

N86 - 28415

ELECTRODYNAMIC INTERACTIONS

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To begin with, I will be concentrating mostly on power and thrust applications, although there are a number of other applications of the electrodynamic tether.

To orient you, (Fig. 1) these two very similar looking spacecraft configurations are exact opposites. This is a power generator, and this is a motor.

The differences are just a little bit subtle. The induced voltage in the tether wire is in the same direction in both cases, and the difference involves whether you allow that voltage to drive a current to generate power.

Or, if you use an onboard power supply with a higher voltage to drive a current in the opposite direction, which then provides thrust.

If you are generating power, the magnetic field's (IXB) force on the current in the tether wire is directed against the orbital velocity and gives you a drag force. Neglecting losses in the system, this force provides exactly the mechanical work ($F \cdot V$, in joules/sec) to balance the amount of power that you are producing (in watts) as electricity.

The forces and currents in the motor operation are in the opposite direction, but the forces and the flow of energy still balance, neglecting electrical resistance losses, air drag and so forth. The electrical power that is involved in driving this current against the induced voltage in the tether is exactly equal to the mechanical energy being added into the orbit by accelerating the spacecraft.

The key factor in doing this is the fact that you have a return circuit, which is stationary throughout, for the current due to the moving "armature wire", if you will, in this "motor-generator" system.

ELECTRODYNAMIC TETHER PRINCIPLES

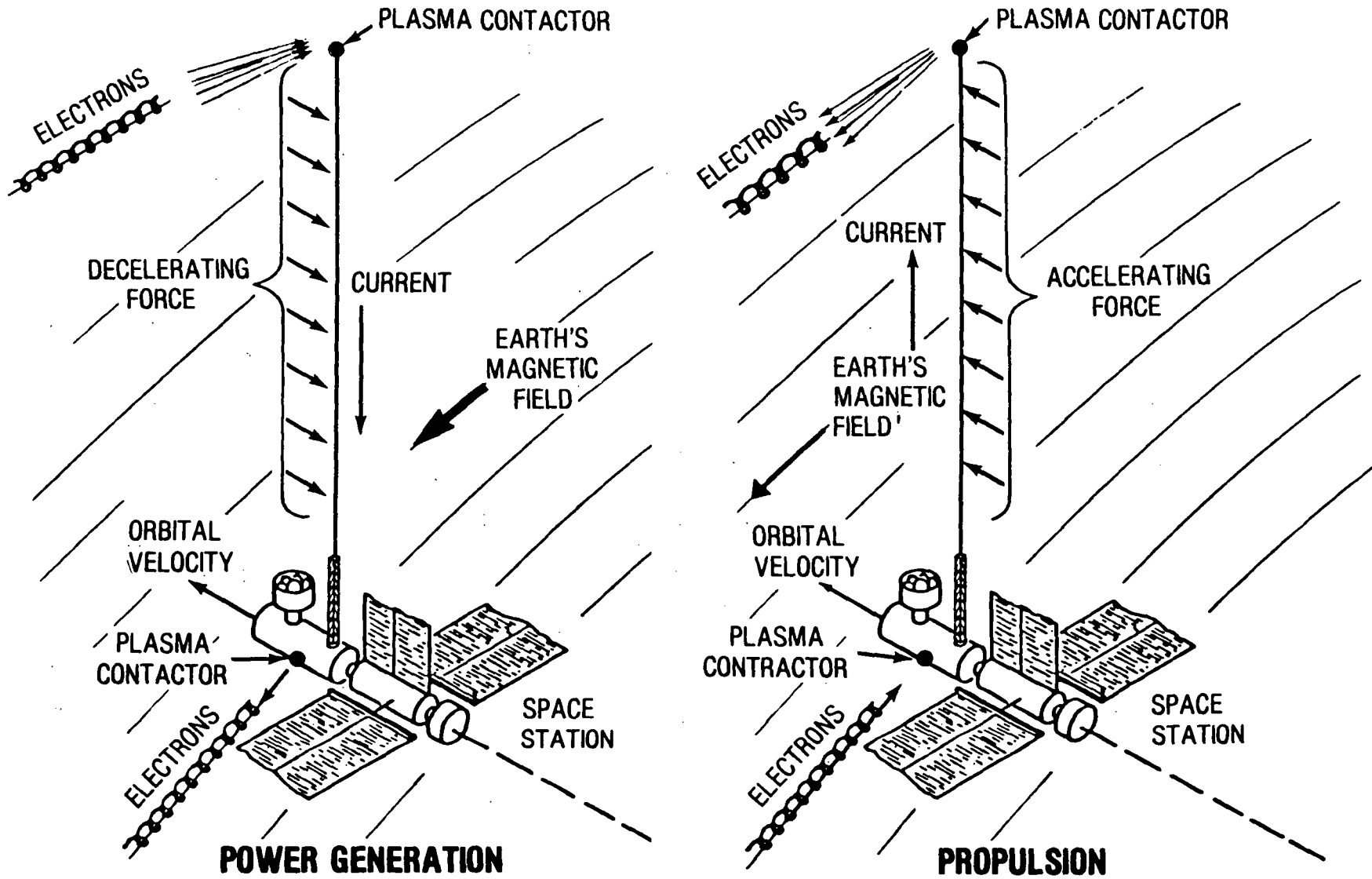


Figure 1

You have to spread these (return circuit) currents out through the ionosphere sufficiently so that ionosphere conductivities are very high and so that you don't produce anomalous resistances in the ionosphere which would prevent the current from flowing. This is largely a function of the plasma contactors that are used, which can be of a number of varieties. There have been three systems most frequently considered. For example, on the TSS satellite, the top contactor here is a conducting balloon. It makes contact over a sufficiently large area of the surrounding ionosphere via a combination of magnetodynamic waves and, mostly, just a large enough physical dimension so that the current in the tether is spread over a large enough surface area that the current densities are reduced to the external ionosphere current densities. The ionosphere can then sustain these currents.

At the bottom end, a similar contact could be made by a conductive surface of the Shuttle (or whatever spacecraft it is attached to), but the surface area required for a given current in collecting ions at this end, as opposed to electrons which have higher thermal currents up here, would be much larger and, in fact, you are limited to very small currents. As a result, it's been proposed to use an electron gun here, which would give the equivalent of a positive current in by ejecting a negative electron current out. This is ejected at a high energy and strongly forces the distribution of the beam of electrons over an effectively large contact region.

The third system for making this contact -- and the one that I'm most interested in -- is a hollow cathode or other plasma generating system, which, instead of producing a physically large balloon or metal shell to collect currents on a conducting surface, generates a conducting surface by producing a plasma, of very high density at the tip of the wire, falling off to ionospheric densities at large distance away.

The thermal currents anywhere within this "plasma ball", if you will, are able to -- should be able to -- conduct the tether currents through the system and provide you with good conductive contact if you are able to maintain this "plasma ball" with a sufficient dimension and you are able to maintain high conductivity through the ball without it being impeded (by magnetic fields or plasma instabilities for example).

Those are the three concepts that have generally been used and that we have been studying the last few years for applications.

This (fig 2) is a summary from about a year ago that really presents, I think, about the state we're in right now.

The findings of interest were our conclusions that, for the primary power and thrust applications, the hollow cathode seems to be far superior to the electron gun for producing high current contact to the ionosphere. This is by no means unchallenged, and it is by no means completely exclusive -- for particular applications, other methods, such as passive collection or electron guns for a particular application, may be desirable.

This led to a study of something that I refer to as the Plasma Motor Generator (PMG) because, as well as being capable of much higher currents, it's capable of being reversible. You can reverse the currents without having to swap ends with the balloon and the electron gun or duplicate them at the two ends. And nobody has to turn a switch to change from one to the other.

These systems, basically, appear favorable for very high efficiency operation at a kilowatt to a megawatt of power and involve much shorter and more massive conducting tethers than the low current systems. Ten to twenty kilometers of aluminum conductor weighing perhaps a thousand to a few thousand kilograms would be used for the tether wire.

The dynamics of these things are also rather different from the light

ELECTRODYNAMIC TETHER

FY84 FINDINGS

- ⊛ ENGINEERING STUDY OF TETHER POWER GENERATOR
- ⊛ HOLLOW CATHODE FAR SUPERIOR TO ELECTRON GUN FOR CURRENT CONTACT
 - * STUDY AND PRELIM DESIGN OF PLASMA MOTOR/GENERATOR SYSTEMS
>90% EFFICIENCY for OPERATION AT 1 KILOWATT - 1 MEGAWATT
 - * 20KW REF SYSTEM: 10 KM #2-AWG ALUMINIUM/TEFLON 1200 KG
 - * 200KW/25 NEWTON REF SYSTEM: 20 KM #00 AL/TEFLON 4100 KG
- ⊛ STUDY OF MASSIVE TETHER DYNAMICS: IXB @20-200KW, NO SATELLITE
 - * GENERATOR REQUIRES VARIABLE DC LOAD IMPEDANCE TO CONTROL I (KW)
 - * MOTOR REQUIRES VARIABLE POWER SUPPLY VOLTAGE TO CONTROL I (N)
 - * PRELIMINARY SHUTTLE/TETHER CHARGING MODEL
 - * FEASIBILITY STUDY OF TETHER/RESISTOJET 2KW/ASTRONAUT CONCEPT
 - * ELECTRICAL COMPONENTS NEED TECHNOLOGY FOR 1-4KV (2KV MIN.)
- ⊛ MOST PROMISING APPLICATIONS IDENTIFIED:
 - * USE WITH SOLAR ARRAY TO OFFSET DRAG IN LEO
 - * USE WITH SOLAR ARRAY TO REPLACE BATTERY POWER STORAGE
 - * USE FOR ORBITAL MANUEVERING PROPULSION
 - * USE WITH FREE-FLYER FOR STATIONKEEPING, THRUST, & POWER
- ⊛ PRELIMINARY DESIGN OF PMG/HOLLOW CATHODE VERIFICATION TEST

tether with a massive satellite at the end. These would have no appreciable satellite on the end at all. The mass of the system providing the stabilizing tension in the tether is entirely in the cable itself, and the deflection forces are dominantly the I Cross B (IXB) force terms. Most of the concepts would involve these systems being permanently anchored to a spacecraft which, of necessity, then would be permanently in orbit, rather than something that you reel out and reel back in for a couple of days operation.

Again, there would be specialized applications using either a disposable tether or perhaps one with a reeling system at the far end of the massive cable to provide additional stability.

The concepts that have appeared most promising to us and are receiving the strongest study right now are using PMG's with solar arrays to provide power to the tether. These are intended mostly to generate thrust, rather than to produce power. These concepts are: A system to offset drag in low earth orbit; To replace batteries to store power during the daytime and then take it back out of the orbit at night, with any solar array based power system; For general orbital maneuvering propulsion, using electrical power only. When used in the thrust mode, the tether provides continuous low thrust levels, without requiring large amounts of mass expended over a long period of time.

Examples of farther-out uses include station keeping for orbital platforms, thrust and power in a combination package, or extremely high delta-V spacecraft for use in orbit around Jupiter or Saturn.

The reason why we've come to favor the hollow cathodes for the current conduction applications is illustrated here (fig. 3).

In terms of the amount of power that can be extracted and the amount of the available electrical energy that is used in the process of carrying these currents to the ionosphere, today's electron guns typically require something

PMG - 20 KW REFERENCE SYSTEM

TETHER LENGTH	10 KM	WORKING TENSION	21 N
NOMINAL VOLTAGE	2 KV	WORKING ANGLE	7 DEG
RATED POWER	20 KW	RATED THRUST	2.5 N
PEAK POWER	125 KW	PEAK THRUST	>40. N
CONDUCTOR	#2 AWG ALUMINUM WIRE DIAMETER 6.5 MM @ 20°C RESISTANCE 8.4 OHMS @ 20°C 7.7 OHMS @ 0°C 7.1 OHMS @ -20°C		908 KG
INSULATION	0.5 MM TEFLON (100 VOLT'S/MIL)		99 KG
FAR END MASS	10 AMP HOLLOW CATHODE ASS'Y (INCLUDING ELECTRONICS & CONTROL)		10 KG
TETHER CONTROLLER	ELECTRONICS & MISC. HDWR. (POWER DISSIPATION LOSSES @1% = 200W)		83 KG
ARGON SUPPLY & CONTINGENCY RESERVE			<u>100 KG</u>
TOTAL			<u>1,200 KG</u>

TETHER DYNAMICS CONTROL	PASSIVE, IXB PHASING	
TETHER CURRENT/POWER CONTROL	DC IMPEDANCE MATCHING	
TETHER OUTSIDE DIAMETER	7.5 MM	
TETHER BALLISTIC DRAG AREA	75 SQ. METERS	
DRAG FORCE @ 10 ⁻¹¹ KG/M ³ (300 KM 1976 USSA-400 KM SOLAR MAX)	.045 N	.36 KW
I ² R LOSSES @ 20 KW		.77 KW
HOLLOW CATHODE POWER		.50 KW
IONOSPHERIC LOSS @ 10 AMP		<u>.05 KW</u>
TOTAL PRIMARY LOSSES		1.68 KW
EFFICIENCY	ELECTRIC (18.68 KW NET @ 10 AMP/20 KW)	93.4%
	OVERALL (20.36 MECH. TO 18.68 ELEC. KW)	91.7%
INCLUDING CONTROLLER/POWER PROCESSER LOSSES @ 1%		<u>.20 KW</u>
TOTAL (NET POWER OUT 18.48 KW)		1.88 KW
FINAL EFFICIENCY	ELECTRIC = 92.4%	OVERALL = 90.8%

Figure 3

like a kilovolt of acceleration voltage for an ampere of current, which consumes a lot of the available power, and also produces a substantial heat problem.

Fig 4 shows the results of a test performed on a hollow cathode assembly recently, for electron extraction. Once the thing reaches an effective turn-on voltage where it becomes conducting for the electrons, you can pull several amperes of electrons from the system with a total extraction voltage of ten or twenty volts.

There are two currents that are flowing in this hollow cathode system. The first is a discharge current, which sustains the plasma in the thing, the data points here were taken for three different sustaining currents; three-tenths of an amp, nine-tenths of an amp, one and a half amps. The second is the current extracted from the system (to the surrounding chamber walls, or a surrounding ionosphere in space), which is plotted along the vertical axis versus extraction voltage on the horizontal scale.

You will notice that, even for extracted currents of an amp or more, well in excess of the basic sustaining current, there is little dependence on sustaining current. The tether current capacity is well in excess of the hollow cathode discharge current, the one you have to expend power to drive with internal power supplies to keep the thing operating. Even the 0.3 amp discharge (less than 10 watts) can easily carry tether currents in excess of an ampere.

There is another characteristic of the hollow cathode system which is perhaps even more attractive. And that is that the tether current can be reversed. You can also use it to draw a positive current.

The positive current drawn from this device is shown as this curve here(labeled "ions"), and this is times ten. It's magnified ten times. It's



SNOO4 HCR — 18 SCCM XENON
 VARIOUS ANODE CURRENTS

actually a rather small current, relatively speaking. But it allows the tether current to be reversed. And, more importantly, this current is not the one that directly provides the current from a tether to the ionosphere. It simply provides the plasma required to maintain conductive conditions. If you turn on an external source of electrons, then, instead of drawing ions from the cathode, it provides a very conductive path for those electrons to reach the cathode, (which was this data here). The thing is able to conduct an electron current that is many times the ion current produced from within its discharge.

The result is that you can design tether systems to operate at higher currents, which get the same power at much lower voltages. This can allow you to either use a shorter tether and operate at operating voltages of one to a few kilovolts, which are more reasonable to engineer power processing systems for, or can allow you to go to extremely high powers.

For tether power generation, as illustrated here (fig 5), we studied net power delivered to a load by a tether length of 20 kilometers, which would give a nominal working voltage of four kilovolts. The curves show net electrical power produced by tethers of three different masses. Heavier cables have lower resistance, allowing higher powers and/or higher efficiency of power production.

To make up this mechanical power (converted to electrical), either you can expend a propellant in a rocket system; which is more efficient for an intermediate term of operations than, for example, fuel cells in terms of kilowatt hours of electricity produced per kilogram of consumables.

Or you can use excess fuel from some other operation.

Or you can kill off excess orbital altitude that you want to get rid of for some reason.

In later applications, this altitude might very well come from some of the

TETHER POWER GENERATOR

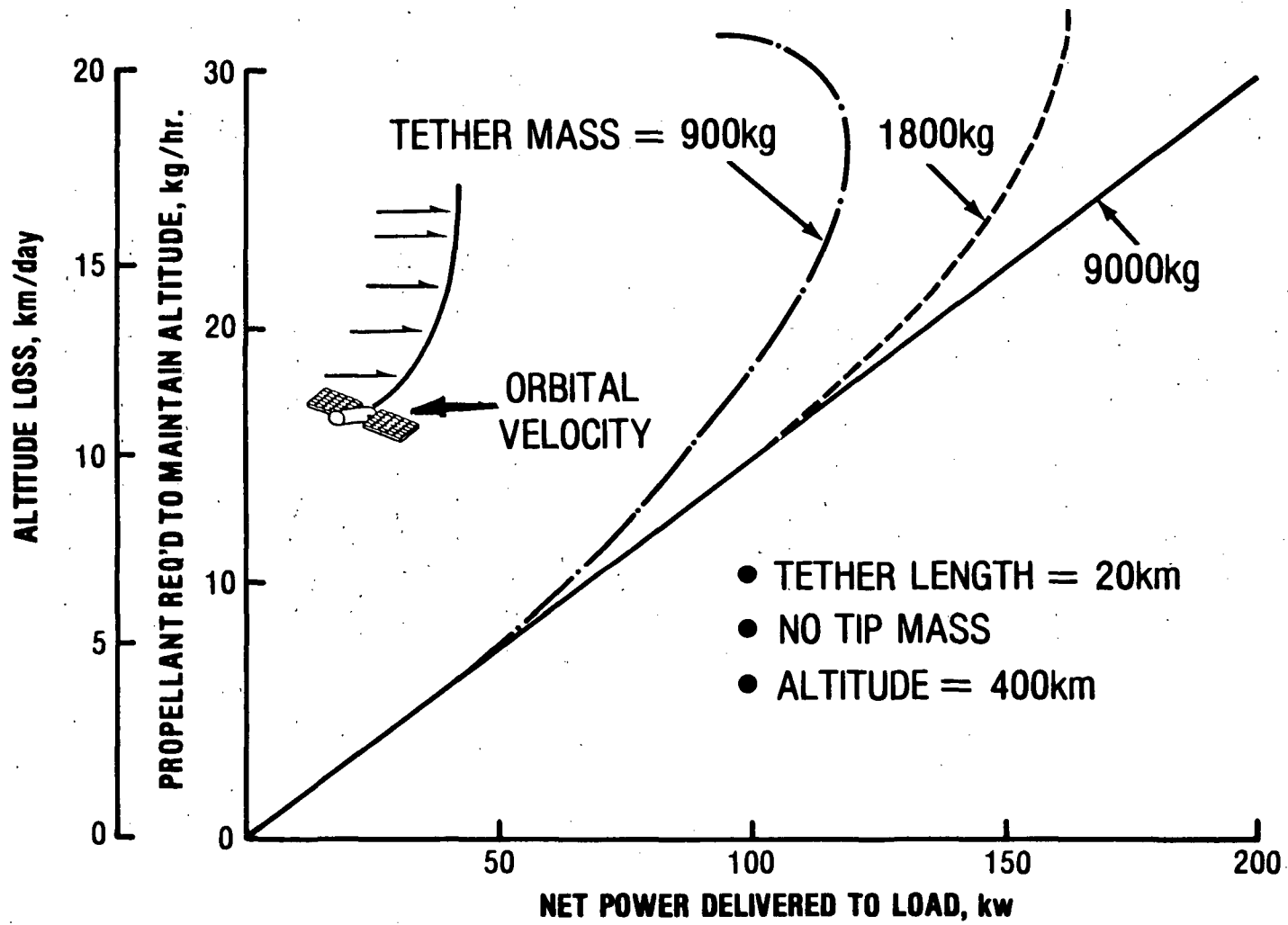


Figure 5

tether transportation concepts where the de-orbiting of the Shuttle is done via a non-conducting tether, which results in boosting the spacestation or whatever to a higher orbit, and you could then utilize that orbital energy (beyond what was needed for drag makeup, among other things) to produce power.

As I mentioned, the concept that I have been finding more interesting is using the thing as a propulsion system. (fig 6) Again, a similar type system at energies of tens of kilowatts would produce Newtons of thrust. This could, for example, maintain the spacestation against the residual atmospheric drag at a lower altitude than they are presently constrained to.

Or, over a period of a number of months or years, if this thrust is continuous, this amounts to a very substantial Delta-V for systems in low earth orbit or in orbits where the magnetic field is high, such as Jupiter orbit.

(Fig. 7) The initial systems we have been looking at would use a small light-weight system with an available power supply of kilowatts to offset drag in low earth orbit. The power required could come either from a large spacecraft like spacestation or a large solar array, perhaps a utility solar array left in orbit between missions.

The payoff is that the fuel that would normally be required to keep a high drag object in orbit is eliminated. In fact, a kilowatt of power consumed in this way in orbit is the equivalent of something like a ton per year of fuel expended for orbit maintenance.

Carrying that a step forward, going to a larger more powerful system, a ten newton thrust system could be capable of continuous operation. This could provide altitude changes for something the size of the spacestation of several kilometers a day, or a hundred kilometers a day for a free flyer.

The total impulse, if you integrate this over a period of time, is extremely impressive.

TETHER THRUST GENERATOR

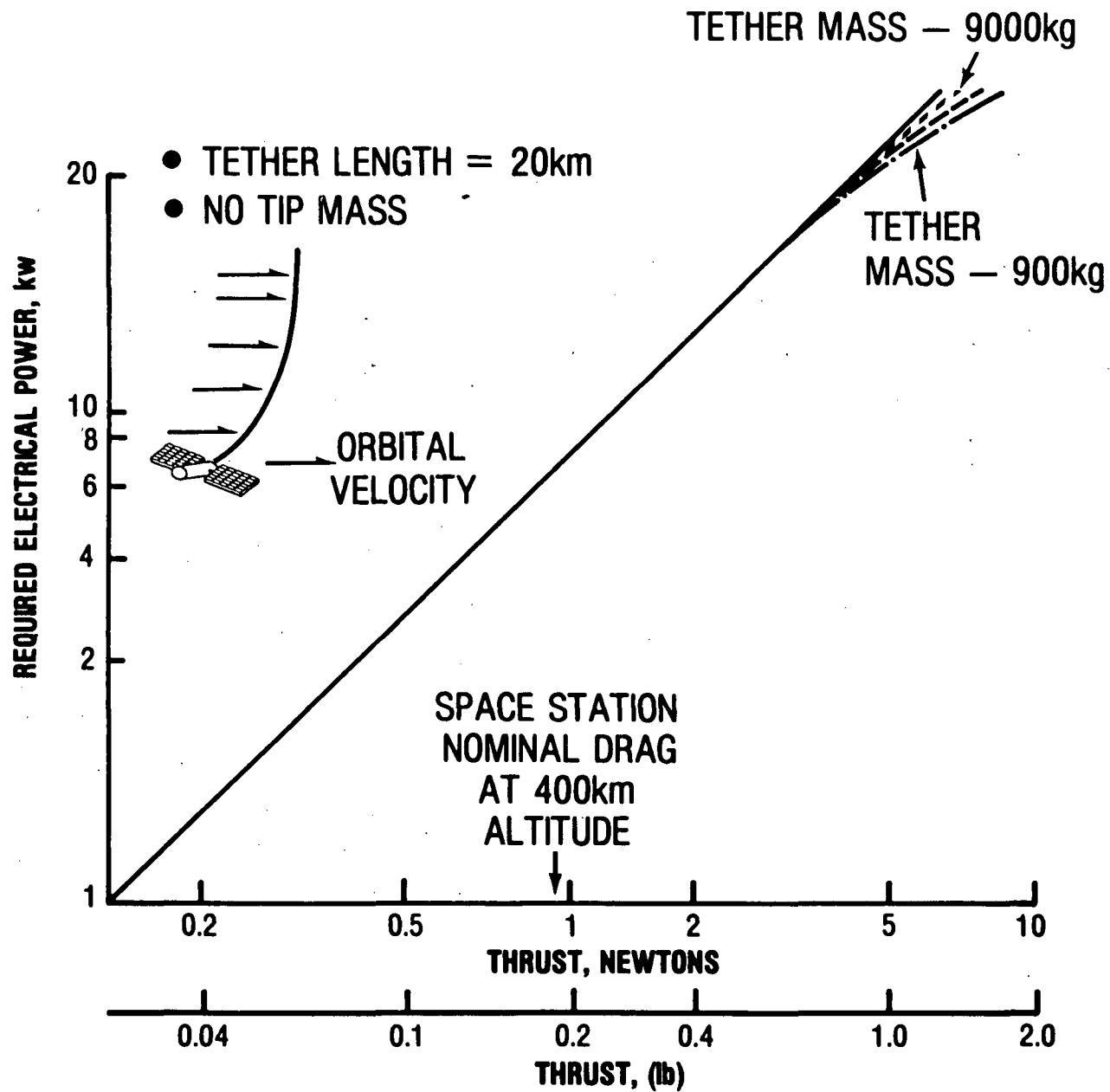


Figure 6

ELECTRODYNAMIC TETHER
RECOMMENDED APPLICATIONS

I. THRUST - USE WITH SOLAR ARRAYS IN LOW EARTH ORBIT TO OFFSET DRAG

100 KG SYSTEM PRODUCING .1 NEWTON THRUST

8 KW/N ELECTRIC POWER CONSUMPTION = .8KW

ELIMINATES DELTA-V FUEL REQUIRED: >1,000 KG/YR

KEEP 100 KW SOLAR ARRAY @ SPACE STATION ORBIT

INCREASE TO 200 KG SYSTEM @ 1-2 N THRUST

KEEP SPACE STATION + 100KW ARRAY IN <300 KM ORBIT ALTITUDE

NO ORBIT MAINT. FUEL REQUIRED; CONSUMABLES = < 60 KG/YR (ARGON)

USES 10-15 KW FROM 100 KW AVAILABLE

II. THRUST - USE FOR ORBITAL MANUEVERING PROPULSION

2,000 KG SYSTEM (PLUS 80 KW POWER SUPPLY: SOLAR, NUCLEAR, WHAT-EVER)

10 NEWTON THRUST - CONTINUOUS AS LONG AS POWER AVAILABLE

ALTITUDE CHANGE

7 KM/DAY - 200,000 KG (SPACE STATION)

30 KM/DAY - 50,000 KG (PLATFORM)

150 KM/DAY - 10,000 KG (FREE-FLYER)

TOTAL IMPULSE: 864,000 N-SEC/DAY (194,000 LB-SEC/DAY)

17 M/SEC/DAY - 50,000 KG (PLATFORM)

86 M/SEC/DAY - 10,000 KG (FREE-FLYER, OMV, OR "TUG")

ORBIT PLANE CHANGE: 30 DEGREE IN 6 MONTHS MAY BE POSSIBLE

"FLY" ENTIRE SPACE STATION DOWN TO 200-250 KM ALTITUDE & MAINTAIN

GROWTH VERSION: 200 N @ 1.6 MW, 20,000 KG + POWER SUPPLY

III. POWER STORAGE - 100KW SOLAR ARRAY SYSTEM

+ 2,000 KG REVERSIBLE MOTOR/GENERATOR TETHER SYSTEM

60 KW THRUST DURING DAY (POWER STORAGE AS ORBIT ENERGY)

100 KW POWER GENERATION DURING DARK

TOTAL SYSTEM WEIGHT 40% OF CONVENTIONAL ARRAY WITH BATTERIES

10% REDUCTION IN SOLAR ARRAY SIZE

60% REDUCTION IN POWER PROCESSING HEAT REJECTION REQUIRED

Another application would be a reversible system, for power storage in place of batteries, which turns out to have a higher theoretical efficiency than charging and discharging of batteries. This application would require operating with about sixty kilowatts of power for thrust during the day, in effect, to "charge" the orbit by boosting the orbit altitude, then to use that excess orbit energy to generate a hundred kilowatts from the tether at night.

We calculate the total system weight as something on the order of forty percent of current state-of-the-art solar arrays and batteries. (see also fig 10). Elimination of batteries is where most of the weight comes from. However, the additional efficiency gives you both a reduction in the solar array size and a reduction in heat rejection that has to be handled by the system.

As a basis for these studies, we have produced something similar to a design curve for calculation of the performance of a system as a function of the net electrical power either put into the system as a motor, or taken from the system as a generator. (fig 8).

The numbers along the top of the plot are orbit drag. This will be one newton; ten newtons here, corresponding to one to a hundred kilowatts of power. You can convert that drag force to equivalent orbital drag power -- or propulsion energy -- which is shown along the bottom scale.

A given system -- this particular system is the 20-kilowatt reference aluminum tether system -- would then have a performance curve approaching an ideal -- a hundred percent efficient system would lie along the diagonal. For power generation, actual systems would be a curve somewhere below and to the right in the region marked "Generator Operation".

The upper left half of the plot will contain corresponding performance curves for operation as a motor.

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900 kg PMG
400 km orbit

ELECTRIC POWER vs ORBIT THRUST/DRAG

10 km tether
#2 AWG Aluminum

Thrust/Drag Force (Newtons) →

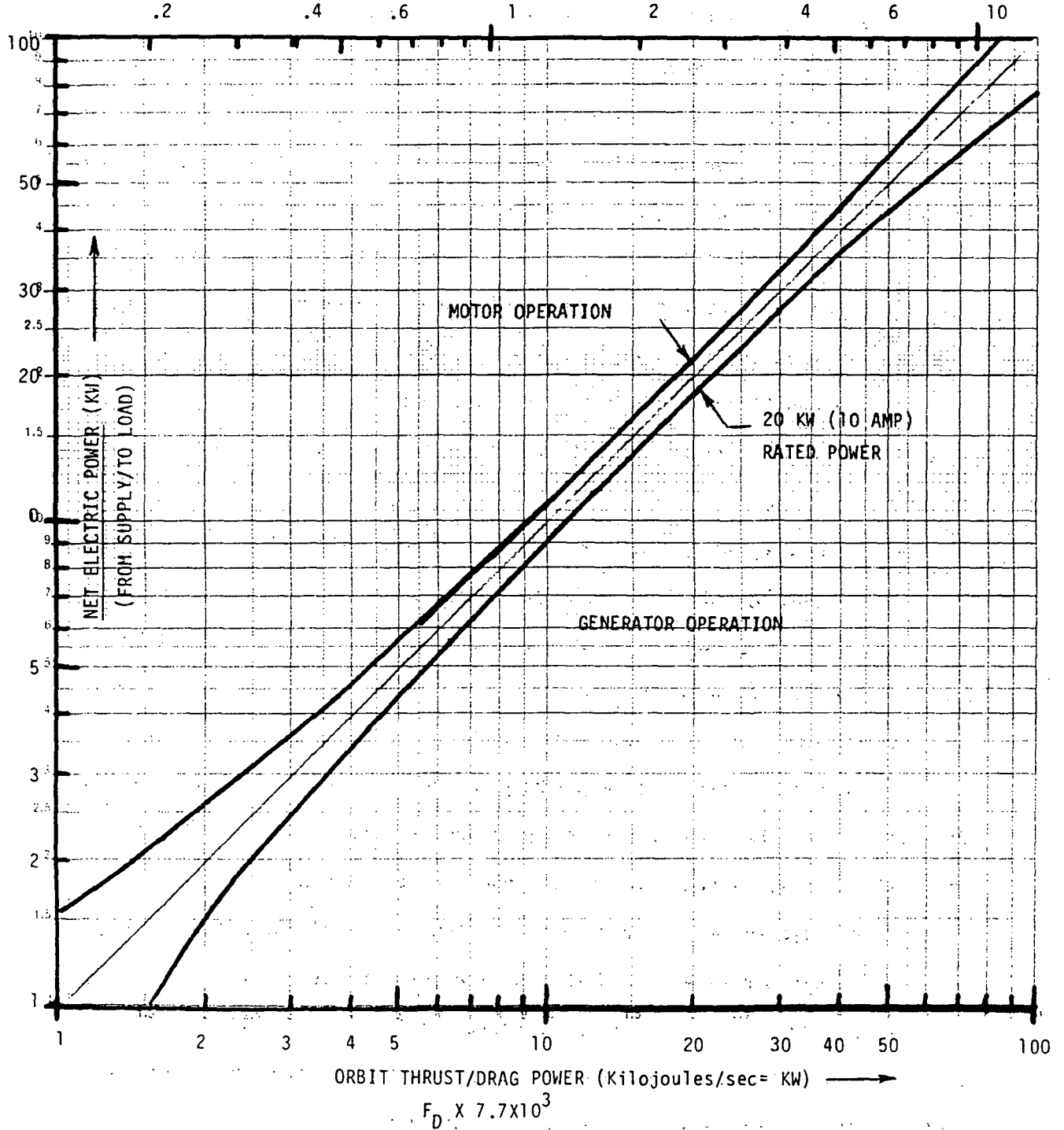


Figure 8

The pair of curves (motor and generator) for an efficient system will be close together. and there will be little power and energy lost in moving it back and forth between them.

For an inefficient system, the curves lie farther apart and you have larger power losses to tolerate in going back and forth between electrical power and power stored as orbital energy.

The system efficiency scales, primarily, with the mass of the tether conductor, if the hollow cathodes can effectively eliminate the power losses in making current contact with the ionosphere. If the estimated effective ionospheric impedance of an ohm is approximately correct, then the primary losses are in resistive loss in the tether wire itself. (Fig. 9)

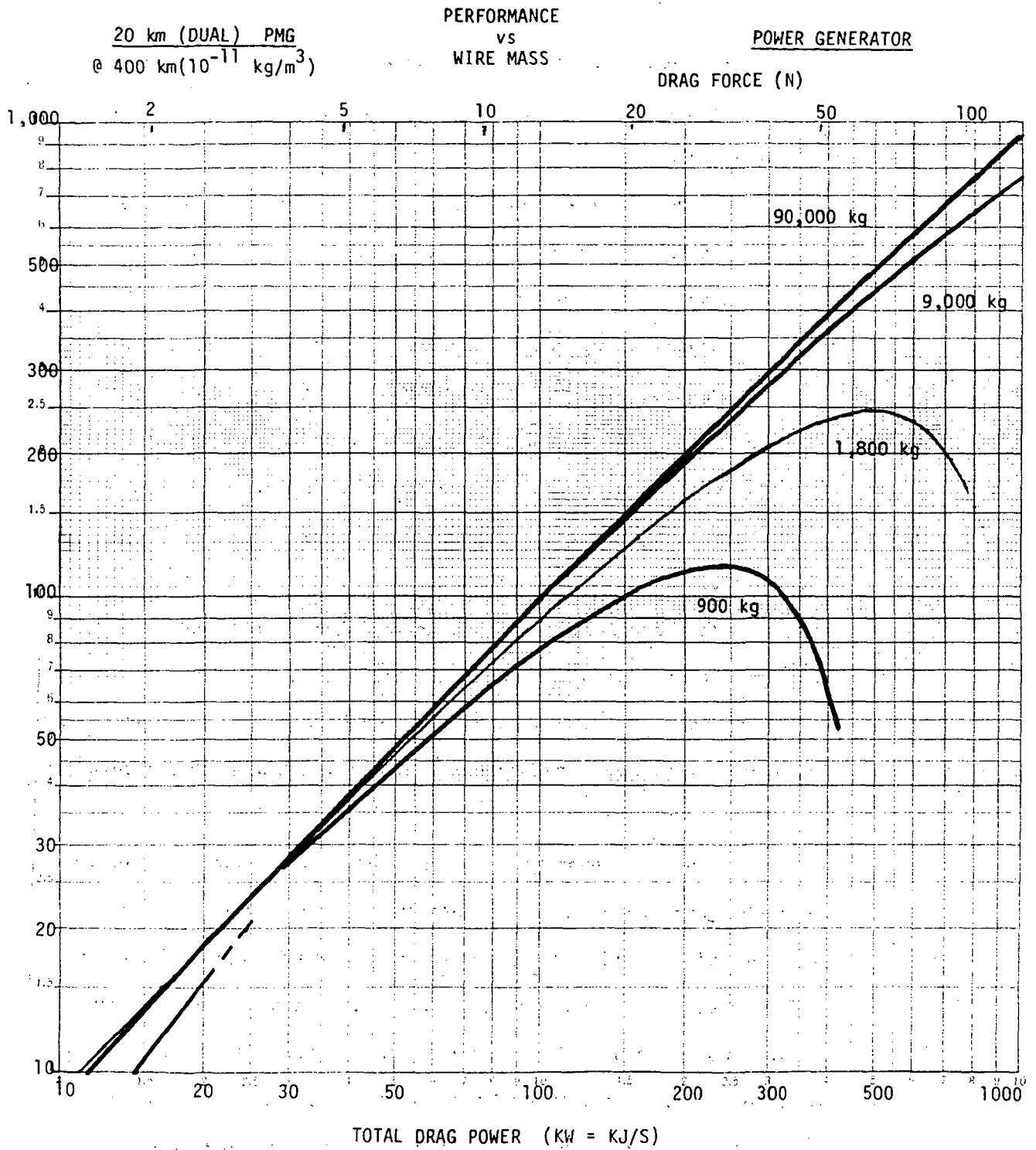
Aluminum is used in these designs as the conductor. It is just about as good as any of the exotic materials that have come to our attention. It is about twice as good as copper on a conductivity per mass basis. Since it's mass in orbit that you have to pay for, and the performance of the system turns out to be almost directly proportional to mass, aluminum looks best for most tethers.

If you want -- if you were curious about how the plot of performance for the nine thousand kilogram system could be extrapolated out here beyond a thousand kilowatts -- if you shifted all these scales by an order of magnitude and made this (full scale) ten thousand kilowatts, then this (the 900 kg curve here) would be the nine-thousand kilogram performance plot. To first approximation. There are some minor differences in the power losses in the hollow cathodes. Eventually it becomes significant. And the ionospheric losses eventually become significant.

For a quick illustration, I'll discuss the replacement of batteries.

This is a plot (fig 10) of resources necessary to operate a 100 KW solar

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array power system. This is versus altitude from 500 kilometers down to 200, and fuel required to reboost or to maintain the thing in orbit. If you ran a solar array and used rockets to reboost it, you would be working on this prohibitive curve. This is one of the reasons why the spacestation is up at 500 kilometers, not down around Shuttle altitudes, because you would have to carry too much fuel up to maintain the orbit.

But, by using these two different versions of this system, you could bring these requirements well down within the practical region to operate at lower orbits with the thing.

Or, up at the higher orbit, the total mass required could be reduced -- immediately -- or, in the second concept, over a period of ten years -- very substantially beyond what the existing system provides.

Then, finally, let's get away from the mundane and move out to Jupiter for a while, to illustrate the power of this thing.

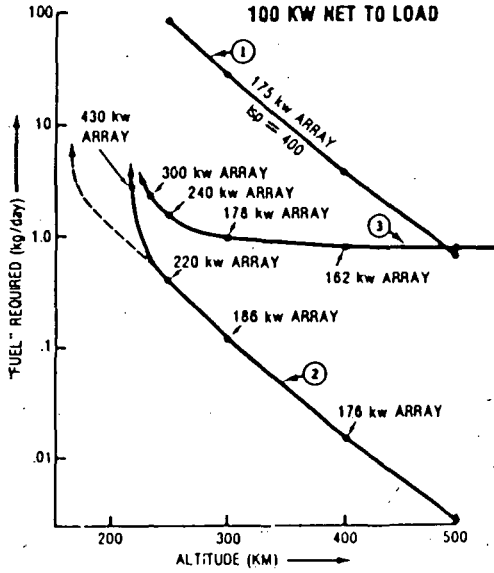
Jupiter gravity is very strong. Fig. 11 shows the total orbit energy versus distance from Jupiter, in Jupiter radii. The scale is from the surface of Jupiter (at 1.0 R_J) logarithmic thru one hundred Jovian radii.

The major moons, Io through Callisto, are shown as points along the plot of orbit energy vs. distance. Also plotted here (I hope this isn't confusing) is orbit velocity and magnetospheric corotation velocity versus distance. The vertical axis, for orbit energy, is expressed in units of megajoules per kilogram, up to a thousand (on the left side). On the right side, I converted this to kilowatt hours per kilogram.

The energy to go even to the moons is very high compared, for example, with the energy required to launch from the surface of the earth to a low earth orbit (about 8 KWHR/kg; for reference this is marked on the plot, near the energy level of Callisto's orbit).

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CONSUMABLES REQUIRED VS ORBIT ALTITUDE



- ① 175KW Array, Batteries, Rocket Reboost
- ② 176KW Array, Batteries, 1KW PMG Reboost.
- ③ 162KW Array, 100KW PMG Storage & Reboost

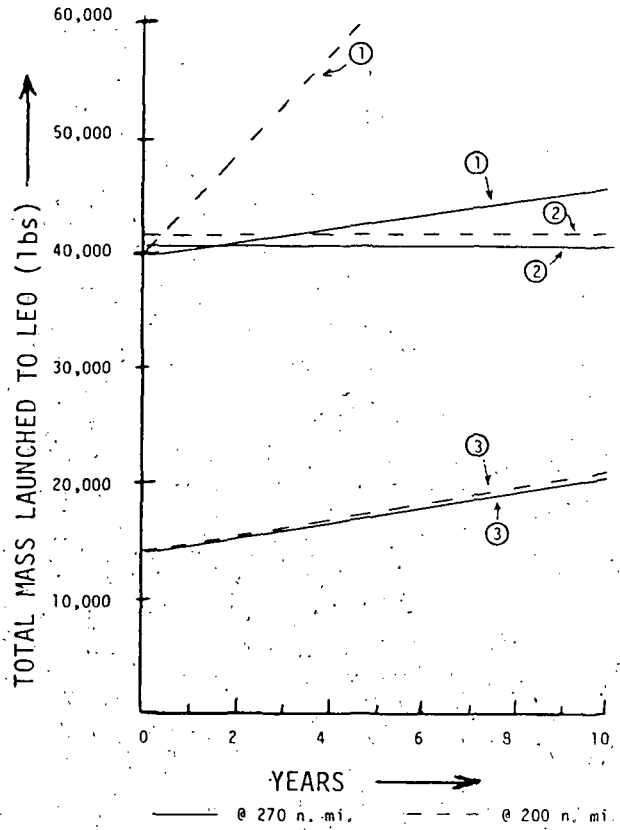


Figure 10

JUPITER ORBIT ENERGY vs RADIUS

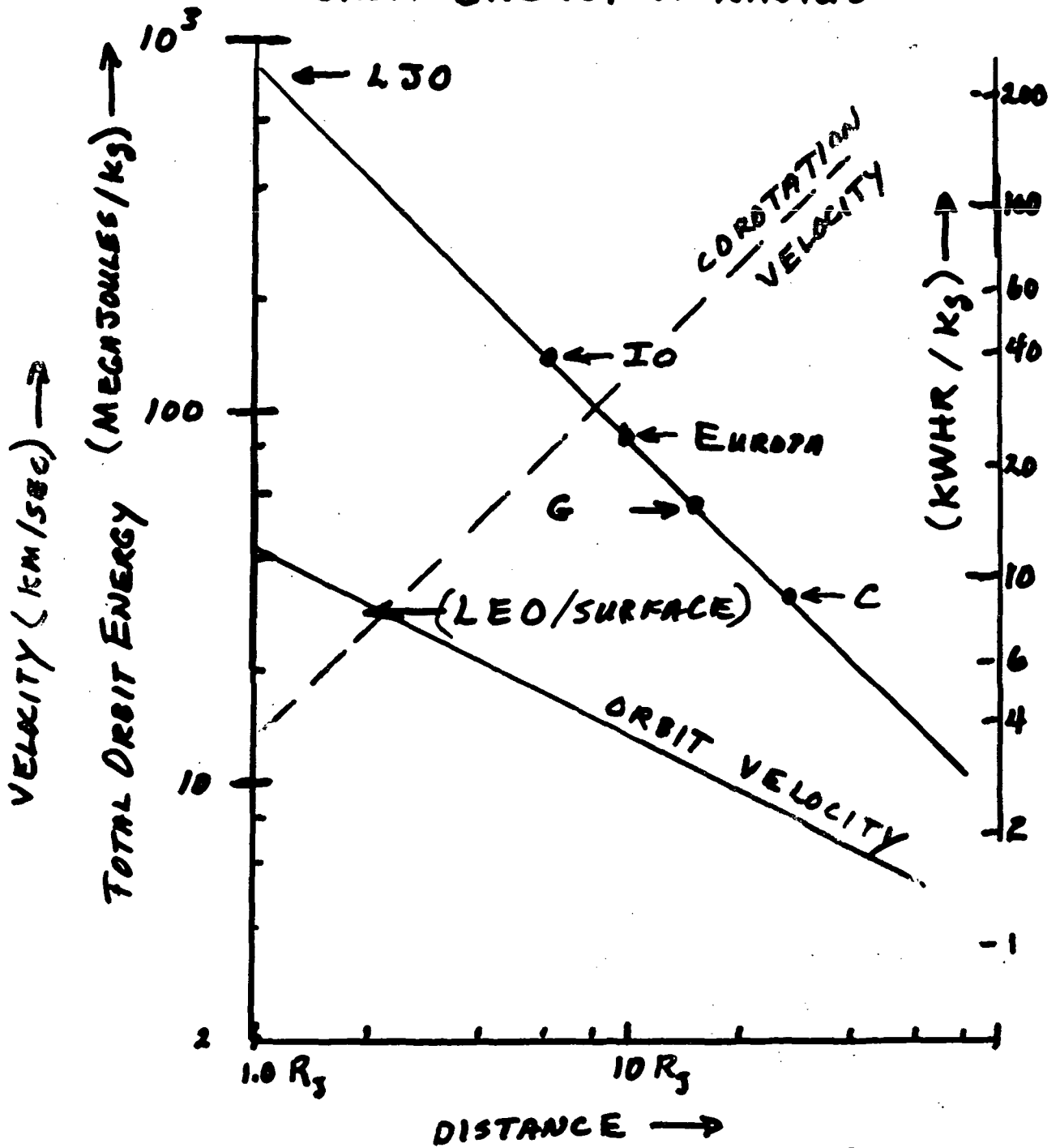


Figure 11

The energy to go to a very low Jupiter orbit is prohibitive for any normal propulsion system.

Yet, a system like some of these large tether systems -- if it operates like it should, and without considering the corotation of the Jovian magnetosphere -- if you express this gravity potential in kilowatt hours per kilogram required to propel the thing, it's something like a little over 200 kilowatt hours per kilogram, well within the capability of a nuclear power supply.

This has two nice applications.

With today's technology, we can get to the moons by doing gravity bouncing back and forth and get into orbits there. But the power is prohibitive to go from there to, say, a low survey orbit (or, later on with fleets of manned vehicles; perhaps to scoop methane from the top of the Jupiter atmosphere to produce gasoline or whatever is important, when that day comes). You can get down there using a tether by dissipating the energy. You don't even have to bring a power supply. All you have to do is use up the excess energy in a resistor or a big radio transmitter or something to get down to the surface.

To come back, if you brought a nuclear reactor with you, those sort of power densities should be available, and this is one way that you might be able to go to the surface of Jupiter and get back with a crew, or get back with a sample, or bring a commercial payload with you, depending on how far in the future you want to project your operation.

The second application uses the magnetospheric corotation effects, and requires that condition to be satisfied.

Since the reference frame for VXB induced voltage and IXB force on the tether is the frame moving with the magnetosphere, the "drag" force produced under tether power generation is calculated with respect to the local

corotation velocity. This becomes negative at distances beyond the synchronous rotation orbit, resulting in acceleration of a spacecraft in circular orbit by the same reaction forces that produce deceleration closer to the planet. The principle is the same as Alfvén's hypothetical solar wind engine.

In that case, a space factory could be located at the synchronous orbit (about $2 R_J$) with two power generating tethers attached. One tether deployed away from the planet would produce a "drag" accelerating the space factory to offset the decelerating "drag" of the second tether deployed downward. The net effect is that power could be produced continuously, with no net change in the orbital altitude. The system would be effectively tapping the rotational energy of the planet to produce electrical power, in quantities limited only by the corotational coupling of magnetosphere to planet.

Operation of such a system around other planets, for example in Earth geosynchronous orbit or a lunar anchored orbit in the solar wind, will require development of superconducting tether wire to be feasible. However, the Jupiter magnetic field is sufficiently strong at synchronous orbit to produce adequate induced voltage and IXB forces to operate with conventional conductors.