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(6) VARIABLE ENERGY BLAST WAVES AND TWO PHASE DETONATIONS.

(7) Final Report.

by

(10) E. K. Dabora



(11) February 1979 (13) 52 p.

(15) U. S. Army Research Office
Grant Nos.: DA-ARO-D-31-124-73-G100,
DAAG29-76-G-0142
DAAG29-77-G-0112

THE UNIVERSITY OF CONNECTICUT
Department of Mechanical Engineering
Storrs, Connecticut 06268



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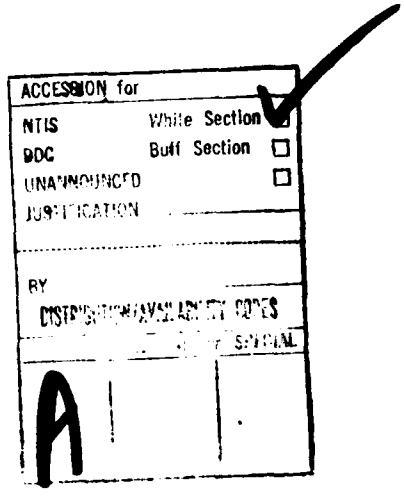
## FOREWORD

This report summarizes the results on the research work performed under Army Research Office grants DA-ARO-D-31-124-73-G100, DAAG29-76-G-0142 and DAAG-29-77-G-0112 which started in January 1, 1973 and terminated in September 30, 1978. All three grants were concerned with variable energy blast waves and their role in the propagation mechanism of two-phase detonations.

Most of the findings have been reported in the open literature and therefore will only be mentioned and summarized in this report. However, recent but as yet unpublished material is included in the form of reproduced manuscripts.

The study was under the direction of Professor E. K. Dabora, Department of Mechanical Engineering with Mr. James J. Murray of ARO as contract monitor. It resulted in one Ph.D. dissertation and, at various times, it involved two faculty members, three Ph.D. candidates, two Master's students and six undergraduates. Information based on this work was disseminated through ten technical presentations and five publications.



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## ABSTRACT

The results of the research work performed to determine the role of blast-waves and mass addition within the reaction zone of spray detonations are summarized. Since most of the findings have been published in the literature abstracts of the relevant publications have been included. One of the publications describes a model for spray detonations in which the relevant parameters are found to be the ignition delay and the energy temporal variation within the reaction zone. The model can predict the minimum energy for direct initiation when these parameters are known.

Recent experiments on laser ignition of fuel drops to simulate the mass addition aspect within the reaction zone are reported in detail. These experiments indicate that mass addition effects are small when compared to the blast wave effects. However, they reveal that, under some conditions, explosive combustion can take place. The experiments appear to be the first of their kind and open up new avenues for research on liquid propellants, fuel-air explosions and detonation transfer.

## I. INTRODUCTION

In certain cases of two-phase detonations such as those in sprays, photographic evidence (1) has indicated that blast waves around the burning droplets form part of the mechanism for the continuued propagation of the detonation wave. While not all liquid fuel- oxidizer combinations which are detonable exhibit evidence of blast waves(2), it was deemed fruitful, where they do, to determine the role of these blast waves on the detonation propagation.

The blast waves that appear within the reaction zone behind the detonation front are due to fast energy addition resulting from fuel and gaseous oxidizer reaction as well as to an effective mass addition to the gaseous medium surrounding the droplet. In the time scale of interest, namely, the reaction time after the passage of the detonation front, both energy input resulting from the heat release and mass addition due to the consumption of the droplet are time dependent. The purpose of the study then, was to assess the effects of these phenomena on detonation propagation.

The structure of the reaction zone is complicated by the convective flow of the gaseous components and the breakup of the burnign droplets. To avoid this complication, the energy and mass addition aspects were studied under controlled conditions in a quiescent gaseous medium. The laboratory techniques used are described in detal in references (3,4,5) and will not be repeated here.

In addition to being instrumental in the development of a model for the propagation of spray detonations (6) this investigation has led to contributions on variable energy (non ideal) blast waves and on laser ignition of liquid fuels.

## II. SUMMARY OF RESULTS

The first part of the work involved the characterization of the differences between variable and instantaneous energy blast waves. In particular the flow

field solution was sought for the general blast wave case in which the energy deposition is of the form

$$E_\alpha = W_\alpha t^\beta$$

where $W_\alpha$ is a constant and where $\beta$ can take on any value between $0 \leq \beta \leq (\alpha + 1)$, with $\alpha = 0, 1, 2$ corresponding to planar, cylindrical and spherical geometry respectively. Analytically, the case of $\alpha = 2$ and $\beta = 1$ was solved by numerical techniques after casting the conservation equations in Lagrangian coordinates (3,7). The general case was also solved by perturbation techniques (8) resulting in propagation and flow field density, pressure and velocity solutions.

Experimentally the cases of $\alpha = 2$ and $\beta = 0, 1$ were simulated by focusing a ruby laser operated in the Q-switched and the "open-lase" mode respectively in a gaseous medium. The density field was measured interferometrically and the results confirmed the analytically expected differences. Details of the findings have been presented in references (3,4).

A model for the propagation of two-phase detonations, based solely on the influence of the variable energy blast waves assumed around each droplet after its ignition, was developed (6). This formed the basis for the theoretical determination of the critical initiation energy and power necessary for the continued propagation of spray detonations (9,10). Two significant parameters emerged, namely, the ignition delay and the energy release temporal behavior due the subsequent reaction of each drop.

The mass addition aspect was studied only experimentally, using a focused ruby laser to irradiate a fixed fuel drop. Details of this portion of the work are to be published (5) but is reproduced in appendix C. The results reveal that little influence to the blast wave can be attributed to the mass addition. However, the experiments have shown, for the first time, that droplet ignition can

seldom be accomplished by a single pulse laser. Only when a double pulse laser is used, ignition occurs, with the indication being that the first pulse serves to breakup and/or evaporate the droplet and the second being responsible for ignition.

The experiments also revealed that for certain combinations of fuels and oxidizers, an explosive combustion can occur. This behavior can be used in performing small-scale laboratory experiments on detonation transfer which are akin to the elaborate field experiments on detonation transfer between two adjoining detonable clouds. Such an arrangement is sometimes used in fuel-air-explosion (FAE) testing or in evaluating the susceptibility of fuel spills, such as LNG, to detonative combustion.

As guidance to the reader, the abstracts of all the publications resulting from this work are reproduced in appendixes A & B and as indicated earlier, reference (5) is reproduced in its entirety in appendix C.

## III. CONCLUSIONS

The conclusions listed below are based on the publications which resulted from this study.

1. A numerical technique based on a Lagrangian formulation that is valid during energy deposition has been developed for predicting the trajectories and flow field properties of variable-energy blast waves having energy deposition variation $E \sim t^{\beta}$. Particularly the case of $\beta = 1$ was solved in detail.

2. A more inclusive solution of the variable energy blast wave was also developed using perturbation techniques. In addition to flow field calculations, blast wave decay coefficient were calculated and the distribution of the kinetic energy within the blast wave was determined.

3. Instantaneous and linear energy spherical blast waves were created experimentally via a high power focused ruby laser in both air and chloroform. Interferometric measurements of the density profiles were determined and the results showed good agreement with numerical calculations. Blast wave trajectories were also in agreement with theory.

4. Laser ignition of liquid fuel drops was attempted in experiments believed to be the first of their kind.

5. Liquid droplets were found difficult to ignite with a single pulse laser; however, when a two-pulse laser with pulses 50-100 μsec apart, ignition was possible.

6. Breakup of the droplet by the first pulse results in a cloud volume three orders of magnitude larger than the original drop volume within a period of 100 μsec. Evidently this process sets the stage for ignition.

7. When oxygen is used as the surrounding gas, explosive combustion of propyl-nitrate and heptane drops was observed occasionally. This is akin to what might happen in two phase detonations. Thus the technique could be used to determine fuel-oxidizer combinations that are conducive to blast waves in the reaction zone of such detonations.

8. The technique could also be used to investigate in a convenient laboratory scale, detonation transfer, sensitivity of liquid explosives and suitability of certain fuels and/or additives in FAE systems.

9. It appeared from the experiments that mass addition due to vaporization of the drop had little effect on any generated blast wave.

10. Not mentioned before, detonation was also initiated in $C_2H_2$-$O_2$ mixture by a focused laser in a spherical and hemispherical soap bubble (5-10 cm diam.) at atmospheric pressure. This technique could also be used in detonation transfer studies.

11. A model for spray detonations was developed. Central to this model is that the blast waves from each drop tend to intensify the detonation front,

thus insuring the continued propagation of the wave.

12. Two key parameters control the strengthening of the front, namely, the ignition delay and the temporal behavior of the energy release.

13. On the basis of this model it is possible to determine the critical energy for direct initiation of detonations in sprays. Also the necessary minimum power for time dependent initiation source can be determined.

14. Minimum energy requirement based on the model was applied to cylindrical detonations of kerosene-air and found to give good results when compared with experiments reported in the literature.

15. Since the key parameters for the model are the ignition delay and the temporal energy deposition behavior, these tow parameters can simply be measured in a shock tube in order to assess the potential of a particular fuel in a FAE device.

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## APPENDIX - A1

### Abstract of Reference (7)

### Predictions of Variable-Energy Blast Waves

Results from a numerical investigation of spherical blast waves with time-dependent energy deposition are reported. A description of the dynamics of these "variable-energy" blast waves is obtained from the solution of a set of nonlinear, partial differential equations that represent the conservation of mass, momentum, and energy in a spherically symmetric flowfield. For the current application, a finite-difference formulation of the governing equations in Lagrangian coordinates was selected, and the time-dependent nature of energy deposited was restricted to a power law input with positive exponent. Numerical calculations were performed during the energy deposition period for linear energy deposition. Propagation and decay of the shock front as well as internal flowfield properties have been obtained for these blast waves in air and chloroform. Results presented include shock front trajectory and Mach number, and radial density and pressure profiles for linear energy deposition in air for the spherically symmetric case.

## APPENDIX - A2

### Abstract of Reference (8)

### Perturbation Solutions for Variable Energy Blast Waves

The trajectory of and the flow field behind blast waves with time varying energy input is determined. Freeman's (1968) Lagrangean coordinate formulation is modified to include both the geometric factor, $\alpha$, for plane, cylindrical and spherical shocks and also non-integer values of $\beta$, the energy input parameter, in a single computational algorithm. Numerical problems associated with vanishing density at the inner mass boundary or "piston face" are then examined and solved. Second order perturbation solutions about the solution for an infinite strength shock are then obtained in Sakurai's (1965) inverse shock Mach number expansion parameter for $0 \leq \beta \leq \alpha + 1$. Tables and graphs of significant numerical coefficients are presented for comparison to, and extension of, results of other authors. Graphs of typical shock trajectories and flow field density, pressure and velocity variations are also presented and discussed.

## APPENDIX - A3

### Abstract of Reference (4)

### An Experimental Investigation of Variable Energy Blast Waves

The results of an experimental investigation of spherical blast waves are reported. Shock trajectories and flow field densities are compared with approximate and/or numerical predictions. The numerical predictions are based upon a finite difference formulation of the conservation equations in Lagrangian coordinates.

Experimentally, blast waves in air and chloroform have been induced by focusing the output of a high energy pulsed ruby laser onto a flat target to form a hemispherical field. Both Q-switched and open lase output were used. The open lase mode results in an approximation of linear energy input. Flow field data were obtained during and subsequent to the energy input interval using a Mach-Zehnder interferometer in conjunction with a high speed rotating mirror framing camera.

Shock trajectories in the form of radius-time (R-t) plots were obtained from the camera records. These shock trajectories were found at early times to follow similarity predictions of $R \sim t^{2/5}$ for instantaneous energy input and $R \sim t^{3/5}$ for linear energy input, while at later times they tended to follow the approximate numerical predictions. Radial density profiles, obtained from interferometric records through Abel integral inversion techniques, agreed with the following predictions. Starting at the shock front and progressing radially inward, it is predicted that for instantaneous energy input, the density decreases rapidly at first and gradually thereafter, asymptotically approaching zero at the blast wave center. Conversely, for the linear energy input mode, the density initially decrease gradually, but then the gradient steepens and the density rapidly approaches zero close to the shock front, thus forming a shell-like region near the shock front.

## APPENDIX - A4

### Abstract of Reference (6)

### A Model for Spray Detonations

In some cases of spray detonations, blast waves originating from the droplets have been observed. These blast waves eventually catch up with the main front thus providing a means of energy transfer to the front and therefore maintaining a steadily propagating wave. The ignition condition necessary for continued propagation is determine on the basis of the following model. The medium is assumed to be a gaseous oxidizer with monodisperse fuel spray having an average spacing to droplet diameter ratio. At sometime, $t_{ig}$, after the passage of the front, the droplet is ignited and a blast wave is initiated. The energy deposition law for the blast wave is assumed to follow $E = Wt^{\beta}$ where E is the heat release from the drop, W = constant, $\beta \geq 0$ and t is the time after the onset of droplet ignition. The blast wave strength at the time of interaction with the front must be of a magnitude sufficient to accelerate the front by an amount equivalent to its deceleration as it moves through the drop spacing. This condition imposes a limit on $t_{ig}$ which has been determined. It is found that the ratio of the ignition delay to the droplet breakup time $t_{ig}/t_b$ depends on a heat release parameter which depends on the stoichiometry, the detonation Mach number, the density ratio $\rho_\ell/\rho_g$ of liquid to gas, the location of the front and $\beta$ which determines the energy-time profile.

For a fuel-oxidizer combination with known $t_{ig}$, $t_b$ the model implies a detonation radius beyond which a detonation is expected to remain steady. This in turn implies a critical radius and therefore a minimum energy for detonation initiation. The model is applied to a kerosene-air mixture and found to imply that $t_{ig}/t_b = 1.3$ which is considered a reasonable value.

## APPENDIX B

# ENERGY AND POWER REQUIREMENTS FOR DIRECT INITIATION OF SPRAY DETONATIONS

by

E. K. Dabora
The University of Connecticut
Storrs, Connecticut 06268

October 16, 1978

Abstract of a paper for presentation at the
XIIth International Symposium on Shock Tubes and Waves
Jerusalem, Israel, July 1979

Detonations in a two phase medium consisting of fuel droplets and gaseous oxidizer are now well documented (1,2,3). These detonations are often accompanied by blast waves which originate near each individual droplet as a result of the partial breakup of the droplet and the evaporation and ignition of the micromist which accumulates in the wake of the droplet. A model for spray detonations in which the role of the blast waves is considered was presented in Ref. 4. The interaction between the blast waves from individual drops with the detonation front serves to accelerate the front. This acceleration is balanced by the decay of the front as it moves through a distance equivalent to the average spacing between drops.

If the heat release profile is described by the form

$$E = W_b t^{\beta} \tag{1}$$

it is shown in (4) that:

$$E^*/D^{\alpha+1} = J_\alpha k_\alpha p_\alpha (R^*/D)^{\alpha+1} M^2 \tag{2}$$

where $R^*/D = (\alpha+1)(t_{ig}/t_b)^m (S/D)/2k$ (3)

and m and k are related to the heat release profile-characterized by $\beta$ - of the individual drops after their ignition. Fig. 1 shows the effects of both the ignition delay and $\beta$ on the critical energy for a spherical detonation in a mixture of a given composition. Similar curves with less pronounced effects are found for the cylindrical and the planar detonations.

A method for determining the effect of fuel-oxidizer ratio on the critical energy will also be described. In brief, the effect is manifested through M, S/D, $t_{ig}/t_b$, m and k. The Mach number can be computed (5) from the known overall mixture ratio, S/D is a direct function of the equivalence ratio $\phi$, and m and k can be determined from computations described in (4).

On the basis of Ref. 6, it is convenient to compare the critical energy for a mixture of a given $\phi$ with that of the stoichiometric mixture. To do this, the variation of $t_{ig}/t_b$ with M needs to be found. In Ref. 7, the ignition delay $t_{ig}$ was conveniently separated into a mechanical time delay, $t_m$, and a chemical time delay, $t_{ch}$. The mechanical delay is estimated to be 1/3 $t_b$ and therefore depends on the Mach number and the drop size. The chemical delay is mostly a function of the stagnation temperature of the convective flow. Examination of the calculations in (7) revealed that $t_{ch} \sim M^{-n}$ where $n>2$ and becomes controlling when the drop size is less than 50-100μ. For sprays with large drops the mechanical delay is dominant, and since $t_b \sim 1/M$, it can be shown that

$$E^*/E_s^* = (k_s/k)(M/M_s)^2/\phi^{1/3} \qquad (4)$$

When $t_{ch}$ is controlling, however, the energy relation becomes:

$$E^*/E_s^* = (k_s/k)(M/M_s)^{2-(n-1)(\alpha+1)m}/\phi^{1/3} \qquad (5)$$

Thus, the propagation Mach number has the biggest effect. However, comparison of Eqs. (4) and (5) reveals that more pronounced effects are found when $t_{ch}$ is controlling and these effects will be described in the paper for representative drop sizes, namely 1000μ, 100μ and 10μ and for heptane and kerosene.

To determine the minimum power requirement for the initiation of a detonation a method based on the variable energy blast wave (8) is devised. If the initiation energy is also of the form given in Eq.(1), it can be shown that for self-similar blast waves

$$E^* = k_\alpha p_o J_{\alpha\beta} \left(\frac{\alpha+3}{\beta+2}\right)^\beta R^{*\alpha+1-\beta} M^{*2+\beta} (a\, t_i)^\beta \qquad (6)$$

Lee and Ramamurthi (9) developed a relation between M*, R* and the induction time. If M* and R* are substituted into Eq. (6) when $\beta = 1$ a relation between $t_i$ and E* can be obtained, so that at $E^*_{min}$ there corresponds a $t_{i_{min}}$ which is <u>approximately</u> equal to the induction time. This is done for the data of $C_2H_2$-$O_2$ reported in Ref. (10), and it was found that $t_{i_{min}} \tilde{=} 1.5$ μsec. The minimum required power can then calculate as

$$P_{min} = E^*_{min}/t_{i_{min}} \qquad (7)$$

which gives for the same data a $P_{min}$ of .075 Mw/cm in good argument with the experiment. Encouraged by this result, the same technique was then used for spray detonations and was applied to kerosene-air. It is found again that β, $t_{ig}/t_b$ and, in particular, the exponent m have profound effects on $P_{min}$ which can be 4-5 orders of magnitude higher than that of a gaseous detonation. Details of these effects will be given in the paper.

NOMENCLATURE

$a$ = Velocity of sound in free stream

$D$ = Drop diameter

$E$ = Energy

$E^*$ = Critical energy, energy/unit length or energy/unit area for $\alpha = 2, 1, 0$ respectively

$E_s^*$ = Critical energy for stoichiometric mixture

$J_{\alpha\beta}$ = Nondimensional blast wave energy integral

$k$ = $\Delta M/M$ when $t_{ig}/t_b = 1$

$k_\alpha$ = $4\pi$, $2\pi$ or 1 for $\alpha = 2, 1, 0$ respectively

$M$ = Chapman Jouguet Mach number

$m$ = Exponent in $\Delta M/M = (t_{ig}/t_b)^{-m}.k$

$p_o$ = Original pressure

$P$ = Power

$R^*$ = Critical detonation radius

$S$ = Spacing between drops

$t_b$ = Breakup time

$t_{ch}$ = Chemical time delay

$t_{ig}$ = Ignition delay

$t_i$ = Energy input time

$t_m$ = Mechanical time delay

$W_\alpha$ = Proportionality constant, Eq. 1

$\alpha$ = Geometric factor = 2 spherical, 1 for cylindrical and 0 for planar waves

$\beta$ = Exponent in Eq. 1

$\phi$ = Equivalence ratio

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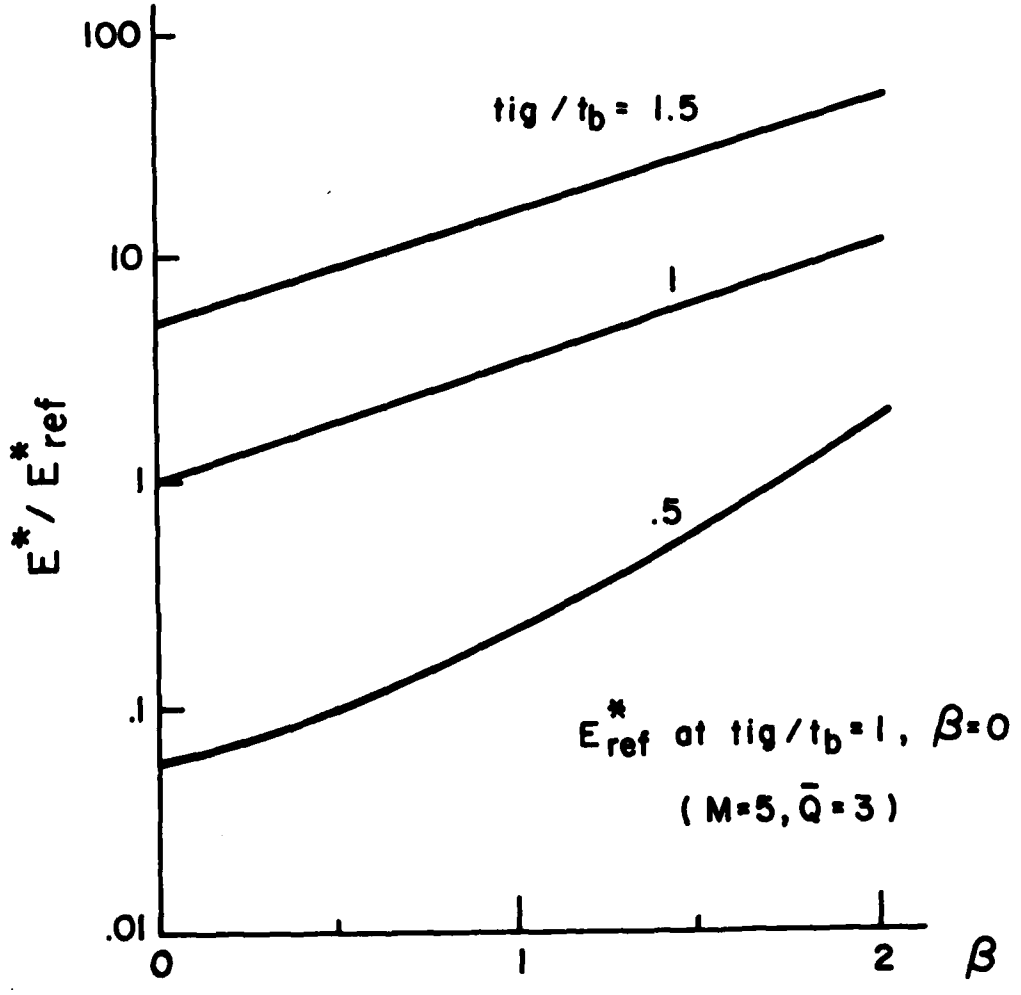


EFFECT OF $\beta$ ON CRITICAL ENERGY
( $\alpha = 2$ )

APPENDIX C

# PHOTOGRAPHIC OBSERVATIONS ON LASER INDUCED EXPLOSIVE COMBUSTION OF FUEL DROPS

E. K. Dabora
University of Connecticut
Storrs, Connecticut 06268

Paper presented at the Conference of Explosions in Dispersed Energetic Materials, November 1978, ARRADCOM, Dover, N.J.

Abstract

Experiments on the interaction of liquid droplet with a high powered ruby laser are described. The laser used could be operated in either the Q-switched mode or the pulsed mode and in most of the experiments the original laser beam is split into two beams which are focused from opposite direction on the droplet. The resulting phenomenon is observed by backlighting or interferometrically and monitored by a pressure transducer placed at 5 cm below the droplet.

The liquids used are water, nitromethane, propyl nitrate and heptane with either air or oxygen as the surrounding gas. Photographic description of the resulting phenomenon is given in some detail. In all cases, the interaction results in the rapid vaporization or break-up of the droplet. A volume change by a factor of 4000 is observed in 100 μsec.

In the fuel cases, it was found that, when the laser is operated in the Q-switched mode, no ignition takes place in air. However, when the laser is operated with two pulses at 50-100 μsec apart, the second pulse apparently induces ignition. Explosive combustion of the cloud formed by the first pulse is sometimes observed when oxygen is the surrounding gas. In such cases, cloud detonations at Mach 2-3 have been determined.

## Introduction

The motivation for the work described in this paper is the desire to gain some additional information on the reaction zone of spray detonations. It has been observed (1) that under certain conditions, after the breakup of the drops in the reaction zone, the reaction near each drop results in a blast wave that originates in the wake of the drop. Such blast waves must eventually catch up with the detonation front and a model for spray detonation making use of this idea has been formulated (2).

The reaction zone in spray detonation is complicated by the fact that immediately behind the front, the gaseous component has a velocity different from the drops. Thus the convective flow over the drops is responsible for the breakup of the drops which eventually leads to reaction. In the experiments to be described, the convective flow is avoided by initiating a reaction in a stationary drop in a quiescent atmosphere, making use of a focused laser. The aim was to find some fuel-oxidizer combinations that could result in a blast wave. Although this aim was not quite satisfied, some interesting results have been obtained and these are reported here.

In examining the literature on laser irradiation one finds that a considerable amount of work both theoretical and experimental has been reported on the interaction phenomenon with solid targets. As examples the works of Covington et al (3) of Pirri (4), Pirri et al (5), Wu and Nebolsine (6,7), and Su and Boni (8) are cited. Considerable work has also been reported on the breakdown of gases by focused high-powered lasers. A bibliographic review on the subject is reported by DeMichelis (9) and a recent review of the phenomena is given by Raizer (10). A focused laser has been used by Director and Dabora to study variable energy blast waves (11) and by Bach et al (12) to study the initiation of acetylene-oxygen detonations (12).

While extensive investigations seem to have been conducted on the interaction of lasers with solids or gases, the interaction with liquids appears to have received little attention. Bell and Maccabee (13) used a $CO_2$ laser to irradiate a water surface and Kafalas and co-workers (14,15) looked at the vaporization behavior of small (10 - 50 μm) water droplets subjected to $CO_2$ laser also. This last work is the closest to the work that will be presented here which has an important distinguishing feature, namely that reactive liquids are used.

## Experimental Arrangement

The experiments were conducted in a cylindrical chamber 19.3 cm dia. x 35.6 cm long provided with observation windows on both ends. At the middle of the cylinder two small, 2 cm diameter windows diametrically opposite to each other are provided to accept the laser beam from two directions when needed. At 90° to the axis of these windows a wire is suspended which is used for hanging the desired drop on its tip. Typically the droplet size used is 1.5-2 mm in diameter. The test chamber axis is placed in the path of one of the beams of a Mach Zehnder interferometer (Zeiss model 1981). Both interferometry and back-lighting were used to observe the phenomena. A Beckman and Whitley Model 200 simultaneous streak and framing camera is used to record the event. For back-lighting a flash unit having 1 msec duration was used. For interferometry the light source was a Spectra Physics Argon Ion laser model 166. When used with an Accoustic Coupler model 365, which in our arrangement is controlled by an HP8011A pulse generator, the unit can be operated in the pulsed mode so that when the streak optical path of the camera is used, a framing record can be obtained. This latter method of obtaining a framing record is preferred to the framing path of the camera, because the exposure time can be only a function of the Argon laser pulse duration which is about 50 nsec. To avoid radiation from the event when necessary, a green filter is placed between the test chamber and the camera.

A TRW ruby laser was used to irradiate the droplet. The laser beam is 1.43 cm in diameter and is focused either directly or first split into two beams and then focused as shown in Figure 1. The laser can be operated in three ways: Q-switched mode, pulsed mode and free-lase mode. Only the first two modes were used in this investigation. In the Q-switched mode the output is 4-5 J with an estimated 2500 $Mw/cm^2$ when focused. When pulsed at 50 or 100 μsec interval the total output for two pulses was 6 - 7 J and in the open-lase mode the output is about 50 J in 1 msec. When double focusing is used the energy of the laser is split 2/3 to 1/3 for the direct and reflected beams respectively.

The method used to hang the droplet on the wire was to insert a hypodermic needle from the side of the chamber, bringing the tip of the needle close to the tip of the wire and injecting the desired liquid from a syringe and finally retracting the needle. The liquids used are water, nitromethane, propyl nitrate and heptane and the surrounding gas was either air or oxygen at atmospheric pressure.

As shown in Figure 1, in some experiments a piezoelectric pressure transducer (Kistler, model 606L) is placed 5 cm below the drop to measure the pressure variation during the event.

## Photographic Results

Most of the early experiments were performed with back lighting. The first liquid tried was water and Figures 2(a) and 2(b) show a sequence of photographs of the breakup and/or evaporation of the drop. As indicated in the figure, the laser radiation is from left to right and the droplet is about 2 mm in diameter. The beginning of the drop breakup can be seen in the third frame of Figure 2(a), at about 6 μsec after the firing of the laser; the breakup is asymmetrical showing a jetting action in a direction away from the incoming laser beam. The drop seems to continuously expand for a duration of over 100 μsec with the expansion rate being high at first, but decreasing later on.

While most of the experiments on water showed similar breakup, there were times when the breakup was somewhat different. Figure 3 shows another type of breakup in which jetting action appears to take place from both directions at about 45° from the laser axis. In this experiment, again the laser was Q-switched and incoming from the left.

The different breakup patterns must be due to the slightly different positions of the focal volume of the laser with respect to the drop and the resulting effects of the wire with respect to the jetting action. The differences in patterns observed here must be considered different from the differences observed by Kafalas and co-workers (14,15), who concluded that a symmetrical breakup occurs when the energy absorbed by the water droplet exceeds the vaporization energy whereas an asymmetrical breakup can be due to the reverse relative magnitude of the energies. In the former, explosive expansion resulting in a blast wave in the surrounding air can take place which is reasoned to be due to liquid superheating.

At this point it is useful to present the pertinent properties of the liquids used in this work. They are shown in Table I where the vaporization energies for 1.5 mm drops are also shown. As we shall see later the vaporization energy for water is larger than the energy absorbed and therefore in our experiments superheating is unlikely.

Another liquid which was tested is nitromethane. Figure 4 shows the breakup phenomenon under back lighting conditions. Here the jetting action appears to take place in the direction of the laser and the growth of the main body of the drop seems to be symmetrical. As indicated in Table I, the vaporization energy for nitromethane is much lower than that of water and therefore it is more likely that the laser energy absorbed by the drop is higher than the vaporization energy and hence the symmetrical growth.

It should be mentioned that with the focused laser, a blast wave always occurs in the gas surrounding the drop. The energy of the initial blast wave must therefore be considered unavailable for absorption by the drop. Figure 5 shows streak schlieren photograph of the initial blast wave for three different conditions. The Q-switched laser direction is from left-to-right. It appears that all three blast waves have the same trajectories. The inner region for the air case represents the expansion of the heated or ionized focal volume of the laser, whereas the inner regions for the water and the nitromethane show the extent of the droplet expansion which is larger for the nitromethane. This can be considered to confirm that the absorbed nitromethane energy is larger than its vaporization energy.

It should be mentioned that may runs with nitromethane, propyl-nitrate or heptane in air, with the laser in the Q-switched mode never resulted in ignition, a fact that was somewhat surprising for both nitromethane and propyl nitrate. This was true even when the laser was focused from two directions. However the situation was different when the laser was operated in the pulsed mode with two pulses at 50 - 100 μsec apart.

Interferometric photographs were obtained in these cases. Starting with Figure 6 the two pulse results for water show the expansion of the water, after the two pulses; both photographs were taken under infinite fringe condition and the interferometer light (argon ion laser) was pulsed at 100 μsec/pulse so the time between frames is 100 μsec. The top photograph shows the luminosity of the second pulse in the first frame and the extent of the expansion of the water which is apparent from the mottled area in the center. The change does not seem to be significant and one must conclude that most of the expansion must have taken place in the first 100 μsec after the first pulse. The bottom photograph shows the luminosity from both pulses and in the second and third frames the blast wave from each pulse can be seen. [In photographs similar to those of Figure 6, the wire appears horizontal and the drop is centered in the vertical fiducial line. When no filter is used to cut down the luminosity of the event, this lumi-

nosity can in effect produce another frame which is superimposed in a random fashion on the framings due to the interferometer light. These latter frames can be recognized by the equidistant fiducial lines.]

An example of the large expansion that takes place in the case of propyl nitrate and heptane is shown in Figure 7. The bottom photograph is taken with a green filter and shows that, in less than 100 μsec after the first pulse much more expansion than water can occur at the same corresponding time. After the second pulse the expansion becomes considerable. In the top photograph the two frames resulted from the self-luminosity of the event. The luminosity is continous after the second frame indicating that ignition must have occured.

The blast waves due to the two pulses are better seen in the streak photographs of propyl nitrate and heptane in oxygen shown in Figure 8. The spatial scale is shown and the time scale can be obtained from the distance between the two vertical bright line representing the two pulses which were 50 μsec apart. In both photographs there appears a third wave which originates at the surface of the expanded droplet or the boundary of the cloud formed from the drop breakup. It is reasoned to be due to the explosive (or a detonation like phenomenon) behavior of the cloud after ignition, inducing a blast wave into the surrounding gas. The explosive behavior is also deduced from the pressure records. Figure 9 shows the pressure records for two cases, one for oxygen alone and the other for propyl nitrate drop in oxygen. In the case of oxygen there are two large peaks, the first one at the beginning of the trace which is due to the first laser pulse and the second, which is after 100 μsec from the first, must be due to the second laser pulse which is also 100 μsec after the first. These pressure spikes are due to the blast waves which apparently travel at the same average speed to the location of the pressure transducer. In the case of propyl nitrate the second spike is larger and the second spike is larger and the time between spikes is less than 100 μsec which is indicative of a faster blast wave. Further, the magnitude of the pressure peak is larger. The faster blast wave can be attributed to the explosive behavior.

Two examples of pressure seconds for heptane-oxygen combustion are shown in Figure 10. In the top record the magnitudes of the peaks are the same but the time between them is again less than 100 μsec. In the bottom record the second peak is low with a gradual increase in pressure to a plateau. This is interpreted to be due to a deflagrative combustion in the cloud.

In the systems used here the explosive behavior in certain combinations does not occur at all times. A summary of the observed results is given in Table II. In general,ignition of the fuel occurs only when two laser pulses are used and explosive behavior can occur only when oxygen is used.

## Quantitative Results

The framing and the streak photographs were used to get an idea of the expansion or the cloud size after drop breakup and the pressure records were used to get a feel for the wave speed inside the cloud in the cases where explosive behavior was observed. Figure 11 shows an interpretation of the photographs represented by Figure 8. The cloud surface is outlined, the blast waves BW1 and BW2 are shown and the time between blast waves $\Delta t_p$ at the pressure transducer location is also shown. From several photographs for both heptane and propyl nitrate the volumetric cloud-drop ratio was determined and plotted in Figure 12. The arrows point to the stoichiometric mixture for the particular combination. It was found that the early breakup is independent of the surrounding atmosphere. In the case of heptane, it is seen that the second laser pulse - usually at 100 μsec - is delivered when the equivalence ratio is about 1/2 whereas in the case of propyl nitrate the equivalence ratio is about 1/5.

To obtain an idea of the wave speed inside the cloud, Figure 11 is reintrepreted in a simplified schematic in Figure 13. If R is the distance of the transducer from the center of the drop, $\Delta t_L$ is the time between laser pulses and $\Delta t_p$ is the time between pressure spikes, then the time for the first blast wave to reach the pressure transducer is

$$t_1 = R/M_1 a_o \qquad (1)$$

whereas the time for the second blast wave to reach it is

$$t_2 = \Delta t_L + R_c/M_c a_o + (R - R_c)/M_2 a_o \qquad (2)$$

where $a_o$ is the speed of sound and subscript c refers to the cloud.

The difference between $t_2$ and $t_1$ is $\Delta t_p$ so that the Mach number in the cloud is

$$M_c = R_c/[R/M_1 - R/M_2 + R_c/M_c - a_o(\Delta t_L - \Delta t_p)] \qquad (3)$$

or for $M_1 \cong M_2 \cong 1$

$$M_c = R_c/[R_c - a_o(\Delta t_L - \Delta t_p)] \qquad (4)$$

This equation was used where explosive behavior was manifested to find that a detonation wave at $M_c$ = 2-3 in the cloud can be deduced from the pressure records.

The laser energy absorbed by the droplet was also estimated. The laser output was measured using a ballistic thermopile (Hadron Model 107) and was found to be 7 J for two pulses. Previous experience (11) has indicated that only about 20% of the energy is delivered to the focal volume, thus the energy to the drop and surroundings is 1.4J. An estimate of the energy responsible for the blast wave, based on blast wave trajectory is found to be .4-.5 J, so the net energy to the drop is about 1 J. This can be compared to the vaporization and combustion energies in Table I. In particular, it appears that the energy absorbed by the droplet is higher than the vaporization energy for both propyl nitrate and heptane but less than that of water for the drop sizes used.

## Conclusions and recommendations

The experiments described in this paper which can be considered exploratory in nature, are believed to be the first of their kind. The original idea behind the experiments was to induce ignition in liquid fuels by laser irradiation. However, this was found to be difficult when one pulse laser is used, but possible when two pulses are used. In the latter case, the first pulse induces rapid vaporization or breakup of the fuel drop to form a small cloud which evidently can be ignited by the second pulse. No attempt was made to systematically change the timing of the second pulse although this would be an obvious parameter that should be investigated in the future.

The total energy input of the laser is of the order of the heat of vaporization but about 50 times lower than the heat of combustion. When oxygen is used as the surrounding gas, sometimes explosive burning can take place with a detonation Mach number of 2-3. The explosive burning induces a blast wave into the surrounding gas and in this respect the phenomenon is akin to what might happen in the reaction zone of two phase detonations.

The method described here could be developed further for use: (a) as a sensitivity measure of liquid explosives and (b) to determine the suitability of certain fuels and/or additives in FAE systems. The biggest advantage is the scale of the experiments involving only minute quantities of the material to be tested.

## Acknowledgments

This work was supported by grants No. DAAG29 76 G 0142 and 77 G 0112 from the Army Research Office, Research Triangle, N.C. The author wishes to thank S. Phillips and J. Grant for conducting some of the experiments.

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TABLE I PROPERTIES OF LIQUIDS USED

| Liquid | W (gm/mole) | ρ (gm/cc) | $T_{boil}$ (°C) | $P_{vap}$@20°C (Torr) | $\Delta h_{vap}$ (J/gm) | $\Delta h_{comb.}$ (KJ/gm) | (1.5 mm drop) $m\Delta h_{vap}$ (J) | $m\Delta h_{comb.}$ (J) |
|---|---|---|---|---|---|---|---|---|
| Water $H_2O$ | 18.01 | 1. | 100 | 17.5 | 2250 | ----- | 3.95 | ----- |
| Nitromethane $CH_3NO_2$ | 61.04 | 1.13 | 101 | 14.9 | 557.4 | 11.6 | 1.10 | 23.1 |
| Heptane $C_7H_{16}$ | 100.2 | .69 | 98.9 | 32.1 | 351 | 44.8 | .42 | 54.4 |
| n-Propyl nitrate $C_3H_7NO_3$ | 105.1 | 1.06 (Ref. 16) | 110 | 18 (Ref. 17) | 337.5 | 18.7 (Ref. 18) | .63 | 34.8 |

TABLE II SUMMARY OF TEST RESULTS

| Drop/Gas | Laser | Ignition? | Explosion? |
|---|---|---|---|
| Nitromethane/air | Q-switched | No | |
| Nitromethane + 10% aniline/air | Q | No | |
| Propyl-nitrate/air | Q | No | |
| Propyl-nitrate/$O_2$ | 2 Pulses - 50 μsec | sometimes | |
| | 2 P - 75 | sometimes | |
| | 2 P - 100 | often | sometimes |
| Heptane/air | Q | No | |
| Heptane/$O_2$ | Q | seldom | |
| | 2 P - 50 | often | |
| | 2 P - 75 | often | |
| | 2 P - 100 | often | sometimes |
| Heptane + 20% n - PN/ $O_2$ | 2 P - 75 | often | |
| | 2 P - 100 | often | |

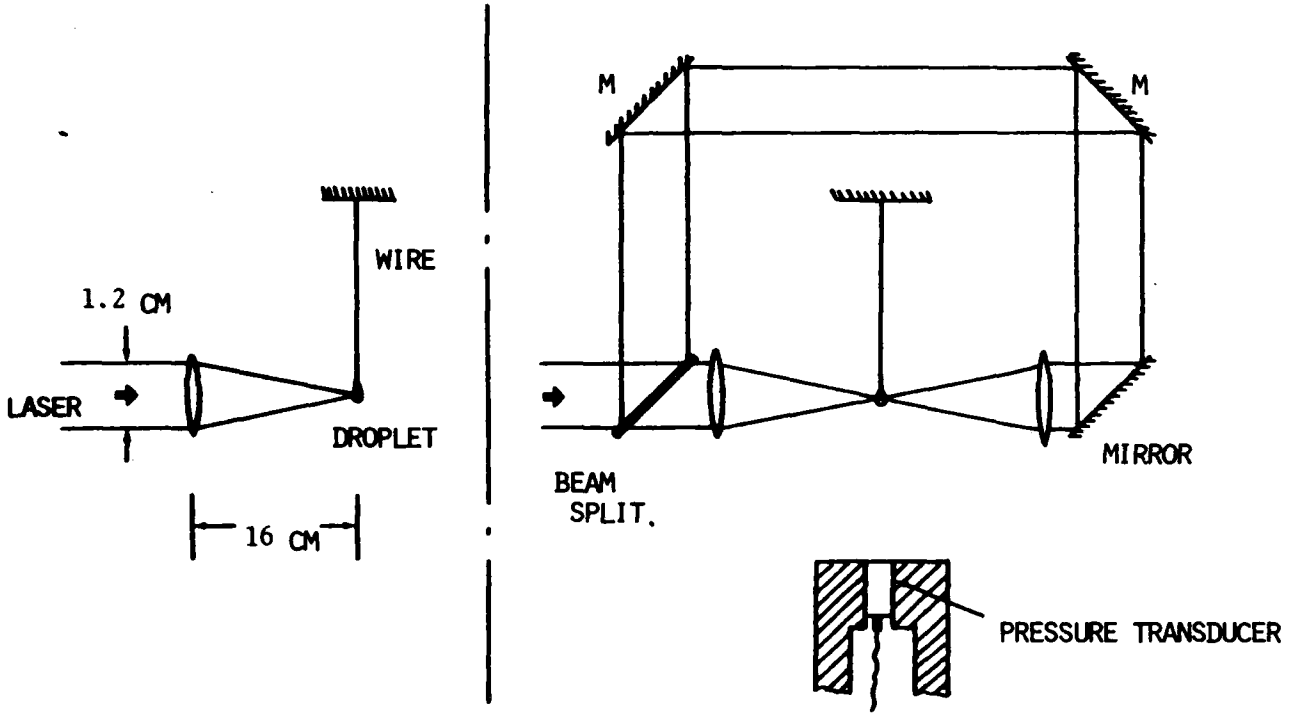



Figure 1. Laser focusing methods.

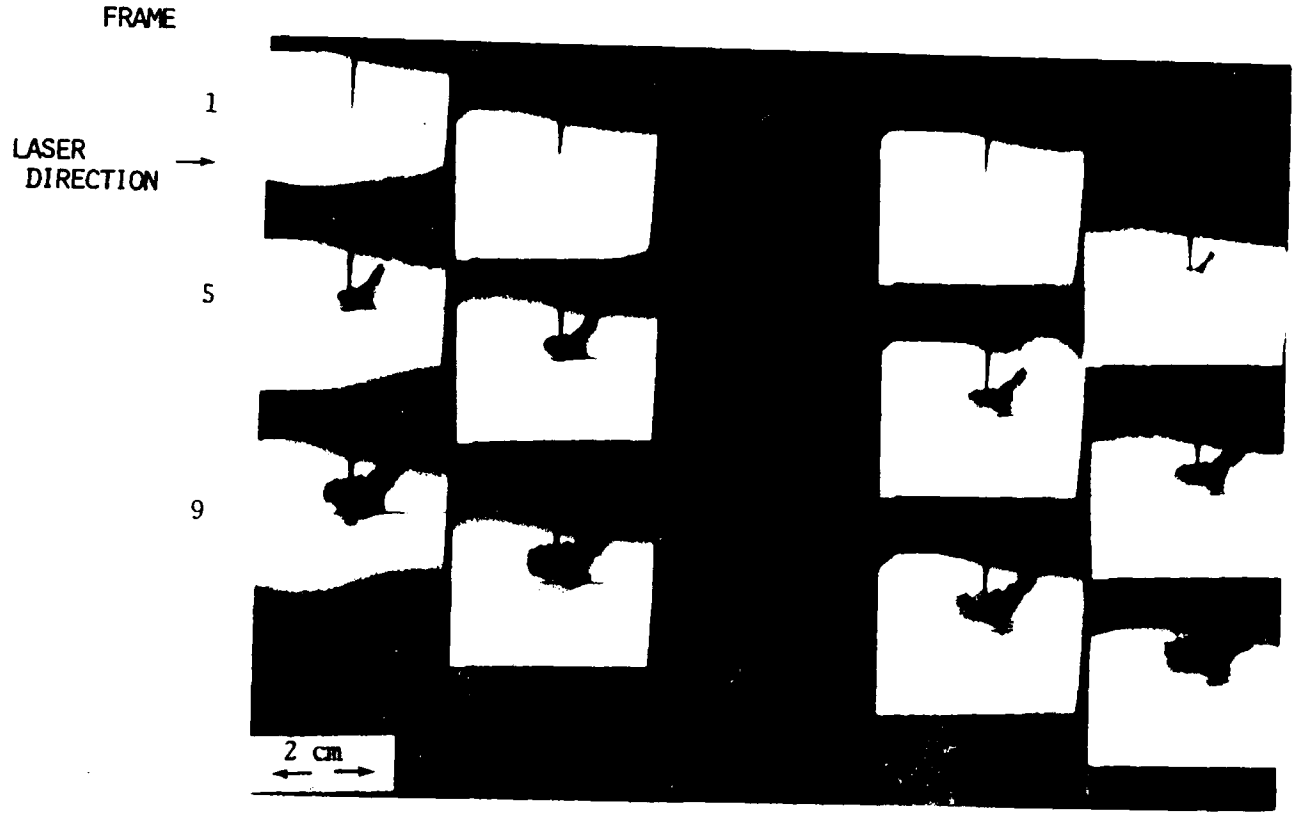
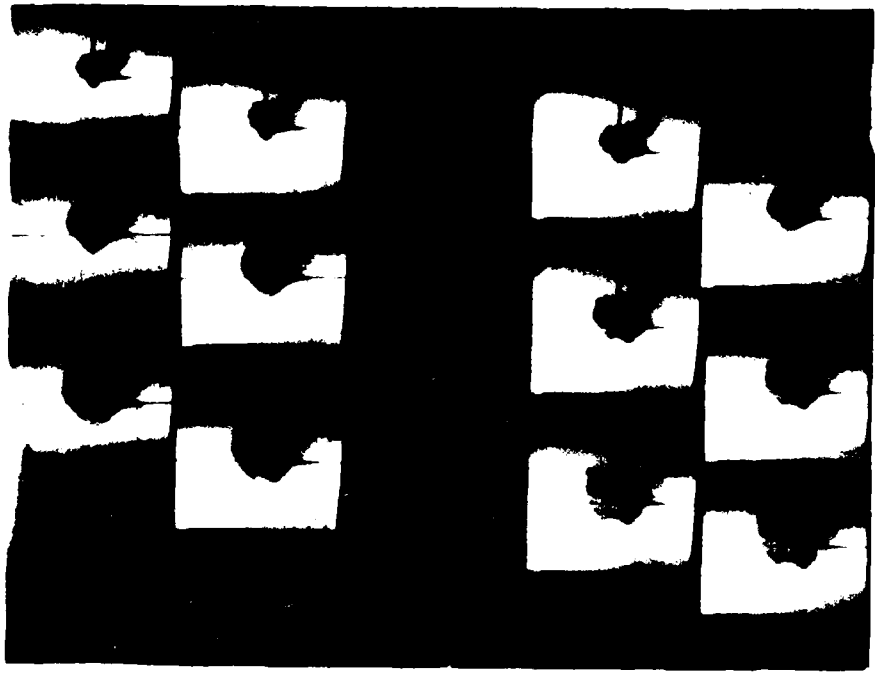


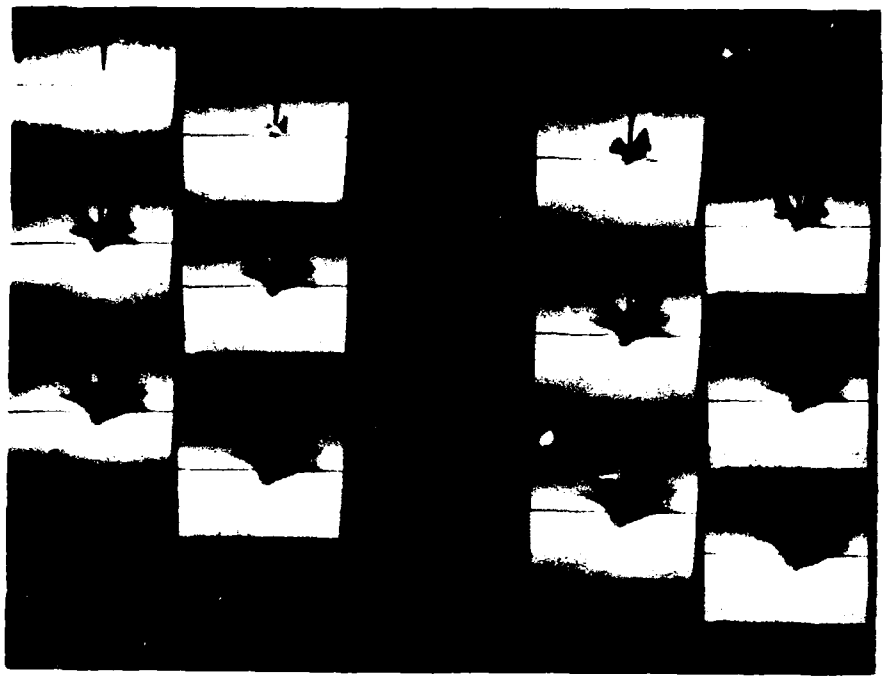

FIGURE 2(A). WATER DROPLET BREAKUP BY Q-SWITCHED LASER (FRAMING INTERVAL = 6.25 μSEC).



⟷ 2 cm, Framing Interval = 6.25 μsec. 750730-17

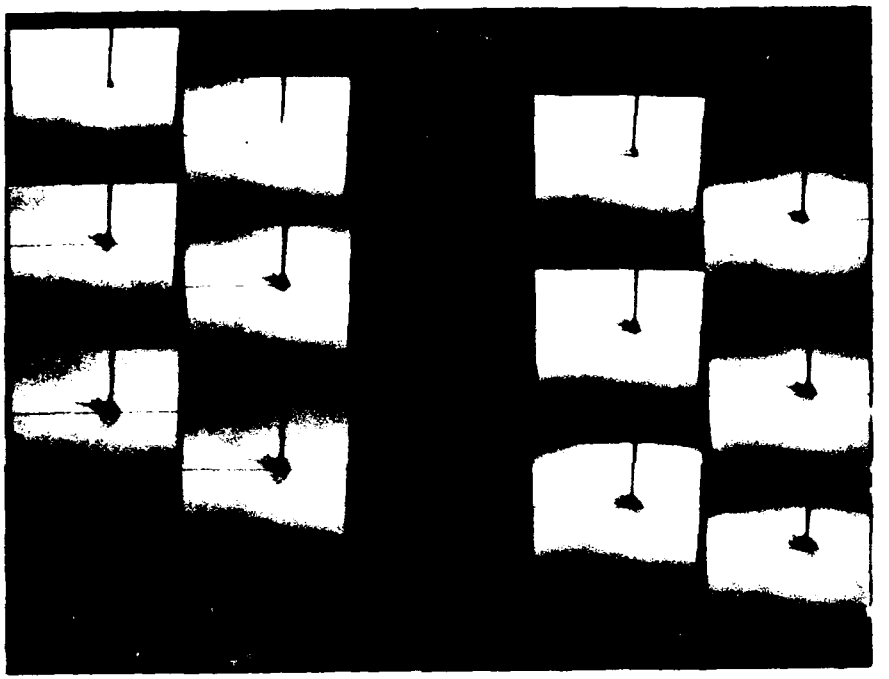
Q-switched; water; 1st frame: Δt = 40 μsec.

FIGURE 2(B). CONTINUATION OF FIGURE 2(A).



⟷ 2 cm, Framing Interval = 6.25; #750806
Q-switched; water.

FIGURE 3. WATER DROPLET BREAKUP BY Q-SWITCHED LASER.



⟷ 2 cm, Framing Interval = 6.25 μsec. #750828
Q-switched; Nitromethane + 10% Aniline drop

FIGURE 4. BREAKUP OF NITROMETHANE + 10% ANILINE DROPLET BY Q-SWITCHED LASER.

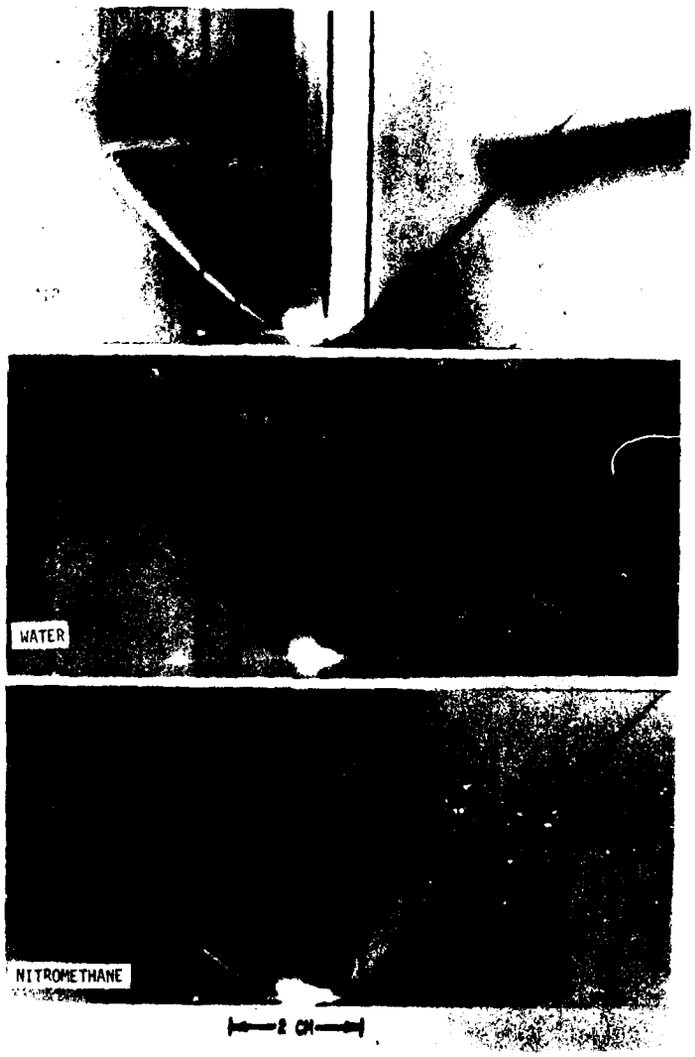



FIGURE 5. SCHLIEREN STREAK PHOTOGRAPHS OF BLAST WAVES IN AIR, WITH WATER AND WITH NITROMETHANE DROPLETS. Q-SWITCHED LASER FROM LEFT TO RIGHT.

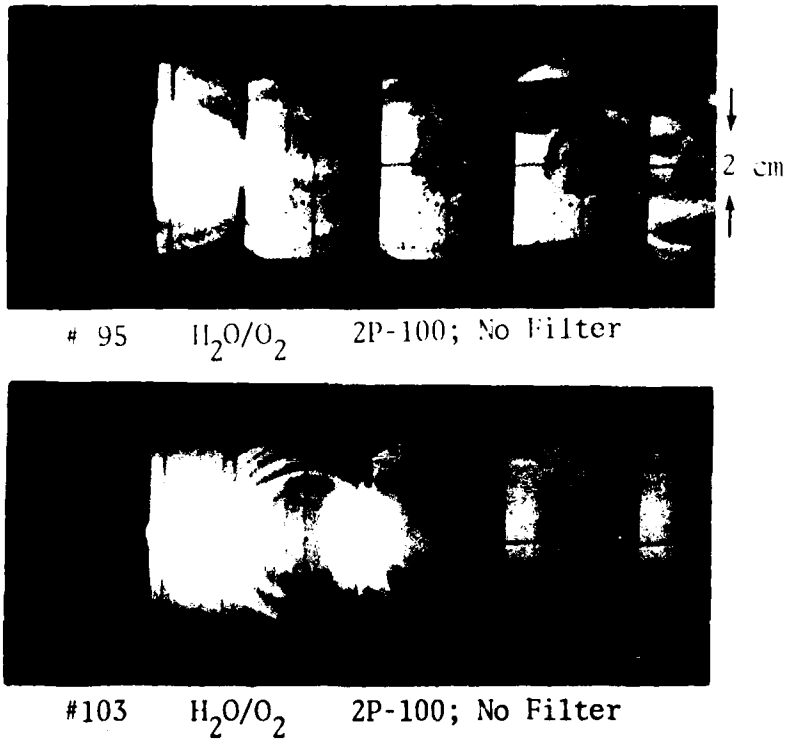
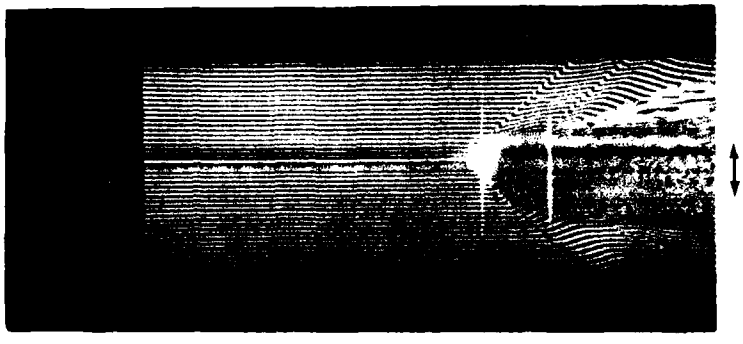



FIGURE 6. INTERFEROMETRIC RECORD OF WATER DROPLET BREAKUP. (FRAMING INTERVAL = 100 μSEC, 2 PULSE LASER AT 100 μSEC)


# 83 $PN/O_2$ 2P/100; No Filter

#119 $PN/O_2$ 2P/100; Green Filter

FIGURE 7. SELF LUMINOUS AND INTERFEROMETRIC RECORDS OF BREAKUP AND IGNITION OF PROPYL NITRATE IN OXYGEN. (FRAMING INTERVAL = 100 μSEC, 2 PULSE LASER AT 100 μSEC)



#138 PN/$O_2$ 2P-50

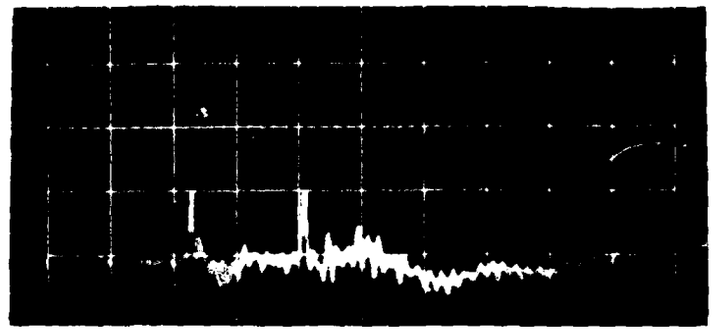
#142 $C_7H_{16}/O_2$ 2P-50

FIGURE 8. INTERFEROMETRIC STREAK PHOTOGRAPHS OF PROPYL NITRATE AND HEPTANE IN OXYGEN. (2 PULSE LASER AT 50μSEC)

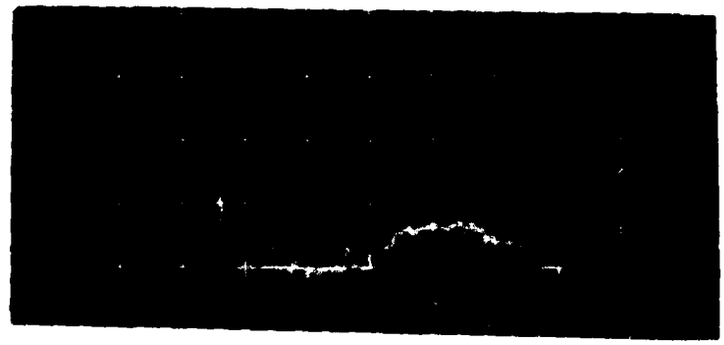
#291 $O_2$ 2P 100

#290 $PN/O_2$ 2P-100; P @ 5 cm
(Vert.: .05 psi/div; Horz.: 50 μsec/div)

FIGURE 9. PRESSURE RECORDS AT 5 CM FROM FOCAL POINT OF LASER. (2 PULSE LASER AT 100 μ SEC IN OXYGEN AND IN PROPYL NITRATE-OXYGEN)



#294 $C_7H_{16}/O_2$ 2P-100 P @ 5 cm
(Vert.: 0.1 psi/div, Horz.: 50 μsec/div)



#297 $C_7H_{16}/O_2$ 2P-50 P @ 5 cm
(Vert.: 0.1 psi/div, Horz.: 50 μsec/div)

FIGURE 10. PRESSURE RECORDS AT 5 CM FROM FOCAL POINT OF LASER.
(2 PULSED LASER AT 100 μSEC AND 50 μSEC IN HEPTANE-OXYGEN)

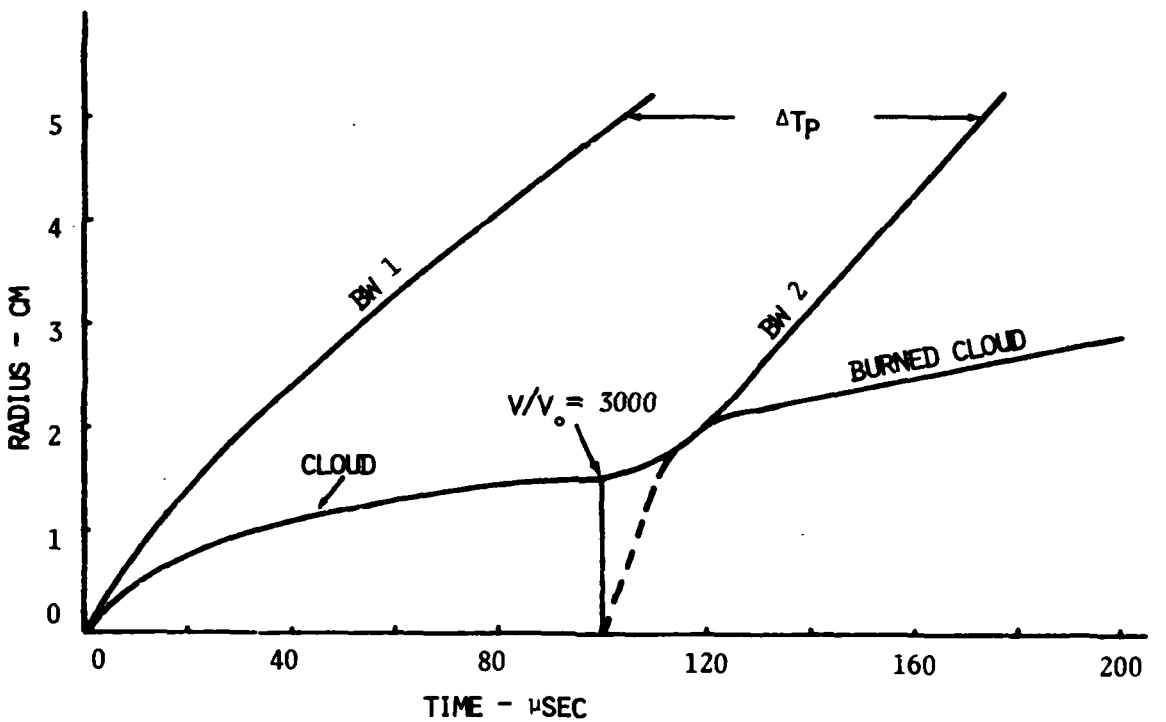



Figure 11. Schematic interpretation of streak records.

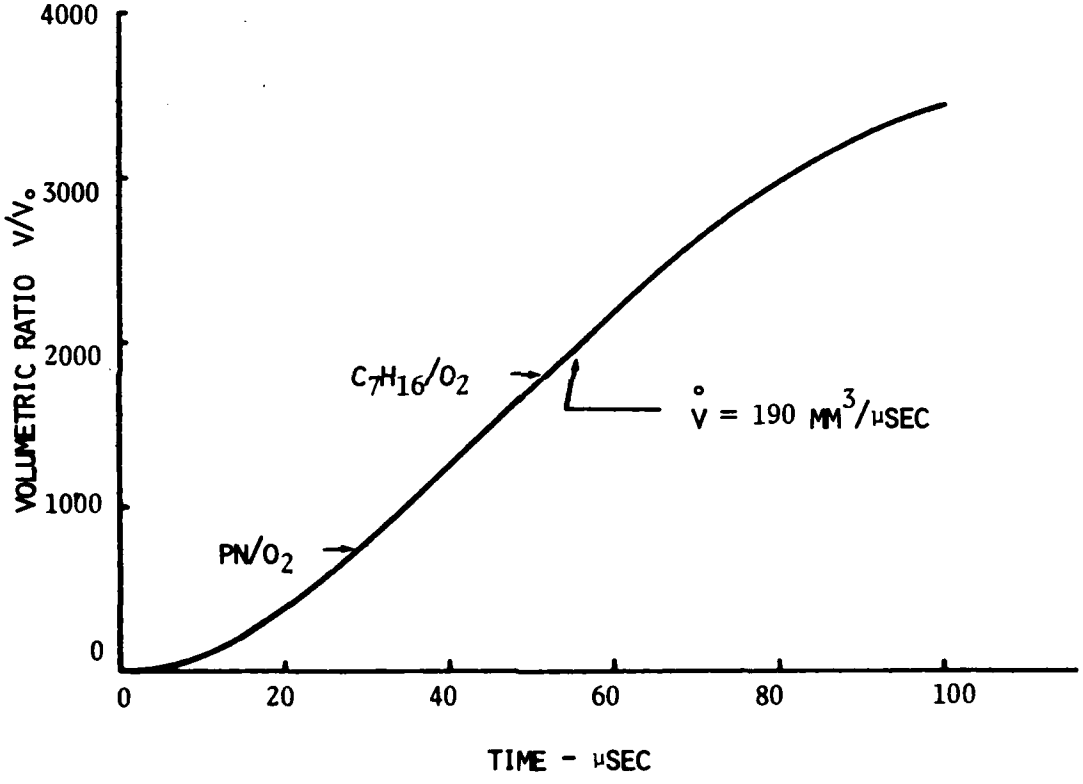



Figure 12. The variation of the volumetric cloud-drop ratio with time.

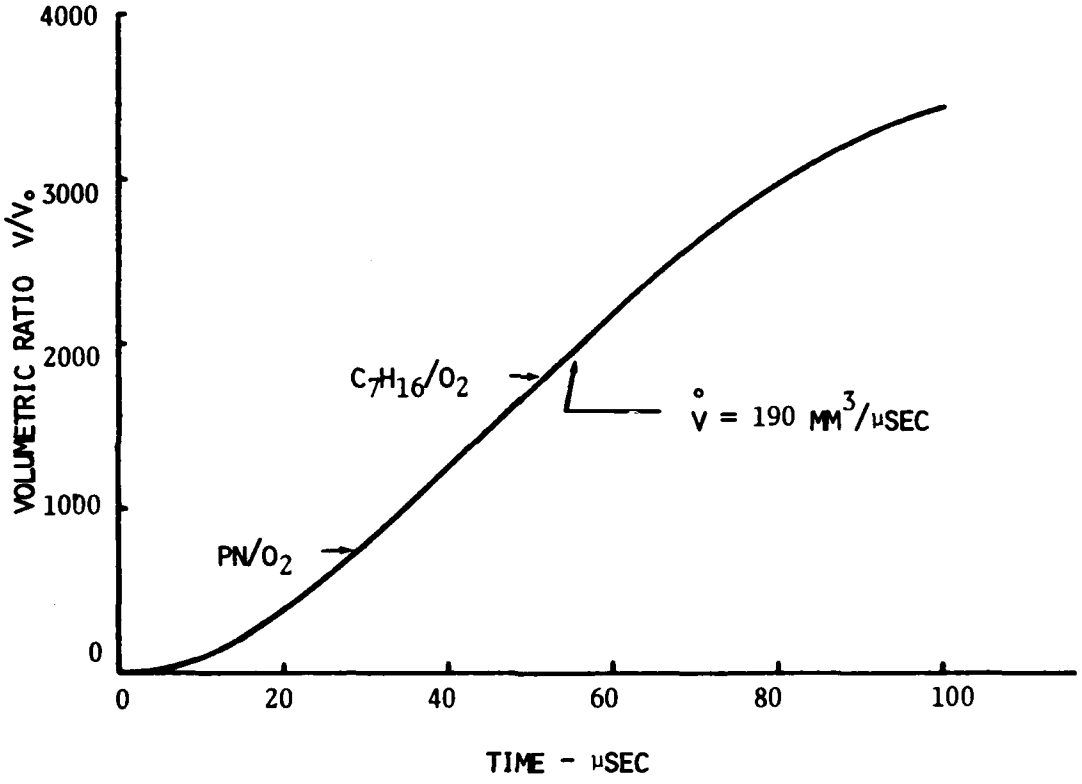



Figure 12. The variation of the volumetric cloud-drop ratio with time.

## APPENDIX D

### LIST OF PRESENTATIONS

1. "Analytical and experimental studies of variable energy blast waves." Proc. Conf. on Mechanism of Explosion and Blast Waves, Yorktown, Virginia. 1973.
2. "An experimental investigation of variable energy blast waves." Proc. 5th Internat. Colloq. on the G.D.E.R.S., Bourges, France, September, 1975.
3. "Predictions of variable energy blast waves." AIAA Fluid and Plasmadynamics Conf., San Diego, Calfornia, 1976.
4. "Two-phase detonations and variable-energy blast waves." FAE Conf. Elgin Air Force Base, Florida, December, 1976.
5. "A model for spray detonations." 6th Int. Colloquium on Gas Dynamics of Explosions and Reactive Systems, Royal Institute of Technology, Stockholm, Sweden, August, 1977.
6. "Critical initiation energy for spray detonations." Eastern States Section of the Combustion Institute, East Hartford, Connecticut, November, 1977.
7. "Variable energy blast waves." Meeting on Research and Exploratory Development in Energetic Materials, ARRADCOM, Dover, New Jersey, October, 1978.
8. "Photographic observation on laser induced explosive combustion of fuel drops." Conference on Mechanisms of Explosions in Dispersed Energetic Materials, ARRADCOM, Dover, New Jersey, November, 1978.
9. "Laser Induced Combustion of Fuel Drops." AFOSR Contractors Meeting, Fort Walton Beach, Florida, January, 1979.
10. "Energy and power requirements for direct initiation of spray detonations." To be presented at the Y h International Shock Tube Symposium, Jerusalem, Israel, July, 1979.

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| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
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| 1. REPORT NUMBER<br>UCONN 0507-121-F | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>Variable Energy Blast Waves and Two-phase Detonation | | 5. TYPE OF REPORT & PERIOD COVERED<br>Final<br>Jan. 1, 1973-Sept. 30, 1978<br>6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>E. K. Dabora | | 8. CONTRACT OR GRANT NUMBER(s)<br>DA-ARO-D-31-124-73-G100<br>DAAG29-76-G-0142<br>DAAG29-77-G-0112 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>The University of Connecticut<br>Department of Mechanical Engineering<br>Storrs, Connecticut 06268 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>U. S. Army Research Office<br>P. O. Box 12211<br>Research Triangle Park, NC 27709 | | 12. REPORT DATE<br>February 1979<br>13. NUMBER OF PAGES |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report)<br>Unclassified<br>15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Two-phase detonations, spray detonations, blast waves, variable energy blast waves, non-ideal blast waves, laser ignition, laser irradiation, liquid fuels, fuel-air explosions (FAE), LNG spills, fuel spills.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The results of the research work performed to determine the role of blast-waves and mass addition within the reaction zone of spray detonations are summarized. Since most of the findings have been published in the literature abstracts of the relevant publications have been included. One of the publications describes a model for spray detonations in which the relevant parameters are found to be the ignition delay and the energy temporal variation within the reaction zone. The model can predict the minimum energy for direct initiation when

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cont.

20. these parameters are known.

Recent experiments on laser ignition of fuel drops to simulate the mass addition aspect within the reaction zone are reported in detail. These experiments indicate that mass addition effects are small when compared to the blast wave effects. However, they reveal that, under some conditions, explosive combustion can take place. The experiments appear to be the first of their kind and open up new avenues for research on liquid propellants, fuel-air explosions and detonation transfer.