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TWO PHASE DETONATION STUDIES CONDUCTED IN 1970

by

J. A. NICHOLLS

THE UNIVERSITY OF MICHIGAN
Department of Aerospace Engineering
Ann Arbor, Michigan 48104

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

March 1971

Grant NGL 23-005-336

NASA Lewis Research Center
Cleveland, Ohio
R. J. Priem, Project Manager

NOTICE

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ANNUAL REPORT

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FOREWORD

This report covers the progress made in the second year, February 1, 1970 to February 1, 1971, on NASA Grant NGL 23-005-336. The study was under the direction of Professor J. A. Nicholls, Department of Aerospace Engineering. Dr. R. J. Priem, NASA Lewis Research Center, was technical monitor.

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ABSTRACT

This report represents an annual progress report describing, in brief, the research conducted on this grant. There are five phases to the project which are described separately. The phases are:

1. Ignition of fuel drops by a shock wave and passage of a shock wave over a burning drop.
2. Propagation of a two phase detonation with a controlled distribution of drop size.
3. The attenuation of shock and detonation waves passing over an acoustic liner.
4. An experimental and theoretical study of film detonations.
5. A simplified analytical model of a rotating two phase detonation wave in a rocket motor.

I. INTRODUCTION

The research covered by this second annual report represents a continuation of our efforts devoted to the study of detonation waves in liquid-gas systems. The motivation for the work is associated with liquid propellant rocket motor combustion instability although certainly the studies are also applicable to internal combustion engines and other jet propulsion engines. The research has been divided into five phases, although all of these are intimately related.

Phase A has been primarily concerned with the breakup and ignition of fuel drops by shock waves. Most of the experimental work has been done and an approximate analytical model of ignition is nearing an end. The work is now shifting to the passage of shocks over burning drops.

Phase B has been devoted to the general structure of two phase detonation inasmuch as serious overpressures are realized. The original work considered a monodispersed system but now the emphasis is on the case of a controlled drop distribution, which of course, will be closer to the actual case.

The aim of Phase C has been to determine the feasibility of arresting a two phase detonation with an acoustic liner. It is recognized that it would probably be necessary to attenuate the shock wave in the early stages of development in order to be effective. Therefore, much of the work, analytical as well as experimental, has treated the case of shocks passing over a liner section.

Another version of the two phase detonation is that wherein the fuel is in the form of a liquid layer on the wall and the shock passes over it. This problem is considered in Phase D and experiments and analyses have been effected with good agreement obtained.

Phase E consists of an analytical study of a rotating two phase detonation wave in an annular rocket motor. This mode of instability has been tied to the primary combustion chamber variables and some work has been done on predicting the instability boundary.

The progress made on each of the five phases will now be described.

II. RESEARCH RESULTS

Phase A - Shock Wave Ignition of Fuel Drops

The experimental study of the interaction of a shock wave with an initially nonreacting fuel drop in an oxidizing atmosphere has been completed. The shattering and ignition characteristics for the two different fuels used, diethylcyclohexane and n-hexadecane, were observed for varying incident shock wave Mach numbers, different ambient pressures, and for differing initial drop diameters. As has been previously reported[1] spontaneous ignition of the fuel drop will occur in certain cases after an ignition delay period that is functionally dependent on the initial drop diameter, the Mach number of the incident shock wave, and the initial oxidizer pressure.*

The nature of the interaction and combustion process is shown for diethylcyclohexane (DECH) drops in Fig. 1 and 2. Figure 1 simply shows the destruction of the DECH drops in an inert atmosphere by aerodynamic forces. It is noted that as the time interval after the initial shock wave interaction with the drops increases, the original drop mass becomes more diffuse and accelerates in the downstream direction. A case in which ignition of the fuel drop

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*A more complete analysis of this work is given in Ref. 2.

occurs due to the shock wave interaction is shown in Fig. 2. Here it is noted that the drops deform and accelerate in a manner identical to that observed for the nonreacting case until approximately 77 μs after interaction. At this time it is noted that additional shock waves appear and that the wake assumes a mottled appearance which is typical of flame shadowgraphs. It is also seen that as the time interval after ignition increases, a considerable quantity of the drop mass is consumed by the combustion process.

Shock wave initiated combustion of a n-hexadecane drop is shown in the streak photograph of Fig. 3. Here the camera is focused on the test section and thus any shadowgraph effects are essentially negated. It is noted that the combustion process, which is wake initiated and accompanied by strong blast waves, is very similar in nature to that observed for the DECH drops. The ignition delay period is again adequately represented by an Arrhenius rate law as is shown in Fig. 4, which presents data for drops having an initial diameter of 930μ. The delay time for the n-hexadecane drops is approximately the same as that observed for the DECH drops. However, it was found in the case of the DECH drops, where the initial drop diameter was varied (932μ, 1520μ, and 2130μ), that the activation energy was a function of the initial drop diameter with the ignition delay time of the smaller drops showing a greater sensitivity to temperature.

Since the drop ignition process is quite closely associated with the aerodynamic destruction of the drop some comparisons were made between the shattering characteristics of water, DECH, and n-hexadecane drops. The breakup time, defined as the time that it takes the drop to accelerate to 60% of the convective flow velocity, for DECH and n-hexadecane drops is found to be in quite close agreement for both burning and non-burning cases; the latter case gives a slightly smaller breakup time as compared with the reacting case. It is found that the breakup time seems to scale quite well with the inverse square root of the dynamic pressure. However, for water drops it has been found that the breakup time is approximately twice as great as for comparable size DECH or n-hexadecane drops. A comparison of the different breakup behavior of a water and of a DECH drop is shown in the streak photographs in Fig. 5 and 6. It is noted that in addition to the longer breakup time for the water drop that the micromist produced by the aerodynamic stripping of mass from the parent drop is much more effective at scattering the light from the xenon flash tube. Assuming that at the breakup time that equal amounts of mass have been removed from the original drop and that it is contained in equal wake volumes it can be shown from elementary light scattering theory that the water micromist is of a smaller diameter and that the number density is higher. It was also observed (during the non-reacting drop shattering studies) that the distance the drop travels is a function of the inverse square root of the dynamic pressure as well as the incident shock wave Mach number.

Based upon the experimental data that have been collected, the development of an analytical ignition model is currently being developed. Observations have shown that ignition does not occur in the first mass which is shed from the drop, presumably because the size of the mist droplets is too small to support a diffusion type flame or that the ignition delay period for this type of ignition is too long. Ignition occurs in the mass of fuel which is shed at some time period after the initial interaction. It has been found that for a given size drop that this time, when nondimensionalized to account for the different dynamic pressures, decreases with increasing Mach number; i. e. there is less mass in the wake of the drop. However, for the same Mach number it has been found that this time increases with decreasing drop size. That is, smaller drops are more completely destroyed when ignition occurs. Based upon the boundary layer stripping analysis for the rate of mass removal from the original drop (this model tends to underestimate the mass removal rate, especially at high dynamic pressures) the amount of fuel in the drop wake has been calculated at the time of ignition. It has been found that there is more than enough fuel present in the form of micro-mist to produce a stoichiometric mixture. In view of the presence of excess fuel in the wake it is now believed that the evaporative behavior of the individual micromist drops must be considered. Hence, the delay period associated with the mist evaporation seems as important as the delay time associated with the stripping process. At present efforts are directed toward calculating the evaporation rates of the micromist with the desire of obtaining gas phase mixture ratios in the wake.

An electro-mechanical device has been designed and is being built which will allow a shock wave to pass over an initially burning fuel drop. The design was based on two major requirements. First, the time interval between ignition of the fuel drop and its subsequent interaction with the shock wave must be kept small to minimize the contamination of the droplets ambient conditions. Secondly, the flow field near the droplet after shock wave interaction must be kept as free of external disturbances as possible.

The selected method of droplet injection involves the sudden retraction of a fine bore hypodermic needle (0.5 mm inner diameter) from which the drop is initially suspended. The drop is formed by fuel flowing through the hypodermic needle. The size of the drop is reproduced by maintaining a hydraulic fuel supply line and imposing a small, measured pressure pulse to the fluid in the line. It has been observed that the formation of secondary droplets, which were encountered by earlier investigators using this method of droplet injection, can be eliminated by the combined effect of using a fine bore hypodermic needle with a chamfered tip, suspending the largest possible drop from the hypodermic needles tip, and retracting the filament at a high speed. Obtaining different size fuel drops will require replacing the hypodermic needle with another needle having a different bore.

Ignition of the fuel drop will be achieved by a short duration spark, the spark gap being formed by a fine steel wire (the ignition electrode) and the hypodermic needle. The hypodermic needle and ignition electrode are retracted immediately after droplet ignition. The ignition and subsequent retraction is triggered by a signal produced by the shock wave passing over a pressure transducer upstream of the test section. The time interval between spark ignition of the fuel drop and its subsequent interaction with the shock wave will be approximately 0.5 ms. In this case, the hypodermic needle and ignition electrode will be partially exposed to the shock wave, but their range of influence will be far removed from the region in which the drop shattering process is occurring.

The range of test conditions will be similar to those used in the study of shock ignited fuel drops. Tests are only planned for the 1520μ drop size, using DECH as the fuel. Comparisons will be made of the various breakup characteristics of a droplet burning prior to shock wave interaction with those of the shock ignited fuel drops. Also to be studied will be the phenomena of flame blow off.

Phase B - Energy Release Patterns

The current objectives in this phase of the research have been to resolve in greater detail the reaction zone structure in spray detonations, and to determine the influences of droplet size distribution on the properties of these waves. For this purpose, a polydisperse spray generator was built, and the detonation facility was modified. These are described in Ref. 1.

The procedure presently being followed in the experiments is basically the same as that used in the earlier work[3], with two exceptions. First, a new technique has been employed for filling the detonation tube with the charge gas prior to a run. In the past, only oxygen or air could be easily used in the vertical detonation tube, and only at atmospheric pressure, because the tube could neither be evacuated nor raised to a pressure much above atmospheric. Evacuation would draw fuel into the tube through the drop generator capillaries while pressurizing would burst the soft-plastic "baggie" used as a lower-end diaphragm. Purging was therefore accomplished previously by blowing oxygen or air through the tube for a period of time, and then quickly sealing it off. In order to use any other charge gas, premixing would have been required. To provide for more accurate and versatile charging, a tank was fitted to the lower end of the tube surrounding the baggie and having a pressure bypass to the main detonation tube. In this way the baggie remains intact regardless of the tube pressure. The tank itself has a Mylar diaphragm on its lower end when used in a run. To prevent drawing of fuel through the capillaries at the upper end of the tube, a large gate valve was installed there below the capillaries. This is closed during charging and open during a run.

The second procedural change consists of carefully cleaning the inner walls of the detonation tube prior to each run. This ensures that the detonation will not be contaminated by residues which adhered to these walls during the preceding run.

Experiments have been conducted in sprays of diethylcyclohexane drops having diameters of 300μ and 750μ. The oxidizer was pure oxygen at atmospheric pressure. The composition of a spray was specified by the "equivalence fractions", a_i, where $a_i = \phi_i/\phi_T$, ϕ_T is the overall equivalence ratio ($\phi_T = \sum_i \phi_i$), and ϕ_i are the "partial equivalence ratios", for each species i. A series of runs was carried out with $\phi_T = .430$, in which $0 \leq a_{750} \leq 1$. The variation of a_{750} could not be executed in a continuous fashion, because of limitations imposed by the drop generator. Figure 7 shows typical pressure histories recorded by a Ragland-type transducer[3] located approximately 9 ft below the point of initiator shock injection. Minor ripples on the oscilloscope traces have been ignored so that the main features of the wave are presented. Appexes on the graphs represent data points. (Note that with a wave velocity of ~ 6000 ft/sec, 1 in. of distance behind the leading shock represents ~ 14 μsec in time.)

These two samples illustrate the general character of all data obtained thus far. There are two primary pressure spikes, separated by a "valley", and followed in position (sometimes also preceded) by other peaks of less intensity. The system of spikes is superimposed on a generally decaying pressure level. The pressure peaks are believed to be decaying plane shock waves, emanating from the wake explosions of successive groups of droplets, and occurring in the reaction zone at an expected average frequency of u_s/d (where u_s is the detonation velocity and d is the mean droplet separation distance).

Figures 8-12 are descriptive of changes which occur in the pressure structure of polydisperse detonations as the spray composition is varied. Shown with the data points on these plots are least-squares polynomial curve fits. The y-axis scale is expanded in each case so as to just include the spread in the data.

Figure 8 shows the magnitude of the pressure spikes which appear in the waves, where P_1 is the pressure upstream of the leading shock, and P_2 is the pressure just downstream. Peak pressures are about 52 times the upstream pressure and 50% greater than the leading shock pressure.

Figures 9 and 10 are indicative of the position in the reaction zone of the principal secondary shock structure. In Fig. 9 the locations of the maximum pressure spikes (as in Fig. 8) are plotted, while Fig. 10 shows the apparent position of the wake ignition plane, taken to be at the point of lowest pressure (or the midpoint) between the two principal secondary shocks. Both figures indicate that the secondary wave structure originates from a point closer to the leading shock as the proportion of 750μ drops is decreased ($a_{750} \rightarrow 0$). This can be attributed to increasing interaction between the drop size as the number density of 300μ drops is increased. The spherical blast waves from individual 300μ drops (which occur ahead of the normal 750μ-drop ignition plane), in passing through the wakes of the 750μ drops, cause premature ignition therein, so that the blast wave system occurs sooner. While this does not appear to significantly affect the magnitude of the peak pressures involved, their earlier occurrence results in a less sustained average over-pressure (Fig. 11); i.e., the impulse per unit area experienced by a point on a surface over which the detonation passes is lower when the spray includes at least some smaller droplets. In Fig. 11, average pressure is defined by

$$P_{ave} = \frac{1}{t_{max}} \int_0^{t_{max}} P\, dt \quad .$$

The value $t_{max} = 30\ \mu sec$ was chosen both because the important features of the waves are completed before this time, and also as a matter of convenience. It is believed that the trend in Fig. 11 would still be found if $t_{max} > 30\ \mu sec$.

Finally, Fig. 12 shows a slight trend toward decreasing detonation velocity as the composition of the spray is varied towards a greater proportion of 750μ drops. This is an expected variation.

All of the data suggest the following theoretical model, which is being developed first for a monodisperse system. In leading shock-fixed coordinates, droplets arranged in a cubic array pass through the leading shock, and, individually, are subjected to the stripping and shattering process described in Phase A. When a plane of droplets reaches the position behind the leading shock which corresponds in time to the interval prior to ignition, the wakes of all droplets in that plane explode simultaneously, thereby individually generating spherical blast waves. These coalesce at a distance from the ignition plane of about half the mean separation distance between droplets, forming two planar shocks, one moving toward the leading shock and the other propagating away from it. Both shocks decay as the region separating them expands. The process repeats in a cyclic manner.

A clearly crucial input to this description is the ignition time delay, which must be obtained from individual droplet dynamics. In addition to the analysis described in Phase A, two theoretical ignition estimates have been made, both of which are essentially thermal theories.

The first of these prescribes ignition as occurring when the rate of heat production due to pre-ignition reaction of fuel vapor in the wake of a given droplet exceeds the rate at which heat can be removed by turbulent heat transfer. The rate at which fuel vapor that is available for combustion is supplied to the wake depends on both the rate at which micromist drops enter the wake, and the rate at which these evaporate therein. Then, the rate of heat production is proportional to the rate of fuel vapor removal from the wake by reaction, which is determined from a reaction rate equation. Heat removal from the wake is borrowed from a simplified wake structure theory. The thermal instability which forms the reaction criterion is applied to the entire wake.

Figure 13 shows the results of this estimate. The results are not discouraging considering the many simplifications involved.

The second model considered predicts ignition when an individual micromist drop establishes a thermal imbalance at some point within its own diffusion layer. Hence the stripping mechanism of the parent drop is not involved, and ignition occurs in the first micromist drops shed.

Inasmuch as the micromist drops are assumed to be carried along with the convective flow, they experience an essentially "stagnant" environment. Turbulent mixing is neglected (in contrast to the first model) so that fuel vapor which evaporates from such a micromist drop is not considered to be removed from its diffusion layer. Ignition is estimated from a consideration of a drop which at $t = 0$ is immersed in stagnant oxygen gas at a pressure and temperature corresponding to conditions of the actual convective flow.

During the induction period preceding ignition, the heat generated by reaction in the diffusion layer of a given micromist drop is not conducted away beyond a distance of the order r_c, the radius (measured from the drop center) at which, subsequent to ignition, a spherical laminar flame will stabilize around the drop. Hence, prior to ignition, the heat of combustion serves to raise the total energy of the gas in this region. It is argued that a thermal ignition will occur somewhere in this region after a certain total energy per unit volume has been added.

The results of such a calculation are shown in Fig. 14, along with experimental data. The data were used to arrive at a suitable choice of the energy level required for ignition.

Phase C - Acoustic Liner Studies

In the early portion of the development of two phase detonation waves, pressure pulses originating from the droplet combustion zones coalesce, strengthen and maintain the wave. To be successful in arresting or slowing the development of the detonation wave, acoustic liners have to attenuate these pressure pulses. To study this aspect analysis of the passage of a shock wave over an acoustic cavity in a shock tube wall has been made.

An approximate analytical model was used to estimate the shock attenuation by finding the mass flow into the cavity from the region of the uniform flow behind the shock wave. This mass flow was estimated by assuming a one dimensional isentropic flow from the stagnation conditions of the convective flow to the static conditions in the cavity using available engineering data on orifice discharge coefficients. The effectiveness of the cavity was assumed to cease when the cavity pressure reached the value of the static pressure behind the shock. For the relatively weak shock waves considered, the time for flow into the cavity was found to be relatively long and the shock velocity change small. The cavity pressure reaches a value slightly lower than predicted and qualitative agreement between analysis and experiments was seen.

Another analytical study that was initiated was to apply tech niques which have been employed in shock tube work for estimation of test time (method of characteristics replacing the cavities by a distribution of sources and sinks with their strengths oscillatory with time representing the inflow and outflow from the cavities). This approach presented formidable problems in formulating suitable schemes for estimating the effects of finite size-spacing of the cavities, and was discontinued in favor of a generalized approach.

The analytical effort is now mainly concerned with the general problem of the attenuation in strength of a shock wave generated in an ideal shock tube having porous walls in the expansion chamber.

The initial values of velocities of the shock wave, the contact discontinuity and the rarefaction front are given by the ideal shock tube relations. The shock wave and the contact discontinuity separate out and the mass outflow through the wall decelerates the shock front and alters both the originally uniform flow field behind the shock and the contact discontinuity velocity. The region behind the shock is now non-homoentropic and the outflow through the porous wall is unsteady and depends on time, position along the wall, wall characteristics and the conditions outside. Simplifying assumptions are made to represent the flow situations as realistically as possible.

We here have an unsteady flow associated with a shock wave (and other discontinuities) in a gas with mass, momentum and energy efflux on its boundary which is itself altering in time. (The boundary changes are not known a priori, but to be obtained in the solution of the problem.) Numerical step by step difference schemes are written in Eulerian Laboratory system of coordinates for the conservation laws of mass, momentum and energy for an ideal gas. Two investigations are possible—specifying the shock motion to obtain the function form of the efflux through the wall, or if the functional form of the wall efflux is known to calculate the shock motion.

In this study the critical relationships between the shock parameters and the wall parameters to obtain optimum shock attenuation and together with the information available now on the dynamics of drop breakup and shock ignition this analysis is aimed to obtain a set of "go - no go" conditions on the development of the two phase detonation wave. It will then be possible to devise and conduct specific experiments to see the attenuation of a developing wave in the presence of a liner.

Phase D - Film Detonations

The results of the simple analysis of film detonations based on vaporization as the rate limiting process and on a one dimensional approximation for the flow in the reaction zone were presented at the Thirteenth Symposium (International) on Combustion in Salt Lake City, Utah. The paper, which was presented, will be published in the proceedings of the symposium.

The more precise analysis of film detonations in which the influence of the boundary layer displacement thickness upon the core flow within the reaction zone is taken into account has been completed. Application of this theory to film detonations provided analytical results in better agreement with measurements than the simpler theory. In particular the improved theory provided a better estimate of the final pressure downstream of the detonation. Comparison of theory with experimental results is shown in Fig. 15 and 16 for film detonations in which one or two walls of the detonation tube of square cross section are wetted.

A key assumption of the film detonation is that the Chapman-Jouguet plane occurs at the point where the film is just completely vaporized. By considering the balance between heat addition and boundary layer displacement it has been possible to demonstrate that this assumption is justified for equivalence ratios which are not too much greater than unity. For very thick films there is insufficient oxidizer to burn all the fuel and then the above assumption regarding the Chapman-Jouguet plane no longer holds.

Experiments on DECH-oxygen film detonations have been continued, and extensive new data over a broad range of equivalence ratios has been obtained. Experiments on the influence of the dilution of the oxidizer with nitrogen have also been made. For small amounts of dilution the effect on propagation appears to be extremely small, as a result borne out by the theoretical calculations. When dilution is increased beyond a certain critical value, initiation of film detonations was no longer possible with out existing means of initiation.

The results described above will be submitted for publication in the near future and also form the bulk of the Ph.D. thesis of Mr. C.S.R. Rao.

Phase E - Theoretical Analysis of a Tangential Two-Phase Detonation

An analysis to study tangential mode combustion instabilities for an annular combustion chamber is completed. This analysis concerns the effects of those parameters used in the design of liquid rocket motors on the strong limit of the tangential mode rotating wave. To carry out the analysis, one assumes the following:

1. The chamber wall is adiabatic and frictionless.
2. The annular chamber is thin as compared to its circumference. As a result, the radial variation of the gaseous motion may be neglected.
3. The wave is a one-dimensional two-phase C-J detonation, propagating at constant angular velocity.
4. Incoming propellant droplets are frozen at their initial condition except in a narrow reaction zone immediately behind the wave. The motion of gases is also independent of that of the droplets.
5. The injection rate of the propellant and combustion efficiency are not significantly affected by the rotating wave motion.
6. The strength of the wave diminishes to that of a weak wave as the nozzle is approached.

Coordinates are fixed on the wave. Jump conditions across the wave are solved for a two-phase mixture of burned gases, unburned fuel and oxidizer droplets. Unlike most other studies on two-phase detonation, the upstream quantities of the wave are not known a priori in this analysis. The condition of steady wave velocity leads to a cyclic condition, which furnishes two equations for the conservations of the specific entropy and total relative enthalpy of the gas phase across the wave. Eight equations may thus be obtained for nine variables, namely, p_o, ρ_o, T_o, v_o, p_1, ρ_1, T_1, v_1 and V_w. The subscripts "o" and "1" denote quantities upstream and downstream of the wave, while V_w is the wave propagation velocity. By using assumptions 5 and 6 it is possible to find a relationship to link the average pressure on the injection plate to the design equilibrium chamber pressure, and this leads to the final equation. The method of characteristics is used to calculate the pressure distribution along the injection plate. This distribution is then integrated numerically to obtain the average pressure. The resulting wave strength is written in terms of nozzle area ratio, specific heat ratio, injection velocity, impingment distance, equilibrium chamber sound speed, chamber diameter and fuel distribution.

The result of the analysis is calculated on the basis of equilibrium running conditions given by Clayton et al[4], and is favorably compared to their experimental data. A typical comparison is shown in the following table.

	P_{min} (psia)	P_{max} (psia)	$\frac{P_{max}}{P_{min}}$	wave velocity (ft/sec)
analysis	139. 5	2230	16	6580
experiments (Clayton)	126	2392	18. 98	6160

Furthermore, the analysis shows that the strength of the wave is independent of the chamber length, directly proportional to the size of the chamber, but inversely proportional to the injection velocity, the nozzle to chamber area ratio, and the impingement distance. It also follows from the analysis that tangential instabilities may be subdued by using a stepped chamber, by increasing the baffle length, and by reducing the fuel distribution on the outer portion of the injection plate (ramp distribution).

The effects of the drop size on the analysis are studied. When the drop size increases while the mass flow of propellants is kept constant, the reaction zone length increases and the energy that is lost due to the lateral expansion within the reaction zone may cause the wave to decay. A simple criterion, that the time required for a sound wave (initiating for the explosion site) to propagate upstream to the leading shock must be equal to or less than the time required for it to propagate laterally in a distance over which the detonation wave extends, is used to set the lower limit of validity of the above "strong wave" analysis and to indicate a stability boundary.

The work of this phase is being written up in complete form and will constitute the Ph.D. thesis of P. Shen.

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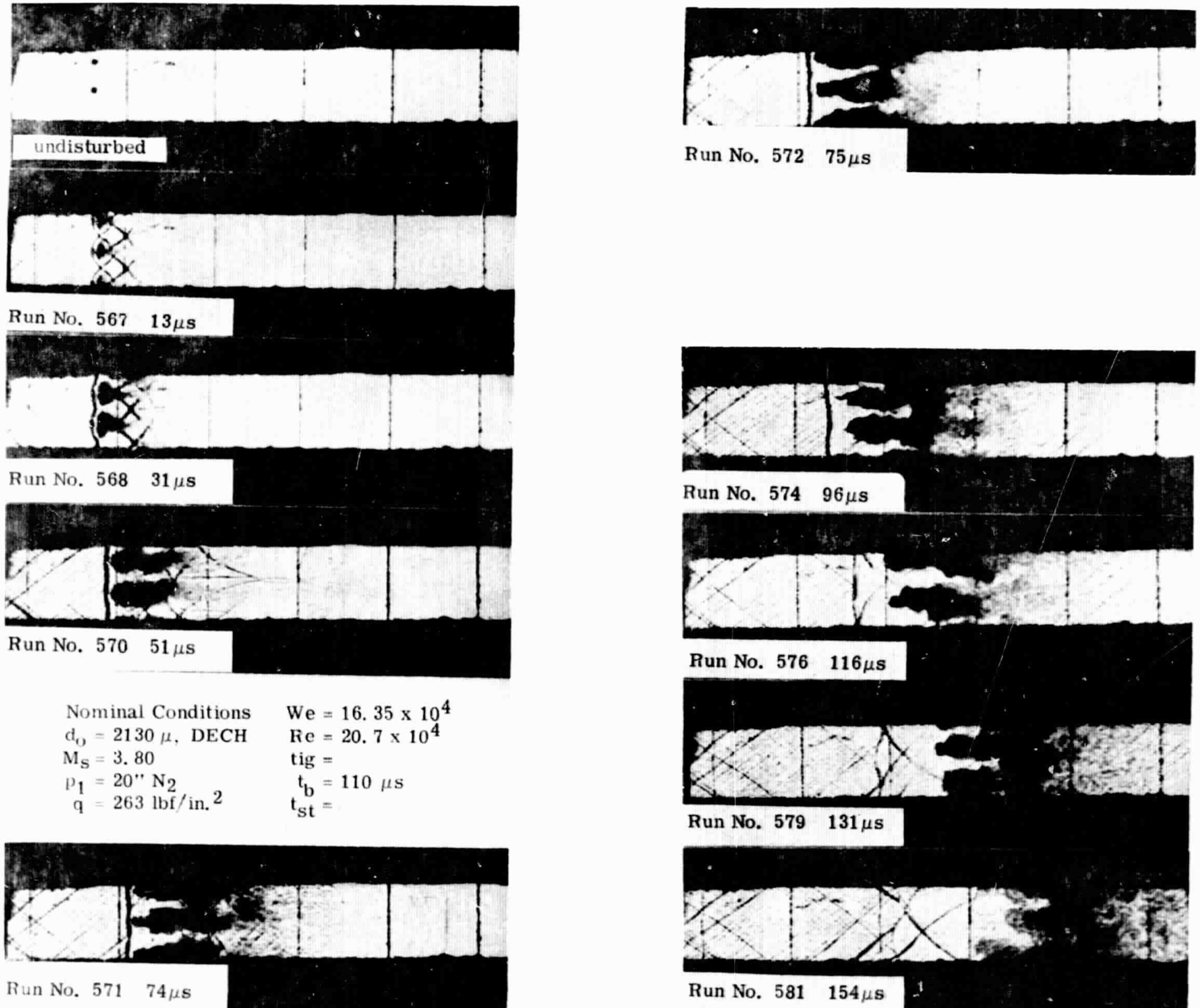
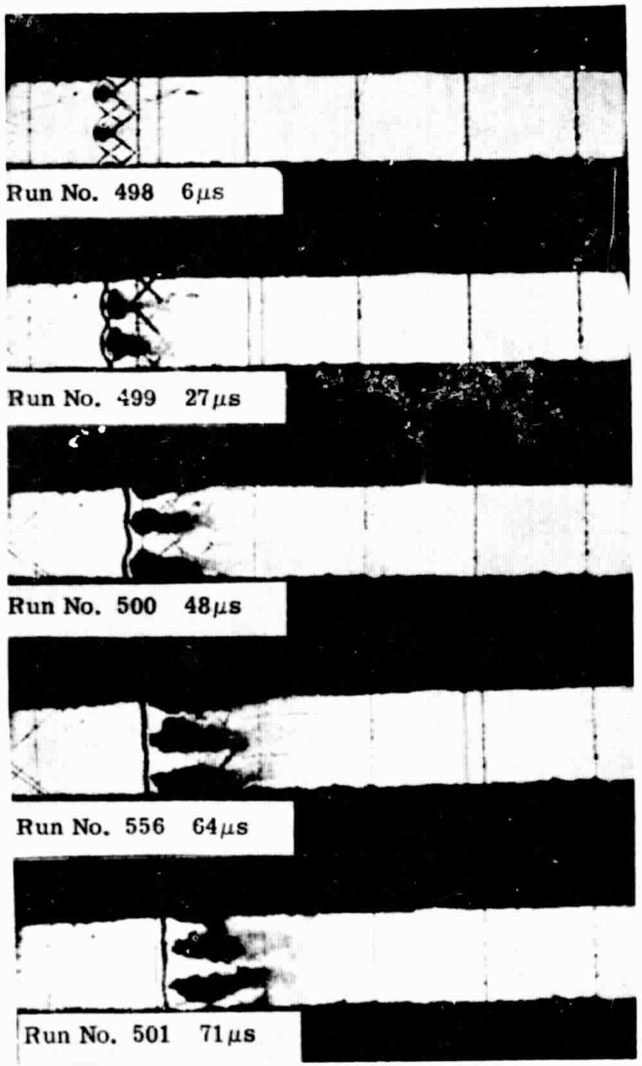


Figure 1. Non-reacting 2130μ DECH Drops.

Nominal Conditions
d_o = 2130 μ, DECH
M_s = 3.75
p_1 = 20'' O_2
q = 255 lbf/in.^{2}

We = 15.91 x 10^4
Re = 18.28 x 10^4
tig = 70 μs
t_b = 128 μs
t_{st} =



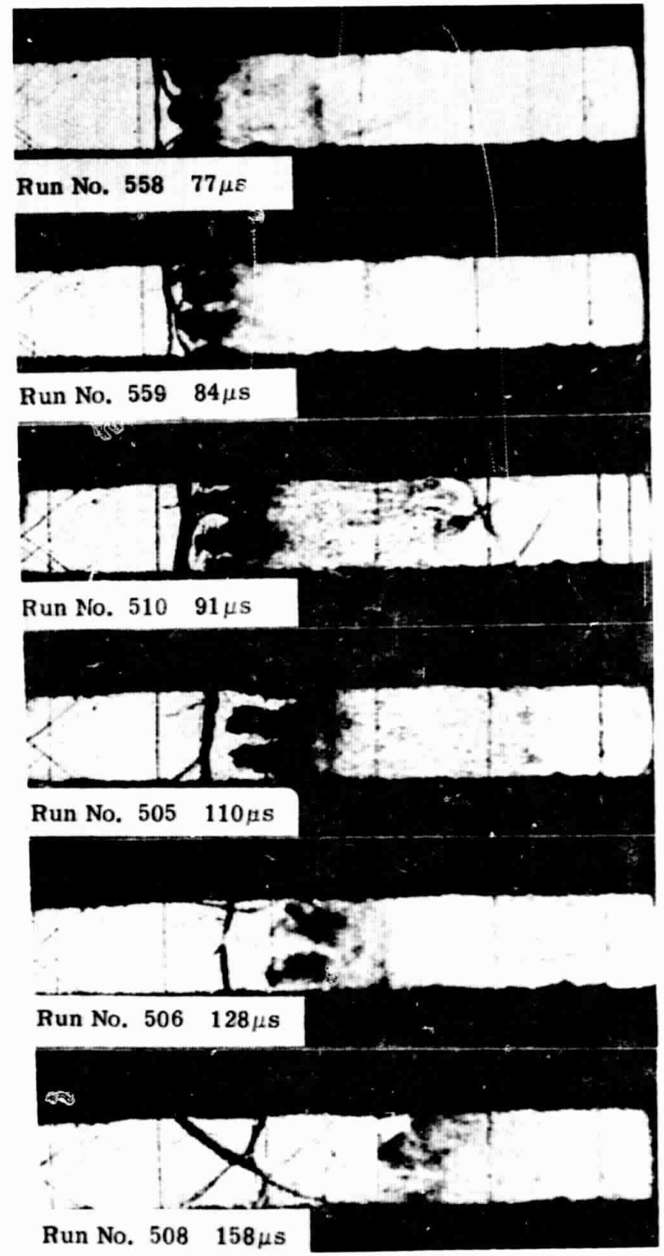


Figure 2. Reacting 2130μ DEC . Drops.

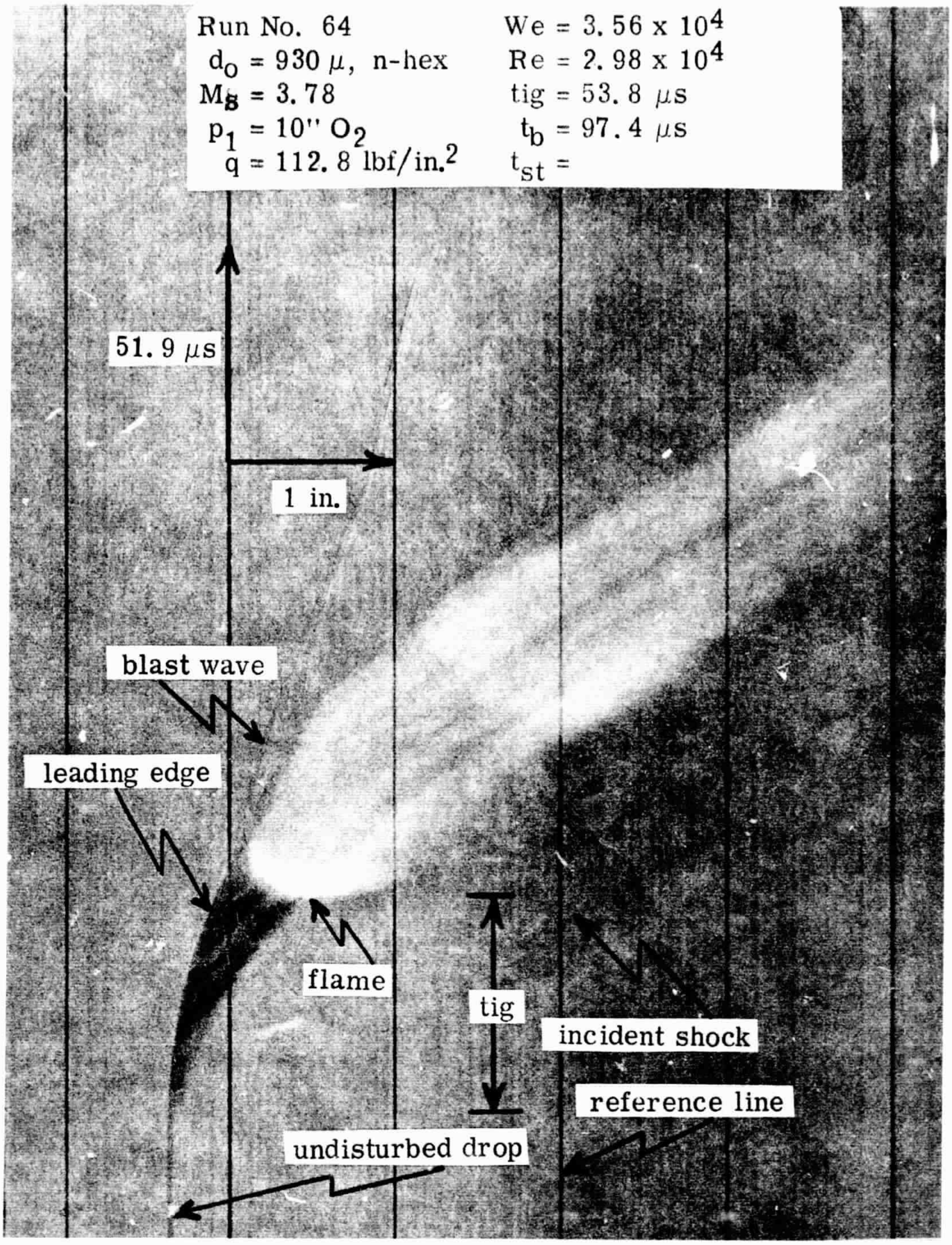


Figure 3. Reacting 930μ N-Hexadecane Drops.

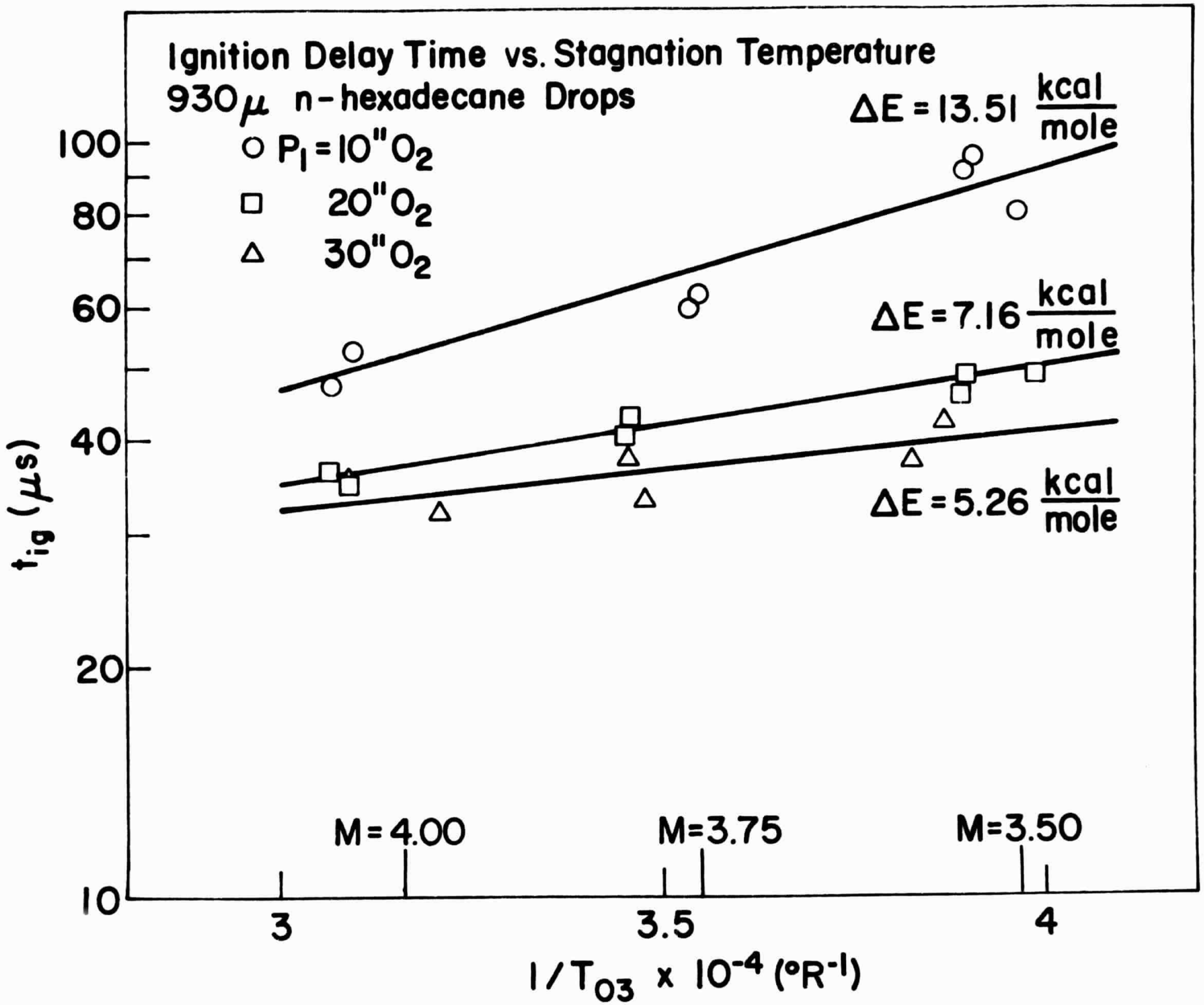


Figure 4. Ignition Delay Time - 930μ N-Hexadecane Drops.

Run No. 451 | We = 4.01×10^4
d_o = 2060 μ, H_2O | Re = 18.07×10^4
M_s = 3.30 | tig =
p_1 = 20" N_2 | t_b = 196 μs
q = 176 lbf/in.^{2} | tst =

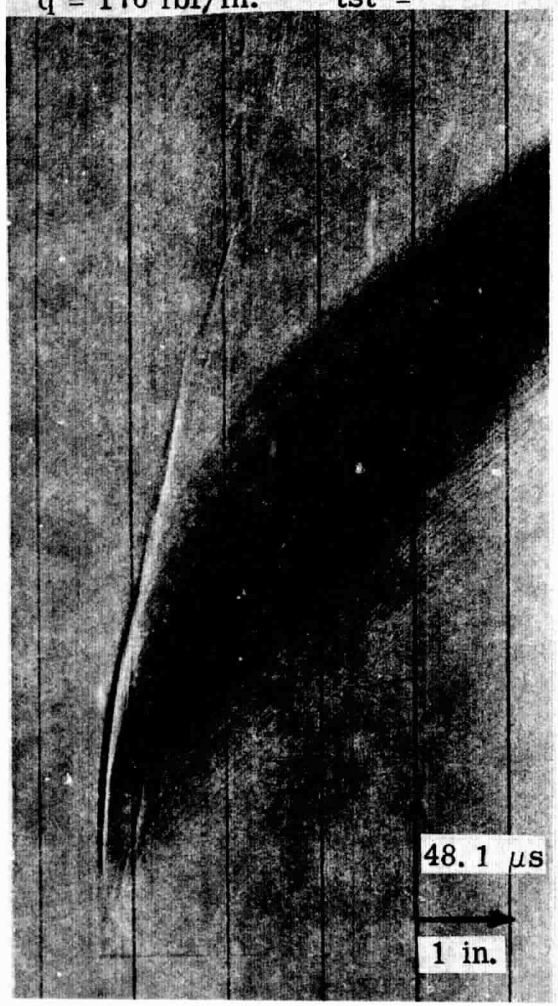


Figure 5. Non-reacting 2060μ Water Drop.

Run No. 346 | We = 11.05×10^4
d_o = 2130 μ, DECH | Re = 18.83×10^4
M_s = 3.30 | tig =
p_1 = 20" N_2 | t_b = 170 μs
q = 176 lbf/in.^{2} | t_{st}

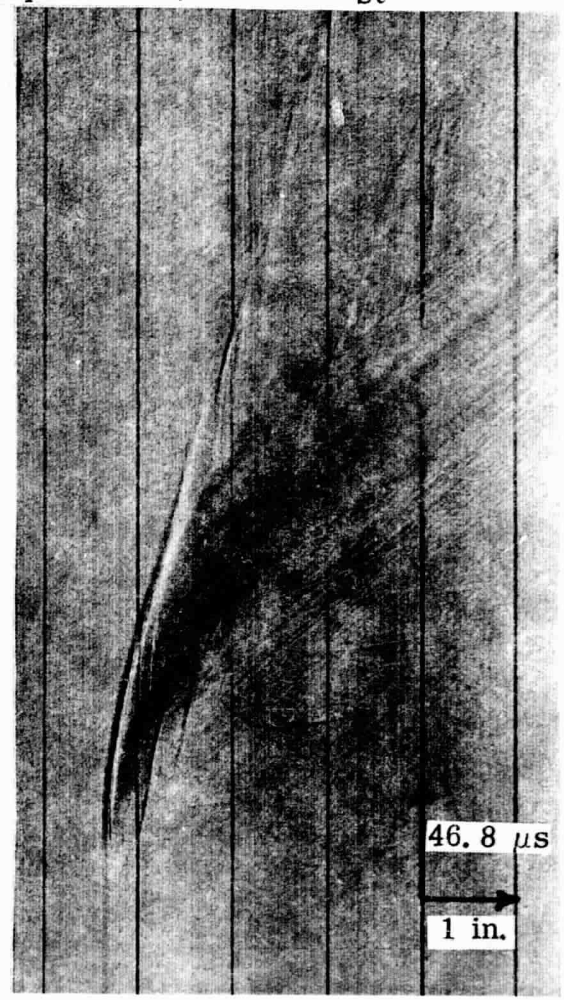
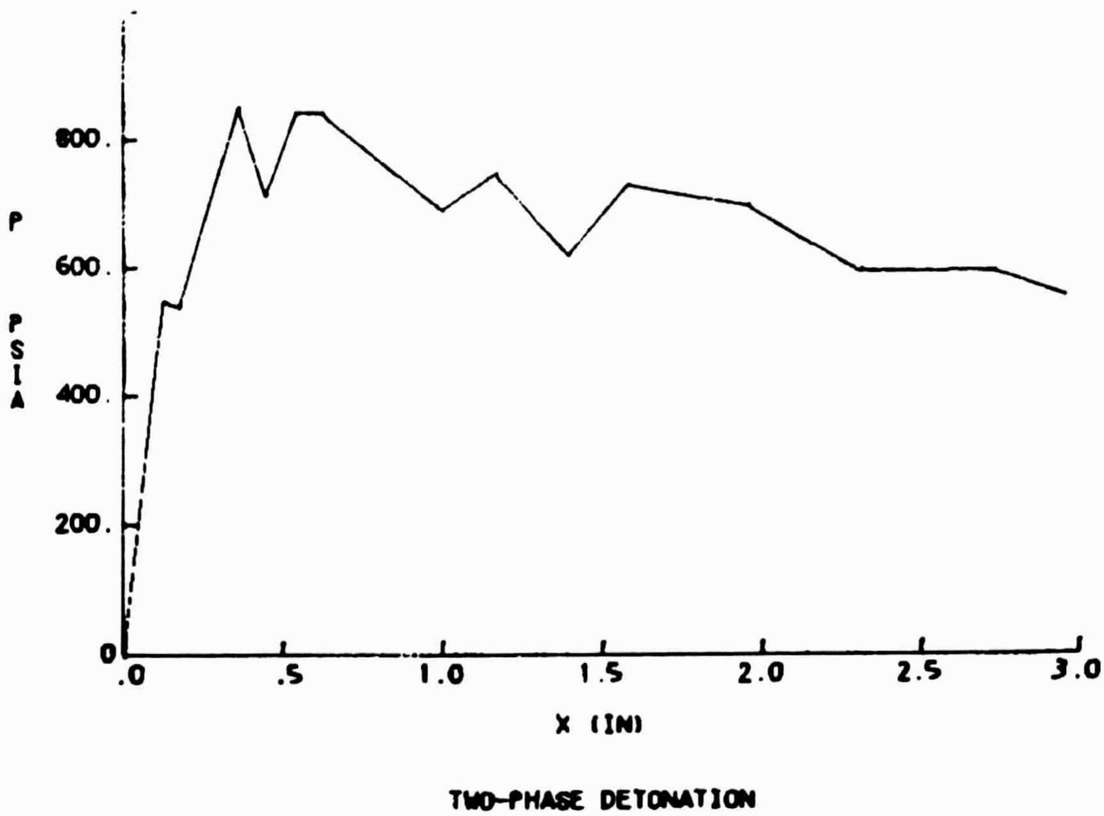


Figure 6. Non-reacting 2130μ DECH Drop.



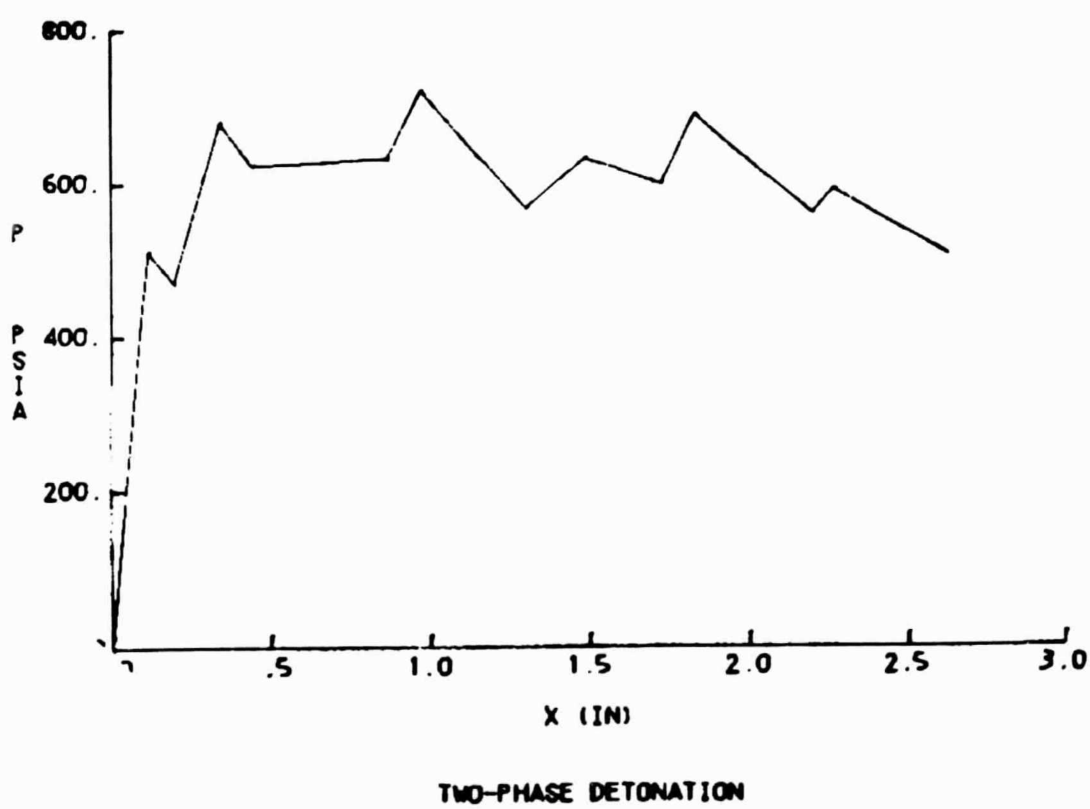
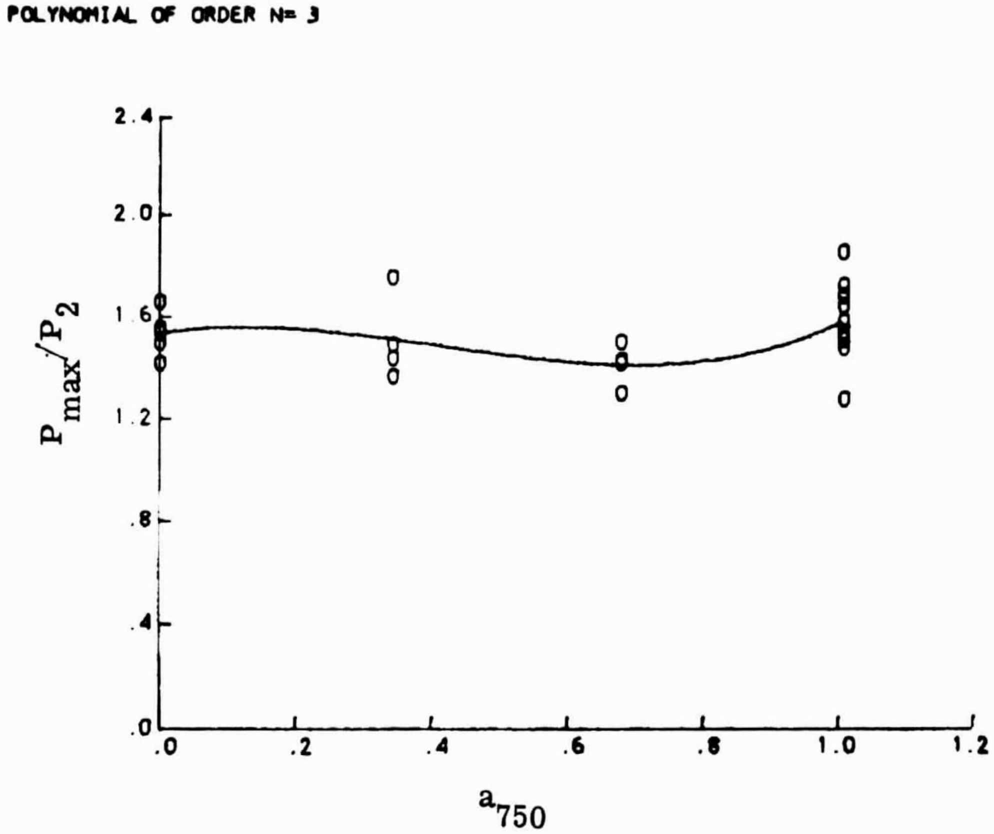


Figure 7. Pressure Distribution Behind Spray Detonation; $\phi_T = .430$. Upper: $a_{750} = 0$; Lower: $a_{750} = .675$.



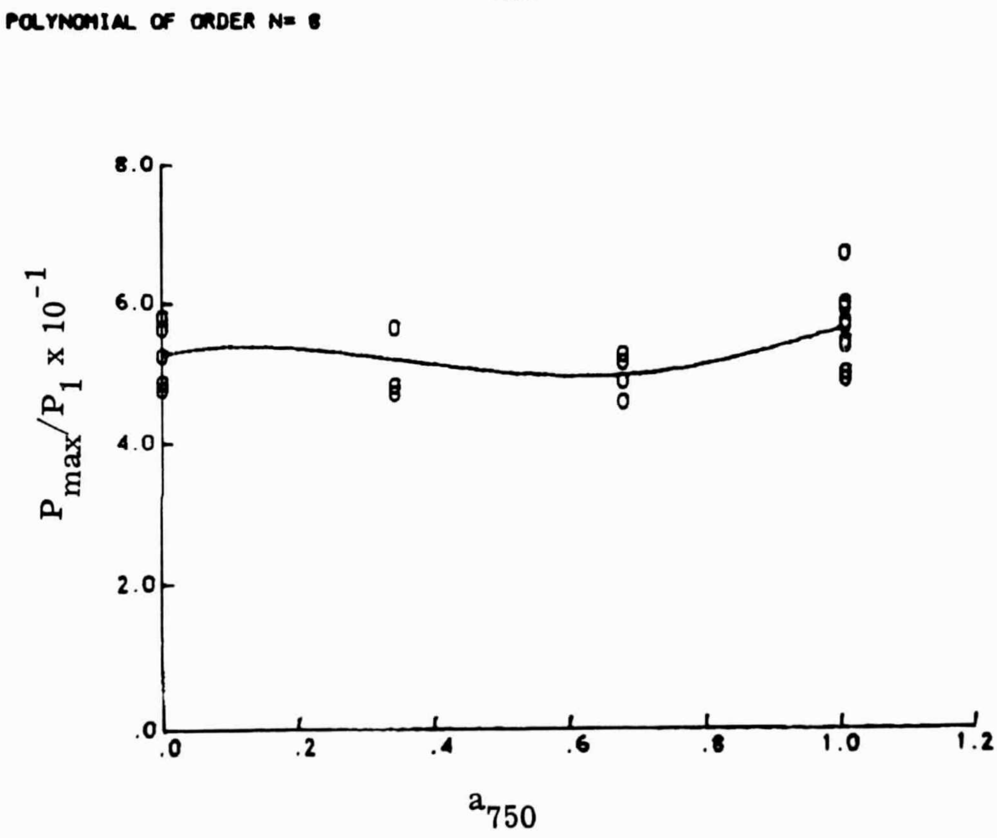
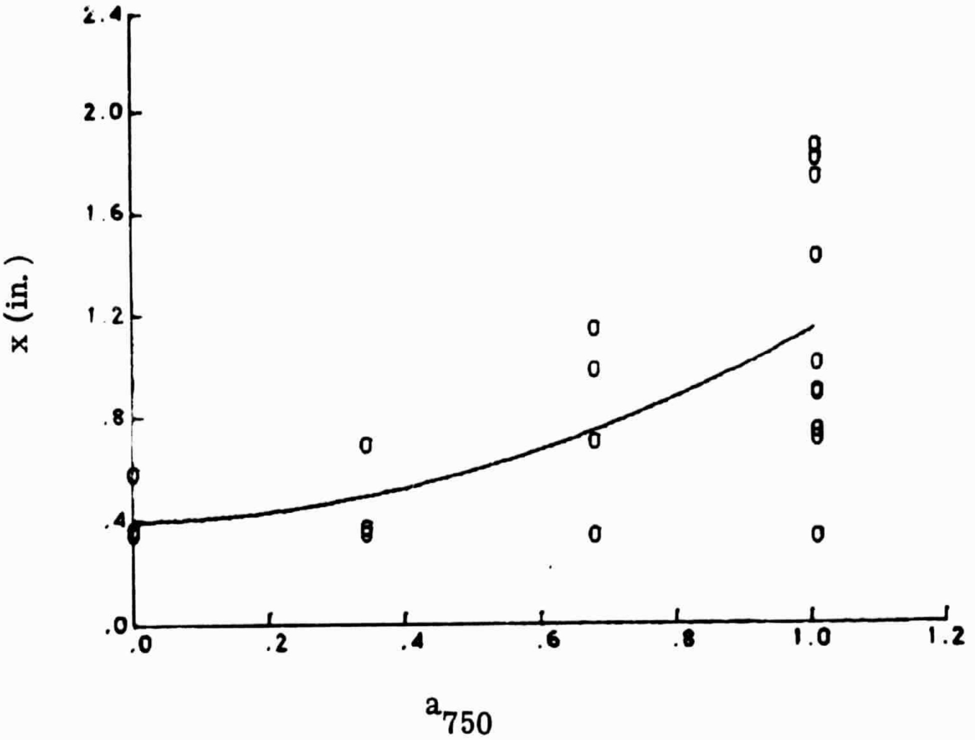


Figure 8. Maximum Overpressure vs. Equivalence Fraction of 750μ Diameter Drops; $\phi_T = .430$, $P_1 = 14.7$ psi.

POLYNOMIAL OF ORDER N= 2



POLYNOMIAL OF ORDER N= 2

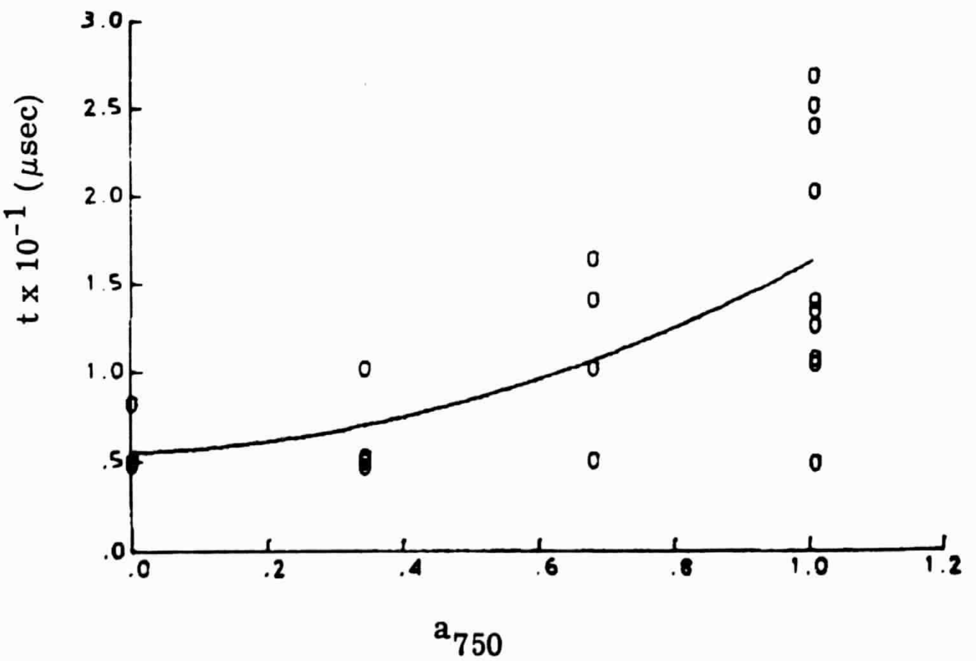
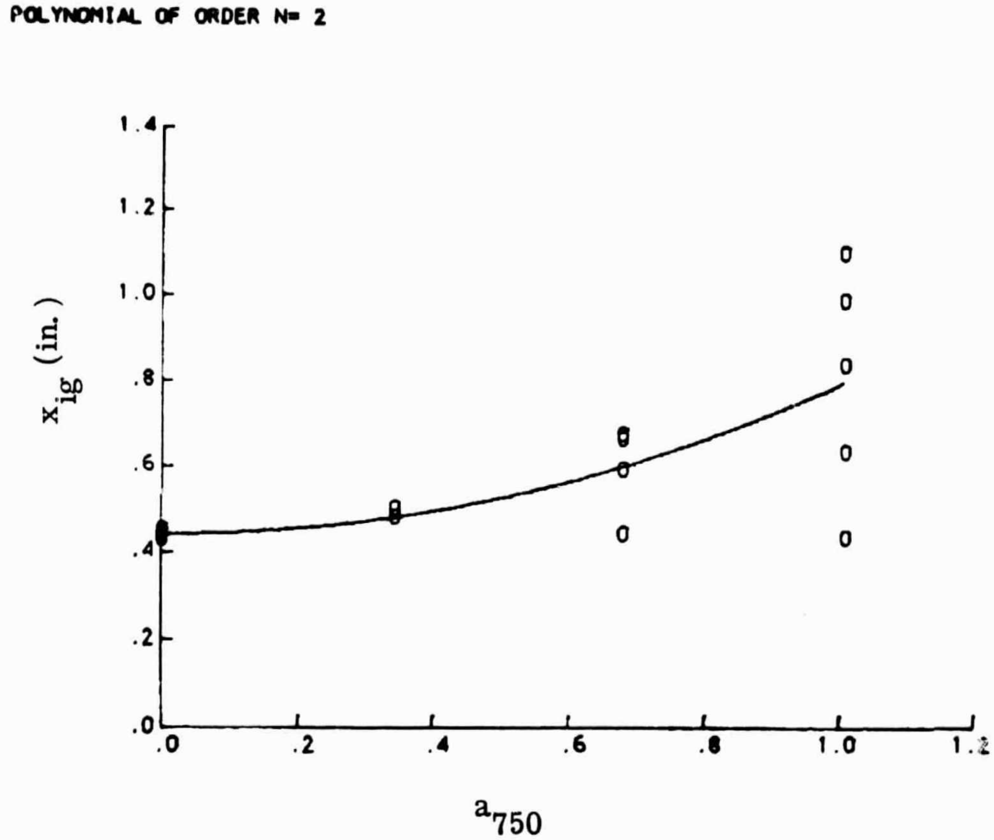


Figure 9. Position Behind Leading Shock and Time of Maximum Overpressure vs. Equivalence Fraction of 750μ Diameter Drops; ϕ_T = .430.



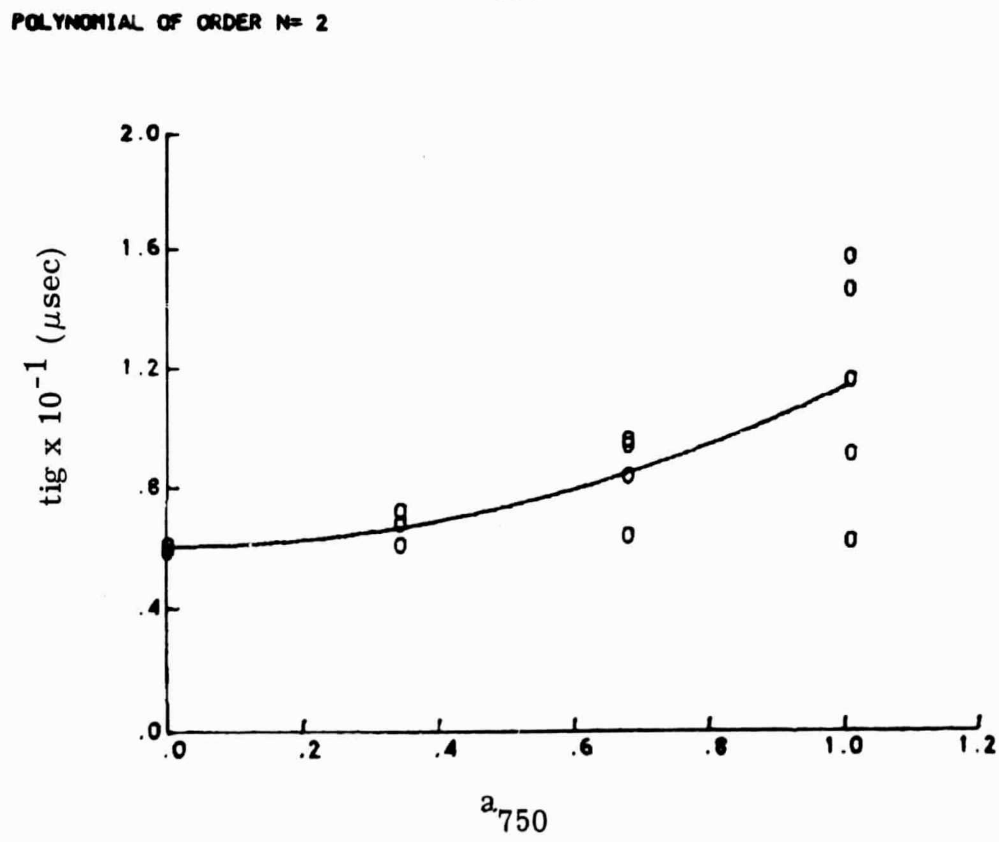


Figure 10. Position Behind Leading Shock and Time of Ignition vs. Equivalence Fraction of 750μ Diameter Drops; ϕ_T = . 430.

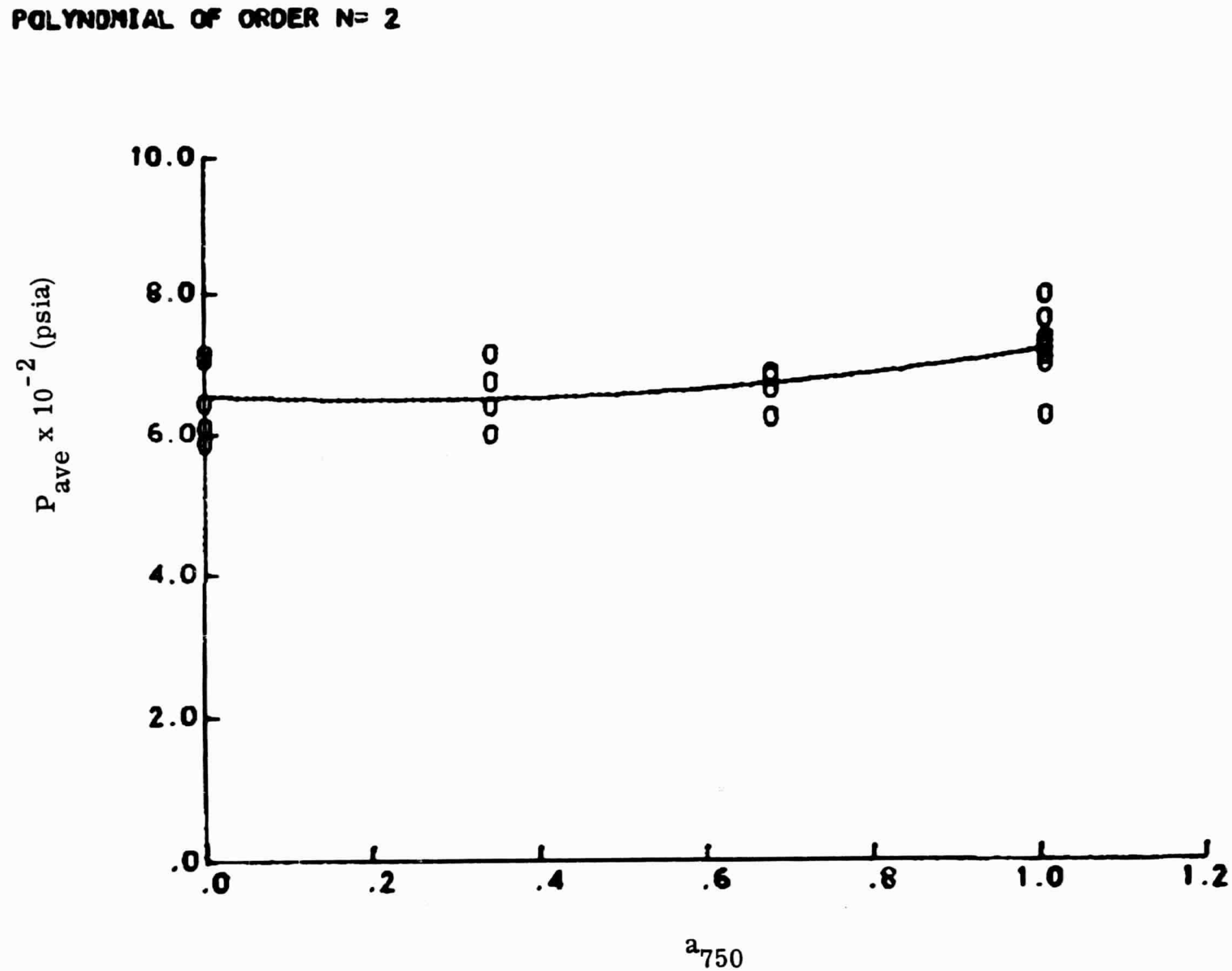


Figure 11. Average Pressure During Initial 3- μsec Period After Passage of Leading Shock as a Function of Equivalence Fraction of 750μ Diameter Drops; $\phi_T = .430$.

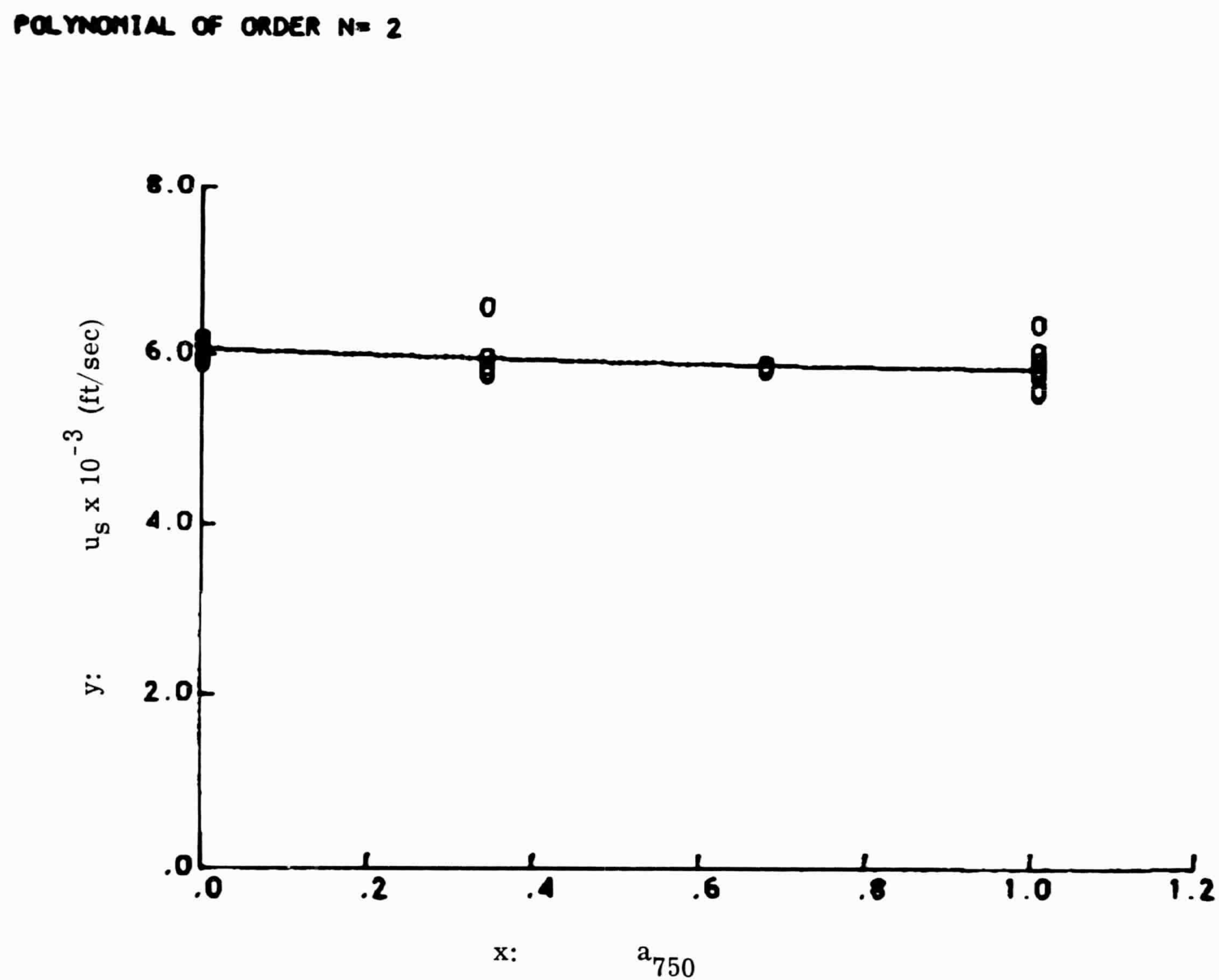


Figure 12. Velocity of Detonation vs. Equivalence Fraction of 750μ Diameter Drops; $\phi_T = .430$.

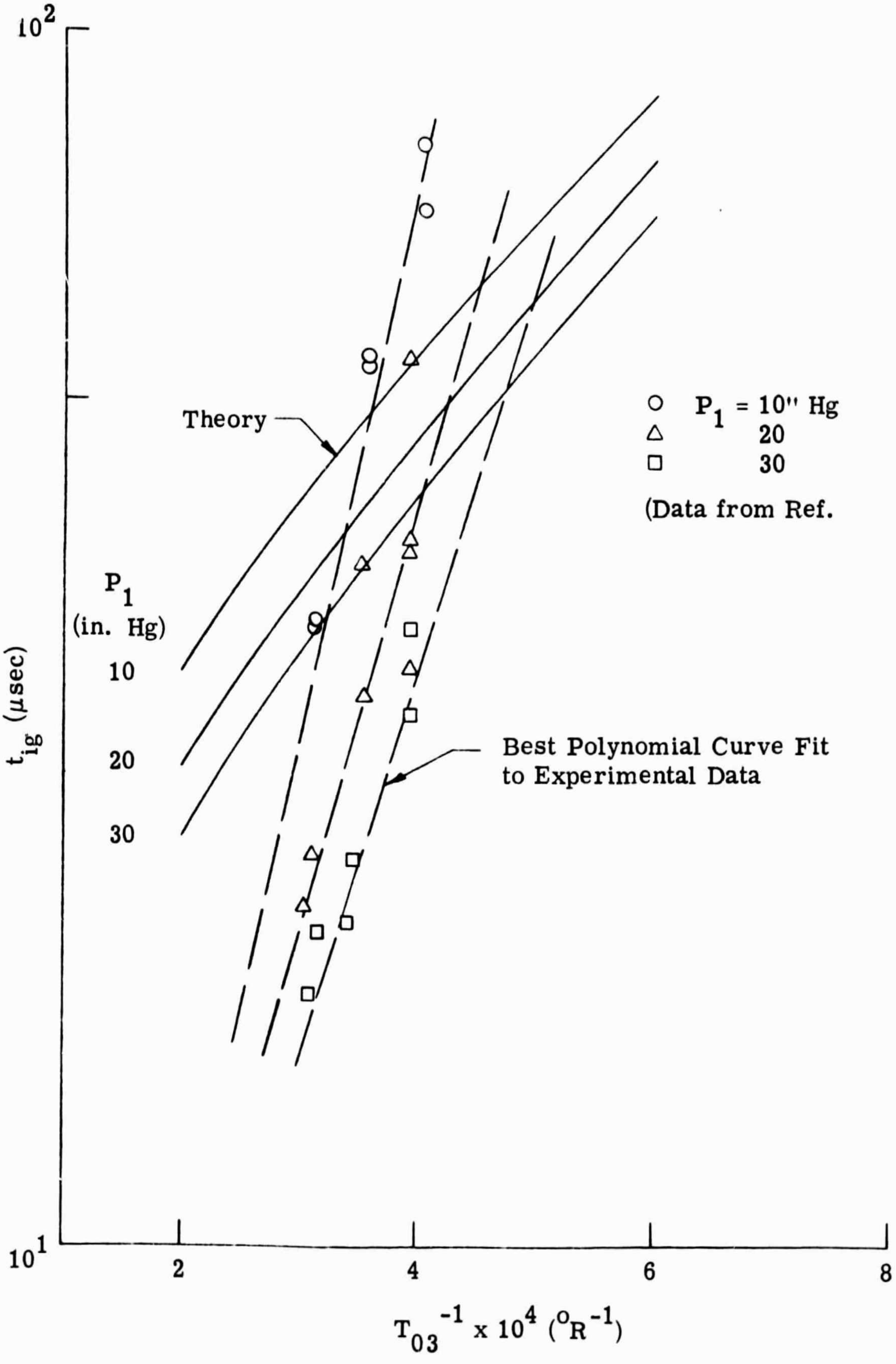


Figure 13. Comparison of Theoretical Ignition Delays with Experimental Data; $D_o = 930\mu$.

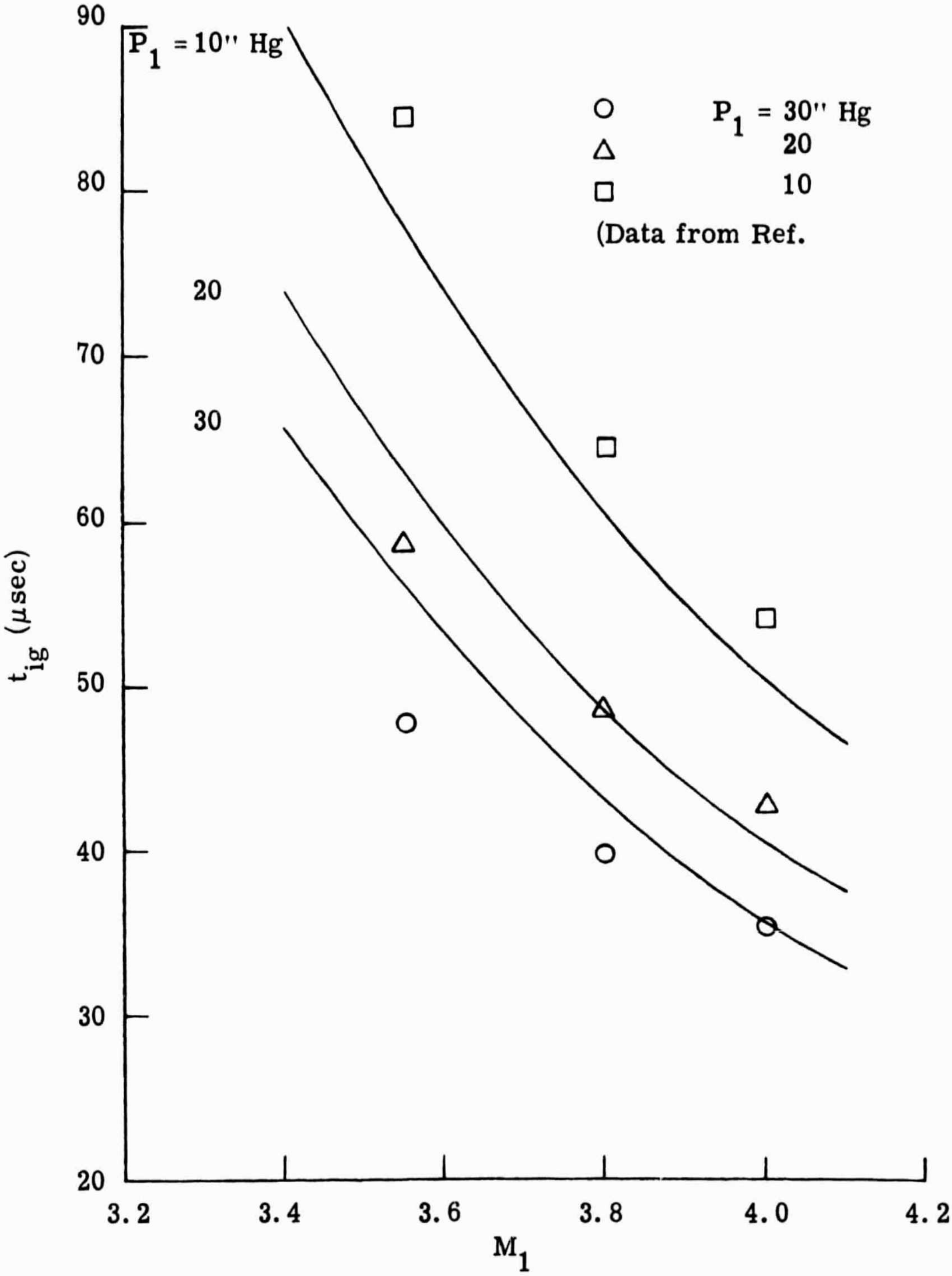


Figure 14. Ignition Time from Single Micromist Droplet Ignition Theory; $D_o = 2130\mu$, $q_{v_T} = 3240$ ft-lb/ft^3.

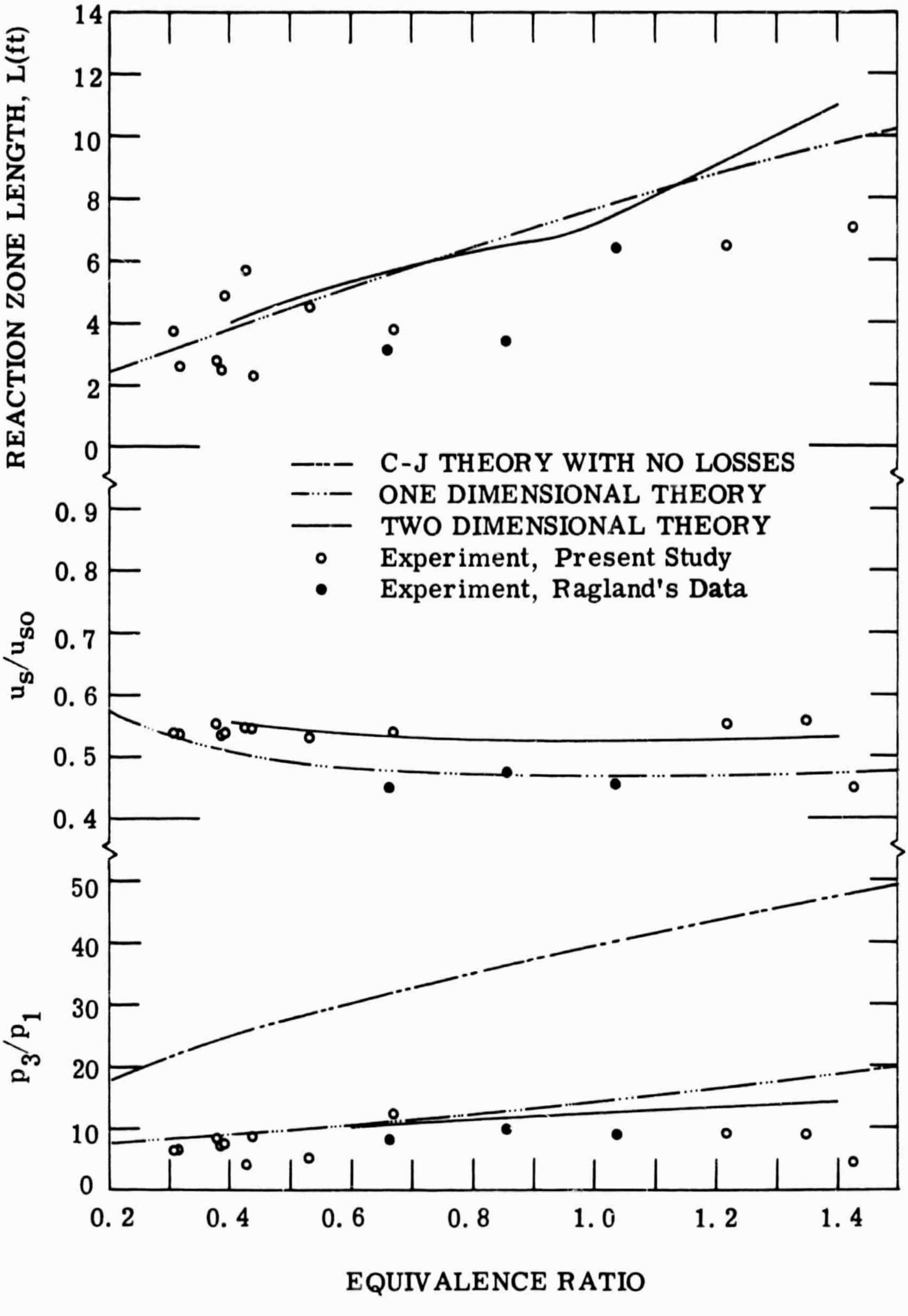


Figure 15. Propagation Characteristics of One Wall Film Detonations—Comparison of Experiment and Theories.

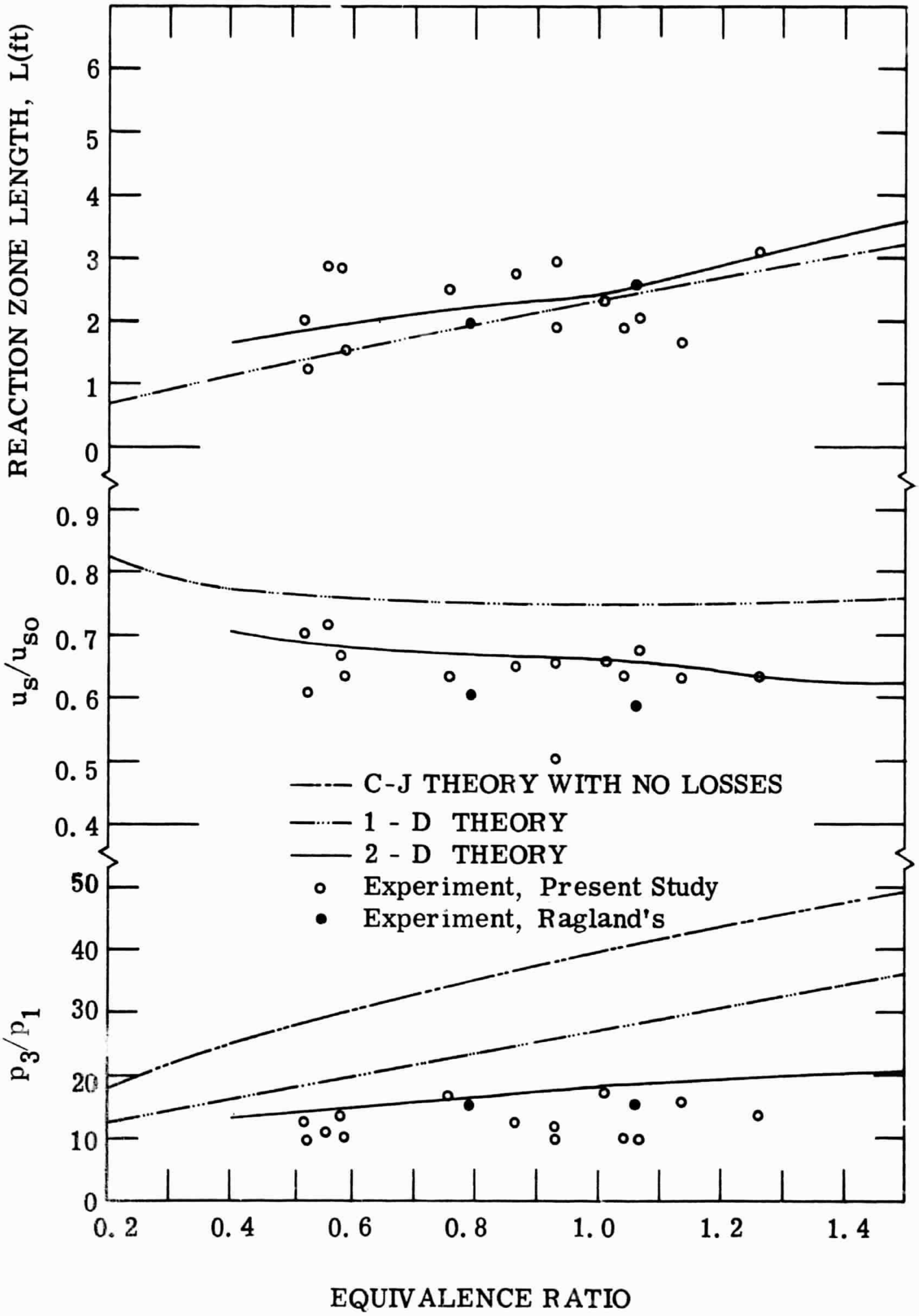


Figure 16. Propagation Characteristics of Two Wall Film Detonations—Comparison of Experiment and Theories.