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SPACE PROPULSION TECHNOLOGY OVERVIEW

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Abstract

This paper discusses Shuttle-era, chemical and electric propulsion technologies for operations beyond the Shuttle's orbit with focus on future mission needs and economic effectiveness. The adequacy of the existing propulsion state-of-the-art, barriers to it's utilization, benefit of technology advances, and the prognosis for advancement are the themes of the discussion. Low-thrust propulsion for large space systems is cited as a new technology with particularly high benefit. It is concluded that the Shuttle's presence for at least two decades is a legitimate basis for new propulsion technology, but that this technology must be predicated on an awareness of mission requirements, economic factors, influences of other technologies, and real constraints on it's utilization.

Introduction

In the past, NASA has enjoyed a rather effective and thorough amortization of its space vehicles. The same will most certainly be true of the shuttle. As with its predecessors, the Shuttle will probably be marked by frequent "product improvements," identified by real Shuttle operating experience, and effected mostly by within state-of-the-art activities. Notwithstanding these improvements, the Orbiter and its main propulsion system will remain the nucleus of the Space Transportation System for several decades, and will function in the future in much the same way as currently perceived, as this country's principal, perhaps only, method of launching humans and cargo to Low Earth Orbit (LEO).

During these next decades, it will become vitally important to literally capitalize on the Shuttle's presence; to develop, maintain, and act on an awareness that benefit/cost will be instrumental to the success of the Shuttle; to understand that the Shuttle will be exposed to an evolving world market for space transportation in which it must complete; and that this competitiveness will be assured only by generation, acceptance, and utilization of new propulsion technology that provides increased economic effectiveness.[1] Future mission concepts offer existent clues as to the desired characteristics of new shuttle-era propulsion. It is marked by the need for high energy missions based on Orbiter operations but beyond the capability of the Inertal Upper Stage (IUS). New propulsion technology is the key to the development of this needed capability in the most effective manner.

The following discussion emphasizes these Shuttle-era, Orbiter-based propulsion technology needs and the economic considerations associated with these needs.

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Orbit-To-Orbit Propulsion

Deep Space Missions

Development of systems based on two currently available technologies, hydrazine/fluorine and ion propulsion will adequately provide the propulsion capability for currently projected deep space missions. High energy missions will require the high specific impulse that ion propulsion provides. Figure 1 is an illustration of such a system, consisting of a cluster of five 2-thruster electric propulsion modules (BIMODS) as the primary conveyence of a science package into orbit around Jupiter. High thrust and long term storability for impulses after extended periods can be provided by hydrazine/fluorine propulsion, with the added advantage of higher specific impulse than current retro-propulsion systems.

Deep space missions, such as retrograde, sample return, and out-of-the-ecliptic missions, by reason of their high energy requirements become very sensitive to electric propulsion power-to-mass ratio. The currently on-going electric propulsion technology effort at NASA Lewis Research Center is directed toward providing the needed improvements of higher specific impulse and increased power per thruster. In addition, improvements in solar power capability are required, specifically the ability of solar power systems to provide high power-to-mass ratio over a range of solar distances from <1 Au to about 8 Au. This will require lightweight photovoltaic arrays, possibly with variable concentrators.

Round Trip Missions

These missions are popularly discussed as those which involve sorties to place, maintain, or retrieve spacecraft commencing and ending at the Shuttle's orbit, with destinations as high as GEO. Since the mission ends where it began, the possibility of reusing the propulsion system is introduced. To illustrate the high energy requirements of round trip missions, for a round trip to GEO, the total velocity change from the Earth's surface is over 80-percent of that which was required for the Apollo Lunar Landing Mission. Technology discussions for round trip missions are divided into three sections below.

High orbits with chemical propulsion. High specific impulse chemical propulsion is adequate for single-stage round trips to GEO, but the cost of such missions during the Shutte-era may be very great. Table 1 shows a comparison of cost for various GEO transportation options. The transportation options shown in the left column range from (top-to-bottom) leaving the vehicle with the payload in GEO (one-shot delivery) to propelling the payload from LEO to GEO to LEO (sorties), the latter being required for manned transfer. The cost shown in the third column from the right is the cost of transporting the payload and the propellant for the mission from Earth to LEO. The cost of the orbit raising vehicle is excluded because it is difficult to estimate. Note that the cost for round trip missions to GEO (the last three transportation options shown) is from $8 M to $77 M higher than the cost for the one way only mission. Since the cost of a vehicle of the size required to transport 7000 kg to GEO (one way) would likely be less than $8 M, it is concluded that expending the vehicle in high orbit costs less than returning the vehicle to LEO for reuse. Further note the cost derivative information in the right hand columns. Should a shortfall in performance exist after vehicle development, the resulting cost impact is much more pronounced for round trip missions than for the one way only mission.

The above conclusions of high cost and high cost sensitivity for round trip missions to GEO cannot change unless specific impulse, mass fraction, and/or Earth-to-orbit launch cost improve significantly. For specific impulse, the required improvement of at least 100 seconds is not possible with chemical propulsion technology. For launch cost, the required reduction is an order of magnitude, which is not conceivable during the shuttle-era. For mass fraction, the required increase (to at least 0.95) can be produced only by very elegant space-based vehicles, with in-space propellant transfer capabilities and near-zero-maintenance features. This would require extensive new technology. Even if all this were done, the space-based operation costs could quickly overwhelm the cost reduction that high mass fraction vehicles enable.

High orbits with electric propulsion. The inherently high specific impulse of electric propulsion allows it to function effectively over high mission velocities, such as LEO-GEO-LEO trips, but the inherent low thrust results in trip times of at least 100 days, which precludes the use of electric propulsion for manned transportation. For cargo transportation, solar electric propulsion could be economically attractive because of low propellant mass, but degredation of the photovoltaic system from van-allen belt exposure offsets this advantage. Current photovoltaic space power systems would lose about 50% of their output on such a mission. Since perhaps 25 kW of end-of-life power is needed for payloads in the multi-thousand kg class and since space power currently costs about $300/W, a cost of about $10 M/mission can be attributed to power degredation alone. Improvements in space power are the clearly indicated factors that will permit the exploitation of solar electric propulsion for orbit raising. Such improvements consist of cost/power reductions, weight/power reductions, and increased van-allen radiation resistance on development of space-annealing techniques which would restore the degraded power. Electric propulsion technology is currently being defined which could positively interact with the above power technology. Such technology is manifested in electric propulsion system concepts which feature higher thrust-to-mass ratio, simplicity, and reduced system cost.

Intermediate orbits. A significant number of placement and retrieval mission opportunities exist at orbits which require substantially less velocity than GEO. Typical of these orbits are high-inclination, low altitude or Shuttle inclination with altitudes to several thousand km. Velocities to these orbits from the Shuttle's orbit range from several hundred to several thousand m/s. Missions which involve retrieval/repair of spacecraft at these orbits are economically attractive, even with existing propulsion technology.

Cargo Placement Missions

Herein is discussed the need to place spacecraft in high earth orbit (HEO) where the round trip is not mandated. GEO is a typical high orbit in future missions. Technology discussions for cargo placement missions are divided into two sections below.

Small "conventional" payloads. These are described as spacecraft of several thousand kg that can be deployed without manned assistance at the destination orbit. The IUS can do these missions but the expense will be high. The cost of transportation for these missions could possibly be reduced without investing in new propulsion technology by development of stages based on liquid bipropellant propulsion. Such a system of stages could reduce the transportation cost by occuping a smaller fraction of the Shuttle's cargo bay length, or by increasing the payload with increased specific impulse, or by reducing the cost of the stage itself. These stages could also have the desired multiple burn and impulse control features not found on the current IUS.

Large space systems. Many shuttle-era mission opportunities which commence in the late 1980's, will be enabled by Large Space System (LSS) technology and are based on very large, low-density structures which require man-assisted and automated deployment and/or assembly in orbit. In many instances, a thousand-fold increase in size from the packaged state to the deployed state is needed, with deployed dimensions of 200 meters or more.

Two mission strategy options to HEO are apppar-ent: (1) transfer of the package to HEO and deployment in HEO, or (2) deployment of the structure in LEO and transfer of the deployed structure to HEO. LSS concepts require men and automated systems in the deployment orbit. Men in HEO will most likely not be available during the time frame required thereby limiting consideration of the HEO deployment option. The second option, deployment prior to transfer from LEO to HEO, is the most likely option. It is particularly attractive because it takes advantage of the Shuttle's unique capability to permit men and machines to take an active role in a highly complex procedure in LEO. It further enables a checkout of the spacecraft in a fully deployed con-ition before a potentially irreversable commitment is made to send it to HEO.

In the deployed transfer option, the structure mass becomes sensitive to the transfer acceleration such that low thrust propulsion is required. Figure 2 illustrates the need for low thrust propulsion. The upper part of the figure displays structure mass, considering the need for the deployed structure to survive acceleration forces, as a function of structure size for several levels of applied acceleration.[2] For an applied acceleration of 2.6 g, typical of IUS, structure mass increases rapidly with structure size. If the applied acceleration is limited to 0.01 g, structure mass increases much more slowly as a function of structure size. For example, for a structure size of 70 m, the structure mass could be more than 8000 kg if the applied acceleration is 2.6 g, but only about 1000 kg if the applied acceleration is 0.01 g. The mass penalty in HEO is greatly magnified when the additional propellant mass required to transfer the structure to HEO is taken into consideration. The cost of the Shuttle launches required to lift the additional mass to LEO is at least $80 M. The bar graphs in the lower part of the figure display the size distribution of structures for 49 missions to HEO.[3] These mission opportunities occur over the next two decades and will therefore use the Shuttle. The benefit on low thrust propulsion is shown at the bottom. For small payloads, up to about 20 m in size, there is no significant benefit in mass or cost over the IUS due to the use of low thrust per se, but there is a benefit due to lower stage volume, higher stage performance, or lower stage cost which could be achieved with low thrust propulsion. For structures in the 30-50 m range, the cost benefit is moderate; for 60-100 m structures the cost benefit is major, in the range of $100 M per mission. For very large structures, 200 m and larger, the use of low thrust propulsion is enabling. The personal communications satellite is an example of this latter large structure category.[4]

Table 2 shows the characteristics of the candidate low thrust propulsion systems, chemical and electric as they apply to LEO-GEO transfer of large structures. With chemical propulsion, the trip times are short, one to three days. With solar electric propulsion, at least 100 days is required which increases the possibility of damage to payload electronics by the Van-Allen belts. For some missions, the additional shielding required to protect the electronics can be so great as the preclude the use of electric propulsion. A range of specific impulse of 350-450 s is possible with chemical propulsion, which is adequate as will be shown later. For electric propulsion, the very high specific impulse yields high payload fractions and introduces the possibility of returning the propulsion system to LEO for reuse. For chemical propulsion, acceleration can be made low enough (~0.01 g) to minimize the effect on large space structures. At this acceleration level, the trajectory can be designed with multiple perigee burns to limit the velocity losses to less than 5-percent while still keeping the transfer time within the 3 day limit shown. Acceleration levels for electric propulsion are at least an order of magnitude lower, which is more than low enough for transportation of very large structures.

Low thrust chemical propulsion represents what is likely to be an enabling technology for the transfer of large space systems. A thrust level of 200 lbf could enable more than a 20-fold increase in the size of a structure that could be delivered to HEO with a single shuttle flight, compared with IUS. Figure 3 shows the range of requirements for low-thrust chemical propulsion. The specific impulse requirement is high and analogous to that obtainable with current, high-thrust technology. The thrust is one to two orders of magnitude below high-thrust technology, with operating times an order of magnitude greater than the state-of-the-art. The specific impulse range implies that hydrocarbon and hydrogen fuels are both possible candidates, each with its own particular set of attributes. Hydrogen offers the highest specific impulse, therefore yielding the highest payload mass while hydrocarbon results in a shorter length stage with more room for the packaged structure in the Orbiter cargo bay. Since the propulsion system cannot economically be flown back to LEO for reuse but should instead remain in HEO, it will be important for the propulsion system to have minimum manufacturing cost consistent with it's performance requirements.

Perhaps the most promising element of low-thrust propulsion is the opportunity for approaching all space missions beyond LEO in a much more cost effective way. It is virtually impossible to cite an example of a past, present, or future spacecraft that does not have some sort of boom, array, antenna, or other appendage that is required to deploy after the system is delivered to its functional orbit or is given a hyperbolic excess velocity. Because deployment failure usually constitutes mission failure under these circumstances, mission developers spend inordinate efforts to develop expensive, highly-reliable, weight penalizing deployment mechanisms whose function ties directly to the success of a multimillion dollar mission. With low-thrust propulsion and the presence of men in LEO that the Shuttle enables, the opportunity to totally decouple mission success from deployment success exists. Spacecraft could be rendered totally operational in the vicinity of the Shuttle and operational status verified before commiting the mission to a space where repair access no loner exists. This new mission strategy philosophy has enormous potential for reducing cost and improving reliability, and is an ideal example of the opportunity that the Shuttle's presence will offer.

On Orbit Propulsion

Small Space Systems

The evolution from cold gas to hydrazine monopropellant was a past significant event that enabled certain missions that were otherwise impossibly constrained by transportation mass limitations. Today evolution to electric propulsion could be equally significant because it provides more functional mass to exist on-orbit for longer periods of time. While electric propulsion is not enabling for most small space systems, it's enhancing effect in commercial space missions literally would amount to millions of dollars increased captial return per year per spacecraft. The addition of just a single transponder on a communications satellite is representative of a captial return of this magnitude. In addition, high pointing accuracy, required by some future missions, is enabled by electric propulsion. While auxiliary electric propulsion can be considered technology that is currently within the state-of-the-art, it seems to suffer from what is best described as a "User's Paradox": Use only what others have used before.

Large Space Systems

The size of large space systems increases the on-orbit control requirements to a point where the total on-orbit control energy approaches the energy to transport the structure from LEO to HEO. Higher gravity torque increases the attitude control requirement. Solar pressure forces increase the station control requirement. Figure control, a requirement unique to large structures, is intensified by the aforementioned attitude and station control requirements, plus the thermostatic effects of uneven solar heating, and the need for high dimensional accuracy. High specific impulse propulsion, such as electric propulsion, will be necessary to meet the high total impulse requirements for large space systems.

Figure 4 is an illustration of a concept which involves a very long boom with an earth-facing flat side running the length of the boom. Concepts such as this which employ four such booms arranged in the form of a crucifix have been studied by NASA-Langley and others. The flat sides typically contain electronics such as phased arrays or waveguides. Once on orbit, a problem typical to these structures is to maintain an earth pointing direction and accurate flatness in the presence of the aforementioned disturbances. The structure is shown in the midst of a roll-type attitude correction. The electric thrusters are mounted at intervals along the boom and are here helping the boom roll so as to avoid torsional strain. Boom relative position errors are sensed by a low-energy laser which is beamed through sights on each electric thruster assembly. Each electric thruster assembly has the intelligence to respond to errors sensed by its sight, hence the entire boom moves as though it were infinitely stiff with respect to the rest of the spacecraft, even though its stiffness is finite, perhaps low. The illustration shows single electric thrusters with grids at each end that can propel from one, or the other; or both ends. They are designed to operate at high specific impulse so as to maximize the operating life of the spacecraft. They are mounted in pairs such that both torques and translation forces can be applied. In Principle, single engines could be conceived that would propel in three directions out of orthaogonally located grids without gimballing such that one engine of this type could do the job of six conventional engines.

Conclusions

The Shuttle's presence for at least the next two decades should be the basis for development and utilization of new propulsion technology for operations beyond the Shuttle's orbit. The direction of this new technology must be predicated on an awareness of many factors. First, the spectrum of possible missions should be continually examined, and judgement provided on serving the majority of mission needs with a minimum of propulsion systems. Second, the awareness of an evolving world market in which the Shuttle will have to complete needs to be addressed, wherein economics will be the driving force, and the key to maintaining domestic preeminence in space will be to exploit Shuttle's capabilities and minimize its limitations. Third, the influence of other technologies on propulsion technology must be continually factored into the direction that the latter takes. As was mentioned previously, space power technology, and large space system technology can have a profound effect on the utilization of propulsion technology. A kind of syntergism should be nurtured between mutually-influencing technologies, perhaps through common organization and planning, most certainly through multiple-theme conferences such as this. Lastly, while much new propulsion technology of value is perceived, certain constraints to its definition and utilization exist today and will continue to exist tomorrow. Examples of these constraints are the previously cited "User's Paradox" and the frequently referred to lack of a mission model. To encourage user acceptance, we must foster the idea that operational demonstrations, including in-space demonstrations, are a necessary part of the technology effort. Regarding the lack of a mission model, technologists will continue to have to deal with perceived needs rather than stated needs, a skill which seems to be improving with time.

Low-thrust propulsion for large space systems is a technology area with potential benefit of proportions we are just beginning to realize. Low-thrust chemical propulsion for orbit-raising of these large systems may be the enabling propulsion option. Electric propulsion for on-orbit control could significantly enhance the utilization of large space system technology. Applications of low-thrust propulsion to other missions besides large space systems is practicable, even to those missions that are not thrust sensitive, and by doing this the opportunity of complete deployment and checkout in the vicinity of the Shuttle is introduced.

Primary chemical propulsion for round trips to high orbits is economically questionable unless significant propulsion advances are accomplished. The prognosis for these advances in the near term is poor. With today's technology (460 sec specific impulse, 0.90 mass fraction, $800/kg launch cost), the cost of such missions would be high and extremely sensitive to vehicle and engine characteristics. There would have to be some vitally important reason to select the round trip mission option over other options to justify the inherent expense.

Primary electric propulsion for orbit raising and for planetary missions is a technology with high potential, with the objectives of high power/mass and high specific impulse for planetary missions, and simple, high thrust-to-mass, low-cost systems for orbit raising missions. This technology and its utilization will, however, be influenced by the extent of new technology achievements in the cost, weight, and radiation resistance of photovolatic space power. Auxiliary electric propulsion is clearly a technology with enormous potential benefit for many near and far term missions, but acceptance has been limited because of the aforementioned User's Paradox. Auxiliary electric propulsion could enable the application of Large Space System Technology to future missions and could realistically increase the objectives to which Large Space System Technology aspires.

References

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3. "Study of Electric Propulsion for Near-Earth Space Missions," Boeing Aerospace Co., Seattle, Wash., D180-24819-1, Oct. 1978.

4. Bekey, I., "Big Comsats for Big Jobs at Low User Cost," Astronautics and Aeronautics, Vol. 17, Feb. 1979, pp. 42-56.

TABLE 1. - COST COMPARISON OF VARIOUS GEOSYNCHRONOUS TRANSPORTATION OPTIONS

Transportation option (○ P/L Origin; ⊗ P/L Destination; Vehicle track)	Vehicle option	I_{sp}, s Specific impulse	γ Vehicle mass fraction	ΔV, m/s Velocity, inc.		M_{PL}, kg Payload mass		M_p, kg Propellant mass	Earth to LEO[a] cost, $M	Δ Cost, $M	
				Up	Down	Up	Down			-5 sec I_{sp}	-0.01 γ
GEO / LEO — Deliver, One-Shot	All-Propulsive	460	0.90	4300	0	7000	0	13540	16.4	+0.3	+0.3
GEO / LEO — Deliver, Flyback	Aeromanuvering	460	0.86	4300	2150	7000	0	23060	24.0	+0.8	+1.9
	All-Propulsive	460	0.90	4300	4300	7000	0	30580	30.1	+1.5	+5.9
GEO / LEO — Retrieve	Aeromanuvering	460	0.86	4300	2150	0	7000	22900	23.9	+0.9	+1.8
	All-Propulsive	460	0.90	4300	4300	0	7000	29260	69.0	+4.7	+15.5
GEO / LEO — Sortie[b]	Aeromanuvering	460	0.86	4300	2150	7000	7000	45960	42.4	+1.6	+3.6
	All-Propulsive	460	0.90	4300	4300	7000	7000	109830	93.5	+6.2	+21.4

[a]Cost to transport Payload and Propellant Mass from Earth to LEO at $800/kg.
[b]Required for Manned Missions to GEO.

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TABLE 2. - LOW-THRUST PROPULSION SYSTEM

CHARACTERISTICS FOR EARTH ORBITAL MISSIONS

Characteristic	Chemical	Electric
Trip time	Short (1-3 days)	Long (~100 days or more) - possible damage to payload
Specific impulse	350-450 sec	High (1500-10000 sec) - yields high payload fractions
Acceleration	Low enough - to minimize effect on structure mass	Very low - desirable for transportation of very large structures

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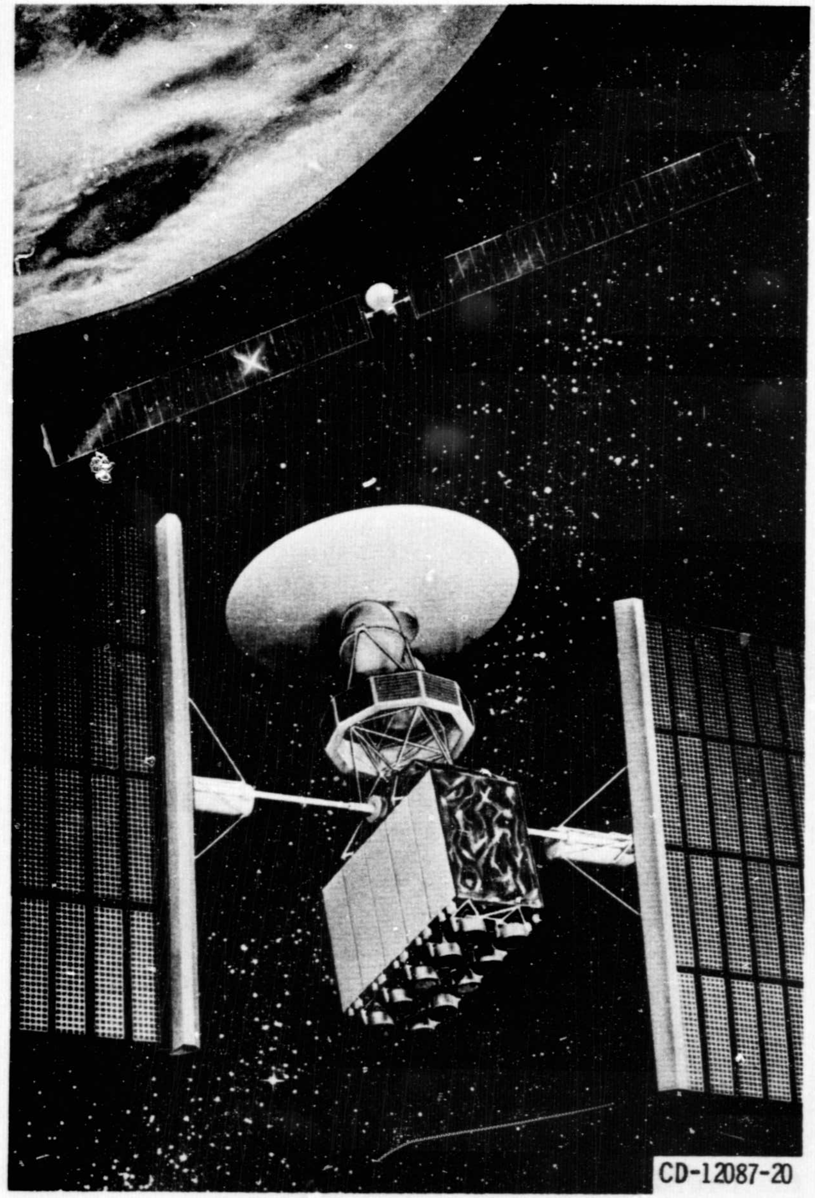


Figure 1. - Solar-electric propulsion for deep space missions.

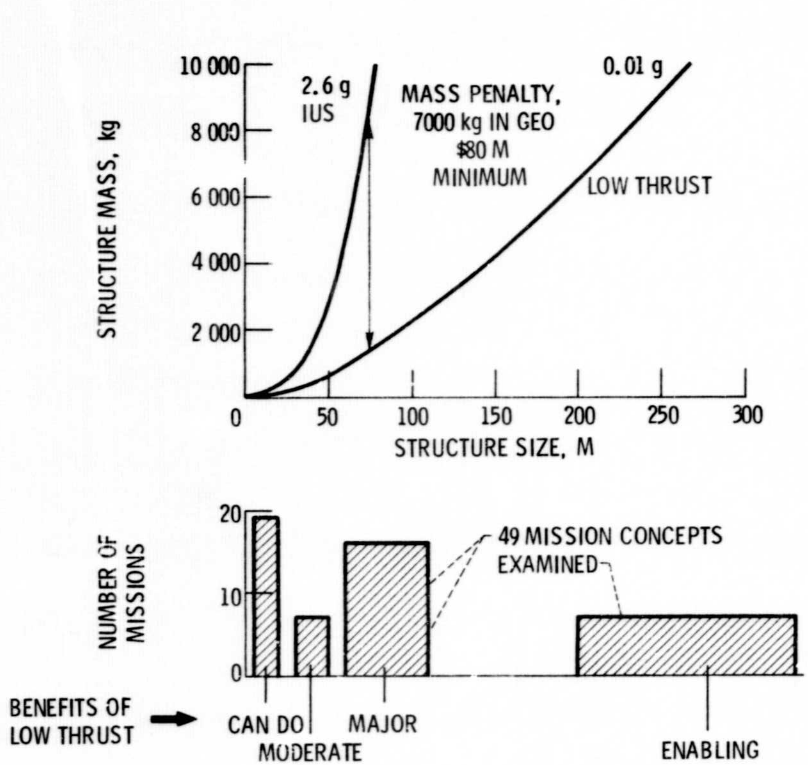
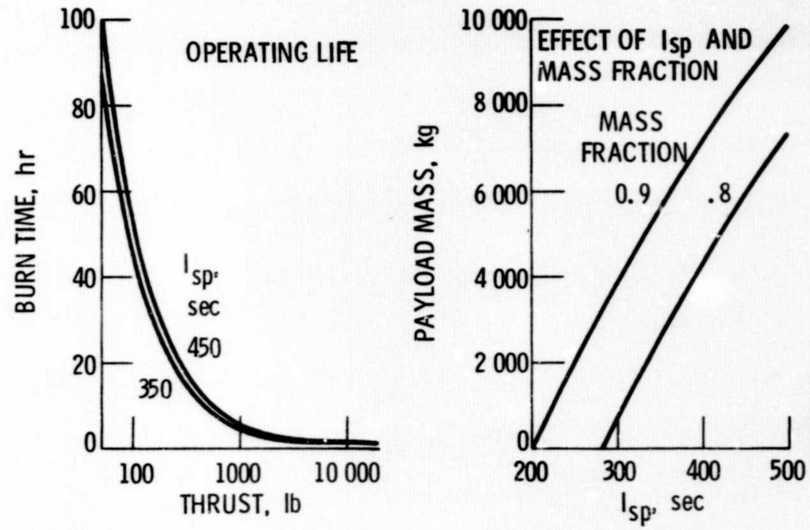


Figure 2. - Effect of low-thrust propulsion on large space systems.



LOW THRUST	100 - 1000 lb
LONG OPERATING LIFE	5 - 50 hr
MULTIPLE RESTARTS	5 - 10
SPECIFIC IMPULSE	350 - 450 sec
MASS FRACTION	.85 - .90
SOFT START	TBD
THROTTLING	TBD
PROPULSION SYSTEM ENVELOPE	.2 - .4 CARGO BAY LENGTH
TOTAL IMPULSE	20×10^6 lb-sec

Figure 3. - Requirements for low-thrust chemical propulsion.

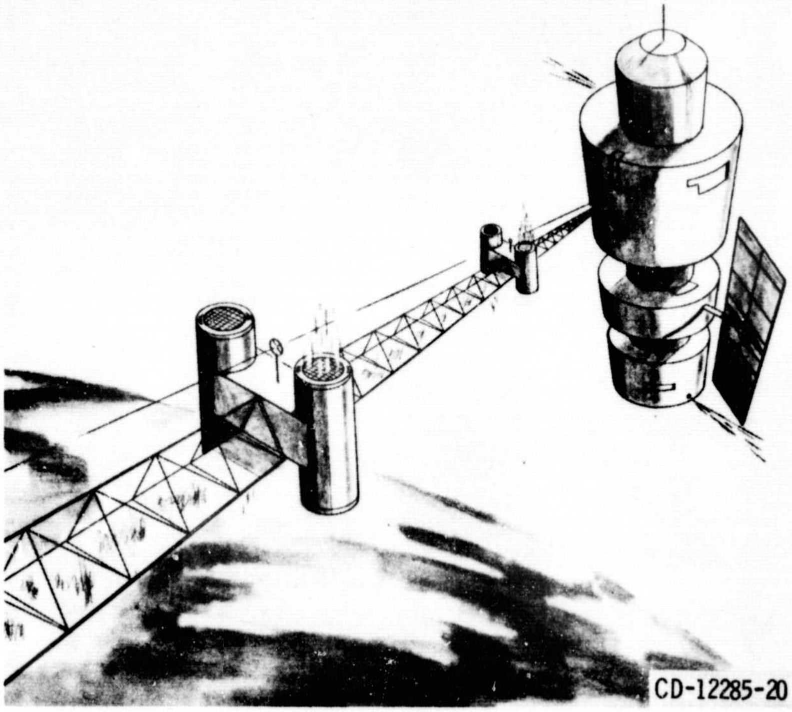


Figure 4. - Large space system on-orbit control using electric propulsion.