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Advanced Electric Propulsion For Space Solar Power Satellites

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August 1999

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ADVANCED ELECTRIC PROPULSION FOR SPACE SOLAR POWER SATELLITES

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ABSTRACT

The sun tower concept of collecting solar energy in space and beaming it down for commercial use will require very affordable in-space as well as earth-to-orbit transportation. Advanced electric propulsion using a 200 kW power and propulsion system added to the sun tower nodes can provide a factor of two reduction in the required number of launch vehicles when compared to in-space cryogenic chemical systems. In addition, the total time required to launch and deliver the complete sun tower system is of the same order of magnitude using high power electric propulsion or cryogenic chemical propulsion: around one year. Advanced electric propulsion can also be used to minimize the stationkeeping propulsion system mass for this unique space platform. 50 to 100 kW class Hall, ion, magnetoplasmadyamic, and pulsed inductive thrusters are compared. High power Hall thruster technology provides the best mix of launches saved and shortest ground to GEO delivery time of all the systems, including chemical. More detailed studies comparing launch vehicle costs, transfer operations costs, and propulsion system costs and complexities must be made to down-select a technology. The concept of adding electric propulsion to the sun tower nodes was compared to a concept using re-useable electric propulsion tugs for LEO to GEO transfer. While the tug concept would reduce the total number of required propulsion systems, more launchers and notably longer LEO to GEO and complete sun tower ground to GEO times would be required. The tugs would also need more complex, longer life propulsion systems and the ability to dock with sun tower nodes.

INTRODUCTION

Beaming electrical energy from space solar power collection satellites to ground users is currently being revisited by NASA.[1,2,3] A myriad of potential methods exists including different orbits, number of spacecraft, power collection technologies and energy transmission techniques.[2,3] The baseline assumed here is termed the 'sun tower' and consists of hundreds of large MWe class power collecting 'nodes' delivered to geosynchronous orbit.[1] The nodes are then connected together to form a tower as shown in Figures 1 and 2. A transmission array is also to be assembled based on a node concept. Each collection node carries the necessary power collection, power distribution, structure, attitude control, etc. necessary for the assembled tower of collectors to function as one spacecraft. The collected power is transferred through each node down to a transmitter array. Total collected power is 1.2 GWe. Total power delivered to the ground is expected to be around 400 MWe. As much as 6000 metric tons of nodes will be combined in geosynchronous (GEO) to makeup the sun tower. Operational lifetime is expected to be greater than 20 years.

Delivery of so many nodes, each allowed to weigh roughly 20 MT at launch, in a timely manner will require a large launch infrastructure and very frequent and affordable launches. Estimates of launch rate are set at three per day. But launch to low earth orbit (LEO) is only part of the transfer; each node must then be delivered to the geosynchronous operating orbit. Choice of the in-space delivery system will have a huge impact on the total number of required launches to LEO and the time to get the whole system from the ground to GEO. Both chemical and high power electric propulsion options for this in-space transfer system are traded in this paper.

ASSUMPTIONS AND ANALYSIS

Mission Assumptions

For this study 20 MT starting masses were assumed in 300 km, 28.5° inclination LEO drop-off orbits.[1] Propulsion systems were then traded for delivering the node to GEO (35786 km, 0° inclination). The figure of merit was then set to be the portion of the initial mass that was useable payload versus the transfer time from LEO to GEO. The relative useable payload fraction can then be used to compare the required launch fleet for each propulsion option.

Each node was assumed to be very 'spacecraft like' instead of just raw materials. It was also assumed that the support systems for GEO operation could be easily adapted for flying the spacecraft from LEO to GEO. The high power of the collector node 2-4 MWe, makes it very attractive to use the free node power for electric propulsion. Such power levels would allow trip times from LEO to GEO in weeks. Unfortunately, this option was discounted due to concerns for docking the large, deployed nodes together. Instead a 200 kW power collection system, based on the same advanced technologies as the main collection node, was assumed to power the electric propulsion system. Such a system would be needed for the transmission nodes anyways. This power system was assumed part of the propulsion system and added at 2.5 kg/kW, representing thin film arrays. Other power systems are being studied such as solar dynamics. [4] Degradation during transit of the radiation belts was neglected since the >20 year solar collection and node support systems were assumed to be highly radiation hardened.

Mission Modeling

All of the sun tower mission scenarios were analyzed with the ELectric Mission Optionizer (ELMO). ELMO provides an analytical way of determining an electric propulsion system's mission performance. By using the Edelbaum[5] ΔV and analytical integration, up to ten separate spiral mission (circular to circular orbit) phases with inclination change can be modeled. Coast times can be placed between the phases. The analysis allows for specific systems (mass, technologies, power level) to be simulated with the higher order mission effects of shading, oblateness (J2), atmospheric drag, solar array power degradation and built in coast times. In addition to ELMO the program, the Thrusting Orbiter with Atmospheric Drag (TOAD) program was used to check the feasibility of starting at 300 km LEO. All chemical systems were assumed to burn impulsively, using a Hohmann transfer to move from LEO to GEO: 4234 m/s ΔV. The electric propulsion systems required 5958 m/s to spiral for LEO to GEO. Twice this ΔV is needed for each of the electric propulsion tug's round trips. Shade time and atmospheric drag impacts on the electric propulsion missions were assessed.

Propulsion System Assumptions

Propulsion systems compared for delivering the sun tower were storable and cryogenic bipropellant chemical systems, Hall and gridded Ion electrostatic systems, and Magnetoplasmadynamic (MPD) and Pulsed Inductive Thruster (PIT) electromagnetic systems. Table 1. compares each of the systems projected parameters. Noted performance includes power processing losses. Higher thrust to power ratios were sought for each of the electrical systems to provide quicker trip times. Lifetime for each system was assumed sufficient for the LEO to GEO mission. All of the systems shown in Table 1 have proven performance at some power level but still need to be developed at high powers for flight. A new proposed technology, Microwave Electro-Thermal thrusters, is also discussed.

A 100 kN Engine using N2O4/MMH propellants was assumed to be representative of a storable, off-the-shelf, bipropellant system. The engine is based on the Ariane 5 L9 Upper Stage. [6] A simple dry mass model of 12% of the fuel mass was assumed. The rocket's performance was assumed to be 340 s. For simplicity, staging was not used.

A 100 kN Engine based on the Titan 4 Centaur Upper Stage was assumed for the cryogenic chemical option. [6] The dry mass was assumed to be 18% of the fuel mass. The rocket's performance was set at 460 s. Again for simplicity, staging was not used.

A 50 kW Hall thruster was assumed to represent an electric thruster with a 2000 sec Isp performance capability. Due to the large amounts of fuel required for the many nodes, a more plentiful fuel than the xenon used today will be needed for the Hall thruster. Krypton propellant was chosen over xenon propellant due to its better availability (roughly 10 times xenon) for so many large spacecraft. [7] As much as 2000 MT of krypton will be needed to deliver the entire sun tower spacecraft. Currently, the world yearly production of krypton is from 200 to 500 MT. Thus several years of production would need to be stockpiled for the complete mission. Argon, much more plentiful and cheap, can also be used in electrostatic thrusters but at performance efficiencies lower than krypton. Another option is to use cheaper and more plentiful metal propellants such as bismuth or mercury to improve thruster efficiency. A more thorough exploration of propellant impacts must be made. Here, krypton is assumed.

Using a direct drive system from the solar arrays the 2000 second Isp krypton Hall system is assumed to have a performance of 44% total efficiency. [8] Such performance is based on NASA Glenn Research Center tests of a TsNIIMASH TM-50 lab device (Figure 3.) and other theoretical estimates. [9,10] Using direct drive from the solar arrays the dry mass of the system is estimated at 170 kg for each 50 kW system. Krypton may be stored supercritically at 24% tankage or cryogenically at <10% tankage. [7] Supercritical storage is assumed for this option for simplicity and use for the +20 years of stationkeeping.

A 2-stage 50 kW Hall thruster system was assumed for the re-useable tug option. Its performance was assumed to be 2000 seconds/44% total efficiency outbound and 5000 seconds/59% total efficiency on the return leg in order to minimize fuel. [9,10,11] The dry mass of the system included a larger power processing unit for 2-stage operation and was set at 405 kg. Cryogenic tankage of 10% was assumed since the tug would not be used for long term, on-orbit stationkeeping of the nodes.

A 50 kW gridded ion thruster was assumed for a higher Isp electrostatic device. Again krypton was the chosen fuel. An Isp of 3000 seconds and an overall efficiency of 50% were assumed. [12] The dry mass was estimated at 430 kg for each 50 kW system with a supercritical tankage of 24% as with the Hall thruster. Several high power laboratory ion thrusters have been built including a 30 kW module (Figure 4.) soon to be tested at NASA Glenn Research center. The design combines 3 sets of DS-1 proven, 30-cm grid sets using a common discharge chamber.

Based on the 130 kW MAI/RIAME laboratory thruster, a 100 kW magnetoplasmadynamic (MPD) thruster was used in this study. [13,14,15] Figure 5 presents a 40 kW Russian MPD. Performance was set at 3500 seconds Isp and 41% overall efficiency. Dry mass was assumed to be 1275 kg for each 100 kW system and the Lithium fuel tankage set at 10%.

A 50 kW Pulsed Inductive thruster or PIT was considered modeled after a TRW lab device. Based on TRW laboratory (Figure 6.) tests using hydrazine propellant, performance was set at 2500 seconds Isp and 38% overall efficiency. [15,16] Dry mass was assumed to be 405 kg for each 50 kW system based on a top-level 40 kW design. The hydrazine fuel tankage was set at 7%.

The Microwave Electro-Thermal thrusters (MET) uses a vortex stabilized, electrodeless, microwave discharge to heat water vapor fuel in a thrust chamber. Testing of a 1 kW device in this class was performed at NASA Glenn Research Center. The Glenn evaluation was not able to substantiate performance claims. Performance as high as 800 seconds Isp and 72% efficiency is claimed for a 40 kW class device. [17]

RESULTS

LEO to GEO Transportation:

On-Board Propulsion Option

Using a 20 metric ton ETO mass an analysis was made to compare advanced propulsion systems. As mentioned previously, initial analyses assumed the entire >2 MW collector node power was available for orbit transfer. Under this assumption transfer times of weeks were possible. This option was later discounted by concerns of docking the deployed nodes together. Consequently, the propulsion system is assumed part of the node with additional 200 kW solar arrays being added to the node and jettisoned or used for stationkeeping power after arrival. The collector node's primary solar arrays would be not be deployed for orbit transfer. A preliminary analyses showed that atmospheric drag starting at LEO was not a problem for the 200 kW system. The propulsion system would still be available for stationkeeping/ACS functions. The 2.5 kg/kW power system was assumed to be based on that of the Space Solar Power system and consisted of thin film arrays. [1] Maximizing payload mass to GEO in reasonable trip times was the figure of merit.

Relative performance of each system is shown in Figure 7 by comparing payload mass and trip time for each system option. The direct drive Hall thruster option provides the best mix of payload performance and trip time. The Hall option also has the lightest dry mass of the system options and provides the quickest trip time - 153 days. As such the lifetime requirement on the Hall thruster is under 4000 hours excluding stationkeeping burn times. The ion, MPD and PIT options provide slightly more payload mass (~8%) but require 45% to 100% longer trip times. This slower trip time is due to these technology's lower thrust levels. Hall and ion thruster payload mass performance could be improved using cryogenic fuel storage but at an added complexity, especially for +20 years of stationkeeping.

Impacts on the earth-to-orbit system are evaluated assuming 6000 MT of payload must be put into GEO. The relative number of launches and complete sun tower system ground to GEO time of all the technology options are shown in Figure 8. One finds that over 1000 launches must be made assuming a cyrogenic chemical system compared to 488 launches using the on-board Hall propulsion system. Interestingly, the chemical concept has a longer start to finish time than the Hall electric propulsion option. Assuming a launch rate of 3 per day, 356 days of launch campaign is required to launch and deliver the 6000 MT to GEO using cryogenic chemical in-space propulsion while only 316 days (from first launched node to last node's GEO arrival) is needed for the on-board Hall concept. Thus the Hall electric propulsion concept requires less than half the launch fleet and provides a quicker ground to GEO time when compared to the cyrogenic chemical system. The ion, MPD, and PIT technologies would require about 35 fewer launches but would still take 20% to 40% longer to transfer all the tower components from the ground to GEO.

To further differentiate between electric propulsion systems a study would need to be performed to show the relative cost difference of 35 extra launches (7% of the total) versus two months longer ground to GEO time orbit plus the additional operations costs of 45% to 100% longer transit times for each spacecraft. Simplicity of design, integration challenges and cost of propulsion systems must be included.

The MET option was not included with the rest of the concepts due to its lack of demonstrated performance at any power level (see propulsion system assumptions). However, assuming the 800 second Isp is possible, almost 1000 launch vehicles would still be required - twice the number needed by the electric propulsion concepts, and similar to the cryogenic chemical system. This is due to the higher ΔV of a continuous spiral transfer. Even assuming a very high efficiency propulsion system the ground to GEO time would be still be 360 days; 44 days longer than the Hall system.

Re-useable Tug Option

The option of using a re-useable 200 kW tug to deliver the sun tower components was explored. In this instance the propulsion system is assumed not part of the node and would not be available for stationkeeping/ACS functions. Maximizing payload mass to GEO in reasonable trip times was again the figure of merit.

The 2-stage Hall concept was assumed for the tug mission and used two setpoints; the outbound stage used a performance of 2000 s / 44% efficiency and the return stage used a 5000 s / 59% efficiency. The tugs would be launched un-fueled; fuel for the outbound and return trips would be provided with each payload node. Cyrogenic krypton storage was also assumed along with a tankage fraction of 10%. The stage mass was roughly estimated to be 2850 kg which includes the 1625 kg propulsion system (no tanks) and the 500 kg power system.

Results showed that the re-useable tug would require 180 days to deliver the node and 64 days to return for refueling and re-use. This delivery time is almost a month longer than the on-board Hall option. Assuming two round trips for each tug, a thruster lifetime of almost 12,000 hours would be required - expensive to develop and qualify for a 2-stage Hall propulsion system. Other electric concepts would have even longer lifetime requirements.

The on-board and re-useable tug systems can also be compared in terms of number of launches and total system delivery time. Again assuming 6000 MT must be put into GEO, one must provide 234, 2-trip tugs to transport 468 node and fuel launches. An additional 33 launches are needed just for the un-fueled 2-trip tugs. Thus only 234 tugs are required compared to roughly 488 on-board propulsion systems. The tug concept also requires slightly more launches, 501 versus 488, compared to the on-board Hall propulsion concept. The hoped for savings in reduction of power and propulsion system mass is more than offset by the need for return fuel and tank mass. The re-useable tug concept also has a longer start to finish time. The tug concept requires a total of 513 days (from first launch to last tug's second arrival) to launch and deliver the 6000 MT to GEO while only 316 days (from first launched node to last node's GEO arrival) is needed for the on-board concept. One could increase the power of the tug's power system to reduce the transfer times but at the cost of heavier tugs and, therefore, more launches.

So one must weigh the cost of saving 254 simpler and cheaper propulsion and power systems with a >60% increase in the total system delivery time, developing a more complex, longer life propulsion system, and perhaps providing some kind of logistics support for refueling and docking in LEO. The relative complexity of the on-board propulsion system compared to the re-useable stage is difficult to estimate. However, one may suppose the re-useable stage would require more than three times the component life-time (~12,000 hours vs. ~4000 hours) and more complex and expensive systems since none of the node's bus systems are used for the transfer. In addition, a rendezvous/docking/attachment/separation system is required for the re-useable stage. Finally, an additional stationkeeping system would need to be added to the sun tower assuming the tug concept; the on-board concept's orbit transfer system would not be available for stationkeeping.

GEO Stationkeeping

Stationkeeping in GEO would require propulsion to offset perturbations from the sun, moon and earth oblateness, similar to those experienced by all geosynchronous spacecraft.[18] Other special perturbations from the solar wind and the transmission beam are unique to the sun tower configuration and must be addressed. From Agrawal the maximum inclination drift rate - North-South - is 0.943 °/year. [23] This is caused by a combination of gravitational forces from the sun (0.269° /year) and from the moon (0.674°/year to 0.478°/year). Thus the drift rate varies from 0.747°/year to 0.943°/year over a 9.3 year period. Since the lifetime is assumed to be >20 years for the spacecraft an average drift rate is assumed. In order to maintain the +/-6° inclination limit a correction burn would be needed only every 14 *years*. One could also keep a tighter tolerance on the orbit and do yearly burns of 45 m/s.

There are also perturbations on the spacecraft orbit in the longitudinal direction. These are almost wholly due to the equatorial bulge of the earth. This ΔV requirement, termed east-west stationkeeping (EWSK), is 1.77 m/s per year maximum and is relatively small compared to the NSSK Δ. The required ΔV depends on the desired location in geostationary orbit. For a +/- 6° EWSK operational band a burn needs to be made every 240 days.

Solar radiation pressure can also perturb the sun tower's orbit. The magnitude of the acceleration from solar radiation pressure is roughly -4.5×10^{-8} A / m (m/s^2) [A = cross sectional area, m = spacecraft mass].[19] With the assumed spacecraft configuration (3.9×10^6 m^2) the force on the spacecraft is only 0.18 N. This force might have to be accounted for depending upon how far the periodic variations caused by this force 'blow' the spacecraft out of the +/- 6° box. This analysis has yet to be made. However, as a conservative assumption, the fuel to offset the 0.18 N force continuously would be only 290 kg/year for the entire station assuming a 2000 second Hall thruster. The equivalent ΔV is only 1 m/s/yr.

Finally, the transmission of so much power in the satellite's nadir direction will also put a disturbing 'thrust' on the spacecraft. Estimates of 2.5 N have been made. Conservatively, offsetting this thrust would require on a single 56 kW thruster (44%/2000 s Hall device) and 4000 kg/year of fuel for the entire station. The equivalent ΔV is 13 m/s/yr.

A yearly ΔV for the combined stationkeeping missions is ~60 m/s assuming yearly north-south stationkeeping. For a 20 year mission 1200 m/s of ΔV is needed, compared to the almost 6000 m/s needed for the LEO to GEO transfer. Assuming each of the 488 nodes contributes to the stationkeeping burns only an additional ~500 hours operation is needed for each set of four, 50 kW thrusters. Added to the on-board orbit transfer burn time the total life of a 50 kW Hall thruster would be <5000 hours. Accounting for engine failures, operation time could be somewhat longer.

Stationkeeping with the other electric propulsion options would have similar propulsion requirements, adjusted based on thruster performance.

CONCLUSIONS

The sun tower concept of collecting solar energy in space and beaming it down for commercial use will require very affordable in-space as well as earth-to-orbit transportation. Advanced electric propulsion using a 200 kW power and propulsion system added to the sun tower nodes can provide a factor of two reduction in the required number of launch vehicles when compared to in-space cryogenic chemical systems. In addition, the total time required to launch and deliver the complete sun tower system is of the same order of magnitude using high power electric propulsion or cryogenic chemical propulsion: about one year. Advanced electric propulsion can also be used to minimize the stationkeeping propulsion system mass for this unique spacecraft.

The PIT technology required slightly fewer launches than the other electric propulsion concepts while the Hall thruster provided the shortest time from LEO to GEO and the shortest ground to GEO times compared to all the other systems, including chemical. The Hall thruster gives the best mix of transfer time and payload performance but more detailed studies comparing launch vehicle costs, transfer operations costs, and propulsion system costs and complexities must be made to down-select a technology. Due to the amount of fuel mass required to place the entire system into geosynchronous orbit, propellants besides xenon (normally used), such as krypton, other noble gases and perhaps metals need to be explored for the electrostatic devices, Hall and ion.

The concept of adding electric propulsion to the sun tower nodes was compared to a concept using re-useable electric propulsion tugs for LEO to GEO transfer. While the tug concept would reduce the total number of required propulsion systems, more launchers and notably longer LEO to GEO and complete system ground to GEO times would be required. The tugs would also need more complex, longer life propulsion systems and the ability to dock with sun tower nodes in LEO.

Further work should be done to assess the usefulness of higher power electric propulsion (MWe class) if the option of using the node's payload power becomes available.

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Table 1 Propulsion System Options

Propulsion Class	***Specific Type***	***Specific Impulse (sec) / Overall Efficiency***	***Pro-pellant***	***System Dry Mass***	***Scaling Source***
Advanced Chemical Propulsion Systems	Storable Bipropellant: ~100 kN Engine	340 s	N2O4/ MMH	12% of Fuel Mass	Ariane 5 L9 Upper Stage
	Cryogenic Chemical: ~100 kN Engine	460 s	LOX/LH2	18% of Fuel Mass	Titan 4 Centaur Upper Stage
Electro-static	Hall : 50 kW, 2.25 N Engine	2000 s / 0.44 (direct drive)	Krypton/ Noble gas mixtures	~170 kg +Tankage (24% supercritical)	High Power TsNIIMASH Lab Device
	2-Stage Hall : 50 kW, 2.25 - 1.2 N throttleable engine	2000 s / 0.44 (direct drive) & 5000 s / 0 .59	Krypton/ Noble gas mixtures	~405 kg +Tankage 10% cyrogenic	High Power TsNIIMASH Lab Device
	Ion: 50 kW, 1.7 N engine	3000 s /0.50	Krypton	~430 kg +Tankage (24% supercritcal)	NASA 30 kW Lab Device
Electro-magnetic	MagnetoPlasma Dynamic (MPD), 100 kW, 2.4 N	3500 s / 0.41	Lithium	~1275 kg + 10% Tankage	130 kW MAI/RIAME Lab Device
	Pulsed Inductive Thruster (PIT) , 50 kW, 1.5 N	2500 s /0.38	N2H4	~405 kg+ 7%Tankage	TRW Device

* The MET system is noted in the text.

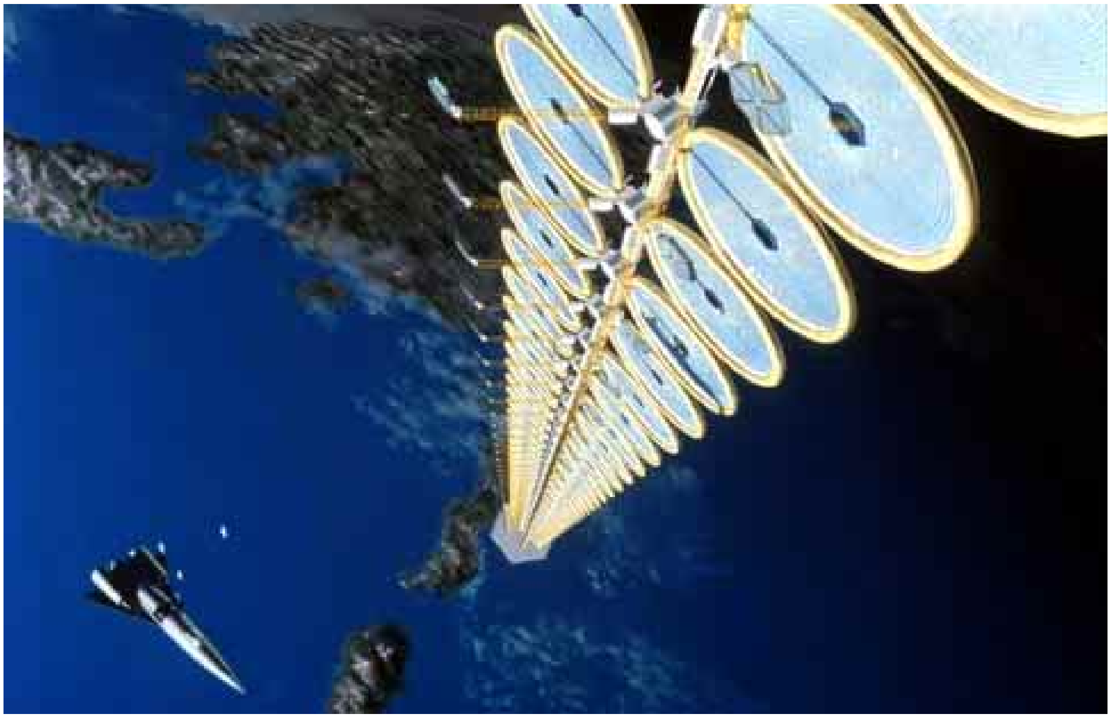

Figure 1. Artist Concept of Sun Tower

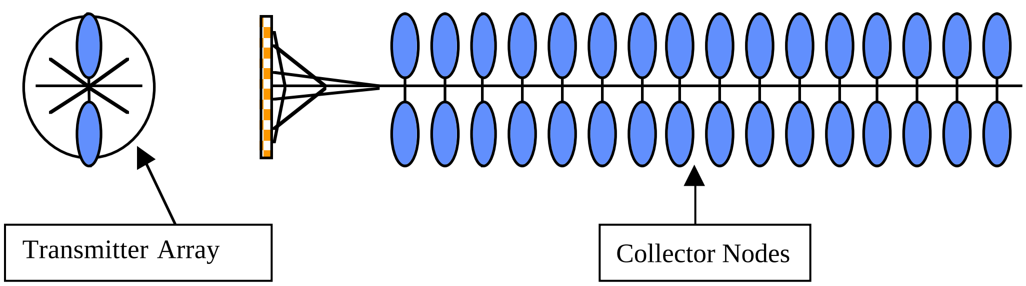

Figure 2. Sun Tower Schematic

Figure 3. TsNIIMASH TM-50 Hall Thruster

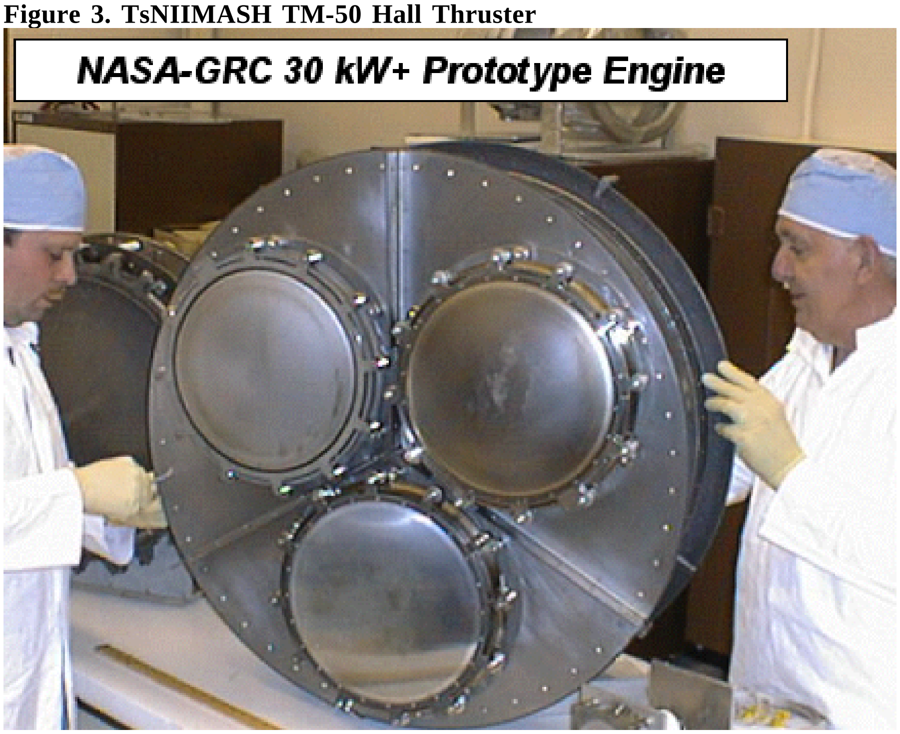

Figure 4. NASA GRC 30 kW Ion Thruster Prototype

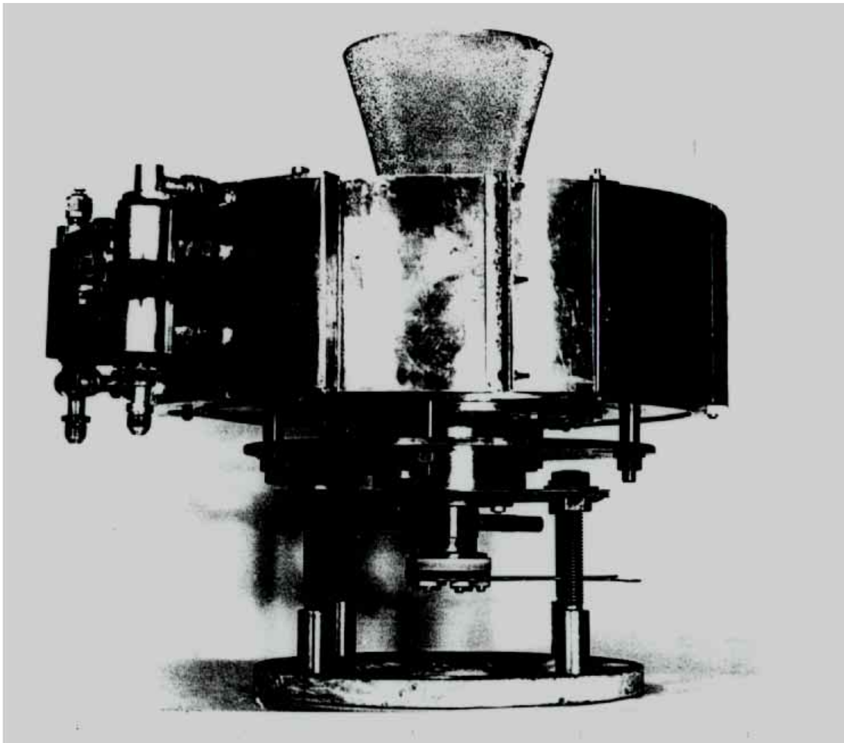

Figure 5. 40 kW Russian MPD Thruster

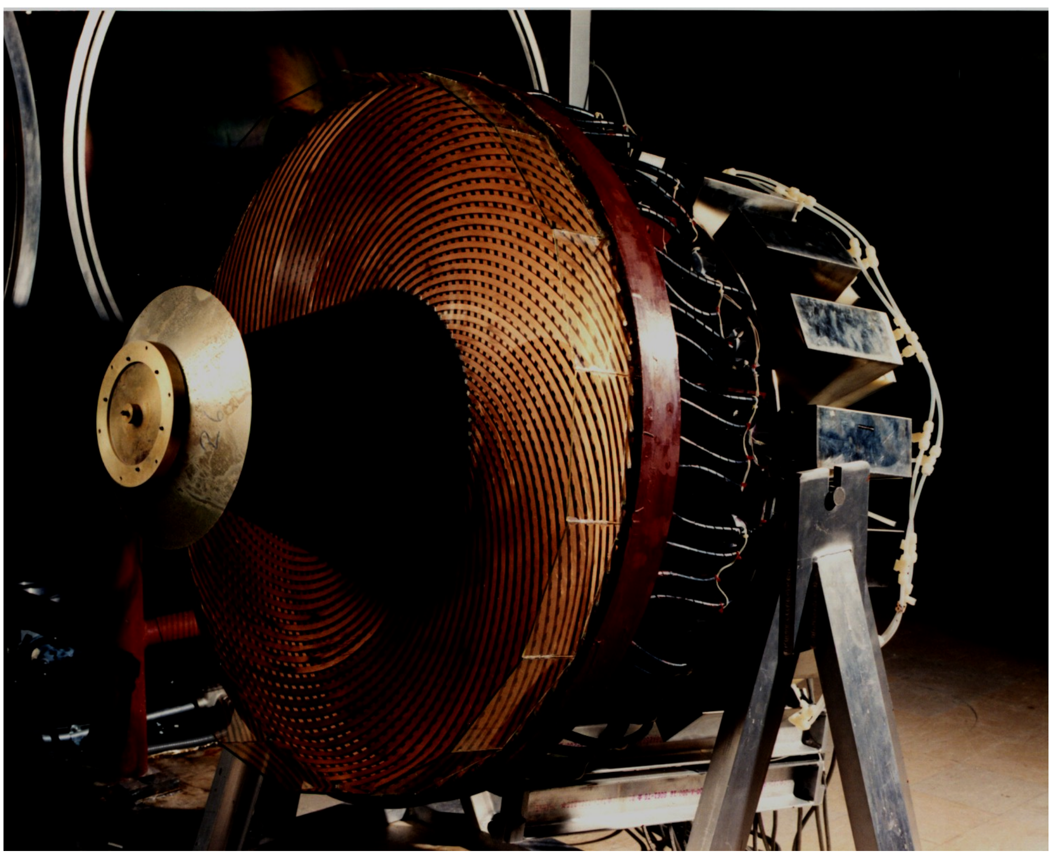

Figure 6. TRW Pulsed Inductive Thruster

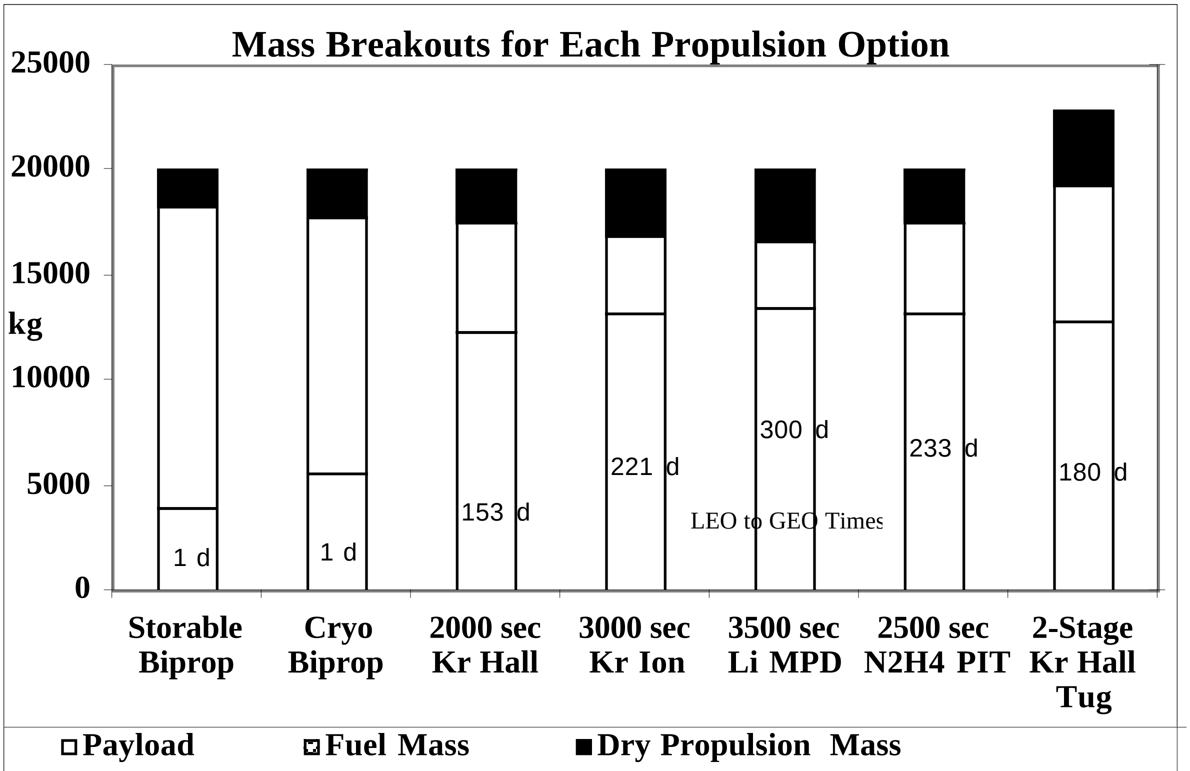

Figure 7. Payload and Trip Time Performance for Various Propulsion Systems

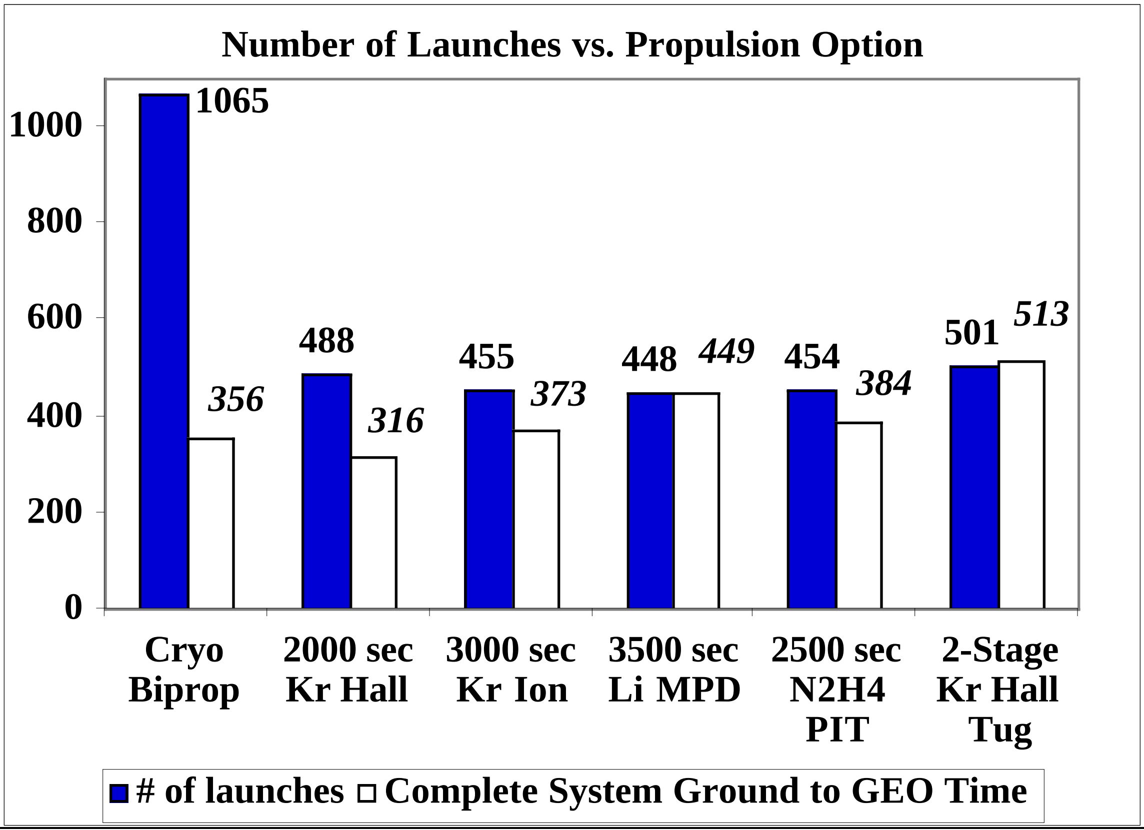

Figure 8. Required Number of Launches and Total Ground to GEO Time for the 6000 MT Sun Tower Satellite

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13. ABSTRACT ***(Maximum 200 words)***

The sun tower concept of collecting solar energy in space and beaming it down for commercial use will require very affordable in-space as well as earth-to-orbit transportation. Advanced electric propulsion using a 200 kW power and propulsion system added to the sun tower nodes can provide a factor of two reduction in the required number of launch vehicles when compared to in-space cryogenic chemical systems. In addition, the total time required to launch and deliver the complete sun tower system is of the same order of magnitude using high power electric propulsion or cryogenic chemical propulsion: around one year. Advanced electric propulsion can also be used to minimize the stationkeeping propulsion system mass for this unique space platform. 50 to 100 kW class Hall, ion, magnetoplasmadyamic, and pulsed inductive thrusters are compared. High power Hall thruster technology provides the best mix of launches saved and shortest ground to GEO delivery time of all the systems, including chemical. More detailed studies comparing launch vehicle costs, transfer operations costs, and propulsion system costs and complexities must be made to down-select a technology. The concept of adding electric propulsion to the sun tower nodes was compared to a concept using re-useable electric propulsion tugs for LEO to GEO transfer. While the tug concept would reduce the total number of required propulsion systems, more launchers and notably longer LEO to GEO and complete sun tower ground to GEO times would be required. The tugs would also need more complex, longer life propulsion systems and the ability to dock with sun tower nodes.

14. SUBJECT TERMS

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