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SYSTEM REQUIREMENTS FOR LOW-EARTH-ORBIT LAUNCH USING LASER PROPULSION[a]

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ABSTRACT

The use of ground-based lasers to launch small payloads but large total masses into low-Earth orbit may prove to be the most innovative and potentially economical approach for accomplishing this important mission. Of the several possible schemes for laser propulsion, two are examined: 1) ablative momentum transfer using pulsed lasers; and 2) heat exchanger thrusters in conjunction with CW lasers. For an entry-level payload of ~50 kg it is found that the former yields payload-to-power ratios of < 0.5 kg/MW with a requirement for an average laser power of at least 100 MW, whereas the latter might yield 1 to 3 kg/MW with a laser power of several 10s of MW. One of the promising approaches that could yield a driver for such a system is the reactor-pumped laser FALCON, which scales to these power levels with the potential for long run times.

INTRODUCTION

The concept of using a ground-based high-power laser as the prime power source for launching payloads into low-Earth orbit (LEO) was first proposed by Kantrowitz in the early 1970s.[1] More recently, the Advisory Committee on the Future of the U.S. Space Program identified two critical areas that need immediate attention. They are the replenishment of the technology base supporting new space propulsion and transportation systems, and the development of reliable and economical Earth-to-space launch systems. Laser propulsion could well be the innovative technology that provides the solution for these requirements. For Earth-to-LEO launch, individual payloads would be relatively small, but high launch frequency in conjunction with overall system simplicity

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would lead to large total launch capacities over acceptable periods of time. In addition, it is estimated that after the initial capital investment, incremental LEO launch costs could be as low as $100/lb, whereas current costs range from $1500 to $3000 per pound. These types of systems would operate with higher I_{sp} (600 to 1000 s or more) than conventional chemical rockets, but in contrast to some of the other innovative propulsion concepts (e.g., ion engines), would have comparable thrust-to-weight ratios.

Major support for research on laser propulsion has come from NASA, as well as from DARPA and the Air Force. Most recently, SDIO has sponsored a program, managed by Lawrence Livermore National Laboratory, which has concentrated on Earth-to-LEO missions using ground-based pulsed laser drivers. The most studied and highest payoff applications have thus been oriented toward Earth launches involving small payloads but large total masses, e.g., the deployment of a Brilliant Pebbles constellation. Other potential applications include such diverse missions as space asset resupply, nuclear waste disposal in deep space, destruction and/or de-orbit of space debris, and SEI propulsion.

The two fundamental approaches for laser propulsion involve pulsed and CW drivers.[2] The pulsed concepts rely on momentum transfer from dynamic ablation of a solid propellant plate. The most promising CW ideas employ a newly designed heat exchanger that uses the laser as an energy source for heating hydrogen propellant. The largest difficulty with these schemes has always been the availability of an appropriately sized laser driver. One of the systems under active development that is easily scalable to the requisite powers, the nuclear reactor pumped laser FALCON, is a credible candidate for such a driver. In the present study we will determine the approximate power requirements for entry level laser propulsion systems operating in both pulsed and CW modes.

BASIC EARTH-TO-LEO SCENARIO

To examine laser propulsion we need a common framework within which to compare the two different approaches. To accomplish this we will use a simple launch trajectory model proposed by Kantrowitz that is consistent with the constraints of laser propulsion.[3] These restrictions maintain the line-of-sight between the ground-based laser and the vehicle, keep the zenith angle reasonable to limit atmospheric attenuation, and allow for an initial altitude for the start of full laser propulsion. The basic launch scenario is shown in Figure 1. A small vehicle is launched vertically from the ground using either an air-breathing laser-driven ramjet or some other auxiliary propulsion system. The use of a conventional rocket stage would be possible, but would be inefficient because of air drag. Above the bulk of the atmosphere, the vehicle switches to full laser propulsion and climbs vertically to an altitude of ~100 km. It then begins to "turn over" and accelerate horizontally toward orbital velocity, which typically occurs at an altitude of 400 km and a range of ~1000 km. A more detailed analysis of laser-driven LEO launch trajectories that addresses many additional issues, including parameter sensitivity and scaling, has been given elsewhere.[4]

Table I
EXAMPLE LEO LAUNCHES

Launch Mass	Payload Mass	Average Thrust	Average Exhaust Power
120 kg	14 kg	1 to 3 kN	4 MW
500	60	2 to 10	12

For the present study we will use two examples, a very low-mass payload of 14 kg (as used by Kantrowitz[3]), and a larger payload of 60 kg that could be significant from a defense perspective. Note that these masses are significantly smaller than that of Figure 1, which was used to provide an alternate illustrative example. Using these smaller masses, Kantrowitz' trajectory model leads to the parameters outlined in Table I. Here the average exhaust power is given by $P_{ex} = \frac{1}{2} m' V_{ex}^2$, where m' is the propellant flow rate and V_{ex} is the mean exhaust velocity. In developing this model it was assumed that the thruster efficiency (exhaust power out/laser power in) was constant at 40%. This gives required laser powers of 10 and 30 MW respectively for the two examples, and then in addition, yields payload-to-power ratios of 1.4 to 2 kg/MW. These overall performance characteristics are probably too optimistic, but we will use the average exhaust power and thrust as basic descriptors for the examples.

PULSED LASER PROPULSION

The interactions employed by pulsed laser propulsion are identical with those that have been studied for many years in the context of directed energy laser weapons. Both applications rely on the recoil momentum generated when a short pulse of laser energy explosively vaporizes the surface of a target plate. Note that since the blowoff is always normal to the propellant plate surface, a symmetric laser beam will maintain the momentum vector parallel to the axis, independent of the angle of incidence; steering can be accomplished from the ground with small shifts of the beam position.

The conventional dependent variables used in studies of impulse lasers (impulse I, impulse coupling coefficient I/E, specific ablation energy Q^*) are directly related to the standard propulsion parameters.[5] Specifically, the propellant exhaust velocity V_{ex} is

$$V_{ex} = g\, I_{sp} = (I/E)\, Q^* ,$$

where g is the gravitational acceleration, and I_{sp} is the specific impulse. Similarly the thruster efficiency η_{th} can be expressed as

$$\eta_{th} = \frac{1}{2} m' V_{ex}^2/P_i = P_{ex}/P_i = \frac{1}{2} (I/E)^2 Q^* ,$$

where P_i is the laser power reaching the target. With these relations we can examine laser propulsion with models that have proven successful in describing impulse laser interactions. Using one such model,[6] we will estimate the minimum power required by a pulsed laser driver capable of achieving the example LEO launches.

The principal independent variables of interest are the pulse fluence F_o, the pulse duration τ, and the target (or propellant) material. Each combination of these parameters gives a unique I_{sp}, η_{th}, and thrust. By adjusting the rep rate or pulse frequency f, we can generate the average exhaust power and average thrust required by the example launches. For the illustrative calculations we will look at two different propellant materials, a generic metal (aluminum) and a generic plastic (Kapton), both of whose laser interaction parameters have been previously determined.[6] Further, we will assume a target interaction area A of 1 m^2, a pulse rep rate f that varies from 10 Hz to 10 kHz, and pulse durations of 1 ns and 1 μs. Finally, the individual pulses are assumed to act independently, with no significant preheating or degradation of the propellant between them. This last can be largely justified by noting that the duty factor is very small, ranging from 10^{-8} (1 ns x 10 Hz) to 10^{-2} (1 μs x 10 kHz).

The results of the model calculations are shown in the four parts of Figure 2. They present the average exhaust power P_{ex} as a function of the average input power P_i for all four combinations of propellant material and laser pulse duration τ. Each plot includes two curves for fixed values of pulse frequency -- f = 100 Hz and f = 1 kHz -- along which the pulse fluence F_o, I_{sp}, and η_{th} vary continuously. Also included in each plot are multiple curves for fixed values of I_{sp} ranging from 200 to 10000 s for aluminum and from 75 to 10000 s for Kapton. Along these latter curves (straight lines with "slope" one) both F_o and η_{th} remain constant, but the rep rate varies over its permitted range of 10 Hz to 10 kHz. Note that the average exhaust power is simply $P_{ex} = \eta_{th} P_i$, and that the average input power is $P_i = f F_o A$. In addition, each plot includes indications for the two values of P_{ex} given for the examples in Table I.

The first observation from these results is that there is a maximum thruster efficiency of $\eta_{th} \approx 25\%$ at $I_{sp} \approx 2000$ s for aluminum, and of $\eta_{th} \approx 15\%$ at $I_{sp} \approx 1000$ s for Kapton. The sets of curves define operating bands with efficiencies generally well below these maxima, typically below ~10% for aluminum and below ~5% for Kapton. The bands for the different pulse widths are similar -- they simply shift diagonally down to the left as the pulse width is shortened. For the values of P_{ex} required by the examples, we find that P_i falls generally in the decade $30 < P_i < 300$ MW. Therefore the reasonable "buy in" power for pulsed laser propulsion seems to be ~100 MW or more. Under these conditions the payload-to-power ratios vary from about one-tenth to no more than 0.5 kg/MW. This is in contrast to 1.4 to 2 kg/MW as previously estimated using $\eta_{th} = 40\%$. It may be possible to improve the efficiency to these higher levels with a more sophisticated coupling scheme, such as the double-pulse thruster,[5] but this would be at a cost of a substantial increase in complexity for the pulsed-laser driver.

CW LASER PROPULSION

The most-studied approach for CW systems uses optics to collect and focus energy from a laser beam through a window to heat propellant gas in a "combustion" chamber. The gas is subsequently expelled through a conventional nozzle.[7] A schematic for such a vehicle is shown in Figure 3. Although this concept has a very high potential efficiency, it suffers from a need for high quality optics that must be maintained in continuous alignment with the laser-driver, as well as a requirement for a complex vehicle incorporating the optics, a cooled nozzle, and other peripheral components.

A promising alternative, especially with respect to Earth-to-LEO launch applications, is the CW heat-exchanger (HX) thruster.[8] Two generic concepts for such a system are shown in Figure 4. The heart of the device is a newly designed, high-performance, solid heat exchanger, which absorbs the laser energy and heats the hydrogen gas propellant. The advanced laminar-flow heat exchanger allows low-pressure, pressure-fed operation (i.e., without pumps) at an incident laser flux of ~10 MW/m^2 (1 kW/cm^2) and relatively low temperatures (~1000°C). The temperature keeps reradiation from the HX acceptably low but limits I_{sp} to 600 - 800 s. Low cost manufacturing techniques for the HX should allow the vehicles to be disposable, while the flat-plate HX design retains most of the major advantages of the pulsed thruster described earlier. No on-board optics are required and the active interaction area would be comparable to the pulsed-laser designs. As suggested in the figure, a variety of nozzle designs is possible. Especially notable is the annular "aerospike" nozzle integrated with the HX. In addition, operation would be essentially independent of the laser wavelength, and the time constant associated with the HX would smooth out both temporal and spatial irregularities. In contrast to the other schemes for laser-propulsion, any source of radiant energy would work well for ground testing purposes. Hence the vehicle development could proceed independently from that associated with the laser driver.

The major difficulty with this system is the need to carry the mass of the propellant tank into orbit. However, the tank could be of relatively light-weight construction such that without the hydrogen fuel the mass of the vehicle would be about 1/3 tank, 1/3 HX, and 1/3 payload. Because these designs are preliminary, their details and the associated costs are quite uncertain. More specific details on the CW HX device can be found elsewhere.[8]

The total efficiency achievable with the CW HX thruster could potentially be as high as $\eta_{th} \approx 80\%$. This is twice the early assumptions for pulsed thrusters and five to ten times greater than the more realistic values given above. Even with the extra overhead associated with the HX and the required tankage, payload-to-power ratios of 1 to 3 kg/MW might realistically be attained. With these parameters, the "buy in" power for the example launches would be several 10s of MW, compared with 100 MW or more for pulsed systems.

DEVICES FOR PRIME LASER POWER

The use of laser propulsion for LEO launch dictates a number of specific requirements for the laser drivers. For pulsed-laser systems we find that an entry level device would have to be sized at an average power of ~100 MW or more. It should be capable of generating energy pulses of up to several 100s of kJ, with pulse durations from below 1 ns to several microseconds, and at rep rates ranging from ~10 Hz to ~10 kHz. It may also require an elaborate pulse format (e.g., double pulse) to achieve reasonable efficiencies. For the CW system described above the entry level power must be several 10s of MW, and there are, of course, no specifications for individual pulses. A final requirement, common to all laser propulsion schemes, is that the driver be able to function for long run times -- minutes continuously for individual launches, and cyclically many times a day to maintain a large total launch capacity.

Although conventional chemical, free-electron, or CO_2 lasers are in principle capable of meeting the requirements for pulsed laser propulsion, there are no current plans to develop systems of the requisite power levels. Similarly, no nuclear powered concepts currently being investigated seem credible for pulsed applications. In contrast, the nuclear reactor pumped CW laser FALCON (Fission Activated Laser CONcept), currently being pursued actively at Sandia, has a number of attributes that may make it ideal for use as a driver with the CW HX thruster.[9]

The most important relevant feature of FALCON is that it easily scales to optical output powers as high as 100 MW, which is more than adequate for the entry-level CW propulsion systems considered here. Because of the nuclear reactor, the device is primarily self-powered and there is no need for appreciable power from the local grid. It also has a high energy content and is therefore capable of long run times without refueling. In addition, it is relatively compact when compared with extrapolations for more conventional non-nuclear laser systems with similar capabilities. The technology employed by FALCON is virtually all near term (e.g., relatively low pressures and low temperatures for its gas flow system) and thus does not require any major breakthroughs before a full-scale device can be contemplated.

One reason for the high-power scalability of FALCON is the fact that it is constructed as a collection of modules. Although this provides for the favorable scaling and keeps the operating parameters modest, it leads to the requirement that a number of laser beams will have to be combined to generate the final high-power output. This relates directly to one of the major issues associated with the device, beam quality. This question is beyond the scope of the present paper; we only note that to perform effectively in a laser propulsion role, a nearly diffraction-limited laser beam will be required, and work to achieve this goal is currently underway. The other issues associated with FALCON relate to the non-technical problems resulting from the use of nuclear power, and to the cost of the laser system, which is at best uncertain.

CONCLUSIONS

The present analysis strongly suggests that using the CW heat-exchanger thruster, in conjunction with the reactor-pumped laser FALCON, is the best near-term approach for an innovative Earth-to-LEO launch system based on laser propulsion. Although individual payloads will be modest for the entry-level system, the total launch capacity can be substantial, and the costs have the potential of dropping by as much as an order of magnitude from current levels.

Pulsed laser thrusters for this mission will probably require very high average powers and complex pulse formats. No drivers that meet these requirements are currently under development. However, the simple modeling does indicate that efficiencies and values for I_{sp} useful for other missions (e.g., in-space maneuvering) may be achievable from other pulsed systems in the future.

To close we note that the capital costs for any realistic high-power laser driver are probably going to be large. This suggests that the required investment will be significantly more likely to occur if other parallel and synergistic applications can be found for the laser. In addition to the other propulsion-related applications mentioned in the introduction, possibilities that should be considered include power beaming both to orbit and to the lunar surface, optical imaging of satellites and/or debris from the ground, and secure long-distance (e.g., Earth to Moon or deep space) communications.

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FIGURE CAPTIONS

Figure 1. Scenario for LEO Launch Using Laser Propulsion

Figure 2. Input and Output Power Scaling for Pulsed Laser Propulsion for: a) Aluminum at $\tau = 1\ \mu s$; b) Aluminum at $\tau = 1$ ns; c) Kapton at $\tau = 1\ \mu s$; and d) Kapton at $\tau = 1$ ns

Figure 3. Schematic for a Direct-Heating CW Laser Propulsion System

Figure 4. Concepts for CW Laser Heat-Exchanger Thrusters

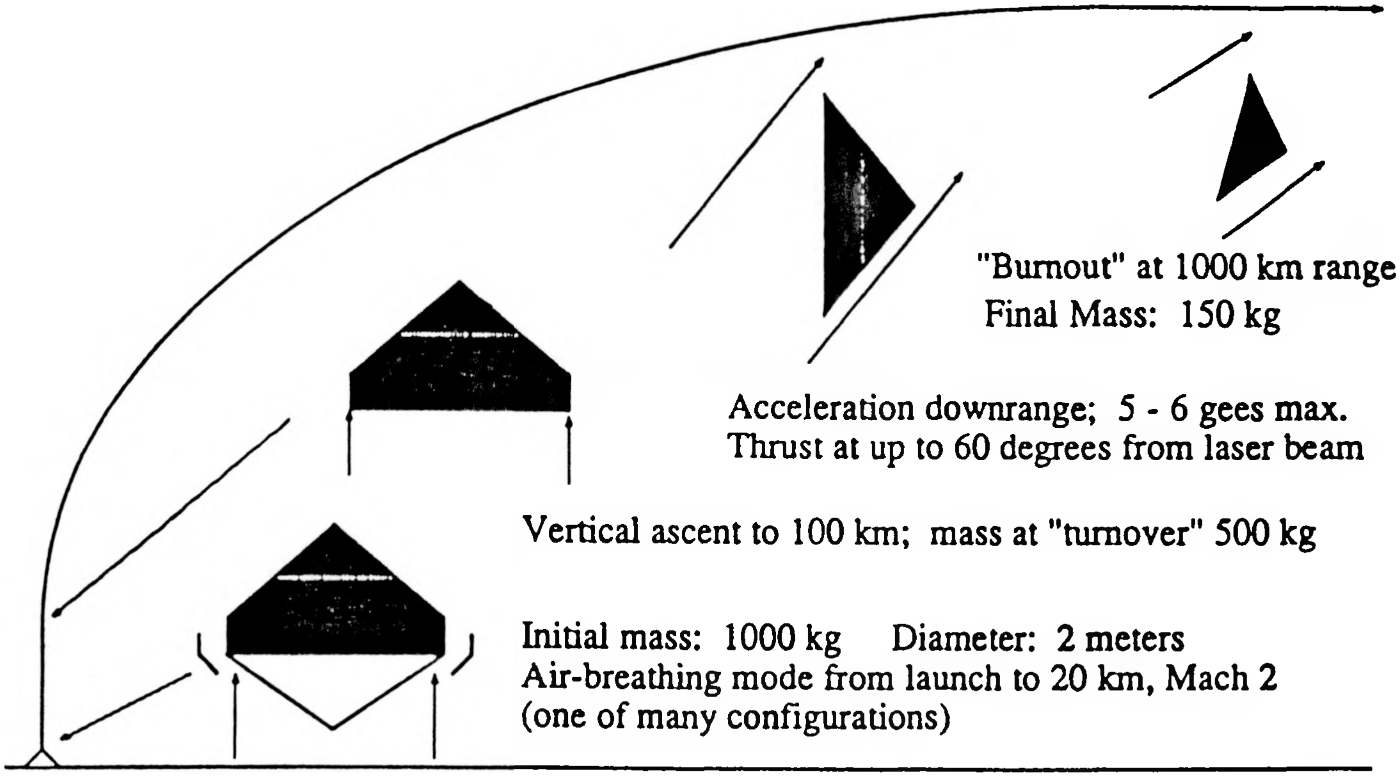

"Burnout" at 1000 km range
Final Mass: 150 kg
Acceleration downrange; 5 - 6 gees max.
Thrust at up to 60 degrees from laser beam
Vertical ascent to 100 km; mass at "turnover" 500 kg
Initial mass: 1000 kg Diameter: 2 meters
Air-breathing mode from launch to 20 km, Mach 2
(one of many configurations)

Figure 1

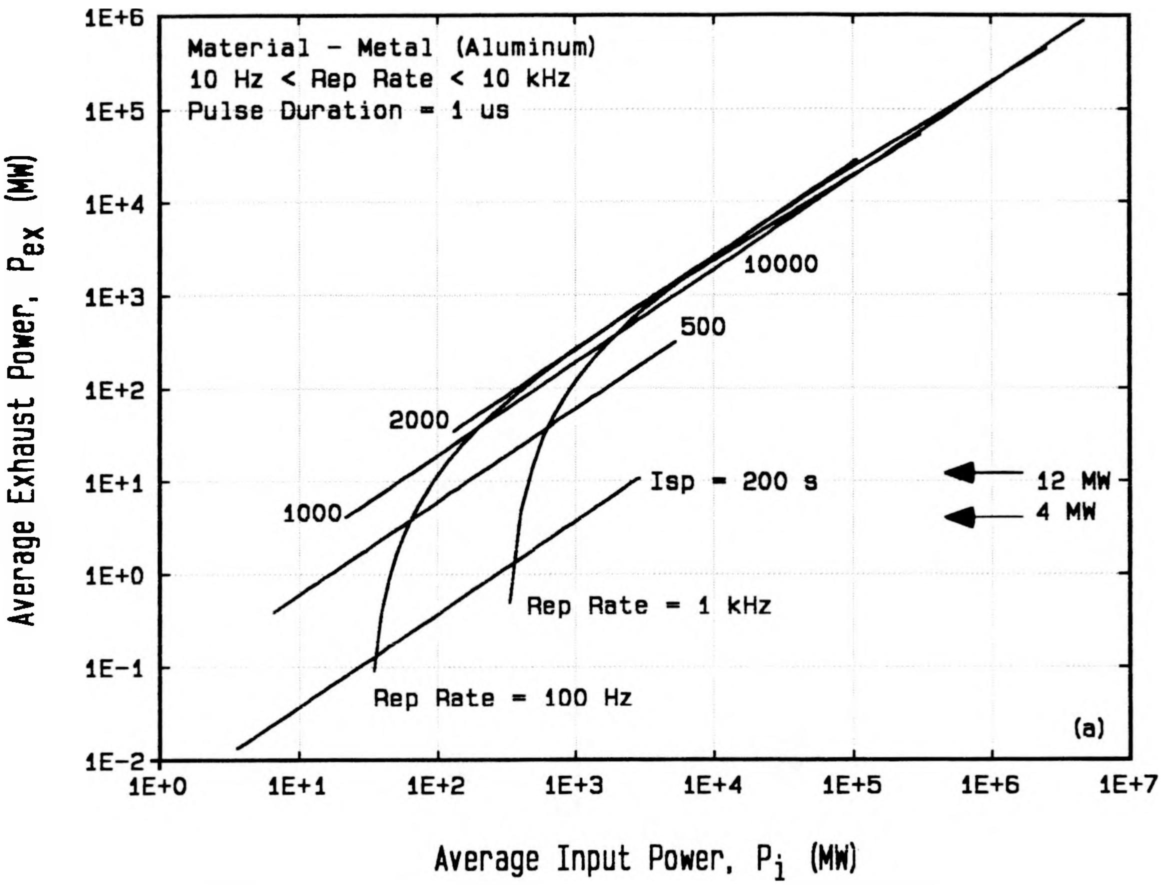


Figure 2 (a)

ALPP6

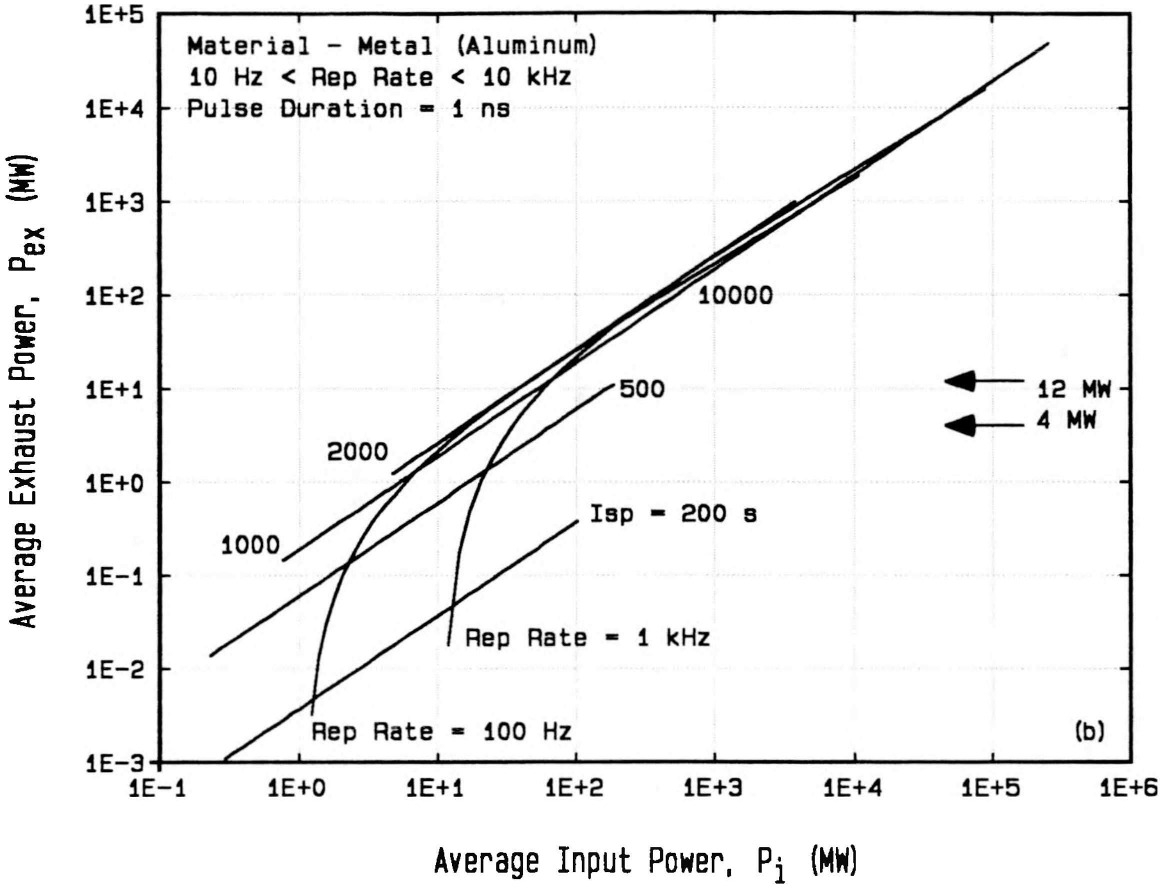


Figure 2(b)

ALPP9

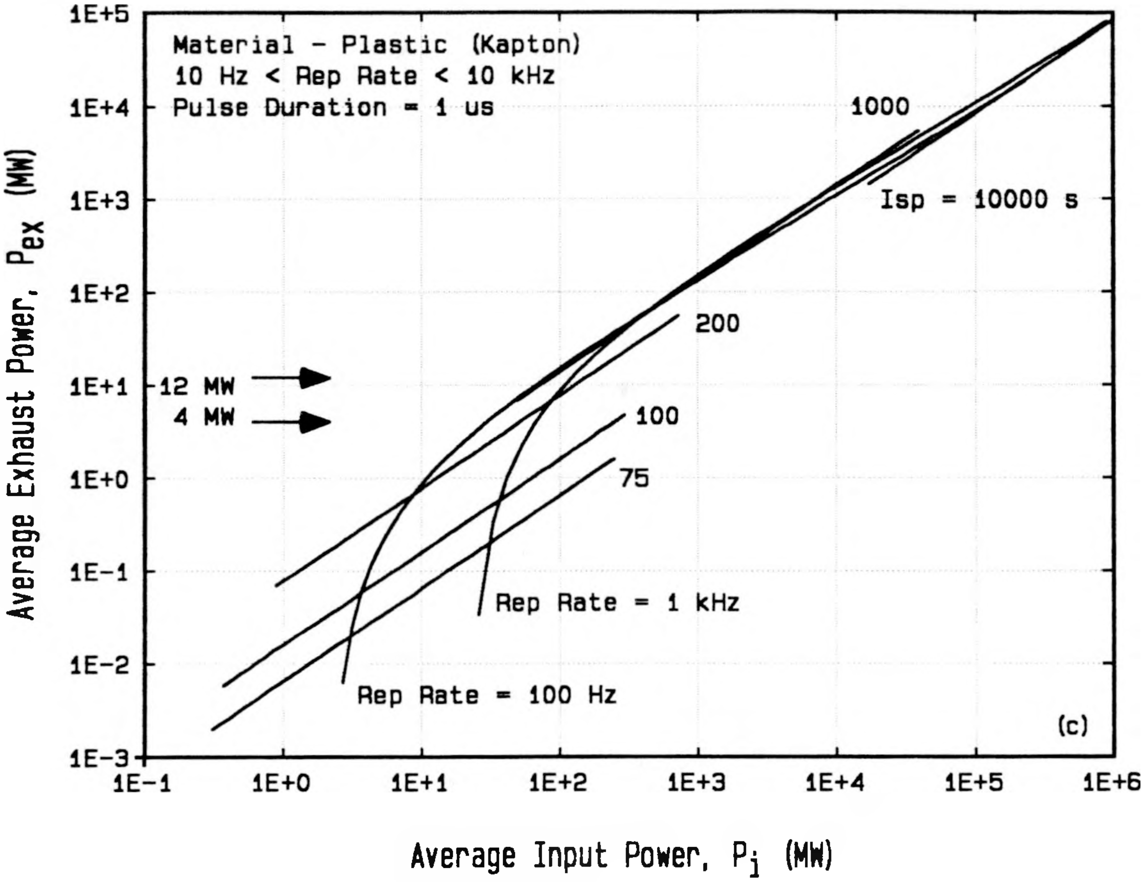


Figure 2 (c)

KAPP6

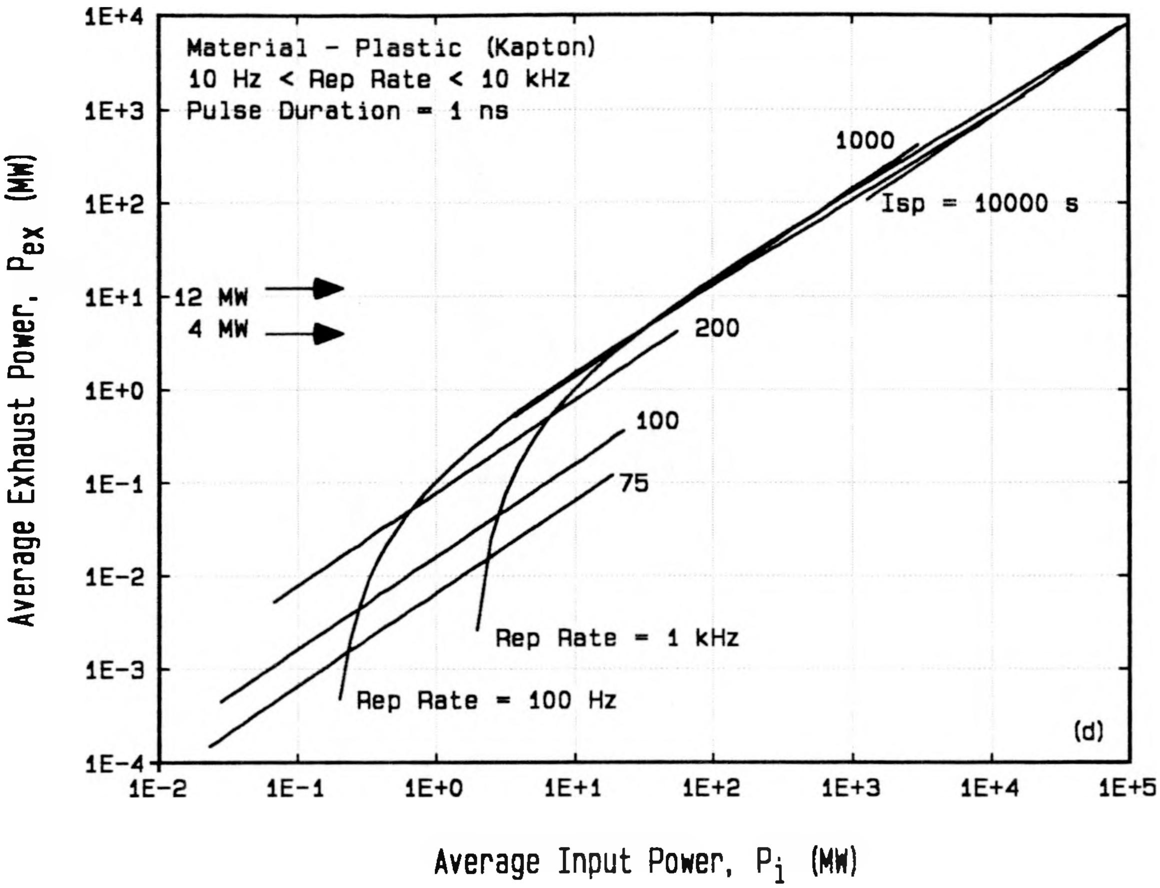


Figure 1(d)

KAPPP9

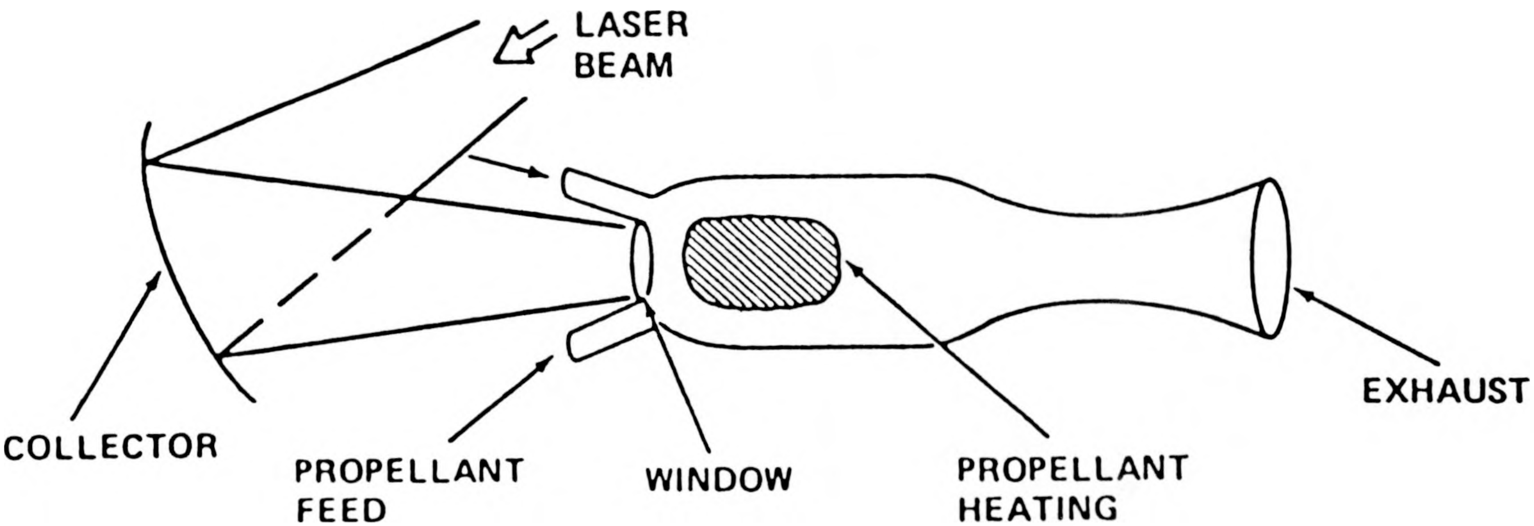
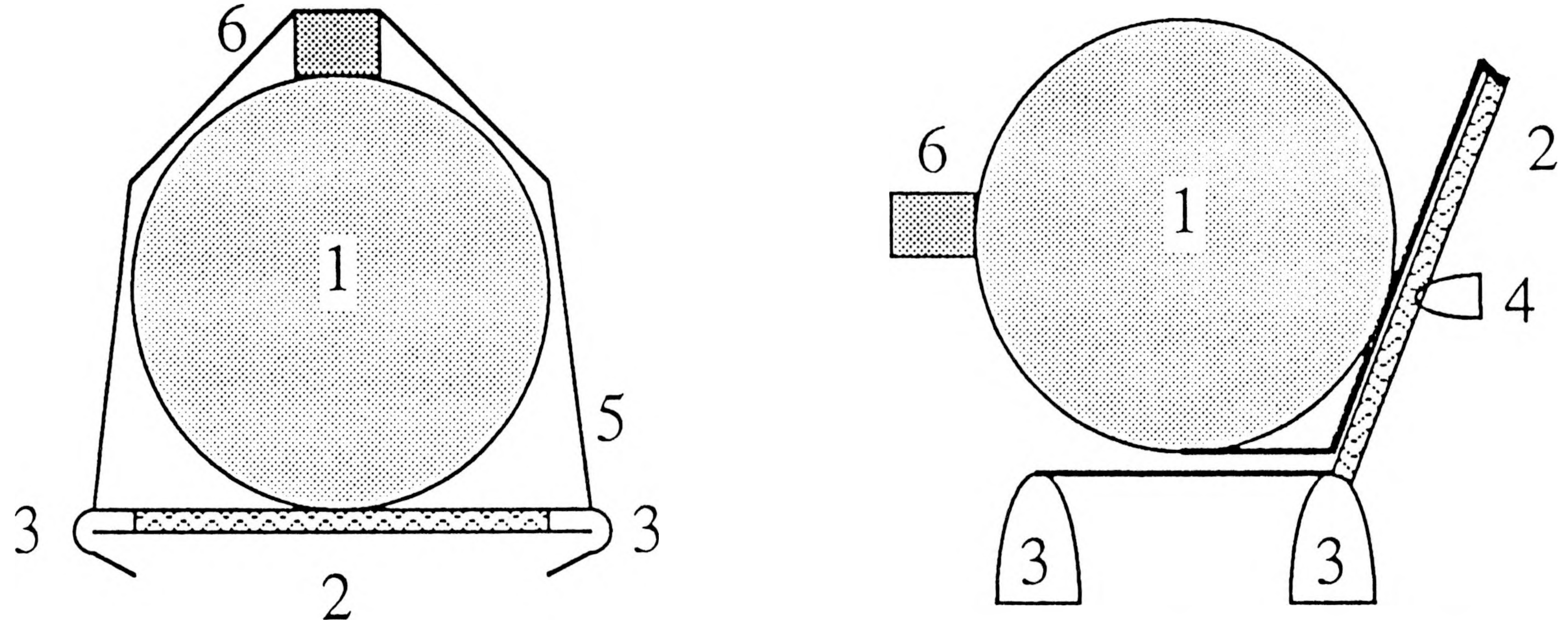


Figure 3

--From Rosen, Pirri, Weiss, and Kemp (1984)

Tail-Fire / Aerospike Nozzle

Side-Fire / Conventional Nozzle



1. Hydrogen Tank
2. Heat Exchanger
3. Main Nozzles
4. Roll-Control Nozzle
5. Stray-Light Shield
6. Payload

Figure A