 percent less than the hydrogen and oxygen consumed by fuel cells producing the same useful power.

(4) The spacecraft's orbital energy is a large reservoir of energy that would permit temporary diversion of power from propulsion to other purposes.

Propulsion Via the Tether

Reversing the current flow through the tether would convert it from a generator into a motor, that is, into a propulsive device. Of course, power from an independent source of, say, the solar or nuclear type would then be required. The voltage and force on the tether would be essentially unchanged from their values for power generation, the force merely changing sign. In this case, no propellant flow would be required, a very favorable condition for long-term missions in low Earth orbit such as that of a space station. Controlling the current flow would control the thrust magnitude. On the other hand, the thrust direction would be aligned with $\underline{J} \times \underline{B}$ and would thus be beyond control.

The overall efficiency of such propulsion by tether would likely be about the same as that for power generation by tether, herein estimated as 0.73. Although this efficiency is lower than already demonstrated values for electric propulsion, the absence of any propellant consumption at all would be a distinct advantage. The reduced propulsive efficiency would, of course, increase the demand for power, and thereby the mass and cost of the powerplant would also increase. This increased demand for power would thus partially offset the advantage of eliminating propellant consumption.

GENERAL DISCUSSION OF TETHERS FOR POWER GENERATION OR PROPULSION

Because essentially no technology exists for power generation or propulsion by means of tethers, there is a variety of questions concerning the overall feasibility of the concepts. On the other hand, the potential benefits of the concepts warrant investigation in a technology program aimed at delineating their true merits. Critical questions center on the interactions of such a conducting tether with the plasma surrounding the Earth. The impedance of this plasma will greatly influence tether design. A highly conductive plasma would permit large currents, a factor producing shorter tethers and lower generated voltages. Although the shorter tether would tend to reduce aerodynamic drag, high plasma conductivity can be achieved only in regions of high particle density, a factor tending to increase aerodynamic drag. The best operational altitude for these conducting tethers is thus an open question that will substantially influence both their design and their potential value.

Plasma impedance will also affect the size of the required electron collector and thus its weight and aerodynamic drag as well. Plasma interactions (chiefly Alfven waves) may add energy to the plasma in regions well beyond the influence of conventional aerodynamics and may thereby increase aerodynamic drag.

In response to the uncertainties concerning interactions of high currents with the Earth's plasma, a prudent program would decrease risk by using low currents and by accepting the long tethers and the high voltages that result. Electric potentials of tens of kilovolts will require not just insulating the tether but also high integrity of this insulation. A pinhole in the insulation would lead to leakage of electrons. Bombardment of the surrounding insulation by these electrons with kinetic energies of, say, 10 keV would chemically decompose that insulation inasmuch as chemical binding energies are only of the order of 1 eV per atom and thus far below the 10 000-eV energy of the electrons. For that reason, a minute defect in the insulation or even a small amount of damage from particles in space can lead to progressive damage and failure of the insulation. Extensive testing of the insulation in high-vacuum chambers here on Earth would aid in delineating the magnitude of the problem and perhaps point the way to its solution.

Power conditioning for tens of kilovolts is state of the art here on Earth but has yet to be evolved for space. In particular, the usual power conditioning for space accepts low input voltage and increases as well as regulates the voltage for supply to the useful loads. In using power from a conducting tether, the power conditioning would be required to reduce voltage for delivery to the loads, a transformation requiring a new technology. An additional factor affecting power conditioning is variation in the generated voltage as the result of variation in $\underline{v} \times \underline{B}$ along the flightpath as well as variation in the properties of the space plasma.

Using tethers for power generation or propulsion would also encounter some of the same problems as does every application of tethers in space, namely, the dynamics and structural problems associated with tether deployment, orbit maneuvers, and rendezvous with other spacecraft.

SUMMARY OF RESULTS

Power generation in low Earth orbit by means of a conducting tether trailed off a spacecraft was studied. Analysis of this concept as well as propulsion (both chemical and electric) to sustain the power-generating tether produced the following results:

1. Assessment of losses in power generation showed that efficiency of power generation might be about 0.73.

2. In the absence of propulsion to sustain the spacecraft, the orbit would slowly decay, the decrease in altitude being 20 km a day if the generated power were 1 kW/ton of total spacecraft mass. Power might be extracted for perhaps a week in an emergency, but this would not be a suitable strategy for any extended mission.

3. If a hydrogen-oxygen rocket were to provide the propulsion to sustain the low Earth orbit of a spacecraft generating power by means of a conducting tether, the propellant consumption would be less than half the consumption of hydrogen and oxygen by fuel cells producing the same power. For missions beyond perhaps a month, neither concept is weight-competitive with solar or nuclear powerplants.

4. If residual hydrogen and oxygen from the shuttle's external tank and orbiter were available to the spacecraft, the rocket-sustained power-generating tether could make better use of these residues than could a fuel cell because (a) the proportions will likely not be stoichiometric and (b) the residues may contain impurities such as helium. Both of these conditions a rocket tolerates better than do fuel cells.

5. A single lightly loaded shuttle might have propellant residues totaling 7 tons. That quantity of hydrogen and oxygen would permit generation of 4.7 kW of power by a rocket-sustained power-generating tether for an entire year.

6. On the other hand, the rocket propellant to sustain a 70-kW power-generating tether for 10 years would total 1000 tons, perhaps 100 times the mass of a solar or nuclear powerplant.

7. A conducting tether could provide useful power plus power for electric propulsion to compensate for its own drag. The propellant could be any available supply of material (such as waste from life support) capable of electrical acceleration to about 4400 m/s (specific impulse of 450 s). The generated power would be divided equally between the useful load and electric propulsion. Not only would fuel cells require the specific reactants hydrogen and oxygen in the stoichiometric proportion but the mass consumption of those reactants would be about 1/3 higher than the propellant consumption of the self-sustaining tether. A self-sustaining power-generating tether would by its nature permit load leveling for peak-to-average powers of 2 to 1, the spacecraft's orbital energy being the energy reservoir.

8. If early in the evolution of the space station discharges of waste from life support run as high as 1 kg per astronaut-hour, use of this mass of waste as propellant in electric propulsion of a self-sustained tether could continuously provide 3.4 kW per astronaut, or 27 kW for a crew of 8.

9. Several questions concerning the feasibility of the power-generating tether must be answered by a technology program before such tethers are used in space. The questions concern the following: plasma impedance in low Earth orbit, use of low currents and high generated voltages to circumvent high plasma impedance, aerodynamic drag on the tether, losses in the plasma, the performance of electrical insulation in space at potentials to tens of kilovolts, and power conditioning for these high generated potentials. These issues are in addition to the usual questions concerning feasibility of tethers in space, namely, the dynamic and structural problems associated with tether deployment, orbit maneuvers, and rendezvous with other spacecraft.

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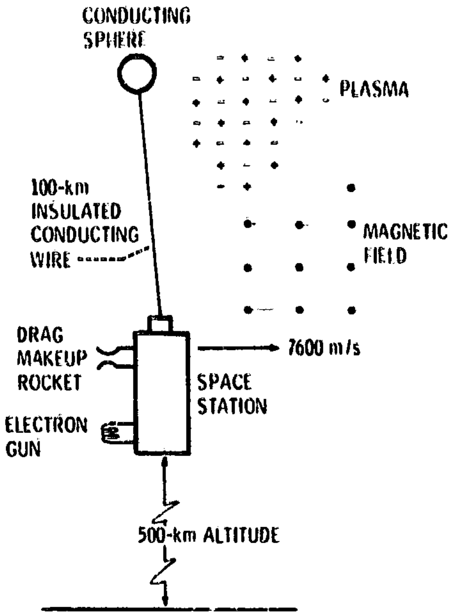

Figure 1. - System elements of a power-generating tether.

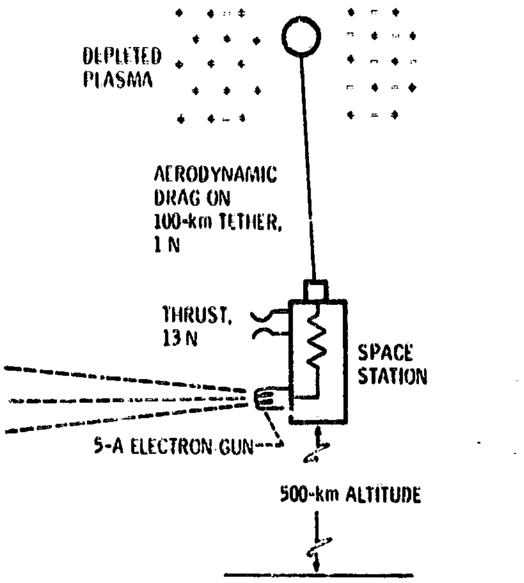

Figure 2. - Operating characteristics of a representative power-generating tether. EMF, 17 500 V; current, 5 A; power, 88 kW; line loss, 14 kW; power to load, 74 kW; electron gun loss, 4 kW; net to station, 70 kW; aerodynamic drag energy loss, 8 kW; total energy drag on space station, 96 kW; efficiency, 73 percent.