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DETONATION OF UNCONFINED LARGE SCALE FUEL SPRAY-AIR CLOUDS

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ABSTRACT

Unconfined heterogeneous two-phase detonations in liquid droplet-air mixtures are investigated. The liquid fuel is placed in a V-shaped channel and is dispersed into the atmosphere to form a cloud by an explosive detonating cord laid along the bottom vertex of the channel. An aerosol cloud 7 m high by about 1.5 m averaged width can be generated in this way with a typical mass ratio of fuel to explosive charge of 150. In the present study the length of channel used is typically 10 m giving a detonable fuel-air cloud of about 100 m^3. Initiation of detonation in the cloud is by a sheet explosive charge mounted on a piece of plywood .3m x 1.2m and the total charge weight used is about 850 gm. For less sensitive mixtures, a 1.5 m initial section of the channel is filled with propylene-oxide. The propylene-oxide driver and the test fuel are disseminated simultaneously. Detonation in the propylene-oxide section is initiated by the sheet explosive and the detonation then transmits from this driver section into the rest of the cloud formed from the test fuel. For insensitive fuels requiring a larger cloud dimension, two parallel fuel troughs spaced 1.2 m apart are used. It is found that propylene-oxide and nitrated hydrocarbon fuels detonate quite readily. For the case of propylene-oxide, significant vaporization of the aerosol is observed prior to initiation so that detonation is essentially in the gas phase. In contrast to Bull's finding, hexane cannot be detonated in the present investigation. However, with secondary shocking of the cloud after it has been formed (but prior to initiation), hexane is found to detonate readily as in Bull's experiment. The secondary shocking provides further fragmen-

tation, evaporation and mixing of the hexane vapor to form a hybrid cloud of liquid, vapor and air. It is found that for low vapor pressure fuels such as decane, detonations are not observed even with pre-shocking of the mixture before initiation. This confirms the importance of the presence of fuel vapor in the cloud to render it detonable.

1. INTRODUCTION

Detonation of mixtures of liquid fuel sprays (droplets or aerosols) and air have been studied extensively in the past two decades[1-6]. Perhaps the most conclusive demonstration of the existence of self-sustained heterogeneous detonations in low vapor pressure liquid fuels (e.g. decane) is the work of Bowen et al[7]. They used very small particles ($\sim 2\mu m$) in pure oxygen at atmospheric initial pressure and were able to observe steadily propagating waves with velocity fluctuations of $\pm$ 1% over many tube diameters. They used a relatively weak ignition source and the detonations were formed via transition from deflagration to detonation. Thus, there was no question of an excessively powerful initiator overdriving the wave in the region of observation. Furthermore, a multiheaded spinning wave was also observed indicating the true universal characteristic of cellular detonation structure. However, for the much less sensitive fuel-air mixtures, attainment of self-sustained heterogeneous detonations of low vapor pressure fuels is less convincing. Perhaps the largest diameter detonation tube used (i.e. 0.5 m diameter by 4.5 m long) was in the study carried out by Smeets[6]. He reported successful heterogeneous detonations in sprays (mean droplet diameter of the order of 350 μm) of low vapor pressure fuels such as decane and hexanol in air. However, a very powerful ignition source ($\sim$ 1 kg of high explosive) was used and this renders the results obtained questionable. It is known that the strong transverse perturbations generated by a strong initiator decay very slowly, if at all, in a confined tube. These igniter generated transverse perturbations play the role of true transverse waves

in a cellular detonation and thus maintain artificially a steadily propagating front. If these strong transverse perturbations are removed (eg. damping by porous walls) or weakened by relaxing the confinement (eg. diverging cross-sectional tube area) the "detonation" will fail since it is incapable of generating its own transverse waves.

Perhaps the best way to demonstrate the detonability of an explosive mixture is to study unconfined detonations in it. Bull et al[5] reported experiments on unconfined detonations in fuel aerosols and air. Fuel droplets of mean diameter of about 15 μm were produced in a 5 m^3 volume by sonic air-blast atomizers. Spherical detonations were initiated by a high explosive charge (typically 25 gm to 500 gm) and had a propagation length of 1.83 m for observation. Bull found that for a high vapor pressure fuel such as hexane, unconfined detonations can be readily initiated with a charge weight of about 25 gm of tetryl which is typical of that for a homogeneous gas phase detonation of hydrocarbon-air mixtures. However, for the low vapor pressure fuels such as decane and dodecane, detonations were not observed even with 500 gm of tetryl initiator. On the basis of further experiments with a mixture of hexane and dodecane as fuels, they concluded that self-sustained detonations may require a certain quantity of fuel vapor to be present prior to ignition.

From all these previous studies, one may conclude that vaporization and turbulent mixing of the fuel vapor with air is the controlling mechanism for heterogeneous two phase detonations. Thus two phase detonations may be said to be in fact hybrid detonations where the fuel

appears in both the vapor and liquid state. Since the scale of Bull's experiments is insufficient to detonate dodecane without the presence of hexane vapor it seems important to carry out further tests on a larger scale to establish the detonability of low vapor pressure fuels in air. The present paper reports recent results of some large scale tests of unconfined detonations in hexane and decane to elucidate further the controlling mechanisms of heterogeneous detonations.

2. EXPERIMENTAL RESULTS

The task of producing a large uniform volume of monodisperse liquid droplets in air is extremely difficult if at all possible. Even if such a monodispersed droplet generator can be designed, gravity settling, droplet coalescence and induced flow by the spray would still tend to render the mixture non-uniform. Lacking a knowledge of the length scale of heterogeneous detonations (as a function of particle size, vapor pressure, type of fuel, etc.) at present, it is difficult to estimate the requirement as to the uniformity of the mixture itself. Thus in the present study it was decided to first emphasize the global features of heterogeneous detonations.

The liquid droplet-air mixture is generated by explosive dissemination of the liquid fuel. A horizontal linear V-shaped metal trough (standard structural 90^{o}-angle) is filled with the liquid fuel which is then dispersed into the atmosphere by detonating primacord (or

MDF-mild detonating fuse) laid along the bottom vertex of the V-channel. Figure 1 shows a schematic diagram of the trough, the plane sheet explosive initiating charge and the high speed camera diagnostics. For a given volume (or mass) of the liquid fuel per unit length along the channel, various strengths of the explosive cord have been tried to get the optimum cloud volume. Typically, the amount of explosive (PETN) used is 20 grains/ft or 4.32 gm/m for a volume of about 1 litre/m of liquid fuel. The typical aerosol-air cloud that is generated above the trough is about 2.1 m at its maximum width and 7 m high. The total cross-sectional area is of the order of 10 m^2. Figure 2 shows selected frames of a high speed movie of the cloud from camera stations viewing the time evolution of the length and width of the cloud. Typically, the length of the trough is about 8 to 10 m giving a total cloud volume of about 80 m^3 as compared to the 5 m^3 volume of Bull's earlier experiments. Initiation of detonation is at one end of the cloud giving a propagation length of about the same dimension as the channel itself (i.e. $\sim$10 m). Compared to the 1.83 m propagation length of Bull's experiment, the present study permits the detonation to be observed over a much longer distance to assess its self-sustenance effectively uninfluenced by the initiation source. For certain fuels in which detonation could not be obtained, it was thought that the width of the cloud is below the critical dimension to sustain an unconfined detonation. The work on the critical channel width[8,9] and the influence of yielding confinement studied by Brossard[10] and Murray and Lee[11] indicate that the minimum dimension of the cloud must be at least greater than the characteristic length scale of the detonation. In the case of homogeneous gas detonations, the characersitic length scale is

the detonation cell size λ . However, for two phase detonations, no clear indication of the existence of a regular cell pattern has been observed to date even though the work of Bowen et al[7] on two-phase fuel-oxygen mixtures does indicate the presence of a multi-headed spinning structure.

To provide a means of generating a wider aerosol-air cloud, two parallel troughs separated by a distance of 1.2 m are used. With two parallel troughs, the width of the cloud is approximately doubled. No direct measurement of droplet size in the cloud has been made. However, from simple analysis based on the work of Mayer[12] and Andersen and Wolfe[13] it is estimated that the particle size ranges from about 20 μm to 50 μm . The mixture composition is not determined but an estimate is made on a global basis from the quantity of fuel dispersed and the volume of the cloud formed as indicated by the high speed movie records.

Initiation of the detonation is achieved by a sheet explosive charge (typically about 850 gm of Deta sheet) mounted on a piece of plywood, .3 m x 1.2 m in size. The explosive sheet is raised on a post so that its bottom is about 1.2 m above the ground. For the less sensitive fuels, a driver section is used rather than increase the solid explosive charge. The first 1.5 m of the trough is separated from the rest so that a different (more sensitive) driver fuel can be used. Propylene-oxide is usually used in the present study for this driver section. The propylene-oxide driver and the test fuel are dispersed simultaneously in the experiment. The solid explosive sheet initiates a detonation in the propylene-oxide portion of the cloud which then transmits into the

remaining portion of the cloud containing the droplets of the test fuel. In this manner, the degree of initiation overdriving is minimized.

A number of liquid fuels have been tested (eg. propylene-oxide, hexane, decane, nitrated hydrocarbons, etc.) However, the emphasis of the experiment has been on hexane and decane in an effort to extend and clarify the previous study of Bull et al[5].

3. RESULTS AND DISCUSSION

A large number of trials have been carried out initially to optimize the proportion of mass of liquid fuel to be dispersed to the dispersion charge weight per unit length of channel. These tests were carried out with water and observed with high speed movie diagnostics. Figure 2 shows typical results of such dispersion tests. It was found that the best results are obtained for a mass ratio of 150 (i.e. mass of liquid fuel to mass of explosive per meter). From the maximum cloud volume estimated from the movie film records, the amount of liquid dispersed was tailored to yield an averaged fuel-air cloud composition that was approximately stoichiometric for all the fuels tried.

For the detonation tests it was decided to first study propylene-oxide since it is a very sensitive fuel with a high vapor pressure at ambient temperatures (442 torr at 293°K). The propagation of detonation through the cloud can then yield information on the dispersion and

uniformity in the cloud with the present method of explosive dissemination. Because of the high vapor pressure of propylene-oxide, it is necessary to pre-chill the metal trough with liquid nitrogen before the liquid fuel is introduced since significant evaporation can occur prior to detonation if the channel is warm. High speed movie records show that shortly after dispersal of the propylene-oxide, the cloud becomes practically transparent indicating that the aerosol has evaporated. Thus for a high vapor pressure fuel such as propylene-oxide the detonation occurs practically in the gas phase rather than as a two phase heterogeneous detonation. This explains the relative ease in detonating propylene-oxide-air mixtures. The detonation is observed to propagate along the entire length of the cloud and the local inhomogeneities in the cloud can be deduced from the shape of the advancing front. The local inhomogeneities, however, are insufficient to cause the detonation to be quenched as it propagates. Due to the unknown detailed stoichiometry of the cloud and its non-uniformity, no attempt is made to measure the local detonation velocity and to compare it with the theoretical CJ values. However, the average velocity of the detonation over the length of the cloud is of the order of 1600 m/sec typical of that for fuel-air mixtures.

It has been found[14,15] that additives such as propyl nitrate and butyl nitrate to kerosene result in the sensitization of the fuel. Some tests in the present series were carried out using nitrated hydrocarbons as fuel. Detonations are easily obtained with results similar to that for propylene-oxide even though the vapor pressure for these fuels is very much lower (typically 0.5 torr at 293^{o}K). No significant evaporation of

the aerosols can be observed (as indicated by changes in the transparency of the cloud after dispersion) prior to initiation. Thus in these cases the detonation is truly one in a two phase heterogeneous unconfined environment.

For hexane, it is found that detonation cannot be achieved in contrast to Bull's previous experiments. Suspecting that perhaps the minimum cloud size could be below the critical value for unconfined heterogeneous hexane-air detonations, the double trough configuration was used increasing the cloud width to 3.5 m. However, even for the larger dimension, hexane aerosols failed to detonate in air. The vapor pressure of hexane at ambient temperature is about 140 torr at 293^{o}K which would render all the dispersed liquid fuel gaseous (i.e. stoichiometric mixture) if equilibrium were achieved with sufficient time for evaporation. The failure to detonate the hexane aerosol in the present case as contrasted with Bull's results could be due to i) a larger particle size and ii) insufficient time for evaporation and mixing to form a detonable hybrid mixture prior to initiation. The study of Smeets[6] indicates that evaporation and turbulent mixing of the fuel vapor with air to be a controlling rate mechanism in two phase detonation. He deduced this from his laser diagnostic investigation of the structure of the reaction zone. In Bull's experiments, where the fuel is disseminated by nozzles, it is envisaged that ample time is available for the hexane droplets to come into phase equilibrium. Also, the flow induced by the nozzle discharge provides the necessary turbulent mixing of the hexane vapor with the air to form a hybrid mixture. In the present tests explosive dissemination

provides little time for evaporation and mixing prior to initiation since the total elapsed time from beginning of dispersion to initiation of detonation is about 100 ms.

In an effort to detonate hexane it was decided to try secondary shocking of the cloud prior to initiation. To achieve this, air shocks are generated by stringing primarcord in zig-zag fashion on two sides of the cloud (Fig. 3). After the initial explosive dissemination in which the aerosol cloud is formed, the primacord is then detonated to produce air shocks to traverse the cloud from the sides. The primacord arrays are placed sufficiently far away from the edges of the cloud so that they do not initiate the cloud. The role of the secondary shocks is to provide further fragmentation of the fuel droplets and also to induce a flow for turbulent mixing of the vapor with air prior to the actual initiation of the cloud itself.

With secondary shocking of the aerosol hexane cloud, detonation could be observed even in the single trough configuration with a maximum cloud width of about 2 m. However, in the single trough configuration detonation over the entire length of cloud is not always observed and the wave appears to be less stable. This suggests that the critical dimension of the hexane-air cloud (with the present method of dispersion) is of the order of 2 m. When the double trough configuration is used giving a cloud width of about 3.5 m, detonation is obtained in every case with secondary shocking.

Figure 4 shows a sequence of selected frames from a high speed movie record of hexane-air detonation in a cloud formed by dispersing fuel from a single trough with secondary shocking from a zig-zag primacord array placed on one side of the cloud (behind the cloud). The first frame of the sequence clearly shows the end of the secondary shocking and the outline of the zig-zag pattern of combustion products of the primarcord is visible through the cloud. The second frame shows the initiation of the driver section and in subsequent frames the hexane-air detonation is seen to propagate the length of the cloud. The averaged velocity of detonation as measured from the high speed film is about 1560 m/sec as compared to 1800 m/sec of the theoretical CJ value for stoichiometric hexane-air detonation.

Using secondary shocking as well as the double trough configuration, it found that decane fails to detonate. This was found by Bull et al[5] also. This suggests that for low vapor pressure fuels, unconfined detonations are very difficult to achieve in air. Even with pre-shocking of the mixture where further atomization occurs, the mixture is not sufficiently sensitized with the amount of vapor present. This suggests that most two-phase heterogeneous detonations are hybrid detonations with some fraction of the fuel in the vapor state premixed with the air prior to detonation. A truly liquid-air mixture without the presence of fuel vapor would be extremely insensitive requiring a very large scale to render the cloud detonable.

4. CONCLUSIONS

The present study of unconfined two phase detonation conclusively demonstrates the importance of the presence of vapor to render an aerosol cloud detonable. Even for the case of hexane, the present method of rapid dissemination by an explosive line charge does not allow sufficient time for the fuel to evaporate and the vapor to mix prior to initiation. Thus it is difficult to detonate hexane in contrast to the previous study of Bull et al[5]. However, with secondary shocking of the hexane-air cloud no difficulty is encountered in detonating it. For the case of low vapor pressure fuels such as decane, even secondary shocking fails to generate sufficient vapor to render the cloud detonable. However, the study of Bowen et al[7] indicates that low vapor pressure fuels with pure oxygen can readily be detonated even displaying the characteristic cellular structure of homogeneous gas phase detonations. Thus in principle low vapor pressure fuels could be detonated in air provided the scale is sufficiently large and the particle size sufficiently small. The present study also indicates that local inhomogeneities are probably not important since the characteristic length scale of the heterogeneous detonation is fairly large. Once initiated, detonations are observed to traverse the entire length of the cloud even though the distribution of the fuel is not expected to be very uniform throughout the cloud for this method of explosive dissemination.

5. ACKNOWLEDGEMENTS

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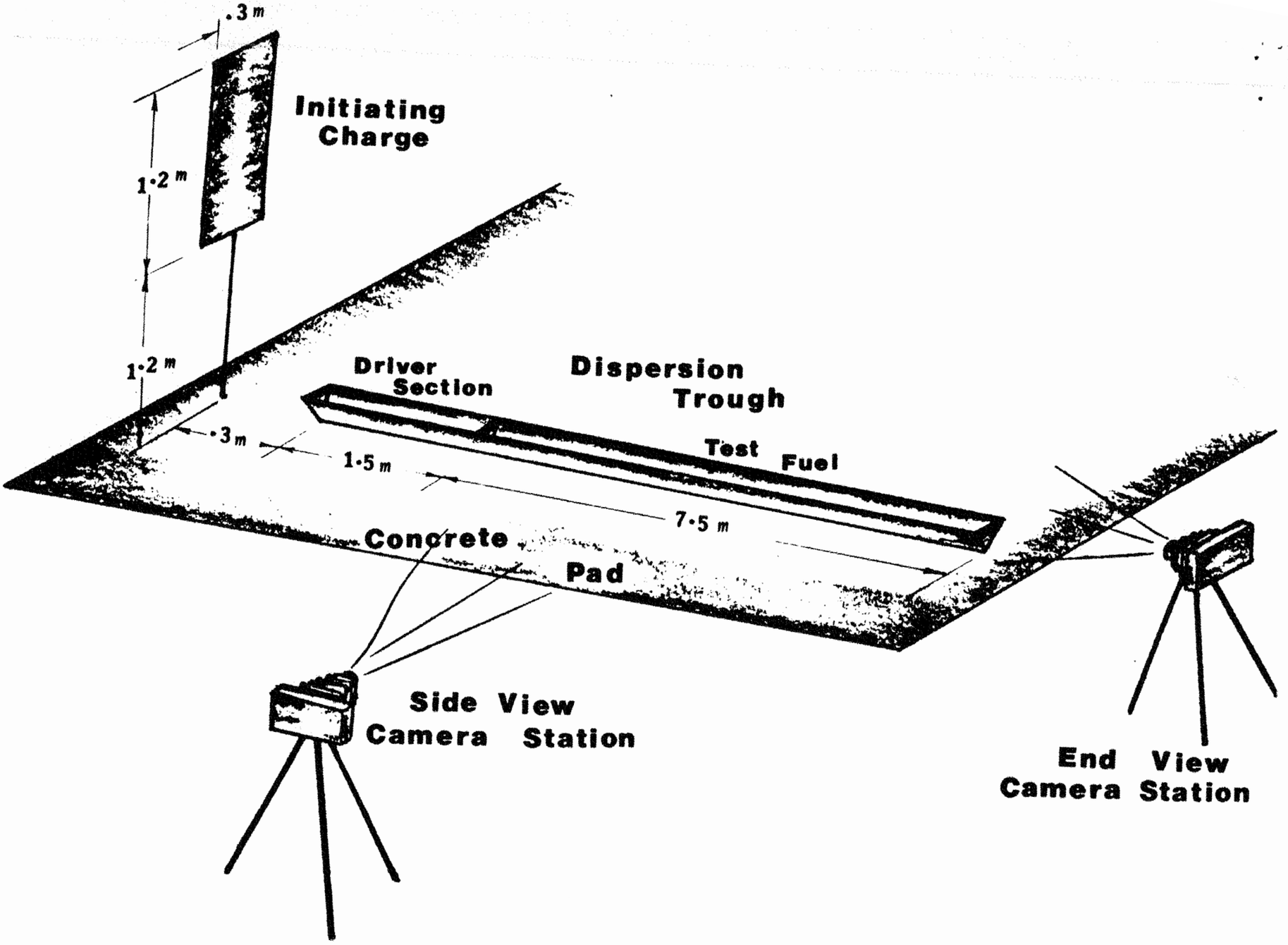
FIGURE CAPTIONS

Figure 1 Schematic Diagram of Fuel Dispersion Trough, Initiating Charge and Camera Stations.

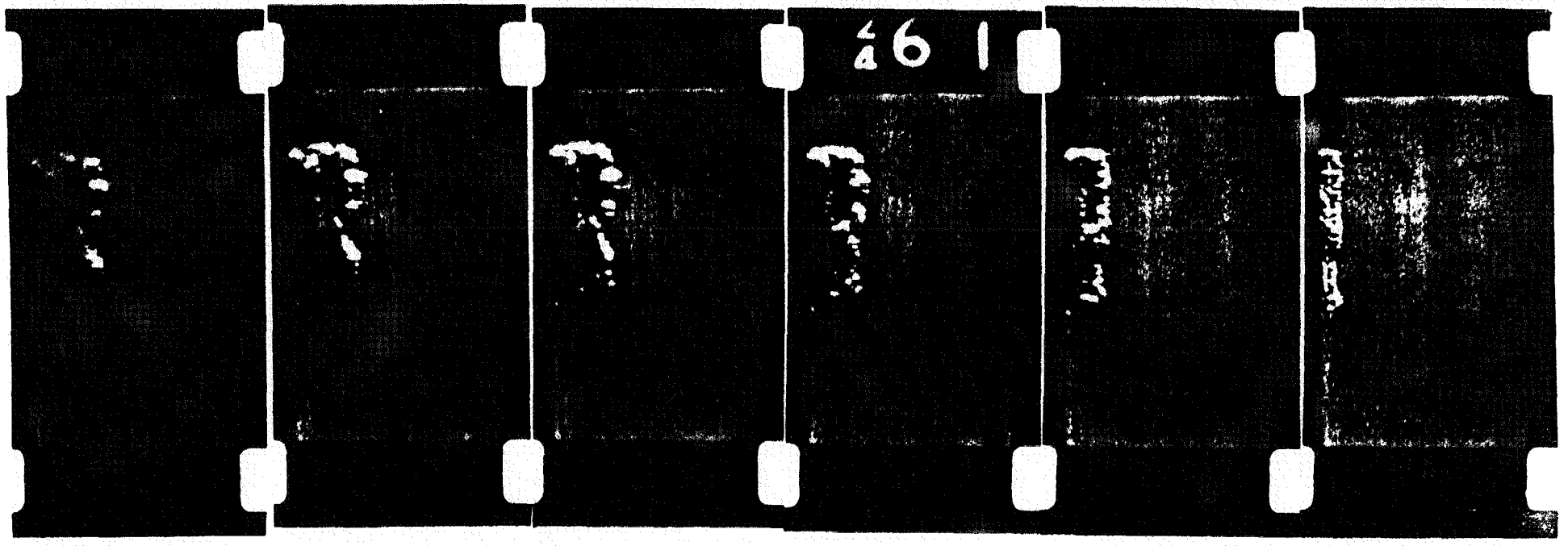
Figure 2. Sequence of Selected High Speed Movie Frames Illustrating Side and End Views of Fuel Dispersion to Form FAE Cloud (100 m^3).

Figure 3. End View of Single Trough Experiment With Fuel Being Poured. Initiating and Secondary Shocking Charges are Clearly Evident at End and Sides of Dispersion Trough.

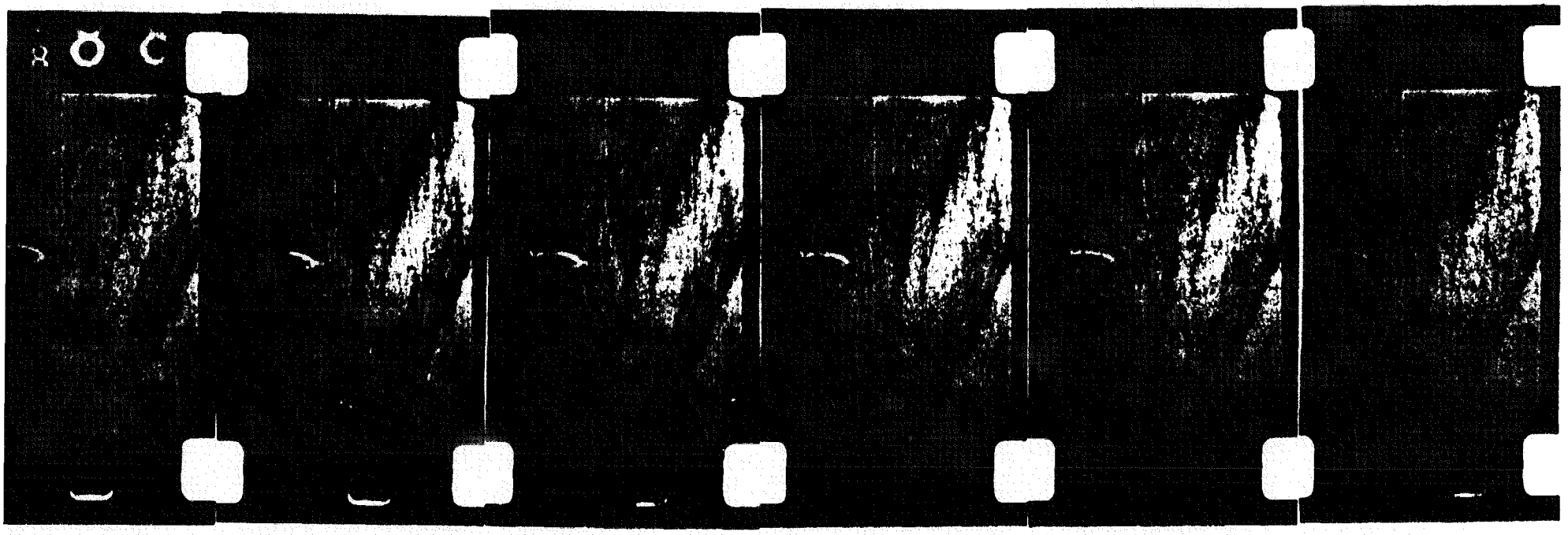
Figure 4. Sequence of Selected High Speed Movie Frames Illustrating the Propagation of Detonation in a Hexane-Air Cloud just after Termination of Secondary Shocking.

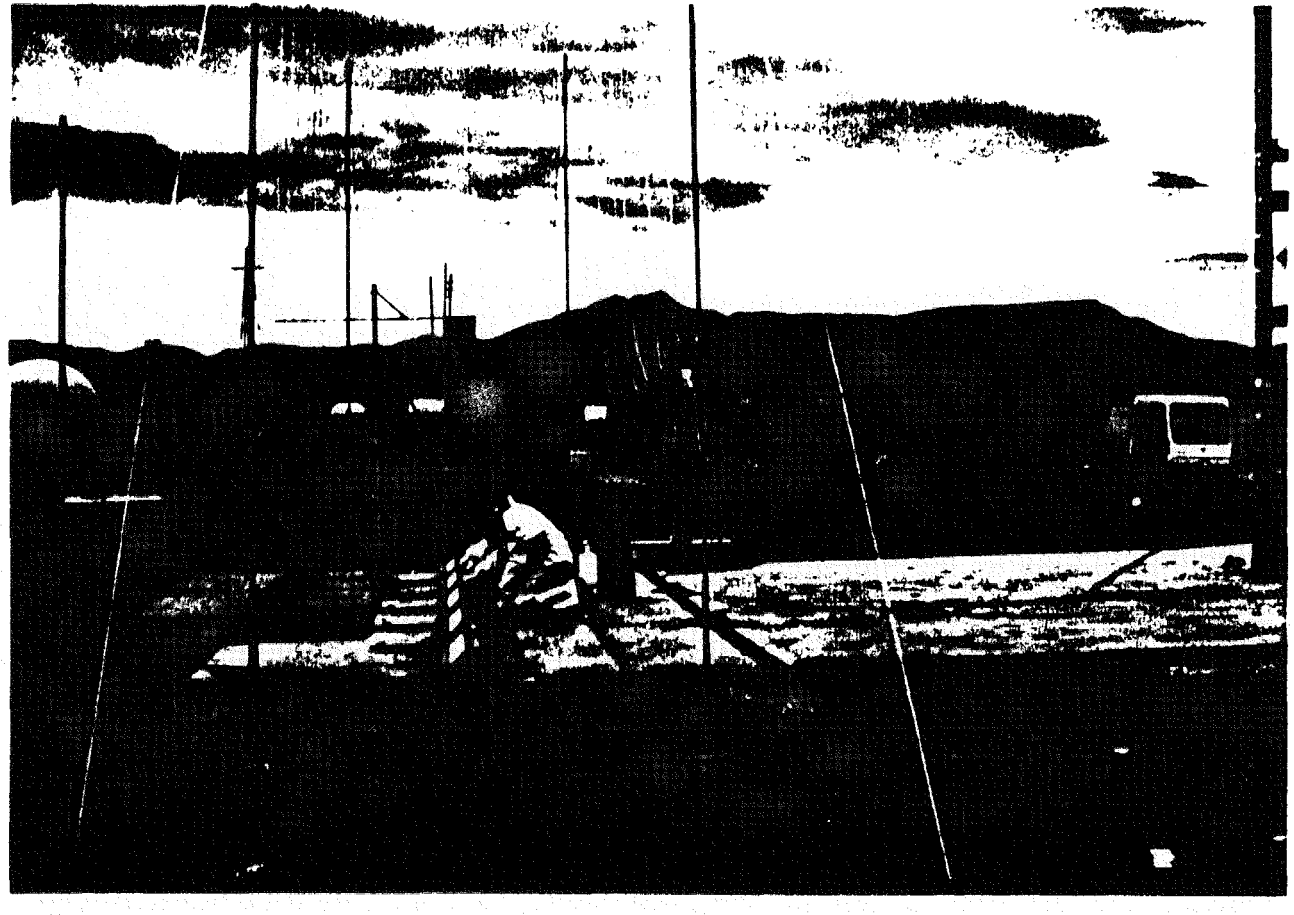

·3 m
Initiating Charge
1·2 m
1·2 m
Driver Section
Dispersion Trough
·3 m
1·5 m
Test Fuel
7·5 m
Concrete Pad
Side View Camera Station
End View Camera Station

FIG·1

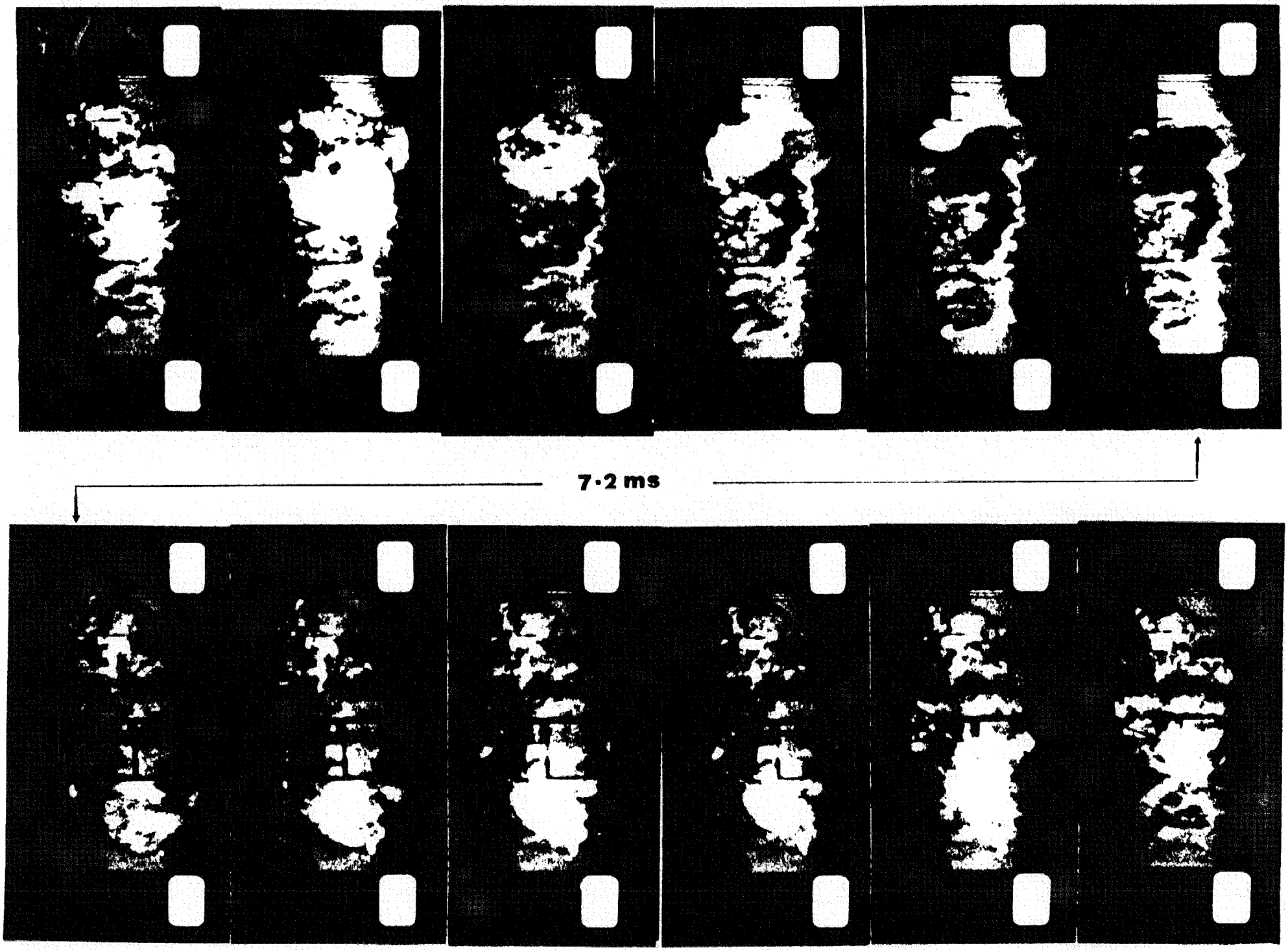


100 ms





FIG·3


7·2 ms