

814. The Burning to Detonation of Solid Explosives.

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The mechanism by which heavily confined columns of solid granular explosives burn to detonation has been studied and it has been shown that the process occurs in a number of stages. Combustion is initiated when a thermal explosion is produced at one end of the column. It is shown that, if the combustion proceeds by a conductive mechanism of energy transfer, the maximum combustion velocity obtainable is of the order of 1 m./sec. Experimentally, much higher combustion velocities are obtained; these are necessary for detonation and are shown to depend on a convective method of energy transfer. A combustion of this velocity produces a series of shock waves which pass into the unchanged explosive. These waves produce chemical reaction in their wake, and a shock exceeding a critical intensity becomes progressively more reactive as it passes through the explosive. A sudden acceleration of the reaction rate behind the shock occurs by a mechanism analogous to thermal explosion, and detonation is produced.

MOST solid explosives can readily be made to detonate only by the detonation wave from another explosive charge or by an intense shock wave, as in "gap" tests.¹ Although the details of initiation of detonation by shock are not yet completely understood it is generally agreed that the process requires the rate of release of chemical energy behind the shock wave to exceed the rate of loss of energy.

In practice, detonation is usually initiated by using one of the small number of explosives such as lead azide which detonate on receiving a relatively mild thermal stimulus. The mechanism by which detonation is achieved in lead azide has been discussed by many workers.²

Explosives, other than lead azide and similar compounds, usually merely burn when ignited and cannot therefore be used in detonators. However, burning in high explosives or propellants can lead to detonation, often after a long delay, particularly if large quantities of material are involved.

It is probably correct to say that, except where initiation is by an intense shock wave, there is no clear understanding of the mechanism by which detonation is achieved in solid explosive charges. This applies both to substances, such as lead azide that show no well-defined burning region, and to other explosives, including secondary explosives, in which burning processes are important. The present investigation deals with the latter type of process and particularly with the mechanism by which narrow columns of heavily confined secondary explosive (*i.e.*, confined closely in a strong container) achieve detonation after a relatively gentle thermal ignition. Four high explosives, RDX (cyclotrimethylene-trinitramine), HMX (cyclotetramethylenetetranitramine), PETN (trinitrophenylmethyl-nitramine, and tetryl, are considered.

EXPERIMENTAL

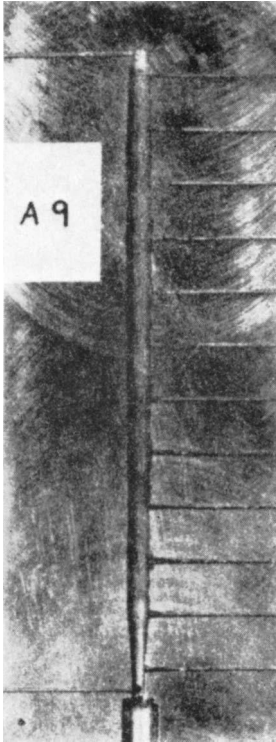
Materials.—These were prepared by Messrs. G. W. C. Taylor and A. T. Thomas of the Explosives Research and Development Establishment, Ministry of Supply, to whom the authors are indebted.

Measurement of Combustion Velocity and Detonation Velocity.—Cylindrical brass tubes, of 2.1 in. external diameter and 0.1 in. internal diameter, were filled with increments of granular high explosive. The incremental lengths were less than the channel diameter, so that density variations were minimised, and the average density of each explosive column was obtained

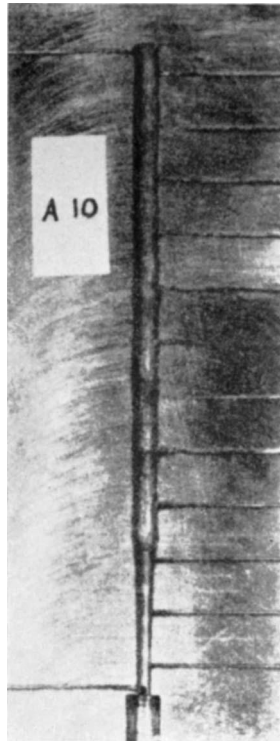
¹ Cachia and Whitbread, *Proc. Roy. Soc.*, 1958, *A*, **246**, 268.

² Andreev, *Phys. Z. Sowjetunion*, 1933, **4**, 120; Garner, *Proc. Roy. Soc.*, 1958, *A*, **246**, 203; Hawkes and Winkler, *Canad. J. Res.*, 1947, **25**, *B*, 548; Grocock, *Trans. Faraday Soc.*, 1958, **54**, 1526; Evans, *Proc. Roy. Soc.*, 1958, *A*, **246**, 199; Ubbelohde, *Research*, 1950, **3**, 207

PLATE 1. *Typical cross-sectional tubes after firing.*

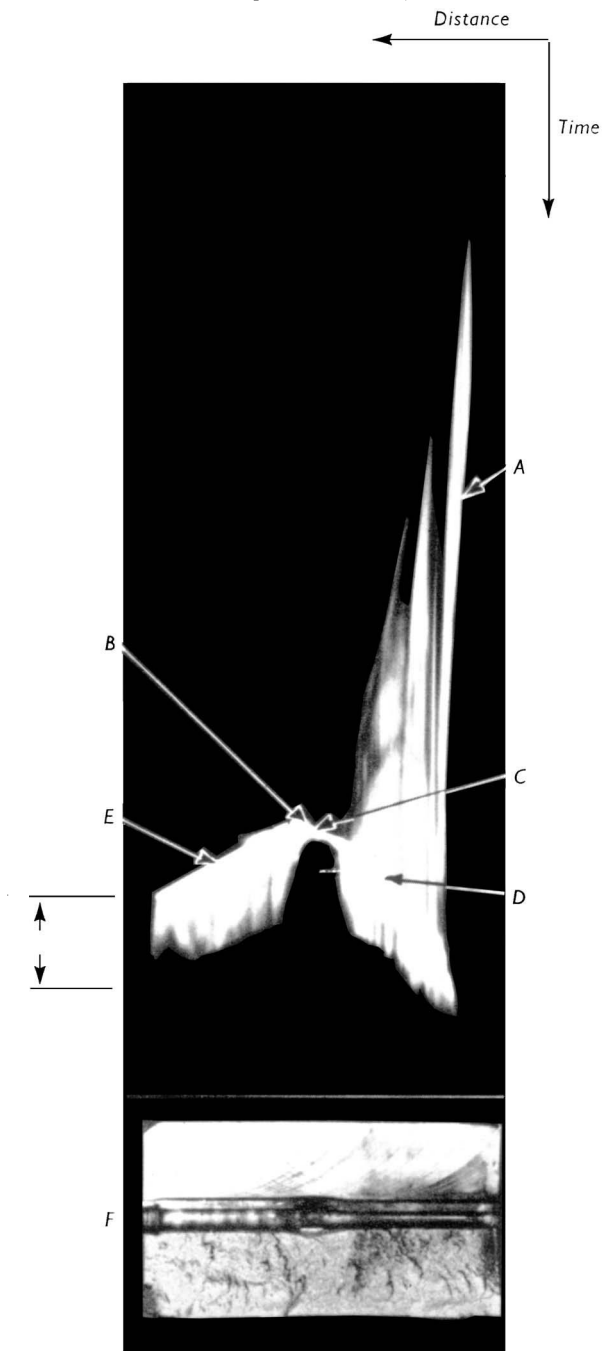


A9. RDX, ignition by F85, d 1.29, length of burning column 1.2 cm.



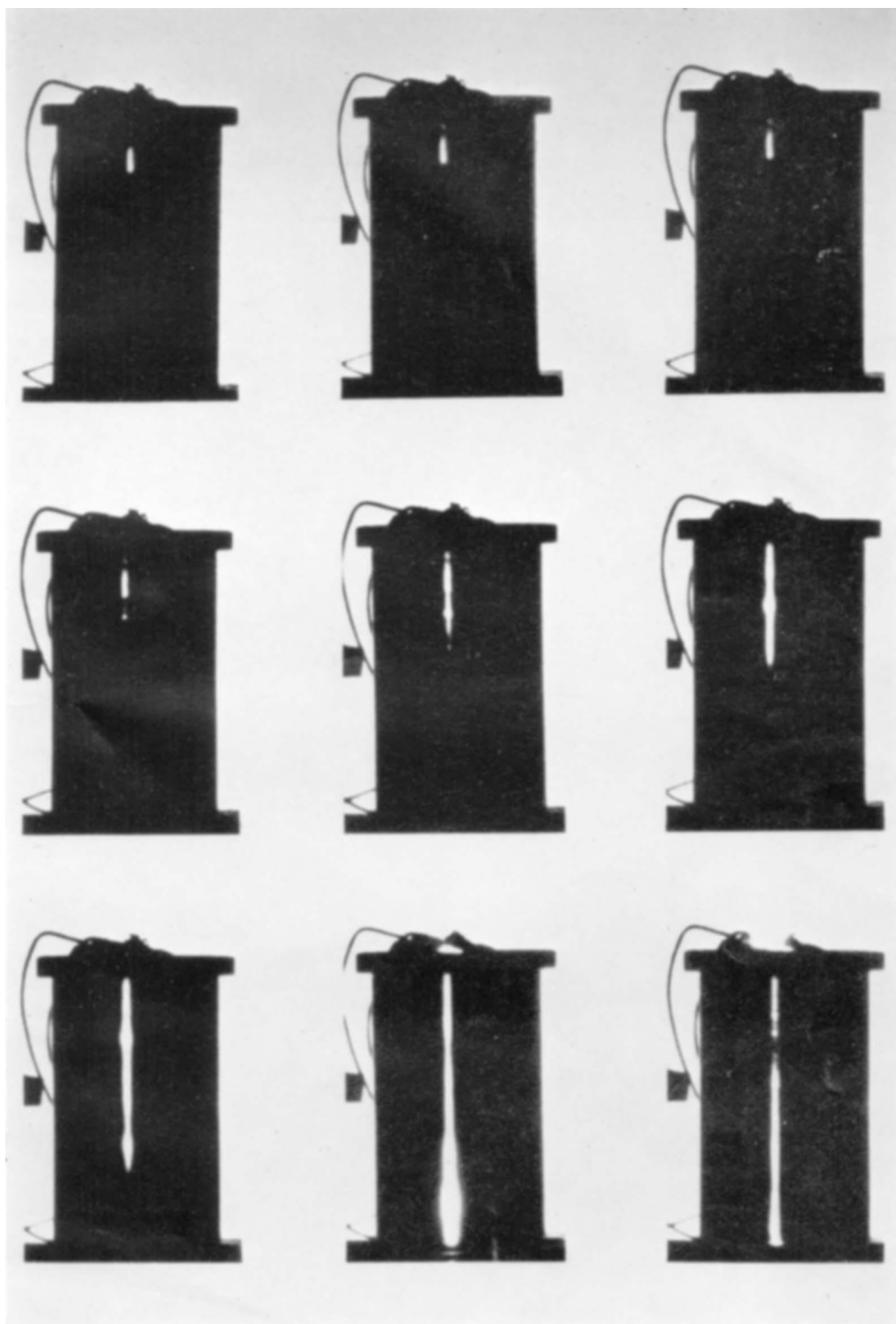
A10. As A9, but d 1.28 and length of burning column 2.8 cm.

PLATE 2. *Burning to detonation of PETN. Record from a rotating-mirror camera (writing speed 1.5 mm. per microsecond).*



A, Combustion; maximum velocity 800 m./sec. B, Onset of detonation, 1.3 cm. ahead of combustion. C, Retonation wave; velocity 6584 m./sec. D, Retonation in combustion products; velocity 3862 m./sec. E, Stable detonation; 6310 m./sec. Δt , Time for Perspex window to fracture, indicating shock velocity of ~ 4000 m./sec. F, Section after firing.

PLATE 3. *Burning to detonation of HMX. Inter-frame time 10 microseconds.*



from its known volume and the weight of explosive used. The brass tubes contained a series of ionisation probes located throughout the length of the explosive column.

The explosive columns were ignited at one end by the flame from a Fuze Electric F85, a graphite bridge igniter filled with lead styphnate. Only two velocity measurements were taken on each tube, the time intervals for the passage of the ionisation front across two pairs of co-axial probes situated 1 cm. and 4 cm., and 8 cm. and 11 cm., respectively from the point of initiation being measured with two microsecond counters. Usually the first pair of probes recorded in the combustion region and the second in the detonation region. The combustion velocity was not constant, so only an average value was obtained.

Further information on the order of reaction at various points in the explosive column was obtained by taking cross-sections of the brass tubes used to contain the explosive column and assessing the damage to the surface of the channels. In the region close to the point of initiation the tube is only slightly expanded and the surface of the channel is smooth. The tube expansion increases steadily with distance from the point of initiation, finally reaching a constant diameter, and from this point onwards the surface of the channel is roughened by striations which are a typical indication of detonation (Plate 1). The length of explosive column required before detonation was achieved could therefore be measured accurately.

Measurement of Gas Permeability of the Explosive Columns.—The gas permeabilities of columns of the different explosives for each of the particle sizes and densities used in the combustion experiments were measured. Four increments of the explosive were pressed under the required conditions into a brass tube 0.6 in. long and of 0.3 in. outside diameter and 0.1 in. inside diameter. The time for a fixed volume of gas to be forced through the column by a head of mercury in a glass U-tube was measured.

Photographic Observations of the Burning to Detonation.—A narrow column of secondary explosive will burn to detonation only if strongly confined and in the experiments described earlier this was achieved by containing the explosive in a very thick-walled brass tube. It was considered that further information would be obtained if a container could be made which allowed the burning-to-detonation process to be photographed.

A satisfactory design consisted of a steel tube with a stepped wedge-shaped Perspex window keyed in against the pressure from the burning explosive. This tube enabled the first successful photographs of the burning to detonation to be taken. A 100,000 frames per sec. framing camera and a rotating mirror "streak" camera were used. The Perspex window gives the smallest possible reduction in the confinement of the steel tube and, because it is machined from solid plastic, its optical qualities can be excellent.

RESULTS

Effect of Explosive Density.—The effect of loading density on the length of burning preceding detonation was investigated for RDX, PETN, HMX, and tetryl. The results for the first three show that, as the density increases, the length of burning necessary before detonation becomes smaller, but there is maximum value of density beyond which the transition into detonation is more difficult.

It was very difficult to ignite tetryl under the experimental conditions and the transition to detonation did not occur readily. Under other conditions, however, tetryl can be burnt to detonation.

The gas permeability of equal lengths of the explosive columns, pressed in four increments into the permeability tubes at different pressing loads, was measured and is plotted against length of burning in Fig. 1. It is seen that as gas permeability increases from crystal density there is a very rapid reduction in the required length of burning column. Finally a limit is reached and there is then some increase as bulk density is approached.

Effect of Particle Size at Constant Loading Pressure.—The effect of varying the particle size at constant pressing load was investigated with the same type of brass tubes and the same technique as above. Experiments were with RDX, PETN, and HMX and a pressing load of 1 ton/sq. in. As the particle size of the explosive is reduced the length of burning before detonation shortens, but a limit is reached beyond which smaller particle size requires progressively increasing burning lengths. For RDX and HMX the optimum size was 251—124 μ . The PETN optimum was at 124—76 μ , and its minimum burning length of 0.2 cm. was considerably shorter than for other explosives. Gas-permeability measurements were made on samples of each particle size, with four increments of equal weight. The dead load on the press was

adjusted to give the same density for each sample. The length of burning before detonation for HMX is plotted against the gas permeability in Fig. 2. The densities used in the burning experiments were not the same as in the gas-flow experiments, so that only qualitative conclusions can be drawn, but it is clear that as the gas permeability increases there is a very rapid reduction in the burning length preceding detonation. A limit is reached, and for the columns of large particle size the burning length then increases again.

FIG. 1. Variation of length (cm.) of burning column and permeability (l/t) for HMX at various densities.

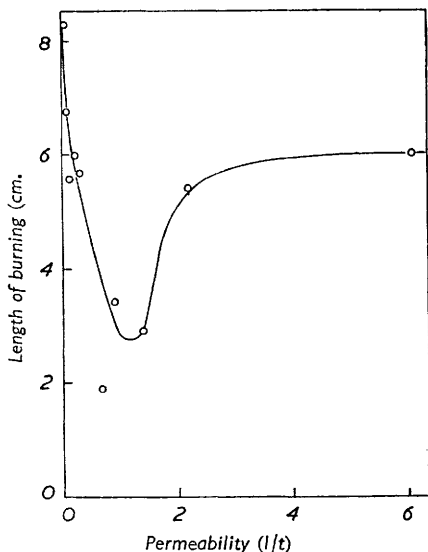
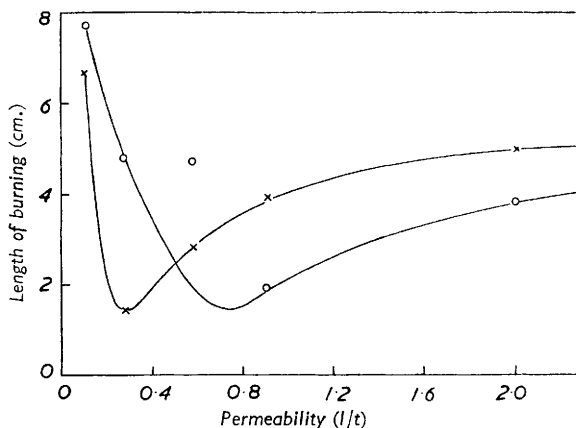


FIG. 2. Variation of length of burning and permeability (l/t) for HMX at various particle sizes.



Effect of Venting.—The effect of inhibiting the escape of combustion products by closing the back of the tube with a tightly fitting brass cap was examined and the results were:

Explosive	Confinement	Burning length (cm.)	Explosive	Confinement	Burning length (cm.)
Unsieved RDX (<i>d</i> 1.39)	Vented	5.5	HMX size 251—124 μ (<i>d</i> 1.28)	Vented	5.2
	Unvented	4.0		Unvented	1.9
PETN size 422 μ (<i>d</i> 1.44)	Vented	1.0			
	Unvented	0.8			

For RDX and HMX, and to a smaller extent for PETN, the interiors of the unvented tubes were stained with carbon products, whereas the vented tubes were clean. For all the explosives, the vented tubes required a longer length of burning before detonation was achieved.

The "Bridge" between Combustion and Detonation.—A typical record from a rotating-mirror camera is shown on Plate 2. Clearly the stable detonation starts ahead of the combustion front and the gap is "bridged" by a detonation wave travelling back towards the oncoming combustion. This reverse detonation wave is sometimes called a retonation wave.

A sequence of framing camera records, shown on Plate 3, shows the burning velocity to be very slow in the early stages (1 cm./sec.) and suggests a convective type of burning in the latter stages, with a velocity of about 1000 m./sec.

DISCUSSION

Mechanism of Initiation of Combustion.—The mechanism by which detonation is achieved in a heavily confined column of granular explosive, after gentle ignition, is complex. The flame from the igniter impinging on the end of the column causes the explosive in this region to decompose thermally and if the flame is of sufficiently high temperature the rate of decomposition of the explosive at this end of the column becomes high. The

system is analogous to one that has been analysed mathematically by a number of workers.³ It is assumed that one surface of a slab of explosive initially at temperature T_1 is instantaneously brought to, and subsequently maintained, at a temperature T_0 . The variation of the temperature T within the explosive slab as a function of time and distance is then calculated. For the one-dimensional semi-infinite case the equation used is:

$$\rho c \, dT/dt = \rho Q \, de/dt + K \, d^2T/dx^2 \quad . \quad . \quad . \quad (1)$$

where K is the thermal conductivity of the explosive, ρ its density, c its specific heat, and Q its heat of reaction per unit weight. de/dt is the rate of reaction. In effect, the equation considers the rate of temperature rise of unit volume of the explosive in the reaction zone in terms of the heat liberated by chemical reaction and lost or gained by thermal conduction. By making simplifying assumptions Cook³ has numerically integrated equation (1). A series of temperature-distance profiles similar to those given in Fig. 3 is obtained and it is shown that, for a given explosive and particular values of T_0 and T_1 after a certain time interval, the temperature at a particular small distance from the interface becomes high. The decomposition rate at this position has, therefore, a high value, and the explosive is said to have undergone a thermal explosion.

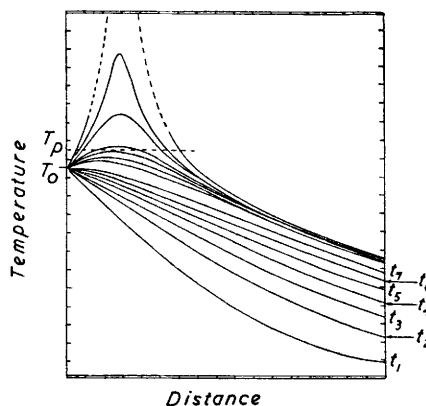


FIG. 3. Temperature-distance profiles.

Combustion with Energy Transfer by Conduction.—The simple theory described in the last paragraph can be extended to enable the velocity of any particular temperature (*e.g.*, T_p in Fig. 3) as it moves through the explosive slab, to be calculated, and it is clear that once the thermal explosion condition has been passed, this velocity is the combustion velocity. Several workers⁴ have used equations similar to equation (1) in calculating flame velocities for gaseous systems. The gas is initially at temperature T_1 , and after passage of the narrow reaction zone the temperature of the gas remains constant at the much higher final temperature T_2 . Boys and Corner,³ by making approximations, show that the combustion velocity is given by an expression of the form:

$$v^2 = [RT_2^2/E(T_2 - T_1) - RT_2^2](KB/c\rho) \exp(-E/RT_2) \quad . \quad . \quad (2)$$

where B and E are the pre-exponential terms and activation energy of the reaction respectively.

Equation (2) has been used⁵ with considerable success in predicting combustion velocities for mixtures of oxidising and reducing agents in which all reactants and products are solids. For a mixture of iron and potassium permanganate Hill⁶ calculated velocities of about 0.1 cm./sec., in close agreement with experiment.

³ Cook, A.R.D.E. unpublished Ministry of Supply report.

⁴ Boys and Corner, *Proc. Roy. Soc.*, 1949, *A*, **197**, 90; Von Karman, Sixth Symposium (International) on Combustion, 1957, p. 1.

⁵ Hill, Sutton, Temple, and White, *Research*, 1950, **3**, 569.

⁶ Hill, *Proc. Roy. Soc.*, 1954, *A*, **226**, 455.

The combustion of solid high explosives is much further removed from the simple model than an oxidising-reducing system, particularly as the products are gaseous. Even if allowance could be made for this, equations of the Boys-Corner type cannot explain the combustion velocities of up to 1000 m./sec. found in high explosives. With a reaction rate of 10^8 sec.^{-1} , as found in detonation zones,⁷ the velocity would be only 1 m./sec. The high experimental combustion velocities must therefore depend on a different method of energy transfer and it is suggested that this is convection, hot combustion products being forced ahead of the reaction zone into the unchanged explosive.

The burning of unconfined columns of low-density PETN, RDX, and HMX in a conventional strand burner has been described by Taylor.⁸ At low ambient pressures "normal" burning rates, which are less than 1 cm./sec., are observed. At ambient pressures higher than a critical value, which varies with the explosive and its physical form, higher velocities up to 1 m./sec.⁹ are observed.

Stages in the Burning to Detonation.—It is now possible to break down into a number of stages the mechanism by which detonation is achieved in a granular solid explosive after gentle ignition. When the flame from the igniter impinges on the end of the column decomposition of the explosive occurs in this region. If decomposition is sufficiently rapid a thermal explosion occurs near the end of the column and a combustion wave starts to move down the column. If the mechanism of heat transfer is by conduction the velocity will certainly be less than 1 m./sec. and will probably be less than 1 cm./sec., as observed by Taylor.⁸ Under the correct conditions the energy-transfer mechanism will be by convection rather than conduction; the transition from the conductive mechanism to the convective mechanism can be seen in Plate 3. Much higher combustion velocities are then possible. Finally a very high combustion velocity of the order of 800 m./sec. leads to the production of detonation by a mechanism which will be discussed below.

The experimental work described here deals in the main with the high-velocity combustion governed by convection and the transition to detonation. All the results support the hypothesis that detonation depends on the build-up of a very high combustion velocity. The velocity of combustion which can be reached by a mechanism of energy transfer in which hot reaction products penetrate into the unchanged explosive will depend on a number of factors among which may be listed (a) the pressure and temperature of the gas products, (b) the resistance of the explosive to the penetration of the gas products, and (c) the efficiency of transfer of energy from the gaseous products to the unchanged explosive.

If backventing is prevented detonation is reached more easily because in the absence of venting the pressure in the combustion zone is higher and the flow of gas forwards is facilitated. The close correspondence between the ease of production of detonation and the air-permeability tests shows the importance of (c). When permeability is altered by varying the density of the explosive column, factor (a) also is important. As the density decreases the permeability increases and this assists the combustion, but at the same time the pressure in the reaction zone must decrease and this retards the combustion. A curve of the type found experimentally (Fig. 1) is therefore expected. Similarly, when the permeability is varied by changing the particle size at constant density, the combustion is made easier as the particle size is increased (Fig. 2) because the permeability of the bed is increased. However a limit is soon reached, because the efficiency of transfer of energy from the gaseous products to the unchanged explosive is reduced by the low surface : volume ratio of the particles of explosive. Changing the explosive will change both the pressure and the temperature of the combustion—heat of explosion will be the most important

⁷ Copp and Ubbelohde, "High Speed Aerodynamics and Jet Propulsion," Oxford Univ. Press, Vol. II, 1956, p. 592.

⁸ J. W. Taylor, personal correspondence.

⁹ Lewis and Von Elbe, "Combustion, Flames and Explosions," Academic Press Inc., New York, 1951, p. 591.

parameter here—and therefore will change the reaction rate. PETN with its high heat of explosion will be different from HMX and RDX.

The combustion will produce gas at an elevated pressure in the reaction zone. Most of this gas will flow backwards but some will flow forwards into the pores of the unchanged explosive. The ratio of the flow forwards to that backwards will be inversely proportional to the resistance to gas flow in the two directions. In addition, the flow in both directions will increase if the combustion velocity increases.

Mechanism by which Detonation is Achieved in "Gap" Tests.—The generally accepted view of the mechanism by which detonation is achieved in "gap" experiments can be made more definite by introducing the concept of a thermal explosion, building up in the wake of the shock wave. If the temperature and pressure immediately behind the shock wave are T and P , the rate of energy loss from this region will be a function of P if shock processes are important, and dependent upon T if conduction processes are important. T will initially be in the region 400–500° C,⁹ so it is not unreasonable to represent rate of chemical reaction by an Arrhenius type equation. The rate (dT/dt) at which the temperature behind the shock front changes can therefore be represented by:

$$dT/dt = (1/\rho c) f(P, T) + (QZ/C) \exp(-E/RT) \text{ (}^\circ\text{C/sec.)} \quad . \quad . \quad . \quad (3)$$

where $(1/\rho c) f(P, T)$ is the energy loss term and $(QZ/C) \exp(-E/RT)$ is the term covering energy gain by chemical reaction.

It is not possible to solve equation (3) as it stands, but a similar equation, which is soluble with certain approximations, has been used by Groocock² to represent the thermal decomposition *in vacuo* of a crystal of an explosive. The crystal is tipped into a reaction vessel at temperature T_A °K. It immediately starts to lose or gain heat to the vessel at a rate proportional to $(T_A - T)$, where T is the temperature of the crystal (the crystal is sufficiently small for the temperature within it to be uniform) and it is also assumed to decompose with zero-order kinetics, so that it gains heat by chemical reaction. The rate at which its temperature changes can therefore be represented by:

$$dT/dt = h/C(T_A - T) + (QZ/C) \exp(-E/RT) \text{ (}^\circ\text{C/sec.)} \quad . \quad . \quad . \quad (4)$$

where h is the total thermal emissivity of the crystal. This equation can be integrated graphically for particular values of the various constants; *e.g.*, values which give a reasonable representation of an organic high explosive and also simplify the calculation are: $E = 46.6$ kcal./mole, $h/C = 10^5$ sec.⁻¹, $Q/C = 4000$ °C/g., and $Z = 2.5 \times 10^{19}$ sec.⁻¹.

The integration gives curves of temperature against time for the crystal and these can immediately be used to obtain curves of reaction rate against time. Four curves of the latter type are given in Fig. 4. For curve *A* it was assumed that at time $t = 0$ the crystal was heated to a temperature of 660° K and then was immediately exposed to room temperature (300° K). It is clear that the reaction rate although initially low rises continuously and explosion occurs after about 0.72 microsecond. Curves *B* and *C* are similar, but for curve *D*, where it is assumed that T_0 is only 640° K, the reaction rate falls continuously and no explosion occurs. The critical condition is that $dT/dt = 0$ when $t = 0$, and by use of this it can be shown that explosion will only occur if the initial temperature, T_0 , of the crystal is greater than 647° K.

Fig. 4 could equally well give a qualitative impression of the reaction rate immediately behind the shock in a "gap" test, provided that equations (3) and (4) are mathematically similar. It is likely that this will be so: in thermal explosion the energy losses increases roughly proportionally to the excess temperature, and in shock initiation the energy losses increase roughly proportionally to the excess shock pressure and temperature. Similarly in both cases the chemical reaction, even if not following the Arrhenius equation exactly, will vary very rapidly with the temperature. Applied to shock initiation, curve *A* of Fig. 4 would represent the entry into the explosive charge of a shock sufficiently intense to

give an initial temperature of 660°K . Reaction would start at a low rate and, at first, the reactive shock would be experimentally indistinguishable from a non-reactive shock. However, after 0.72 microsecond the reaction rate immediately behind the shock would suddenly become high and at this stage the reactive shock would change to stable detonation. In the 0.72 microsecond induction period the reactive shock would have gone some distance into the receptor charge, say 1.4 mm., and detonation would start at this point.

For a slightly less intense shock, giving an initial temperature of only 640°K , the reaction rate behind the shock would fall continuously (curve *D*) and the latter would soon become completely non-reactive.

There are two main differences between thermal initiation of explosion and shock initiation of detonation. (a) Thermal explosion normally occurs in a stationary system and gives no direct method by which any wave associated with it can accelerate to a high velocity. In shock initiation the shock is moving at a high velocity and acceleration to the detonation velocity arises naturally when the reaction rate in its wake becomes very high. (b) In thermal explosion the "spiral" leading to explosion contains only temperature and reaction rate: chemical reaction causes a rise in temperature which in turn causes a rise in reaction temperature which in turn causes a rise in reaction rate. In shock initiation the "spiral" is more complex. The shock raises the temperature of the explosive; the consequent chemical reaction causes a rise in pressure in the already shocked material;

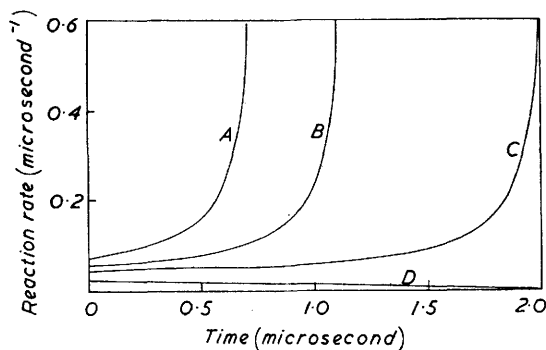


FIG. 4. Variation of reaction rate (microsecond⁻¹) and time (microseconds). *A* = 660°K , *B* = 655°K , *C* = 650°K , *D* = 640°K .

pressure pulses moving through the already compressed material catch the shock up and reinforce it; the reinforced shock gives a higher temperature, and so on.

Mechanism by which High-velocity Combustion Leads to Detonation.—Suppose that a combustion wave of constant velocity has just been established in a confined column of granular explosive with limited rear-venting. The reaction zone will be a region of high pressure and temperature, and the combustion will be propagated by the convective method of energy transfer described above. In addition, a compression wave will precede the combustion into the unchanged explosive at a high velocity—the velocity of sound in this material. The compression wave as it passes through the explosive will do work on the explosive and there will be a transfer of energy from the wave to the explosive. Consequently, as the head of the compression wave proceeds progressively farther ahead of the combustion wave, the pressure increase at the head of the wave becomes progressively less. The mechanism is essentially the same as that by which a shock wave degrades in a non-reactive material. The pressure profile near the combustion region is maintained by the constant high pressure of the combustion region—it is only the head of the compression wave which degrades.

For a combustion of higher, but still constant velocity, the profile would be similar, except that the pressure in the reaction zone will be higher and the rate of working on the explosive immediately ahead of the zone will also be higher. Consequently the pressure gradient in this region will also be greater.

For an accelerating combustion there will be two groups of effects. The first will be the progressive change of the pressure profiles of a low-velocity combustion into those of a higher-velocity combustion. The second will be the effects due to the acceleration itself. It is well known⁹ that in gases an accelerating combustion propagates a series of compression waves. The later waves, passing through already compressed gas, travel faster, and eventually they all coalesce to form a shock wave. A similar effect will be found in the system under consideration, and the acceleration of the combustion will tend to maintain the compression front as it moves ahead of the combustion.

It is thought that the final stage in the production of detonation in a solid burning-to-detonation system has the same mechanism as that occurring in "gap" tests. There are two mechanisms by which the necessary intense compression wave can be built up. The first is that to occur in gases, mentioned above. In this case the first intense compression wave as it proceeds progressively further ahead of the combustion wave is reinforced by additional shocks due to the acceleration of the combustion. Finally, the shock intensity exceeds the critical "gap test" shock intensity for the explosive and starts the growth process leading to detonation. It is probable from the experimental results that, if this is the mechanism, the important reinforcement of the shock wave will occur when the combustion front is accelerating from, say, 100 m./sec. to 1000 m./sec. The shock velocity throughout this period will be greater than 2000 m./sec., so that the point at which detonation is achieved will be progressively further ahead of the combustion front the longer the build-up takes. A separation of 1 cm. will be present if detonation is initiated in a few microseconds, and only in long charges will it be possible for detonation to be delayed 20 or 30 microseconds after the establishment of rapid combustion. In gaseous detonations of this type shock reflections off the end of the tube, if this is sealed, are often important and it might be that long delays before the production of detonation in solids might be explained in these terms.

In the second method it is considered that the reinforcement of shocks at the shock front is relatively unimportant. This will be true if the shock front degrades more rapidly than it can be reinforced by the accelerating combustion. On this theory a constant-velocity combustion will be sending out a continual series of compression waves, which will be most intense just as they leave the combustion and will quickly die away as they pass into the unchanged explosive. With an accelerating combustion (or a constant-velocity combustion in which the venting is progressively reduced), the pressure in the reaction zone will increase and with it the intensity of the shock waves emanating from it. Finally, a shock wave may be produced at the front of the combustion which exceeds the critical "gap test" intensity and this, instead of degrading, will build up to detonation after the usual induction period.

It is seen that for both mechanisms there is a separation between the combustion front and the point where detonation is produced. For the second mechanism this is exactly equivalent to the "run up" length in gap tests. The critical wave will appear when the combustion velocity (or venting) reaches a critical condition and there are no limitations on the time for this. For the first mechanism the separation includes the "run up" length, but adds the length that the shock has gone ahead during the acceleration of the combustion.

In both cases a reverse detonation wave will go back from the point where detonation is produced. This reverse detonation wave will degenerate into a shock wave when it reaches the already burnt region. The convective combustion, the non-luminous shock, the detonation wave, the retonation wave in the unconsumed explosive, and the retonation wave in the combustion products are all clearly shown in the streak camera photograph (Plate 2).

It has been suggested that the mechanism by which detonation is finally initiated is similar to the mechanism by which detonation is initiated in "gap" tests. It seems clear that this can be true only if the pressures developed in the combustion zone are of the same

order as those found effective in "gap" tests. Marlow and Skidmore¹⁰ have shown that a shock in cast 60/40 RDX/TNT will become reactive and initiate detonation only if its pressure is greater than about one-tenth of the detonation pressure. The pressure that must be built up to initiate detonation in granular explosives which are much more sensitive to shock than RDX/TNT is therefore likely to be considerably less than one-tenth of their detonation pressures, and there seems no reason why pressures as high as this should not be built up in the combustion region. The expansion of the brass tube found experimentally in the combustion region, although much less than in the detonation region, is in accord with the suggestion that the pressures in this region are very high.

Both mechanisms for the production of the intense shock, which starts detonation, depend upon the acceleration of the combustion wave. Experimentally it is clear that in the heavily confined columns of explosive the combustion is accelerating, and two mechanisms by which this can occur are suggested. First of all, the convective-combustion mechanism is self-accelerating. As the combustion rate increases, the pressure in the combustion zone increases (with consequent increase in temperature and reaction rate) and the hot gases go ahead more rapidly into the unchanged explosive. Secondly, the shock effects build up progressively and, even when they are below the level at which they can initiate reaction themselves, they will assist the following combustion by raising the temperature and pressure of the explosive.

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¹⁰ Marlow and Skidmore, *Proc. Roy. Soc., A*, **246**, 285.
