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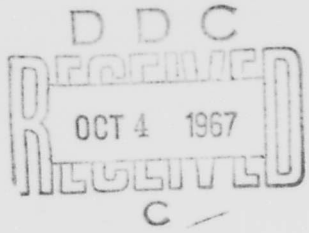

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Formation of cavities and microjets in liquids and their role in initiation and growth of explosion

By F. P. Bowden F.R.S. and M. P. McOnie

Surface Physics, Cavendish Laboratory, University of Cambridge

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[Plates 9 to 14]

The role of discontinuities, such as bubbles of gas and cavities, in the initiation and growth of explosion in liquids has been studied experimentally by means of high speed framing photography.

It is shown that micro Munroe jets can be formed at the surface of a gas bubble which has been trapped in the liquid explosive between two impacting surfaces and is being rapidly compressed. As the compression continues these jets are projected at high speed into the gas. Similar jets can be produced between two drops of explosive which are coalescing during impact. These jets may facilitate the initiation of burning both by increasing the impact velocity of the liquid and by dispersing the liquid within a pocket of compressed and heated gas.

The reaction grows first as an accelerating burning. The pressure developed in this burning zone has, in the early stages, the effect of closing up and removing any cavities which may exist in the explosive directly ahead of the flame front, so that the reaction advances into a homogeneous zone of liquid that is free from discontinuities. It is not until the comparatively slow burning breaks through the homogeneous high pressure zone, and reaches a zone of liquid containing numerous cavities and bubbles, that the burning is able to transform quickly into a much faster and more violent explosion. The discontinuities are then able to sustain the rapid propagation of explosion.

This region of discontinuities can be created in initially homogeneous liquids enclosed between solid surfaces by pressure waves which travel through the confining solids and ahead of the subsonic burning. If these pressure waves increase the distance between the confining surfaces substantially or are converted into rarefaction waves by reflexion, they can produce regions of tension in the unreacted liquid and disrupt it well ahead of the reaction zone. The bubbles of gas or cavities that are formed in this way by the precursor waves create an environment which is conducive to the rapid transition from burning to explosion.

Introduction

There is strong evidence that the initiation of explosion in liquids by impact or by shock is essentially a thermal process. A small region of the explosive is heated to a temperature at which fast reaction can occur. If the shock is very powerful (*ca.* 60 to 100 kbar) it can raise the temperature to a sufficiently high value simply by the rapid compression of the liquid itself. The propagation of high velocity detonation in a homogeneous liquid is sustained in this way. For gentler shocks, however, it is necessary for some discontinuity, cavity or bubble to be present in the liquid so that the energy of the shock or impact can be concentrated in this region and a localized hot spot can be formed. Some of the important ways in which these discontinuities can assist the initiation and the growth of the explosion are: (i) the adiabatic compression and heating of gas spaces; (ii) the reinforcement or the local distortion of shock waves; (iii) the dispersion of the explosive into fine particles; and (iv) the formation of micro Munroe jets (Bowden

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& Yoffe 1952, 1958; Winning 1956; Campbell, Davis & Travis 1961; Johansson 1958; Andreev 1958; Bowden 1963; Mader 1964).

There is evidence that, for mechanical impact and very gentle shock waves, where the pressure in the main shock front may be *ca.* 1 kbar or less and the duration long (perhaps some milliseconds), (i) and (iii) can be particularly important. If the shock is very gentle, γ (the ratio of specific heats, C_p/C_v, of the gas) is significant; if it is intense, γ does not matter because any gas or vapour can produce a high enough temperature. For moderate shocks, however, (e.g. in a 'gap' test), where the pressure in the shock wave may be *ca.* 5 to 30 kbar and the duration short (microseconds), we may expect that all the methods can operate but that (ii), (iii) and (iv) can be particularly important.

The geometry of the striker and the distribution of the explosive have a marked influence upon the ease with which cavities or pockets of gas can be formed during impact and consequently upon the sensitivity of the explosive. Distribution of the liquid as an annulus, a number of small drops or two parallel strips renders it particularly sensitive to impact (Bowden & Yoffe 1952).

Rapid heating of an included gas pocket, however, does not necessarily lead to initiation of a high explosive during an impact of low or moderate energy (Johansson & Selberg 1956; Bowden & Yoffe 1958). Initiation is achieved when an exothermic reaction can be easily started within the hot bubble or in a thin layer of explosive in contact with it. These favourable conditions can occur when the liquid explosive is dispersed as droplets within the bubble, or when thin layers or convex surfaces project into the cavity. It will be shown that high speed microjets of liquid can be formed when an annulus or a number of small drops of explosive are subjected to impact. These jets may aid initiation both by increasing the velocity of impact of the explosive and by dispersing it within a cavity in the form of very fine particles.

This paper describes experiments showing the formation of these microjets under various conditions. It also shows how cavities can be formed in the explosive ahead of the burning zone and illustrates their role in transforming the reaction into an explosion.

Experimental

The present experiments with explosive liquids were made with the aid of an A.W.R.E. C4 rotating mirror camera. This can take 140 frames at intervals of 5·0 μs and with a frame exposure time of 1·3 μs. The event was photographed in black and white on Kodak R60 panchromatic recording film. Since the film was not sufficiently sensitive to record light from the explosion until the final stage of violent reaction, the event was illuminated externally in transmission by a Mazda FA 2 xenon-filled flashtube. This light source was fired by the discharge of four 33 μF capacitors in parallel charged to 2·7 kV, giving an output of 500 J. The decay time of the light was sufficiently short to avoid the superposition of a second sequence of photographs on the first.

In the first experiments with explosive liquids the movement of the liquid during impact and the growth of explosion initiated by impact were studied.

Nitroglycerine was placed on a flat armourplate glass anvil (3 in. diameter) and was then hit by a flat armourplate glass hammer (1¼ in. diameter). The glass hammer was attached to the end of a fall hammer of the pendulum type and similar to that described by Bowden, Mulcahy, Vines & Yoffe (1947). The velocity of impact was about 250 cm/s, which corresponds to an impact energy of about 3 J.

Microjets in liquids

Earlier experiments (Bowden & Brunton 1961) showed that a shock wave passing over a curved liquid surface of appropriate shape could produce a micro Munroe jet. A small quantity of water was held in a strong steel chamber with a small orifice at one end. When a sudden shock pressure was applied to the water through a rubber disk at the other end of the chamber, the water was projected at high speed from the orifice. If the water–air interface was concave to the air, the main cylinder of water was preceded by a micro Munroe jet moving at much higher velocity. This process of jet formation is similar to that occurring on a large scale when a concave metal liner in a shaped explosive charge collapses into a high speed Munroe jet (Birkhoff, MacDougall, Pugh & Taylor 1948). It was suggested (Bowden 1963) that tiny Munroe jets might be formed when a compression wave arrives at a bubble or a curved surface of a small cavity in an explosive and that they could play an important part in the initiation and growth of the explosion. Watson & Gibson (1964) have confirmed that comparatively large scale jetting occurs when a shock wave falls on bubbles on the surface of a liquid explosive and that the jets can initiate explosion, probably by shock heating, when they impinge on another surface at sufficiently high velocity.

Results

Compression of a single cavity

In one set of impact experiments nitroglycerine was distributed as an annulus on an anvil and struck by a falling hammer. During impact the liquid explosive flowed outwards and inwards so that a single cavity containing air was trapped at the centre of a liquid film between the approaching surfaces and was rapidly compressed. The three frames of figure 1, plate 9, are taken from the same photographic sequence and show different stages in the compression of the central air space. The outer edge of the liquid film lies outside the field of view. The cavity in this experiment is elliptical. A tiny jet is formed at the region of maximum curvature of the concave liquid surface (frame *a*) and is forced at high speed (30 to 50 m/s) into the air pocket as the compression continues (frames *b* and *c*). A second jet is formed at the opposite side of the bubble (frame *b*) and is also projected rapidly into it (frame *c*). At a later stage (not illustrated in the frames shown) these two jets collide. The dark areas round the cavity and the point from which the microjet has sprung are probably either regions of liquid dispersed by the strong liquid flow under impact, or, more likely, areas where the curved liquid surface between the plates has caused the light from the flash tube to be reflected

(*a*) (*b*) (*c*)

FIGURE 1. Formation of microjets during impact on an annulus of nitroglycerine. A falling hammer has hit the annulus and trapped a single cavity containing air at the centre of the liquid film. As the cavity is compressed tiny jets of liquid are formed in the regions of maximum curvature of the concave liquid surface and are ejected (at about 30 to 50 m s^{-1}) into the central cavity. Interval of 10 μs between *a* and *b* and 5 μs between *b* and *c*. Diameter of field of view, 4·3 mm.

(*Facing p.* 40)

FIGURE 2. Formation of micropets between coalescing drops during impact. A falling hammer has struck hemispherical drops of nitroglycerine and is flattening them. (*a*) Two large drops coalesce; (*b*) two jets, formed at the highly curved region of contact, are projected at about 30 m s^{-1} away from the gap; (*c*) one of the jets hits a neighbouring drop. Interval of 25 μs between *a* and *b* and 5 μs between *b* and *c*. Diameter of field of view, 6·3 mm.

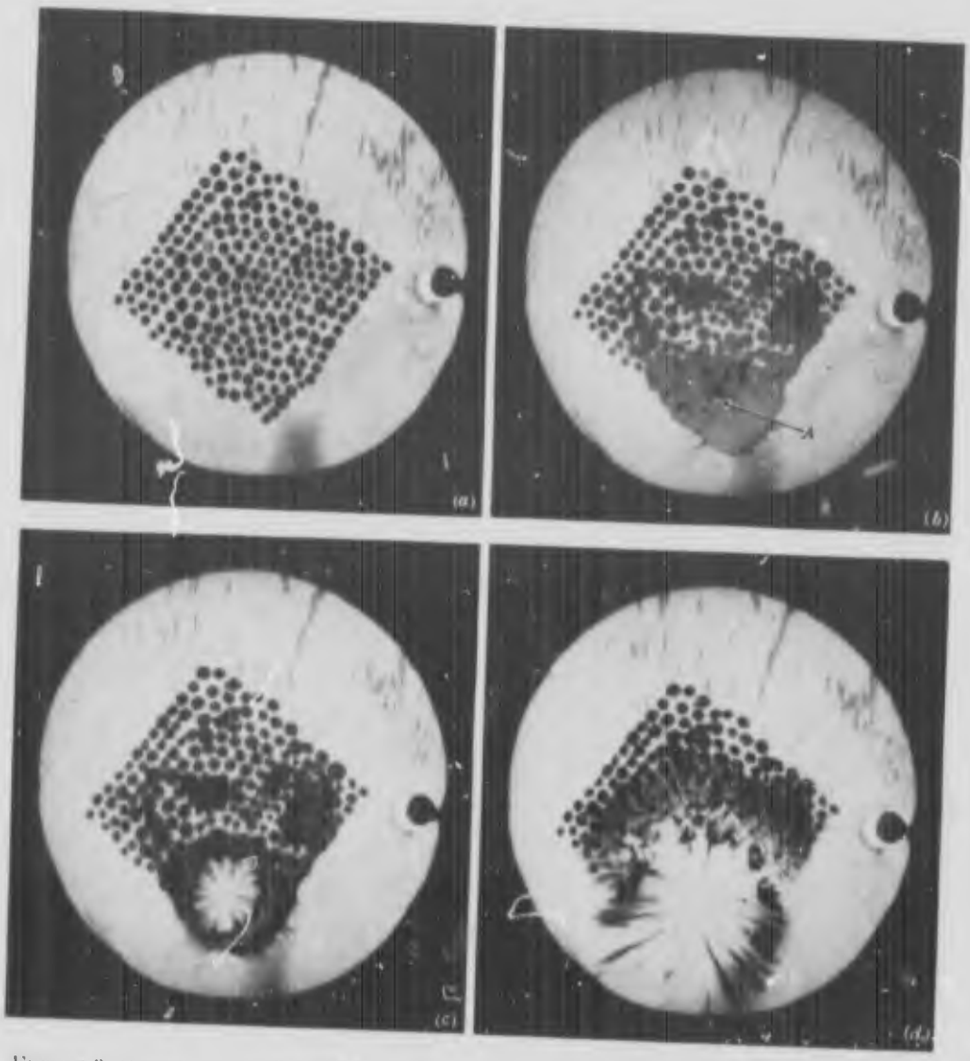

FIGURE 3. Growth of burning (initiated by impact) to explosion in a droplet distribution of nitroglycerine. (*a*) Original distribution of hemispherical drops; (*b* and *c*) accelerating fast burning. Initiation occurred at *A*, where a single air pocket was sealed about 10 μs before *b* and was then rapidly compressed and heated. (*d*). The flame has broken through into the dispersed region and the burning has transformed into a violent and faster explosion. Interval of 10 μs between *b* and *c* and 5 μs between *c* and *d*. Diameter of field of view, 2·9 cm.

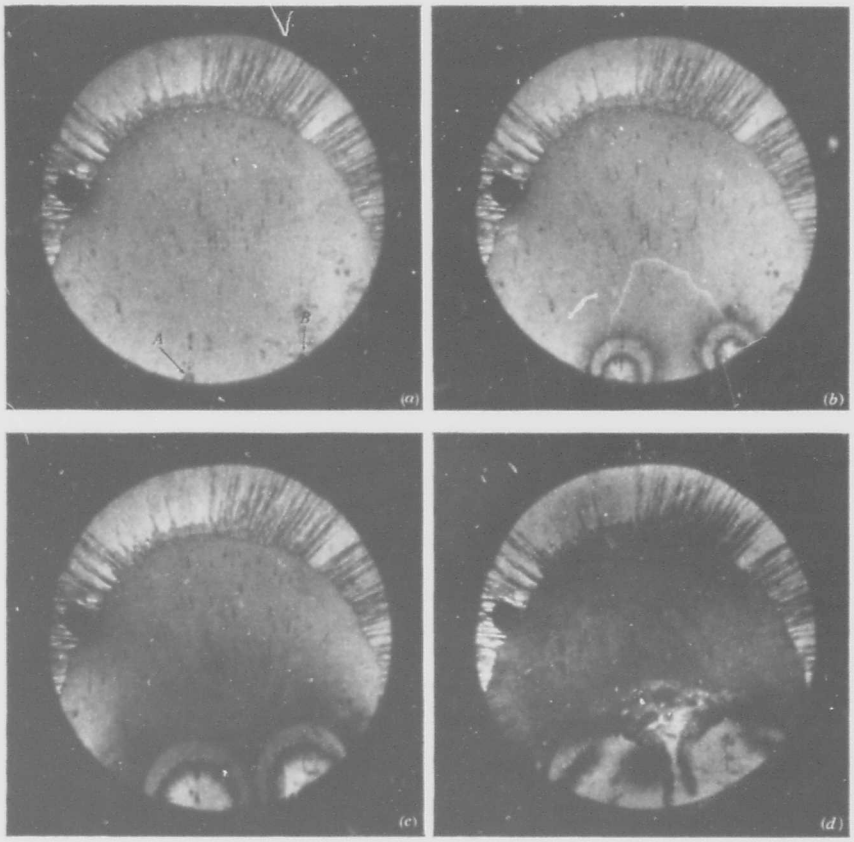

FIGURE 4. Growth of burning (initiated by impact) to explosion in a single drop of nitroglycerine containing grit. (*a*) Initiation of independent zones of burning (*A* and *B*) on two grit particles; (*b* and *c*) two zones of accelerating burning advance into homogeneous liquid. (*d*) The two flame fronts have coalesced. Since the combined flame front has reached the dispersed liquid, the burning has been transformed into a powerful explosion. Interval between frames: 5 μs. Diameter of field of view, 2·9 cm.

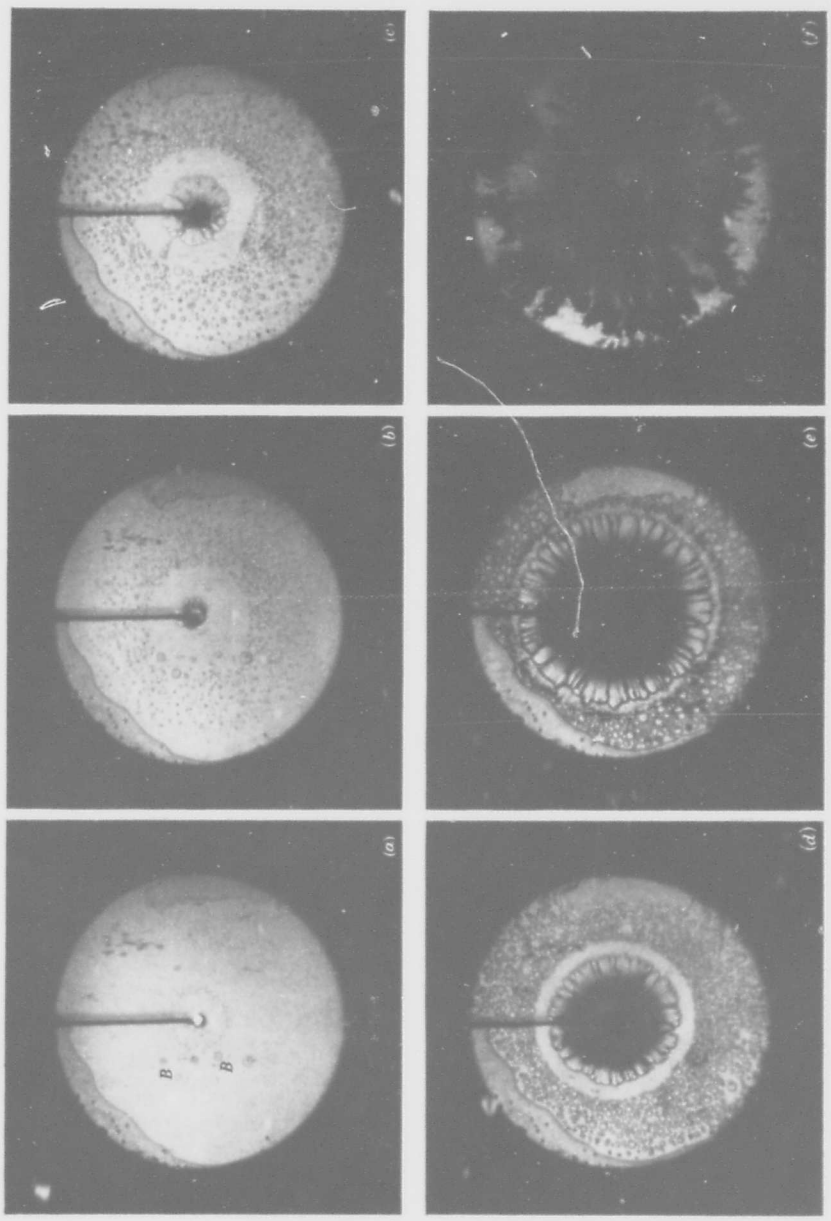

FIGURE 6. Growth of burning (initiated by spark) to explosion in a thin film of nitroglycerine. (*a*) Passage of spark and initiation of burning at the centre; (*a* to *e*) growth of burning. The liquid adjacent to the flame is compressed and free from cavities; beyond the homogeneous region it is in tension and cavities are formed. (*f*) The flame breaks through the homogeneous zone to the cavitation zone and the burning transforms into a rapid explosion. Times (*μs*): *a* 5, *b* 15, *c* 25, *d* 41, *e* 51, *f* 61. Diameter of field of view, 2·5 cm.

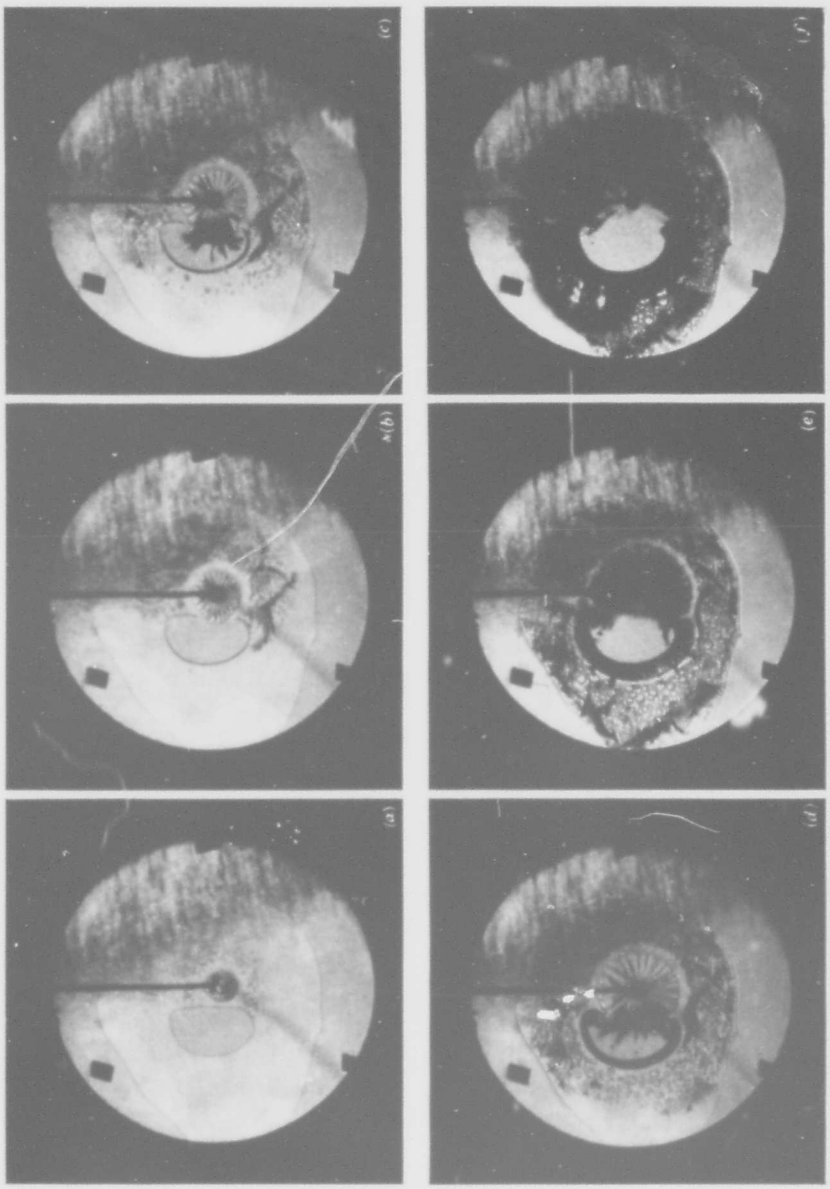

FIGURE 8. Influence of a large air bubble upon the development of reaction in a thin film of nitroglycerine. Burning was initiated by a central spark about 5 μs before *a*. The large bubble (nearly 10 mm across) is too large to be compressed to any great extent (frames *a* and *b*) before the burning reaches it (frame *c*). Burning is initiated along the air liquid interface (frames *c* and *d*) and transforms into explosion (frame *f*) before the original burning. Interval between frames, 5 μs. Diameter of field of view, 3·3 cm.

outside the field of view. Although no propagating burning was observed in either these or subsequent frames, complicated liquid flow patterns were seen later.

Impact on liquid drops

A droplet distribution of a liquid explosive is also extremely sensitive to initiation by impact. Initiation is often caused by the compressive heating of gas pockets which have been trapped between coalescing drops. Microjets, however, can again be formed under these conditions. This is illustrated in figure 2, plate 10, which shows various stages as a number of hemispherical drops (about 1 to 1½ mm in diameter) are flattened and coalesce during impact. The two large central drops have just begun to coalesce in frame *a*. Shortly afterwards a small jet is formed at each side of the highly curved region of contact and is then projected at high speed (about 30 m/s) away from the cusp (frame *b*). In frame *c* one of the jets hits a neighbouring drop. Frequently the coalescing drops seal off an air space at the same time as the microjets are formed between them. The jets are then projected into the cavity during compression as in figure 1, plate 9. Further dispersion of the liquid within the air pocket occurs if the jet travels across the cavity and impinges upon the opposite side. In these experiments the impact is comparatively gentle and the jet velocities are too low to cause initiation by striking another surface.

Explosion of a droplet distribution

The initiation and growth of explosion in a droplet distribution of nitroglycerine under the same conditions of impact is shown in figure 3, plate 11. Typical diameters of the hemispherical drops in the original distribution (figure 3*a*) were between ⅓ and 1 mm. A small amount of methyl violet was added to the nitroglycerine in order to enhance the contrast in the photographs.

As a result of a slightly skew impact the drops in the bottom corner coalesce first and trap small inclusions of air. Initiation has occurred at A (figure 3*b*) where an air pocket was sealed (about 10 μs before figure 3*b*) and then rapidly compressed. The reaction grows first as a burning, which accelerates and has reached a velocity of *ca.* 350 m/s by figure 3*c*. The flame front compresses the nitroglycerine directly ahead of it and closes up the cavities so that it is homogeneous (see later).

When the flame breaks through the homogeneous liquid into the dispersed region, the comparatively gentle burning transforms into a violent explosion (figure 3*d*) propagating through the nitroglycerine at a velocity greater than 1200 m/s. The explosion is sufficiently violent to shatter the glass anvil and hammer. A value of 1800 m/s was obtained in another experiment for the velocity of the final phase of explosion in a droplet distribution of nitroglycerine under the same conditions of impact.

A powerful explosion can arise therefore from one initiation site, provided that the burning encounters an inhomogeneous region so that it is able to grow rapidly and transform into an explosion. In another similar experiment initiation has been observed at as many as five independent sites within a period of 10 μs. In each case the initiation occurred at a trapped and compressed cavity. Each reaction

zone grew first as an independent accelerating burning until the individual regions of burning merged to form a single burning zone about 15 μs after the first initiation. When the flame front encountered an inhomogeneous region consisting of intact drops, dispersed liquid and air (about 25 μs after the first initiation), the burning again transformed into a powerful and fast explosion.

Explosion of a drop of nitroglycerine in the presence of grit

Foreign particles of hard grit added to a liquid or solid explosive can confer a high impact or friction sensitivity on the explosive (Taylor & Weale 1938; Copp, Napier, Nash, Powell, Skelly, Ubbelohde & Woodward 1948; Bowden & Gurton 1949). Bowden & Gurton found that all the grits which sensitize these explosives to initiation either by friction or impact have melting points above a certain value, which lies between 400 and 550 °C. They concluded therefore that the increased sensitivity under these experimental conditions is due to the formation of localized hot spots on the surfaces of the grit particles as they are rubbed against another piece of grit or against the confining surfaces.

The impact initiation of burning in a single drop of nitroglycerine containing grit and the transition from burning to explosion are illustrated by figure 4, plate 12. About 70 particles of carborundum whose dimensions were between 89 and 104 μm were added to a continuous drop of nitroglycerine (8 mm diameter) on the flat glass anvil. The liquid was dyed with methyl violet to enhance the photographic contrast. The falling glass hammer struck the drop and started to flatten it several hundreds of microseconds before figure 4*a*. The impact imparted a maximum lateral velocity of 45 m/s to the edge of the drop, where it also caused high speed jetting at 50 to 70 m/s. Scratch marks on the glass are visible in figure 4*a*. These show the paths of the grit particles which have been rubbed across the glass surfaces at velocities up to 10 m/s. Since the grit particles tend to cluster, it is likely that they are often rubbed against one another. When the liquid does not explode, grit particles are frequently recovered embedded in the glass after the experiment.

In figure 4*a* the edge of the liquid has stopped moving outwards and the hammer is virtually stationary. While there is no sign of reaction 5 μs before this in the preceding frame (not shown), two independent zones of reaction (*A* and *B*) are visible at the edge of figure 4*a*. These represent initiation on two grit particles.

As figure 4 shows, the development of reaction is similar to that which occurs after impact initiation of small drops of nitroglycerine (see figure 3). Each zone of reaction advances first into a region of compressed homogeneous liquid and therefore propagates as an accelerating burning. The flame front on the left accelerates quickly to over 350 m/s between frames *b* and *c* and to *ca.* 650 m/s between frames *c* and *d*; the other flame accelerates at a rate which is only slightly lower than this. Ahead of the homogeneous zone the liquid appears darker and is apparently in tension and dispersed by cavitation. When the explosive between the two flames has been burnt by the two advancing reaction zones, the flame fronts coalesce (between frames *c* and *d*). As soon as the combined flame front (frame *d*) is able to break through the homogeneous region and reach the highly

dispersed liquid it is transformed very rapidly (within *ca.* 5 μs) into a powerful explosion.

As in the case of a droplet distribution, the powerful explosion of nitroglycerine containing grit can arise from a single point of initiation almost as quickly as from two or more initiation sites. The delay between initiation at a single particle of grit and the onset of the final phase when the burning encounters the dispersed liquid can be less than 25 μs.

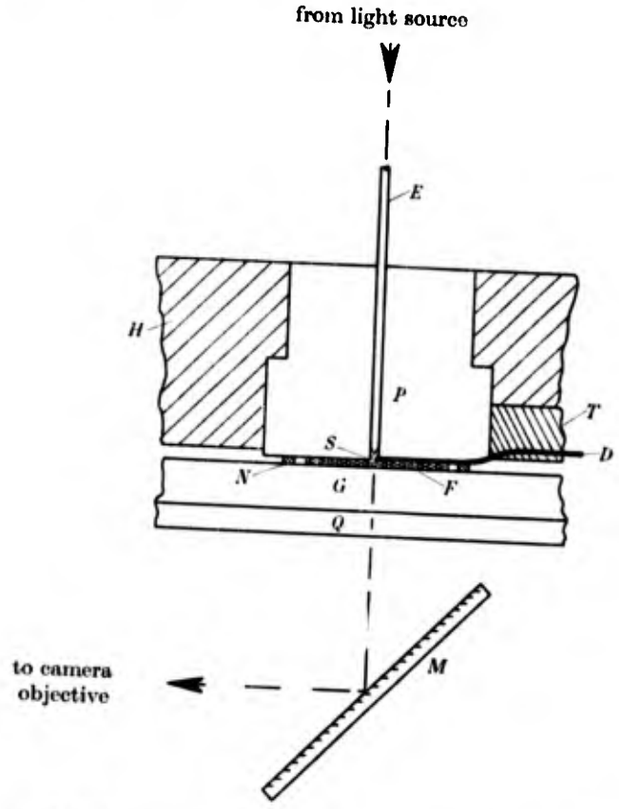

FIGURE 5. Apparatus for initiation of a thin film of liquid explosive by a spark. *D*, horizontal electrode; *E*, vertical electrode; *F*, thin film of explosive; *G*, glass disk; *H*, cylindrical steel holder; *M*, plane mirror; *N*, metal spacers; *P*, upper Perspex disk; *Q*, lower Perspex disk; *S*, spark gap; *T*, insulator.

Growth of the burning to explosion and the role of the precursor wave

In order to study the various stages from initiation through burning to explosion more easily, a series of experiments was conducted in which reaction was initiated by an electric spark instead of by gentle impact.

The simple arrangement of the explosive and its solid confinement is shown in figure 5. A thin film of explosive *F* was enclosed between the flat surfaces of a glass disk *G* below it and a Perspex disk *P* above it. The disks were separated by three small metal spacers *N* to ensure that the thickness of the film was uniform

initially. The Perspex disk fitted tightly into a hole in the middle of a cylindrical steel holder H, which provided additional confinement since it was strapped to a steel support. While the lower half of the Perspex disk was $1\frac{1}{4}$ in. in diameter, the upper half was only 1 in. in diameter in order to prevent the Perspex from being forced out of the hole by the high pressure generated during reaction. The diameter of the field of view on the photographs was therefore restricted to 1 in. The glass disk G (3 in. diameter and $\frac{1}{4}$ in. thick) below the explosive lay on a second Perspex disk Q (3 in. diameter and $\frac{1}{8}$ in. thick). The edge of this Perspex disk rested on the steel support. The hole at the centre of the support allowed light from the flashtube which had passed along a vertical axis through the explosive and its confinement to fall on to the plane mirror M, which reflected the light towards the objective lens of the camera. One of the electrodes E was fixed in a vertical hole along the axis of the upper Perspex disk P. The other electrode D was placed in a horizontal groove along a radius of the bottom face of the same Perspex disk and was insulated from the steel holder by Tufnol T. The electric spark was generated in a small gap S between the two electrodes by the rapid discharge of a capacitor charged to 4 kV. This gap was located in a small reservoir of liquid explosive at the centre of the film.

The process of growth of reaction from initiation through burning to explosion and the importance of cavities in the transition to explosion are shown in figure 6, plate 13. The thickness of the film of nitroglycerine (0·13 mm) was similar to that shown in the impact experiments. Several small bubbles of air were deliberately included (at B, B in figure 6a) in the otherwise homogeneous film.

The first frame shows the spark and initiation of burning in the small central reservoir of nitroglycerine. In the succeeding frames the reaction spreads through the thin film where it grows first as an accelerating burning. These frames show also the formation of an annular zone containing many bubbles and cavities in the unreacted liquid ahead of the central flame. As the burning develops these bubbles and cavities become larger and more numerous. In frames a to e the flame is separated from this zone of bubbles by an annular region of liquid that is free from bubbles. The movement of the flame front relative to the zone of bubbles and the onset of explosion are shown in figure 7, which is a distance-time diagram of the zone boundaries along a typical radius. The diagram shows the positions of the zones in several frames from the original sequence which have not been included in figure 6. (The first frame in figure 6 was taken at 5 μs.) Curve I is the accelerating flame front. Curve II represents the outer edge of the bubble-free zone and the inner edge of the bubble zone. The velocity of this boundary varies considerably, starting at 230 m/s and falling to the low value of 30 m/s. Although it then gradually increases and reaches 260 m/s, it does not exceed the velocity of the flame front after frame c. Curve III is the head of the bubble zone, which propagates at a constant velocity of 750 m/s through the whole film.

It is suggested that the zone of bubbles and cavities is created by pressure waves produced in the confining glass and Perspex plates when they are distorted by the developing reaction. These pressure waves in the solids run ahead of the subsonic burning in the liquid and thus perturb the liquid ahead of the flame

front. If this precursor wave causes a significant increase in the separation between the confining surfaces or if it is transformed into a rarefaction wave, e.g. by reflexion, it will produce a substantial reduction in pressure in the unreacted liquid. Bubbles and cavities are formed where the liquid is in tension and provide a favourable environment for the rapid growth of the burning so that it eventually passes over to explosion.

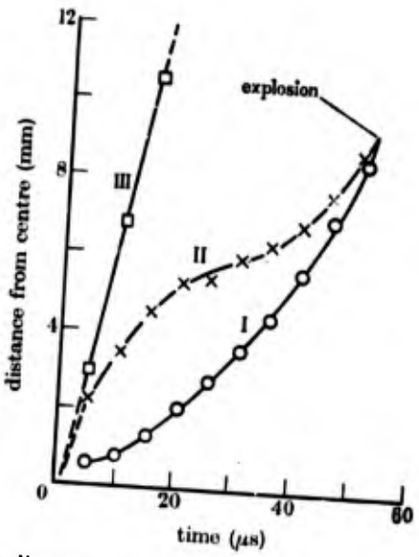

FIGURE 7. Distance-time diagram of zone boundaries in figure 6. I, Accelerating flame front. Velocity has reached 300 m/s just before transition from burning to explosion. II, Boundary between bubble-free zone and bubble zone. III, Outer edge of bubble zone. Velocity 750 m/s.

It will be seen that at first the pressure generated by the central burning is able to compress the material directly in front of the flame sufficiently to remove any small bubbles or cavities before the flame front reaches them. The reaction zone is therefore surrounded by an annular zone of liquid under high pressure and free from discontinuities. The small bubbles of air originally present in the liquid at *B*, *B* are also compressed and disappear when this high pressure region reaches them. The gas or vapour in the bubbles and cavities is not heated sufficiently during the rapid compression to cause initiation of reaction. So long as the pressure developed in the reaction zone is effective in creating a region of homogeneous liquid directly in front of it, the reaction cannot grow rapidly and continues to propagate as a steadily accelerating burning. The velocity of the burning is 150 and 230 m/s in figures 6*c* and *d* respectively and has reached only 300 m/s in frame *e*.

It is not until the flame succeeds in breaking through the homogeneous zone and reaches the zone containing numerous cavities and bubbles that the burning is able to grow at a much faster rate and transform within a very short time into

a much quicker and more powerful explosion (frame *f*). The bubbles and cavities are then able to sustain the rapid propagation of the explosion. The explosion is now too fast to be recorded by the camera and is sufficiently violent to shatter the confining solids. From experiments in which the final stage of explosion is visible on two successive frames, values between 1200 and 1600 m/s have been obtained for its velocity of propagation.

Influence of a large air bubble upon the development of reaction

It has been shown that explosion occurs when the material in front of the flame is no longer compressed sufficiently by the high pressure in the burning zone to remove the numerous bubbles and cavities before the flame encounters them. The dimensions of these bubbles can vary from less than 0·1 mm to slightly more than 1 mm. If a single larger bubble of air is included in the original explosive film comparatively close to the initiation site, it has a striking influence upon the growth of burning to explosion, because it is too large to be removed by compression before the burning reaches it. This is illustrated by figure 8, plate 14. A thin film (0·06 mm thick) of nitroglycerine was confined between two Perspex disks each of which had a diameter of 3 in. A large air bubble, nearly 10 mm across, was deliberately included near the centre of the thin film.

A spark was generated in a small central reservoir of nitroglycerine about 5 μs before figure 8*a* and initiated burning, which is seen advancing through the liquid in frames *a* to *e*. These frames show also the two characteristic zones—the homogeneous zone adjacent to the flame and the zone of bubbles surrounding the clear liquid—which accompany the burning regime. The former zone is produced when the pressure generated in the reaction zone compresses the material directly ahead of the flame sufficiently to remove bubbles from the latter zone. The bubble is, however, too large to be compressed to any great extent (frames *a* and *b*) before the reaction reaches it (frame *c*). Unreacted explosive vapour and hot gaseous products from the reaction zone and probably also drops of unreacted liquid are then thrown across the air pocket towards the liquid on the opposite side. It is probable that mixing of unreacted liquid and vapour with hot products occurs during this process and leads to further burning within the air inclusion. When the burning nitroglycerine and products strike the liquid around the bubble, they initiate burning in the nitroglycerine at numerous sites along the long air/liquid interface (frames *c* and *d*). The flame which advances into the liquid from each of these sites accelerates rapidly over a wide front.

The action of precursor waves which are produced in the confining Perspex both by the new reaction around and within the air bubble, and by reaction in the original central area causes appreciable disruption of the liquid close to the new burning zone around the inclusion. There is therefore only a short delay between the initiation of burning around the bubble and its transformation into explosion between frames *e* and *f*. The new region of burning is able to penetrate into the zone of small bubbles before the original region of burning and therefore passes over to explosion sooner.

Growth to explosion in liquids of higher viscosity

The experiments suggest that the formation and sealing of cavities and their effect in supporting reaction are determined by the pressure rather than by viscous flow of the liquid. In order to test this, some experiments were made with liquids of higher viscosity. In one set of experiments 3 % of nitrocellulose was added to the nitroglycerine. Although this increased the viscosity appreciably, the behaviour was essentially the same as with nitroglycerine. Further experiments were made with a highly viscous liquid (7·2% nitrocellulose and 92·8% nitroglycerine), which was almost a gel. The viscosity was about 1000 P at room temperature (the viscosity of nitroglycerine is about 0·5 P at 15 °C, Peterson 1930). The pattern of behaviour remained the same. The initial velocities of both the burning front and the outer boundary of the homogeneous zone were similar to the corresponding velocities in the more mobile nitroglycerine. Again, the burning passed over to explosion only when it succeeded in reaching the discontinuous zone.

Effect of the confining solid

An essential step before the transition to explosion is the ability of the pressure wave to move ahead and cause cavitation. If the pressure wave is transmitted through the confining solids, this can only occur when the velocity of elastic waves in the solids is greater than the burning velocity. Since the velocity of elastic waves in glass (longitudinal velocity: 5600 m/s) and Perspex (longitudinal velocity: 2700 m/s) is considerably greater than the sonic velocity in nitroglycerine, which is usually considered to be about 1800 m/s, precursor waves can propagate in these solids and can easily break up the explosive ahead of the subsonic burning. The effect of confining nitroglycerine by a solid of low sonic velocity was examined by enclosing the liquid between two disks of a silicone rubber (I.C.I. 'Silcoloid' 201). The velocity of an elastic wave in this material is about 100 m/s, which is lower than the normal burning velocity. No explosion was observed or heard in any of these experiments, even when the nitroglycerine was initiated by sparks of very high energy. This supports the view that the disruption of liquid by precursor waves in the confining solids is an important factor in the growth to explosion.

Discussion

The first stage of propagating reaction in a small quantity of liquid initiated by an energy source of low intensity is an accelerating burning. The pressure developed in the burning zone is able at first to compress the material directly in front of the flame sufficiently to seal any small bubbles or cavities before the flame front reaches them. Evidently the gas or vapour in these cavities is not heated sufficiently by compression to cause initiation of reaction at their explosive walls. The reaction zone is therefore surrounded by a 'quiet' zone of liquid that is free from discontinuities. So long as the reaction advances into this region of homogeneous liquid, it cannot grow quickly and continues to propagate as a relatively slow burning at

a speed of up to several hundreds of metres per second. The initial inhibition of fast growth of reaction by the high pressure in the burning zone is consistent with a previous observation (Bowden & Gurton 1949) that a high initial pressure in a liquid film does not favour a transition to explosion. If a large bubble of air is included in the liquid comparatively close to the initiation site, it cannot be removed by compression before the flame reaches it and is therefore able to assist the rapid growth of burning to explosion.

After a thin film of liquid enclosed between solid surfaces has been initiated, pressure waves are produced in the confining solids, since they are deformed by the high pressure of gases in the burning zone. These waves play a particularly important role in the development of reaction in a confined film that is initially homogeneous. The elastic properties of the solids are also significant in the growth process, for, if the velocity of an elastic wave in the solid exceeds the burning velocity, the waves travel ahead of the burning through both the solids and the liquid. The precursor waves are then capable of producing cavitation in the liquid ahead, either by causing an appreciable change in the separation of the containing surfaces, or by being transformed into rarefaction waves, for example, by reflexion. There is evidence that standing vibrations may occasionally be set up in the solids.

As mentioned in the introduction, cavities can facilitate the growth of an explosion in several ways. For example, we have seen that a cavitated zone creates an environment that is favourable for the rapid growth of burning, so that it eventually passes over to explosion. As soon as the flame is able to break through the homogeneous region and penetrate into an inhomogeneous zone containing numerous cavities (or droplets), the burning is able to grow at a much faster rate and transform within a very short time into a considerably quicker and more violent explosion. The explosion then advances readily through the inhomogeneous region. The discontinuities may either be present originally in the liquid or, if the velocity of the elastic waves in the confining solids is sufficiently high, they may be formed there by the mechanical action of the developing burning. It is found that it is the elastic properties of the confining solids rather than viscous flow of the liquid that affects the formation and removal of cavities and their part in the growth of reaction. If burning were initiated in a liquid which is not confined by a solid boundary, rarefaction waves would not be created and cavities would not be formed in the liquid ahead of the burning. The reaction would then continue to propagate as a burning into compressed homogeneous liquid.

It is likely that the final stage of explosion in a thin film of liquid propagates in a similar way to the low velocity detonation (*ca.* 2000 m/s) in larger charges, where surface area of the explosive (Taylor 1952) and liquid breakup (Van Dolah, Watson, Gibson, Mason & Ribovich 1963) are important factors in the propagation of the low velocity detonation. The cavities in thin films are probably able to facilitate the transition to explosion and then sustain its rapid propagation at over 1000 m/s by presenting a large surface area of unreacted liquid to the advancing reaction front. Areas of intense reaction round and within the cavities would account for the pitting and pock marks produced by an explosion on confining surfaces of brass (Bowden, Eirich, Mulcahy, Vines & Yoffe 1943). If the

detonation velocity attains the value corresponding to the stable high velocity (*ca.* 8000 m/s), it can then be sustained in a homogeneous liquid by the compressional heating of the liquid by the intense shock wave.

Another important effect of a cavity is the formation of jets during impact on an inhomogeneous distribution of liquid explosive. When an annulus of liquid is struck by a hammer, a gas bubble is trapped in the liquid and rapidly compressed. Microjets are readily formed at the region of maximum curvature of the liquid surface of the gas bubble. Again, microjets are frequently produced between two impacted and coalescing drops. The velocity of these jets is an order of magnitude higher than the impact velocity. When the jets are projected at high speed into a cavity containing entrapped gas that has been rapidly heated by compression, they may therefore frequently assist initiation by exposing a large surface area of explosive to the hot gas. This process will be particularly important during gentle impact, when the rate of heating and maximum temperature of the gas are comparatively low, owing to the continuous diffusion of heat through the explosive away from the gas/liquid interface while the bubble is still being compressed. In initiation by gentle impact of an inhomogeneous distribution of liquid, therefore, the cavity acts both by concentrating the energy of impact into a small region and by dispersing the explosive in a fine microjet.

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13 ABSTRACT

The role of discontinuities, such as bubbles of gas and cavities, in the initiation and growth of explosion in liquids has been studied experimentally by means of high speed framing photography. It is shown that micro Munroe jets can be formed at the surface of a gas bubble which has been trapped in the liquid explosive between two impacting surfaces and is being rapidly compressed. As the compression continues these jets are projected at high speed into the gas. Similar jets can be produced between two drops of explosive which are coalescing during impact. These jets may facilitate the initiation of burning both by increasing the impact velocity of the liquid and by dispersing the liquid within a pocket of compressed and heated gas. The reaction grows first as an accelerating burning. The pressure developed in this burning zone has, in the early stages, the effect of closing up and removing any cavities which may exist in the explosive directly ahead of the flame front, so that the reaction advances into a homogeneous zone of liquid that is free from discontinuities. It is not until the comparatively slow burning breaks through the homogeneous high pressure zone, and reaches a zone of liquid containing numerous cavities and bubbles, that the burning is able to transform quickly into a much faster and more violent explosion. The discontinuities are then able to sustain the rapid propagation of explosion. This region of discontinuities can be created in initially homogeneous liquids enclosed between solid surfaces by pressure waves which travel through the confining solids and ahead of the subsonic burning If these pressure waves increase the distance between the confining surfaces substantially or are converted into rarefaction waves by reflexion, they can produce regions of tension in the unreacted liquid and disrupt it well ahead of the reaction zone. The bubbles of gas or cavities that are formed in this way by the precursor waves create an environment which is conducive to the rapid transition from burning to explosion.

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Low velocity detonation propagation						
High velocity detonation propagation						