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# Comparative Lightcraft Impulse Measurements

W.O. Schall, H.-A. Eckel, W. Mayerhofer, W. Riede, E. Zeyfang
German Aerospace Center (DLR) – Institute of Technical Physics
Stuttgart, Germany

F.B. Mead, Jr., C.W. Larson, W.M. Kalliomaa
Advanced Concepts Section, AFRL/PRSP
Edwards AFB, CA

## Abstract

The impulse coupling coefficients of two radically different laser propulsion thruster concepts (lightcrafts), each 10 cm in diameter, have been measured under equal conditions using two different pendulum test stands. One test stand and one lightcraft of toroidal shape were provided by the U.S. Air Force Research Laboratory. 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. The laser was operated with two configurations: 1) a stable resonator (flat beam profile); and, 2) an unstable resonator (ring shaped beam profile). A first series of experiments was carried out in the open laboratory environment. Propellant, therefore, was either the surrounding air alone, or Delrin as an added solid propellant. The coupling coefficient was determined as a function of the laser pulse energy. In a second series, the same experiments were repeated at various reduced pressure levels with the German lightcraft suspended in a vacuum vessel. This simulates the conditions of a transitional flight from within the atmosphere to outer space. As an additional parameter the specific mass consumption of Delrin (gram/Joule) was measured for each parameter set, allowing the determination of the average exhaust velocity in vacuum.

## 1. Introduction

Beamed energy rocket propulsion was first promoted by Kantrowitz in 1972[1]. Although many investigations had been started thereafter, utilizing both the pulsed and the cw mode of laser operation, no lasers with sufficiently high powers were available at those times and the interest began to fade. In the mid-eighties Rensselaer Polytechnic Institute (RPI) took up this idea and created a special type of thruster configuration, later dubbed "lightcraft"[2,3]. This name became the synonym for spacecrafts that derive their propulsive energy from beamed laser power. Various sized models have been built and flight-tested successfully by the US Air Force Research Laboratory (AFRL) in cooperation with RPI at the High Energy Laser Systems Test Facility (HELSTF) at White Sands Missile Range, NM[4,5]. In 1997 DLR (German Aerospace Center) began with wire-guided flight tests of a particularly simple model in the laboratory[6,7].

In contrast to most other types of rocket propulsion (chemical, electrical, nuclear...) the source of propulsive energy is derived from a laser beam sent to the spacecraft from a remotely located laser source. The energy is collected by a concentrating optical system and focussed into the thrust chamber, where the propellant matter breaks down and produces a high-temperature, high-pressure plasma. The expanding plasma exerts an impulse to the structure and pushes the vehicle in a pre-defined direction.

An important figure of merit for pulsed laser beam heated thrusters is the impulse coupling coefficient $c_m$. It is the ratio between the momentum transferred to the lightcraft $m_L \cdot v_L$ and the incident laser energy E and is of fundamental importance for the scaling of the propulsion properties of the lightcraft. $m_L$ and $v_L$ are the mass of the lightcraft and its velocity after one pulse. Practical units in the SI-system, as used throughout this paper, are $10^6$ Ns/J = 1 N/MW. If on-board stored propellant is used, the specific fuel consumption $\mu = m_e/E$ is another important parameter. Here, $m_e$ is the propellant mass exhausted per laser pulse of energy E. Practical units are $10^{-9}$ kg/J = 1 µg/J. By virtue of the balance of momentum $m_L \cdot v_L = m_e \cdot v_e$, the ratio $c_m/\mu$ yields the nozzle exhaust velocity $v_e$. For flights into the Earth orbit without staging exhaust velocities well above 5 km/s are required. Therefore, high fuel consumptions can only be tolerated if the coupling coefficient is equally high.

The US lightraft (USL) and the German lightcraft (GL) have the same diameter, but differ radically in their optical arrangement. The USL is of toroidal configuration with a parabolically shaped central spike that focuses the laser beam onto a ring at the outer shroud. It operates like a plug nozzle (Fig. 1a). The breakdown occurs along this focal line either in the surrounding air or on a ring of solid propellant. The GL is of bell shape also with a parabolic contour, however, with a focal point on the central axis. It resembles more a conventional nozzle (Fig. 1b). Propellant is also either the air inside the bell or solid propellant placed near the focal point. Since both lightcrafts are of the same size, it is of interest to directly compare their performance.

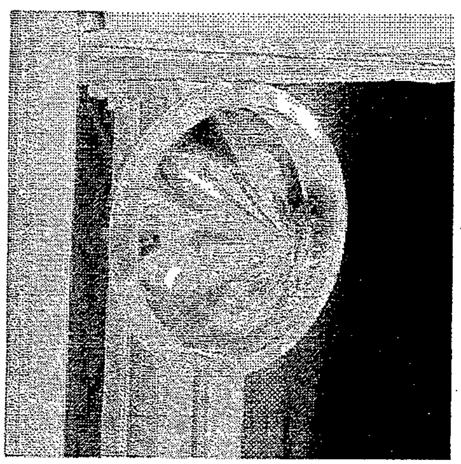

Fig. 1a US Lightcraft

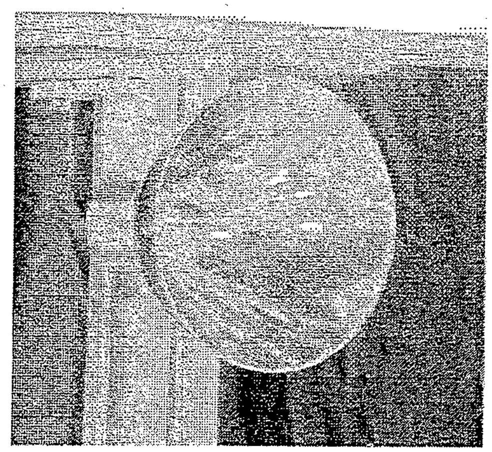

Fig. 1b German Lightcraft

The coupling coefficient is usually measured for a single laser pulse with a pendulum. The AFRL uses a rigid pendulum with non-neglible mass of the pendulum structure. For a horizontal suspension of the lightcraft a counter-weight to the lightcraft is necessary. The German pendulum consists only of the lightcraft and very thin suspension strings. It was of interest to compare the results from the two penduli setups under equal conditions.

The German pulsed multi-spectral laser allows power coupling by either a stable resonator, producing a near-top hat beam profile of 80 mm in diameter at the resonator exit, or with an unstable resonator. A better utilization of the active medium with the unstable resonator makes higher laser powers possible. The near field mode pattern is a rectangular frame with 100 x 130 mm outer dimensions and 60 x 90 mm inner dimensions. Unstable resonators allow a high focal concentration. In a first campaign for both lightcrafts* the coupling coefficient in

* This part of the research has been kindly supported by contract through AFRL/EOARD

air at local atmospheric pressure has been determined with both penduli, both resonator configurations, and with and without additional solid propellant (Delrin) as a function of the laser pulse energy. In a second campaign, the GL was suspended in a vacuum chamber (Fig. 2) and all tests with the stable resonator have been repeated at various pressure levels, including vacuum at $p < 1$ mbar. These measurements are relevant for the flight transition from the atmosphere to the vacuum in space.

**2. Experimental conditions**

As laser source the DLR multi-spectral laser was used, operating on the $CO_2$ 10.6 µm wavelength with pulses of 12 µs duration[7]. The pulse energy could be adjusted from 80 J to 310 J for the stable resonator configuration and between 100 J and 410 J for the unstable resonator configuration. During campaign 1 the laser energy has been monitored online by reflecting 3.4% of the energy from a KCl wedge surface onto a calibrated power meter. The fine alignment of the lightcraft was done by adjustment to burn patterns on paper. By the time the KCl wedge suffered under the pulse peaks. In the second campaign radiation escaping from a small hole in the total reflector of the resonator was utilized for the online power monitoring. This radiation was calibrated to the directly coupled beam energy via the KCl wedge. A concave copper mirror with a radius of 10 m was employed to reduce the beam diameter to the diameter of the receiving mirror of the two lightcrafts. In this case the incident beam was slightly convergent.

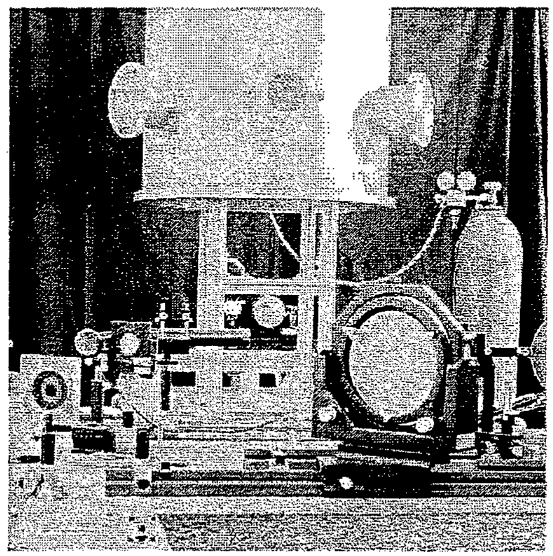

Fig. 2 Lightcraft vacuum test stand, opened

The pendulum displacement of the US pendulum has been measured by a digital rotational position sensor with a resolution of 10.000 digits per 360°. The initial velocity at the rest point can be derived from the maximum displacement. For the German pendulum a diode based laser distance measuring system with a position resolution of 0.1 mm has been applied. The diode laser beam was reflected from a reflective sheet on the rear of the lightcraft back to the system. All data, including the pulse energy, were sent to a PC that directly determined the coupling coefficient.

For the determination of the ablated or evaporated mass of the solid fuel, the Delrin ring for the USL or a Delrin pin for the GL were weighed on a precision scale (accuracy ± 0.15 mg) before and after the acceptance of 3 pulses of equal energy. Every data point has been repeated at least 3 times and seemingly dubious series a second time.

The vacuum vessel for the measurements at reduced pressure has an inner diameter of 800 mm and a height of 1150 mm. It is equipped with a KCl window of 140 mm diameter through which the laser power pulse enters the vessel and a second, smaller window on the rear for transmitting the diode laser beam. The pressure was read manually from two manometers with range 0 – 1000 mbar and 0 – 130 mbar. The pendulum length in the vessel was 645 mm.

Fig. 2 shows the opened vessel with the GL in place. The large mirror in the foreground is the bending mirror for the laser beam, coming from the right.

## 3. Results of campaign 1

Experiments in this campaign were devoted to accommodate differences from the two measurement approaches and to compare the influence of two basic laser beam distributions of a stable and an unstable resonator. Furthermore, fundamental performance differences between the two lightcraft geometries were of interest.

### 3.1 Comparison of the pendulum results

It was observed that the results for the USL coincide to within experimental error for both penduli in connection with the unstable resonator, but came out slightly higher with the stable resonator. For the GL the results derived from the US pendulum measurements were always substantially higher (~13 %) than those derived from the German pendulum. This difference can be explained in part from the properties of the pendulum structure of the US pendulum, which has a non-negligible mass of the pendulum structure itself. The discrepancy increases linearly with the fraction of the pendulum mass to the total mass. This fraction is smaller for the USL because a counter-weight is added to the lightcraft weight, as mentioned above. It is believed that due to the more ideal configuration the German pendulum gives the more correct results.

### 3.2 The coupling coefficient for the USL

Fig. 3a shows the measured lightcraft impulse as a function of the laser pulse energy. The resonator for these measurements was of the unstable type. Two cases are shown: Operation in ambient air with and without Delrin as solid propellant. The impulse increases nearly linearly with the applied pulse energy. However, the impulses with Delrin as an additional propellant are two and half times higher than with just air. For each propellant case two experimental series were run: In the case without Delrin the mass of the lightcraft was almost doubled in the second series to check its influence on the experimental result. It turned out to be insignificant. In the case with added Delrin the experimental series was also repeated, because the first series showed too large a scatter in the data. The scattering is apparently due

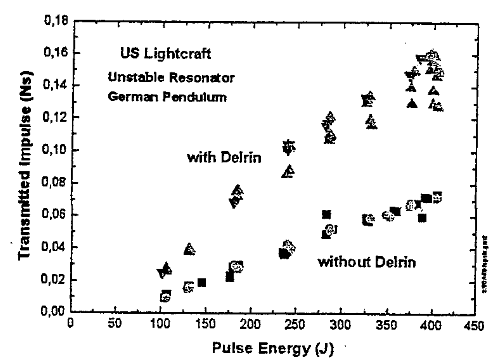


Fig.3a Transmitted Impuls<sup></sup>e to US Lightcraft with and without Delrin as propellant

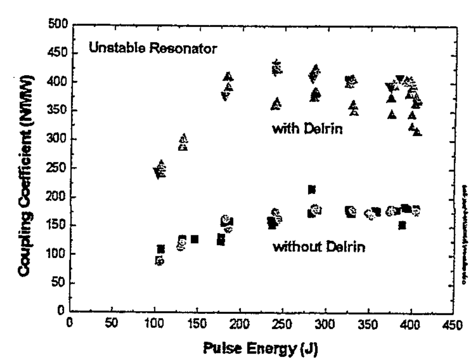


Fig.3b Coupling Coefficient for US Lightcraft, as in Fig. 3a

to the different state of ablation of the material. It was observed that after an extended time of operation the Delrin ring shows a narrow groove along its circumference that may change the ablation and plasma expansion process. Dividing the impulse by its respective energy value of the laser pulse yields the coupling coefficient (Fig. 3b). The coupling coefficients found with air alone are limited to values below 200 N/MW. In the case of the stable resonator even lower values were measured with a very high spread at the higher pulse energies only. At lower energies no regular breakdown is observed. In this case the intensity at the long focal line is insufficient to guarantee a homogenous breakdown along the circumference of the line. Much better data were obtained with Delrin as additional propellant. With the unstable resonator reproducible peak values of 430 N/MW have been found at a pulse energy of 250 J. There appears a roll-over of the coupling coefficient for even higher pulse energies. However, it should be kept in mind that this is not equivalent to a simultaneous reduction of the momentum imparted on the lightcraft. The momentum still increases with energy, as seen in Fig. 3a, only at a lower rate. — period

The functional dependence of the coupling coefficient with the pulse energy differs for the stable resonator beam (Fig. 4). In this case a continuous rise with the energy over the whole experimental range can be observed. It starts with approximately 175 N/MW at 80 J and grows linearly to about 280 N/MW at 175 J. Then, it continues to grow at a reduced rate to 380 N/MW at the maximum energy of 310 J. Therefore, we can expect that higher pulse energies will result in even higher coupling coefficients. The lower values for the stable resonator may originate from the lower intensities on the target surface as a result of the larger focal diameter for this laser beam.

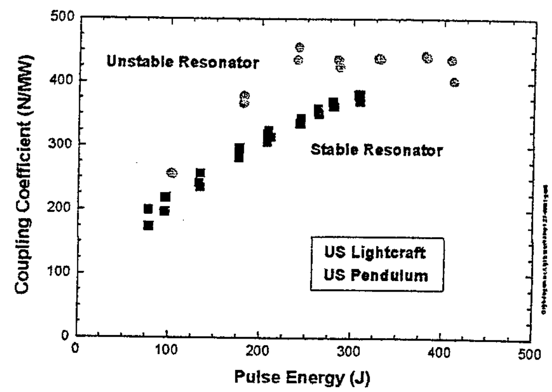

Fig. 4 Comparison stable vs. unstable resonator for the US Lightcraft

3.3 The coupling coefficient for the GL

The coupling coefficient for the German lightcraft in both resonator configurations is shown in Fig. 5. In this campaign the GL has only been operated without additional solid fuel. The $c_m$-values in this case are much higher than for the USL. At an energy of 60 J they start with 250 N/MW with a large spread of ± 15 % and climb more or less linearly to 320 N/MW ± 8 %. This is not surprising, since all incoming energy is concentrated at one spot and the breakdown in air is supported by a metal needle (1.6 mm diameter) extending from the apex of the parabolic shell beyond the focal point at 10 mm distance. (Beside the function to support the breakdown in air it served later as the fixture for Delrin cylinders in experiments, where Delrin was used as additional

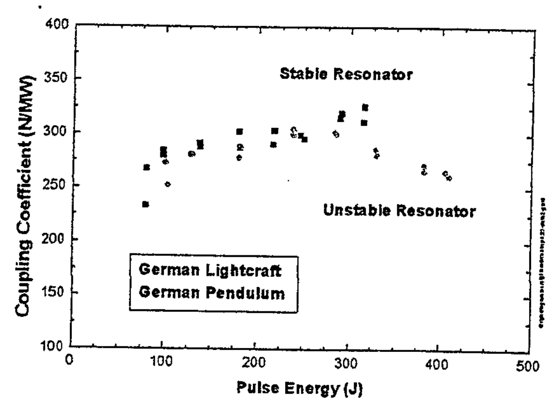

Fig. 5 Comparison stable vs. unstable resonator for the German Lightcraft

propellant.) On the other hand, the rate of increase of the coupling coefficient for the stable resonator configuration is much smaller than in the corresponding situation for the USL with Delrin.

sentence structure

The GL performs also differently with the laser beam from the unstable resonator. While the rise of $c_m$ at energies below 250 J is similar to that with the stable resonator, it inverts its sign after a maximum of 300 N/MW and drops again to 260 N/MW at 410 J. This drop is strong enough that the rate of increase of the momentum dI/dE drops by 40%.

If, inspite the different propellants, the GL with air only is compared to the USL with both Delrin and the surrounding air it is found that the higher concentration of energy in the GL produces higher enthalpies in the plasma and thus higher impulses. In the case of the stable resonator the coupling coefficient for the USL with additional Delrin surpasses that of the GL only for pulse energies in excess of 200 to 250 J. Apparently, the additional mass of the solid fuel is necessary to compensate for the lower plasma enthalpy and thus the lower exhaust velocity. The situation is different for the laser beam from the unstable resonator. While $c_m$ seems to saturate for the USL close to 450 N/MW, it decreases for the GL to only two thirds at the highest accessible pulse energy. For the GL the expenditure of energy does not result in an increase of useful enthalpy.

## 4. Results of campaign 2

During the operation of the USL it was observed that a chemical reaction between the evaporated Delrin and the surrounding air takes place and produces a flame. This raises the question about the effect of a release of chemical energy in addition to the energy supplied by the laser beam. While the performance of a lightcraft operated in air in terms of produced momentum is of significance for saving fuel weight during the flight through the atmosphere, it is irrelevant for the flight in space, which is the major part during the ascent to orbital altitudes. Or, the additional momentum from the exhausted air may be used to compensate the air drag, that increases with the square of the flight velocity and becomes particularly high in the vicinity of the sonic transition. It is very difficult to predict a priori the influence of reduced pressure on the performance of the lightcraft because of counter-acting processes: reduced exhausted mass vs. higher expansion velocity. The experiments of campaign 2 were dedicated to shed some light into these situations.

Only experiments with the GL have been performed in the vessel using the superior stable resonator configuration. During the experiments it was of course inevitable to supply the GL also with solid Delrin fuel, since at zero pressure it is the only mass that can be exhausted. This has been done by inserting small Delrin cylinders on the ignition needle. Three cases have been investigated: 1. A Delrin cylinder of 15 mm x 8 mm ∅ with a focal intensity distribution around the circumference of the cylinder; 2. a similar Delrin cylinder with 10 mm ∅, having a somewhat lower intensity; and finally 3. a short cylinder of 8.5 mm x 8 mm ∅ with the focal spot on the cylinder front side.

The utilization of a vessel allowed a change in the composition of the surrounding atmosphere. In particular, the exclusion of oxygen by using a nitrogen atmosphere could answer the question of the chemical part of energy production in the fuel.

After all, the simultaneous observation of the mass consumption during the tests made it possible to determine the (average) exhaust velocity during the pulse. With air only this is virtually impossible, because the exhausted fraction of the air is unknown. In cases with

Delrin estimates become possible under certain assumptions. The derived exhaust velocity can be compared to the necessary value for orbital flights.

### 4.1 Operation in air at reduced pressures

Fig. 6 shows the coupling coefficient for four selected pulse energies as a function of the surrounding pressure. No additional propellant was used in these experiments. For the applied lower pulse energies the coupling coefficient increases to a maximum around 260 N/MW at pressures between 200 and 400 mbar. This maximum is only slightly surpassed at the higher pulse energies. The imparted absolute momentum increases proportional to the pulse energy, but becomes nearly independent of the pressure above a certain level. Below this pressure level the momentum and hence the coupling coefficient drops more or less rapidly towards zero, as less air is available for the propulsion. The pressure, where the momentum begins to drop, is a function of the laser pulse energy. At the higher energies the reduction sets in with pressures below 500 mbar, while for the lowest applied energy it is delayed down to 200 mbars. Because of this delay the coupling coefficient remains higher on the low pressure side for the lower pulse energies.

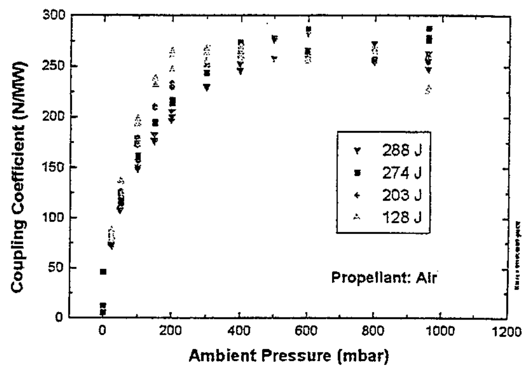


Fig.6 Coupling Coefficient in air at reduced pressure and for different pulse energies

The amount of gas in the thrust chamber can apparently be increased until the available pulse energy is capable to raise all gas to a certain energetic level. More gas (at a higher pressure) can attain the same energetic level only, if the pulse energy is increased simultaneously. Whether this process can be continued to atmospheric pressure can only be decided for even higher pulse energies that are not available at present.

### 4.2 Operation with Delrin in air and nitrogen at reduced pressures

For a pulse energy of 252 J the same procedure was repeated with Delrin as additional solid propellant. A Delrin pin of 15 x 8 mm ∅ was used for these experiments. The result is shown in Fig. 7 and compared with the previous results in air alone. At pressure zero (and 50 mbar) the Delrin vaporization accounts for a coupling coefficient in the range of 180 – 270 N/MW. The number of shots on the Delrin pin is part of the origin for the large scatter in the data. As air is added, the coupling coefficient rises faster than the comparable curve with air lone. About 525 N/MW were obtained at atmospheric pressure. alone

The continuous and stronger rise of the curve with Delrin in air compared to air alone nurished the suspicion that a chemical reaction between Delrin vapor and oxygen might contribute to the energy deposition. This was proven by exchanging the air in the vessel for nitrogen from a bottle. The result is also shown in Fig. 7. Now, the momentum curve with Delrin is displaced by a constant factor from the curve with air alone. This displacement factor is the impulse part of Delrin vapour that adds to the part of the surrounding gas.

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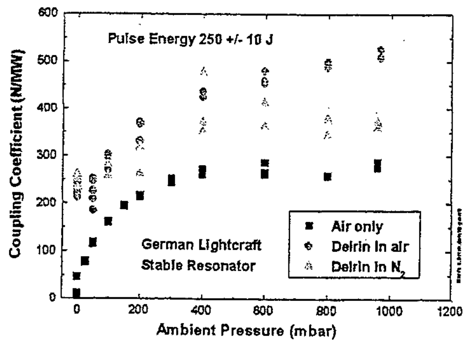


Fig. 7 Coupling coefficient vs ambient pressure for different conditions

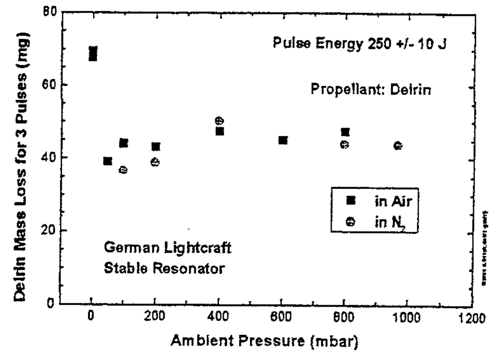


Fig. 8 Delrin mass loss vs ambient pressure

The lost Delrin mass after every three shots at the same condition was determined by weighing. Then a new pin was inserted for the next pulse condition. It was observed that statistically the second shot on a new target produced the highest impuls and further shots led to a subsequent decrease until the pin was destroyed by fracturing. The result of the mass loss in an environment of air and of nitrogen for the same experimental series as in Fig. 7 is shown in Fig. 8. Except for pressure zero the mass loss was independent of the gas pressure and the gas composition. (The reason for the higher value at pressure zero is unknown.) This finding supports the assumption that a chemical reaction between the Delrin vapour and oxygen is the source of the higher momentum in high pressure air.

4.3 Influence of the focal condition on the performance

Fig. 9 compares the the coupling coefficients for different operational conditions and for various pulse energies. The highest curve in Fig. 9 shows that the coupling coefficient with a Delrin pin of 8 mm diameter at atmospheric pressure actually attains its highest value ( ~ 650 N/MW; absolute maximum measured) at the lowest pulse energy and drops with increasing energy. Again, this does not mean that the absolute momentum imparted to the lightcraft does fall in the same way. It actually increases by 60% over the same energy range. A similar drop is observed under vacuum conditions for a however starting at 400 N/MW.

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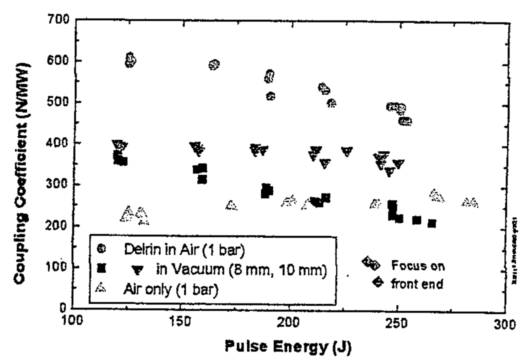


Fig. 9 Coupling coefficient vs pulse energy for various operational conditions

The reduction in the coupling coefficient at higher pulse energies may be explained by a shielding effect due to plasma absorption at too high a laser intensity on the Delrin surface. A lower intensity at the same pulse energy should then lead to a better coupling. This was tested using a pin with dimensions 16 x 10 mm ∅. Due to an approximate calculation the intensity at the surface should be reduced by 35%. Fig. 9 shows that this prediction was indeed correct. Slightly higher values were obtained at the low energy end and only a very weak drop is observed for increasing pulse energy. In contrast to the thinner pin more mass is evaporated from the Delrin surface, increasing by over 75 % over the energy range (Fig. 10). Therefore, the increase in momentum is directly coupled to the exhausted mass.

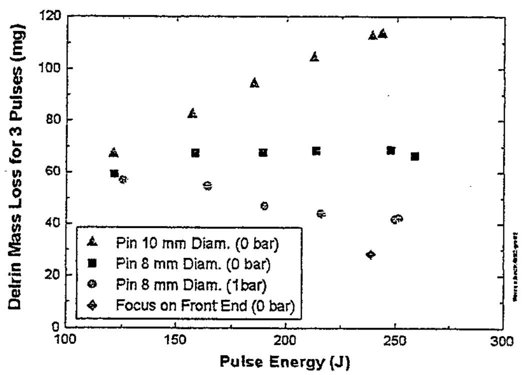


Fig. 10 Delrin mass loss vs. pulse energy for different operational conditions

The opposite case was tested by using a Delrin pin of only 8.5 mm length. The focal area is now on the front end of the pin and has about a ten times higher intensity than on the side wall of the cylinder. The coupling coefficient barely attained 100 N/MW. Because of the low performance this test was only performed at an energy of 240 J. The experiment with a focus on the front end also served another investigation: In the case with the focus on the side wall the evaporated material at first predominantly expands in the radial direction, perpendicular to the anticipated thrust vector. A gasdynamic effect is then required to turn the exhaust direction and produce the thrust. If the focus is placed on the front side then the evaporated or ablated material can produce the thrust directly (as suggested in ref. 9) and a better efficiency might be obtainable. This could not be demonstrated in the experiment. However, the impulse was strong enough to press the Delrin pin so strongly on the holding needle that it was difficult to remove it. Furthermore, Delrin is a plastic material and it is conceivable that a significant fraction of the impulse is translated into plastic deformation of the pin.

4.4 Exhaust velocity and jet efficiency

Calculation of

The knowledge of the coupling coefficient and the exhausted mass allows to calculate the exhaust velocity directly. In vacuum the exhaust velocity amounts to 2.25 km/s at the low energy level and is nearly independent for the 8 mm ∅ pin. For the 10 mm ∅ pin it increases to 2.6 km/s at the higher pulse energies (Fig. 11). It is interesting to note that the front end evaporation leads within the experimental error to the same velocity value. These values are only correct under vacuum conditions. As soon as air is exhausted additionally, the velocity changes. Since the amount of air is unknown, it is not possible to calculate the real velocity. However, for a rough idea it may be assumed that the efficiency of the energy deposition in the propellant is independent of its composition. In this case, the momentum and the energy balance equations can be

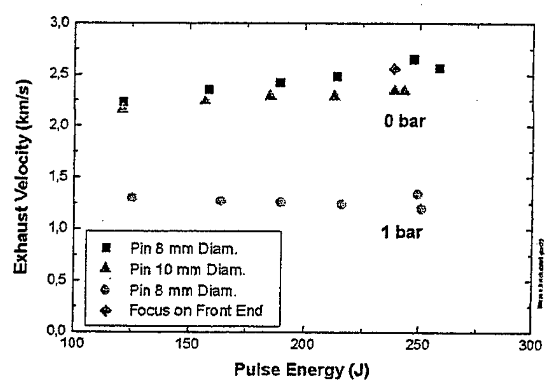


Fig. 11 Average exhaust velocity vs. pulse energy for different operational conditions

solved to yield the common velocity and the fraction of air mass. The result for the 8 mm ∅ pin in atmosphere is also shown in Fig. 11. The exhaust velocity is reduced to approximately 1.3 km/s independent of the deposited pulse energy. As the surrounding pressure is increased from 0 to 1000 mbar the amount of exhausted air mass grows from 0 to 3.7 times the mass of exhausted Delrin. However, as the pressure grows the Delrin combustion effect certainly effects this result. It is therefore more appropriate to look at this number in a nitrogen environment. It is found that the ratio of nitrogen mass to delrin mass has a maximum of 2.1 around 400 to 600 mbar and then drops to 1.6 at 1000 mbar. Consequently, the exhaust velocity has a minimum of 1.4 km/s and then increases above 1.5 km/s.

Knowing the exhaust velocity, the jet efficiency can be calculated as well. It is the ratio of kinetic energy of the exhaust jet $m_e \cdot v_e^2/2$ and the laser pulse energy E. This efficiency varies between 0.35 and 0.4. The remainder of the pulse energy is obviously lost in radiation, heat transfer to the chamber walls, absorption in the mirror surface, deformation work and other possible mechanisms.

## 5. Conclusions

Quite a few conclusions can be drawn from the sum of the experimental series:

- If a rigid pendulum with non-negligible mass is to be used, a correction factor depending on the mass ratio should be applied.
- The operation in air alone requires a much higher intensity than the combination with a solid fuel. The bell shaped thruster geometry with a focal point appears more appropriate for this task. The breakdown in such an arrangement can be supported by a metal needle extending to the focal point.
- The bell shaped nozzle also allows a more efficient use of the air than the open plug type nozzle, because of a better gasdynamic control of the expanding gas.
- As has already been demonstrated in ref. 7 the properties of the laser beam, in particular the beam quality, are of great importance for the performance characteristics of the lightcraft.
- For the applied laser pulse energies below 300 J, $c_m$ did not suffer from a pressure reduction down to at least 500 mbar. Higher pulse energies should be tested, however, to find out if this pressure limit goes further up with higher energies.
  If a reduction in $c_m$ by 1/3 to ½ is admitted, propelled altitudes as high as 20 km can be reached without additional propellant. There is no need for a balloon launch, as suggested for instance by Phipps et al.[9]. This is an important result, since the transition through the atmosphere is very mass consuming otherwise, because of the air drag. A better adaption of the nozzle geometry to this operation mode may even improve the transmitted impulse[10].
- Release of chemical energy can greatly improve the coupling coefficient. It should therefore be considered to operate a hybrid lightcraft. Experiments pointing in this direction have already been published by Liukonen[11].
- In our experiments the pulse shape was not matched to the propellant. It was obviously too long and a significant part of the energy was absorbed in the plasma without contributing to the thrust process. Too high an intensity could partly be compensated by changes in the Delrin pin geometry. On the other hand, more mass is then vaporized. This increases the specific mass consumption and does not lead to a higher exhaust velocity. Other fuels with a higher ablation power are necessary, that hopefully turn the power into a higher velocity of a smaller mass fraction. Laboratory tests of this kind will be difficult, because of the possibility of depositions of the fuel on the window of the vessel. In this respect Delrin was ideal.

- A direct thrust effect from ablation could not be demonstrated in our experimental arrangement, for most part due to the unmatched intensity on the front side of the pin.
- The exhaust velocities of 2.5 km/s that have been derived for the vacuum case are much too low for a single stage to orbit flight. This too, will require other fuels.

~~Their~~ There remains interest in a number of additional experiments like such as, for instance, the comparison of the performance of the USL under reduced pressure conditions. Due to the different intensity level on the target ring a different behaviour is expected. The contour of the GL should be modified to increase the coupling in air. Other, more suitable propellants must be looked for and tested including such that will react chemically, if ignited by the laser beam. The laser pulse should be modified in length in both directions. It had already been demonstrated in ref. 7 that a shortening of the pulse could improve the coupling coefficient in air. Finally, higher laser pulse energies and other wavelengths are of interest as well.

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