443. *The Explosive Initiation of Trinitrophenylmethylnitramine by Projectile Impact.*

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The initiation of trinitrophenylmethylnitramine by projectile impact has been studied by high-speed photography and it is shown that the initiation originates from the shock wave which enters the explosive on impact. The shock wave releases energy and the resulting balance of energy gained and lost by the shock wave determines the probability of detonation.

GRIFFITHS and GROOCOCK [1] have described the mechanism by which columns of solid granular explosive burn to detonation. They showed that the process occurred in a number of stages and that the final stage was the shock initiation of the explosive. Macek [2] has considered the conditions of pressure and density which govern the propagation of compression waves through unchanged explosive and has also suggested that the transition from burning to detonation was due to a shock which arose in the burning medium. Initiation by weak shock waves therefore represents a field of great interest in the study of the burning to detonation transition.

Numerous workers, *e.g.*, Cachia and Whitbread,[3] Marlow and Skidmore,[4] and Cook [5] have considered the shock initiation of explosives in the " gap-test " type of experiment. Spells and Woodhead [6] have studied the initiation of detonation by projectile impact,

[1] Griffiths and Groocock, *J.*, 1960, 4154.
[2] Macek, *J. Chem. Phys.*, 1959, **31**, 162.
[3] Cachia and Whitbread, *Proc. Roy. Soc.*, 1958, *A*, **246**, 268.
[4] Marlow and Skidmore, *Proc. Roy. Soc.*, 1958, *A*, **246**, 285.
[5] Cook, " The Science of High Explosives," Reinhold Publ. Corp., New York, pp. 83—84.
[6] Spells and Woodhead, *Nature*, 1957, **179**, 251.

using an explosively accelerated projectile. They showed that delay between the arrival of the projectile and initiation of the explosive was too short to be resolved by the technique used and could not exceed a time of the order of 1 μsec. Sultanoff [7] has studied the sympathetic initiation of high explosives by pressure pulse and has shown the importance of a reaction occurring in the core of the explosive and the changing shape of the profile of this reacting core with various lengths of explosive. Whitbread [8] has photographed the initiation by shock of an RDX crystal and showed that nearly all the crystals detonated in the reverse direction. Recently, Whitbread [9] has considered the initiation of detonation by shock and demonstrated that the controlling factor in the initiation was the shock wave in the explosive. Projectiles of specified composition and shape were used to provide shocks of known intensity and shape.

The present paper considers the initiation of trinitrophenylmethylnitramine by the impact of a fast-moving projectile fired from a 0·5 in. gun.

Experimental

Materials.—The high-explosive charges were prepared by Messrs. D. McKenzie and H. B. Young of the Armament Research and Development Establishment, to whom the authors are indebted.

Projectile Attack.—The experimental arrangement is shown in Fig. 1. A 0·5-in. smooth-bore gun (C) was used to propel a cylindrical steel projectile (diam. 0·5 in., length 0·5 in.) at a

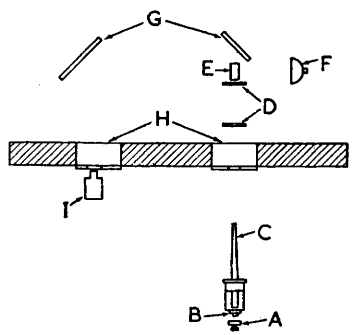


FIG. 1. Experimental arrangement for the initiation of explosives by projectile impact.

A, Falling hammer for actuating striker pin. B, Striker pin. C, 0·5″ Browning gun (smooth bore). D, Velocity screens connected to microsecond chronometer to record projectile velocity. E, H.E. charge (suspended). F, Flash bulb reflector for background illumination. G, 45° Mirrors. H, Portholes. I. Camera.

freely suspended cylindrical explosive charge (E) (length 3·0 or 1·5 in., diam. 1·5 in.) of tetryl (2,4,6-trinitrophenylmethylnitramine).

The velocity of the projectile was measured by using two " make " velocity screens (D) placed 1 ft. apart between the gun and the explosive charge. The time of travel of the projectile over this distance was recorded by a Cintel microsecond counter chronometer. In this way the velocity of the projectile was obtained for a series of weights of propellant used in the 0·5 in. cartridge case, enabling a calibration curve for velocity–weight of propellant for the gun to be obtained. It was found that the relation between velocity and weight of propellant used was linear and that the spread of velocity was not great. The velocity screens were therefore dispensed with for later work.

Photography.—A modified Fastax framing camera and a Beckman and Whitley framing camera were used to study the resulting reaction in the explosive. The Fastax camera was adapted to a conventional " streak " camera by removing the framing block and introducing a focal-plane slit. This enabled records to be obtained over a relatively long time although at a low writing speed. The long and variable delay between the firing of the gun and the appearance of light from the reaction in the explosive makes synchronisation with the Beckman and Whitley camera difficult. Records, however, have been obtained at framing rates below the maximum.

The longitudinal side of the charge was viewed by means of a mirror placed at 45° to the

[7] Sultanoff, *J. Soc. Motion Picture & Television Engineers*, 1960, **69**, 113.
[8] Whitbread, Proc. of 31st Internat. Congress Industrial Chemistry, Liége, Sept., 1958.
[9] Whitbread, Proc. Les Ondes de Détonation, C.R.N.S., Gif-sur-Yvette, August, 1961.

charge and the camera; another mirror at 45° to the axis of the charge and at 90° to the first mirror brought an end-on view of the charge into the field of the camera.

Only the light emitted on the surface of a solid explosive charge can be photographed. Often, in growth problems, the reaction begins inside the charge and in these circumstances it is difficult to decide between the absence and the obscuration of light. For this reason various lengths of charges were studied, the end-on face being photographed *via* a 45° mirror. This enabled the progress of the reaction inside the charge to be built up from a number of shots. As such an assessment is dependent on the reproducibility of the phenomenon from charge to charge, only qualitative conclusions can be drawn.

The field of the explosive and projectile at impact was back-lighted so that photographs were obtained in silhouette. The resulting records enabled the delay, velocity, and direction of the reaction in the charge to be determined.

Results

A number of shots were fired at a velocity of 553 m./sec., a velocity at which there is a 99·99% probability of the charge detonating. A typical streak record is shown in Plate 1. Light appears immediately at the leading edge of the charge and initially there is an apparent high velocity of reaction. At a distance of 2·2 cm. away from the impacted end the velocity of detonation is normal at 7500 m./sec.

Records were next taken with the velocity of the projectile reduced to 394 m./sec., a velocity at which there is a 50% chance of the charge detonating. Two typical streak records are shown in Plates 2 and 3. In Plate 2 light first appears 2·6 cm. away from the impacted end of the charge, and detonation proceeds forwards at a velocity of 6850 m./sec. and backwards at an apparently much higher velocity. The 45° mirror shows the emergence of the air shock from the charge six microseconds before the emergence of the detonation wave from the end of the charge. This correlates with the first appearance of light on the perpendicular view.

The charge length was then reduced from 3·0 in. to 1·5 in. A streak camera record is shown in Plate 3; the velocity of the projectile was 394 m./sec. Light is first evident at the non-impacted end of the charge. Detonation proceeds stably in the reverse direction at a relative velocity of 8300 m./sec. The reproduction of the record *via* the 45° mirror is not good. The negative shows detonation starting at a point off the charge axis and as a consequence there is a difference in time between the first appearance of the air shock on the two sides of the charge viewed.

Further records were taken with a Beckman and Whitley framing camera, with a charge 1·5 in. long and a projectile velocity of 825 and 682 m./sec. Two typical records are shown in Plates 4 and 5. In Plate 4 light first appears at the non-impacted end of the charge, and detonation then proceeds back down the charge. The dark lines seen across the records are the strings supporting the charge. Much of the detail of the detonation is lost owing to the high framing interval of 2·3 microseconds. Nevertheless an indication is given of a core reaction inside the charge, proceeding in the forward and the reverse direction. At the same time reaction grows outwards.

In Plate 5 light again appears first at the non-impacted end of the charge, but in this case only at one corner. Once again much of the detail is lost in subsequent frames but nevertheless a core reaction is apparent and is clearly seen to be non-axial by the tilting of the emergent air shock.

Examination of the projectiles recovered after firing reveals some features of interest. The damage to the projectile is related to the order of reaction in the explosive and examples are shown in Plate 6 of projectiles recovered after (a) non-detonation, (b) detonation, axial initiation, and (c) detonation, non-axial initiation, and (d) an unfired projectile. When the explosive charge does not detonate the projectile is seen to be slightly expanded at its leading face. When the explosive charge detonates on its axis the leading face of the projectile is sharply " mush-roomed " out and the projectile is squashed by the detonation wave. This indicates that a detonation wave travelled towards the oncoming projectile and it must therefore mean that detonation in the attacked explosive started ahead of the projectile.

Sometimes, as was shown earlier, non-axial initiation of the explosive occurs and the projectile recovered from this type of firing is shown in Plate 6. The damage to the projectile is similar to that seen in the previous case, but in addition there is an indentation in the leading face. Detonation started ahead of the projectile as before, but not on the axis, and some type of peripheral initiation occurred resulting in a minor hollow-charge effect as shown by the hole in the projectile.

Discussion

The mechanism of the initiation of explosives by projectile impact is complex. From the experimental results described in this paper a qualitative mechanism can be suggested.

The first mechanism to be considered is that the initiation takes place on the surface of the projectile as it drives through the explosive, heating it by friction and transfer of energy as the projectile is decelerated. In Plate 6 the projectiles recovered after firing show that detonation started ahead of the projectile. In addition, the times to detonation are all of the microsecond order. Griffiths and Groocock [1] showed that where initiation was not by shock much longer times would be expected. It is suggested therefore that initiation does not take place on the surface of the projectile, but in the shock wave which is propagated into the explosive when it is impacted by the projectile.

On impact of the projectile with the explosive a shock wave will move forward into the explosive whilst one of equal pressure moves back into the projectile; the pressure in the explosive is maintained until the rarefaction arrives at the projectile explosive interface. It was previously shown [1] how the rate of reaction behind a shock wave entering an explosive varied with time for particular initial conditions of pressure and temperature, and this is illustrated in Fig. 2 which is reproduced from ref. (1).

Curve A of Fig. 2 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 reaction 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. During 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 less intense shock (curve D) the reaction rate behind the shock would fall continuously and it would soon become completely non-reactive. Intermediate cases are represented by curves B and C.

In the present system, therefore, when the projectile impacts on the charge a shock wave proceeds into the charge. The intensity of the shock and hence the energy produced in the explosive will depend on the velocity of impact, the cross-sectional area, and the length of the projectile.[9] (Only the velocity of the projectile was varied during the present investigation.) If the velocity of the projectile is high the intensity of the transmitted shock will also be high and detonation will occur after only a short delay (curve A). A projectile at a lower velocity will transmit a less intense shock into the explosive and detonation will occur after a longer delay (curves B and C). An even lower velocity will lead to a shock such that the rate of reaction falls continuously and the charge will fail to detonate (curve D).

If this type of interpretation is correct it would account for the experimental evidence obtained. In order to simplify the explanation of the photographic records, three diagrams are reproduced in Fig. 3 indicating the manner in which a detonation wave is established in the explosive for three different initial conditions of loading.

In Fig. 3(a) a high-velocity projectile is considered and detonation is established very quickly at X. This would correspond to curve A of Fig. 2. In considering the progress of the reaction from this point onwards it must be borne in mind that the cross-sectional area of the projectile is less than the cross-sectional area of the explosive. Initiation can start anywhere along the plane of the explosive impacted, and for the present purpose it has been taken as a point either on or off the axis of the explosive. It is important to note that initiation starts inside the explosive charge and the position of this point on the axis of the charge will determine when light first appears on the surface of the charge. Care must therefore be taken in distinguishing between the absence of light and hence reaction, and the obscuration of light by the explosive.

In Fig. 3(a), after detonation is established at a time T_2 it grows outwards and appears at the surface at a time T_3. The delay time Δt_2 ($T_3 - T_2$) is not an initiation delay; it is the time taken for the detonation to traverse the distance from the point of initiation to the surface of the explosive charge. So from T_3 onwards the streak camera will record a normal detonation velocity, but before T_3 (in the region from T_2 to T_3) it will record a phase velocity (in this case a horizontal component of a radial velocity). This type of initiation is illustrated in Plate 1 where the interval $\Delta t_1 + \Delta t_2$ corresponds to a distance

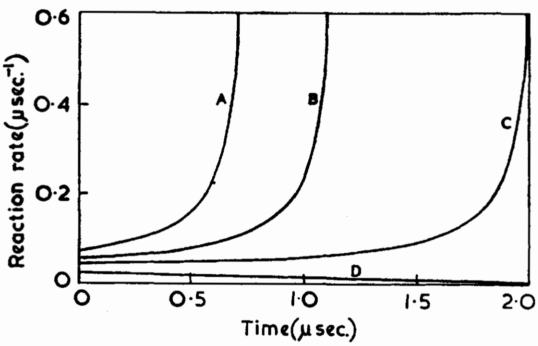


FIG. 2. Graph of reaction rate in the wake of a shock against time, for different initial shock pressures. A, B, C lead to thermal explosion, but D to failure.

$(T)_{t=0}$: A, 660°; B, 655°; C, 650°; D, 640° K.

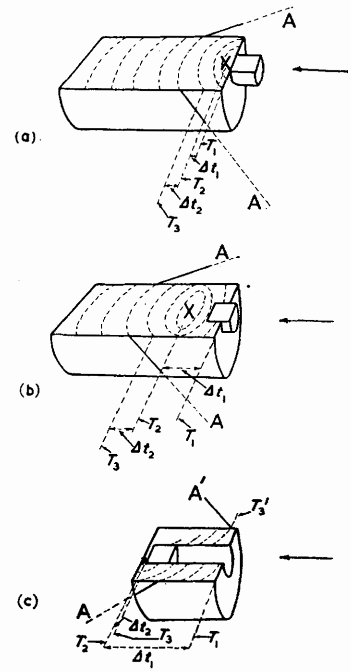
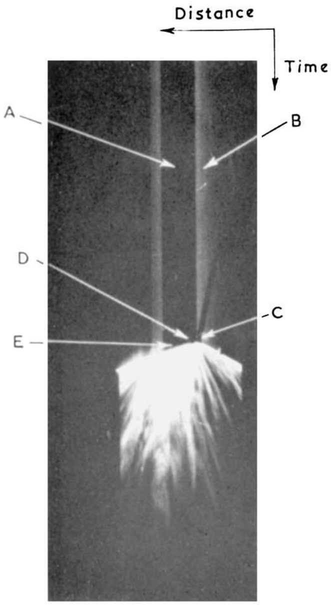
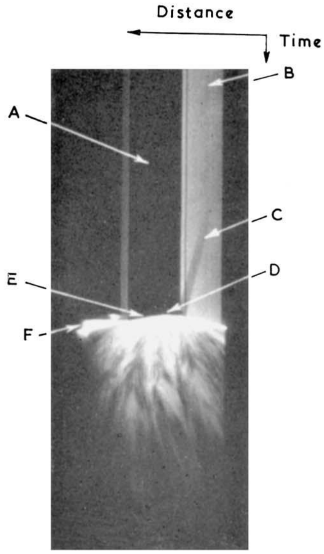


FIG. 3. Charge length: (a) 3″; (b) 3″; (c) 1·5″. Arrows denote direction of projectile attack. A = Air shock from T_3 outwards; A′ = air shock from T_3' outwards.

along the charge of 2·2 cm. From that point onwards a normal detonation velocity of 7500 m./sec. is recorded.

In Fig. 3(b) a lower-velocity projectile is considered and detonation is established at X after an induction period Δt_1, where T_1 is the time of impact and T_2 is the time initiation started at the shock front ahead of the projectile. (This would correspond to curve B or C in Fig. 2.) After detonation is established it grows outwards and appears at the surface at a time T_3 and, as before, in the region from T_2 to T_3 a high-phase velocity would be recorded. From T_3 onwards the normal detonation velocity would be observed. At the same time a similar process occurs in the reverse direction—a retonation—and this too will require time to grow out to the surface. This type of initiation is illustrated in Plate 2. Light appears first 2·6 cm. away from the plane of impact and initially a high-phase velocity of detonation is observed corresponding to the region from T_2 to T_3 followed by a normal detonation velocity of 6800 m./sec. corresponding to the region from T_3 onwards. A retonation of high-phase velocity is also recorded corresponding to the





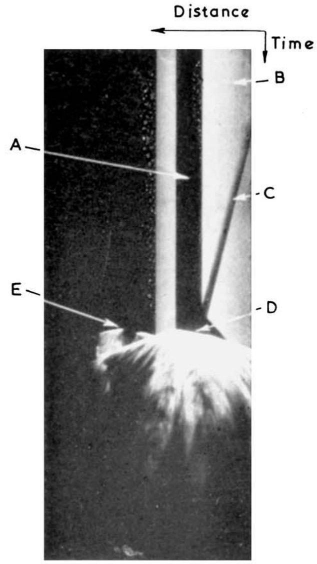


PLATE 1. PLATE 2. PLATE 3.

PLATES 1, 2, & 3. Shock initiation of tetryl. Writing speed $\frac{1}{3}$ mm. per microsecond. A, Charge silhouette. B, Back lighting.

PLATE 1. C, Projectile silhouette, velocity 553 m./sec. D, Stable detonation 2·2 cm. from initiating end. E, Detonation velocity 7500 m./sec.

PLATE 2. C, Projectile silhouette, velocity 394 m./sec. D, Onset of detonation 2·6 cm. from initiating end. E, Detonation velocity 6850 m./sec. F, End-on view of change *via* 45° mirror.

PLATE 3. C, Projectile silhouette, velocity 394 m./sec. D, Retonation velocity 8300 m./sec. E, End-on view of charge *via* 45° mirror. Delay between impact and detonation = 27 microseconds.

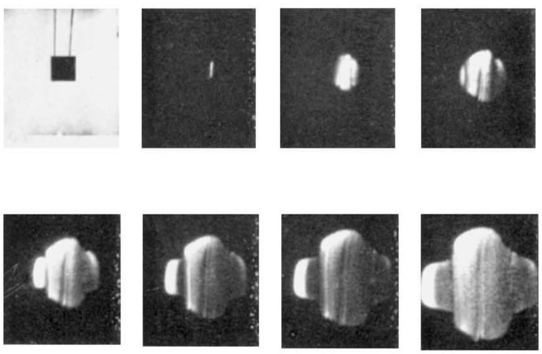


PLATE 4. Shock initiation of tetryl. Inter-frame time 2·3 microseconds. Projectile velocity 2700 ft./sec.

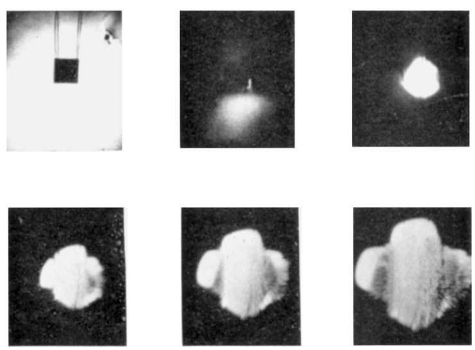


PLATE 5. Shock initiation of tetryl. Inter-frame time 4 microseconds. Projectile velocity 2230 ft./sec.

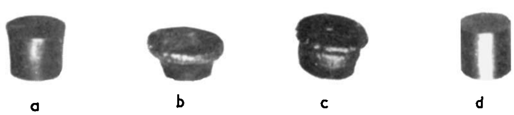


PLATE 6. Projectiles: (a) not detonated; (b) detonation, axial initiation; (c) detonation, non-axial initiation; (d) unfired.

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region from T_2 to T_1. In Plate 2 the charge length available was not sufficient for the retonation to establish itself on the surface and therefore only a phase velocity was recorded. The emergence of the detonation at T_3 is confirmed by the 45° mirror view which shows the air shock many microseconds ahead of the detonation front.

In Fig. 3(c) a shorter length of explosive charge is considered together with a low-velocity projectile and a non-axial initiation of the explosive. The conditions again correspond to curve B or C but, in this case, the reaction rate reached a high value (point X) at approximately the end of the charge and off the charge axis. Detonation is established at X after an induction period Δt_1 where T_1 is the time of impact, T_2 is the time when initiation started at the shock front, in this case at approximately the far end of the charge. After detonation is established it grows outwards and appears at the surface on one side of the charge very quickly, owing to the non-axial initiation point. At this stage the detonation is not established over the whole cross-section of the charge but takes a further interval Δt_2 before appearing at T_3. From T_3 onwards the streak camera will record a phase velocity due to the non-axial initiation.

This type of initiation is illustrated in Plate 3. The 45° mirror record indicates a point initiation off the axis of the charge and illustrates clearly the delay between the appearance of air shock on the two sides of the charge (T_3T_3'). Only a retonation is recorded in the perpendicular view. Initially the retonation has a high-phase velocity corresponding to the region from T_2 to T_3, which decreases but does not fall to the normal detonation velocity since the length of the charge is not sufficient to enable the detonation front to be established in a direction parallel to the charge axis.

The framing camera records reproduced in Plates 4 and 5 illustrate an axial and a non-axial initiation. In Plate 4 light first appears at the non-impacted end of the charge and over the major part of the diameter of the charge. Initiation in this case started at a point before the end of the charge and would correspond to curve B in Fig. 2. In Plate 5 light again appears first at the non-impacted end of the charge but at only one corner of the charge. Initiation in this case occurred at a later time than that shown in Plate 4 and in fact a lower-velocity projectile was used. The initiation would correspond to curve C in Fig. 2 and in particular to the wave diagram shown in Fig. 3(c).

A mechanism has been suggested for the initiation of an explosive by projectile impact in which the shock wave entering the explosive on impact initiates reaction which releases energy. The energy available from this reaction will counteract losses and, if sufficient, will reinforce the shock which will accelerate into a detonation. The probability of detonation is therefore controlled by the balance of energy gained and lost by the shock wave. This mechanism has been suggested before [1,3] for the "gap-test" type of experiments and by Whitbread [9] for projectile attack experiments. All the experimental evidence discussed in this paper can be accounted for on this mechanism. Cook [5] has suggested a heat-pulse theory to account for the shock initiation of homogeneous explosives. A heterogeneous explosive has been used in the present investigation and there does not seem to be any need to depart from a simple energy-balance mechanism to account for the experimental results obtained.

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