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To: J. W. Ford

From: J. D. Myers and P. M. Brown

Subject: Thrust Producing Capability of Lasers

Reference: Memorandum, "The Further Study of the Interaction of High Power Density Laser Radiation and Stainless Steel," to P. Rosenthal from J.D. Myers, 11 March 1964, File: C27-004

Introduction

In the referenced memorandum, certain measurements were made which indicated that pressures caused by the rapid evaporation of material from the surface of a stainless steel plate were sufficient in magnitude, to cause displacement of the molten material underneath. The magnitude of the pressure was found to be about 500 atmospheres at power densities of 8000 kw/cm^2. This memorandum presents the results of an experiment designed to measure directly the thrust associated with this evaporation recoil pressure.

Experimental Procedure

It was decided that a simple experiment involving a focused laser beam and a ballistic pendulum would best illustrate the magnitude of the thrust. A suitable ballistic pendulum was constructed using a cylindrical section of carbon and some 12-micron-diameter nylon string. The pendulum was then situated so that the laser beam was focused on the carbon as shown in Figure 1.

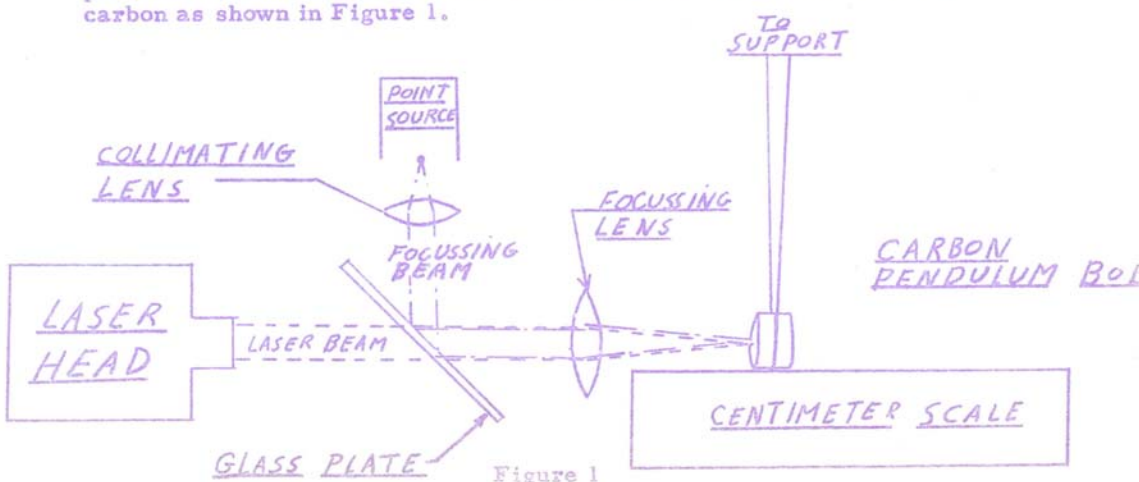

Figure 1

The movement of the pendulum was recorded on Polaroid film using a stroboscope for lighting. In this way, multiple images of the pendulum were obtained indicating the extent of the displacement. A measurement of the dampening of the pendulum due to air was also recorded on film in the same manner.

Analysis

Since, in this case, the pendulum is initially at rest and its mass remains essentially constant and can be assumed to be located entirely in the pendulum bob, the thrust is given by the following expression:

$$T = mv$$

where T = thrust
m = mass of pendulum bob
v = instantaneous change in velocity at equilibrium position

The velocity of the pendulum bob at the equilibrium position can be obtained from its displacement in the following manner:

For a pendulum, the kinetic energy at its equilibrium position is equal to its potential energy at maximum displacement.

Thus,

$$\frac{1}{2} mv^2 = mgh$$

or,

$$v^2 = 2gh$$

where g = acceleration due to gravity
h = vertical displacement of pendulum bob

Since the length of the pendulum is large compared to the displacement of the bob (30/1), we can use the following expression which relates the vertical displacement of the bob to its horizontal displacement.

$$h = \frac{d^2}{2r}$$

where h = vertical displacement
d = horizontal displacement
r = height of pendulum

Thus,

$$v^2 = \frac{g d^2}{r}$$

or,

$$v = \sqrt{\frac{g}{r}}\ d$$

and the thrust is given by:

$$T = \sqrt{\frac{g}{r}}\ md$$

A correction term (Δd) must be added to d to compensate for the energy dissipated by the pendulum due to air friction. In this experiment, the correction factor was determined by allowing the pendulum to swing through a measured displacement and recording the difference in the displacement each side of equilibrium position for one complete swing. The correction term is then taken as one-half of the difference. Thus, the final form for the thrust is as follows:

$$T = \sqrt{\frac{g}{r}}\ m(d + \Delta d)$$

Results

A total of seven different shots were recorded on film using approximately identical laser pulses. The displacements for these seven shots are given in Table I.

Table I

Shot No.	Displacement (cm)
1	2.3
2	2.4
3	3.0
4	2.0
5	2.2
6	1.9
7	2.2
	Ave. 2.3 cm

The following facts were noted:

1. A typical laser pulse is characterized by the parameters given below:

pulse length	—	800 μ sec
peak power	—	8 kw
total energy	—	3 joules
power density at focus	—	8000 kw/cm^2

2. The loss in mass of the pendulum during the experiment was small (0.2 mg) and can be neglected.

3. The correction term (Δd) was found to be 0.4 cm for pendulum swings comparable to the 2.2 cm displacement encountered in the experiment.

4. The length of the pendulum (r) is 77 cm.

5. The mass of the pendulum (m) is 63 mg.

Plugging these values into our expression for thrust, we have

$$T = \frac{980}{77} \quad (63 \times 10^{-3}) \cdot (2.2 + 0.2)$$

$$T = 0.54 \text{ dyne-sec}$$

or, since 1 dyne-sec = 2.25×10^{-6} lb-sec

$$T = 1.2 \mu\text{lb-sec}$$

The efficiency of this particular laser-pendulum material is not very good. The energy imparted to the pendulum bob is given by the following expression:

$$E = mgh = mg\frac{d^2}{2r}$$

Plugging in appropriate values, we find:

$$E = (63 \times 10^{-3})\,(980)\,\frac{(2.4)^2}{154}$$

$$E = 2.3 \text{ erg} = 2.3 \times 10^{-7} \text{ J}$$

Since three joules were available in the laser beam, this represents an efficiency of 10^{-7}.

A hint as to the means of increasing the energy transfer can be found in the expression for the evaporation recoil pressure in the referenced memorandum.

$$P \propto \frac{I}{\lambda}$$

where P = pressure
I = power density
λ = specific heat to vaporize

For carbon, $\lambda \cong 10^{13}$

By going to a steel pendulum ($\lambda \cong 10^{11}$), the pressure and therefore the thrust should be increased by an order of magnitude or more. Another factor which can be increased by better than an order of magnitude is power density (smaller spot size). Therefore, by proper choice of materials and power densities, the maximum thrust available from such a laser-material system as described here should be greater than 10^{-4} lb-sec.

Recommendations

The possibility of producing significant thrust using a laser beam has been demonstrated. Areas which must now be investigated include the following:

1. Experimental verification of the relationship between power density and thrust.

2. Experimental verification of the relationship between specific heat of vaporization and thrust.

3. Optimization of parameters to maximize thrust.

Recognizing that this phenomenon is relatively free of prior investigation at this time, it is felt that a significant advantage can be gained by this Laboratory if an effort is made now to pursue this subject to the fullest extent. It is proposed that such an effort begin with a systematic evaluation in the three areas mentioned above.

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