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ABSTRACT

Recent advances in the development of reactor-pumped lasers (RPL's) have stimulated renewed interest in the concept of laser-powered propulsion. This paper surveys a number of laser propulsion concepts and identifies the one that is most promising from the standpoint of practicality. It is proposed that a ground-based FALCON (Fission-Activated Laser CONcept) RPL can provide primary power for this launch vehicle design. The laser-vehicle system could launch small payloads into low-earth orbit (LEO) with high repetition rates and at low costs per kilogram. For the favored design, thruster efficiencies are currently estimated to be about 50%, with 80% being seen as a potentially realizable goal after further design refinements. Laser launch system simulations indicate that, with a buy-in laser power of 10 MW, it will be possible to obtain specific impulses in the range of 600 to 800 seconds and payload-to-power ratios of 1 to 3 kg/MW.

1. RPL PROPULSION FOR LEO MISSIONS

The concept of RPL-propulsion to LEO is illustrated in Figure 1. A ground-based laser (GBL) system is used to beam radiant power to an ascending launch vehicle. The laser beam is focused onto the launch vehicle's heat exchanger (HX) with the use of a steerable beam director having a deformable mirror. The mirror has the capability of pre-distorting the beam so as to compensate for wavefront distortions caused by atmospheric turbulence. Real-time control signals for the mirror are provided by an adaptive optics unit which uses a low-power laser beam to sense the degree of turbulence and distortion. With these corrections, the laser beam incident upon the vehicle's HX is nearly diffraction-limited.

A number of laser-powered propulsion system designs have been proposed during the last decades. Many of these are variations on the basic continuous-wave (CW) direct-heating thruster design, which will be described later.¹⁻⁸ A more recent advance in laser-powered vehicle design has been developed and promoted by J. T. Kare at Lawrence Livermore National Laboratory.⁹⁻¹² The Kare design was used to obtain the performance parameters displayed in Figure 1.

The design by Kare uses a CW laser source, a metallic HX, and liquid-hydrogen propellant. This so-called CW/HX launch vehicle can provide specific impulses of 600 to 800 seconds, which is well above that obtained with conventional chemical thrusters. The overall thruster efficiency is estimated to be about 50%, but it may be possible to achieve 80% efficiency after additional design refinements. The ratio of deliverable payload mass to laser power is about 1 to 3 kg/MW.⁹⁻¹³

The GBL system design depicted in Figure 1 assumes a CW-laser power output of 10 MW, which is the estimated buy-in power for such systems.¹³ Payloads having masses in the range of 10 kg and greater are of importance, and have acquired the descriptive name "microsat". With a 10-MW laser it would be possible to cost-effectively deliver very large total payloads to LEO as sequences of small payloads having masses of about 10 kg and greater. System simulation results indicate that the Kare laser-powered launch vehicle design will be capable of delivering about 14 kg of payload to LEO with a laser producing 10 MW of output power.

2. ADVANTAGES OF GBL PROPULSION

The use of a GBL system to remotely provide power for launch vehicle propulsion has a number of advantages over conventional methods. Most important is the fact that the primary power source does not have to be carried into orbit with

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MASTER

872

the vehicle itself. Only the propellant, the propellant tankage, the solid heat exchanger, and the payload are onboard the vehicle during its ascent. This makes possible a significant increase in the ratio of payload mass to initial launch mass.

GBL-powered launch vehicles are relatively simple in design. Much of the complexity and weight associated with conventional power production subsystems has been removed from the vehicle and transferred to the ground. These vehicles can be constructed at much lower total cost, as a result of their overall structural simplicity. Furthermore, this cost savings can be enhanced by mass-production of the vehicles.

The cost per kilogram of payload promises to be much lower than for conventional launch systems. Current estimates are that, for a large total payload delivered in small packages at high repetition rates, the cost per unit mass may be smaller by an order of magnitude.¹³ The GBL-powered method also enjoys the advantage of being synergistic. Once the laser system is available for launching vehicles to LEO, it can also be used for other applications. Two examples are beaming laser power to geosynchronous-orbit (GSO) satellites and utilizing laser power for industrial processing of material surfaces.

3. APPLICATIONS OF GBL PROPULSION

Many applications of GBL-powered propulsion have been proposed. It would be ideal for rapid delivery of small, high-value items to the proposed US space station or to the Russian Mir station. The same would apply to other large space systems being assembled in LEO. Life-support resupplies, electronic replacements, small zero-g experiments, biological test samples, and special tools are examples of small payloads that could be delivered quickly and efficiently.

Laser-powered propulsion could be used to provide remote power for an orbital transfer vehicle (OTV). This would result in lowering the costs of raising communications satellites from LEO to GSO. Laser-powered OTV's could also be used to transfer retired satellites having nuclear power systems into safer orbits. They could ultimately prove to be one of the most practical means of delivering construction materials and resupplies to a lunar-base, as well.

A GBL-powered vehicle could be used to launch a special scientific package into LEO for the acquisition of important data from transient events. Examples are super nova, unexpected solar phenomena, transient ozone layer effects, and unusual weather patterns. GBL-powered vehicles could ultimately be used to dispose of nuclear waste in deep space. Launching small packages would lower costs and reduce the risk associated with an unsuccessful mission.

4. CW DIRECT-HEATING THRUSTER DESIGN

Figure 2 represents one of the most studied designs for using a CW laser system to power a launch vehicle. A collecting mirror is used to concentrate the incident laser beam and direct it through an optical window in the wall of the heating chamber. The propellant gas is directly heated by the beam and thrust is developed as the super-heated gas expands through the throat of the nozzle. An advantage of this design is that it is potentially capable of providing very high thruster efficiencies.²

A disadvantage of this design results from the use of the onboard beam collector and alignment control system. Together they make the design very complex, potentially costly, and quite massive. Another disadvantage is that the presence of the window restricts the laser wavelengths that can be used. Extremely high optical transparency is essential for preventing power losses and thermal damage to the window. The high temperature of the absorption region or "hot spot" within the chamber is also a concern. It requires that materials used to construct all portions of the chamber would have to be highly temperature resistant.²

5. PULSED-LASER THRUSTER DESIGN

The pulsed-laser vehicle in Figure 3 uses a high-power laser with pulsed format. The leading pulse serves to ablate a thin layer of solid propellant, while the second pulse superheats the resulting gases. The thrust that is generated by this process

is always perpendicular to the propellant surface. The ascending vehicle can be steered by shifting the beam axis with respect to the center of the propellant plate.¹⁴⁻¹⁶

The specific impulses obtainable will be high. For an aluminum propellant it is estimated to be about 2000 seconds. However, the overall thruster efficiency will be low, with 25% being the maximum for aluminum propellant. Because the laser beam has a pulsed format, the thrust will be pulsed as well. The vehicle is therefore vulnerable to structural vibrations induced by the thruster. The payload-to-power ratio is low, ranging from 0.1 to 0.5 kg/MW. Launching even a small payload would require a power output of about 100 MW.¹³

6. CW/HX THRUSTER DESIGNS

The use of a high-performance solid HX is a recent and important innovation in the design of laser-powered launch vehicles. Figure 4 represents two versions of a HX thruster recently developed by J. T. Kare.¹¹ Each requires a CW laser to generate thrust by heating liquid-hydrogen propellant carried onboard the vehicle.

In the first design the HX is located at the base of the vehicle. Hydrogen propellant is fed through the exchanger where it absorbs thermal energy. Thrust is developed as the heated propellant expands through the "aerospike" nozzles. Because the HX is located at the base, it is necessary to boost this vehicle to a point above the GBL site before the laser is initially "fired". In addition, the laser beam will have to propagate through the propellant plume to irradiate the HX as the vehicle ascends through the atmosphere.¹³

In the second design the HX is located on the side of the vehicle, so it is not necessary to position the vehicle very high above the GBL site at the onset of laser-powered ascent. Furthermore, the laser beam does not have to propagate through the propellant plume during the ascent. This version utilizes conventional thruster nozzles which generate thrust more efficiently than the "aerospike" nozzles. Attitude control nozzles (not shown) can be used to tip the vehicle so that the HX is always in direct view of the beam director.¹³

7. CW/HX THRUSTER OPERATION

The CW/HX thruster has a number of desirable operational characteristics. The flow of hydrogen propellant within the HX is laminar, as a consequence of numerous smooth-flow channels. This results in much lower pressure loss than in conventional propellant-feed systems and provides excellent heat transfer characteristics, as well. The flow of propellant can be largely driven by pressure generated within the propellant tank itself. Thus, the use of a conventional pumping system is not required, resulting in greater simplicity and lower total mass.^{11,13}

An important characteristic of the CW/HX design is that a variety of nozzle designs can be utilized to develop thrust. The "aerospike" nozzles used in the first version can develop adequate thrust and can be cheaply manufactured. The more conventional nozzles appearing on the second version can provide greater overall thruster efficiency, but they are more expensive to manufacture.

Another important characteristic of the CW/HX launch system is that its operation is independent of the laser beam's wavelength. Thus, during the launch vehicle's design and testing phases, alternative power sources can be used in place of the designated laser. Thruster operation is also relatively insensitive to both spatial and temporal irregularities in the incident laser beam. The thermal conduction properties and the propellant flow characteristics of the HX tend to reduce both types of irregularities quite effectively.

8. PERFORMANCE PARAMETERS FOR CW/HX THRUSTERS

The liquid hydrogen propellant to be used by the thrusters is stored in a pressurized cryogenic tank onboard the vehicle. The tank's mass must be kept as small as possible to avoid adverse affects on the vehicle's overall performance.

Consideration of the materials and construction techniques required indicate that the total dry mass of the vehicle will be distributed almost equally among the payload, the solid HX, and the propellant tank.¹¹⁻¹³

The overall efficiency of the CW/HX thruster systems has been estimated to be about 50%. With additional design refinements, this could be increased considerably, with 80% being a potentially realizable goal. System performance parameters have been determined using simulations, in which the thruster efficiency was set at the more conservative value of 40% to provide better comparisons with CW direct-heating thruster designs.¹¹⁻¹³

An important measure of performance for earth-to-LEO launch vehicles is the ratio of the payload inserted into orbit to the required output power of the GBL system. For the CW/HX vehicle designs, this ratio is estimated to be in the range of about 1 to 3 kg/MW. Thus, for a "microsat" having a mass of about 10 kg, a GBL output power of the order of 10 MW will be adequate.¹¹⁻¹³

The required incident laser intensity at the exterior surface of the HX has been estimated to be about 10 MW/m². This will provide the optimal operating temperature for the HX, which is estimated to be about 1000°C. Many materials typically used in vehicle construction can readily survive this temperature. In addition, heat loss by reradiation will not be a serious problem.¹¹⁻¹³

The specific impulse produced by the CW/HX laser-powered thruster is estimated to be 600 to 800 seconds. This is considerably higher than that provided by chemical thrusters, but is lower than for some of the CW direct-heating thruster designs. However, when all performance parameters are considered, the CW/HX thruster design proves to be superior to its competitors.¹¹⁻¹³

9. ADVANTAGES OF RPL's

The FALCON (Fission-Activated Laser CONcept) RPL is being developed by the Department of Energy at Sandia National Laboratories. The laser's power is supplied by fission fragments which are produced in its reactor. Small-scale laser-physics experiments have demonstrated lasing at a number of near-infrared wavelengths and at intrinsic efficiencies of 1-3%.¹⁷⁻²⁰

RPL's have a number of design and operational characteristics that make them ideally suited for providing CW power to small launch vehicles. The RPL is a self-powered laser system, and so does not have to be located near electric power generation facilities. Nor does it require the transportation of large volumes of toxic chemicals to or from the GBL site.

Laser propulsion from earth to LEO will require continuous laser power for about 500 seconds. RPL's are well suited on this count, as well. The energy content of an RPL's fuel is very high, so power can be provided for long periods of time between refuelings. Furthermore, RPL's are compact, requiring the smallest ground facilities of all high-power laser systems proposed.

Tests already conducted with sub-scale FALCON RPL components demonstrate that current technologies are sufficient for many aspects of its operation. Additional tests, design enhancements, and full-scale construction will require technologies that are at most near-term, so no significant breakthroughs are required.

The FALCON laser will be at least as safe to operate as many commercial reactors already on-line. The total amount of radioactive inventory is orders of magnitude lower than for commercial systems. In addition, the power density is about an order of magnitude smaller. The FALCON RPL operates at relatively low temperatures and gas-flow pressures, which greatly reduces the likelihood of an accidental release.

10. FLIGHT PLAN FOR A CW/HX VEHICLE

A flight plan has been developed which is consistent with the requirements for the CW/HX laser-powered launch vehicle design.¹³ The beam director must have a clear line-of-sight to the vehicle during the entire laser-powered ascent to orbit. Also, the angle between the beam and the local site zenith must be maintained at less than about 60 degrees, to assure that adaptive optics can adequately compensate for wavefront distortions.

For the first CW/HX design, laser-powered flight begins after the vehicle has been boosted to a point well above the ground-based laser site. This can be accomplished with the use of a small solid-fuel rocket. For the second design the vehicle must be initially displaced horizontally with respect to the laser.

For both CW/HX designs the GBL system is used to provide power for a nearly vertical ascent to an altitude of about 100 km. Then a laser-powered pitch-over maneuver is performed in preparation for orbital insertion. Next, the vehicle accelerates under laser power until orbital velocity is achieved at an altitude of about 400 km and a down-range distance of about 1000 km. Small on-board thrusters can then be used to trim the orbit.

11. RESULTS AND CONCLUSIONS

Simulations of laser-powered launch vehicles have been performed at Sandia National Laboratories. Performance parameters have been obtained for the CW/HX vehicle design and the FALCON laser. The flight plan described in the last section was used and the thruster efficiency was conservatively set at 40%. Comparisons with other competing laser-powered launch vehicle designs were performed.¹³

Table 1 shows results of flight simulations for the CW/HX vehicle design. Two payload masses have been considered. The 14-kg payload, which was used by A. Kantrowitz in his original studies,¹⁴ is typical of so-called "microsat" payload masses. The 60-kg payload is of greater interest for missions requiring the delivery of large total payloads to LEO.¹³

Table 1. CW/HX Performance Parameters

<u>Parameter</u>	<u>Payload 1</u>	<u>Payload 2</u>
Payload mass	14 kg	60 kg
Launch mass	120 kg	500 kg
Laser power	10 MW	30 MW
Exhaust power	4 MW	12 MW
Thrust	1-3 kN	2-10 kN
Payload/power	1.4 kg/MW	2.0 kg/MW

The total launch mass, including the propellant mass, is provided for each of the two payload values. The laser output power required and the resulting payload-to-power ratio are also included. Note that the 14-kg payload can be launched into LEO with a 10-MW laser, and that tripling the laser power will result in a four-fold increase in the mass of each deliverable payload.

GBL-powered propulsion is an innovative and promising method of launching small payloads into LEO. It may reduce the cost per kilogram of payload by an order of magnitude. Of the several vehicle designs considered, the CW/HX case is the simplest and has the best overall performance characteristics, as determined by simulations. One of the most important advantages of laser-powered propulsion is that it utilizes a reusable primary power source, rather than one which is

consumed and discarded with each launch. Furthermore, when the laser is not being used to power small-payload launch vehicles into LEO, it will be available for other applications such as power beaming to satellites and industrial processing of material surfaces.

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Figure 1. A 10-MW FALCON reactor-pumped laser can deliver a 14-kg payload to low-earth orbit (LEO).

Hydrogen propellant heated via metal heat exchanger (J.T. Kare)

Specific impulses of 600-800 sec

Thruster efficiency of 50%, with potential for 80%

Payload-to-power ratio of 1.4 kg/MW

Microelectronics makes an emerging market for "microsats"

Other designs by Krier (U. of Ill.) and Keefer (U. of Tenn.)

Figure 2. CW laser direct-heating thruster design (adapted from Rosen, Pirri, Weiss, and Kemp).

Laser beam is redirected by mirror attached to vehicle

Beam is transmitted through window in chamber

Continuous heating of propellant gas occurs in conventional chamber

Efficiency is potentially very high

Vehicle design is complex, costly

Window transparency and optical alignment are critical

Operating temperature is very high

Figure 3. Pulsed-laser-beam thruster design (adapted from A. Kantrowitz).

Laser pulses ablate solid propellant

Simple propellants used (Al, Kapton)

Ablation produces impulse, delta-V

Thrust is always normal to propellant

Steering performed by shifting beam

Pulsed format is required

Specific impulse is very high

Max thrust efficiency is low

Payload-to-power ratio is very high

Buy-in power is 100 MW/m²

Figure 4. CW heat-exchanger thruster designs (adapted from J. T. Kare, LLNL).

Tail-Fire / Aerospike Nozzle

Side-Fire / Conventional Nozzle

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