PRELIMINARY ONE-DIMENSIONAL INVESTIGATION OF THE INITIATION OF LOW-DENSITY PETN BY HYDROGEN-OXYGEN DETONATION WAVES

by

A. H. Makomaski

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SUMMARY

Various aspects of the problem of initiation of a uniform layer of PETN by head-on collisions of plane hydrogen-oxygen detonation waves are considered. It was found that low-density (1 gm/cc and 0.87 gm/cc) disc pressings of PETN 1.5 in. dia. x 0.15 in. thick consistently appeared to detonate when the initial pressure of the stoichiometric hydrogen-oxygen mixture was about 13 atm or more and the length of the detonation tube was approximately 4 in. Detonation of the PETN was inferred from the deformation of the steel containers which held the pressings rather than from a direct measurement of detonation velocity in the pressing. It was not possible to verify in these tests whether the detonations were of high order.
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NOTATION

\begin{align*}
a & \quad \text{sound speed} \\
D & \quad \text{detonation velocity} \\
m & \quad \text{molecular weight} \\
M_s & \quad \text{shock Mach number} \\
n & \quad \text{mole} \\
p & \quad \text{pressure} \\
 & \quad \text{gas constant per mole} \\
S & \quad \text{shock velocity} \\
T & \quad \text{temperature} \\
u & \quad \text{particle velocity} \\
v & \quad \text{specific volume} \\
 & \quad \text{density} \\
 & \quad \text{specific heat ratio} \\
\text{Subscripts} \\
d & \quad \text{detonation} \\
f & \quad \text{final} \\
i & \quad \text{initial} \\
s & \quad \text{shock} \\
\end{align*}

Subscripts (1) to (4) are defined in Fig. 1 and refer to the quasi-steady states in a shock tube flow. Other subscripts are defined elsewhere, as used.
1. INTRODUCTION

Chemical solid explosives are widely used for generating strong pressure waves (usually of destructive nature) in the surrounding media. The strength of such generated waves depends on the amount of chemical energy released in the explosive, the rapidity with which this energy is released, as well as the magnitude of pressure and the speed of sound in the detonation products. It is known that the time required for completion of 'high' explosive detonation in explosives of common dimensions is of the order of one microsecond, which compares favourably with other systems of rapid energy discharge. This behaviour of explosives is to be utilised to generate strong imploding shock waves in the UTIAS Implosion Driven Hypervelocity Launcher to create by wave shaping a quantity of compressed, hot gas capable of propelling light objects at hypervelocities (Ref. 1).

The usefulness of explosives as generators of shock waves of high Mach numbers derives from the fact that very high pressures (\( \sim 10^5 \) atm) and sound speeds are produced in the detonation products. For example consider the following equation applying to strong shock waves generated in a one-dimensional shock tube (Ref. 2) shown in Fig. 1

\[
M_s \approx \frac{\gamma_1 + 1}{\gamma_4 - 1} \frac{a_4}{a_1}
\]  

(1)

where

- \( M_s \) is the Mach number of the shock wave advancing into the gas initially in contact with the solid explosive (driven gas),
- \( \gamma_1 \) and \( \gamma_4 \) are the isentropic indices of the driven gas and the gaseous detonation products respectively,
- \( a_1 \) and \( a_4 \) are the speeds of sound in the driven gas and the gaseous detonation products respectively.

The importance of high speed of sound \( a_4 \) (and low \( \gamma_4 \)) in producing large \( M_s \) is evident from the equation.

Although the highly compressed detonation products have complicated equations of state, the relationship between pressure and density can be expressed by a gamma law (Ref. 3) with \( \gamma \) about 3 (which is of course rather high for shock-tube operations).

Consider PETN with the properties as given in Ref. 4 (Table IV).

\[
\rho_s = 1.00 \text{ gm/cc} \\
D = 5560 \text{ m/sec} \\
p_d = 73800 \text{ atm}
\]
The following relationships for $a_4$ and $p_4$ are used, following Ref. 5:

$$a_4 = \frac{1}{2} (3/2)^{1/2} D = 3405 \text{ m/sec}$$
$$p_4 = \frac{1}{2} p_d = 36900 \text{ atm}$$

$\gamma$, $a$ and $p$ of the driven gas must be known to complete the calculations.

The amount of compression which can be achieved by an imploding wave depends (in part) on the symmetry and uniformity of the initial shock wave formed in the vicinity of the explosive. It is clear that for optimum performance, the explosive must release its energy over its whole surface simultaneously. It is proposed therefore (Ref. 1) that a spherical symmetrical gaseous detonation wave be used to cause such simultaneous release of energy in the explosive as well as to preheat the combustible gases which are used for propelling the projectiles.

Consider therefore, the case of the generation of the shock wave into the products of detonation of a stoichiometric mixture of hydrogen and oxygen (in the actual launchings hydrogen - or helium-diluted mixtures will be used). For simplicity the final gaseous state as determined for the case of constant volume combustion will be used. Thus from Ref. 6 (Table I) for an initial pressure of 20 atm:

$$\gamma_1 = 1.197$$
$$a_1 = 1634.4 \text{ m/sec}$$
$$p_1 = 212.0 \text{ atm}$$
$$T_1 = 4053^0 \text{K}$$

The equation relating pressure ratio across the diaphragm and the pressure ratio across the shock is (Ref. 2),

$$\frac{p_4}{p_1} = \frac{p_2}{p_1} \left[ 1 - \frac{(\gamma_4 - 1)(a_1/a_4)(p_2/p_1 - 1)}{2\gamma_1 \sqrt{2\gamma_1 + (\gamma_1 + 1)(p_2/p_1 - 1)}} \right]^{\gamma_4 - 1} \quad (2)$$

Thus with $\gamma_4 = 3$, $a_4 = 3405 \text{ m/sec}$ and $p_4/p_1 = 36900/212 = 174$, Eq. (2) yields $p_2/p_1 = 4.64$. The corresponding temperature ratio is $T_2/T_1 = 1.39$, giving $p_2 = 985 \text{ atm}$ and $T_2 = 5632^0 \text{K}$. The corresponding shock velocity is 3405 m/sec and the particle velocity behind the shock is 2386 m/sec. Therefore even in a one-dimensional geometry very significant pressures and temperatures can be obtained. In the case of an imploding shock wave very much stronger shocks can be generated. This is discussed in detail in Ref. 1.

From the above it can be seen that solid explosives offer a powerful means to achieve the high-temperature, high-pressure conditions needed for hypervelocity research provided the explosive is initiated uniformly and achieves detonation almost instantly. As very little is known about the process of initiation proposed in Ref. 1, the present study was
undertaken with the object of investigating the feasibility of detonating solid explosives by gaseous detonation waves.

It is instructive to list the properties which were sought in the "ideal" explosive for use in the launcher.

1. The explosive should detonate to full ideal detonation velocity instantaneously upon impact of a gaseous detonation wave in a mixture of reasonable initial pressure (say $\geq 10$ atm.)

2. It should be safe to handle, insensitive to small jars such as those experienced in closing combustion chamber and should not detonate due to accidental exposure to a spark, a lighted cigarette etc. This requirement is particularly important as the UTIAS launcher is operated by graduate students with limited experience in handling explosives.

3. Preferably the layer of explosive should be capable of being cast safely (since a hemispherical liner is required). This may require an explosive of low melting point.

4. The explosive liner should have sufficient mechanical strength to maintain its shape while it is being placed in the combustion chamber and while the chamber is rotated into its firing position. (For the mechanical design of this chamber see Ref. 7).

5. The explosive liner should not detonate under the action of the hydrostatic pressure of the gaseous mixture introduced to the combustion chamber prior to its ignition.

6. The liner should be completely uniform in order to have the same initiation and detonation properties over its whole surface.

7. The explosive should be reasonably inexpensive and readily obtainable.

The field of explosives covers a variety of solid explosive materials possessing a wide range of sensitivities, chemical compositions and rates of reaction. They may be divided into two groups: (a) the detonating or 'high' explosives and (b) the deflagrating or 'low' explosives (Ref. 8). The detonating explosives have high rates of reaction hence very high pressures are generated. The deflagrating explosives have slow rates of reaction hence yield low pressures. The detonating explosives may further be subdivided into primary and secondary explosives. The former, mostly inorganic compounds, are very sensitive to impact and are usually employed in detonators. The secondary explosives are less sensitive to mechanical or heat impacts and are hence more practicable for use in larger quantities. The secondary explosives are normally ignited by detonators and often require boosters as well. Thus, broadly speaking, the primary explosives
are the type which can be detonated by a hot source, while the secondary explosives detonate as a result of a shock transmitted from another explosive (Ref. 9). The primary explosives have been rejected to date for the UTIAS launcher on the grounds of safety. The deflagrating explosives are also not suitable, as owing to their slow rates of reaction they would not provide sufficient amount of compression in the launching gas. The only suitable type is the secondary high explosive.

It is known that homogeneous explosives of normal density require a pressure pulse of upwards of 20 kbars for initiation. For example, cast 50/50 pentolite with a pressure pulse of 25 kbars will detonate within a distance of 20 to 25 mm from the initial boundary and with a pulse of 100 kbars, within about 4 mm (Ref. 10). Low density pressings require substantially lower pressures. The work of Seay and Seely (Ref. 11) shows that pressures as low as 2½ kbars are capable of initiating PETN of density 1 gm/cc. Since such pressures can be achieved during a head-on reflection of a detonation wave in a stoichiometric mixture of hydrogen and oxygen at an initial pressure of 50 atm (see Sec. 2), it was decided to use this explosive for the present investigation.

This report describes the experiments made in an apparatus of one-dimensional geometry. This geometry was chosen for the following reasons:

1. The amount of explosive required would be only 1/57 times that for the whole hemisphere (radius of hemisphere 4 in; diameter of flat disc 1½ in).

2. The analysis of the wave pattern is simpler.

3. Gaseous detonations can be achieved at the same distance from the ignition point at lower initial pressures and/or lower energies for ignition in a one-dimensional geometry than in a spherical geometry.

2. COMBUSTION OF HYDROGEN-OXYGEN MIXTURES IN A DETONATION TUBE

Before proceeding to the discussion of the initiation of low-density PETN, it is necessary to consider the combustion and hydrodynamic phenomena in the detonation tube. As far as this investigation is concerned the sole purpose of the gaseous combustion is to create a certain pressure history on the explosive surface. The intention is to control the gaseous combustion to achieve the pressure pulse required to initiate the explosive. As will be shown later, this initiation of a detonation in explosives is achieved by applying pressure at a certain minimum rate to reach or exceed a critical value for detonation. The relief of the pressure should also not be too rapid. (Ref. 12).
It is well known that rich mixtures of hydrogen and oxygen will detonate in a tube if ignited at one end provided a sufficient amount of energy is put in by the ignitor. After a short transition period a fully developed detonation wave is created at a certain distance from the point of ignition. This distance, called "detonation induction distance", depends mainly on the richness of the mixture, the initial loading pressure, the amount of energy given to the mixture in ignition and the tube diameter. This distance has been measured by several workers. Figure 2 summarizes the results from three different sources (Refs. 13, 14 and 15). The induction distances are measured in centimeters, initial pressure in atmospheres and richness of the mixture by the "dilution index" $V_i$, representing the number of additional moles of hydrogen for each mole of oxygen in the mixture, considered is $2H_2 + O_2 + V_i H_2$. As Fig. 2 is intended to give the general trend only, no corrections of any kind are attempted to allow for the other contributory factors. It is seen that for stoichiometric mixtures at pressures above 30 atm the detonation induction distance is practically zero.

The detonation characteristics of hydrogen-oxygen mixtures have been calculated by Bollinger and Edse (Ref. 16). Unfortunately, these calculations were made for a higher temperature (313.16°K) than is usually met in the laboratory. For this reason, in the calculations to follow, all the detonation properties (particularly pressures) will be somewhat underestimated. The relevant information is given in Tables II and III for four different initial pressures. Using these results it is now possible to estimate the pressure history at the end of the detonation tube. From Table III for higher pressures, the ratio of pressures across the detonation wave is about 20. On head-on reflection, the pressure is further increased by a factor of 2.5 (using $\gamma = 1.2$), yielding a ratio of 50 for the final to initial pressure. Thus with the initial pressure of, say 100 atm (maximum attainable using commercial gas bottles with regulators), the final instantaneous pressure on reflection is 5000 atm. In this simplified calculation we have assumed that the width of the reaction zone is zero. If the finite width of the reaction zone is taken into consideration then the ratio of the peak pressure to initial pressure will be larger (see Sec. 10).

Although the estimate is a pessimistic one, this approach is satisfactory since the detonability of the explosive will have to be found by experiment in any case. At high initial pressures the detonation induction distance is negligible. It is therefore in order to employ Taylor's model (Ref. 17), which assumes instantaneous creation of the detonation wave, to solve approximately the problem of the interaction of the reflected shock wave with the centred rarefaction wave, which is assumed to be attached to the detonation wave, in order to determine the pressure history on the explosive surface. This has been done assuming constant gamma of 1.2 in the interaction zone. The detonation wave characteristics used were those calculated by Bollinger and Edse (Ref. 16): velocity of detonation wave 3073 m/sec; speed of sound downstream of detonation wave 1683 m/sec; mixture $2H_2 + O_2$ at initial pressure of 100 atm and initial temperature of 313°K. This interaction is shown in Fig. 3. The derived pressure history
on the explosive surface (assumed rigid for this purpose) is shown in Fig. 4. It is seen that a pressure of 4 to 5 kilobars will exist in the explosive for several microseconds. If we consider the possibility of the reflection of the shock wave from the explosive/steel contact surface, the pressure will be even higher. It is reasonable to expect therefore, that a detonation wave in a stoichiometric mixture of hydrogen and oxygen will detonate low-density PETN with initial pressure of 100 atm. and possibly lower.

3. IGNITION OF SOLID EXPLOSIVES

The mechanism of ignition of homogeneous secondary explosives appears to be well understood. Most authors agree that detonation results from shock-heating of the explosive (Ref. 18). The mechanism for inhomogeneous explosives is much more complex. In addition to the heating effect due to the main shock wave, local hot spots are created as a result of shock interactions with the inhomogeneities. These hot spots are centres at which thermal decomposition starts hence energy released there, may reinforce the main shock to help cause detonation (Ref. 18).

The process of ignition and propagation of detonation is basically a heat balance problem in which the heat accumulated in the explosive is the result of chemical energy generated during the decomposition of the explosive minus the heat loss to the surroundings (Ref. 8). The rate at which heat is given off during chemical decomposition increases rapidly with temperature while the rate at which heat is lost increases with temperature but at a lower rate. It is clear therefore that as the explosive is heated, once the rate at which heat is given off by decomposition exceeds the rate at which the heat is lost to the surroundings, the process is self-accelerating until explosion occurs. This is true for any method of initial heating whether it be by shock-heating or gradual heating due to heat transferred to the unreacted explosive from the flame, as when the explosive is burning slowly. On decomposition, the gaseous products create pressure gradients the magnitude of which depends on the rate of decomposition. If this is sufficiently large (or there is a large increase in the burning area (Ref. 19) which will cause pressure to increase), then strong shock waves are propagated at the speed of sound relatively to the reacting gases (Chapman-Jouguet postulate). These shocks can be self-supporting if they heat the explosive to such an extent that an appreciable amount of chemical energy is released in the vicinity of the shock which energy is then used up to reinforce the shock. Such a steady-flow situation (with the coordinate system attached to the shock) is known as detonation. To initiate detonation it may be only necessary to initiate deflagration, if the mass of the explosive is large enough, and rely on the exothermicity of the process to achieve detonation. Usually, however, detonation is caused by the application of a strong shock wave originating from a primary explosive.

In the present application using secondary explosives, in which detonation is to be achieved within a distance of the order of several milli-
meters, initiation by shock-heating is considered. Since the shock in the explosive is transmitted as a result of the impact and reflection of a hydrogen-oxygen detonation wave, its magnitude (except for the initial fraction of a microsecond - Sec. 10) is in the present case limited to about 5 kilobars peak value as discussed in Sec. 2.

As already mentioned, the work of Seay and Seely (Ref. 11) shows that low density (1 gm/cc corresponding to 44 percent voids) PETN detonates with shocks of 2½ to 5 kilobars with the depth of initiation between 2 and 7 mm. In these experiments the arrangement was such that a plane shock wave followed by a constant-pressure region (for the duration of the experiment) was produced.

In the present experiments where the pressure is relieved immediately it reaches its peak, it may be necessary to reach higher peak pressures to achieve detonation than with a constant-pressure pulse. (See Refs. 20, 12 and 11 for discussions of pressure pulse requirements for detonation).

An enhancing effect is the confinement of the explosive disc except for the surface exposed to the gaseous detonation. This prevents rarefaction waves entering from the side of the reacting explosive (as they would in any unconfined charge) to decrease the rate of decomposition. In the present case the reflected shock wave from the explosive/steel backing interface can further increase the pressure and temperature and hence the rate of decomposition of the explosive.

Seay (Ref. 21) discusses the possible mechanism of detonation of low-density explosives. It is suggested that "the reaction might proceed in a fine powder formed by spalling or that this powder might initiate reaction on impact with the next grain". The alternative suggestion is that "material in jets resulting from shocked irregularities attains a very high temperature when stagnated against the next downstream grain". It is clear that whatever the mechanism of achieving it, high temperatures must be rapidly reached in one or more centers within the explosive.

4. PREVIOUS WORK ON IGNITION OF EXPLOSIVES IN DETONATION TUBES

Shock tubes (Refs. 22 and 23) and detonation tubes (Ref. 14) have been used in the past to initiate deflagration in solid propellants. From the open literature, it appears that only Andrew and Maslov have used a detonation tube to cause detonation of secondary explosives (Ref. 24). Their tube had a 38 mm bore and was 1 m long. The gaseous mixture of nearly stoichiometric composition (64% H₂, 33.5% O₂, 2.5% other gases) was ignited by the explosion of a crystal of lead azide. The explosive under investigation (0.35 gm) was placed at a distance of 90 cm from the point of ignition. Three explosives were tested: blasting gelatine, pentaerythrite-tetranitrate and picric acid. It was found that pentaerythrite-tetranitrate exploded at the pressure of 20 atm (cast explosive) and at 10 and 15 atm
(powdered explosive). Andreev and Maslov use the word "exploded" rather qualitatively, i.e., to indicate that the tube holding the charge was destroyed. It is not possible to determine from this description whether the detonation was of high-order or not.

Andreev and Maslov, referring to the hypothesis put forward by Andreev and Chariton (Ref. 25), explain the explosive initiation as the action of high energy particles obtaining in the detonation of the hydrogen-oxygen mixture. To initiate a self-propagating reaction, the concentration of these particles must exceed a certain minimum value, hence a certain minimum pressure of the gaseous mixture is required for the detonation of the explosive, as was verified experimentally.

The above results are indeed very promising as far as PETN is concerned. However, Andreev and Maslov used relatively small quantities of explosives (0.35 gm). Such quantities may be comparatively easy to handle and manufacture, and in particular the casting should present much less difficulty than do larger quantities. The problem therefore is still that of manufacture (either pressing or casting). The additional problem not encountered in Andreev and Maslov's work is the necessity to detonate gas mixtures over short distances (equal or less than the radius of the hemisphere (Ref. 7)). For these reasons the present work on PETN, considered as intermediate between the small scale tests and the full launcher project, was undertaken.

5. PROPERTIES OF PETN

Pentaerythritol tetranitrate has been widely studied. Reference 26 gives the methods of preparation and crystallization and discusses the various physical and chemical properties. This information will not be repeated here. Of greater interest are the detonation properties of PETN. Calculations of these properties have been done by a number of authors. The results can be found in Ref. 8 and 27. As an example the results of Paterson (Ref. 4) are reproduced in Table IV.

Paterson used the following equation of state for the product gases

\[ p_z V_z = n_z R T_z \left( 1 + \frac{b_1}{V_z} + 0.625 \frac{b_2}{V_z^2} + 0.287 \frac{b_3}{V_z^3} + 0.193 \frac{b_4}{V_z^4} \right) \]

(This equation defines the symbols used in Table IV. In addition

\[ K_z = 1 + n_z \frac{R}{C_z} - \frac{\alpha}{\alpha V_z} \]

where \( R \) is the gas constant, \( C_2 \) the specific heat at temperature \( T_2 \) and \( \alpha \) the covolume in the equation \( p_z (V_z - \alpha) = n_z R T_2 \).
The product composition was assumed to be independent of \( v_0 \), the initial specific volume. Reference 4 contains defects of the method of calculation. Table IV shows clearly the strong dependence of the detonation velocity and pressure on the loading density of the explosive. It appears that by suitable selection of the loading density an optimum compromise may be attained between the desire to have the maximum detonation pressure (or velocity) to achieve a maximum compressive effect in the launching gas and the necessity to minimize the loading on the combustion chamber walls to prolong its life.

It is also interesting to compare the composition of products of reaction for three modes of combustion: detonation, impact and decomposition. This comparison is given in Table V which shows a wide variation of products depending on the particular combustion mode. The decomposition products are also given by Rideal and Robertson (Ref. 29).

6. EXPERIMENTAL TECHNIQUES

The apparatus which is shown in Figs. 5 to 7 allows explosive samples (weight up to about 7 gm) in the shape of a disc of \( 1\frac{1}{2} \) in. dia. to be exposed to head-on impact of a gaseous detonation wave developed in a \( 1\frac{1}{2} \) in. x 4 in. long chamber. The initial pressure of up to 100 atm can be used. Initially a quantitative method of detection of detonation was tried using a pressure gauge with a ballistic adapter (following the experience with shock tubes at UTIAS) situated near the explosive sample. Unfortunately, due to seizing of the piston and electrical interference from the exploding wires, this method was found unsatisfactory. Since a limited time was available for these tests (the gas loading system and firing unit used were those of the UTIAS launcher and could be used only when the launcher was not operated), it was decided to limit the experimental work to the observation of the condition of the explosive container in contact with the explosive. This investigation is described in Secs. 8 and 9.

6.1 Combustion Chamber

A cross-section of the combustion chamber is shown in Fig. 5. It consists of three parts held together with six 2 inch diameter Holo Krome bolts. The center block which contains the \( 1\frac{1}{2} \) in. dia. chamber cavity, 4 in. long, carries all the instrumentation. A general view of the apparatus is shown in Fig. 6. The disc of explosive (see the Appendices for the method of preparation) is placed in an expendable steel container attached by a stud to the left-hand end plate (Fig. 7). The gas mixture is ignited by exploding wires at the right-hand end plate (on Fig. 5). Stations 1, 2 and 3 (Fig. 5) can be used for probes such as ionization or luminous flux gauges. Also stations 1 and 2 (in different circumferential positions) were specially designed to accommodate Kistler 635B pressure adaptors. The distance between the stations is \( 1\frac{1}{2} \) in.
The explosive container carries an O-ring with 2 back-up rings. A second, larger diameter O-ring is incorporated between the end plates and the centre block. Following the experience of Ref. 30 the grooves for these O-rings are partly in the block and partly in the end plates. These O-rings are backed-up by stainless steel rings.

The right-hand plate (Fig. 5) carries the high-voltage electrode in its centre. The conical portion of the electrode is supported against the high internal pressure by a 3/8 in thick disc of Spauldite G-5-766*. This is a glass fabric with melamine resin binder with the compressive strength of 70,000 psi and good dielectric properties. The cylindrical sleeve is made of teflon. As this gradually burns off, additional sleeves have to be added from time to time.

6.2 Gas Loading System

The gas loading system shown in Fig. 8, is basically the same as for the UTIAS hypervelocity launcher (see Ref. 7). A bottle, nominal volume 176 in³, has been added so that the gases can mix prior to the entry into the combustion chamber. The gas mixture is prepared according to the partial pressures of hydrogen and oxygen measured on a Heise bourdon-type gauge (for 1000-1500 psi range on a JLT transducer-type gauge).

6.3 Ignition of Mixture

In experiments at low pressures it has been noticed that the detonation wave front was curved (Ref. 31). In the present tests, it was desired to keep the gaseous detonation wave front as plane as possible in order to minimize the radial pressure gradients and to achieve as uniform and simultaneous detonation of the explosive discs as possible. Therefore in principle it is necessary to ignite the gas in a whole plane normal to the chamber axis. This is difficult to achieve in practice. The following practical compromise has been adopted. Four exploding wires were arranged in the form of a cross as shown in Fig. 9. The copper wires, 0.004 in. dia. and about 1 inch long, are connected in parallel. The centre of the cross is attached to the central electrode (shown in solid black in Fig. 5). The plate itself is used as the other electrode. The wires are exploded by discharging a 7.5 μF condenser through a 5C22 thyatron. It was found that consistent explosions were obtained with the condenser charged to 6 kv (corresponding to a stored energy of 135 joules). Although the system was capable of 10 kv, usually only 6 kv were used to prolong the life of the thyatron.

The firing circuit is shown in Fig. 10. The 5C22 thyatron is triggered by the discharge of a 1 μF condenser charged to 250 v.

* Manufactured by Spaulding Fibre of Canada Ltd.
through a 2D21 thyatron and a 1 K resistor. The 2D21 thyatron is triggered by either grounding or applying a positive pulse to its grid.

7. PRELIMINARY EXPERIMENTS

To detect explosive detonation a Kistler 605B/635B pressure gauge was available. This transducer is a quartz piezoelectric device fitted with a ballistic adaptor and is capable of measuring pressures up to 200,000 psi. It is used in conjunction with a charge amplifier and an oscilloscope. Owing to comparatively long rise time (manufacturer quotes 7 μsec for a similar 605B/633B gauge), it is not capable of following the rapid pressure change through the detonation wave or shock wave front. It was hoped, however, that it would detect qualitatively the existence of large pressure pulses. The output of this gauge in common with all high-impedance devices, was found to be greatly affected by stray electrical discharges (see also Ref. 32). Figure 11 shows the charge amplifier outputs for three different nominally identical experiments. The pressure gauge was exposed to atmospheric pressure only and was situated in the vicinity of the exploding wire. These wires were exploded by discharging 135 joules through them. As the equivalent gauge calibration is approximately 6000 psi/cm it is seen that these transients can be a source of considerable error for the first 200 μsec after explosion of the wires*.

The combustion chamber is also equipped with three combined ionization/luminous flux gauges at stations 1, 2 and 3. The purpose of these prototype gauges was to check correlation between the luminosity and the ionization signals with the hope that subsequently luminosity signals (using fast-response photo-diodes or photo-multipliers) might be used to measure incident detonation wave velocity, to detect the occurrence of explosive detonation and perhaps to measure the velocity of the shock wave propagating back into the already burnt gas. The gauge construction is shown in Fig. 12. The ionization pins, made from ordinary sewing needles, are mounted in a double-bore transparent quartz tube. The needles are potted into the quartz and the quartz into the stainless steel body by means of epoxy resin. As an additional precaution a hypodermic tube (not shown) is placed inside the probe to support the quartz (It was later found that this was unnecessary as the quartz was bound very strongly to the probe body.) Inside the probe were Philips OAP 12 photo diodes. These small inexpensive devices, which in this application were used as photovoltaic cells were connected directly to an oscilloscope without any bias voltage or load resistance.

These combination gauges have been used to measure the

* This problem has been investigated further. It has been shown that by careful attention to shielding and by the avoidance of ground loops in the instrumentation, that this source of noise can be reduced considerably. The results will be reported in a forthcoming report by R. F. Flagg.
speed of the detonation wave in a stoichiometric mixture of hydrogen and oxygen at initial pressure of 400 psi. The electronic circuit used (Fig. 13) was the same as that described by Knight and Duff (Ref. 33).

Figure 14 shows the output from the ionization gauges (top trace) and the photo diodes. The numbers against the traces correspond to the stations as defined in Fig. 5. It is seen that the correlation between the ionization signals and light signals is quite good considering the response capability of the photo diodes. Figure 15 shows similar results with much faster sweep speeds. These runs (especially Fig. 15) confirmed that at 400 psi initial pressure detonation is achieved with practically zero detonation induction distance, since the time intervals between stations 3 and 2, and 2 and 1 were equal to theoretical detonation values. (By interpolation of the results in Table III the detonation velocity at 400 psi is 10,200 ft/sec and the time to cover 1\( \frac{1}{2} \) in. is 12.3 \( \mu \)sec.)

These gauges were used with initial pressures in the range 80-450 psi. It was noticed that the quartz became steadily less transparent until (after 12 runs) it was completely non-transparent due to, undoubtedly, internal shattering. When the initial pressure was raised to 900 psi the ionization pins melted. Although these gauges have not proved suitable for this work, their simple construction might make them very attractive in less hostile conditions. Owing to their response time limitations (cut-off frequency 50 kc/s), the OAP 12 photodiodes are probably more useful for detection of oscillations in the detonating type of combustion (see Figs. 16 and 17) or for deflagrating combustion.

Pyrex glass was also tried for window construction (without pins) but after only two tests with the initial pressures of 800 and 850 psi, it too became non-transparent.

8. TESTS ON LOW-DENSITY PETN

The expendable explosive containers (Fig. 18) were made from ULTIMO-4 steel*. This was used either heat treated (yield point of 275,000 psi and Brinell hardness number 555) or was left in the annealed state (yield point 85,000 psi, Izod 75.0).

Most of the tests were done on PETN of density 0.87 gm/cc and thickness 0.15 in. The initial pressures were in the range of 8 to 98 atm. Table VI gives the measurements of the annealed containers in the critical pressure range. At 13 atm and above the containers distorted by a measurable amount. The amount of distortion was substantially constant

* Manufactured by Atlas Steels Limited, Welland, Ontario. Typical analysis of steel (as quoted by the manufacturer) is: Carbon 0.40; Manganese 0.75; Phosphorus 0.030; Sulphur 0.030; Silicon 0.20; Chromium 0.75; Nickel 1.75; Molybdenum 0.40.
for pressures up to about 98 atm indicating that the distortion was due to explosive detonation only. Only the distortion in the hole diameter "C" markedly increased as the initial gas pressure increased from 13 atm (increase of 0.007 in) to 98 atm (increase of 0.012 in). The axial distance "D" decreased by about 0.007-0.008 in. for all pressures. The increase in the outside diameter "A" was about 0.005 in. at lower pressures and 0.006 in. at higher pressures.

For comparison, a test was made on a 0.3 in. thick layer \((\rho = 0.87 \text{ gm/cc}, 7.38 \text{ gm of PETN})\) at about 94 atm. This resulted in the increase in "C" of 0.031 in. in "D" of 0.015 in. and in "A" of 0.015 in. (the container jammed in the combustion chamber block). In the critical pressure range tests were also made on pressings of density 1 gm/cc (Table VII) to facilitate comparison with Seay and Seely's work (Ref. 11). The distortion of the containers was now more pronounced and again the explosive detonated when the initial pressure was 13 atm or more. No tests were made at higher pressures.

For the runs shown in Table VI and VII the following procedure was adopted. Hydrogen and oxygen were introduced into the mixing bottle (see Fig. 8) which was first evacuated to a pressure of about 1\(\frac{1}{2}\) mm Hg. The gases were allowed to mix for 10 minutes. To allow for a very slow leak (~ 1 percent of initial \(p\)) a small amount of additional hydrogen was added after that time. The procedure was to introduce the premixed gases into the chamber and to close the 100,000 psi valve. The mixture was allowed to mix with the air in the chamber for 2 minutes and the combined gases were exhausted through one of the pressure gauge holes closed with a blank. New mixture was introduced from the mixing bottle and the procedure repeated. After two such releases (three for the 8 - 13 atm runs) the resulting pressure was noted. As this pressure differed a little from the desired pressure, additional hydrogen and oxygen were introduced directly from the bottles. When this state was achieved 3 minutes were allowed before igniting the mixture. It was felt that with this procedure a well-mixed gas of sufficiently accurate composition was obtained.

In the present combustion chamber the distance between the exploding wires and the surface of the explosive was about 10 cm. Referring to Fig. 2 it is seen that this distance is sufficient to achieve detonation if the pressure is somewhat above 10 atm. Runs 104 and 107 (Table VI) and runs 111 and 112 (Table VII) represent the borderline cases where lack of detonation of explosive can be attributed either to non-detonation of the hydrogen-oxygen mixture or to the reaching of a limit for the explosive. Nonetheless, these results support the work of Andreev and Maslov, who used a much longer detonation tube.

The annealed containers usually distorted without marking the surface. On some containers \(Y\)-shape depressions were observed on the surface (see runs 99 and 102 on Fig. 19. A limited amount of work was done using hardened ULTIMO-4 containers. At high pressures the containers

* see footnote on page 14
cracked badly at one place on the rim as shown in Fig. 19 (top container). At lower pressures no such single big cracks were obtained. Also very small cracks (detected under the microscope) were found with gaseous detonations only.

From the distortion of the physical dimensions of the explosive container and the condition of the surface it can be reasonably concluded that detonations were produced in the PETN. However, to verify the present qualitative results, quantitative data such as measurements of detonation velocity and pressure in the PETN pressing (which may be difficult for such thin discs, if not impossible) will be required.

9. TESTS ON OTHER EXPLOSIVES

The distinct advantage of low-density PETN pressings, apart from the comparatively safe preparation, is the possibility of varying the detonation velocity and pressure by varying the density of the pressing. There is no difficulty in pressing flat discs and possibly shallow concave shells but considerably difficulty may be experienced in pressing hemispherical shells. Since Andreev and Maslov reported that cast PETN also exploded (at 20 atm initial pressure), it was decided to try and cast a disc of PETN. Two different methods were tried.

1. The explosive container was heated to 150-155°C. When a small amount of PETN was added, it decomposed vigorously or exploded.

2. The container was heated to 100°C and PETN added. The container was further heated slowly until the PETN started to melt. Before even one half of the PETN was molten, the already molten part started to decompose.

From this experience it was felt that casting of PETN in some quantity would be very difficult, if not impossible.

Next it was decided to try and distribute crystals of PETN (m. p. 138.5 - 141°C) in an explosive of much lower melting point. The explosive chosen was DINA (Bis-nitroxyethylnitramide) with m. p. of 51.9 to 52.8 °C. The procedure was to melt 2.635 gm of DINA in the explosive container heated to 60°C. PETN (weight 2.635 gm) was added slowly while stirring with a thin wooden stick. The result was a thick slurry which could be stirred to uniformity. However, it was not possible to get an even surface. The resulting disc was about 0.11 thick. The total weight was 5.27 gm and the mean density was 1.66 gm/cc. Owing to the high

* Further measurements of the wave velocity in stoichiometric mixtures of oxygen and hydrogen in this chamber, over a range of initial pressures of 6 to 24 atmospheres, have shown conclusively that a slightly over-driven detonation wave is produced in the initial mixture in this apparatus at an initial pressure of 13 atmospheres. These results will be released in their entirety in a future publication by R. F. Flagg.
viscosity of the slurry, the 50:50 ratio of PETN:DINA was about the highest that could be subsequently employed in the manufacture of the hemispherical shells for the launcher. This sample was tried at about 57 atm initial pressure but it did not detonate. It became clear that very high pressures, much higher than can be employed usefully in the launcher, would be required to detonate this mixture. This investigation was therefore discontinued.

Sheet explosive Dupont EL-506-A2 (thickness 0.084 in) was also tested. This material is basically PETN combined with other ingredients to give a flexible sheet. The explosive did not detonate when the initial pressure was about 98 atm.

The explosives investigated in this programme were basically secondary explosives and hence for detonation required transmission of strong shock waves from the adjacent medium. In the application to the hypervelocity launcher (if we were to use low-density PETN), this requires the creation of spherical detonation waves in the gases in combustion chamber. This places stringent limitations on the combustible mixture composition and may require a more energetic ignition system. These difficulties are more pronounced for a spherical geometry than for the present one-dimensional experiment.

Obviously, it would be preferable to use explosive layers which can be detonated by gaseous deflagration waves. This, however, will probably necessitate the use of a primary explosive (such as lead azide, tetracene etc.) to sensitize the main layer of secondary explosive.

10. DISCUSSION OF RESULTS

The minimum initial gas pressure for detonation of the PETN pressings by a detonation wave in stoichiometric oxygen and hydrogen was found to be about 13 atm. This compares favourably with Andreev and Maslov's results of 10 atm (powdered PETN) and 20 atm (cast PETN). This comparison can only be approximate since it is not known whether, as discussed before, the pressure of 13 atm is the true limit for the explosive. Also, since Andreev and Maslov did not consider shock heating as the mechanism of initiation, it is difficult to interpret their results in this light as the orientation of the explosive samples (relatively to the incident detonation wave) is not stated.

It is also instructive to make a comparison with the results of Seay and Seely. To do so it is necessary to analyze the way in which the gaseous detonation waves, by reflection, generate shock waves in the PETN pressing. Assuming the ratio of peak pressure after reflection to initial gas pressure of 50 (as calculated in Sec. 2), then this corresponds to the peak pressure of 650 atm or approximately 0.65 kbar. Even if (optimistically) the pressure increase due to the reflected shock wave from the explosive/steel interface is considered, then the maximum pressure is

* see footnote on p. 14.
In Fig. 20 are reproduced the results of Seay and Seely (Ref. 11) showing the depth of initiation versus the shock pressure in the PETN pressing. If for example it is assumed that detonation occurs 2 mm from the explosive/steel interface, then the pressure required behind the shock reflected from the explosive/steel interface to cause detonation would be about 4 kbar.

To account for this wide difference in pressures it appears necessary in drawing Fig. 3 to include a finite width of the detonation wave as it is known that the pressure ratio across a shock wave of the same velocity as the detonation wave preceding the reaction zone is much greater than the pressure ratio across the whole detonation wave - see Table II. Also in drawing Fig. 3 a more realistic situation is represented by considering the compressibility of the unreacted pressing.

No experimental data regarding the thickness of the \(2\text{H}_2 + \text{O}_2\) detonation waves at pressures much above 1 atm is available. The results quoted by Fay (Ref. 34) indicate that for initial pressures of 1 atm the thickness of the \(2\text{H}_2 + \text{O}_2\) detonation waves is of the order of 1 mm. This thickness decreases with the increase in pressure and by extrapolation of the graph (given in Ref. 34), it appears that at, say, 15 atm the thickness is zero for all practical purposes. However, for the purposes of discussion, it is assumed that the width of the wave is \(1/10\) mm at the initial pressure of 15 atm.

The problem of reflection of a gaseous detonation wave from a rigid wall is discussed by Edwards, Williams and Breeze (Ref. 35), while Payton (Ref. 36) considers the problem of transmission of shock waves into a compactible material. It is possible to combine the two problems to obtain an \((x, t)\)-diagram of the reflection of the detonation wave and transmission of a shock wave into the explosive, treated as an unreacting compactible medium. The shock Hugoniot from Ref. 11 which is reproduced in Fig. 21 is used. This graph can be treated as a Hugoniot only if little chemical reaction takes place at this early stage. This is approximately true in practice. It should be mentioned that this Hugoniot has been obtained from results on an unconfined wedge of explosive where the shock pattern is not truly one-dimensional owing to rarefaction waves entering the wedge from the sides when the wedge is shocked by a shock wave transmitted from the brass layer (for details of the method see Ref. 11). For lack of more relevant results it is necessary to use this data.

The graph of Fig. 21 can be represented by the following equation. The regions are defined in Fig. 22.

\[
p_4 = \frac{u_4}{62.1} - 2.37 \quad \text{for} \quad 2 \leq p_4 \leq 4.5
\]
where \( p_4 \) is the shock pressure in kbars

and \( u_4 \) is the particle velocity in m/sec

By neglecting the initial pressure and applying the normal shock equations we can obtain

\[
S_3 = 1600 - \frac{239}{u_4} \times 10^3 \text{ m/sec}
\]

where

\( S \) is the shock velocity in m/sec

For example when \( p_4 = 2 \text{ kbar}, \) and \( u_4 = 271 \text{ m/sec}, \) \( S_3 = 723 \text{ m/sec} \)

and \( p_4 = 3 \text{ kbar}, \) and \( u_4 = 333 \text{ m/sec}, \) \( S_3 = 886 \text{ m/sec} \)

It must be understood that the heterogeneous PETN pressing is here considered to be homogeneous for hydrodynamic purposes only (Ref. 11). The calculated PETN shock pressure and velocity really have no meaning as far as the mechanism of ignition is concerned since initiation is the result of localized high-temperature spots and not due to some average temperature determined from the strength of the initiating shock as defined here (see for example Ref. 18).

The resulting shock pattern is shown in Fig. 22 (the part above BCDE is shown qualitatively only). Following Ref. 35 the detonation wave is represented by a shock wave \( S_1 \) followed by a uniform region of compressed still unreacting gas at the end of which is a very thin reaction zone, where the chemical reaction is brought rapidly to completion resulting in the Chapman-Jouguet state. The detonation wave is followed by the rarefaction wave \( R_1, \) the width of which depends on the distance of the detonation wave from the closed end of the tube where the mixture is ignited. To obtain state (3) in Fig. 22 it is necessary to match conditions behind shocks \( S_2 \) and \( S_3 \) so that \( p_3 = p_4 \) and \( u_3 = u_4. \) The \( p \) vs. \( u \) relationships for states (3) and (4) are plotted in Fig. 23, which gives

\[
\begin{align*}
p_3 &= p_4 = 3.01 \text{ kbar} \\
u_3 &= u_4 = 334 \text{ m/sec}
\end{align*}
\]

It is seen that owing to the compressibility of the pressing the pressure \( p_3 \) is reduced by about 20 percent from that attainable with a rigid wall \( (u_3 = 0). \) The values of \( S_2 \) and \( S_3 \) corresponding to the point of intersection are

\[
\begin{align*}
S_2 &= 720 \text{ m/sec} \\
S_3 &= 886 \text{ m/sec}
\end{align*}
\]

This is as far as it is possible to proceed with reasonable confidence in the drawing of Fig. 22. It is now important to determine the velocity of the head of the rarefaction wave \( R_3 \) in order to define the high
pressure region (4) in the explosive. Unfortunately little is known regarding the speed of sound in such crushed inhomogeneous materials. However an estimate may be made using the data of Fig. 21. Assume that the speed of sound in the crushed pressing of density $\rho_4$ is given by $(K / \rho_4)^{\frac{1}{2}}$ where $K$ is the bulk modulus defined by

$$
\left( \frac{dp}{dv} - \frac{v_0}{v} \right) p_4
$$

It can be shown that the volumetric strain of the pressing due to compression by $S_3$ is $u_4/S_3$. From a plot of $p_4$ vs. $u_4/S_3$, $K$ at 3 kbars is of the order of 76 kbars. This, with $\rho_4 = 1.605 \text{ gm/cc}$ (calculated from the normal shock wave equations) gives the speed of sound of 2180 m/sec. The high pressure $p_4$ is thus terminated at the point E.

It is necessary to comment on the construction of the region (3). In drawing Fig. 22 it was assumed that the head of the reaction zone R. Z. 2 is moving with the constant velocity equal to the local speed of sound. (In region (2) by separating the reaction zone R. Z. 1 and the shock $S_1$ by a constant width of 0.1 mm we assume in effect that R. Z. 1 moves with the velocity of $S_1 - u_2$ i.e. 577 m/sec with respect to the gas (2)).

The physical situation, however, is far more complicated. Since the temperature in region (3) is 4056°K, the induction time for ignition would be very much shorter (see for example Ref. 37) than in region (2) where the temperature is 2176°K. Further it is conceivable that a gas particle (see the indicated path) might ignite shortly after being compressed by $S_2$ and prior to the arrival of R. Z. 2. This is a rather important possibility as it may affect the pressure history at the explosive surface.

This analysis which is a purely gasdynamic one can only indicate the duration of high pressure of any element of explosive if it is treated as chemically inert. If we consider only region (4) then Fig. 22 indicates the maximum duration of $p_4$ of the order of 0.05 $\mu$sec. This compared to Seay and Seely's results (implying that to achieve detonation a constant-pressure pulse of 3 kbars would have to last for several microseconds) appears much too short to cause high order detonation. The problem is quite complex, the initiation of the explosive probably taking place due to the application not only of the uniform pressure $p_4$ but also due to the whole pressure history which occurs after region (4) disappears. The most likely conclusion is that detonations (see for example Refs. 38 and 39) have been established in the present tests. for initial pressures greater than $\approx 12.5$ atmospheres.

These results must therefore be considered of a preliminary nature. It is obvious that a considerable amount of work is still needed. It would be logical to determine the critical pressure for detonation as accurately as possible and to do that for various pressing densities and
given sizes (the dependence of detonation velocity, in tubes of various diameters, on particle diameter is clearly revealed in Ref. 39). It would also be valuable to obtain the history of pressure $p_3$ using fast response pressure transducers, such as described by Soloukhin (Ref. 40).

As pointed out by Seay (Ref. 21) little is known about the passage of shock waves in materials composed of regions of greatly different acoustic impedances, such as porous explosive pressings. This is true for both reacting and unreacting materials. It appears to the writer that this field especially has to be much better understood before we can with confidence predict the ignition behaviour of low-density explosive pressings. Some pioneering work in this area is reported in Refs. 36, 41 and 42.

11. ADDITIONAL SUGGESTIONS FOR FURTHER WORK

As the sole object of these experiments was to assist in the development of the UTIAS hypervelocity launcher, the length of the detonation tube was limited to 4 inches, which is the same as the radius of the hemispherical chamber. From the point of view of studying only the behaviour of explosives, it would of course be preferable to have a long tube (about 3 to 4 feet long) to ensure that gaseous detonations can be achieved at even atmospheric pressures. As can be seen from Fig. 2 no information is available on gaseous detonation induction distances for pressures above 25 atm. One can see that at high pressures the detonation induction distance for stoichiometric mixtures of hydrogen and oxygen is zero. However, no prediction can be made for diluted mixtures. If a long tube is used so that the time between the discharge in the exploding wires and the arrival of the detonation wave at the opposite end of the tube exceeds the duration of the induced transients in the piezoelectric pressure gauges, one may again consider using such gauges in the vicinity of the explosive to detect detonations.

More analytical and experimental work is needed for better understanding of the process of the head-on reflection of gaseous detonation waves from both rigid and "crushable" walls, especially the pressure history on the walls. It would be interesting to photograph on a smear camera the $(x, t)$-plane of the development of the gaseous detonation wave, its reflection and the detonation of the explosive itself. For this purpose a quick-closing photographic shutter would have to be acquired or developed.

The PETN pressings as used in this work were somewhat fragile and care had to be taken to prevent crumbling. A method should be found for strengthening them.

12. CONCLUSIONS

It has been shown that in a detonation tube 4 inches long PETN disc pressings of density 0.87 gm/cc and 1.0 gm/cc, 1.5 in dia x 0.15 in
thick detonate when the initial pressure of the stoichiometric hydrogen-oxygen mixture is about 13 atm or more. A 50/50 DINA/PETN mixture and sheet explosive EL-506-A2 did not detonate when the initial mixture pressures were 57 and 98 atm respectively. It has been found that manufacturing difficulties precluded the use of cast PETN.
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**TABLE I**

Constant-Volume Combustion of Stoichiometric Mixtures of Hydrogen and Oxygen (Ref. 6)
### TABLE II

Composition of Gas Resulting from Detonation of Stoichiometric Mixture of Hydrogen and Oxygen (Ref. 16)

\[ T_1 = 313.16^\circ K \]

<table>
<thead>
<tr>
<th>( p_1 ) atm</th>
<th>( p_{o_2} ) atm</th>
<th>( p_o ) atm</th>
<th>( p_{H_2} ) atm</th>
<th>( p_H ) atm</th>
<th>( p_{o_2} ) atm</th>
<th>( p_{H_2O} ) atm</th>
<th>( p_{2H} ) atm</th>
<th>( p_{2H}/p_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.745876</td>
<td>0.638231</td>
<td>2.952802</td>
<td>1.390335</td>
<td>3.036375</td>
<td>9.236365</td>
<td>18.00</td>
<td>18.00</td>
</tr>
<tr>
<td>5</td>
<td>3.457926</td>
<td>2.651718</td>
<td>14.53298</td>
<td>5.581083</td>
<td>15.41088</td>
<td>50.86544</td>
<td>92.5</td>
<td>18.5</td>
</tr>
<tr>
<td>25</td>
<td>16.20487</td>
<td>10.66765</td>
<td>71.40139</td>
<td>21.67408</td>
<td>78.30594</td>
<td>291.7461</td>
<td>490.0</td>
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<td>100</td>
<td>61.59676</td>
<td>35.43535</td>
<td>279.3280</td>
<td>69.52653</td>
<td>316.8585</td>
<td>1307.255</td>
<td>2070</td>
<td>20.7</td>
</tr>
<tr>
<td>$p_1$ atm</td>
<td>$T_{2D}^\circ K$</td>
<td>$T_2^\circ K$</td>
<td>$p_{2D}$ atm</td>
<td>$p_{2D}/p_1$</td>
<td>$p_2$ atm</td>
<td>$p_2N.S/p_1$</td>
<td>$a_2$ m/sec</td>
<td>$D$ m/sec</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------</td>
<td>--------------</td>
<td>--------------</td>
<td>--------------</td>
<td>----------</td>
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</tr>
<tr>
<td>1</td>
<td>3646</td>
<td>1981</td>
<td>18.00</td>
<td>18.00</td>
<td>32.270</td>
<td>32.27</td>
<td>1522</td>
<td>2826</td>
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<td>5</td>
<td>3954</td>
<td>2102</td>
<td>92.50</td>
<td>18.50</td>
<td>172.10</td>
<td>34.42</td>
<td>1618</td>
<td>2918</td>
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<tr>
<td>25</td>
<td>4296</td>
<td>2210</td>
<td>490.0</td>
<td>19.60</td>
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<td>36.562</td>
<td>1667</td>
<td>3007</td>
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<tr>
<td>100</td>
<td>4641</td>
<td>2296</td>
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<td>3819.0</td>
<td>38.19</td>
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<td>3073</td>
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</table>
# TABLE IV

Calculations for PETN (C$_5$H$_9$O$_{12}$N$_4$) (Ref. 4)

<table>
<thead>
<tr>
<th>Load. Dens.</th>
<th>Products gm mol/kg</th>
<th>$n_2$</th>
<th>$Q_2$</th>
<th>$b$</th>
<th>$\lambda$</th>
<th>$k_2$</th>
<th>$v_2$</th>
<th>$T_2$</th>
<th>$10^{-5} \Phi_2$</th>
<th>$D$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO$_2$ CO H$_2$O N$_2$</td>
<td>gm/cc</td>
<td>gm</td>
<td>cal/cc</td>
<td>cc/cc</td>
<td>gm</td>
<td>gm</td>
<td>gm</td>
<td>gm</td>
<td>oK</td>
<td>atm</td>
</tr>
<tr>
<td>1.50</td>
<td>9.6 6.2 12.7 6.3</td>
<td>0.035</td>
<td>1412</td>
<td>0.874</td>
<td>0.458</td>
<td>0.647</td>
<td>0.540</td>
<td>5340</td>
<td>1.88</td>
<td>1550</td>
<td>8150</td>
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<tr>
<td>1.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Calculations taking into account effect of rotation of the CO$_2$ molecule

<table>
<thead>
<tr>
<th>CO$_2$ CO H$_2$O H$_2$ O$_2$ N$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50 9.5 6.3 12.6 0.05 0.02 6.3 0.0348 1400 0.874 0.458 0.647 0.540 5300 1.88 1550 8140</td>
</tr>
<tr>
<td>0.75 7.8 8.0 12.5 0.2 0.9 6.3 0.036 1276 0.897 0.627 0.954 0.973 4740 0.413 1200 4480</td>
</tr>
</tbody>
</table>
### TABLE V

Percentage Composition of Products of Reaction of PETN (Ref. 28)

<table>
<thead>
<tr>
<th></th>
<th>NO₂</th>
<th>NO</th>
<th>N₂O</th>
<th>N₂</th>
<th>CO₂</th>
<th>CO</th>
<th>H₂</th>
<th>O₂</th>
</tr>
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<tbody>
<tr>
<td>Detonation</td>
<td>--</td>
<td>5.3</td>
<td>--</td>
<td>22.8</td>
<td>37.0</td>
<td>26.7</td>
<td>6.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Impact</td>
<td>--</td>
<td>24.3</td>
<td>5.3</td>
<td>9.4</td>
<td>19.1</td>
<td>35.4</td>
<td>6.5</td>
<td>--</td>
</tr>
<tr>
<td>Decomposition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(210°C)</td>
<td>12.0</td>
<td>47.6</td>
<td>9.5</td>
<td>1.6</td>
<td>6.3</td>
<td>21.0</td>
<td>2.0</td>
<td>--</td>
</tr>
</tbody>
</table>
# TABLE VI

Low-Density PETN ($\rho = 0.87 \text{ gm/cc}$) Measurements of Explosive Containers Before and After Test

Material: ULTIMO-4 (annealed)  
Thickness of explosive: 0.15 in.  
Gas mixture: $2\text{H}_2 + \text{O}_2$

<table>
<thead>
<tr>
<th>Run #</th>
<th>Container #</th>
<th>Initial pressure of mixture atm.</th>
<th>Explosive Type</th>
<th>Energy Stored in condenser joules</th>
<th>All dimensions in inches</th>
<th>Top value after test</th>
<th>Bottom value before test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>101</td>
<td>4</td>
<td>24.5</td>
<td>A</td>
<td>135</td>
<td>2.491</td>
<td>2.459</td>
<td>1.487</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.486</td>
<td>2.455</td>
<td>1.481</td>
</tr>
<tr>
<td>102</td>
<td>11</td>
<td>15</td>
<td>A</td>
<td>135</td>
<td>2.490</td>
<td>2.460</td>
<td>1.485</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>2.486</td>
<td>2.455</td>
<td>1.478</td>
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<tr>
<td>108</td>
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<td>15</td>
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<td>135</td>
<td>2.492</td>
<td>2.458</td>
<td>1.485</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>2.486</td>
<td>2.453</td>
<td>1.479</td>
</tr>
<tr>
<td>113</td>
<td>22</td>
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<td>135</td>
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<td>2.440</td>
<td>1.488</td>
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<td>2.435</td>
<td>1.480</td>
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<td>115</td>
<td>21</td>
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<td>135</td>
<td>2.476</td>
<td>2.445</td>
<td>1.486</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td>2.470</td>
<td>2.440</td>
<td>1.479</td>
</tr>
<tr>
<td>103</td>
<td>13</td>
<td>8</td>
<td>A</td>
<td>375</td>
<td>2.483</td>
<td>2.453</td>
<td>1.478</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.483</td>
<td>2.453</td>
<td>1.479</td>
</tr>
<tr>
<td>104</td>
<td>8</td>
<td>10</td>
<td>B</td>
<td>375</td>
<td>2.486</td>
<td>2.453</td>
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<tr>
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<td>2.453</td>
<td>1.478</td>
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<tr>
<td>107</td>
<td>3</td>
<td>12</td>
<td>B</td>
<td>135</td>
<td>2.485</td>
<td>2.454</td>
<td>1.480</td>
</tr>
<tr>
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<td></td>
<td>2.486</td>
<td>2.454</td>
<td>1.480</td>
</tr>
<tr>
<td>Run #</td>
<td>Container #</td>
<td>Initial pressure of mixture atm.</td>
<td>Explosive Type</td>
<td>Energy Stored in condenser joules.</td>
<td>All dimensions in inches</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
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<td>---------------------------------</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
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<td>15</td>
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<td>2.478</td>
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<td>2.441</td>
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<td>13</td>
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<td>2.456</td>
<td>1.479</td>
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<td>2.440</td>
<td>1.481</td>
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<tr>
<td>112</td>
<td>18</td>
<td>12</td>
<td>B</td>
<td>375</td>
<td>2.470</td>
<td>2.442</td>
<td>1.479</td>
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<td>2.441</td>
<td>1.479</td>
</tr>
<tr>
<td>111</td>
<td>15</td>
<td>11</td>
<td>B</td>
<td>375</td>
<td>2.471</td>
<td>2.442</td>
<td>1.480</td>
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<td></td>
<td></td>
<td>2.470</td>
<td>2.441</td>
<td>1.480</td>
</tr>
</tbody>
</table>

**TABLE VII**

Low-Density PETN ($\rho = 1.00$ gm/cc) Measurements of Explosive Containers Before and After Test

Material: ULTIMO-4 (annealed)
Thickness of explosive: 0.15 in.
Gas mixture: $2H_2 + O_2$
FIG. 1  (x, t) DIAGRAM OF BASIC SHOCK-TUBE FLOW
FIG. 2 DETONATION INDUCTION DISTANCES (in cm.) FOR HYDROGEN-OXYGEN DETONATIONS

- Ref. 14
- Ref. 15
- Ref. 13
Mixture $2H_2 + O_2$
Initial Pressure 100 atm.
Initial Temperature 313°K
$\phi = 1.2$

Distance from point of ignition in.

FIG. 3 REFLECTION OF A DETONATION WAVE IN A 4 INCH TUBE

Pressure
atm.

Time after ignition of mixture-microseconds

FIG. 4 PRESSURE HISTORY ON SURFACE EXPLOSIVE
FIG. 5 CROSS-SECTION OF THE COMBUSTION CHAMBER
FIG. 6  GENERAL VIEW OF THE APPARATUS SHOWING THE 4-WIRE IGNITOR ON THE LEFT.

FIG. 7  END PLATE AND ATTACHED EXPLOSIVE CONTAINER
Combustion Chamber

Gas Mixing Bottle

Vacuum Pump

Rupture Disc

Vacuum Gauge

Air operated valve

Manually operated valve

Check valve

H₂  O₂

0 - 1000 psi Heise gauge

0 - 2000 psi JLT gauge

FIG. 8 GAS LOADING SYSTEM
FIG. 9 EXPLODING WIRES

FIG. 10 FIRING UNIT
FIG. 11  ELECTRICAL INTERFERENCE SIGNALS
Vertical Scale  500 mV/cm (Ch. ampl. 0.2)
Horizontal Scale  50 µsec/cm

Ionization pins
Dia. 0.026 in.
Gap 0.020 in.
Length protruding 1/16 in.

Probe body (made from 416 stainless steel heat treated)
O.D. 0.370 in.

Double-bore transparent quartz tube
DIA. 0.151 in.

FIG. 12  IONIZATION/LUMINOUS FLUX GAUGE

Philips OAP 12 photo diode
FIG. 13 IONIZATION GAUGE CIRCUIT (SAME AS IN REF. 33)
FIG. 14  

$2\text{H}_2 + \text{O}_2$; initial pressure 400 psi.

Top trace: ionization gauge; 40 V/cm, 50 $\mu$sec/cm
other traces: OAP 12 photodiodes (bottom trace nearest ignition point)
0.2 V/cm; 50 $\mu$sec/cm

FIG. 15  

$2\text{H}_2 + \text{O}_2$; initial pressure 400 psi

Ionization gauge: 40V/cm, 10 $\mu$sec/cm
OAP 12 photodiodes 0.2 V/cm, 10 $\mu$sec/cm
FIG. 16
$2 \text{H}_2 + \text{O}_2 + 2\text{H}_2$; initial pressure 200 psi
OAP 12 in position s
1 m sec/cm
50 mv/cm

FIG. 17
$2 \text{H}_2 + \text{O}_2 + 2\text{H}_2$; initial pressure 200 psi
OAP 12 in position s
50 mv/cm
0.2 msec/cm.
FIG. 18  EXPLOSIVE CONTAINER (Dimensions given in Tables VI and VII)
FIG. 19  APPEARANCE OF EXPLOSIVE CONTAINERS
AFTER TEST
FIG. 20  DEPTH OF INITIATION vs PETN SHOCK PRESSURE (REF. 11)

FIG. 21  PETN SHOCK HUGONIOT (REF. 11)
FIG. 22 REFLECTION OF GASEOUS DETONATION WAVE FROM UNREACTING PETN PRESSING

Unit of pressure: Kilobar
Unit of velocity: m/sec

\[ a_1 = 536 \]
\[ \gamma_1 = 1.4 \]
\[ p_1 = p_5 = 0.015 \]
\[ S_1 = 2978 \]
\[ a_2 = 1413 \]
\[ u_2 = 2401 \]
\[ p_2 = 0.5454 \]
\[ S_2 = 720 \]
\[ a_3 = 1929 \]
\[ u_3 = u_4 = 334 \]
\[ p_3 = p_4 = 3.01 \]
\[ S_3 = 886 \]
\[ a_4 = 2180 \]
FIG. 23  SHOCK HUGONIOTS FOR SHOCKS S₂ AND S₃
APPENDIX I

Precipitation of Crystals of PETN*

A solution of 50 gm of pure PETN in 500 ml of acetone at 20-25°C was filtered into a 2 l. beaker into which a 1000-1200 rpm stirrer was placed. While the stirrer was rotated 600 ml of water was added at the rate of 30 ml per second. After subsequent stirring for five minutes it was discontinued, whereupon separation occurred into a floating and a non-floating layer. The upper layer, filtered by suction and vacuum-dried at 20-25°C, weighed 21 gm and consisted of needles of length about 10 times that of cross-section. The lower layer (29 gm) was similar. Neither contained more than 5% of finely-divided material.

Under identical circumstances except that a Chemap vibromixer with 2.5 inch perforated disc pumping upward was used instead of the rotating stirrer. The crystals in the upper layer were of average and uniform length of 100 μ and breadth of 10 μ (type A). The average and uniform length and breadth in the lower layer was 160 μ and 15 μ respectively (type B). There was no finely-divided material in either crop. The total recovery was 46 gm.

* This preparation made by Dr. G. F. Wright and Mr. H. Huber is a development of the methods described to the author by L. B. Seely (Stanford Research Institute) and T. S. Sterling (Canadian Armament Research and Development Establishment), to whom he is grateful for this assistance.
APPENDIX II

Preparation of Low-Density PETN Charges

The exploded view of the apparatus is shown in Fig. A1. The plunger is attached to a Carver Laboratory press. The explosive container is placed on the thin ring and the brass ring is fitted on top of the container. The weighed sample is then placed in the container and distributed evenly with a spatula. The assembly is then placed under the press and the plunger pressed down to the desired thickness.
FIG. A1  APPARATUS FOR PRESSING LOW-DENSITY PETN DISCS (scale full size - inches)