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LASER PROPULSION

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16. Abstract

The use of an Earth-based high-power laser beam to provide energy for Earth-launched rocket vehicles is investigated. The laser beam energy is absorbed in an opaque propellant gas and is converted to high-specific-impulse thrust by expanding the heated propellant to space by means of a nozzle. This laser propulsion scheme can produce specific impulses of several thousand seconds. Payload- to gross-weight fractions about an order of magnitude higher than those for conventional chemical Earth-launched vehicles appear possible. There is a potential for a significant reduction in cost per payload mass in Earth orbit.

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SUMMARY

The use of an Earth-based high-power laser beam to provide energy for a rocket vehicle is investigated. The laser beam is absorbed within a rocket nozzle by an optically opaque propellant such as seeded hydrogen. The energy that is absorbed in the gas is converted to high-specific-impulse thrust by expanding the heated propellant through a nozzle. The specific impulse that yields the highest payload into Earth orbit per total energy consumed lies in the range of 1200 to 2000 seconds. The payload fraction is in the range of 0.20 to 0.40 of the initial gross takeoff weight for a specific impulse of 2000 seconds and for thrust-to-initial-weight ratios of about 1.2 to 4.0. Because the payload fraction is about an order of magnitude higher than that for conventional chemical rocket means for placing payload in orbit, the cost of the vehicle per pound of payload could be an order of magnitude lower. Large electric power stations are required. This could be the most important cost factor unless the powerplant amortization is shared by using it for other purposes. The powerplant could be used, for example, for producing hydrogen, oxygen, and electric power, for desalinization, for chemical processing, for waste disposal, for sewage treatment, etc. The propellant cost and the electrical energy cost (at commercial rates) are a small fraction of the total launch costs.

A detailed cost and overall system analysis is beyond the scope of this report. The main purpose of this report is to describe a technique that can be used to place payload in orbit by using high-power ground-based lasers and to show that a possibility exists that the cost might be very low compared to those of other means. A further detailed overall system and operation study would be required to substantiate this possibility fully.

INTRODUCTION

At the seventh annual meeting of the AIAA at Houston, Texas, Kantrowitz (ref. 1) stated that it seemed likely to him that lasers with powers of the order of thousands of megawatts are an important possibility. He also observed that the energy change in transferring a mass from the surface of the Earth to a low-altitude orbit around the Earth was about 3.56×10^{7} joules per kilogram (4.5 kW-hr/lb) and that the cost of this energy is about $0.044 per kilogram ($0.02/lb). Potentially, therefore, it may be possible to place mass in orbit with energy costs of fractions of dollars per kilogram.

The purpose of this report is to explore a technique for using high-power lasers for propelling an Earth-launched vehicle that places payloads into orbit. In this technique, high-power Earth-based laser beams interact with vehicles so that they are propelled from the surface of the Earth. The high-intensity laser beam captured by a propellant produces high enthalpy gases which are expelled to produce thrust. For example, the laser beam could be absorbed by an optically opaque gas, such as seeded hydrogen. The hydrogen gas and seed particles are injected through porous walls of the nozzle, as shown in figure 1(a). In another approach the laser beam impinges on an ablative plate at the base of the nozzle, and the high-intensity beam causes the plate to evaporate. The hot gas that is generated in the absorption or ablation process will expand away from the plate to produce thrust. A nozzle skirt could be placed around the outer perimeter of this plate to better direct the expansion of the gases in the rearward direction and thereby greatly increase the efficiency of the energy conversion.

The use of the proposed laser propulsion technique may not be limited to placing payloads in orbit. The device might also be used to accelerate payloads on direct trajectories to any of the planets, asteroids, or comets or into orbit around the Sun. In addition, the laser propulsion system might also be used on Earth for transcontinential, transoceanic, or world-wide transportation. In these applications it would be used to place vehicles into free-flight ballistic trajectories. The vehicle would have the capability of maneuvering and landing at the destination site much as the return stage of the space shuttle. The vehicle could also use a laser beam at the destination to provide braking thrust to decelerate and land.

This report presents the results of simple calculations to indicate the potential of such a propulsion system. Calculations are made to determine payload fractions; power and energy requirements; the effect of specific impulse, initial acceleration, and laser efficiency; and the cost of electrical energy and propellant. An overall cost-effectiveness study which includes such factors as vehicle structure cost, land-based powerplant and laser cost, and development cost is beyond the scope of this report.

SYMBOLS

C_N nozzle coefficient

D laser optics diameter, m

E_b laser beam energy collected at engine, J

E_e electrical energy used to drive laser, J

g local gravitational acceleration during flight, m/sec^2

$\bar{g}$ average gravitational acceleration during flight, m/sec^2

g_0 Earth surface gravitational acceleration, 9.81 m/sec^2

h enthalpy of heated propellant at inlet of nozzle, J/kg

I_{sp} specific impulse, sec

k thrust-to-initial-weight ratio

m vehicle mass, kg

m_{pay} payload mass, kg

m_p initial propellant mass, kg

m_{tot} initial vehicle mass, kg

t_B engine firing time

ΔV vehicle velocity increment, including drag penalty, m/sec

α propellant mass fraction, m_p/m_{tot}

η_b overall beam transmission efficiency

λ light wavelength, m

$\theta_{1/2}$ half-angle of beam divergence, rad

DESCRIPTION OF PROPOSED LASER PROPULSION SYSTEM

A schematic drawing of the laser propulsion system proposed in this report is shown in figure 1(a) and (b). The high-energy laser beam is directed toward a propellant injection plate located within a nozzle. The laser beam energy is absorbed by hydrogen (or other gas that flows through the injection plate and walls of the nozzle) seeded with seed particles such as carbon or natural uranium to render it opaque.

The propellant enthalpy and hence specific impulse are determined by dividing the beam power by the rate of propellant flow. The lower the propellant flow rate or the higher the beam power, the higher the enthalpy. The hot propellant and vaporized seed mixture is expanded to space. A nozzle skirt is provided to direct the expansion and thus provide a more efficient conversion of thermal power to thrust force. The nozzle skirt is protected from the high-temperature radiating and expanding gases by an opaque boundary-layer film along the surface. This film is provided by utilizing a porous and/or a slotted wall that allows injection of a film with absorbing seed material entrained. The flow of propellant and seed vapor in the film will have the effect of reducing the specific impulse. The technique of using seeded gas to absorb radiated thermal energy has been studied in detail for gas-core nuclear rockets (ref. 2). Specific impulses of over 5000 seconds appear to be feasible when this approach is used.

It is important that the laser beam be accurately and reliably pointed toward the nozzle. One way to accomplish this may be to have the beam direction slaved to signals from the laser-propelled vehicle (see fig. 1(b)). For example, auxiliary laser beams that are parallel to the main power laser beam could be used for this procedure. The auxiliary beams could be directed to guidance detectors that are located outside the propulsion system. If the auxiliary beam begins to drift off the center of the target of the detector, signals are sent to the Earth-based high-power laser system that automatically corrects the pointing of the high-power and auxiliary beam. If the auxiliary beam wanders too far off the target of the detection system, the main laser beam can be reduced in power by some predetermined schedule so that no damage to the laser propulsion system or vehicle results.

The intensity of the laser beam (kW/cm^2) is determined by the desired propellant injection enthalpy and flow rate per unit area. Beam intensities of the order of megawatts per square centimeter may be required. Such beam intensities are presently attainable in relatively small (less than 30-kW) gas lasers. Several or a large number of laser beams could be used to transmit the necessary power to the propulsion system if some limit in laser size were reached. Each laser could be individually directed or they could be coupled. It may be advantageous to use many lasers to provide redundancy or permit operation with lower power lasers if the power level for a single laser becomes a limiting factor.

It will be necessary to use lasers in frequency ranges where windows exist in the atmosphere of the Earth and to locate the laser bases at sites where beam attenuation or spreading by clouds, smog, or turbulence is minimized. This, of course, is to minimize the power loss in the laser beam. It is also desirable to use very efficient lasers to minimize the ground electrical power requirements. Atmospheric turbulence will tend to spread the laser beam. It would therefore be desirable to locate launch sites on mountain tops to minimize this effect.

The trajectories that are required to place the laser-propelled vehicles in orbit will probably be different from conventional trajectories. It is required to have a direct line of sight during the entire propulsion period between the Earth-based laser system and the accelerating vehicle. This may lead to optimum Earth orbits that are elliptical rather than circular.

The direction of the thrust vector produced by the laser propulsion system need not be parallel to the incoming laser beam. The vehicle could be canted of the order of 45°

from the laser beam direction if desired, as shown in figure 1(a). The only limitation is that the laser beam be absorbed within the nozzle.

Preliminary design studies indicate that the thrust-producing portion of the laser propulsion system would probably not be heavier or more complicated than conventional chemical rocket engines.

ANALYSIS

The propellant is assumed to absorb all the laser beam energy that arrives at the vehicle. Thus, the propellant enthalpy is

$$h = \frac{\text{laser beam power}}{\text{propellant flow rate}} \tag{1}$$

The specific impulse is related to the enthalpy by the equation

$$I_{sp} = \frac{1}{g_0}\sqrt{2C_N h} \tag{2}$$

where an overall nozzle expansion coefficient $C_N = 0.64$ is used to account for the non-ideal expansion energy losses due to viscous effects and nozzle wall heat transfer. Rearranging these equations gives the results that are plotted in figure 2:

$$\frac{\text{laser beam power (W)}}{\text{propellant flow rate (kg/sec)}} = \frac{(I_{sp}g_0)^2}{2C_N} \tag{3}$$

The laser beam power per unit thrust, plotted in figure 3, is calculated from

$$\frac{\text{laser beam power (W)}}{\text{thrust (N)}} = \frac{h}{I_{sp}g_0} = \frac{I_{sp}g_0}{2C_N} \tag{4}$$

The propellant mass fraction α is determined from the classical rocket equation

$$\alpha = 1 - \exp\left(\frac{-\sum \Delta V}{g_0 I_{sp}} - \frac{\bar{g}t_B}{g_0 I_{sp}}\right) \tag{5}$$

where

$$\sum \Delta V = \Delta V_{ideal} + \Delta V_{drag} \tag{6}$$

Here ΔV_{ideal} is the ideal mission velocity, for example, 8080 meters per second (26 500 ft/sec) for a low-orbit mission. A constant value of 1070 meters per second (3500 ft/sec) is arbitrarily assumed to account for atmospheric drag and the fact that the orbit will be elliptical rather than circular. The gravity losses are approximated by $\bar{g} = 0.8\ g_0$ (which is conservative for thrust-to-initial-weight ratios of 1.2 to 4.0). Noting that $t_B = I_{sp}\alpha/k$ and substituting in equation (5) result in the following equation:

$$I_{sp} = \frac{-\sum \Delta V}{g_0\left[\ln(1 - \alpha) + \frac{0.8\ \alpha}{k}\right]} \tag{7}$$

This equation is solved for α in terms of I_{sp} and k with the results shown in figure 4.

The payload mass fraction is calculated by using this propellant mass fraction and an assumed rocket system structural weight fraction of 0.20. The resulting equation, used in plotting figure 5, is

$$\frac{m_{pay}}{m_{tot}} = 1 - 0.20 - \alpha \tag{8}$$

The laser beam energy per payload mass in Earth orbit, plotted in figure 6, is calculated by using equations (3), (7), and (8) in the following equation:

$$\frac{E_b}{m_{pay}} = \frac{E_b}{m_p}\ \frac{m_p}{m_{tot}}\ \frac{m_{tot}}{m_{pay}} = \frac{h\alpha}{0.8 - \alpha}\left(\frac{J}{kg}\right) \tag{9}$$

The electric energy per payload mass depends on an assumed overall beam efficiency $E_e = E_b/\eta_b$. This value of η_b includes the ground-based electric-laser conversion efficiency and the laser beam transmission efficiency. The ground-based electric energy per payload mass is shown for various assumed overall efficiencies in figure 7.

The required electrical powerplant capacity per unit mass of payload, plotted in figure 8 is calculated from

$$\frac{\text{ground base power}}{\text{payload mass}} = \frac{E_e}{m_{pay}}\ \frac{k}{I_{sp}\alpha} \tag{10}$$

The dollar cost of energy per payload mass in Earth orbit is calculated by assuming an electrical energy cost of $\$1.39\times10^{-9}$ per joule (\$0.005/kW-hr). The energy cost per payload mass, plotted in figure 9, becomes

$$\frac{\$}{m_{pay}} = 1.39\times10^{-9} \frac{E_e}{m_{pay}} = \frac{1.39\times10^{-9}\, h\alpha}{\eta_b(0.8 - \alpha)} \left(\frac{\$}{kg}\right) \tag{11}$$

The dollar cost of liquid hydrogen propellant per payload mass is calculated by using a projected future cost of $0.22 per kilogram ($0.10/lb) for liquid hydrogen (ref. 3). The propellant cost per pound of payload becomes

$$\frac{\$}{m_{pay}} = 0.22 \frac{m_p}{m_{tot}} \frac{m_{tot}}{m_{pay}} = 0.22 \frac{\alpha}{(0.8 - \alpha)} \left(\frac{\$}{kg}\right) \tag{12}$$

DISCUSSION OF RESULTS

The characteristics of laser propulsion systems are examined in a stepwise fashion. First, basic quantities such as beam power required per unit of propellant flow and thrust are determined. Then ratios of payload and propellant mass to takeoff mass are computed for a range of specific impulses. From these ratios the total energy and power required per unit of mass in orbit are calculated. This information then permits calculation of the cost of electrical energy and propellant for placing mass in orbit. No attempt is made to determine vehicle structure or Earth-based powerplant costs.

Beam Power Requirements

Calculations were first made of the beam power required per unit propellant flow rate as a function of specific impulse by using equation (3) (see fig. 2). It was assumed that 64 percent of the arriving laser beam power was converted to thrust. The power required to produce thrust varies as the square of the specific impulse. About 1.20×10^6 kilowatts per kilogram per second (5.5×10^5 kW/(lb/sec)) is required for a specific impulse of 4000 seconds.

Figure 3 shows the corresponding laser beam power per pound of thrust produced, as given by equation (4). The laser beam power per unit of thrust varies directly with specific impulse. At a specific impulse of 4000 seconds the required laser beam power per unit of thrust is 30.6 kilowatts per newton (135 kW/lb). Figures 2 and 3 do not depend on propellant properties, so they apply for any gaseous propellant. Different propellant properties would yield different propellant temperatures and different limiting specific impulses depending on the radiating characteristics of the propellant.

Payload Mass Ratios for Earth Orbit Mission

The propellant- to total-mass ratio was calculated from equation (7) for a mission that is equivalent to placing payload in a low-altitude Earth orbit. It was assumed that a velocity increment including drag losses of 9150 meters per second (30 000 ft/sec) and an average gravity force of 0.8 g were representative for this mission. The propellant- to total-mass ratio is plotted in figure 4 as a function of specific impulse and thrust-weight ratio. For a specific impulse of 4000 seconds the propellant mass ratio varies from about 0.39 to 0.25 as thrust-weight ratio is varied from 1.2 to 4.0. At 2000 seconds the propellant mass ratio varies from about 0.60 to 0.40 for the same range of thrust-weight ratios.

Figure 5 shows the corresponding payload- to total-mass ratio from equation (8) with the empty or hardware weight (total weight less payload and propellant) assumed (conservatively) to be 20 percent of the total weight. For a specific impulse of 4000 seconds the payload- to total-mass ratio varies from 0.41 to 0.55 as thrust-weight ratio varies from 1.2 to 4.0. At 2000 seconds the payload- to total-mass ratio varies from about 0.20 to 0.40 for the same range of thrust-weight ratio. Above 4000 seconds the payload fraction begins to level off with increasing specific impulse.

Electrical Energy Requirements for Earth Orbit Mission

Figure 6 presents the laser beam energy per unit payload mass placed into low-altitude orbit as a function of specific impulse and thrust-weight ratio. It is interesting to note that a minimum in laser beam energy per payload mass occurs for specific impulses in the range of about 2000 to 1200 seconds as thrust-weight ratio varies from 1.2 to 4.0, respectively. The minimum value of laser beam energy varies from about 7×10^8 to about 3×10^8 joules per kilogram (90 to 40 kW-hr/lb) for the same variation in thrust-weight ratio.

The minimum in energy required to place a unit payload mass into orbit as a function of specific impulse can be explained as follows. For low specific impulse the payload fraction is small because the propellant mass required to place a given payload into orbit is large. The initial vehicle weight then becomes large for a given payload, which then requires an increasing amount of total energy to place the given payload into orbit. For high specific impulse the propellant fraction becomes small and the total vehicle mass approaches a lower limiting value equal to the empty weight of the vehicle and the payload. In this case the energy required to accelerate the propellant to the high jet velocities corresponding to the high specific impulse becomes much greater than the energy required to accelerate the vehicle. Between the extremes of low and high specific impulse there is a best value which minimizes the total energy required to place a unit mass into orbit. The more ambitious the mission (the greater the velocity change required for the payload), the higher the specific impulse that minimizes the energy required to accelerate a given payload mass.

It is possible to determine the ground powerplant energy required to place payload mass into orbit if the overall efficiency of converting the ground-based power into power absorbed by the engine is assumed. Figure 7 shows the ground-based electric energy required to place a unit of mass into Earth orbit for assumed values of overall beam efficiency of 10, 30, 50, and 100 percent.

The exact value of overall beam efficiency will depend on several loss mechanisms. First, production of a laser beam from electrical energy involves a laser efficiency. Efficiencies up to 47 percent have been obtained experimentally (ref. 4), and Herzberg (ref. 5) claims that efficiencies approaching 100 percent may be ideally possible (assuming isentropic flow in a closed-cycle gas dynamic laser). Second, there is beam attenuation due to atmospheric scattering and absorption. Clear air transmission studies (ref. 6) indicate that transmission efficiencies of 85 percent are possible through a clear atmosphere. Third, there may be energy losses unless the laser beam diameter is less than the engine capture diameter. For an orbital system this requires that the beam divergence $\theta_{1/2}$ be at most about 5×10^{-6} radians if the capture diameter is 10 meters (32.8 ft) at a distance of 1000 kilometers (620 miles). In comparison, the recent Moon ranging experiments (ref. 7), which represent state-of-the-art collimation, obtained $\theta_{1/2}$ values of 2×10^{-6}, which would require a diameter of 4 meters (13 ft). With astronomical telescope mirrors the theoretical beam divergence λ/D can be made as small as 10^{-7} (5-m (200 in.) mirror operating at visible wavelengths). However, atmospheric turbulence tends to increase the divergence, and, for example, resulted in the larger value in the Moon ranging experiments. With additional research on methods for reducing turbulent divergence, it may be possible to attain lower divergence values.

In addition, precision laser beam pointing with a pointing accuracy of 10^{-6} radian would be required to keep the beam centered. The beam pointing system could be patterned after several high-precision star tracking systems such as used in the existing Orbiting Astronomical Observatory (OAO) or the proposed Manned Orbiting Telescope (MOT). These designs could be adapted to accommodate the larger moments of inertia and driving torques that may be characteristic of the laser beam system. The OAO has demonstrated a pointing accuracy of 5×10^{-7} radian, and the proposed accuracy of the MOT is 5×10^{-8} radian (see ref. 8). It thus appears that the required 10^{-6}-radian beam pointing accuracy could be met by adapting state-of-the-art techniques. Further study is required to determine what pointing response rates are needed to follow in-flight disturbances adequately and to identify drive system requirements.

The preceding discussion indicates that the overall efficiency of converting ground-based electrical energy to heat energy on board the vehicle may be at least 10 percent and possibly better than 50 percent.

Figure 7, which was calculated for a thrust-weight ratio of 1.5, shows that the optimum specific impulse is about 1600 seconds. The optimum specific impulse is independent of the beam efficiency. For an overall efficiency of 10 percent the required electrical energy per unit of payload mass in orbit is 5.5×10^{9} joules per kilogram (700 kW-hr/lb). If the efficiency were 100 percent, 5.5×10^{8} joules per kilogram (70 kW-hr/lb) would be required to place payload in orbit. This is to be contrasted to the ideal of 3.56×10^{7} joules per kilogram (4.5 kW-hr/lb) quoted by Kantrowitz (ref. 1).

The difference between the ideal energy requirement and the actual value depends on several factors. A typical case at a thrust-weight ratio of 1.5 and specific impulse of 1600 seconds illustrates these factors. With the assumed nozzle energy conversion coefficient of 0.64, only 64 percent of the beam energy is converted into propellant kinetic energy. Because of the difference between vehicle and jet velocity, only about 36 percent of the propellant jet kinetic energy is converted into vehicle energy. Of this, about 30 percent is used for payload acceleration because the payload is about 20 percent of the total mass. Multiplying these factors gives a payload orbital energy that is 7 percent of the beam energy. This accounts for the large difference between the laser beam energy calculated in this report and the ideal payload energy given by Kantrowitz.

The required electrical power per unit of payload mass for the Earth orbital mission is calculated from equation (10) and is shown in figure 8. This can be used to determine the required powerplant capacity for a given payload. For the thrust-weight ratio of 1.5 it is seen that the power is lowest near the optimum specific impulse of 1600 seconds. For the 30 percent overall beam efficiency the required electrical power is about 2750 kilowatts per kilogram (1250 kW/lb) of payload. The cost of the powerplant would be a major consideration and should be included in a detailed mission cost study. Although power requirements will be large, the powerplant cost is nonrecurring and should be amortized over many launches. The powerplant could be used for other purposes between shots. For example, the electrical energy could be used to produce hydrogen and oxygen, for emergency electrical power, for chemical processing, for sewage disposal, for desalinization, etc. In addition, there may be other means for producing the high intermittent powers required for laser propulsion. A complete cost analysis of a whole system including factors such as this and the cost of the vehicle structure is beyond the scope of this report.

Energy and Propellant Cost of Placing Payload in Orbit

The cost of energy for placing payload in orbit with the laser propulsion system described in this report is calculated from equation (11) by using an assumed cost per unit of electrical energy on Earth. Assuming the rate for large quantities of electrical energy is $\$1.39\times10^{-9}$ per joule ($0.005/kW-hr) permits the calculation of the data shown in figure 9. The cost for electrical energy in dollars per unit payload mass is plotted as a function of specific impulse and overall beam efficiency. For a 30-percent overall beam efficiency at the optimum specific impulse of 1600 seconds, the energy cost for placing payload in orbit is $2.60 per kilogram ($1.20/lb) of payload.

With a projected price for large quantities of liquid hydrogen at $0.22 per kilogram ($0.10/lb) (ref. 3), the propellant cost is calculated from equation (12) and amounts to $0.64 per kilogram ($0.29/lb) of payload. (This is independent of overall beam efficiency.) For the case of 30-percent beam efficiency, the combined electrical energy and propellant cost is then about $3.30 per kilogram ($1.50/lb) of payload.

OTHER COMMENTS

The laser propulsion system proposed in this report ought to be scalable provided the beam area is controlled in flight to conform to the capture area of the engine; that is, the cost of propelling small payloads on a per unit mass basis should not be greatly different from that for propelling large payloads providing beam spreading is not a limitation. With such limitation large systems may be relatively more efficient. Nevertheless, it appears that the beam spreading and other problems can be studied independently of the laser powered engine development in small-scale ground tests. The technique of laser propulsion, therefore, could be developed initially on a relatively small scale.

The laser beam power requirements for a vehicle with a gross weight of 454 kilograms (1000 lb) would be about 250 megawatts for an Earth orbit mission. This would place about 91 kilograms (200 lb) of payload into Earth orbit. To place 22 700 kilograms (50 000 lb) in orbit would require a total beam power of about 60 000 megawatts delivered to the vehicle.

Such high power levels are beyond the current state of the art of lasers. However, there evidently does not appear to be any fundamental reason why a laser beam of this power is not possible (ref. 1). If it develops that a practical limit does exist and is less than the total power required, then possibly many lower power lasers could be ganged together to point at a common aiming point, namely, the laser rocket, to provide the total power.

The technology that is currently being developed for containing gaseous fissioning fuel operating at temperatures of about 100 000 K (ref. 2) is directly applicable to the problem of absorbing the laser beam energy in the laser rocket. In both cases very high intensity thermal radiation must be absorbed in a propellant gas that is heated by the absorption to temperatures measured in tens of thousands of degrees Kelvin. The energy must be almost completely absorbed by gases and/or vapors or solid seed particles which are subsequently vaporized. If not, then the radiation intensity is sufficient to vaporize the walls from which the propellant flows. Reference 2 indicates potential feasibility of absorbing sufficient radiation in gases enclosed in walls operating at room temperature to produce specific impulses in the range of 5000 to 7000 seconds. The radiant absorption and wall shielding in the laser nozzle may be reduced because the pressures will be lower than the 1000 atmospheres of the gas core. In addition, the wall shielding mechanism, as well as other processes in the nozzle such as expansion with nonuniform heat addition and radiant transport of heat, require additional study to determine maximum specific impulse more precisely.

Beam spreading and transmission through the atmosphere require additional investigation. Information in these areas would apply to the present laser propulsion concept, as well as to the general problem of efficient laser-beam power transmission from Earth to a spacecraft. The beam spreading effects of atmospheric turbulence, as well as refractive index change (due to local atmospheric heating), are being studied elsewhere. For all weather operation, beam scattering and attenuation by clouds, smog, and precipitation in the atmosphere need to be investigated further. Also, research is needed on lasers that operate efficiently at wavelengths where atmospheric absorption is minimized. For precise beam pointing the response rate and driving torque capabilities of present star tracking systems probably need to be increased.

Laser propulsion may be used for other missions. It may be desirable to use it for higher ΔV missions than for placing payload in Earth orbit. Either higher acceleration or longer beam path lengths would have to be used in this case. Another interesting application may be for a global Earth transportation system. The vehicle would be accelerated into a ballistic trajectory and then land at its destination either by aerodynamic braking and gliding or by means of a reverse laser braking propulsion system.

CONCLUSIONS

The following conclusions were drawn from this study of the use of an Earth-based high-power laser beam to provide energy for Earth-launched rocket vehicles:

1. It appears feasible to use Earth-based laser beams to provide energy to accelerate payloads from the surface of the Earth to Earth orbits.

2. An order of magnitude reduction in hardware weight (hence cost) per kilogram of payload delivered to orbit may be possible by using the laser propulsion scheme described in this report in place of conventional chemical rocket powered launch systems. (The payload fraction is about an order of magnitude higher.)

3. The laser propulsion system requires a very large ground-based power supply that is used intermittently. Unless the powerplant is used for other purposes, or unless

a special low-cost power supply is devised, the major cost of placing payload in orbit with a laser propulsion system will probably be the amortization of the power supply.

4. The cost of electrical energy for placing payload in Earth orbit by using laser beam propulsion would be about $2.60 per kilogram ($1.20/lb) if 30 percent of the ground-based electrical energy used for the laser were transmitted to the vehicle. The corresponding propellant cost is $0.64 per kilogram ($0.29/lb) of payload.

5. The optimum specific impulse for placing payloads in Earth orbits is in the range of 1200 to 2000 seconds. This is to be compared to the 5000 seconds which probably is attainable for the laser system by using gas-core nuclear rocket technology.

Lewis Research Center,
National Aeronautics and Space Administration,
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112-28.

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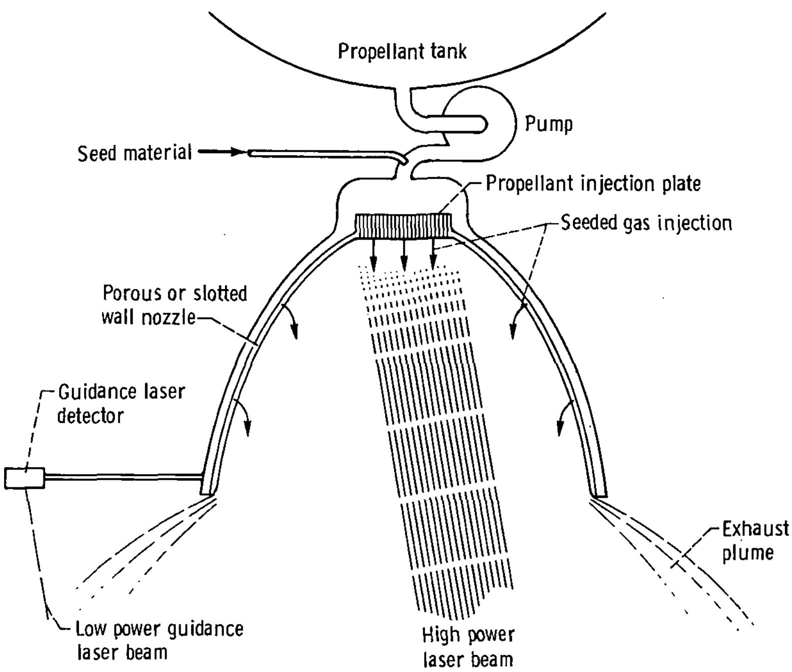
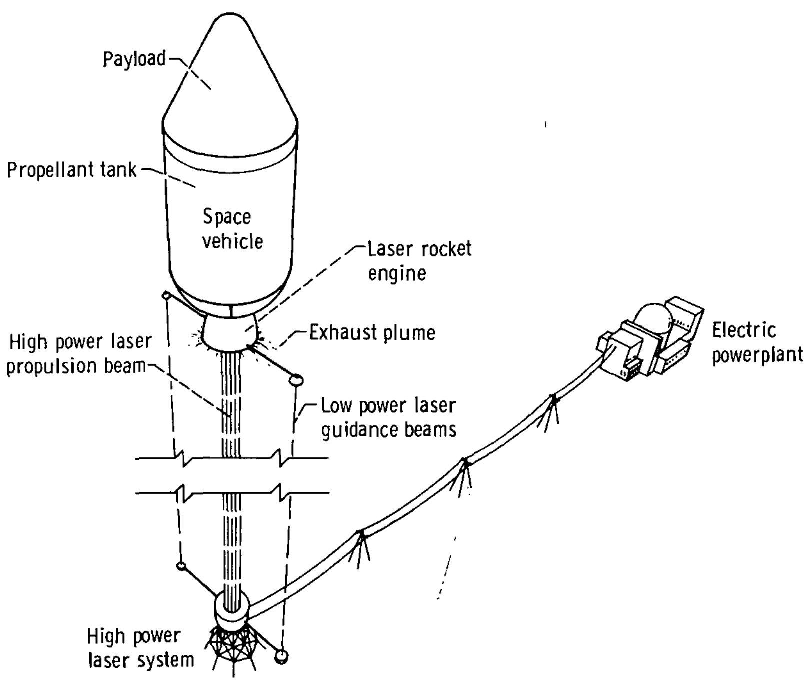


(a) Schematic of laser rocket engine.



(b) Propulsion vehicle and ground station.

Figure 1. - Laser rocket system.

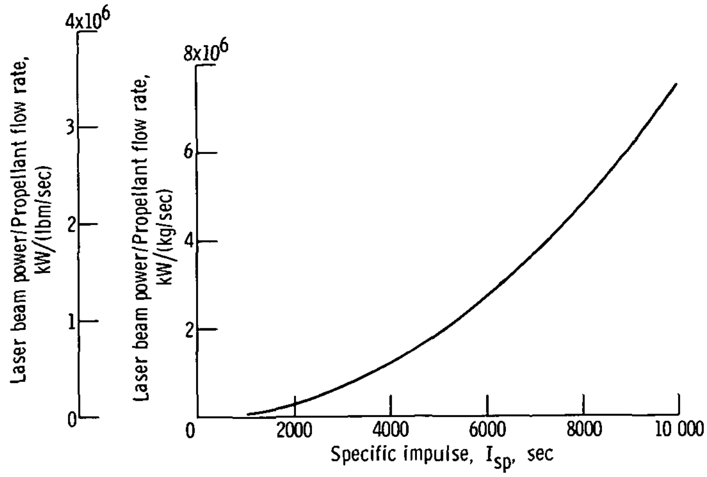


Figure 2. - Beam power per unit of propellant flow rate for various specific impulses.

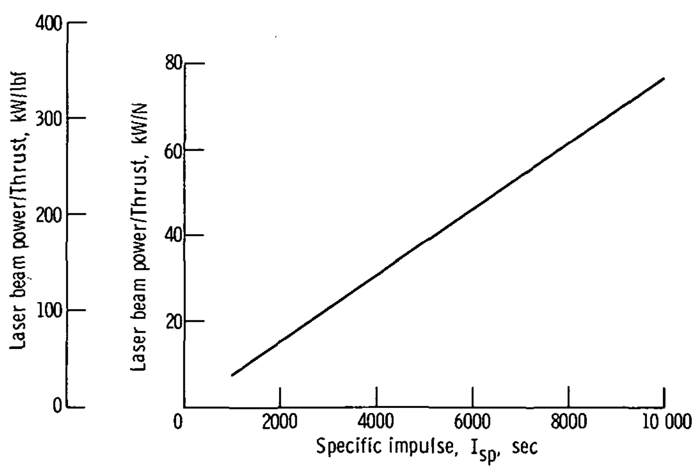


Figure 3. - Beam power per unit of thrust for various specific impulses.

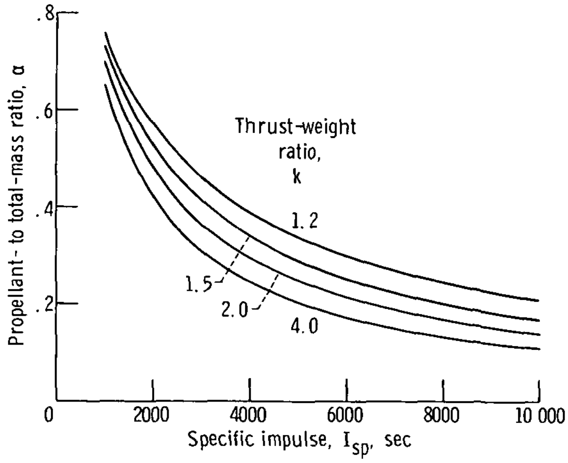


Figure 4. - Propellant- to total-mass ratio for various specific impulses and various thrust-weight ratios. Vehicle velocity increment, 9150 meters per second (30 000 ft/sec); average gravitational acceleration during flight, 0.8 of Earth surface gravitational acceleration.

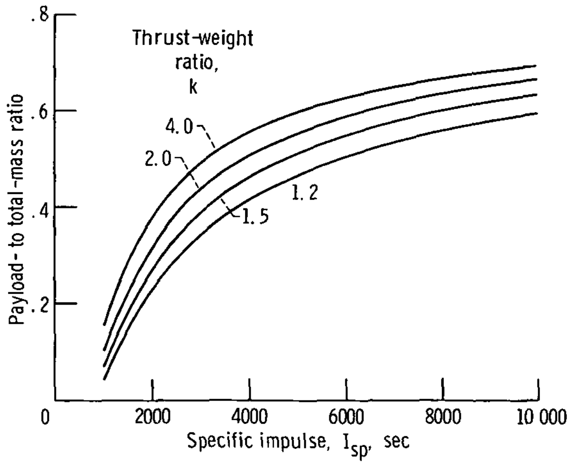


Figure 5. - Payload- to total-mass ratio for various specific impulses and various thrust-weight ratios. Vehicle velocity increment, 9150 meters per second (30 000 ft/sec); average gravitational acceleration during flight, 0.8 of Earth surface gravitational acceleration; ratio of structural to total mass, 0.20.

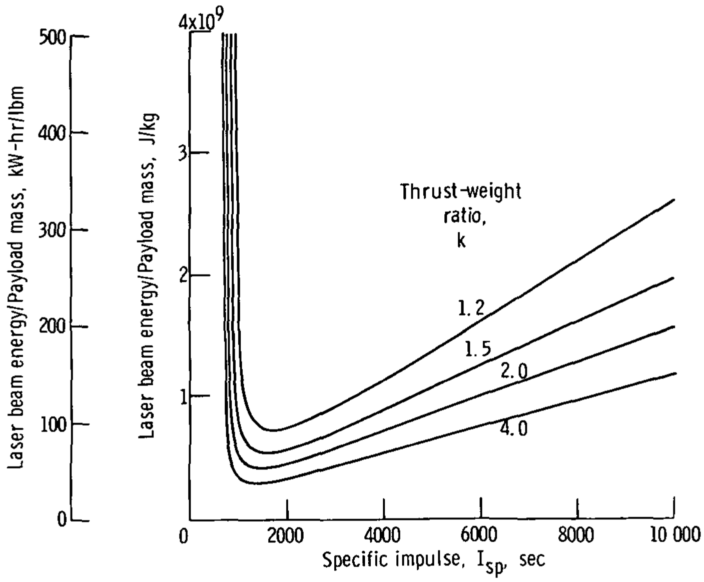


Figure 6. - Beam energy per unit of payload mass for various specific impulses and various thrust-weight ratios. Vehicle velocity increment, 9150 meters per second (30 000 ft/sec).

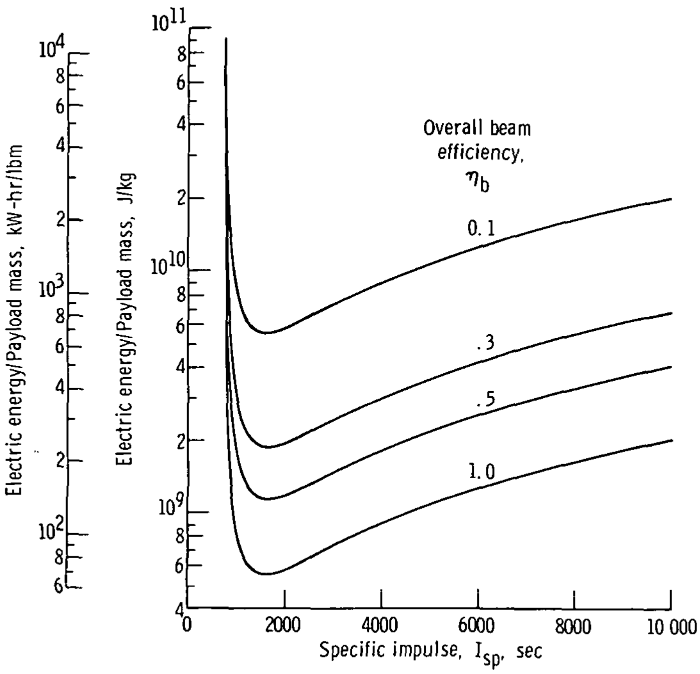


Figure 7. - Variation of electric energy per unit of payload mass with specific impulse for various overall beam efficiencies. Thrust-weight ratio, 1.5.

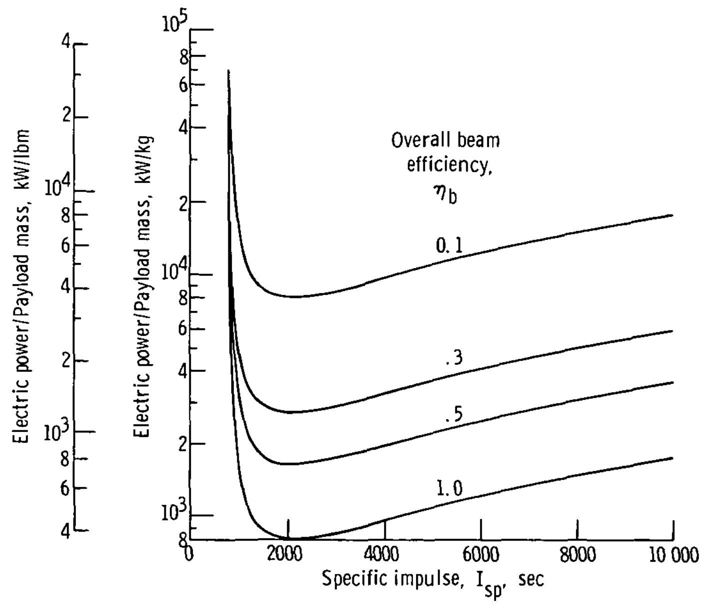


Figure 8. - Variation of electric power per unit of payload mass with specific impulse for various overall beam efficiencies. Thrust-weight ratio, 1.5.

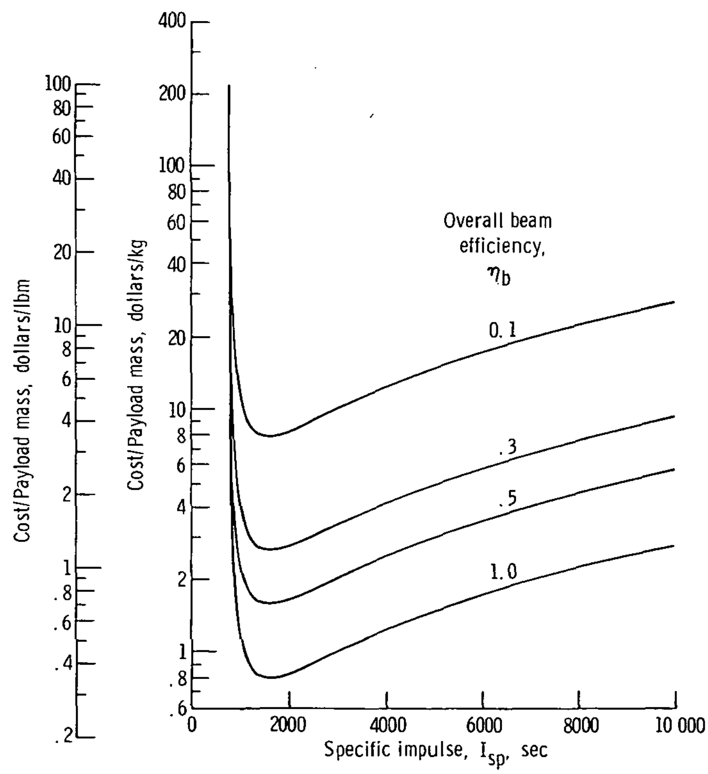


Figure 9. - Variation of electric energy cost per unit of payload mass with specific impulse for various overall beam efficiencies. Thrust-weight ratio, 1.5.

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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