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A Status Report of the X-50LR Program – A Laser Propulsion Program

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A STATUS REPORT OF THE X-50LR PROGRAM– A LASER PROPULSION PROGRAM

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ABSTRACT

The Lightcraft Technology Demonstration (LTD) program was initiated in 1996, by the Air Force Research Laboratory's (AFRL) Propulsion Directorate at Edwards Air Force Base. The program was planned in three phases. Phase I, Lightcraft Concept Demonstration, was to demonstrate the feasibility of the basic concept. This phase ended successfully in December 1998.[1,2,3,4] The basic conclusion of all this work was that the feasibility and basic physics of the Lightcraft concept had been adequately demonstrated, and that a much larger 100 kW class laser would be required to completely accomplish Phase II.

Phase II, Lightcraft Vertical Launches to Extreme Altitudes, was initiated in January 1999, and was a five-year effort designed to extend Lightcraft flights in sounding rocket trajectories to 30 km, or the edge of space, with a 100 kW class CO_2 laser. The first step of the Phase II vertical flight test program was to extend Lightcraft vertical free-flights to significantly higher altitudes in the range of 150 to 300 m using the 10 kW PLVTS laser.[5] Tenth-scale, laser-powered vehicles were used. With this size vehicle, laser flight tests were conducted at the High Energy Laser Systems Test Facility (HELSTF), White Sands Missile Range (WSMR), New Mexico, using the 10 kW, Pulsed Laser Vulnerability Test System (PLVTS), CO_2, electric discharge laser. The first composite, ceramic shroud components for the Lightcraft vehicle were fabricated, laboratory tested for performance, and flight tested. Performance details were subsequently presented comparing the composite material shroud with the all-aluminum vehicles, which had been used for most of the program.[6]

INTRODUCTION

In a 1969 invention disclosure,[7] Robert Geisler at the Air Force's Rocket Propulsion Laboratory was the first to recognize that laser-propelled rockets were possible using high powered lasers. He envisioned beamed energy from a ground based laser being absorbed by a heat exchanger and transferred to a working fluid. The heated fluid, such as hydrogen or ammonia (See Fig. 1), was to produce thrust by expansion through a nozzle as in a conventional chemical rocket. An analysis of this laser propulsion concept and several other ideas were presented in the 1972 Air Force's Project Outgrowth Report.[8]

In May of 1972, a seminal article by Dr. Arthur Kantrowitz,[9] of AVCO Everett Research Laboratory, introduced the concept of launching payloads to Earth orbit using high power ground-based lasers (GBL). He envisioned using gigawatt class lasers to ablate an on-board solid propellant.

During the late 1980's, the Lightcraft Technology Demonstrator (LTD) concept was analytically developed at Rensselaer Polytechnic Institute by Myrabo under a Space Defense Initiative Office (SDIO) program.[10] For this concept, the forebody aeroshell had been designed to act as an external compression surface for the airbreathing engine inlet. The parabolic shaped afterbody mirror served a dual function as a primary receptive optic for the laser beam and as an external plug nozzle expansion surface. The primary thrust structure was the centrally located annular shroud. The shroud provided air through the inlet that acted as an energy absorption chamber for plasma formation. In the rocket mode, the air inlet was closed. The full-scale vehicle was 1.4 meters in diameter with a dry mass of 120 kg. Fully fueled, that vehicle would have an initial mass of about 240 kg, and would be launched into orbit with a 100 MW class infrared GBL. This laser propelled vehicle was designed to be a single-stage-to-orbit (SSTO), airbreathing to Mach 5 and 30 km; a laser thermal rocket, using liquid and/or gaseous propellants, at higher altitudes and in space. Once in space, the Lightcraft was to use its one-meter diameter optical system to provide, for example, Earth surveys from low Earth orbit (LEO) with 8 to 15 cm resolution in the visible light frequencies. Such a device was simple, reliable, safe, environmentally clean, and could have a very high all azimuth on-demand launch rate. This study provided the starting point for a development program at the

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In 1996, the Air Force Research Laboratory's Propulsion Division at Edwards AFB initiated a program based upon the 1989 design developed at Rensselaer Polytechnic Institute.[10] That initial program had as its main objective the launch of a laser-propelled vehicle into a suborbital trajectory within a period of 5 years in order to demonstrate the concept and its attractive features.

The initial Phase I, Lightcraft Concept Demonstration, was designed to demonstrate the feasibility of the basic Lightcraft concept. Both laboratory and outdoor flight tests were successfully conducted during this effort. This phase ended successfully in December 1998.[1,2,3,4] The basic conclusion of all this work was that the feasibility and basic physics of the Lightcraft concept had been adequately demonstrated, and that a much larger 100 kW class laser would be required to continue the advancement and complete development to an actual operational vehicle.

Phase II, initiated in Jan 1998, continued with the performance characterization of several #200 series models developed during Phase I. The #200 series consisted of a number of different sized vehicles all scaled to the same optical f-number (See Fig. 2). These models exhibited stability and self-centering in the near-field laser beam. Outdoor vertical free flights with the Model #200-solid ablative rocket (SAR) impacted the plywood beam dump at a little under 40 m in Jul 1999.[5,6]

With the extended lifetime and enhanced performance demonstrated by the addition of an ablative propellant, it was proposed to develop a laser "hand-off" technique using the Model #200-SAR vehicle and the PLVTS laser.[6] This is a complex maneuver, involving several different optical telescopes, applied in hopes of achieving altitudes on the order of 150 to 500 m.[6] Altitudes achieved during these tests were slightly in excess of 55 m.

In January 2001, a revised Phase II program was initiated to scale-up and develop the Model #200-¾ vehicle concept to an eventual 50-cm focal diameter, completely functional, flight vehicle that could be launched into space. This EXperimental 50-centimeter Laser Rocket (X-50LR) program borrowed certain aspects of the previous LTD program, but forged a new "team" concept with appropriately modified scheduling and funding.

THE X-50LR PROGRAM

Background

The Laser Rocket concept is a revolutionary and radical departure from chemical rocket technology. Laser Rockets use air as a propellant up to an altitude of ~30 km and on-board propellants at higher altitudes and in space. Ascent propulsion is provided by the projection of laser energy from a high power GBL through a large diameter beam director. The Laser Rocket receives the laser energy and converts a propellant, which can be either air or some other working fluid carried on-board, into a high temperature and pressure plasma (i.e., Laser Rocket propellant energy densities are at least an order-of-magnitude beyond the present limits of chemical combustion) through the use of a concentrating, parabolic, reflecting surface at its rear. The laser launch facility is initially expensive; but it stays on the ground, is never at risk during launch, and is reusable thousands of times.

The entire infrastructure required to launch a Laser Rocket will have no resemblance to that used for today's chemical rockets. No huge motorized tractors to move vehicles, no skyscraper gantries, or standing army of mechanics and technicians. There will be no toxic fuels, no explosive hazards, and no large propellant farms. Laser Rockets will be wheeled to the launch stand on small carts from a nearby clean-room (i.e., where dozens of vehicles are assembled, stored until they are needed, and pre-launch service/checks occur) and lifted gently onto a launch platform by two or three persons. The launch from the laser control room will be quick and easy. A laser operator pushes a button to initiate the launch sequence, and at time zero the Laser Rocket lifts-off and accelerates directly into LEO.

Objective

The goal of the 5-year, X-50LR program is to develop and launch a fully functional 50 cm Laser Rocket to the edge of space (e.g., 30 to 50 km) in a sounding rocket trajectory. The X-50 Laser Rocket concept is being designed to be both a very low cost launch vehicle and nanosatellite in a single unit capable of eventually being launched to low-Earth-orbit (LEO) during a future Phase III effort.

The current X-50LR program will develop the Laser Rocket, the associated miniaturized satellite components necessary for fully functional operation, and the necessary laser launch facility components. These will be used in combination to demonstrate very low cost space access and all azimuth "launch on demand" to altitudes representative of a LEO. The flight tests will be designed to also demonstrate a favorable approach to orbital insertion (e.g., acquiring tangential orbital velocity). This demonstration will include all the subscale elements of a full-scale, operational space access system and vehicle.

X-25LR Development

Development of a 25-cm vehicle is currently in progress. This initial step involves a size that is viewed as the minimum size required to adequately demonstrate attitude control (i.e., both lateral and pointing) and other features before scaling up to the 50 cm vehicle. This development of the Laser Rocket goes "hand-in-hand" with that of the control system development, with the goal of developing and eventually flight testing a fully controlled composite 25 cm vehicle. To accomplish this size increase, the all aluminum, 10-cm Lightcraft design has been scaled to a 25 cm focal diameter Laser Rocket with functional air inlets.

The AFRL's X-50LR program plans to build upon the work accomplished at the 25 cm size to develop a fully functional, electronically controlled, 50 cm, composite-material model with functional supersonic air inlets. Functional micro-electronic sensor systems will be developed in parallel with the overall vehicle concept's guidance and control and propulsion related functions to demonstrate one of many possible military mission capabilities. Launches will most likely take place at White Sands Missile Range (WSMR) using a 100 kW class, CO_2, electric discharge laser, the major components of which are already on site. The initial launches with the 100 kW class laser will initially be vertical sounding rocket type trajectories to 30 km and above; but ultimately, sub-orbital "ballistic" trajectories may need to be considered to fully demonstrate readiness for full scale development. This demonstration program is designed to provide the necessary confidence to proceed with the development of an operational megawatt-class launch facility and a full-scale, 100 cm (X-100LR), operational Laser Rocket designed for military and civilian applications. A go/no-go decision gate is scheduled at the end of the current X-50LR program to decide whether or not to proceed with operational development.

Recently, fabrication of the first, all composite, 25 cm Laser Rocket was completed. This work was accomplished by SMJ Carbon Technology. Several additional models will be fabricated now that the technique of making an all composite vehicle has been mastered. These vehicles will be used during a series of tests planned for the near future. The first several models will be taken to WSMR and tested, first in the laboratory to characterize performance and then in short pop-up flights to characterize their flight dynamics. Additional models will be used for development of an active attitude control system that will maintain the vehicle in the beam (lateral control) and keep the vehicle pointed at the laser.

Study of Laser and Vehicle Requirements and Costs

A study of laser and vehicle system requirements and costs was initiated at the beginning of FY 2001, with Flight Unlimited in Flagstaff, AZ, to determine if Laser Rocket vehicles powered by laser energy beamed from ground-based or airborne lasers can cost effectively perform future Air Force missions. This effort will also provide parametric computer models for exploring the potential of Laser Rockets and laser systems for the estimated range of laser propulsion efficiencies that appear achievable.[6] This work has been on-going for nearly two years and will be completed by the end of this fiscal year.

German Collaboration

At the end of 1998, the Institute of Technical Physics of the German Aerospace Center began some basic investigations of a simple lightcraft configuration, and wire-guided flights and pendulum measurements of the impulse coupling coefficients were conducted in the laboratory. The lightcraft was made of a thin Aluminum sheet drawn over a paraboloid, and had a diameter of 10 cm and a height of 6.25 cm. The focal distance from the apex was 1 cm. The inner surface was polished for better reflectance. The mass of the shell without any modification was 17 g and was increased by 5g when a thin tube was added for sliding on a wire. Tests of the lightcraft utilized the DLR multi-spectral laser, operating with CO_2 gas at a wavelength of 10.6 microns. Performance results of the lightcraft tests were presented at Santa Fe, NM in 2000.[7]

In Sep 2000, the AFRL initiated an experimental program through the European Office of Aerospace Research and Development (EOARD) with the Institute of Technical Physics, Stuttgart, Germany. Due to the differences in the experimental setup and the reported coupling coefficients, it was of common interest to directly compare the performance of both the DLR and Air Force lightcraft concepts. Thus the coupling coefficients of two radically different laser propulsion thruster concepts, each 10 cm in diameter, were measured under equal conditions using two different pendulum test stands. One test stand and one Lightcraft of toroidal shape were provided by the AFRL. The other test stand and a bell shaped (i.e., a paraboloid) lightcraft were those of the German Aerospace Center (DLR). All experiments employed the DLR electron-beam sustained, pulsed CO_2 laser with pulse energies up to 400 J.[11]

Theoretical Developments

Analysis of overall energy conversion in laser propulsion has been theoretically developed.[12,13] Experimental studies of the Lightcraft Model 200-¾ that absorb laser energy and convert that energy to propellant kinetic energy were carried out. Thermodynamics predicted that the upper limit of the efficiency of conversion of the internal energy of laser heated air to jet kinetic energy, α, is ~0.3 for EQUILIBRIUM expansion to 1 bar pressure. This analysis captured the equation of state of the partially ionized propellant under conditions of chemical equilibrium. This upper limit of α is nearly independent of the specific internal energy between 1 and 100 MJ/kg, for temperatures from 2,000 to 24,000 °K at a density of 1.18 kg/m^3. The upper limit efficiency for optimum FROZEN expansion of laser heated air is $\alpha = 0.27$. With heating of air at its Mach 5 stagnation density (5.9 kg/m^3 as compared to STP air density of 1.18 kg/m^3) these efficiencies increase to $\alpha \approx 0.55$ (equilibrium) and $\alpha \approx 0.45$ (frozen). Optimum blowdown from 1.18 kg/m^3 to 1 bar occurs with expansion ratios ~ 1.5 to 4 as internal energy decreases from 1 to 100 MJ/kg. Heating of Mach 5 air at stagnation density requires larger expansion ratios, 8 to 32, for optimum expansion to 1 bar. Figure 3 shows the coupling coefficient (laser heated air at STP) vs alpha as a function of exit velocity, internal energy, expansion ratio, and exit pressure for equilibrium expansion.

Attitude (Lateral and Pointing) Control Propulsion

In May 2000, the AFRL initiated a Phase I Small Business Innovation Research (SBIR) contract with SY Technology, Inc., in Huntsville, AL, to start the development of a lateral and attitude control system for the Lightcraft. Lateral control is required to keep the vehicle properly positioned in the laser beam throughout its launch into orbit. Attitude control is required to keep the vehicle oriented properly with respect to the beam (i.e., pointed at the GBL). The Phase I goal was to determine the requirements of the control system and then to design and demonstrate control technologies which meet these requirements. The Phase I control concept was based upon the dimensions of a quarter-scale (25 cm) Lightcraft design.

Recently, SY Technology's Phase II proposal was approved, with a reasonable start date of Oct 02. The ultimate aim of the Phase II effort is to deliver major attitude control components suitable for use in the 25 cm Laser Rocket flight testing program.

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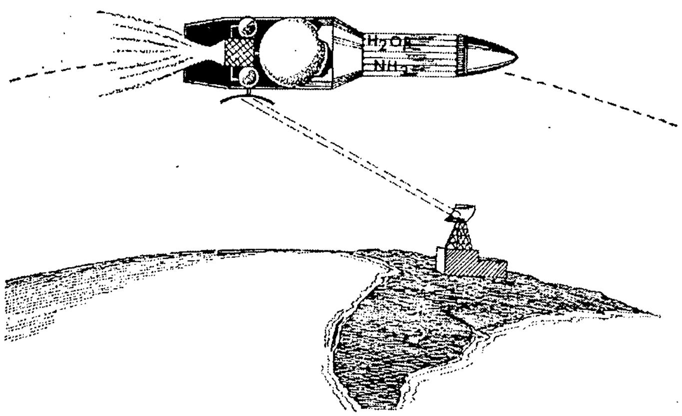

Figure 1. Laser Thermal Propulsion Concept

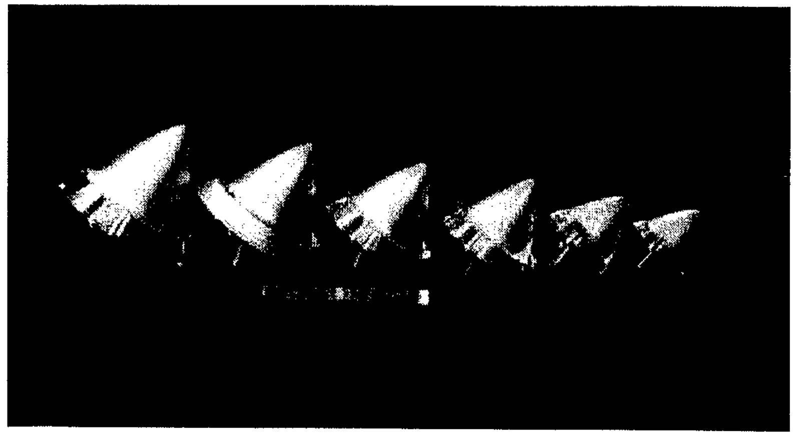

Figure 2. Phase I Lightcraft Size Variation

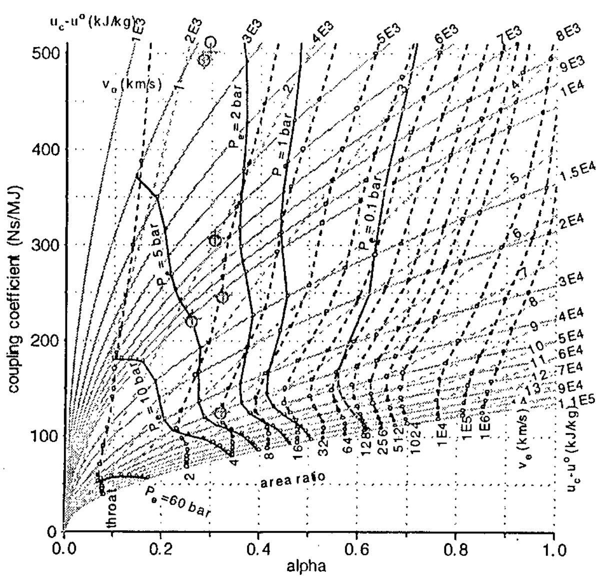

Figure 3. Laser Heated Air At STP