LIGHTCRAFT PROPULSION TECHNOLOGY FOR LOW COST ACCESS TO SPACE

A dream held by most rocket scientists over the past 50 years has been the achievement of low cost, routine access to space. Many science fiction stories are based on the assumption that spaceflight will become as common as driving your car to the local market. The Space Shuttle has made spaceflight by reusable vehicles somewhat routine, but it still costs nearly $10,000 per kilogram to launch a payload into low Earth orbit (LEO).

The invention of the laser in the late 1950s inspired many to speculate about the possibility of using beamed energy to transport objects into space and then move them around once they get there[1]. Some have even dreamed of using beamed energy to send spacecraft to other star systems. It was quickly realized, however, that extremely high-powered lasers with excellent beam qualities would be required to make this concept a reality.

For ground-launched systems like the Space Shuttle, chemical propellants are used to power the vehicle via combustion of a fuel with an oxidizer. These chemical propellants constitute over 80% of the initial mass of a typical launch vehicle. The use of beamed energy, by contrast, has the advantage of leaving the energy source for propulsion behind. The attractiveness of this feature has prompted work towards the development of a propulsion system based on the beamed-energy concept.

The first free flight tests were conducted inside Test Cell 3 at HELSTF to reduce the costs associated with range safety. It was quickly determined that the best flights were obtained by spin stabilizing the Lightcraft prior to launch. Flights that reached the ceiling of the test cell (4.27 meters) were rapidly achieved.

The free flight tests were then moved outdoors. A crane was used to position a laser beam stop at a height of about 30 meters, obviating the need to obtain special range safety clearance. Since the flight vehicles are only passively controlled via spin stabilization, wind was a factor during these tests, although it was found that the optimized geometry of the lightcraft causes the vehicle to center itself in the beam, acting as a “beam rider” and reducing the effects of small wind velocity.

A series of successful tests demonstrated the first spin stabilized vertical free flight of an object propelled by a pulsed laser, obtaining a maximum flight distance of about 30 meters (Figure 4). The usable laser power drops to approximately half at about 30 meters, and this combines with heating effects in the current Lightcraft design to cause the vehicle to slow down past about 20 meters, and to hover at a distance of about 30 meters.

Flight to Space

A 100 kW pulsed carbon dioxide laser is being designed by Air Force and industry researchers, with funding and systems support from NASA.

which is the measure of thrust per laser pulse energy, for various designs of the focusing optic and thrust cowl[2]. The measured coupling coefficients were between 100 to 143 N-s/MJ. The optimum design[2] contains a closed inlet, a rounded nose, a parabolic reflector with a focus at the inner surface of the cowl, and an outer shroud over the cowl that contains an inward curve at the rear edge.

Additional indoor tests were aimed at examining the details of the shock propagation to determine the optimum design of the Lightcraft vehicle and pulse duration of the laser[3]. A 3 ns pulsed Nd:YAG laser, doubled to 532 nm, was used on a horizontal test stand to obtain Schlieren and shadowgraph images of the hot exhaust flow field during expansion of the pulsed CO_2 laser atmospheric breakdown. A narrow bandpass filter, centered at 532 nm, was used to remove most of the broadband radiation from the laser-generated plasma. A controllable delay was used to obtain shadowgraph images at discrete delay times up to 6,000 μs after the first arrival of the CO_2 pulse at the focal point of the lightcraft. A series of these shadowgraph photos are shown in Figure 2. Notice that the shock front propagates around the edge of the Lightcraft after about 80 μs. Images after about 140 μs show considerable turbulence.

Wire-guided flight tests followed the thrust stand tests. These tests measured the initial acceleration of the vehicle at various laser pulse energies and repetition rates. Following these tests, horizontal wire-guided tests, depicted in Figure 3, saw the vehicle travel as much as 121 meters along the wire using an active laser beam pointing and tracking system.

The U. S. Air Force and the National Aeronautics and Space Administration formed a joint effort in 1997 to determine the feasibility of using high-powered lasers to launch small spacecraft into LEO. This effort grew out of the Lightcraft Technology Demonstrator (LTD) concept funded by the SDIO (Strategic Defense Initiative Office) Laser Propulsion Program in the late 1980s. The original LTD concept envisioned a 100 MW-class ground-based laser propelling a 120-kg, 1.4-m diameter craft into LEO. The unique benefit of such a launch system would be the capability to rapidly place many relatively small payloads into a variety of orbits. Potential uses for such small satellites range from temporary replacement of critical, malfunctioning commercial communication systems to rapid response capability for military intelligence gathering in trouble spots throughout the world.

Lightcraft Technology Demonstration Program

The current program, sponsored by the Air Force Research Laboratory Propulsion Directorate and NASA Marshall Space Flight Center, is a modest version of the original LTD project. The initial AF/NASA program makes use of current manufacturing techniques in the construction of the Lightcraft and existing lasers to propel them.

Lightcraft vehicles consist of an axisymmetric off-axis parabolic collection mirror that concentrates pulsed infrared laser light into an annular focus. The basic concept, illustrated in Figure 1, consists of a forebody aeroshell, an afterbody optic/expansion nozzle, and an annular cowl or shroud. The forebody serves as a protective shield for the payload. The afterbody serves the dual functions of primary receiving/focusing optic for the pulsed laser energy and external expansion surface, or plug nozzle, for the propulsive force resulting from laser breakdown of the working fluid. The annular cowl acts as the primary thrust structure, utilizing the hot plasma expansion to propel the vehicle. Currently all parts are machined from aluminum, although several other materials for the annular cowl are under development.

The laser used in the feasibility testing of this concept is the U. S. Army 10 kW Pulsed Laser Vulnerability Test System (PLVTS), a closed cycle carbon dioxide laser based at the White Sands Missile Range High Energy Laser Systems Test Facility (HELSTF) in New Mexico. The power of the 18 μs pulsed laser is sufficiently high - up to 490 Joules per pulse at a rate of 28 Hz - that atmospheric breakdown occurs, producing a superheated plasma shock wave that propels the flight vehicle along the direction of the laser beam. Unfortunately, the beam quality of this laser is relatively poor, with a fairly large divergence, several "hot spots" within the beam, and a square beam profile that contains a hole in the center. The limited laser power and large beam divergence limits the current Lightcraft vehicles to about 20 to 50 grams mass and 10 to 16 centimeters in diameter, restricting current flight altitudes to about 50 meters.

Flight Tests

The program began with a series of ground tests to determine the optimal design of the lightcraft to be used with the PLVTS laser. A small pendulum-type thrust stand was used to measure the coupling coefficient, Such a laser should provide the capability to reach vertical altitudes of at least 30 km and demonstrate the feasibility of this technology for low cost access to space.

Successful vertical test flights to the edge of the atmosphere will point the way toward larger systems to place usable payloads into low Earth orbit. It is estimated that approximately one megawatt of laser power is needed to place each kilogram of payload into orbit. Multi-megawatt lasers are possible with current state-of-the art technologies. Although the capital investment associated with building such a laser is large, the equipment stays on the ground and can be used thousands of times. The development cost of a Lightcraft launch capability are comparable to the development costs of reusable launch systems, but operational costs will be much lower than chemical rockets of similar size used as launch vehicles. The eventual cost of launching objects to LEO using laser propulsion could be as low as $100 per kilogram.

There are many problems to overcome before a low cost, reliable laser propelled launch system becomes a reality. These challenges include development of active on-board flight control to compensate for atmospheric variances, such as wind and dust, advanced high-temperature materials for the propulsive surface of the cowl, and miniaturized on-board propellant management for cooling and delivery of a gaseous working fluid for flight above the atmosphere. The current program will address these issues over the next few years.

More information and photographs of these Lightcraft experiments can be found at the web site www.ple.af.mil and the other links therein.

REFERENCES:

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3. F. B. Mead, Jr., L. N. Myrabo, and D. G. Messitt, "Flight and Ground Tests of a Laser-Boosted Vehicle," 34th AIAA/ASME/ASE/ASEE Joint Propulsion Conference, paper AIAA 98-3735, July 13-15, 1998.

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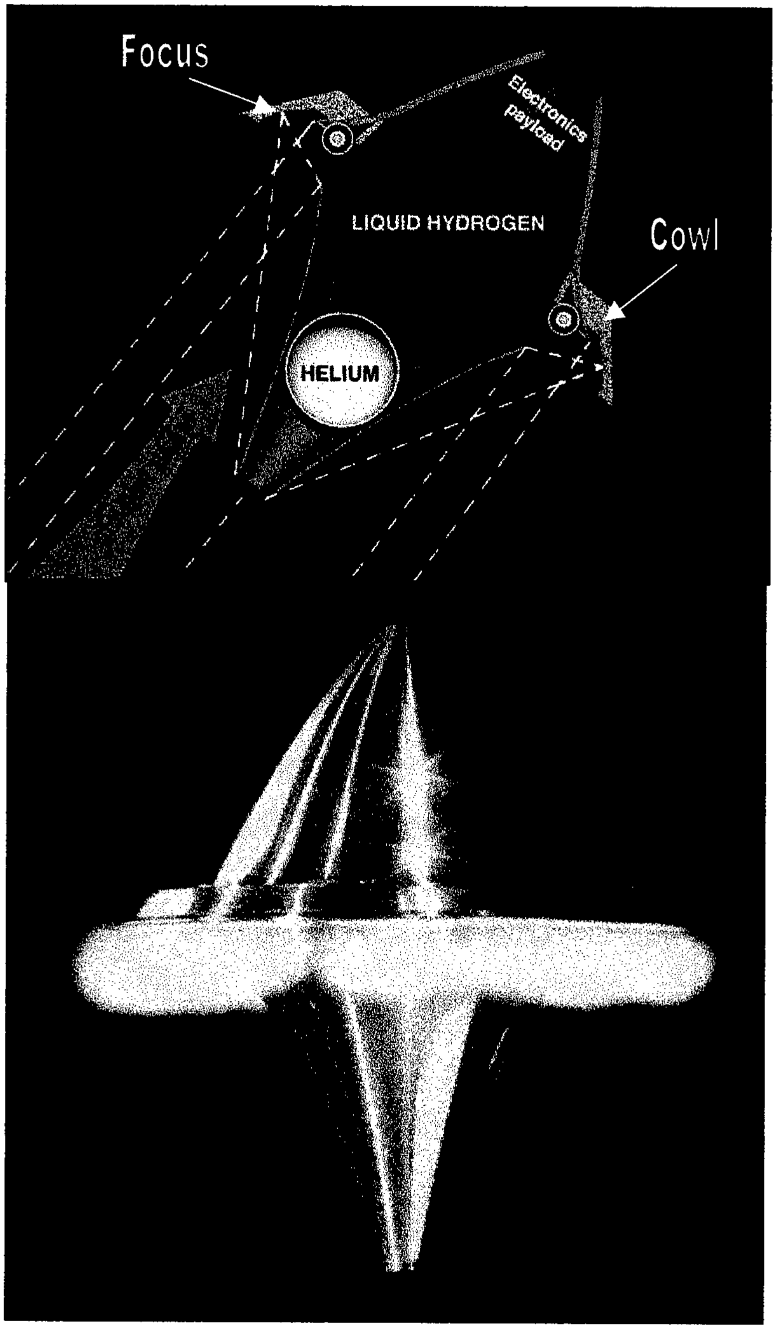

Figure 1. Upper photo: Conceptual design of a lightcraft vehicle. This design includes on-board propellant for cooling of the cowl and to use as a working fluid outside the usable atmosphere. Craft flown to date do not include this on-board propellant nor internal guidance electronics. Lower photo: Lightcraft vehicle during laser pulse. The laser direction is from the bottom of the page, impinging onto the parabolic mirror, focusing the 18 μs carbon dioxide laser pulse in an annular ring at the inner surface of the cowl and causing atmospheric breakdown, propelling the craft upward.

Figure 2. Laser shadow graphs of the shock propagation of an 18 μs carbon dioxide laser pulse impinging on a lightcraft vehicle. The upper left picture shows the vehicle before arrival of a laser pulse. The upper right picture shows the shock after a 30 μs delay, the lower left picture after an 80 μs delay, and the lower right after a 140 μs delay.

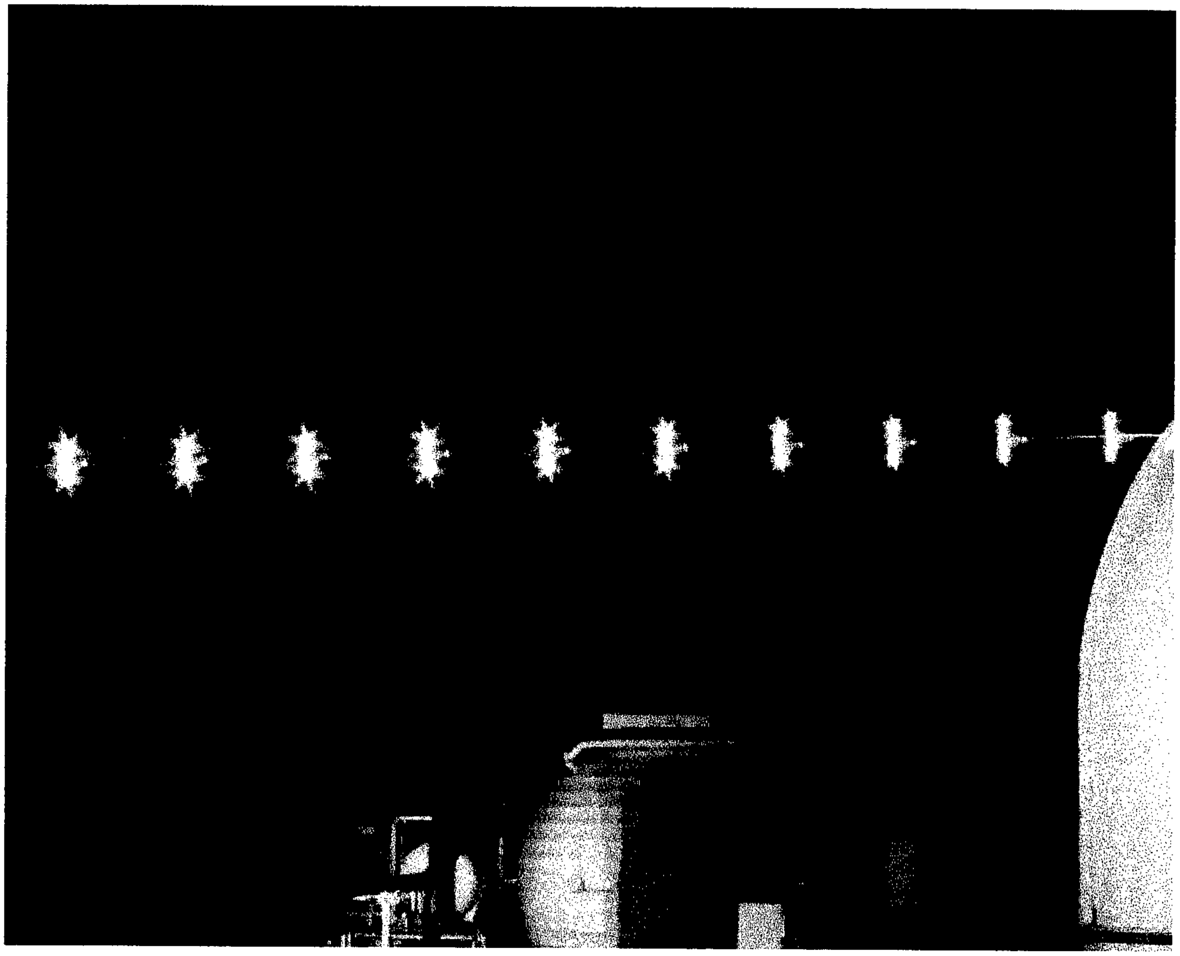

Figure 3. Time exposure of an outdoors, wire-guided, horizontal flight-test. The lightcraft moves from right to left.

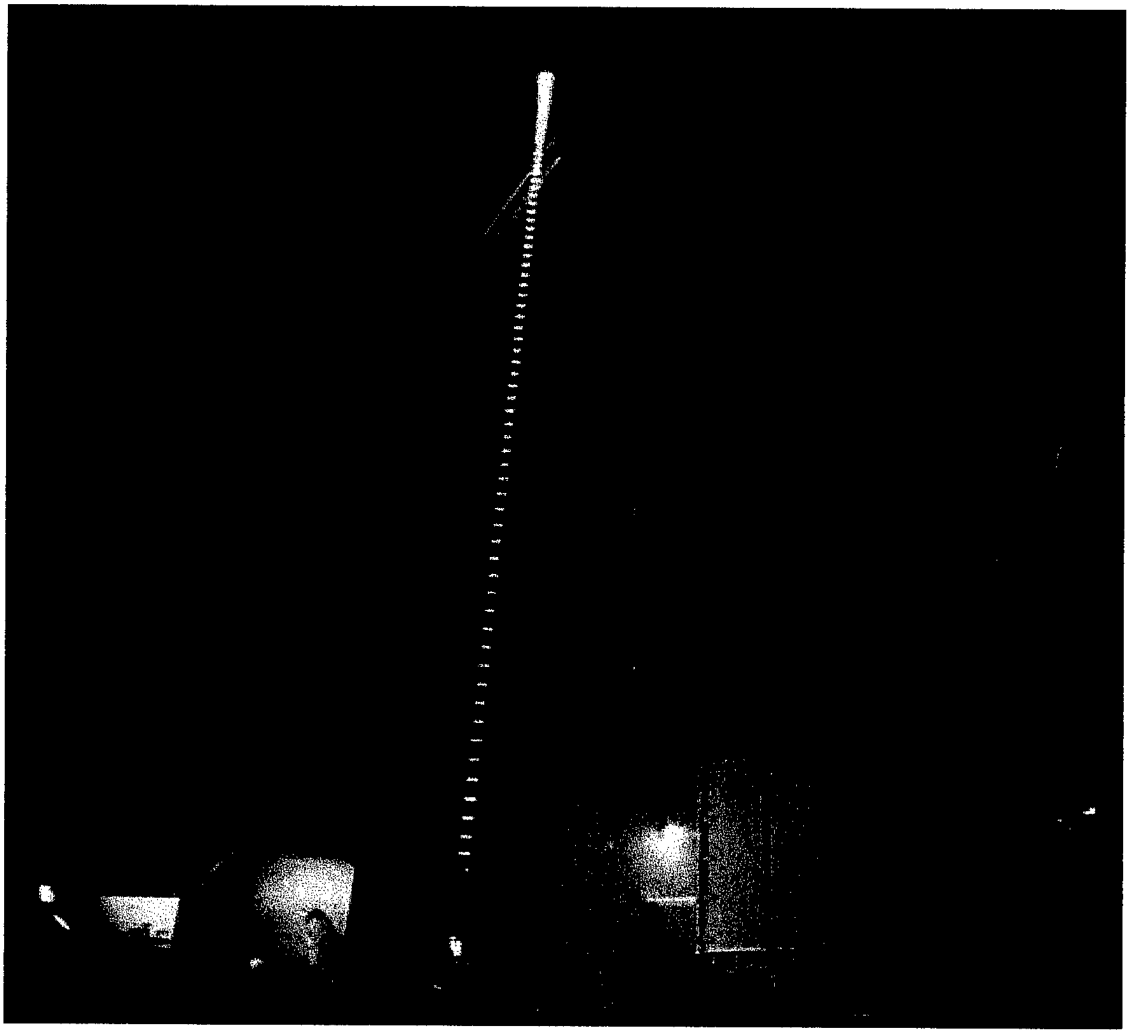

Figure 4. The successful unconstrained flight test of the small scale Lightcraft vehicle demonstrates the feasibility of using high powered pulsed lasers to propel spacecraft into orbit. Preliminary flight tests reached an altitude of approximately 30 meters. This technology advance has the potential to reduce the cost of launching small payloads into space to less than $1000/kg.