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The Air Force Laser Propulsion Program spanned nearly 10-years and included about 35-weeks of experimental research with the Pulsed Laser Vulnerability Test System of the High Energy Laser Systems Test Facility at White Sands Missile Range, New Mexico, WSMR/HELSTF/PLVTS. PLVTS is a pulsed CO2 laser that produces up to 10 kW of power in ~ 10 cm^2 spot at wavelength of 10.6 microns. The laser is capable of a pulse repetition rate up to 25 Hz, with pulse durations of about 20 microseconds. During the program basic research was conducted on the production of propulsion thrust from laser energy through heating of air and ablation of various candidate rocket propellant fuels. Flight tests with an ablation fuel (Delrin) and air were accomplished with a model Laser Lightcraft vehicle that was optimized for propulsion by the PLVTS at its maximum power output, 10kW at 25 Hz, 400 J/pulse. Altitudes exceeding 200-feet were achieved with ablation fuels. The most recent contributions to the technology included development of a mini-thruster standard for testing of chemically enhanced fuels and theoretical calculations on the performance of formulations containing ammonium nitrate and Delrin. Results of these calculations will also be reported here.

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Perspective on One Decade of Laser Propulsion Research at Air Force Research Laboratory* (Preprint)

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Abstract. The Air Force Laser Propulsion Program spanned nearly 10-years and included about 35-weeks of experimental research with the Pulsed Laser Vulnerability Test System of the High Energy Laser Systems Test Facility at White Sands Missile Range, New Mexico, WSMR/HELSTF/PLVTS. PLVTS is a pulsed CO2 laser that produces up to 10 kW of power in ~ 10 cm^2 spot at wavelength of 10.6 microns. The laser is capable of a pulse repetition rate up to 25 Hz, with pulse durations of about 20 microseconds. During the program basic research was conducted on the production of propulsion thrust from laser energy through heating of air and ablation of various candidate rocket propellant fuels. Flight tests with an ablation fuel (Delrin) and air were accomplished with a model Laser Lightcraft vehicle that was optimized for propulsion by the PLVTS at its maximum power output, 10kW at 25 Hz, 400 J/pulse. Altitudes exceeding 200-feet were achieved with ablation fuels. The most recent contributions to the technology included development of a mini-thruster standard for testing of chemically enhanced fuels and theoretical calculations on the performance of formulations containing ammonium nitrate and Delrin. Results of these calculations will also be reported here.

Keywords: Pulsed Laser Ablation Propulsion Delrin Lightcraft
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INTRODUCTION

The concept of laser propulsion was conceived in 1969 at the Air Force Rocket Propulsion Laboratory (AFRPL) by Dr. Robert L. Geisler.[1] During 1970, under the direction of Donald M. Ross, a group of 28-scientist/engineers at AFRPL conducted “Project Outgrowth,” which was a systematic study of the Geisler laser propulsion concept and numerous other Advanced Propulsion Concepts. Under the editorship of Franklin B. Mead the findings of “Project Outgrowth” were published in June 1972. Nearly simultaneously, in May 1972, the most-cited laser propulsion paper appeared, “Propulsion to Orbit by Ground-Based Lasers,” authored by “Arthur Kantrowitz.[3]

The objective of the “Project Outgrowth” was to predict and analyze advanced propulsion concepts that could occur during the subsequent 40-years. It was the seed that spawned the modern era of studies of advanced concepts. “Project Outgrowth” also set forth a philosophy for evolution of chemical propulsion that is reminiscent of the modern-day, goal-oriented technology development program known as “Integrated High Payoff Rocket Propulsion Technology,” IHPRPT.

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The laser propulsion concept has been further defined in about 140 peer- reviewed publications since 1973, which are listed in the Appendix. This list does not include conference papers published in great numbers by AIAA, by SPIE (in six International High Power Laser Ablation Conferences since 1998), and by AIP (in five International Symposia on Beamed Energy Propulsion since 2002). Figure 1 shows that the frequency of peer-reviewed publications has increased dramatically during the last decade.

Proof of concept experiments were initiated by the Air Force Research Laboratory, AFRL in 1996. Since that time the vehicle that became known as the Laser Lightcraft was perfected and flight tests to more than 200-feet altitude were conducted at White Sands Missile Range. Progress was reported in numerous news releases and television documentaries worldwide, and about 40-research papers[4-44] were published under the auspices of AFRL in conference papers and symposia. Several independent research projects and cost-sharing collaborations with AFRL were carried out in the United States[36,41,42], Germany[21,22,31], and Japan that also produced numerous research papers, reports, and articles in the peer-reviewed literature.

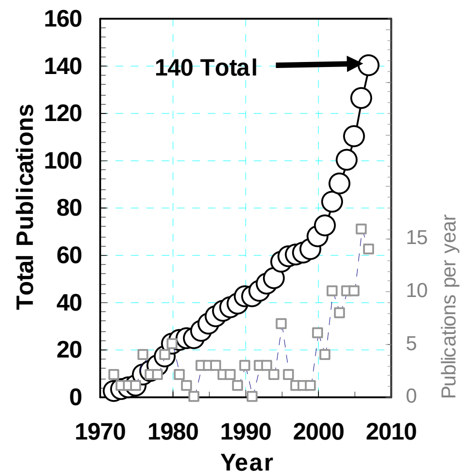

FIGURE 1 – Peer Reviewed Publications on Laser Propulsion. Source: Web of Science Data Base. See Appendix for list of 140 peer-reviewed laser propulsion articles: authors, title, journal, volume, year, first page.

ENERGY CONVERSION IN LASER PROPULSION

A simple equation may be written down to express the final kinetic energy of a laser propelled vehicle, E_f, as a product of several efficiencies and the wall plug electric energy, E_{wall}:

$$E_f = \frac{1}{2}mv^2 = \eta\, \alpha\, \beta\, \gamma\, \delta\, E_{wall} \qquad (1)$$

where, η = propulsion efficiency (conversion of jet kinetic energy to vehicle kinetic energy), α = expansion efficiency (conversion of internal propellant energy to jet kinetic energy), β = absorption efficiency (conversion of laser energy at vehicle to internal propellant energy), γ = transmission efficiency (conversion of laser energy at ground to laser energy at vehicle), and δ = laser efficiency (conversion of electric energy to laser energy at ground).

Propulsion efficiency depends on the mission thrust profile[28,32]. Unit propulsion efficiency may be achieved when the propellant jet velocity matches the vehicle velocity[32]. Transmission efficiency and laser efficiency[33] are a few percent.

Absorption and expansion efficiency are several tens of percent[16,20,23,24,26], so that the overall energy conversion in laser propulsion should be in the neighborhood of a few percent. The specific kinetic energy of a payload in LEO is about 32 MJ/kg. Thus, a 1 MW laser operating with 10% overall energy conversion efficiency (Eq. 1) for 5-minutes is capable of launching a 1 kg payload to LEO.[29,30,33-35,38].

CHEMICALLY ENERGETIC PROPELLANT-CONCLUSION

Calculations of the theoretical performance of Delrin/ammonium nitrate propellant formulations were carried out to determine the potential enhancement obtainable by supplementing laser energy with various amounts of chemical energy[40]. The apparent value of the αβ product (Eq. 1) in chemically energetic propellant depends on the formulation. With stoichiometric combustion at oxidizer/fuel ratio of 5.3, HCHO + 2 $NH_4NO_3 \rightarrow 5\ H_2O + CO_2 + 2\ N_2$ is possible, and with fuel-rich combustion at O/F = 2.7, HCHO + $NH_4NO_3 \rightarrow H_2O + CO_2 + N_2 + H_2$ is possible. Figure 2 shows the results of calculations carried out with a chemical equilibrium applications code available from NASA/Glenn. The figure shows that the apparent αβ product (Eq. 1) may be increased to values as high as 400%. Also, variable specific impulse propulsion that produces high propulsive efficiency by matching vehicle velocity with propellant exit velocity may be achieved. Thus, in principle, if chemically energetic propellant is used, payload potential increases to several kg for the 1 MW laser example cited above.

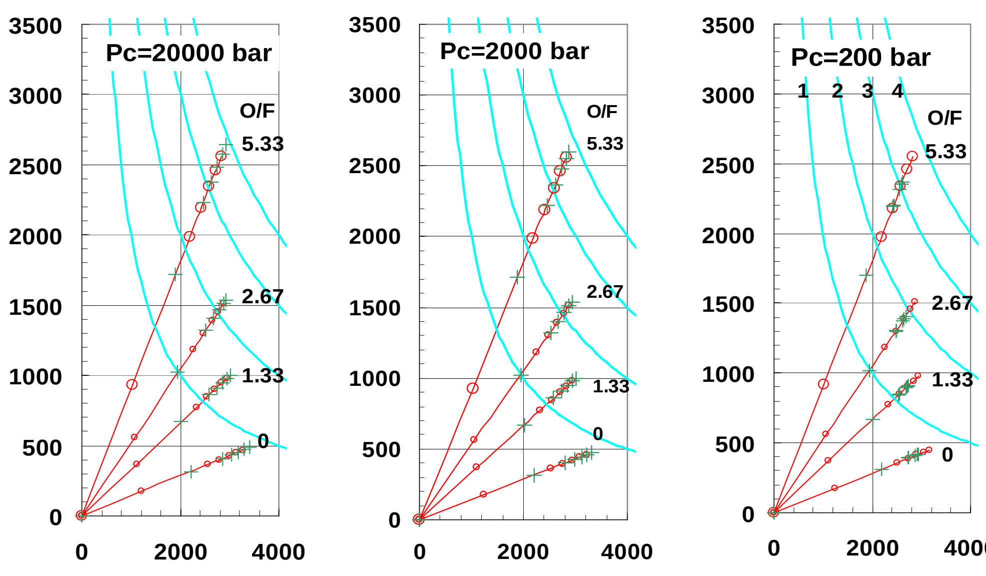

FIGURE 2. Coupling coefficient (ordinate, N/MW) vs Isp (abscissa, m/s) for various formulations of Delrin with AN: O/F = 5.33, 2.67, 1.33, 0, and addition of 7 MJ/kg of laser energy at constant pressure (200000, 2000, 200 bar), followed by expansion with expansion ratios of ε = 1, 4, 8, 16, 32, 64, using NASA CEA code, chemical equilibrium code. Hyperbolic constant apparent efficiency lines (constant apparent αβ) are shown at 100%, 200%, 300%, and 400 %.

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