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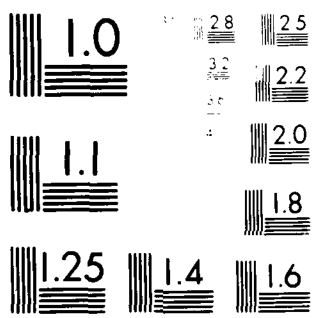

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PULSED LASER PROPULSION

P. E. Nebolsine,* A. N. Pirri,+ J. S. Goela,$
G. A. Simons$ and D. I. Rosen*

Physical Sciences Inc.
Woburn, MA 01801

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Experiments have been performed to assess the performance of a rocket that is propelled by the absorption of radiant energy from a remotely stationed, repetitively pulsed laser. A fluid mechanical model was developed for a conical nozzle to predict the necessary laser parameters for high specific impulse performance. Experiments using pulsed CO_2 TEA lasers were performed with conical and parabolic nozzles. At one atmosphere background pressure a maximum specific impulse of 900 to 400 s was obtained with an energy conversion efficiency (exhaust energy/laser energy) of 50%. At 10^{-4} atmospheric background

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PULSED LASER PROPULSION*

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ABSTRACT

Experiments have been performed to assess the performance of a rocket that is propelled by the absorption of radiant energy from a remotely stationed, repetitively pulsed laser. A fluid mechanical model was developed for a conical nozzle to predict the necessary laser parameters for high specific impulse performance. Experiments using pulsed CO_2 TEA lasers were performed with conical and parabolic nozzles. At one atmosphere background pressure a maximum specific impulse of 900 $\pm$400 sec. was obtained with an energy conversion efficiency (exhaust energy/laser energy) of 50%. At 10^{-4} atmospheric background pressure, a specific impulse of 450 $\pm$ 50 sec. was obtained with a self focusing parabolic nozzle and argon propellant and 1000 $\pm$ 100 sec. for hydrogen. Scaling laws for high thrust - high specific impulse rocket systems are discussed.

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I. INTRODUCTION

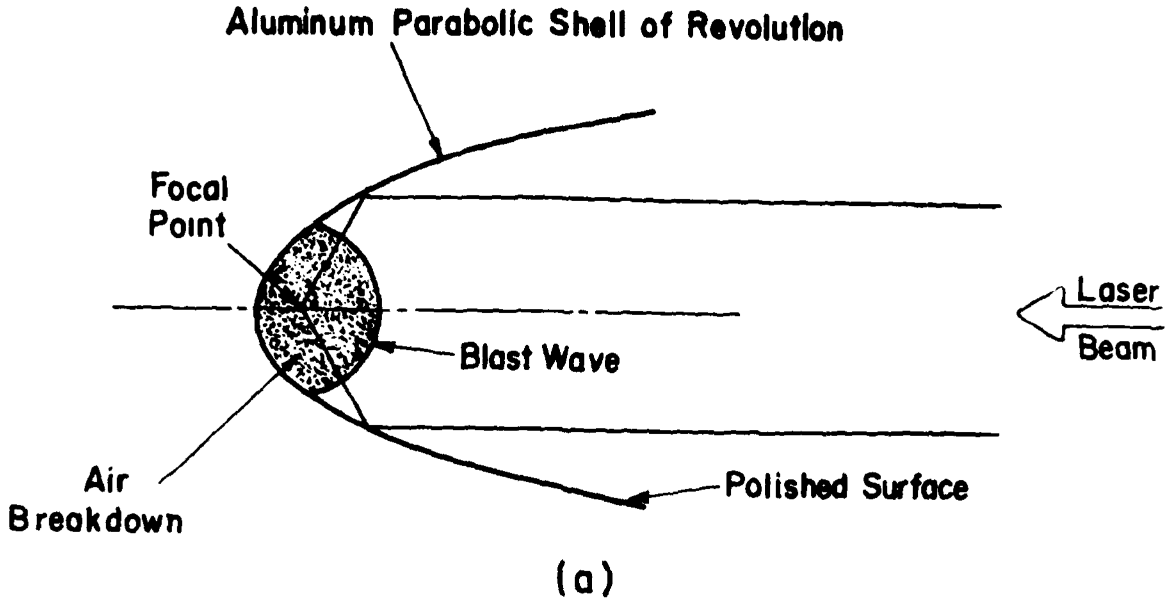
In recent years, several authors[1-10] have discussed and analyzed the possibility of beamed laser energy for rocket propulsion, often with specific reference to the application of high power, ground - based lasers. The concept is deceptively simple: provide a high energy density for propulsion without the encumbrance of a massive on-board power supply by absorbing radiation from a remotely stationed high-power laser. Since the radiation absorbing propellant may be a high temperature plasma, the specific impulse can be very large, i.e., > 1000 sec. The achievable thrust is limited by the available laser power, and with a remote energy source larger payload/ vehicle weight ratios are possible compared to chemical propulsion rockets.

The multiple pulsed laser rocket propulsion experiments described in this paper are an out growth of single pulse and CW experiments. These past experiments, described in Ref. 4, measured the specific impulse and thrust/laser power that was obtained with existing laser systems. Steady-state simulation experiments were performed in a vacuum chamber with solid propellants, and pulsed laser propulsion, along with the laser - powered pulse jet concept, was introduced.[4] A steady-state or CW laser propulsion system is a system whose thrust remains constant in time while the laser beam continuously provides the energy source for converting propellant mass to exhaust kinetic energy. It was found in Ref. 4 that a high ratio of thrust to laser power can be obtained by simply using the laser to vaporize a solid surface. However, in order to obtain high specific impulse it is necessary to add energy to the vapor in a stable manner. The heating of a gas by external radiation downstream of a nozzle throat was found to be inherently unstable when the gas is initially weakly ionized and absorbs radiation via inverse Bremsstrahlung. The stability of laser-heated flows both upstream and downstream of a nozzle throat is not adequately understood and is a very complex issue.[7] However, it appears that stable heating of a propellant in a steady-state manner may best be accomplished by heating the gas upstream of a throat such that the beam direction and the propellant flow direction are the same. This would require a laser window in the absorption chamber that will tolerate transmission of significant laser intensities along with high pressures for long periods of time.

The alternative approach to CW laser propulsion that circumvents the stability problem is to utilize a pulsed laser as described in this paper. The techniques for obtaining large thrust and specific impulse with a pulsed laser are an outgrowth of various experimental and theoretical problems in laser effects.[11-15] When a high power pulsed laser is focused to a high intensity in a gas or on a solid surface, a high temperature, high pressure plasma, which propagates up the laser beam, is initiated. Provided the pulse is sufficiently short that the high pressure gas remains in the vicinity of a surface or nozzle wall, this method is an efficient propulsion mechanism. The propulsion system operates in a way similar to detonation propulsion systems that have been proposed for use in high pressure environments.[16-20] Periodic "explosions" in the nozzle transfer the detonation or laser energy to the working fluid. The two most significant potential advantages afforded by a pulsed laser propulsion system over a CW laser propulsion system are 1) simplicity in engine design as a result of permitting the laser beam to enter the nozzle via the exhaust plane, and 2) elimination of constraints resulting from plasma instability. However, the power conversion efficiency (efficiency of converting laser power to power in the rocket exhaust) must be determined. In Ref. 4 a low power conversion efficiency was obtained because the pulse time of the laser was too long. In addition, with pulsed laser propulsion, thrust is obtained when laser energy is converted to kinetic energy by a continuously weakening shock wave traversing the propellant gas. The relative efficiency of generating thrust in this manner is not known _a priori_ to be the same as when converting laser power to thrust in a steady process.

As a result of our past theoretical study the laser requirements for an experimental test of pulsed laser propulsion concepts were specified, and a suggested experiment was presented.[9] Our experimental objective is to determine the relative efficiency of a pulsed laser propulsion system and the specific impulse and thrust as a function of laser power, pulse repetition frequency, ambient conditions and propellant mass flow. The nozzle configuration is taken to be an idealized extension of the concept introduced in Refs. 2 and 4. A schematic of the single pulse nozzle configuration[2,4] is presented in Fig. 1a. The nozzle walls focus the incoming beam to yield a breakdown in the propellant at the focus. With a short laser pulse, the resulting shock becomes a blast wave which propagates to the nozzle exit plane, converting all of the high pressure gas behind it into a force on the nozzle wall. This nozzle was designed for single pulse operation only. Therefore, no considerations of propellant supply were necessary. In Ref. 9, the fluid mechanics of a repetitively pulsed laser propulsion system was analyzed, and thus, the fluid dynamics of the propellant feed system has been included.

The strength of the laser induced blast waves and laser repetition rate specifies the propellant mass flow. Specifically, the laser induced blast waves stop the propellant flow through the throat until the pressure at the throat weakens to the plenum pressure and then the flow restarts. This process is called acoustic valving. The configuration analyzed is shown in Fig. 1b. The nozzle drawn with a solid line is the parabolic self focusing nozzle. However, for simplicity this nozzle is replaced by a conical nozzle which is shown dashed in the figure. The angle of the cone is chosen such that the exhaust gases leave the exit plane at the same angle relative to the thrust axis as with the parabolic nozzle. The beam is assumed to be focused externally so that the focusing angle equals the cone angle. The propellant is treated as a steady source flow entering at the apex or "throat" of the conical nozzle, and periodically laser induced blast waves are ignited at $r = 0$ where r is



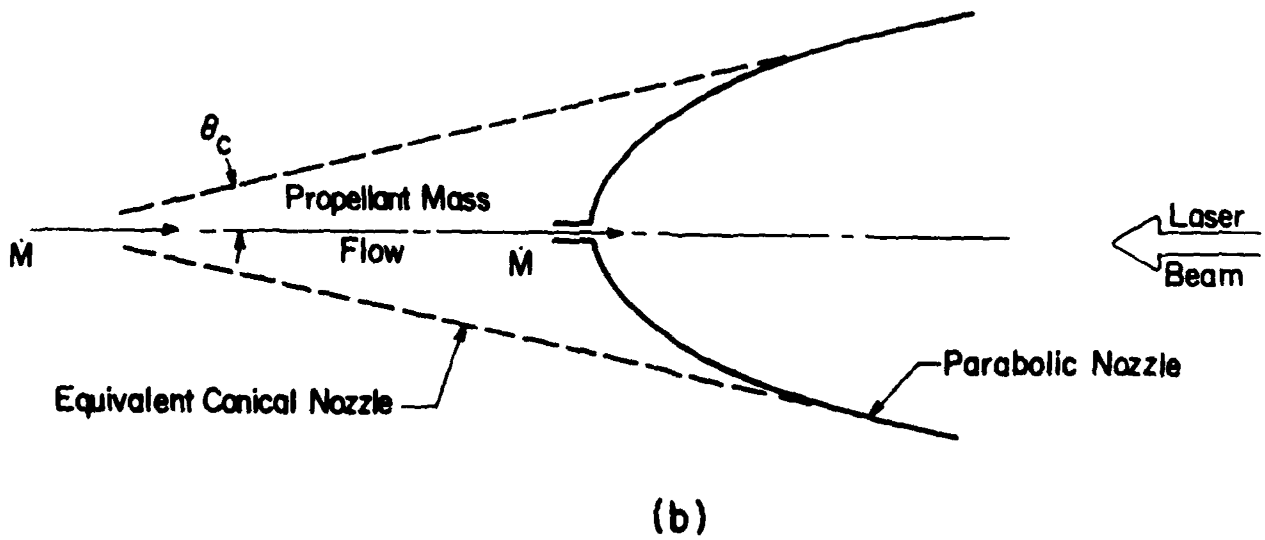


Fig. 1 a) Single Pulse Propulsion Concept as Introduced in Ref. 4

b) Multiple Pulse Propulsion Concept and Equivalent Conical Nozzle measured from the apex. The blast waves process the propellant to obtain high exhaust velocities necessary for high specific impulse operation.

In Section II, the theory of pulsed laser propulsion when the gas expands into a vacuum and also the theory for operation with background pressure is reviewed. The experiments using conical nozzles at 1 atmospheric backpressure and experiments with the parabolic nozzle at 10^{-4} atmospheric pressure are presented in Section III. Conclusions are presented in Section IV.

II. THEORETICAL STUDIES

A fluid mechanical model has been developed to assess the performance of the laser-powered thruster concept shown in Fig. 2. The model utilizes blast-wave theory to calculate the thrust and specific impulse in a vacuum environment. The details of the theory for operation in a vacuum environment are presented in Refs. 3 and 4, and briefly reviewed here. The nozzle is initially treated in a conical geometry for simplicity, and an equivalence between the conical and parabolic nozzle is assumed. The theory for a single pulse is developed by considering the blast wave propagating into the non-uniform density field induced by the release of propellant in the throat region. A pulse sequencing theory extends the single pulse theory to multiple pulse operation. This is done by propagating each blast wave into an amount of propellant determined by the throat conditions and the time between laser pulses. After a blast wave has processed the propellant, the propellant isentropically expands out the nozzle and thrust is obtained with high specific impulse. An example result for the laser energy requirements in a vacuum environment is presented in Fig. 3 for a conical nozzle.

In Fig. 3 the time between laser pulses is plotted versus the orifice diameter (diameter of throat through which the propellant is fed into the breakdown region). The propellant is taken to be helium which passes into the throat from a plenum chamber at 3 atmospheres stagnation pressure. This pressure is sufficient to "choke" the propellant flow. ρ^* and u^* are the propellant density and velocity, respectively, in the throat before the laser pulse breaks down the propellant and ignites the blast wave. The energy conversion efficiency is the ratio of energy in the blast that results in thrust to the laser energy. The results in Fig. 3 are for an assumed 50% energy conversion efficiency where efficiency is the ratio of energy in the laser induced blast wave to laser energy. An operating corridor for multiple pulse laser

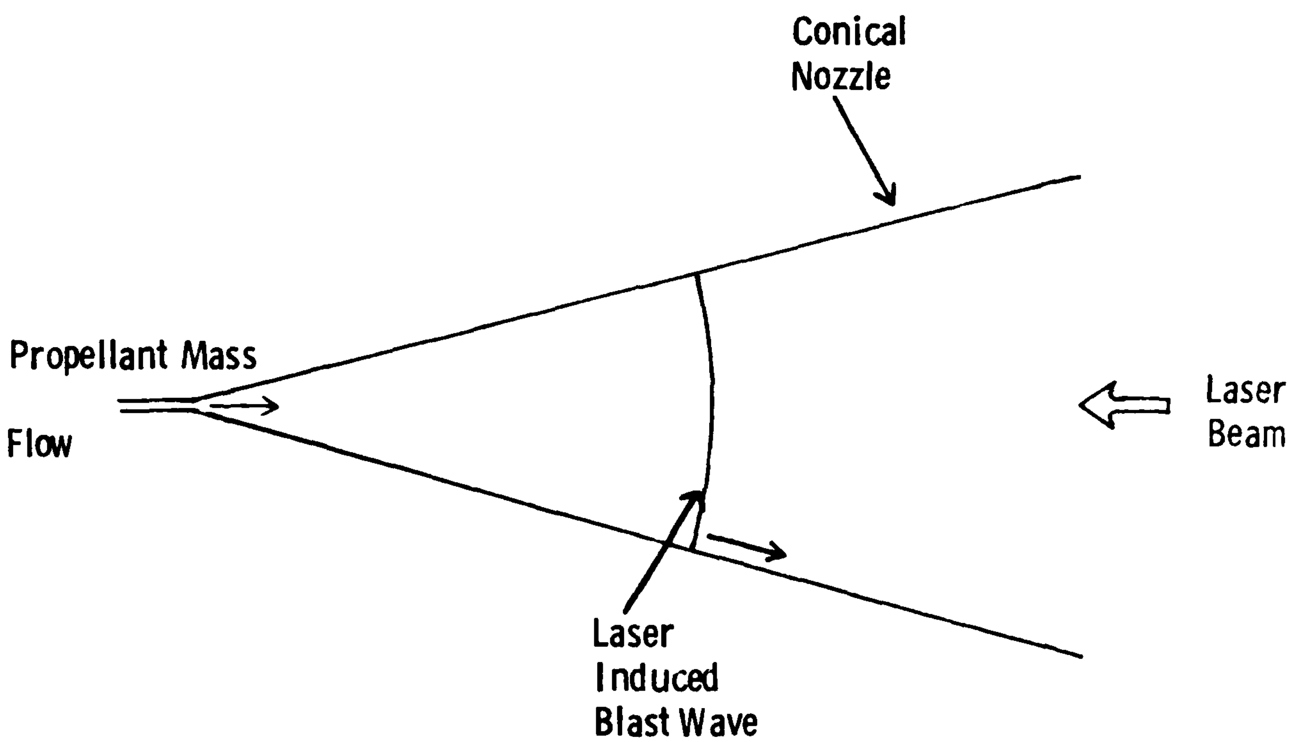


Fig. 2 Conical Nozzle with Externally Focused Laser Beam

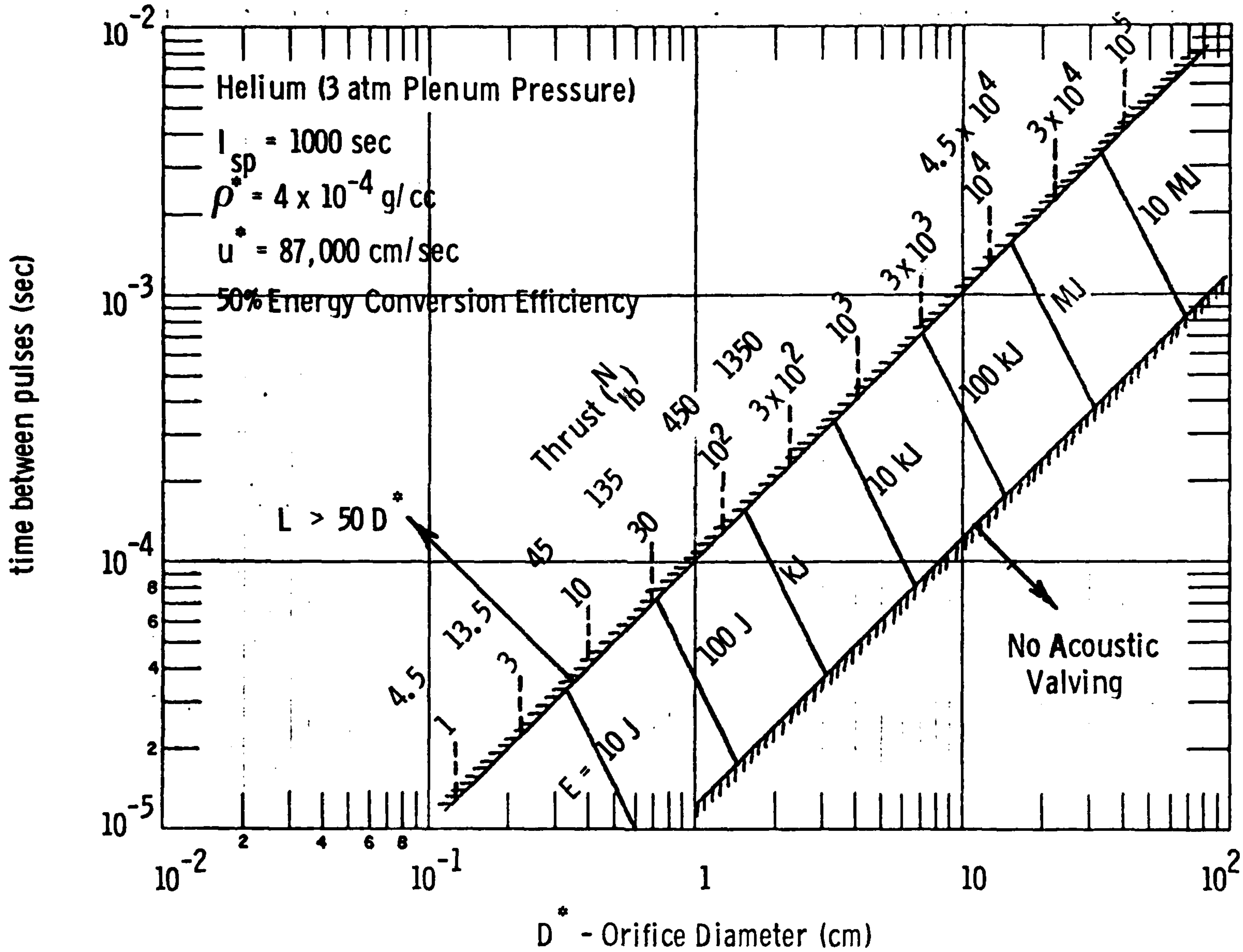


Fig. 3 Laser Energy Requirements: Vacuum Operation

propulsion at a specific impulse of 1000 sec is delineated in Fig. 3. The upper boundary of the corridor is set arbitrarily where the length of the conical nozzle is equal to fifty times the throat diameter. It is felt that an aspect ratio greater than 50 may be undesirable for full scale operation due to engineering and weight considerations. The lower boundary of the corridor is set by propellant feed considerations. To the right of this boundary the time between pulses is so short that there is insufficient time for propellant to enter the nozzle between laser pulses. This is designated as the acoustic valving limit. Constant energy lines are shown within the operating corridor and vertical lines of constant thrust are presented. As an example, a 100J per pulse laser operating at 7×10^{-5} sec between pulses (14,285 pps) is capable of powering a 30 lb (135 Nt) thrust rocket engine that has a throat diameter of 0.7 cm and a length (if it were conical) of 35 cm. Similarly, a 100 KJ per pulse laser at 7×10^{-4} sec between pulses (1,428 pps) will power a 3000 lb (1.35×10^{4} Nt) thrust engine with a 7 cm throat and a conical length of 3.5m.

When the pulsed laser-powered thruster is operating in an air environment, the laser requirements are altered by two effects. First, the propellant flow into the nozzle is characterized as flow through a highly overexpanded nozzle. A normal shock sits in the nozzle close to the throat (prior to the laser breakdown) and most of the flow is subsonic in the diverging section of the nozzle. This results in a reduction of the repetition frequency necessary to attain a specified specific impulse. In addition, since the background pressure reduces the propellant expulsion velocity after breakdown, it is possible for shocks from subsequent laser breakdowns to propagate into the hot propellant from a previous laser pulse. Thus, multiple shocking of the propellant is a feature of high pulse repetition rates in an atmospheric environment. It has been shown that the specific impulse obtained for operation in a background gas can be related to the vacuum specific impulse by

$$I_{sp} = \frac{3}{4} \times \frac{t_{conv}}{\Delta t} \times (I_{sp})_{vac \text{ at } \Delta t = t_{conv}}$$

where t_{conv} is the time for the unshocked propellant to reach the exhaust plane in an ambient gas environment, Δt is the time between pulses and $(I_{sp})_{vac}$ at $\Delta t = t_{conv}$ is the calculated vacuum specific impulse when the time between pulses Δt is set equal to the convection time.[21]

The map of the laser energy requirements for operation in a one atmosphere background gas is presented in Fig. 4. It can be seen, when Fig. 4 is compared to Fig. 3, that the effect of the background gas is to reduce the repetition rate necessary to obtain the constant specific impulse with the same ratio of nozzle length to throat diameter. Thus, shorter nozzles and slower repetition rates are optimum for operation in a one atmosphere environment.

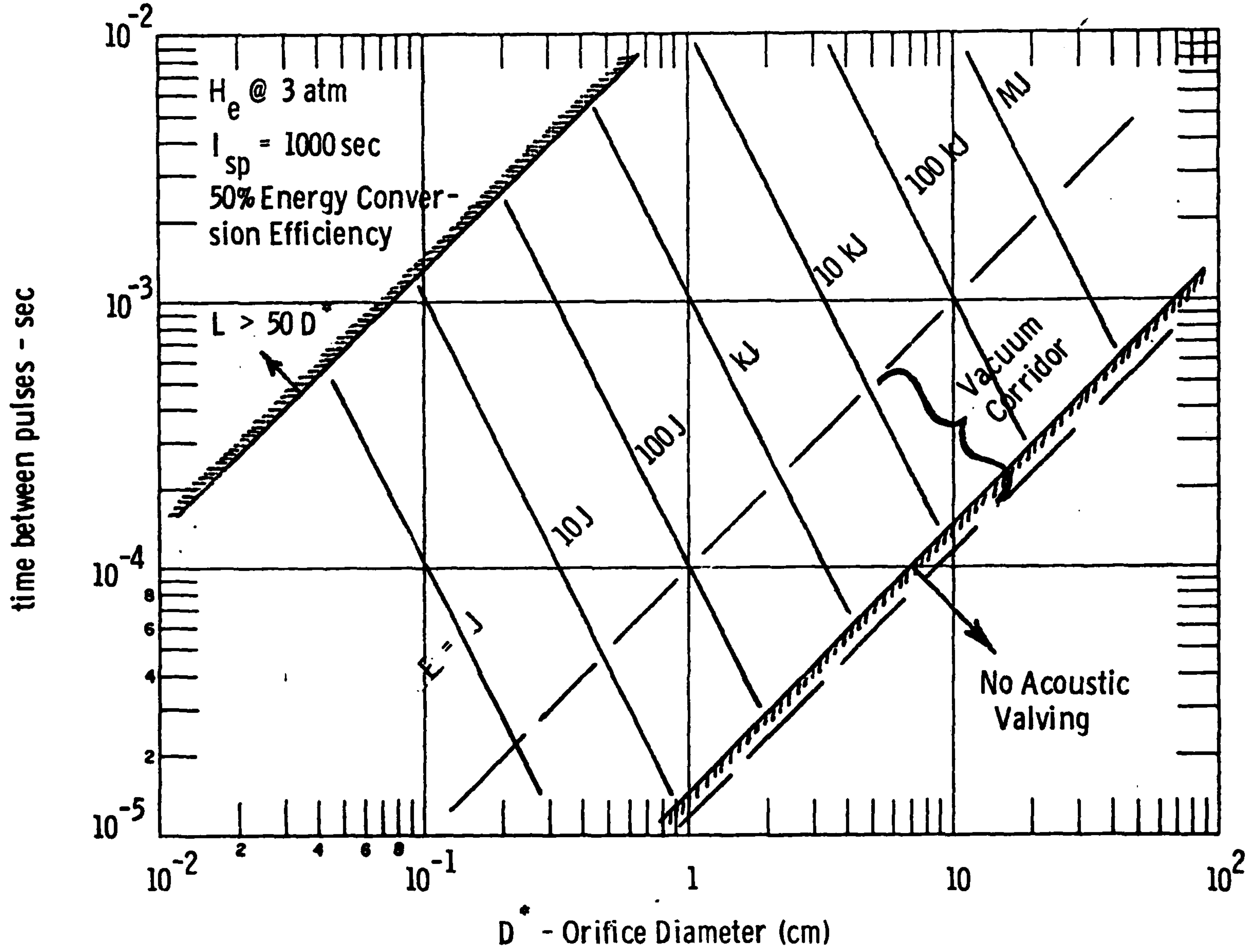


Fig. 4 Laser Energy Requirements: One Atmosphere Background

III. EXPERIMENTAL STUDIES

Using the theory summarized above to design the nozzle and the laser system parameters, we have performed small scale experiments to 1) verify the theoretical predictions of high specific impulse obtainable with the pulsed laser-powered thruster concept, 2) measure the time averaged specific impulse and thrust versus laser parameters, and 3) study the effect of finite exit plane pressure on thrust and specific impulse. The experiments were carried out using several independently triggered CO_2 TEA lasers, (Lumonics, Model 103). Each laser delivers up to 11J in energy over a pulse time of approximately 3 μsec. Two nozzle geometries were utilized. A conical nozzle was first used since direct comparison with the theory is possible. For these experiments each laser beam was focused externally with 30 cm focal length mirrors into the nozzle resulting in a focal point at the throat. A schematic of the conical nozzle design is shown in Fig. 5. The length shown is the design length for vacuum operation. However, since the nozzle length for one atmosphere operation is less than 4 cm, the nozzle skirt was constructed in removable sections. A self-contained plenum was attached to the nozzle and contains sufficient propellant for operation with up to four laser pulses. A latex diaphragm was used to maintain the plenum pressure at 3 atm until the experiment begins. A spark is used to break the diaphragm and the lasers are triggered in sequence at a programmed time between laser pulses. The sequence of events consisting of the diaphragm breaking, throat opening in less than 60 μsec, propellant flowing down the nozzle for approximately 130 μsec and the lasers firing was verified with pressure transducer and optical transmission data.

Experiments were performed with the conical nozzle in a one atmosphere environment. Helium was chosen as the propellant and two laser pulses were used. The principal diagnostic for determining the specific

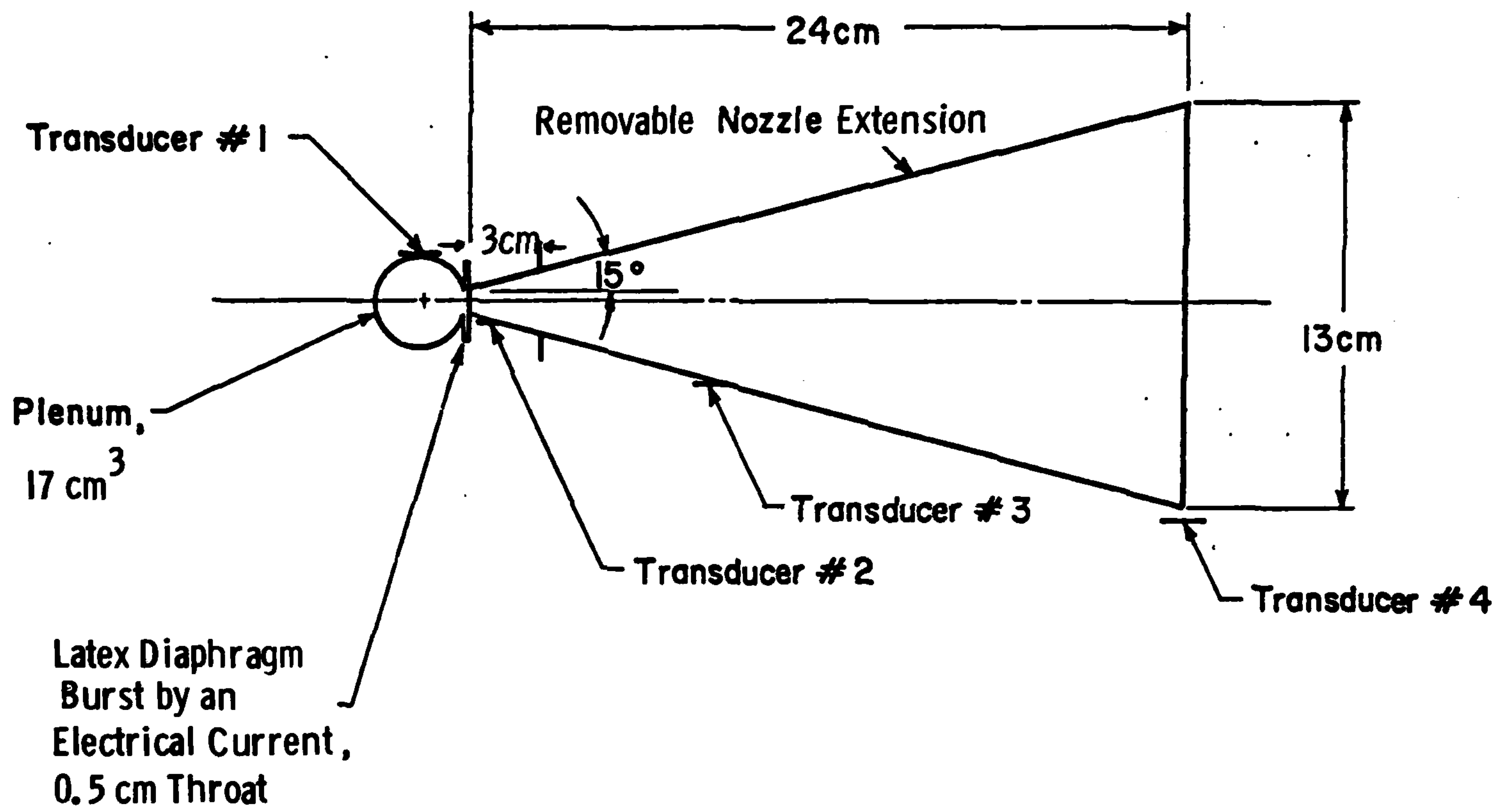


Fig. 5 Conical Nozzle Design

impulse was a ballistic pendulum to measure the impulse delivered with each laser pulse. Pressure transducer results were also used along with blast-wave theory to verify the results obtained with the pendulum. Determination of the specific impulse proceeds as follows. The specific impulse, I_{sp}, is defined as

$$I_{sp} = \frac{T}{\dot{m}g} = \frac{\text{Impulse}}{\Delta mg}$$

where T is the average thrust obtained per pulse, $\dot{m}$ is the average propellant mass flow rate between pulses, g is the acceleration of gravity and the Impulse is the incremental increase in impulse between the first and second laser pulses.

$$\Delta m = \rho^* u^* A^* \Delta t$$

where A^* is the throat area. For the experimental conditions, $\rho^* u^* A^* \approx$ 5.5 gm/sec. This is an upper limit to the mass flow rate since it assumes that immediately after the diaphragm opens, the propellant efflux is at the steady state rate. Data were taken at a time between pulses, Δt, of 30, 60 and 120 μsec. An impulse of 17 dyne-sec/Joule was observed. Results for the specific impulse versus the time between laser pulses for the two CO_2 laser pulses are shown in Fig. 6. Also presented in Fig. 6 are the theoretical predictions using the theory for one atmosphere background operation outlined in Section 2. The theoretical results were obtained for energy conversion efficiencies of 100%, 50% and 25%. From the theory/data comparison it may be concluded that an energy conversion efficiency of 50% is most representative of the data obtained for these chosen laser parameters. The theoretical limiting specific impulse with the lasers and nozzle used occurs when the time between laser pulses becomes so short that there is not

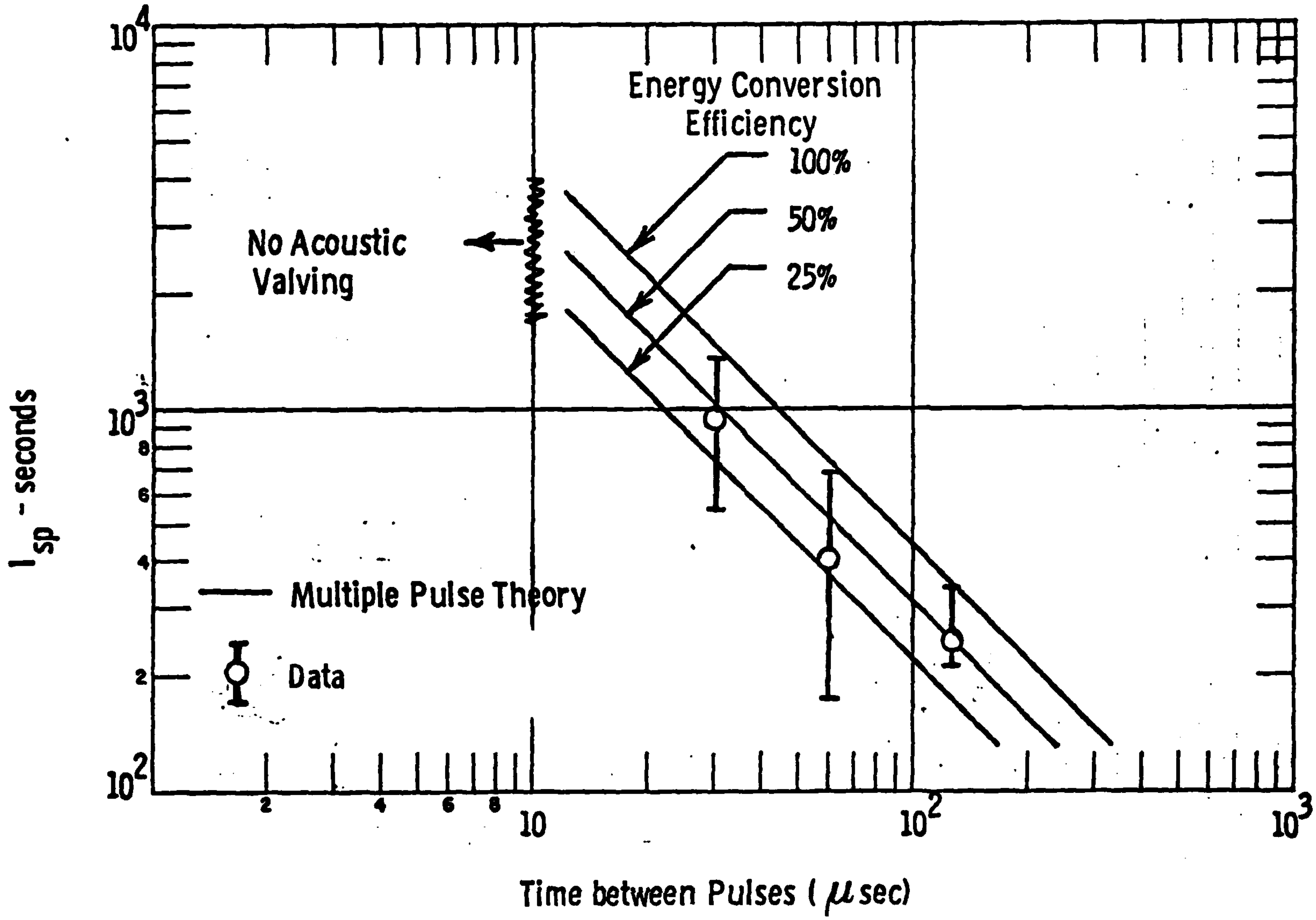


Fig. 6 Two Pulse Data with Conical Nozzle - One Atmosphere Background

sufficient time for the propellant to flow into the breakdown region downstream of the throat. This "no acoustic valving" limit is also denoted in Fig. 6.

A schematic of the parabolic nozzle rocket is presented in Fig. 7. The propellant mass flow was controlled by a solenoid valve rather than the latex diaphragm used for the conical nozzle experiments. Two experimental areas were pursued: 1. determination of the energy conversion efficiency of laser energy into blast wave energy and 2. determination of the specific impulse for the 2nd pulse. Energy conversion efficiency measurements were made for hydrogen, helium, nitrogen and argon propellants as a function of mass flow rate. The blast wave energy was determined from pressure transducer (Sunstrand 211B4) measurements. The pressure transducer data was used as input to blast wave theory to deduce the blast wave energy. Mirels and Mullen[22] have developed the formula for shock location, R, in a supersonic flow as function of time, t,

$$R = Ct^{2/3}$$

where C is a constant equal to

$$[(9/4I_B)\,(E_{BW}V_\ell/\dot{m})]^{1/3} \quad .$$

For a parabolic nozzle, I_B is a numerical constant equal to 0.733 for $\gamma = 1.4$ and 0.436 for $\gamma = 1.67$. The other parameters are the blast wave energy, E_{BW}, the "cold" propellant limiting velocity, V_ℓ, and the propellant mass flow rate, $\dot{m}$. Similar formulas were developed by Simons and Pirri only for conical nozzles.[9] Another method of reducing the data is to use the measured shock strength. Both types of data reduction yield similar results when the blast wave is strong which is required to use Mirels and Mullen's analysis. The experimental data is presented in Fig. 8. We note the increasing blast wave energy with increasing mass flow rate. This is well correlated with

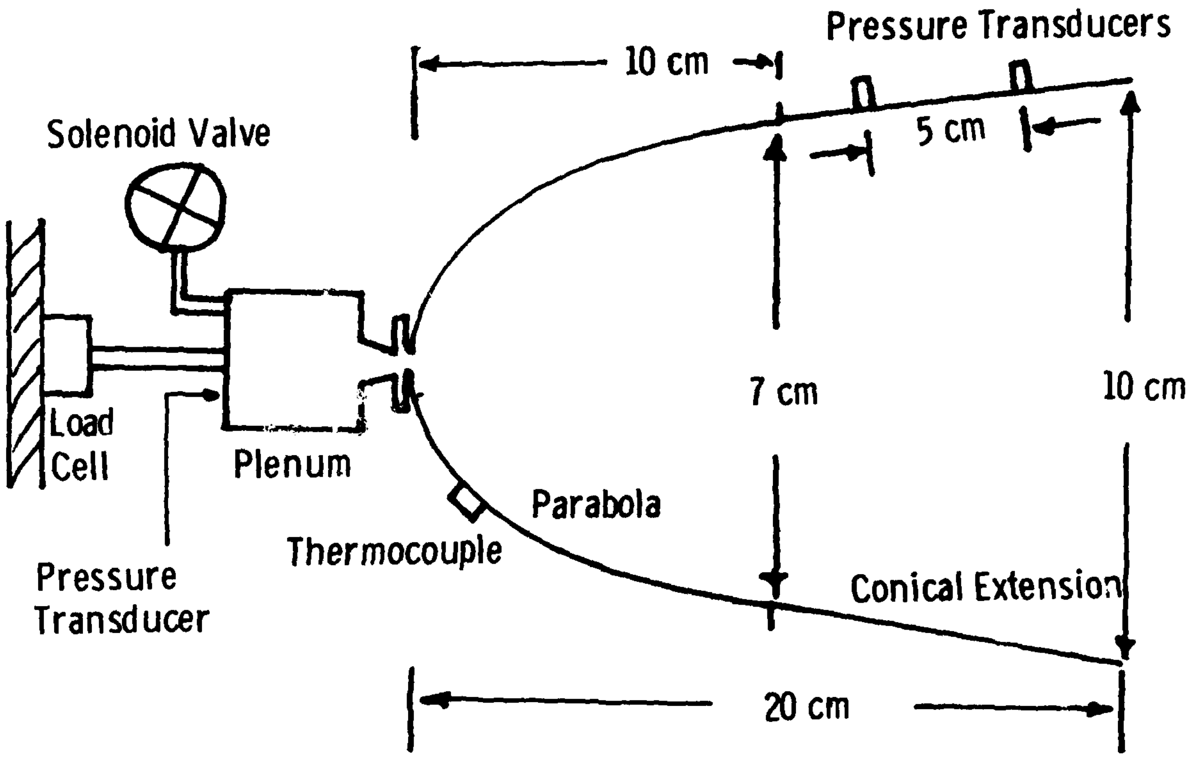


Fig. 7 Parabolic Rocket Schematic

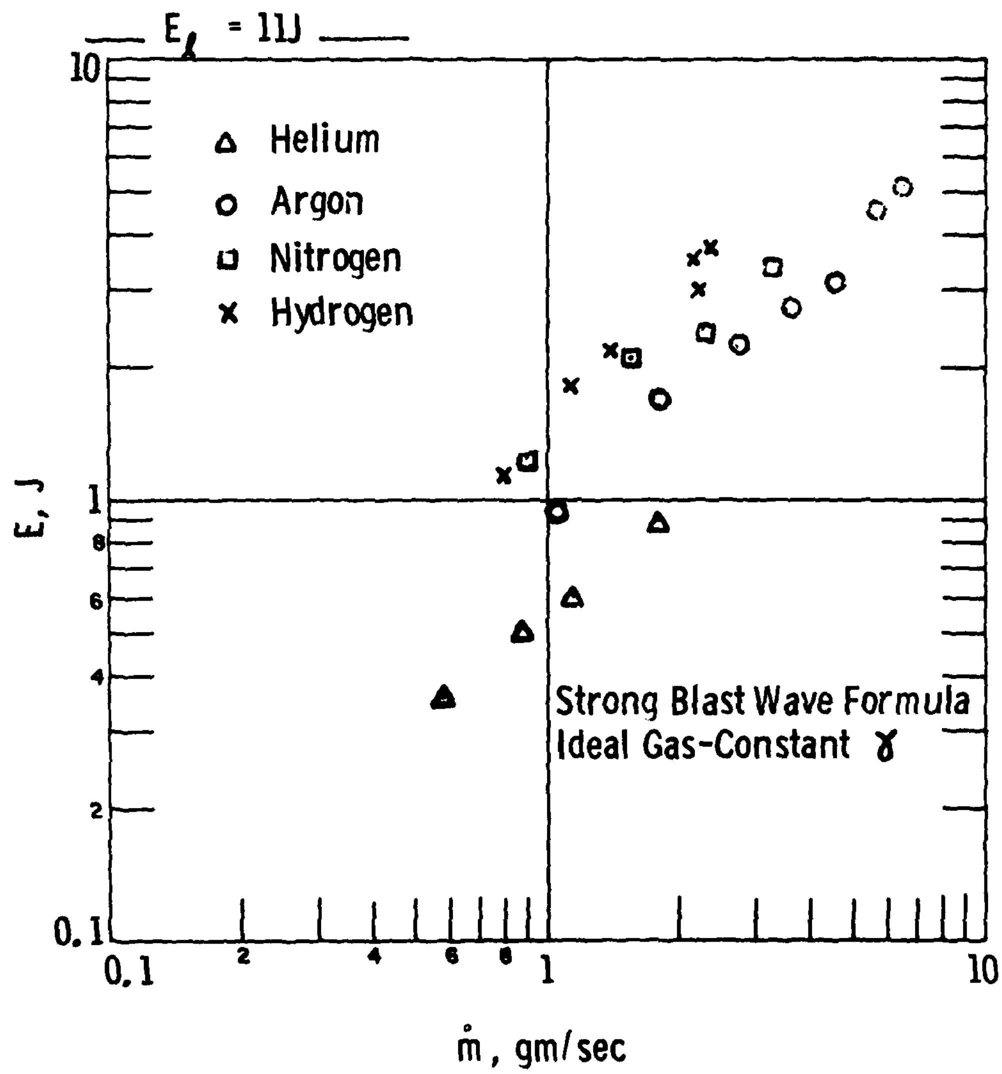


Fig. 8 Blast Wave Energy vs ṁ

the absorptance of the propellant as a function of mass flow rate. Relative optical absorptance was determined using a pyroelectric detector which monitored the laser energy reflected out the nozzle. An example of the comparison between laser energy into blast wave conversion efficiency and normalized optical absorptance is shown in Fig. 9 for hydrogen as the propellant. We note the strong correlation between optical absorptance and energy conversion efficiency. The trend of the optical absorptance can be explained by the inverse Bremsstrahlung absorption process. As the density is decreased, the absorption length increases so that less energy is absorbed.

The specific impulse was determined for hydrogen and argon propellants using two pressure transducers. In contrast to the situation discussed above where the propellant filled the nozzle, high specific impulse operation is achieved when the propellant does not fill the rocket. Therefore the pressure transducers are detecting the passage of the mass front instead of the shock front. The laser repetition rate was chosen so that the nozzle would only be partially filled with new propellant for the second pulse. This is appropriate so that the shocked propellant has an area or volumetric expansion to convert thermal energy into directed kinetic energy or thrust.

The data for argon propellant is shown in Fig. 10 and Fig. 11 for the hydrogen propellant. As expected, a higher specific impulse was achieved with hydrogen compared to argon. This is because of the lower stagnation temperature required for hydrogen versus argon. Yet both of these propellants achieved approximately 40% conversion efficiency at the maximum observed specific impulse. Further work is necessary to explore the limitations of conversion efficiency and rocket performance as a function of laser parameters and rocket design.

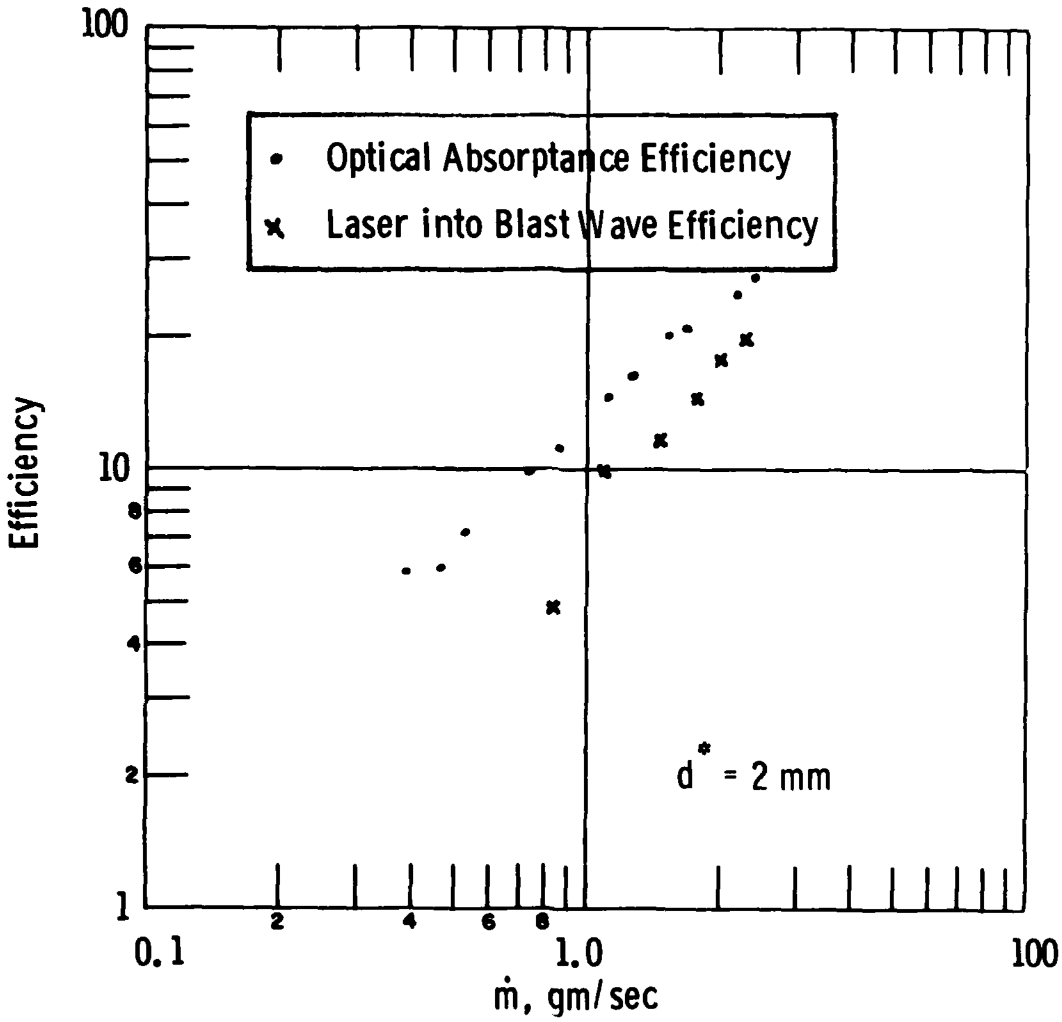


Fig. 9 Efficiency vs ṁ for Hydrogen

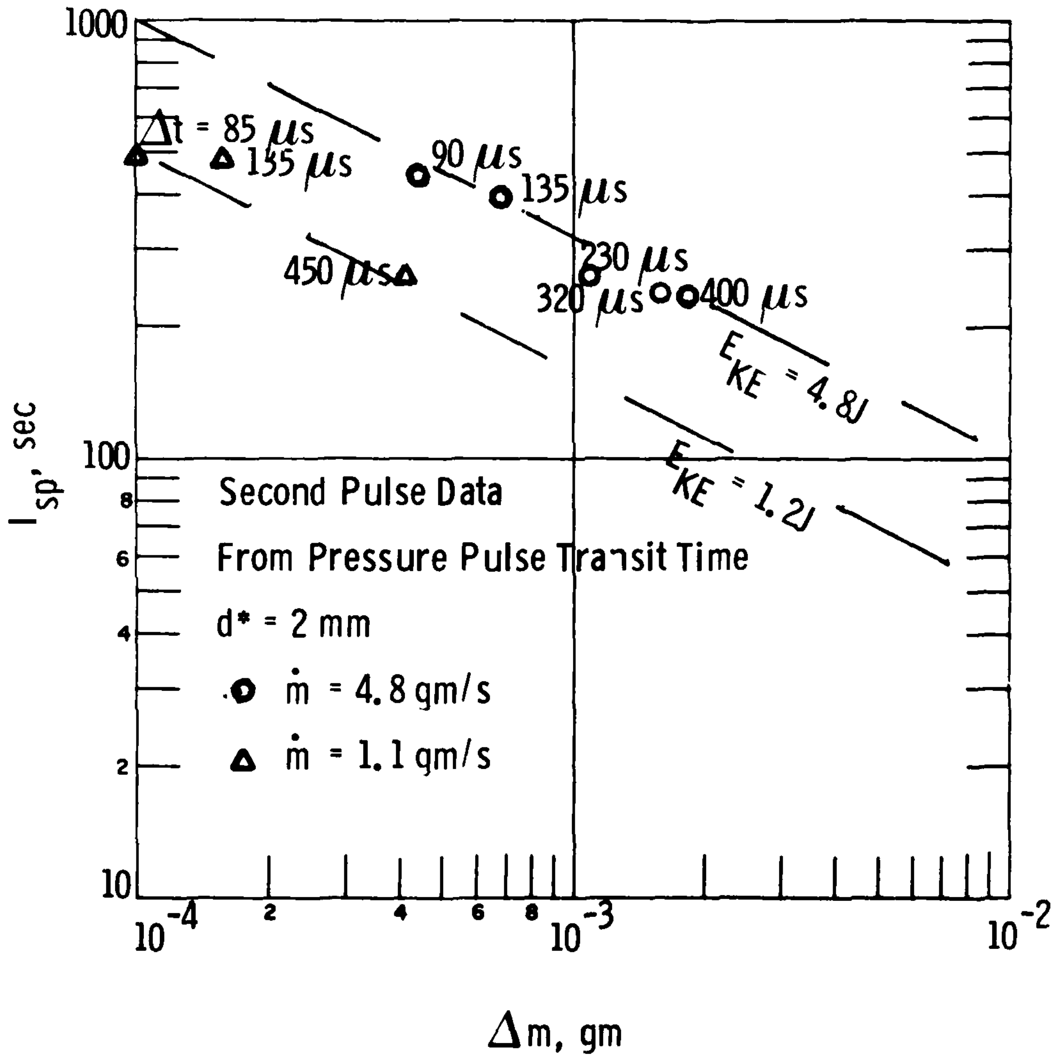


Fig. 10 I_{sp} vs Δm for Argon

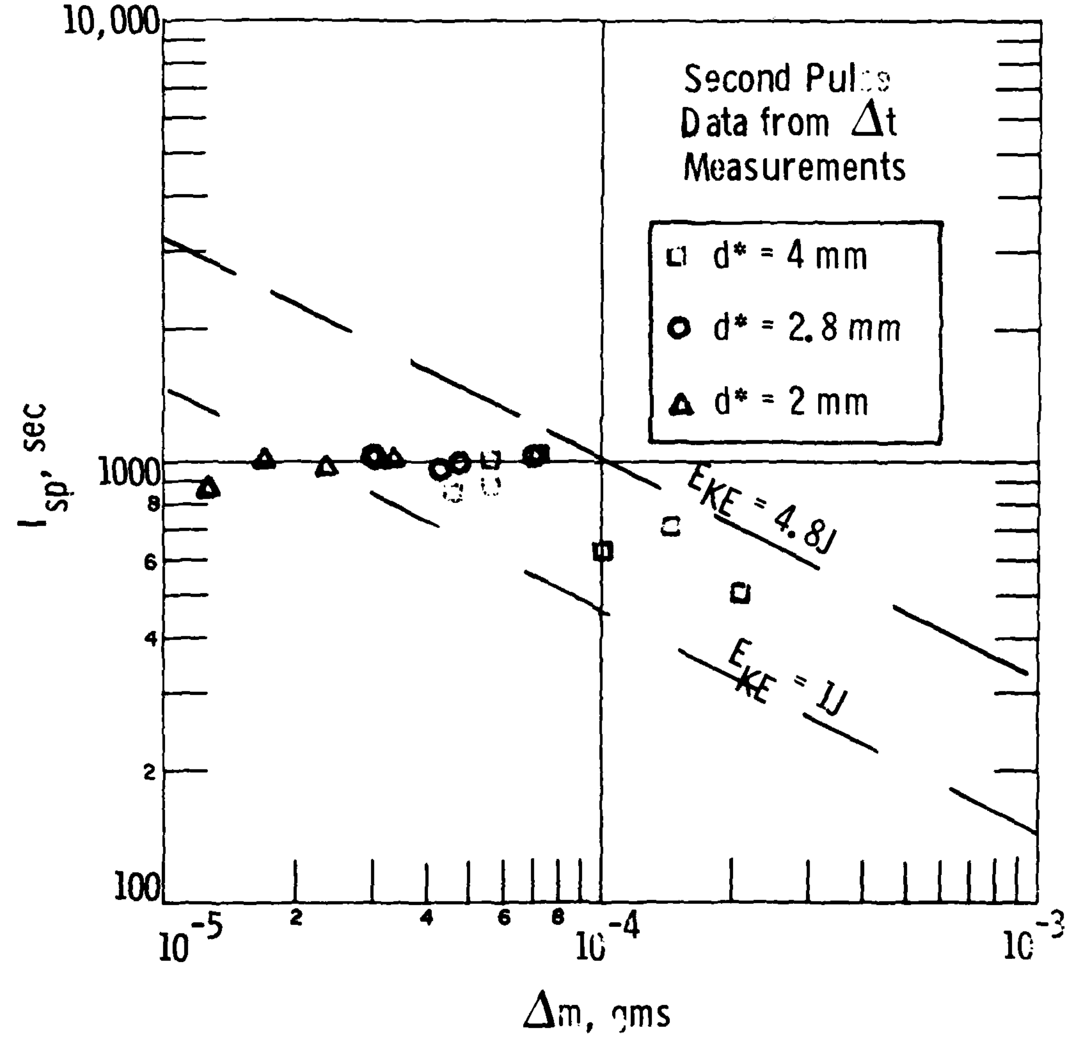


Fig. 11 I_{sp} vs Δm for Hydrogen

IV. CONCLUSIONS

The experiments with good comparison with theory have demonstrated that pulsed laser propulsion is capable of high specific impulse operation. Therefore, this propulsion concept should be considered for earth launch and orbit to orbit transfer missions. Because of the high cost of high power lasers, pulsed laser propulsion is most likely to be economically competitive with other systems for high launch rates of small payloads.

The experimental and theoretical results presented above have demonstrated that 1) the self-focusing pulsed laser-powered thruster is a working concept, 2) a 500-1000 sec specific impulse can be obtained, 3) gaseous propellant feed systems are reliable for self-regulating propellant flow, and 4) parabolic nozzle focusing yields a strong laser breakdown in the propellant and significant thrust to laser power ratios.

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