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Two Phase Detonation as Related to Rocket Motor Combustion Instability

by

Professor J. A. Nicholls

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

February 1969

Contract NASr 54(07)

Technical Management
NASA Lewis Research Center
Cleveland, Ohio
Dr. R. J. Priem

Gas Dynamics Laboratories
Department of Aerospace Engineering
UNIVERSITY OF MICHIGAN
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FINAL REPORT

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FOREWORD

This report is the final report on NASA Contract NASr 54(07), which covered the period February 1, 1964 through January 31, 1969. This research was concerned with the role of two phase detonation in rocket motor combustion. 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 for the past year whereas Mr. Bruce Clark served in that capacity in the earlier years. The research is continuing under NASA Grant NGL 23-005-907.

Contributors to this report include:

C. W. Kauffman, Ph. D. Candidate—Section II. D
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Major participants in this research program who have left the university include Dr. E. K. Dabora, who was project leader and co-director for part of the time, and Doctors K. W. Ragland and A. A. Ranger, who did their doctoral dissertations on the project. The active participation of these people is gratefully acknowledged.

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TWO PHASE DETONATION AS RELATED TO ROCKET MOTOR COMBUSTION INSTABILITY

I. INTRODUCTION

The research covered by this contract was directed at an investigation of the possibility and pertinence of detonations in liquid-gas systems (two phase or heterogeneous detonation) typical of liquid rocket motor operation. It soon became clear that two phase detonations were easily generated and that the aerodynamic shattering of the liquid drops played an important role in the mechanism. Also, it was found that the presence of a liquid film on the walls, without any droplets, was capable of supporting a similar two phase detonation. Attention has also been given to the study of the ignition of single fuel droplets behind strong shock waves and the attenuation of shocks and two phase detonations by acoustic liners.

In the following section on Research Results the various subdivision efforts of the project are presented. The work on the distribution of energy release behind the shock is not discussed separately but is covered under Spray Detonations. It also awaits further definition and understanding of drop ignition characteristics. Where possible, the various aspects of the problem are covered by reference to our past publications. Only that information not previously reported is presented in any detail.

II. RESEARCH RESULTS

A. Spray Detonations

Our basic technique in the study of two phase detonation has been to produce a relatively homogeneous dispersion of uniform size drops in an oxygen atmosphere in a long vertical tube. The drops have been produced by a number of vibrating capillaries and then allowed to fall downward. Diethylcyclohexane fuel drops (very non-volatile) in the size range of 290μ-2700μ were used for the most part, although a few experiments were run with benzene (much more volatile) with essentially no observeable differences. Ignition was achieved by the shock wave from an auxiliary shock tube which fired into the main chamber just below the drop generator.

Detonation waves were easily generated for sufficiently rich mixtures. Velocities, pressures, and heat transfer rates were determined. Spark schlieren, streak schlieren, and streak self luminous photographs were taken. Theoretical studies were also conducted which treated the detonation wave as a Chapman-Jouguet wave with an extended reaction zone, so that heat transfer and frictional losses in the reaction zone were important. Agreement between experiment and prediction was quite good when the losses were taken into account and the reaction zone length was taken as the drop break-up time. Thus the velocity deficit is proportional to the drop diameter. Details of these studies are available in the several project reports and publications[1-10].

B. Shattering of Liquid Drops

The aerodynamic shattering, or breakup, of liquid drops is an important part of the two phase detonation process. If vaporization were the only mechanism, the reaction zone length would be so long as to preclude sustained detonation. Accordingly, a separate study was performed on the shattering problem. In view of the application to rocket problems, the studies were directed to high Weber number and Reynolds number conditions. A shock tube was used and the drops were water. Shocks of varying strength were passed over various size water drops in air so that a range of dynamic pressures, relative Mach numbers, Weber numbers, and Reynolds numbers were covered. The conditions were such that breakup via the stripping mode, as contrasted to the bag type, was always encountered. Image converter camera and streak photographs were taken. Acceleration histories, breakup times, and breakup distances were determined. These studies are reported in detail in the project reports and publications[1-4, 11, 12]. Briefly, it was found that the drops broke up after traversing a distance behind the shock equal to 25 drop diameters. Also, the non-dimensional breakup time, $\bar{T}_b = (\rho_2/\rho_\ell)^{1/2}\, U_2/D_o\, t_b$ (where ρ_2 = density of gas behind the shock, ρ_ℓ = density of liquid, U_2 = convective velocity behind shock, D_o = initial drop diameter, and t_b = breakup time) was found to depend only on M_2, the Mach number of the gas flow relative to the drop. $\bar{T}_b$ varied from 4.2 for low subsonic M_2, up to about 5.6 for $M_2 = 1$, and then decreased for $M_2 > 1$.

C. Liquid Film Detonations

It has been experimentally established that a self sustaining detonation wave can propagate in a tube containing oxidizer when the fuel exists in the form of a thin layer on the tube walls. The structure and mechanism of propagation of such a two phase detonation has been reported[5, 8, 13]. A comprehensive picture of a film detonation in shock fixed coordinates is sketched in Fig. 1. Immediately after passage of the initial shock front, the oxidizer is compressed, heated and set into motion. The boundary layer becomes turbulent soon after passage of the initial shock front so that, for all practical purposes, the boundary layer may be considered to be entirely turbulent. The mass addition to the boundary layer is due to vaporization and atomization but it is assumed that the rate of atomization is very small compared to the rate of vaporization in a turbulent boundary layer. Also, it is assumed that chemical reaction rates are very large compared to the rate of vaporization. These assumptions tacitly imply that the reaction zone ends as soon as the liquid layer is vaporized.

A quasi one dimensional formulation with mass addition, skin friction, and heat transfer within the reaction zone has been used[8, 9] and expressions for $U_s/(U_s)_o$, p_3/p_1, a_3/a_1, ρ_3/ρ_1, and T_3/T_1 have been given as functions of M_S, L, C_D, and C_H. U_s and $(U_s)_o$ represent the propagation speed of a detonation wave in a two phase mixture and in an all gaseous mixture respectively; p, a, ρ, T, M_S, L, C_D, and C_H represent static pressure, speed of sound, density, temperature, wave Mach number, reaction zone length, drag coefficient, and heat transfer coefficient, respectively. The subscripts 1 and 3 refer to conditions upstream of the shock and the Chapman-Jouguet plane, respectively. The values of M_S, L, C_D, and C_H for two phase detonations are not known. In order to predict M_S, and L, knowledge of C_D, C_H and q_w (the rate of heat transfer to the liquid) is necessary, but the transfer coefficients are functions of Mach number. Also these transfer coefficients must be treated separately for the cases of development of a boundary layer over a dry wall and over a wet wall. Now the transfer coefficients behind homogeneous gaseous detonations and the development of a turbulent boundary layer with mass addition and chemical reactions have been treated before[14, 15]. These techniques have been used to arrive at an approximate method for predicting the characteristics of liquid film detonations.

Since the shock induced turbulent boundary layer is complex, it was further assumed, in order to simplify the initial calculations, that the outer flow may be approximated by the conditions at the C-J plane, i. e., the conditions behind the detonation wave are used to estimate the boundary layer development.

In order to quickly evaluate the merit of the physical model indicated, it is assumed that the film detonation propagation speed is known from experiments. Using the simplified theory, reaction zone lengths are calculated. They are compared with earlier experimental results in Table 1.

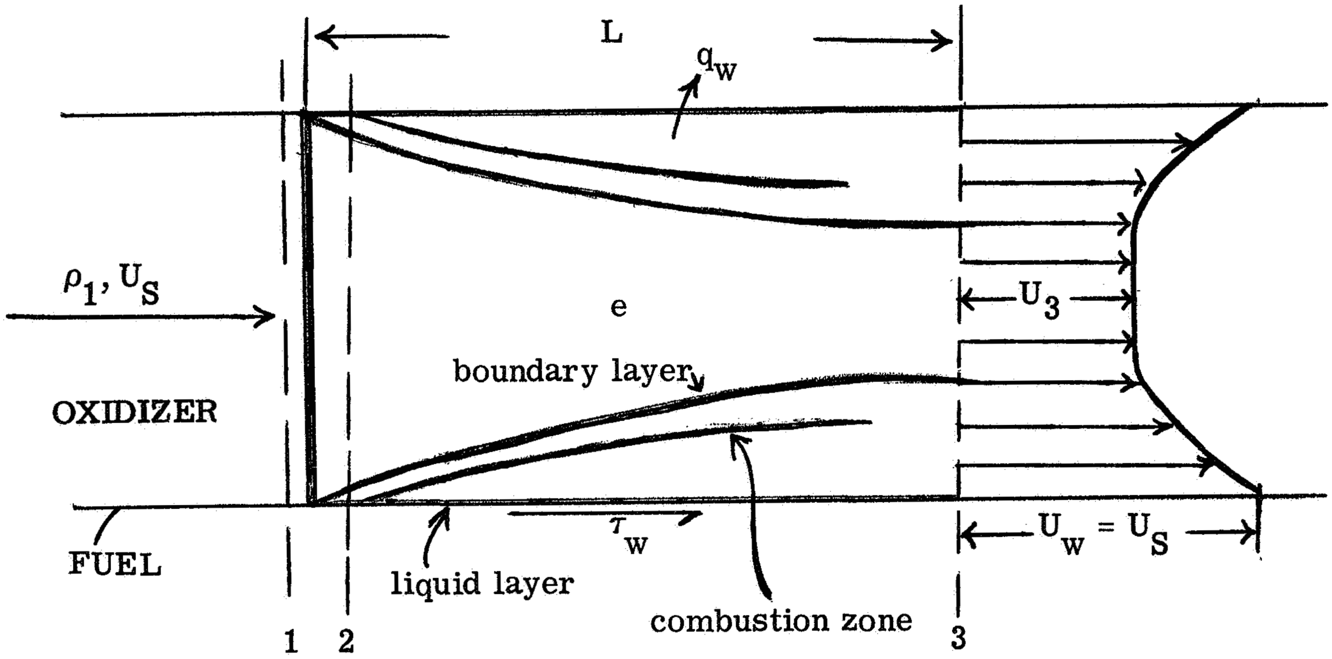


Figure 1. Detonation Wave in Shock Fixed Coordinates.

TABLE 1. Film Detonations—Experimental Results and Analysis (Chemical Reactions in Turbulent Boundary Layer)

Run No.	Description	M_s	Mass Ratio	Reaction Zone Length Measured L feet	Reaction Zone Length Computed L feet
362	Liquid on Two Walls	4.21	.31	2.57	2.325
379		4.05	.23	1.96	1.73
348	Liquid on One Wall	3.24	.301	4.77-5.44	5.02
361		2.95	.193	3.1	3.33
351		3.24	.25	3.4	4.06

TABLE 2. Run 379—Two Walls Wetted

Iteration	U_D	L	p_3/p_1
0	7215		
1	5110	1.94	22.3
2	5040	1.905	21.9
3	5050	1.965	21.9
Measured	4340	1.955	14.9

$\phi = .23$
Equivalence Ratio = .79
$\Delta H = 18,650$ Btu/lbm
Fuel - Diethylcyclohexane
Oxidizer - Oxygen

The reaction zone lengths are predicted to within an accuracy of 10-20%. This agreement is encouraging and so the physical model appears to be a reasonable approximation.

In the actual case, however, the propagation speed of a two phase detonation wave is not known a priori. For this case an iteration method has been used to compute this speed. To commence iteration, initial values for $(U_s)_o$, T_3/T_1, U_s/U_3, m_3/m_1, and γ_3 are assumed to be equal to that of a detonation wave in a homogeneous mixture with the same mixture ratio (γ_3 is the ratio of specific heats and m is the molecular weight). These values have been computed for the case with $C_D = 0 = C_H$[16]. Using the simplified theory, transfer coefficients and heat transfer rates are computed. Assuming that all the heat that is transferred to the liquid is utilized in vaporization and that the reaction zone ends soon after vaporization is completed, the length of the reaction zone and transfer coefficients, C_D and C_H can be computed. Now $U_s/(U_s)_o$ can be estimated using the expression developed in one dimensional theory since C_D, C_H, and L are known. Using the newly obtained values for U_s, C_D, C_H, and L, the ratios p_3/p_1, a_3/a_1, ρ_3/ρ_1 and T_3/T_1 are computed. The final results from the first iteration are used as initial values for the second iteration. The iteration scheme appears to converge and thus hopefully may be repeated until the required accuracy is obtained. The results of a sample calculation and experimentally observed values are compared in Table 2. After the third iteration, the propagation speed is predicted to within 17% and the predicted reaction zone length is very close to the experimentally observed value. The pressure ratio shows appreciably more discrepancy between theory and experiment.

With all the gross approximations, the analytical results appear to be in reasonably good agreement with experiments. So, it is now proposed to develop a more accurate layer theory to include the effect of incomplete combustion and the interaction between boundary layer and detonation wave. Also, it appears desirable to establish experimentally or analytically the relative importance of rates of vaporization and atomization. Some experiments are being planned to investigate the validity of certain major assumptions and to obtain more accurate data, particularly regarding the reaction zone lengths and pressure ratios.

D. Ignition of Fuel Droplets by Shock Waves

The two phase detonation studies indicated the need for establishing definitive criteria for the ignition of a fuel droplet by an incident shock wave in an oxidizing atmosphere. A study has been undertaken to establish under what specific conditions droplet ignition is possible, and to observe the details of the combustion process.

Before the droplet combustion studies could begin it was necessary to modify the apparatus used by Ranger in his studies of the aerodynamic shattering of water droplets. The modifications permitted the use of combustible fuel droplets instead of water droplets, the generation of higher Mach number shock waves, and the control of the composition of the atmosphere surrounding the fuel droplet.

In the experiments conducted to the present, it has been established that under certain conditions it is indeed possible to ignite a fuel droplet with an incident shock wave. In these experiments only one size of DECH fuel droplet has been used, 1580μ, but the incident shock strength has been varied between Mach 3 and Mach 4, and the surrounding atmosphere has been set at 10, 20, and 30 inches mercury of oxygen or nitrogen. The latter, of course, will not support combustion, but it has been used to observe the dynamics of the shattering of non-burning DECH droplets. It has been found that for this size droplet an incident shock having a Mach number of 3.5, or higher, propagating into oxygen leads to reliable ignition for any of the initial pressure levels used.

Perhaps the most interesing result of the study thus far is that combustion is not initiated at the stagnation point of the droplet. The appearance of combustion is first noted in the wake of the fuel droplet. It apparently originates in the micro-mist which is removed from the equator of the droplet during the shattering process. This flame which first appears at some period of time after the shock wave interacts with the droplet—ignition delay time—then propagates upstream to the stagnation point of the droplet and downstream to a point where there is presumably no longer a combustible fuel micro-mist/oxidizer mixture. This combustion process is clearly shown in the two attached streak schlieren photographs which illustrate the combustion of a 1580μ droplet in a 20 inch mercury oxygen atmosphere when struck with a Mach 4.0 shock wave. Run 125 (Fig. 2) shows strictly the aerodynamic shattering of a DECH droplet in a nitrogen atmosphere, while Run 143 (Fig. 3) shows the auto-ignition of the fuel droplet after an ignition delay period. The details of the flame propagation have been calculated for the case where the incident shock is M = 4.0 and the pressure of oxygen is 10 inches of mercury. These calculations show that at the initiation of combustion the flame is propagating at a velocity of 5200 ft/sec and that it slows to 2200 ft/sec as it nears the stagnation region. If the wake temperature is taken to be approximately the stagnation temperature, this yields a speed of sound in the wake of 2600 ft/sec. Hence, it would appear that the wake combustion is of the detonative type. An examination of the photograph of Run 143 shows that there is a wave which originates in the wake, and that it interacts strongly with the bow shock wave substantially modifying its behavior.

It now seems desirable to systematically delineate the effects of droplet sizes, surrounding atmosphere, and the strength of the incident shock wave on the mechanisms of flame initiation and propagation.

E. Acoustic Liner Studies

Acoustic absorbing liners have been used with some success in the prevention of sustained pressure oscillations in liquid propellant rocket engines. These offer a means of obtaining stable operation while retaining other components that provide optimum system performance. Turbojet experience

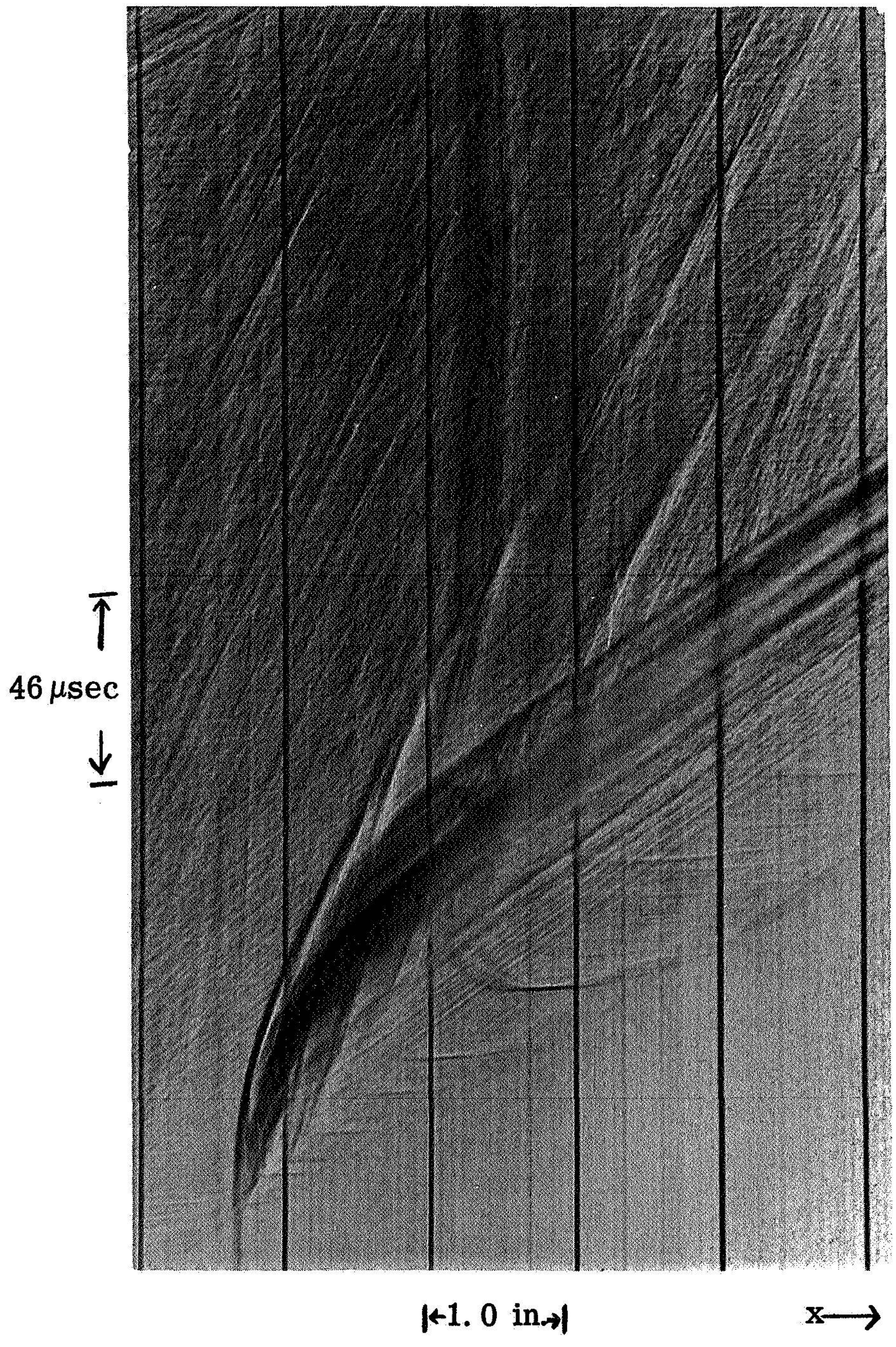


Figure 2. Shock Passing over a DECH Drop in N_2. Run No. 125, $d = 1580\,\mu$, $M_1 = 3.95$, $p_1 = 20$ in. N_2, $w_1 = 4230$ ft/sec, $M_2 = 1.549$, $w_2 = 3520$ ft/sec.

Figure 3. Shock Passing over a DECH Drop in O_2. Run No. 143, $d = 1580\,\mu$, $M_1 = 4.05$, $p_1 = 20$ in. O_2, $w_1 = 4370$ ft/sec, $M_2 = 1.562$, $w_2 = 3390$ ft/sec

and experimental investigations have demonstrated that pressure oscillations can be suppressed by lining the combustion chamber with a perforated liner to absorb the kinetic energy of the oscillations, even though the mechanisms causing the suppression in a practical application are not completely understood. The extensive experimental work done using these acoustic liners have brought to light many basic guide lines in their selection and design.

The steep fronted, high amplitude waves that have been observed in liquid propellant rocket motors are detonation-like in character. The close coupling of the pressure front to the mass and energy release, which is implicit with detonation processes, may require different approaches to solutions for wave attenuation than would be required for classical resonance effects. Detonation waves in sprays are both developed and maintained by pressure pulses caused by droplet-convective flow interactions. Conceding that a fully developed wave is very hard to damp out, experiments on the effect of the liner in the induction zone may throw light on the detailed mechanism of attenuation of detonation waves. Given a method of attenuating a pressure pulse and thus delaying the buildup of the detonation wave, one should be able to greatly increase the distance required to form a detonation wave, if not fully damp it out. Such a method of attenuation is offered by the acoustic liner.

An experimental study of shock wave-acoustic liner and detonation wave-acoustic liner interactions has been initiated. The methods of drop generation and ignition developed for our previous experiments will be used to control the drop diameter and mixture ratio at a test section made with two-dimensional acoustic liner walls. The existing detonation tube has been modified to allow fully developed or developing detonation waves or plane shock waves to enter the test section under controlled conditions. This allows the wave speed to be measured as a function of initial wave speed as well as drop size, mixture ratio, and cavity size. Pressure histories can be recorded both along the test section centerline and inside the cavities and the wave velocity can be measured by positioning pressure switches along the length of the detonation tube. Streak and spark photographs can be taken to record the velocity variation with distance and to show the wave structure. The flow pattern near and within the acoustic cavities can also be observed.

The type of liner presently being tested consists of cylindrical cavities connected to the detonation tube by rectangular slits acting as the neck of the cavities, a portion of such a test section is shown in Fig. 4. For this particular section, the diameter of the holes is 1/2 inch and the total length would be 18 inches. Upstream and downstream of the test section the inside tube dimensions are 1 5/8 by 1 5/8 inches (nominal), which makes these sections flush with the inside of the liner section. Various sizes and spacing of cavities can be accommodated in the liner section. The design of additional test sections will be guided by the present experiments. Porous sintered metals are also being considered as candidates for liner construction material.

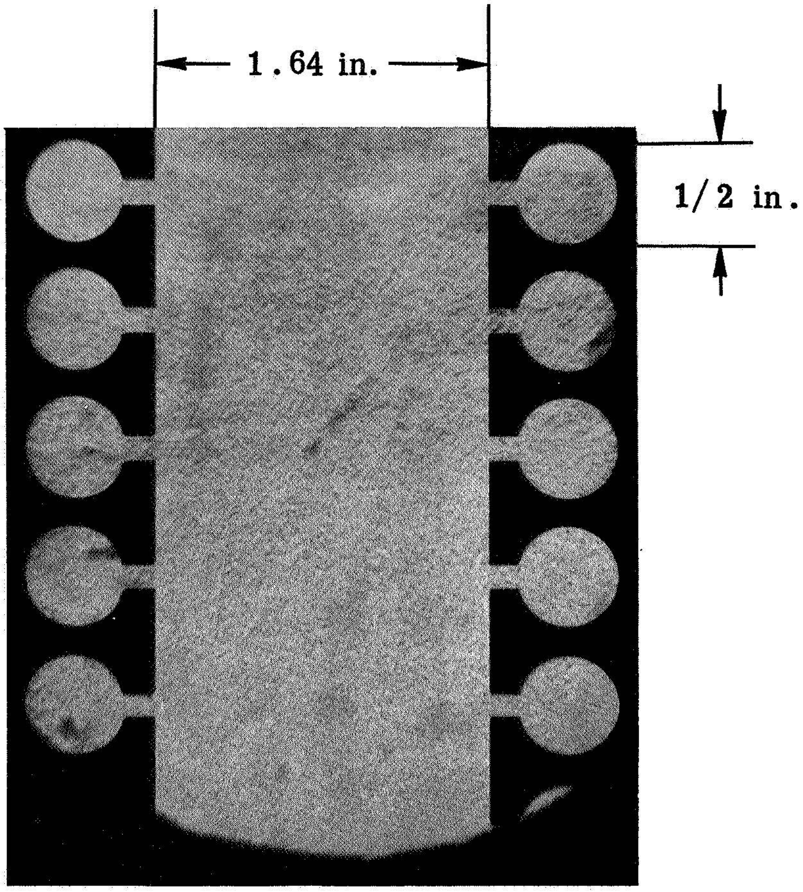


Figure 4. Test Section: 1/2 in. Cavities

Reproducible experiments have been made on the attenuation of plane shock waves (Mach 1.4 and Mach 2.7) in the acoustic liner test section using solid walls, 1/2 inch cavities, 1 inch cavities, and a step expansion area ratio of 2.72 to 1, length 12 7/8 inches. The velocity profiles for these four cases are shown in Fig. 5. The location of the test section is indicated on the abscissa. For the case of solid walls, the usual gradual shock decay is observed (except for an unexplained short increase in the test section), while for the 1/2 inch cavity liner the apparent decrease in velocity in the test section is slightly more than that for the 1 inch cavities. As would be expected, in the open expansion case there is a large initial drop in velocity inside the test section, however, the velocity increases before the wave leaves the test section. In the test section, the velocity decreases by 150-300 fps, but at a station 3 ft below the test section, the velocity has returned to within 8 fps of its initial value for all cases.

Optical observations of the flow pattern in the liner section have begun. Initial work on 1/2 inch cavity liners has indicated some interesting features regarding the interaction of an initially plane shock wave with the cavities. Typical spark shadowgraph and spark schlieren photographs are presented in Fig. 6($M \sim 1.4$, air).

As the main shock passes over a cavity entrance, first an expansion and then a shock wave is formed. These waves move out into the center of the tube and interact with the main shock as well as the waves coming from the

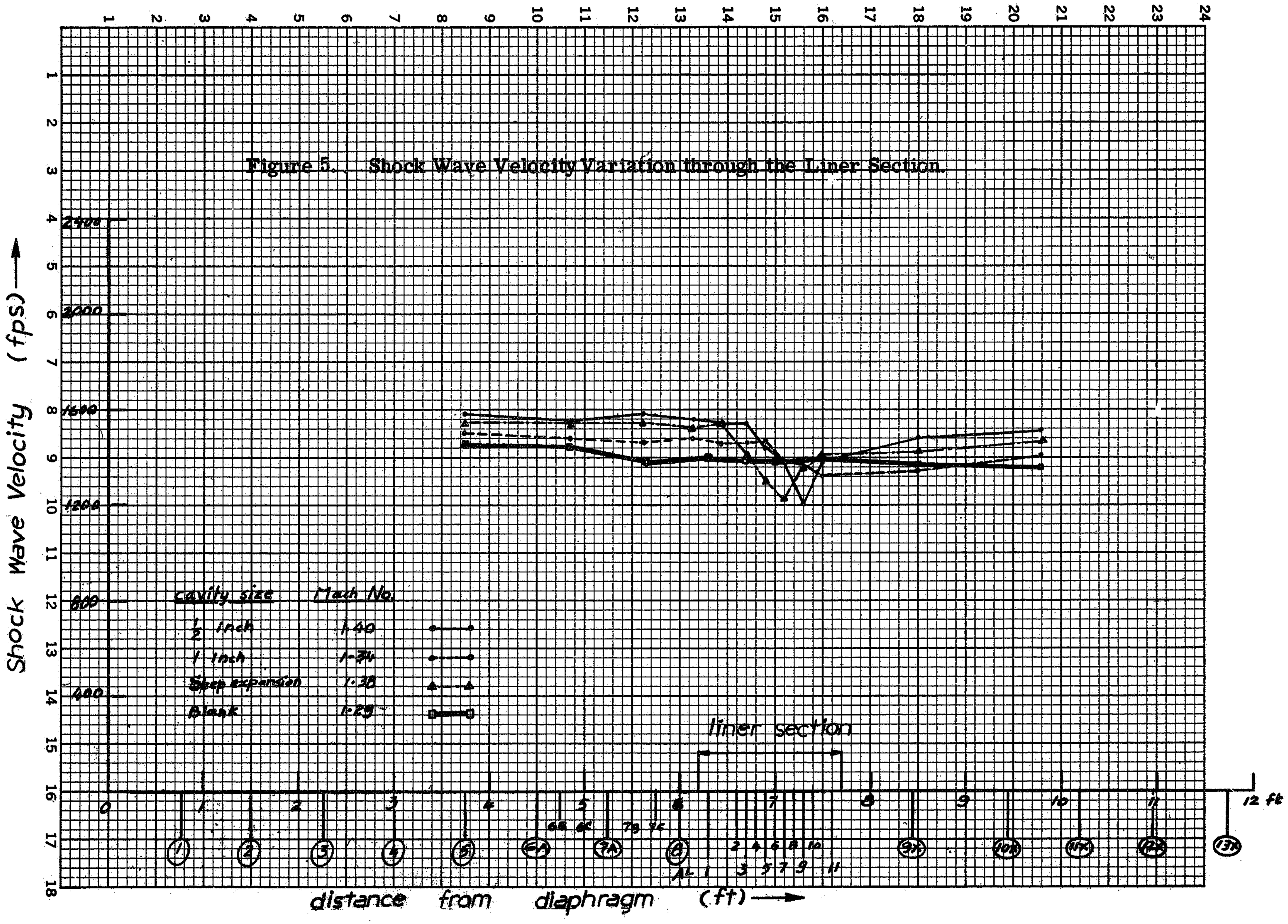
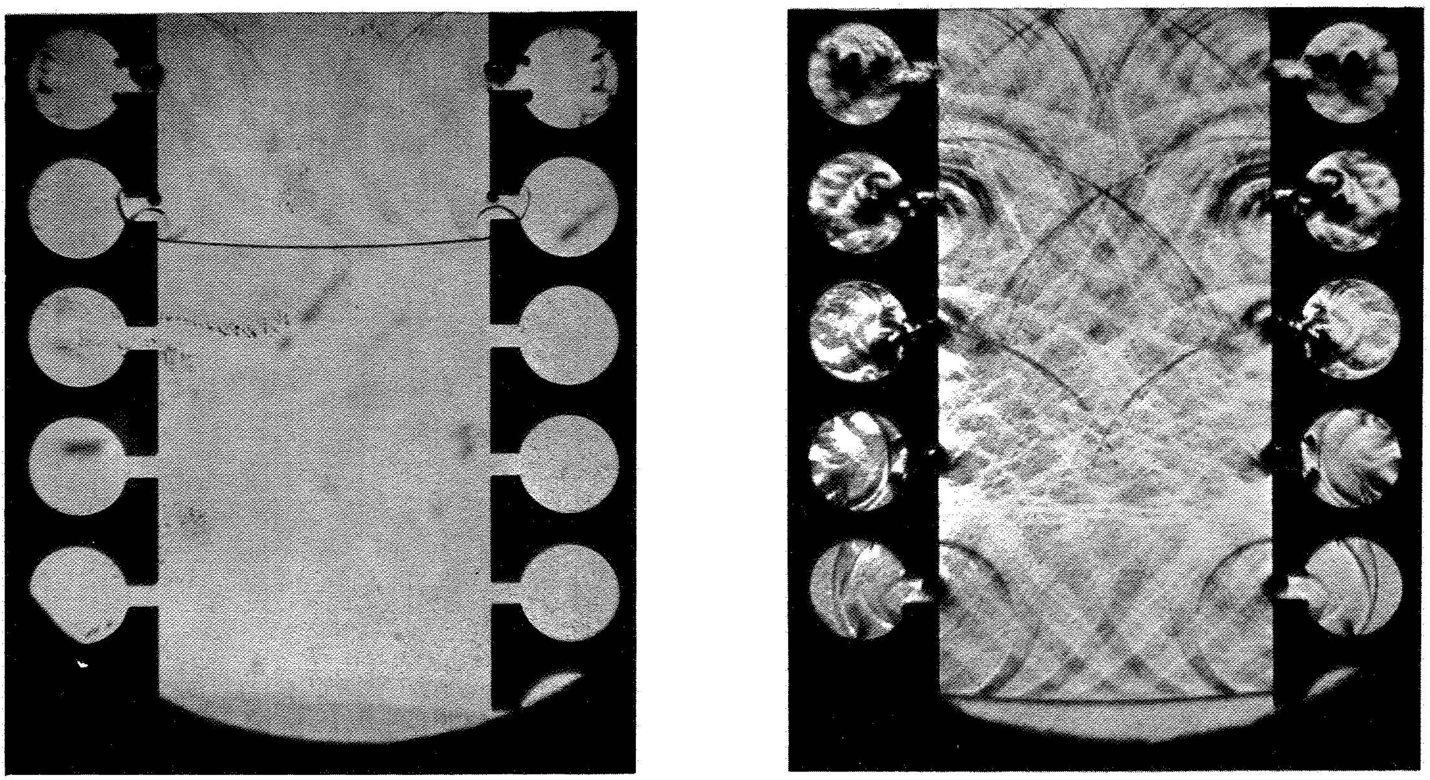


Figure 5. Shock Wave Velocity Variation through the Liner Section.



(a)

Shadowgraph showing the vortices and the formation of expansion and shock waves at the mouth of the cavities.

(b)

Spark-Schlieren photograph showing the wave interaction in the tube and the flow into the cavities.

Figure 6. Shock Wave Interaction with 1/2 in. Cavities (Mach No. ~ 1.4)

opposite wall, resulting in symmetric wave patterns. Because the waves from adjacent cavities interact, the distance between cavities has a quantizing effect on the attenuation mechanism. These wave interactions result in a net increase of entropy and the corresponding decrease in the available energy causes the main shock wave to slow down.

Energy is fed from the main shock wave laterally into the cavities and this also causes the main shock wave to slow down. As mass flows into the cavities three distinct vortices are formed and viscous effects cause these vortices to dissipate. The shock waves moving in also create a turbulent flow in the cavity and the increase in entropy reduces the available energy. Under certain conditions back flow from the cavities to the detonation tube can be expected.

Additional tests are needed to confirm the above description but if confirmed, it may be possible to qualitatively estimate the effect of the geometrical parameters of the cavities on the attenuation of the wave. Any such model of the events, combined with data obtained from streak photographs, will help in making engineering estimates for other configurations.

III. SUMMARY

Two phase spray detonations and liquid film detonations have been found easy to generate in the laboratory. Determination of propagation rates, pressures, heat transfer rates, and general structure have been made. The significance of aerodynamic shattering of the drops has been studied and discussed. These studies led to the adviseability of further investigation of: 1) the unsteady ignition and burning processes that can lead to very high local pressures; 2) a better understanding of the film detonation with turbulent boundary layers; and 3) the use of acoustic liners to attenuate shock or detonation-like processes. Some of the initial work on these latter phases has been discussed in the foregoing section but the work will continue under NASA Grant No. NGR 23-005-907.

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