THE IMPEDANCE MIRROR TECHNIQUE FOR MEASURING DETONATION REACTION TIMES

H. Dean Mallory

Naval Weapons Center
China Lake, California

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by
H. Dean Mallory
Research Department

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Naval Weapons Center
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(U) An experimental technique is described by which detonation reaction zone structure is rendered visible in high-speed photographs. Using the time-resolving streak camera, the technique yields both induction and reaction times when these separate zones are present. Data on detonating 75/25 nitromethane/acetone solutions are presented showing good correlation with the Soviet electromagnetic method of measurement. This new technique is more flexible than the electromagnetic method and can yield more data.

INTRODUCTION

All explosives react when heated and show accelerated reaction as the temperature is increased. Cook-off studies show times to explosion of seconds to hours and these data are sometimes used to calculate kinetic parameters such as heat of activation. The very short reaction times such as those associated with steady state detonation are an important but nearly inaccessible part of the total picture. Measurements of these very short times are important to ongoing programs such as Trident propellant detonation and fragment initiation of explosives so that these processes can be modeled and understood.

In view of these needs the present project using the new impedance mirror technique was completed. An impedance mirror is a block of Plexiglas which is aluminized on one side to form an optically good mirror. If a detonation wave strikes the mirror on the metallized side, a pattern corresponding to the pressure variations within the reaction zone is momentarily impressed into the mirror. A streak camera observing from the second surface side of the mirror sees these patterns as a function of time and in this way the reaction time can be measured. Detonations typically have wave fronts containing fine structure due to fluctuations in pressure and flow. In solids, intrinsic voids in the crystal structure further add to the roughness of the wave front. Although the technique has not been developed to the point where it is applicable to all explosives, we believe it to be an advance in the state of the art. In some respects the present technique is unique and yields information unobtainable in any other way. Also, as a completely independent experimental method, it is additionally important in confirming data obtained by other methods.

HISTORICAL SKETCH

In the past, reaction zone measurements have been made with some success by two methods. The first of these was a "plate-push" method, where velocity imparted to aluminum disks was recorded. Ordinary low pressures (such as atmospheric pressure and its changes) can be measured by the deflection of a diaphragm as is done with an aneroid barometer. The plate-push method is somewhat related to this, but since explosion destroys the assembly, measurement of deflection of the plate is not useful; rather the velocity of deflection is recorded. The velocity of deflection is then related to the pressure induced in the plate, by the hydrodynamic equation $P = \rho_o Du$, where P is pressure, ρ_o is the density of the aluminum plate, D is shock velocity through the plate, and u is one-half the free surface (or deflection) velocity.

In this test, as in all reaction zone measurement methods, we seek one-dimensional flow. The charge is of sufficient diameter that edge effects do not distort the center of the detonation wave, and that measurements are made in the center portion of the plate where there is reasonable assurance that the wave is flat. A flat detonation wave is induced in the test charge by use of a plane wave booster, manufactured under rigid quality control to secure the flattest wave possible (usually ±0.05 microsecond over the entire face of the booster).

Early plate-push tests[1,2] used an array of spaced, charged pins to record plate velocity, although gap closure recorded by streak photography was also used with greater convenience but somewhat less accuracy.[3,4] Later, photographic methods for observing the plate were refined to give good accuracy and resolution.[5,6] All plate-push techniques suffer from a common fault, in that the metal plate accelerates in a series of finite steps that result from repeated shocks in the metal. The significant velocity is the first step only, and as thinner plates are used to measure pressures in the reaction zone region, acceleration steps are closer together and of shorter duration. In the limit, as the plate approaches vanishing thickness, steps are of infinitesimal duration and have long ceased to be measurable. However, the Chapman-Jouguet point has been measured for a few explosives, and since that pressure marks the end of reaction, the extent of the reaction zone is known for these explosives. Fine structure ahead of the Chapman-Jouguet boundary, including the much shorter induction zone, has been seen only by an "impedance mirror technique," which is the subject of this report. Before describing this newer work, an electromagnetic method of reaction zone measurement will be described. Chronologically, the electromagnetic method was developed between the plate-push and the impedance-mirror methods, and has yielded an important data point for impedance mirror calibration.

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[1] Mallory, Dean H. "Propagation of Shock Waves In Aluminum," J APPL PHYS, Vol. 26, No. 557 (1955).

[2] Duff, Russel E., and Edwin Houston. "Measurement of the Chapman-Jouguet Pressure and Reaction Zone Length in a Detonating High Explosive," J CHEM PHYS, Vol. 23, No. 1268 (1955).

[3] Deal, W. E. "The Measurement of Chapman-Jouguet Pressure for Explosives," in *Second ONR Symposium on Detonation*, 9-11 February 1955, Washington, D. C. and White Oak, Md. Washington, D. C., Office of Naval Research, 1955. P. 209.

[4] Deal, W. E. "Measurement of the Reflected Shock Hugoniot and Isentrope for Explosive Reaction Products," PHYS FLUIDS, Vol. 1, No. 523 (1958).

[5] Eden, G., and P. W. Wright. "A Technique for the Precise Measurement of the Motion of a Plane Free Surface," in *Proceedings of the Fourth Symposium (International) on Detonation*, 12-15 October 1965, White Oak, Md. (ACR-126) White Oak, Naval Ordnance Laboratory, 1965. P. 573.

[6] Davis, W. C., and B. G. Craig. "Smear Camera Technique for Free Surface Velocity Measurements," REV SCI INSTRUM, Vol. 32, No. 579 (1961).

"The electromagnetic method is based on the law of electromagnetic induction. As a result of the motion of a conductor in a magnetic field, there is induced in it an EMF (ε, related to the velocity of the conductor u, its length ℓ, and the intensity of the magnetic field H. Knowing H, ℓ, and ε, it is easy to determine the velocity u. The conductor (or probe) is usually a piece of aluminum foil bend in the shape of a stirrup, the length of the crosspiece being the working length. The probe is mounted in the explosive in such a way that its crosspiece is exactly perpendicular to the direction of propagation of the detonation."[7] With this method the probe can be immersed in a liquid explosive, or the crosspiece can be pressed between flat explosive pellets. The thin foil is swept along at nearly the particle velocity of the explosive, and decelerates with the particles throughout the reaction zone. In this way, the changing particle velocity throughout the zone is measured as is the time duration. A good discussion of the method along with its experimental difficulties is given by Jacobs and Edwards.[8] The Soviet workers under Dremin used the electromagnetic induction method to measure the reaction time for diluted nitromethane (75% nitromethane, 25% acetone) with good results, but found that in pure nitromethane the zone was too short to be resolved. By the impedance mirror technique, we confirmed the measurement for 75/25 nitromethane/acetone (0.4 microsecond) and, in addition, measured the reaction time for pure nitromethane.

IMPEDANCE MIRROR TECHNIQUE

Under strong shock pressures, Plexiglas is reasonably compressible. Further, a metal film which has been evaporated on the Plexiglas surface stretches and undulates with the surface, even when that surface is under unequal dynamic compression.[9] This effect is used as a basis for the impedance mirror technique. When an uneven pressure structure in the shock wave impacts the mirror, a high-speed camera viewing the mirror from the opposite side indicates mirror distortion as a characteristic print of the shock wave.

For measurement of reaction time by the impedance mirror technique, the explosive, nitromethane diluted with acetone, was contained in an

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[7] Dremin, A. N., O. K. Rozanon, and I. G. Koba. "Investigation of the Reaction Time for Liquid Explosives by the Electromagnetic Method," COMBUST EXPL SHOCK WAVES, Vol. 1, No. 52 (1965). FIZIKA GORENIYA, Vol. 1, No. 93 (1965).

[8] Jacobs, Sigmond J., and David J. Edwards. "Experimental Study of the Electromagnetic Velocity-Gage Techniques," in *Fifth Symposium on Detonation*, 10-11 August 1970, Pasadena, Calif. Office of Naval Research, Washington, D.C., 1970. P. 413.

[9] Mallory, H. Dean. "Evidence of Turbulence in the Reaction Zone of Detonating Liquid Explosives," J APPL PHYS, Vol. 37, No. 4798 (1966).

aluminum tube whose length varied from 1/2 inch to 30 inches. Inside tube diameters varied from 2 1/2 inches to 5 inches, although in steady state detonation or in an overboosted condition, tube diameter exerted little effect. Both sizes were above the failure diameter of the 75/25 nitromethane/acetone mix of concern. The booster end of the tube was closed by a 1/8-inch-thick aluminum plate and the working end, observed by the camera, was closed by the impedance mirror. Our standard booster was a 4-inch-diameter plane-wave lens having a Composition B disk 1 inch thick behind it. With this booster, the wave in diluted nitromethane was always initially overdriven—the more so the shorter the nitromethane tube. As will be shown, the overdriven condition extended several inches into the tube. A slot in the aluminum tube adjacent to the mirror served for filling liquid explosive, and for access to wipe air bubbles from the mirror face prior to the shot. Air bubbles adhering to the mirror produced Monroe jets, which cause spurious patterns on the photographs. (These bubbles can be easily swept off with a camel's hair brush or with a long wire, if care is taken to avoid scratching the mirror.)

Nitromethane is a solvent for Plexiglas, and pinholes always exist in the evaporated metal film. Therefore, a 0.01-millimeter film of polyvinylidiene chloride (Saran) was applied to the metallized side of the mirror before assembly. This film retards solvent attack and mirror degradation for about five minutes, which allows ample time for firing. The very stretchable Saran film can be applied wrinkle-free to the mirror only when surfaces are thoroughly wetted with water and liquid detergent, or wetting agent. It can be rolled on with a rubber squeegee, trimmed, and while still wet, attached to the Plexiglas edge with transparent pressure-sensitive tape (3-M Magic Transparent Tape or equivalent) which sticks slightly when wet. After several days of air drying, or after a few hours of slow drying under vacuum (to prevent bubble formation under the film), retained water diffuses away to leave the Saran film clinging electrostatically to the mirror. The film clings rather strongly; adhesives were never used to help support the mirror. Both the aluminum plate closure and the Saran-covered mirror are attached to the charge tube by RTV Silastic. A schematic arrangement of the setup is shown in Figure 1. (The Composition B disk has been omitted for simplicity—the disk was not omitted in a real test.) A further change sometimes made in real tests was use of a full reflecting mirror at the light source, with the light source moved just to the edge of the turning mirror. This change makes little difference in the records if the distance from the impedance mirror to the light source is, say, 1 1/2 meters. What it does do is greatly increase the light intensity to the camera.

EXPERIMENTAL TREATMENT

WAVE PATTERNS

Wave fronts are quite characteristic, because the pressure developed in detonation principally determines reaction kinetics. In turn, reaction

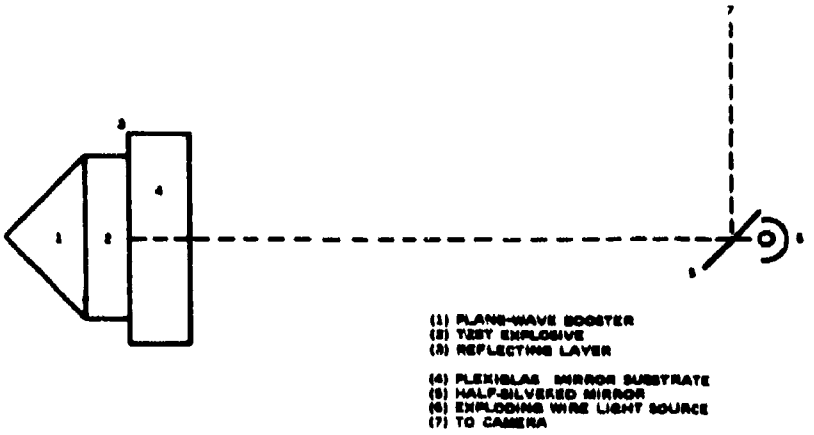

FIGURE 1. Schematic of Impedance Mirror Shot Assembly.

kinetics control the size of the cells.[10] Cells are determined by the interaction of pressure wavelets at the front.[11] Shocks in inert liquids impacting a mirror show no discernible structure, and the phenomenon of a shock wave striking a mirror can be seen, sometimes, only with difficulty.

A typical head-on impact still photograph is shown in Figure 2, which shows an overdriven detonation wave in 55/45 nitromethane/acetone. The pebble-like texture of the mirror surface is caused by an imprint of the wave front into the Plexiglas mirror substrate. The regions (cells) of high-pressure make a deeper imprint into the mirror than do troughs of lower pressure, and in the troughs (the wiggly white lines) mirror reflectivity is still high. The cells have a certain average size which is quite repeatable from shot to shot. However, if the pressure level is changed by changing the booster strength or the degree of acetone dilution, the cell size changes.

These effects are seen in homogeneous liquid explosives. Complicating factors, such as addition of solid crystals and plastic binders, add their own characteristic qualities to the wave imprint, and may overshadow and distort effects by pressure cells. An example of this is shown in Figure 3, which was produced by head-on detonation impact in pressed PBXN-3. The notable structure is due to the plastic binder around the granules from which the explosive was pressed.

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[10] Urtiew, P. A., A. S. Kusubov, and R. E. Duff. "Cellular Structure of Detonation in Nitromethane, " COMBUST AND FLAME, Vol. 14, No. 117 (1970).

[11] Soloukhin, R. I. "Structure of a Multifront Detonation Wave in a Gas," COMBUST EXPL SHOCK WAVES, Vol. 1, No. 23 (1965). FIZIKA GORENIYA, Vol. 1, No. 35 (1965).

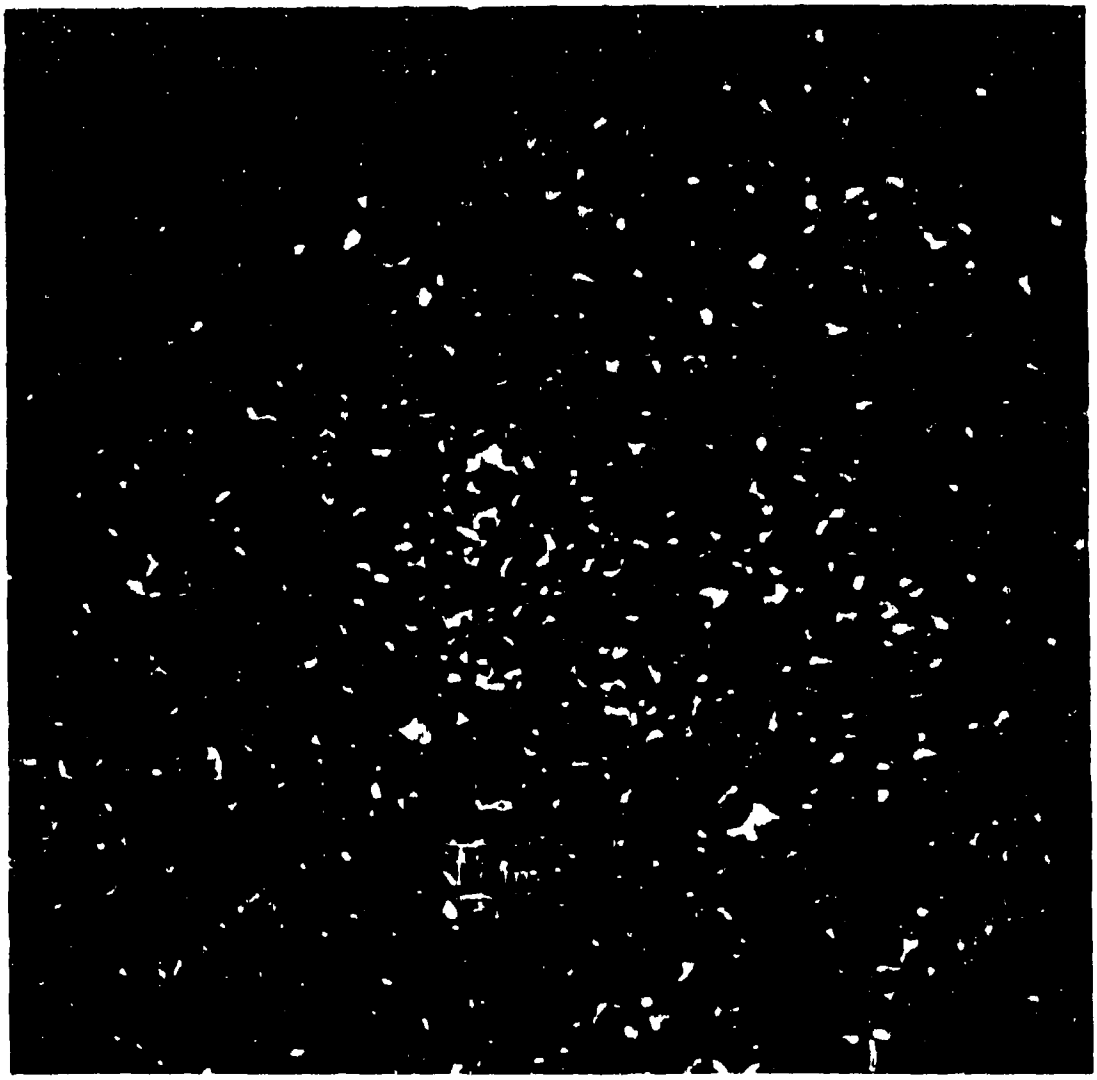

FIGURE 2. Three-Quarter-Microsecond Framing Camera Photograph of Impedance Mirror Impacted by Head-on Detonation Wave in Overboosted 55/45 Nitromethane/Acetone. Photograph was taken about 1/2 microsecond after wave impact.

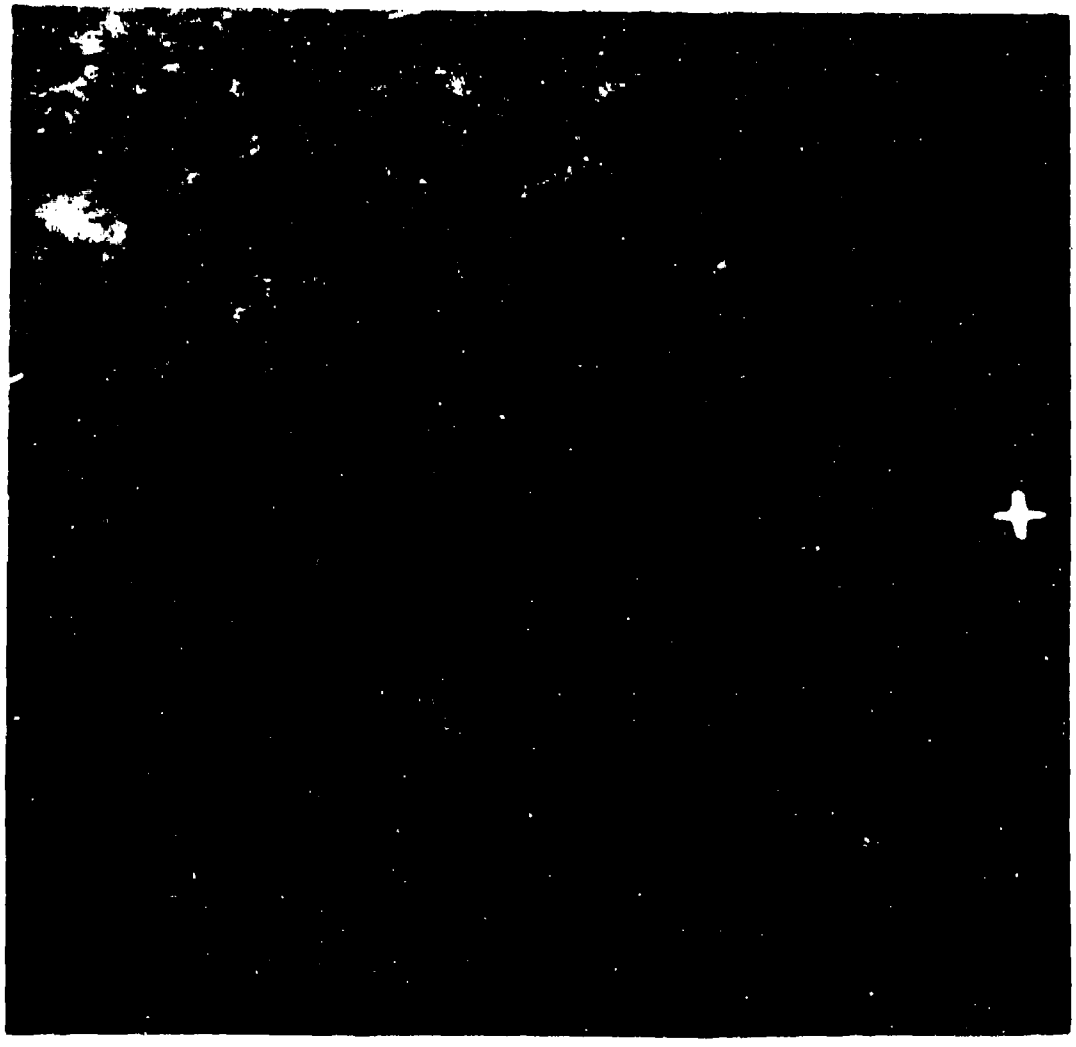

FIGURE 3. Three-Quarter-Microsecond High-Speed Camera Photograph of Detonation Flow in Pressed PBX-N3. Impedance mirror impact about 1/4 microsecond prior to photograph.

A further example of the rich detail in a detonation front is shown in Figure 4. This photograph displays a head-on impact of a front with a mirror, by detonation in 75/25 nitromethane/acetone. There are three noteworthy features. First, the central portion has the same pebble-like texture seen in Figure 1 but on a smaller scale. In this shot, acetone dilution was 25% instead of 45%, so pressure in the reaction zone is higher, the zone is thinner, the pressure wavelets collide more quickly with one another and, therefore, cells are smaller. Second, prominent veins separate regions of different texture. Finally, there are regions present which are nearly smooth. The smooth regions, of course, have cells of smaller size, and in extreme cases where cell size could be zero (no cells existing), the wave has failed in that region. If cells are small, the wave may be building up in that region. From the photograph alone, we cannot say which regime is active. We do know that, by control of tube diameter and booster size, the wave was set up to fail; it would have failed had it run long enough. However, when failure begins nature tries to sustain the wave by changing wavelet interactions and cell size, so that local regions could have been at higher than normal pressures. In any event, for the measurement of reaction zones we want steady state conditions where conditions are as uniform as possible over the entire front. Zones can be measured under conditions as they are in Figure 2.

So far we have shown only high-speed still photographs of the wave front. These are useful in comprehending what the front looks like at a particular point in time. But we really want a time history of the front so we can determine how long a particular regime persists, which is to say we want to know how long the reaction lasts. It was mentioned earlier that the evaporated metal layer of the mirror undulates with the Plexiglas substrate and stretches without breaking as the pressure field passing through it changes. Using a streak camera, which smears out the image over the film, we have a time axis whereby we can see how a particular point on the mirror changes with time. Due to the formation, growth, and decay of the pressure cells, the mirror reflectivity changes as the shock wave passes through the reflective layer and the various regions within the reaction zone are visible.

MEASUREMENT OF TIME

A streak camera looks at an object through a slit typically 0.002-inch wide and a couple of inches long. The long slit thus defines a distance axis (in our case across the face of the impedance mirror). Early camera models (rotating drum cameras) had the film move to smear out the slit image on the film, and to develop the time axis. Modern versions of the drum camera use a rotating mirror and stationary film, which gives better time resolution. Our camera was ordinarily run at a speed to provide slit image motion on the film of 10 millimeters per microsecond. Thus, if a measured event on our film is 10 millimeters long, its time duration was one microsecond.

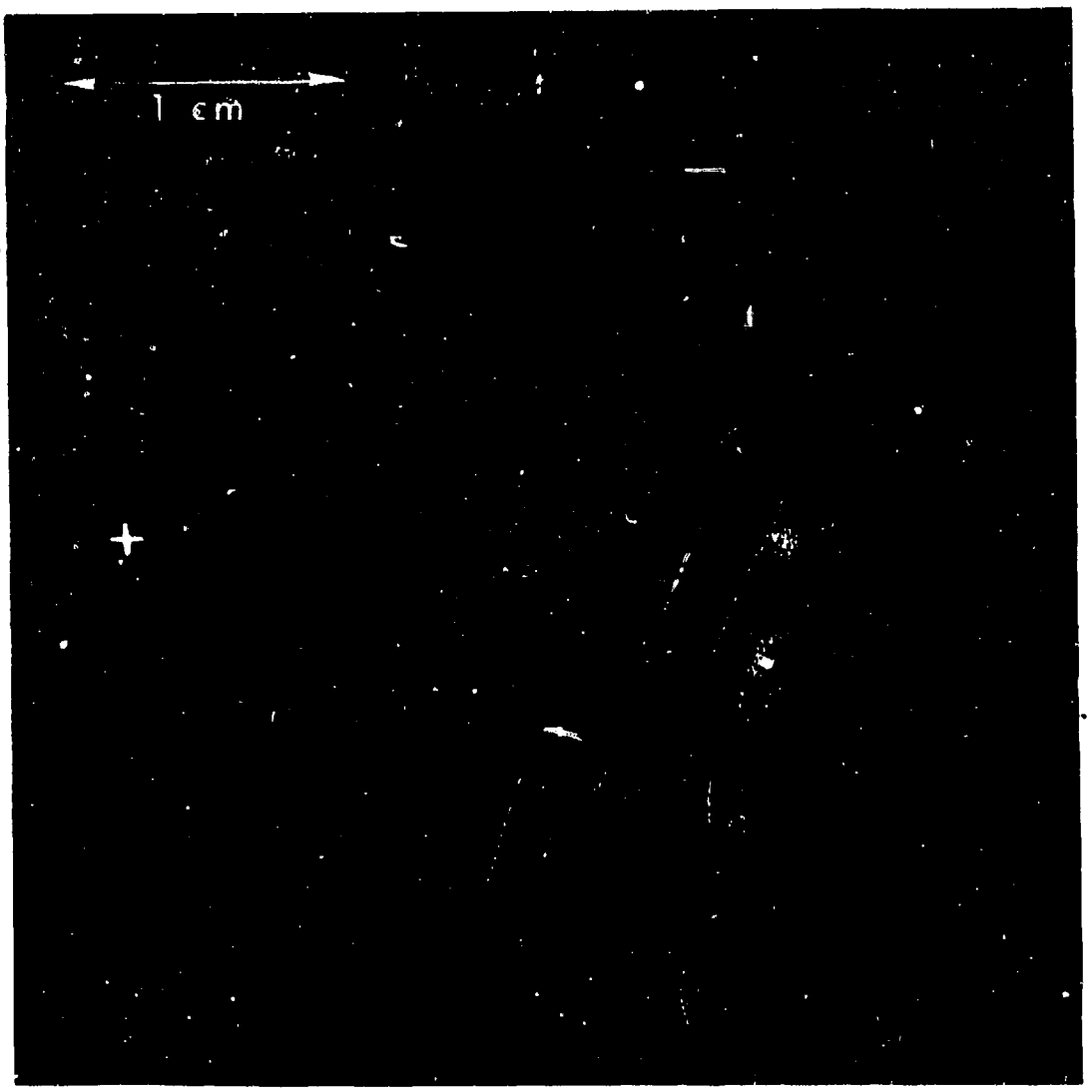

FIGURE 4. Three-Quarter-Microsecond Photograph of Impedance Mirror Impacted by Detonation Front in 75/25 Nitromethane/ Acetone. Wave was beginning to fail when impact occurred.

The impedance mirror was so named because the shock impedance (ρD, the product of density times the shock velocity) of Plexiglas is nearly a match to that of nitromethane or a 75/25 solution of nitromethane with acetone. As a practical matter, this means that when the nitromethane detonation wave (a reactive shock) passes from the nitromethane into the Plexiglas and becomes a nonreactive shock, no reflected wave passes back into the nitromethane from the interface, which would change the reactive zone pressure level and affect the reaction time. With pure nitromethane the detonation reaction is so fast that not much detail can be seen. We have therefore used a technique of gas dynamicists, who dilute a reactive mixture with argon to stretch reaction time. We have diluted nitromethane with acetone to a degree (65% acetone) where the solution will not ordinarily detonate, but then strongly overboosted the material to force it to react. With this device, both an induction zone and a reaction zone become visible.

Existence of a reaction zone has never been doubted even before it could be measured—explosives do react and they do so in finite time—therefore there is a reaction zone. An induction zone has always been doubted even though one should logically exist. Consider the cook-off test; at a given temperature an explosive cooks for a given time before exploding, and as the temperature is increased the cooking time is decreased. A shock wave heats the explosive to a given high temperature, and it should cook for a (short) time before reacting. This short cooking time is just the induction time. If reaction does, in fact, start at the front of the detonation wave, then at some point between moderate temperatures (where the cook-off time is minutes) and the high shock temperatures (where the cook-off time is zero), the explosive had to change its behavior, and to some workers this does not seem logical. In their view, the induction zone, immeasurably short, exists ahead of the reaction zone. Be this as it may, by dilution and overboosting, an induction zone is visible. An example is shown in Figure 5.

In the figure, distance across the mirror face runs up and down. Time runs from left to right. Initially, in region 1, the camera sees only specular reflection from the mirror. Then, instantaneously across the mirror a shock front arrives and changes the reflectivity; this is the beginning of region 2—the induction region. There are wavelets of pressure extending through this region, as can be seen from mildly varying reflectivity. If there were zero activity here, region 2 would appear as uniform as region 1 (ignore the horizontal lines, they are due to dust particles on the jaws of the slit). The induction time under these particular experimental conditions of dilution and boosting is about 1/3 microsecond, but it would be shorter with less acetone dilution or stronger boosting. Region 3 shows violent reaction and very large cells. Keep in mind that a horizontal straight edge laid on the photograph shows the temporal reflectivity of a single point on the mirror with time increasing from left to right. In region 3 a point on the mirror oscillated from a reflecting position to a position of

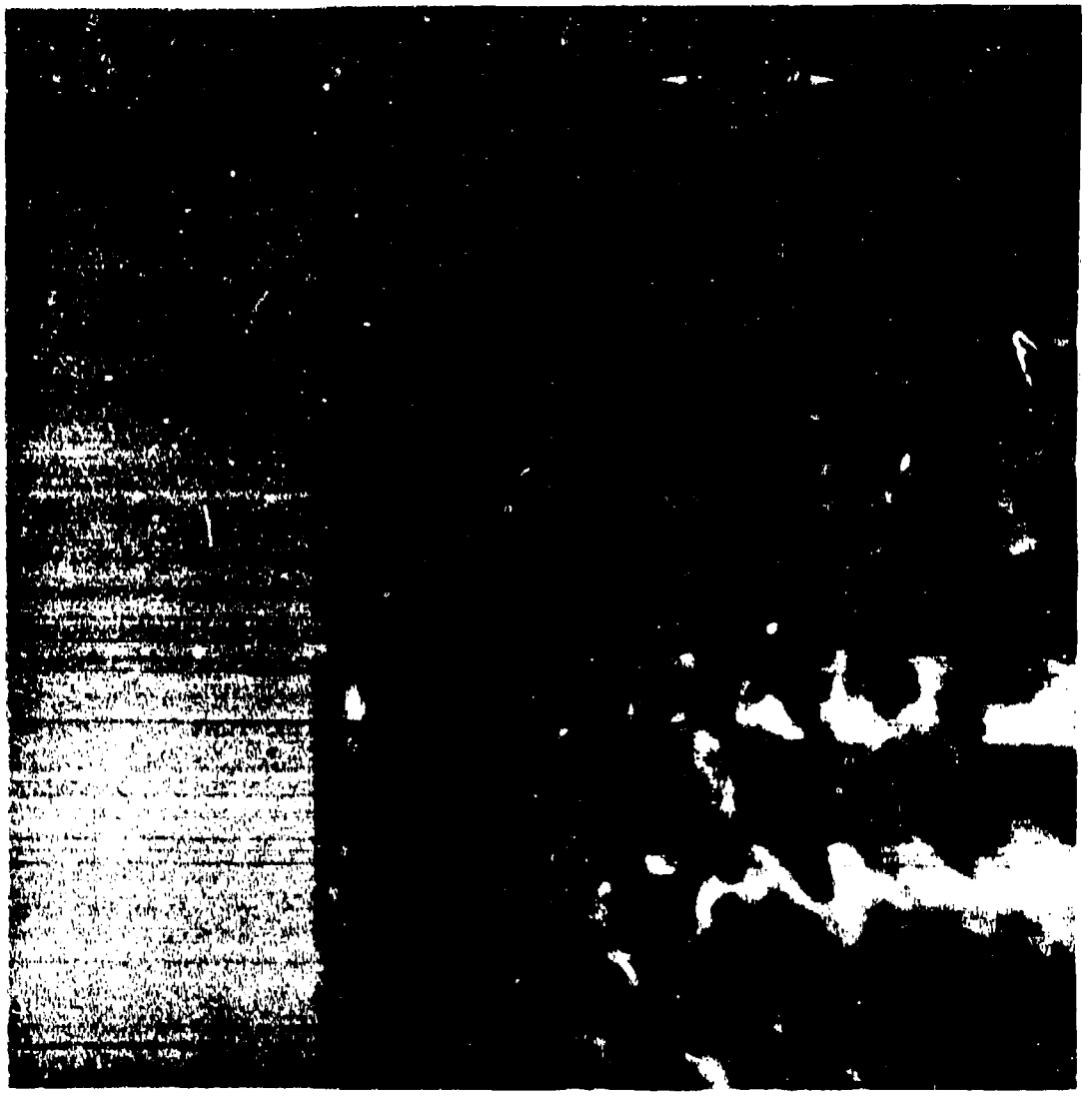

FIGURE 5. Streak Camera Photograph of Impedance Mirror Impacted by the Detonation Wave in 35/65 Nitromethane/Acetone Overboosted by Composition B.

extinction several times per microsecond. As the shock wave passes through the reflecting layer, we actually see the reflecting layer further and further back in the reaction zone. Thus in the course of passing through, the reflecting layer shows the degree of activity in successive layers completely through and behind the zone. By this time the nonreactive shock is well into the Plexiglas, but the Plexiglas remains transparent and we observe through it. Somewhere between region 3 and 4 the activity begins to die away, and to the right of region 4 the mirror is quite even though translating toward the camera at high velocity. The Chapman-Jouguet plane, which is the end of the reaction zone, is marked by just this vertical line across the photograph where reaction dies away. Our need now is to decide where to draw this line.

Looking at a series of similar photographs, the eye can reasonably distinguish between regions of different activity. Of course, people with different eyes will see such a line in slightly different positions. Line placement by visual estimate is not an objective way of determining the extent of the reaction zone. However, a photomultiplier device, scanning the wave through a slit parallel to the shock front, can average light and dark areas across a photograph to show the regions more objectively.

RECORD READING

For real-time data recording of detonation reactions, we used a Gaertner model M120 PC photoplate comparator which has a built-in photomultiplier scanner. We added an encoder to electrically sense the x-position of the moving bed, and interfaced the system to a Wang 720 computer and Wang 702 printer-plotter output. The Wang 720 was programmed to interrogate the encoder and photomultiplier and plot the readings as a point on a graph. The program (see appendix A) works in real time and plots one point each computer cycle. Since the comparator bed can be moved very slowly, it is easy to get a plotted point for each micron of bed movement. Appropriate magnification factors in the computer program produce a graphed output of any desired size. One ordinarily wants the largest graph consistent with feed paper size, and with suppression of background noise.

A printout of the photomultiplier output for a typical 75/25 nitromethane/acetone record is shown in Figure 6. The inked lines have been added to show how the records were read. As can be seen from Figure 5, different horizontal scans will produce slightly different times for the zone width. We have tried to average these times, and this average is given as our best estimate of the zone width.

INTERPRETATION OF ZONE WIDTH

In a shocked inert liquid such as acetone, the pressure in the liquid can be square-step and there seems to be no possibility of points of

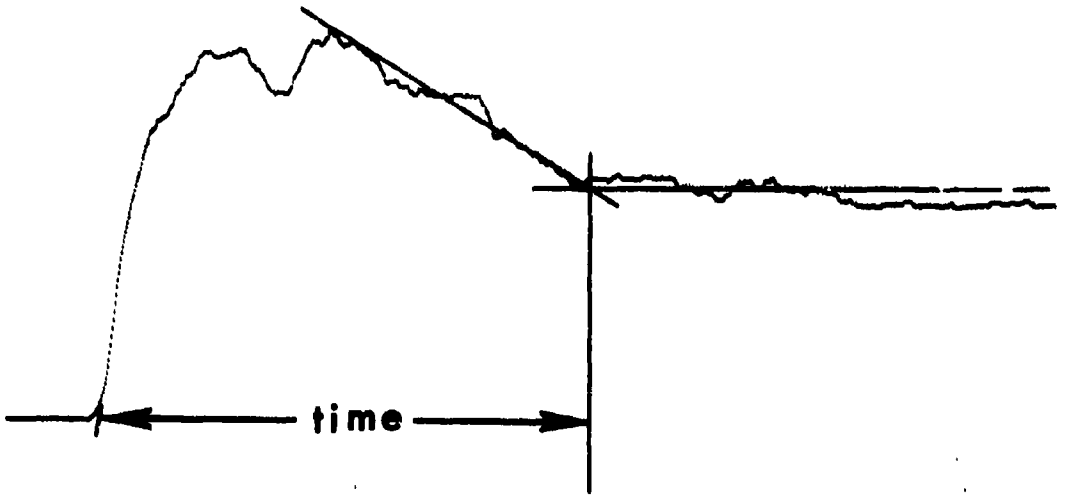

FIGURE 6. Plot of Photomultiplier Output for 75/25 Nitromethane/Acetone. Time is read directly from graph.

pressure discontinuity. The flow is plane-laminar. If we now add nitromethane to the acetone, the solution will be inert up to some point, but at slightly higher concentration reaction will begin. We can expect that reaction will begin at some interval after shock heating was applied. Figure 5 shows just these conditions. At some greater dilution (for the same booster shock strength) or some lesser booster shock (for the same dilution), the reaction had to begin at a few discrete points. Such an example is shown in Figure 7, and in this particular case the reaction never built up. The induction time is about normal for this dilution although there are a few points of reaction (deflections of the mirror) at half the induction time. This emphasizes the statistical nature of the reaction process and its buildup from discrete points. The point-discrete nature of the process implies the presence of pressure wavelets which spread from these points only to collide with one another to produce other points of high pressure by their interaction. Only if these points are sufficiently numerous will the reaction proceed to completion. This stage can be achieved either by increasing booster strength or increasing the concentration of nitromethane. When either action is taken the reaction front moves closer to the shock front and small bumps appear on the previously plane shock front. This is shown in Figure 8.

From this photograph, only small pockets of unreacted material appear to be present at the front. This is the presently accepted concept of the reaction zone. A diagram showing wavelet interactions is shown in Figure 9. It is presumed that such a description holds for all higher concentrations of nitromethane. At this dilution, smaller unreacted

pockets appear to be present at the wave front but they are already less distinct and as concentration is further increased the wave front will assume a smooth edge presumably because the camera can no longer resolve the wavelet fronts. If the reaction front has in average moved to the wave front, measurements of the reaction zone should start at the wave front and extend to the Chapman-Jouguet plane. A time-resolved photograph of the wave front in 75/25 nitromethane/acetone is shown in Figure 10.

We have postulated that the generally lighter region behind the wave front of Figure 10 marks the upper limit of the reaction zone. The zone cut-off line is not sharp in the photograph and it may not be sharp in fact. We know that the mirror will conform to pressure irregularities and that when these irregularities smooth out, the mirror will follow and assume a more planar aspect. Since the camera sees specular reflection from the mirror, any pattern impressed into the mirror will reflect less total light than a plane. The region of dynamic wavelet interaction within the reaction zone is then the least reflective region in the streak photograph, and as the pressure field passing through the mirror becomes steady the mirror becomes more planar and reflects increasing light. As was mentioned previously, the electromagnetic technique has given us a reference point for calibration of the impedance mirror since that method has been used to measure the reaction zone in 75/25 nitromethane/acetone.[7] The time measured by Dremin and his co-workers was 0.4 microsecond for a charge 7 inches long, and an unspecified booster. Since the value corresponds to our steady state value which begins after about 10 inches of run, we can assume that his booster was less vigorous

FIGURE 7. Impedance Mirror Record of Beginning Reaction in 35/65 Nitromethane/Acetone. Induction time is 1/3 to 1/2 microsecond.

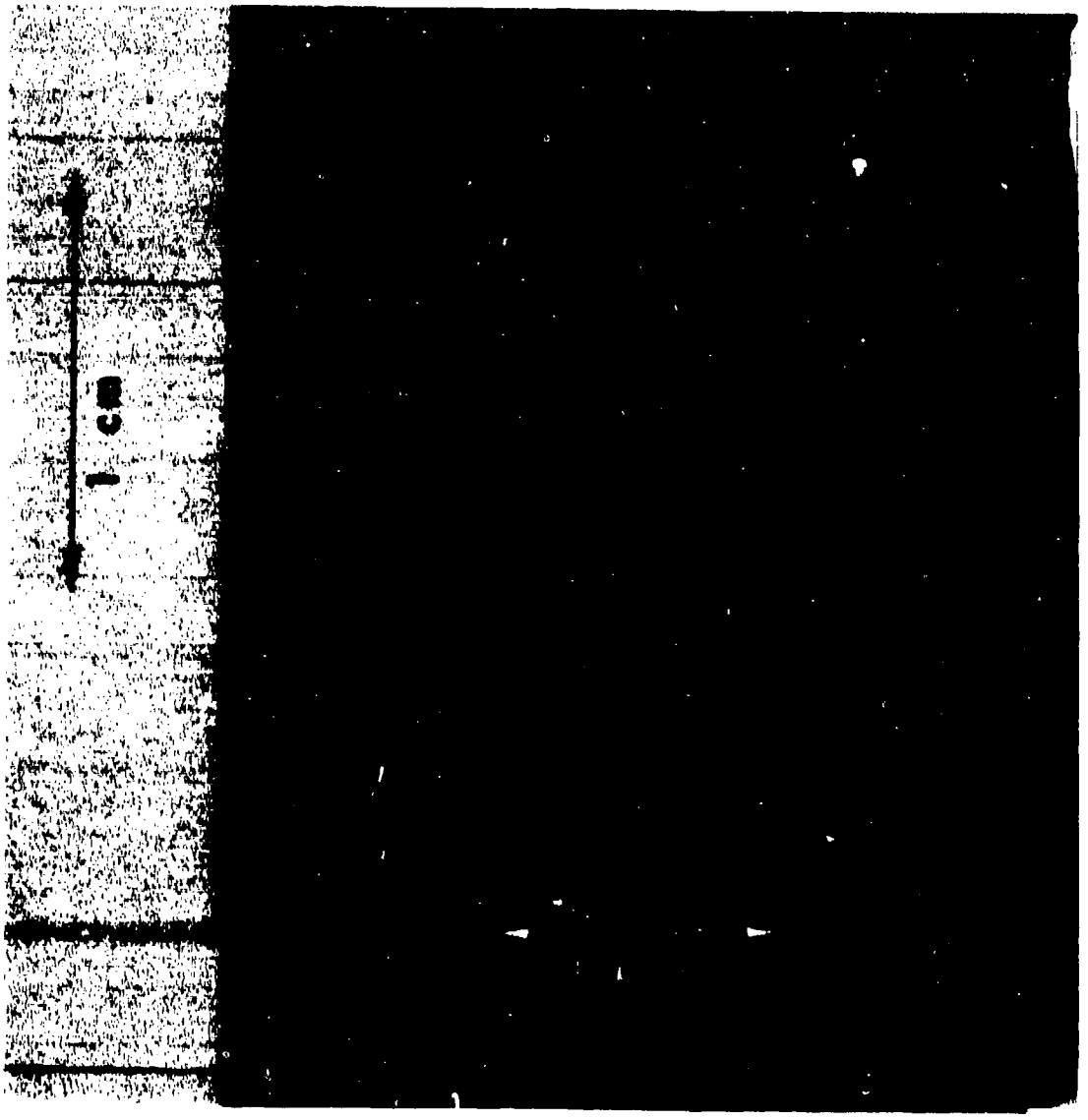

FIGURE 8. Impedance Mirror Streak Record of Detonation in 45/55 Nitromethane/Acetone. Same booster as for Figure 5.

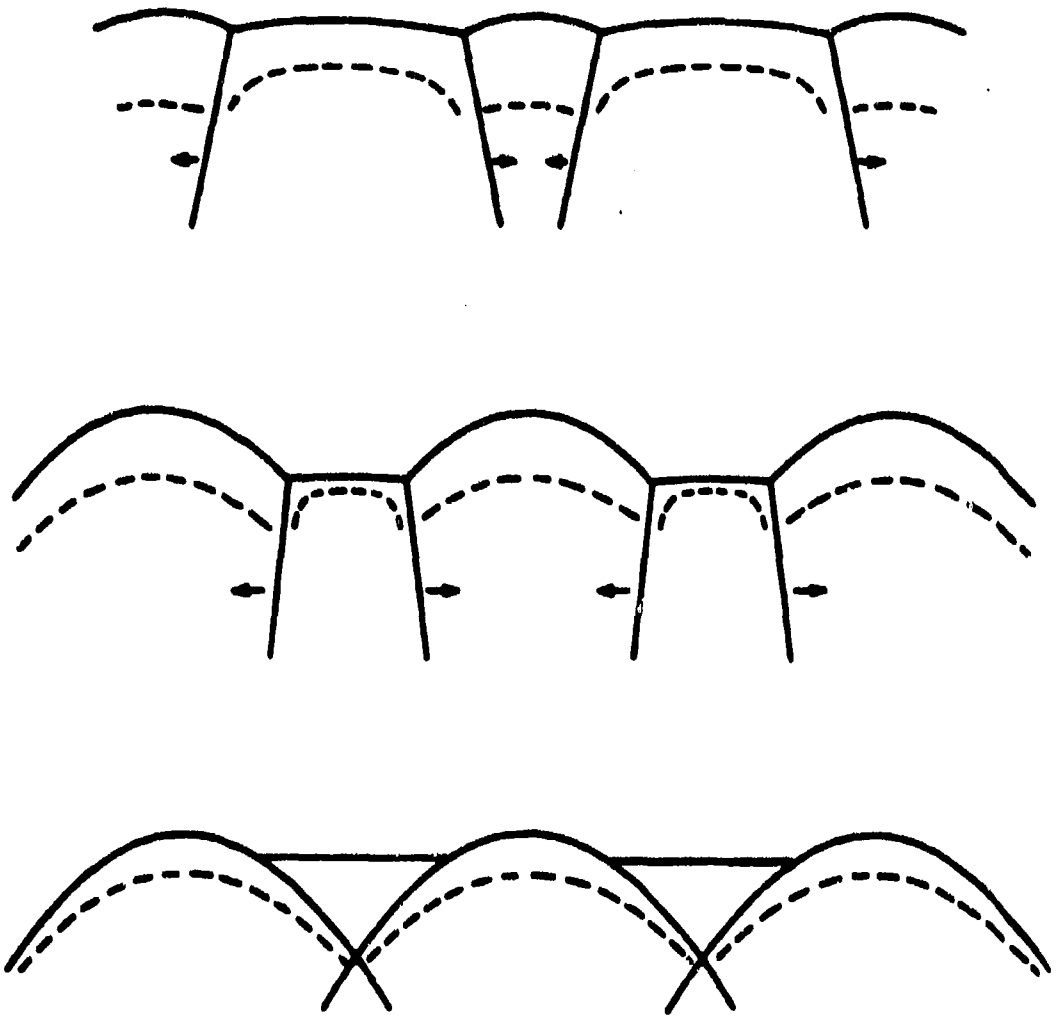

FIGURE 9. Development of Front Structure. The wave moves from bottom to top of figure. Dashed lines indicate end of the reaction zone (After Fickett[12]).

[12] Army Research Office. *Mechanism of Propagation of Steady Detonation,* by Wildon Fickett. (ARO-D Report 70-4, publication UNCLASSIFIED.) Durham, N. C., ARO, October 1968. P. 223.

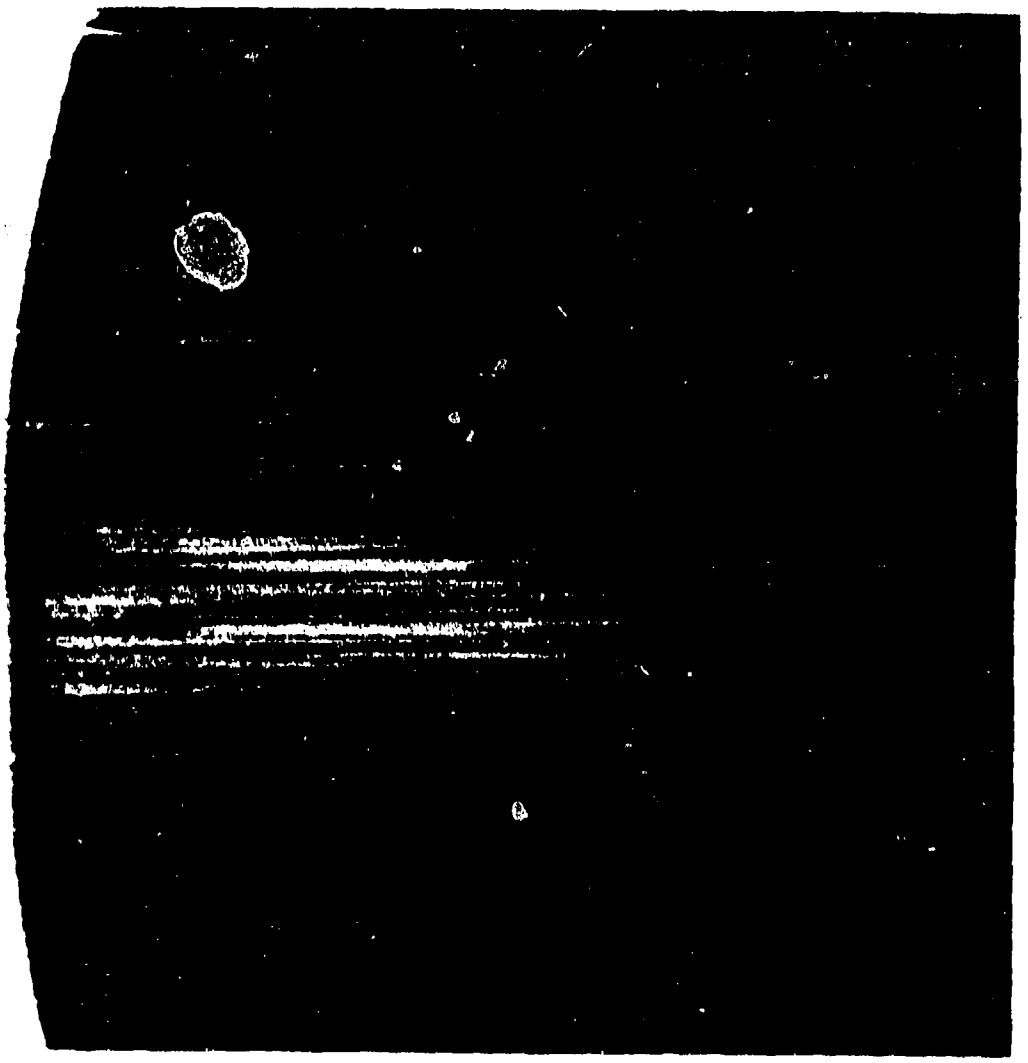

FIGURE 10. Impedance Mirror Streak Record of Detonation in 75/25 Nitromethane/Acetone. For overdriven 7.62-centimeter-long charge.

than ours, and overboosting effects had died out before reaching his electromagnetic probe placed 7 inches into the charge. By reference to the electromagnetic value we can infer that the dark zone in the impedance mirror records is in fact due to the reaction zone and that its time duration marks the reaction time. We can also be reasonably sure that a reflected wave has not changed the zone width since Plexiglas is well matched in shock impedance to the diluted nitromethane. This can be seen from Figure 11, which shows the Plexiglas data of Liddiard[13] along with the ρU slope of 75/25 nitromethane/acetone. The matching conditions show the pressure to be 90.1 kbar, which compares well with the electromagnetic value of $P = 1.045 \times 5.75 \times 1.51 = 9.07 \times 10^{10}$ dynes/cm^2 or 90.7 kbar.

Reaction time values for various charge lengths and our standard booster are shown in Figure 12.

CONCLUSIONS

Features of a detonation wave such as induction time, turbulent cell size, reaction time, and nonplanarity due to microdetonations within the reactive region are features which can be seen with ease by the impedance mirror. Changes in reaction zone thickness due to rarefaction waves at a charge edge have been postulated, but have only recently been observed experimentally—and there again, with the impedance mirror.

With this new experimental method the important subject of detonation buildup—deflagration to detonation transition—can be observed in detail. In these cases the detonation pressure is relatively low, and this is just the region where the mirror works best. In the high-pressure regions—above the detonation pressure of TNT—the mirror is not applicable in its present form because reflectivity is lost in less than 1/2 microsecond after the metallized layer is touched by the wave front. The reason for this effect is not yet known, but it is known to happen with aluminum, nickel, titanium, and gold. The high-pressure regions are amenable to the plate-push and electromagnetic methods, however, and these regions can be studied if so desired. Deflagration to detonation transitions and the entire region of unsteady detonation seem of greater importance at the present time, and these regions can now also be examined experimentally.

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[13] Liddiard, T. P., Jr. "The Compression of Polymethyl Methacrylate by Low Amplitude Shock Waves," in *Proceedings of the Fourth Symposium (International) on Detonation*, 12-15 October 1965, White Oak, Md. (ACR-126) White Oak, Naval Ordnance Laboratory, 1965. P. 214.

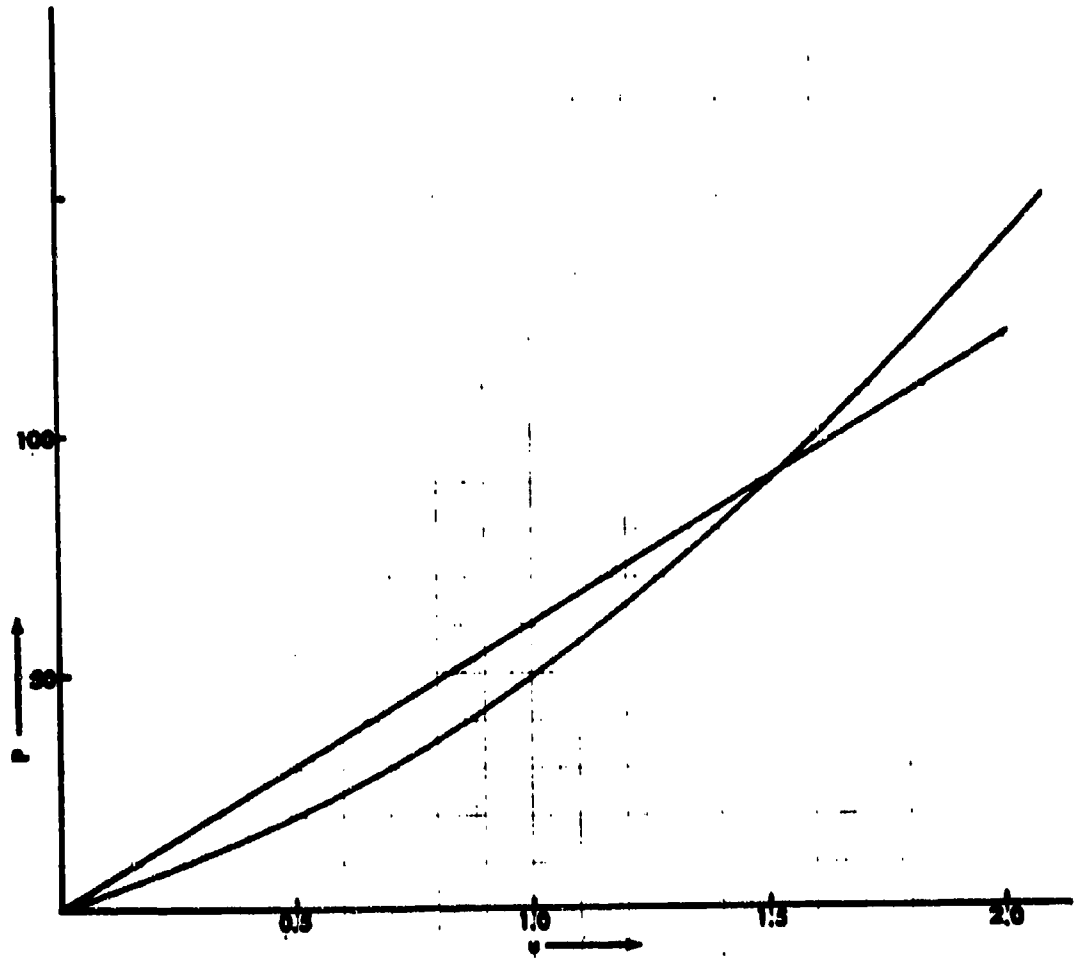

FIGURE 11. The Curved Line Is $P = \rho_o U_u$ for Liddiard's Plexiglas Equation $U = 2.56 + 1.69u$. The straight line is $\rho U = 1.045 \times 5.75$ for 75/25 nitromethane/acetone. The intersection point at P = 90.1 kbar compares well with P = 90.7 computed from the Chapman-Jouguet value of u from the reference cited in Footnote 7.

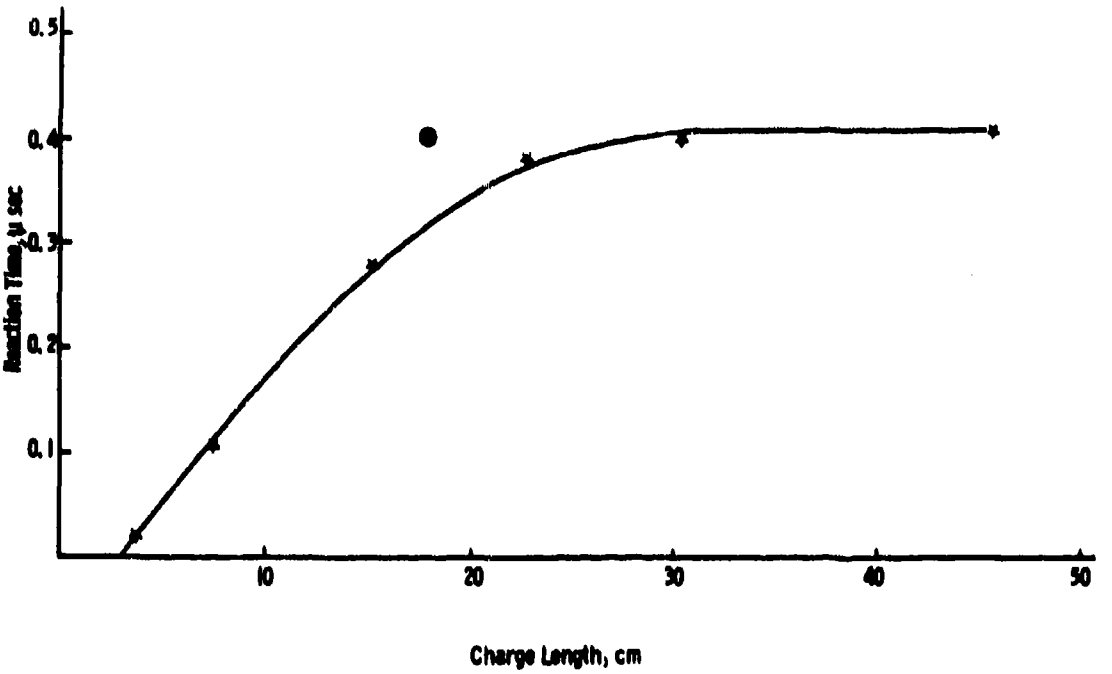

FIGURE 12. Impedance Mirror Values for Reaction Time in 75/25 Nitromethane/Acetone. The dot (•) indicates electromagnetic value.

Appendix A

WANG 720 COMPUTER PROGRAM FOR REAL-TIME DATA READING OF DETONATION REACTION RECORDS

The microcomparator bed is capable of widely varying rates of travel. When operated at very low speed, one data point for each micron of comparator bed travel can be identified and plotted. For many of the records, resolution of this degree is unwarranted, the output graph from the Wang 702 printer-plotter being too long for a single pass. For this reason the x-coordinate magnification factor is sometimes changed. This is easily done by changing the number in register 03 (steps 10, 11). We normally use 2 to 10 in register 03. The photomultiplier magnification can also be changed from the value of 200 (steps 40-42 below) shown. We have used values from 200 to 1200 depending on film intensity and background noise in the record.

(0) Mark	(20) st dir	(40) 2	(60) X
(1) 0	(21) 04	(41) 0	(61) re dir
(2) 0	(22) group 2	(42) 0	(62) 09
(3) st dir	(23) 01	(43) X	(63) ( )
(4) 05	(24) ↑	(44) ↓	(64) write α
(5) Mark	(25) re dir	(45) st dir	(65) 0906
(6) 1	(26) 03	(46) 09	(66) end α
(7) 5	(27) X	(47) group 2	(67) re dir
(8) st dir	(28) ↓	(48) 01	(68) 06
(9) 03	(29) st dir	(49) ↑	(69) ↑
(10) 1	(30) 07	(50) re dir	(70) re dir
(11) 0	(31) group 2	(51) 03	(71) 05
(12) st dir	(32) 00	(52) X	(72) skip if y<x
(13) 06	(33) chg sign	(53) X	(73) search
(14) write α	(34) -dir	(54) 07	(74) 1
(15) 0102	(35) 04	(55) -	(75) stop
(16) end α	(36) re dir	(56) 1	(76) end program
(17) group 2	(37) 04	(57) 0	
(18) 00	(38) chg sign	(58) 0	
(19) chg sign	(39) ↑	(59) 0	