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H. Östmark[a]; R. Gräns[a]
[a] Swedish Defence Research Establishment, Stockholm, Sweden

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LASER IGNITION OF EXPLOSIVES: EFFECTS OF GAS PRESSURE ON THE THRESHOLD IGNITION ENERGY

H Östmark and R Gräns

Swedish Defence Research Establishment

S-10254 Stockholm, Sweden

ABSTRACT

This paper describes a method for measuring the effect of initial gas pressure and the type of gas on the threshold ignition energy of several high explosives. The method is based on a 300 W CW CO_2-laser. An extensive study of these parameters for PETN and RDX is also presented. These high explosives all show a strong decrease in ignition energy/power with increasing initial gas pressure. The gases tested are air and nitrogen. The studied pressures are in the interval 0.1 to 10 MPa. The ignitability of PETN and RDX was tested at a laser pulse width of 1.2 ms. All tested high explosives had a lower ignition energy/power in air than in nitrogen at low pressures (<2 MPa), whereas RDX and PETN had a lower ignition energy in nitrogen than in air at high pressures (>4 MPa). For TNT the time to ignition, measured as a function of air pressure, decreased with increasing pressure. These results are interpreted as a multiple phase ignition process. The method was also used for obtaining ignition data for TNT, Comp B-3 and Torpex.

INTRODUCTION

Laser ignition of explosives is a fairly new technique, about 25 years old. Its pioneers were Brich et al.[1,2], Menichelli and Yang[3]. Their work and most of the other work since then has dealt with the ignition of detonation in explosives. Only a few studies have dealt with the ignition of deflagrations.

The laser ignition method developed at the Swedish Defence Research Establishment has proved useful in the study of the ignition processes of pyrotechnical mixtures[4,5]. The application of this method to high explosives (HE) has shown that the energy necessary for ignition depends on the surrounding gas pressure[4]. A model for solid phase thermal ignition with no pressure dependent parameters has been proposed by Harrach[6]. Using this model we can conclude that the ignition process studied here is not solely a solid phase reaction but is in fact a complex process where gas, liquid and/or solid phase reactions are involved.

A FTIR study of the thermal decomposition of RDX has shown a pressure dependence of the thermolysis products[7]. Studies of pyrotechnics[8] and composite propellants[9,10] have shown that these exhibit a similar pressure dependence on the ignition parameters. The energy necessary for initiation of a detonation by laser light is reduced at least 40 times when a glass plate is placed in front of the HE sample[11]. This indicates a similar behaviour as for thermal ignition, i.e. vapour phase processes, for the laser initation of detonations. A theoretical model for this has been presented by Chernai[12].

The processes of ignition of high explosives have to be better understood both as a base for mathematical modelling, and for more practical purposes such as the construction of laser ignition systems. Hazard evaluation in practical

situations, such as the use of HE in high pressure environments (e.g., launching of shells where set-back ignition can occur[13]), also necessitates the understanding of their ignitability at high pressures.

This study has been undertaken in order to determine the influence of pressure on the ignition thresholds in order to achieve a better understanding of the basic thermal ignition processes. The parameters studied were ignition energy as a function of the surrounding pressure for RDX and PETN; and, for TNT, the time to ignition as a function of pressure. The influence of both nitrogen and air were studied. The method was also used for obtaining ignition data for TNT, Comp B-3 and Torpex, to be used in a model for set-back ignition[13].

EXPERIMENTAL

The experimental equipment, see Figure 1, consists of a 300 W CW CO_2-laser (Coherent CR41), a shutter for producing pulses in the interval 0.8 ms - CW, equipment for measuring the beam parameters and the laser energy / laser power, a photo diode (range 300-700 nm) for measuring the reaction light, and an explosive chamber. The laser beam had a Gaussian intensity distribution I(r), which, in the plane of the sample, can be measured with the following function:

$$I(r) = I_0 e^{-\frac{r^2}{w^2}}$$

The maximum intensity of the beam, I_0, is related to the total power, P, of the laser through the relation:

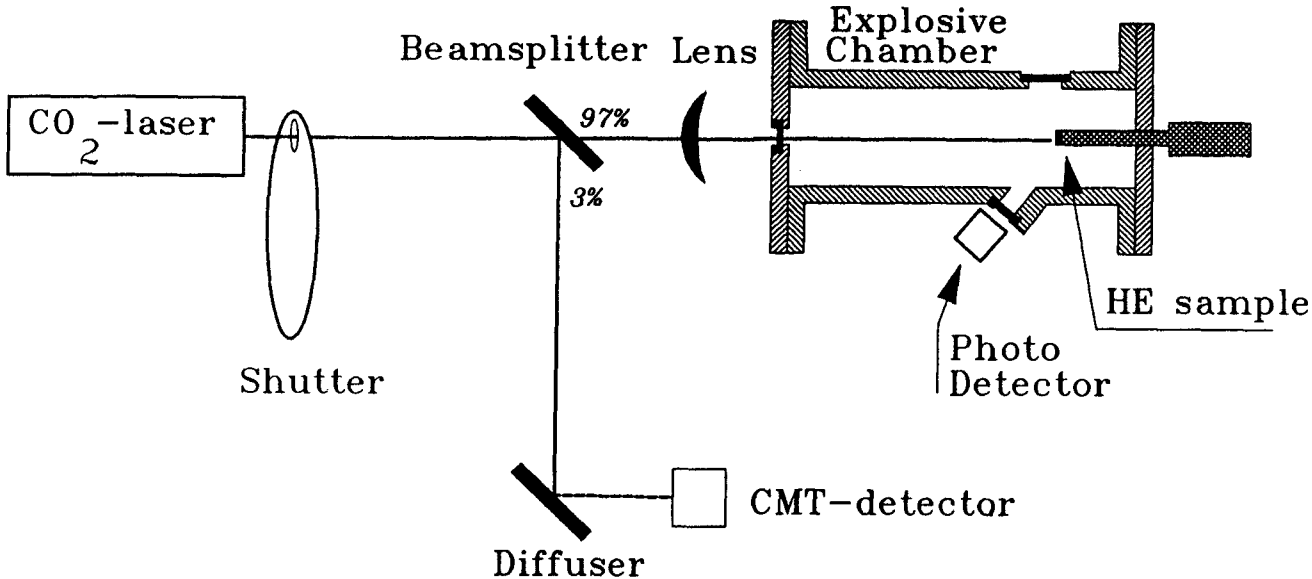

FIGURE 1.

Experimental setup.

$$I_0 = \frac{P}{\pi \omega^2}$$

By using the above formulas and measuring the beam radius, ω, and laser power, P, it is possible to obtain the laser beam intensity distribution in absolute units. The beam intensity distribution was measured with a Laser Beam Analyser (ALL GmbH LBA 1/A) and fitted to a Gaussian intensity distribution using the I_0 and ω as parameters. The laser power, P, was measured with a calorimetric power meter (Coherent Radiation 213). The laser pulse width, τ_p, was measured with a CMT detector. The laser fluence, ϵ, was calculated as $\epsilon = I_0 \tau_p$

The experimental setup is described in earlier works[4,5]. The main difference in this work is that a new explosive chamber, which can be used for an initial gas pressure of up to 10 MPa and has facilities for photographing and performing measurements in the reaction zone, has been developed. The HE samples had a size of 2 mm thickness by 10 mm in diameter. For RDX and PETN the sample was pressed to 95% of the theoretical maximum density (TMD). TNT, Comp B-3 (RDX/TNT 60/40) and Torpex (RDX/TNT/Al/wax 35/40/22/3) were cast to long cylinders and then cut to the desired size.

The measurements for PETN and RDX were conducted as up-and-down measurements (30 tests) by varying the laser fluence at a fixed laser pulse width (1.2 ms). The results from the up-and-down measurements were analysed with the ML14 computer code[14] in order to determine the mean and standard deviation of the ignition fluence. It proved very difficult to ignite TNT using the up-and-down technique. Instead the time to ignition as a function of pressure at constant laser power was measured, and this only in air. To get comparable

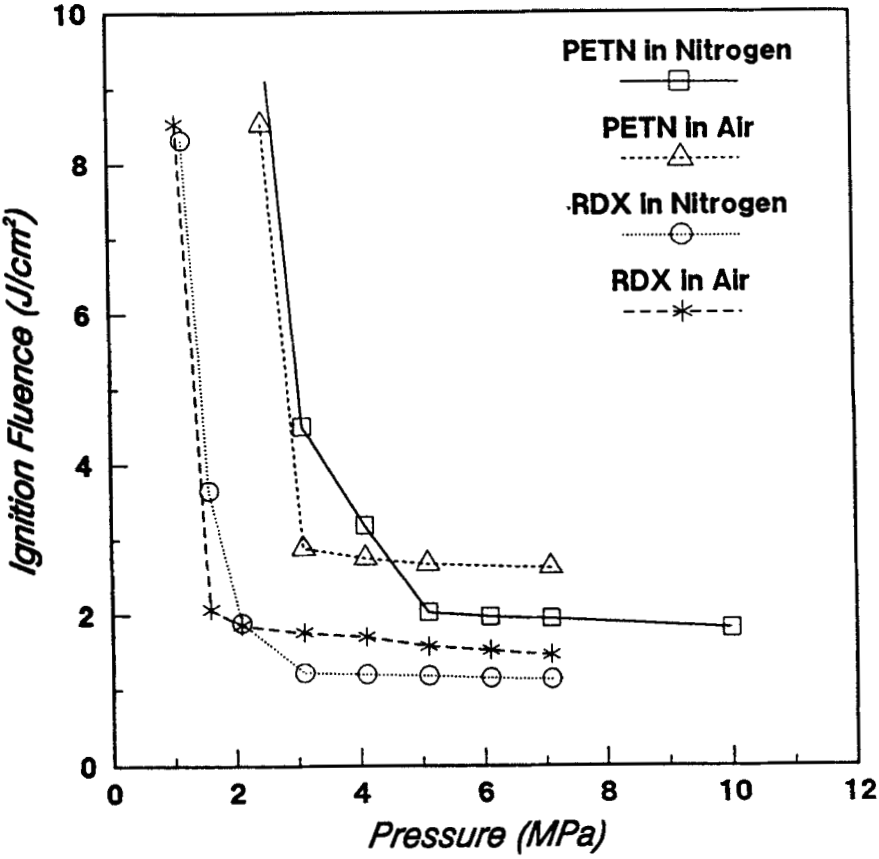

FIGURE 2.

Ignition fluence versus pressure for RDX and PETN.

data the same technique was used for Comp B-3 and Torpex. The time to ignition was measured with a photo diode (see Figure 1). Ten to twenty measurements were taken at each pressure setting, and the mean value and the 95% confidence interval were calculated.

The use of a carbon dioxide laser, which has a wavelength of 10.6 um (in the middle of the IR region), as an ignition source offers a possibility of starting a reaction purely thermally, thus avioding any chemical or mechanical disturbances. Some problems will occur when using a laser as ignition source: The sample has a finite absorptivity, which can be measured with an IR spectrophotometer. If the decomposition is large before the laser power ceases, it is possible that any gaseous decomposition products will absorb part of the energy. In our case this has been avoided, for the most part, either by using the laser in pulsed mode or by using a low laser power. This means that the time span during which gaseous products occur, mostly near the ignition point, is small compared to the total exposure time. The HE sample reflects some of the incident power, and the amount of reflected power may vary with time. For the results and discussion given in this paper we will assume a constant reflectivity coefficient. A technique for time resolved reflectivity measurements has been published by Holy[8].

RESULTS

The effect of pressure and type of gas on the threshold ignition energy for RDX and PETN was measured. The results are shown in Figure 2. The parameters for obtaining this data were as follows: Pulse width 1.2 ms, beam radius 0.98 mm, and an up-and-down series of 30 shots. The ignition energies given here are not corrected for the reflectivity of the HE, which may be estimated to about 0.7-0.8 (R = 0.71 for RDX at 10.6 um[15]).

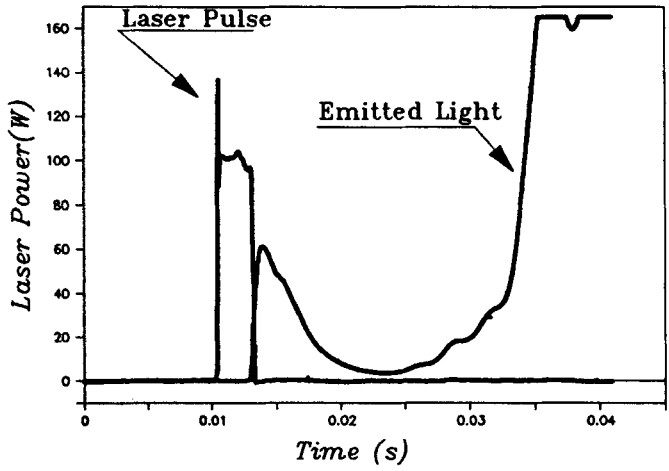

FIGURE 3.

Example of a registration in the low pressure regime (PETN at 2 MPa).

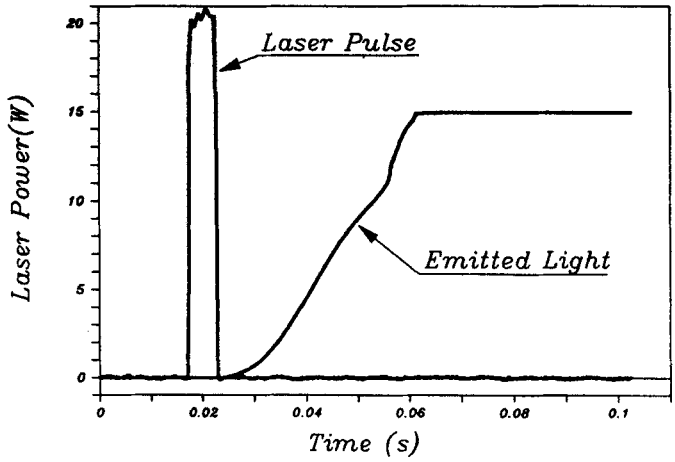

FIGURE 4.

Example of a registration in the high pressure regime (RDX at 3 MPa).

Representative examples of registrations from the ignition measurements on RDX and PETN are shown in Figures 3 & 4. In these figures the light emitted from the reaction is shown in arbitrary units. Figure 3 is for a low pressure, 2 MPa, and Figure 4 is for 3 MPa. In the low pressure regime the ignition is preceded by a light pulse due to a vapour phase reaction which is clearly observable with the naked eye as a luminous cloud ejected from the sample before the deflagration starts. The light emission behaviour is similar for RDX and PETN and the shift between the two modes for each HE occurs at the same pressure as that of the break in the curve of pressure dependence (Figure 2). By measuring the emitted light from different angles and by using an iris to measure the light emitted from a selected part of the reaction zone it was possible to show that the first light occured in the gas phase and that the strong light emitted later was from the solid surface. In the high pressure regime no signs of a pre-ignition light emission were found. The products occuring in the pre-ignition reaction zone have been analyzed with masspectrometer analyses[16]. These measurements have given evidence for both a gas phase reaction and liquid and/or solid phase reactions.

The data for the time to ignition for TNT, Comp B-3 and Torpex are given in Table 1. The uncertainty given is the 95% confidence interval for the mean value. Figure 5 shows the time to ignition measurements for TNT, Comp B-3 and Torpex in air. The measurement parameters were: Laser power 21 W, beam radius 0.5 mm. With our laser it was impossible to ignite TNT in a nitrogen atmosphere even at a power level of 200 W and a pressure of 5 MPa.

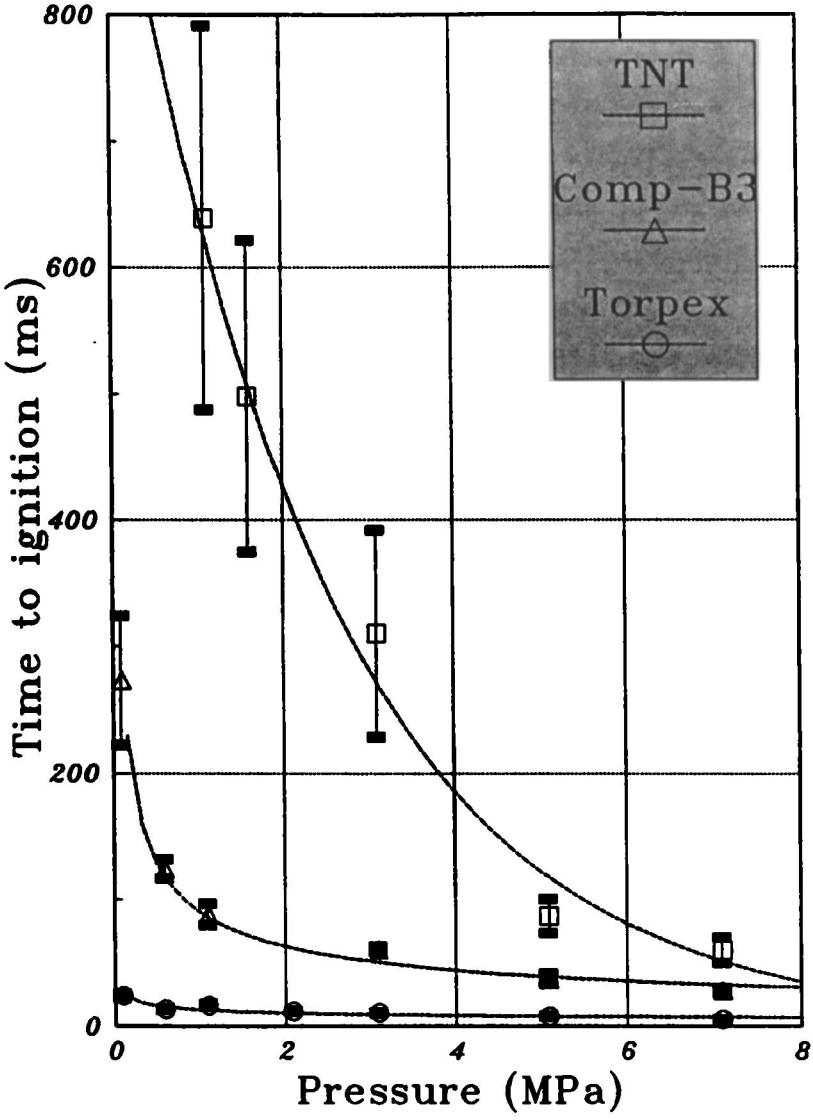

FIGURE 5.
Time to ignition versus air pressure for TNT, Comp-B3 and Torpex. Vertical bars indicate the 95% confidence interval. Laser power 21 W. Beam radius 0.5 mm.

TABLE 1.

Time to ignition versus pressure for TNT, Comp B-3 and Torpex. The values in brackets are the 95% confidence interval.

	Time to ignition (ms)		
Pressure (MPa)	TNT	Comp B-3	Torpex
0.1		273 (222-324)	23.7 (21.8-25.6)
0.6		124 (116-132)	13.5 (13.0-13.9)
1.1	639 (487-791)	87.9 (79.4-96-3)	
1.6	498 (374-621)		
2.1			11.8 (11.4-12.1)
3.1	310 (228-392)	60.1 (58.1-62.0)	10.4 (10.0-10.8)
5.1	86.7 (73.2-100.1)	37.3 (33.3-41.3)	8.0 (7.7-8.3)
7.1	59.8 (49.9-69.6)	28.0 (25.8-30.2)	5.3 (5.4-5.6)

DISCUSSION

The laser ignition method has proved very useful in the study of the effect of initial pressure and the type of gas on the ignition processes. Some distinct properties of the ignition processes are worth recognizing:

- The ignition energy/power decreases with increasing pressure.
- RDX and PETN have two distinct pressure regimes; one at low pressures (<2 MPa) where the ignition energy depends very strongly on the pressure, and one at high pressures (>3 MPa) where the ignition energy is only weakly dependent on the pressure.
- At low pressures (<2 MPa), RDX, PETN and TNT have lower ignition energies in air than in nitrogen.
- In the high pressure regime, RDX and PETN have lower ignition energies in nitrogen than in air.

Using the experimental observations above one can construct a mechanistic model for the multi-phase ignition. The condensed phase is heated by the laser beam and starts to vaporize or decompose to gaseous products (for RDX e.g. NO_2, NO, H_2CO, N_2O) which diffuse into the gas phase in front of the sample and begin to react. This reaction in turn gives energy feedback to the condensed phase and enhances decomposition. The presence of decomposition products in the gas phase has been shown by combining the laser ignition measurements with mass spectroscopy[16] and raman spectroscopy[17] studies of the pre-ignition reaction zone.

The mechanistic model outlined above explains the following behavior: At low pressure a strong pressure dependence exists due to the fact that the reaction

rate for a bimolecular reaction in gas phase is proportional to the pressure squared. At high pressure the gas phase reaction zone is collapsed onto the sample surface, possibly because the pressure is high enough to condense the decomposition products, and depends only weakly on the pressure. The model also explains why the ignition energy is lower in air than in nitrogen at low pressures, since all tested high explosives have a negative oxygen balance and thus get a higher energy contribution from the reaction with oxygen. The model does not, however, explain the lower ignition energy in nitrogen than in air at high pressures. The influence of different types of gas (N_2/O_2 and, preferably, He and Ar) on the ignition behaviour in the high pressure regime have to be studied more extensively before any definite conclusions can be drawn. This mechanistic model is being evaluated by further mass- and raman-spectrometric studies as well as high speed photograpy.

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