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## TECHNICAL REPORT NO. 724

# IGNITION AND COMBUSTION OF LIQUID HYDROCARBON FUELS IN SUPERSONIC FLOW

Simon Slutsky
Forman Williams
Jose Tamagno

June 1969

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# ABSTRACT

An experimental study was carried out to investigate the combustion of a liquid hydrocarbon (hexane) injected into a supersonic stream. Injection modes included wall and central injection configurations. Extremely rapid and intense heat release phenomena were obtained. It was concluded that this mode of combustion could be made to compete with that of pure gas phase combustion for many technological applications.

A preliminary theoretical model of the combustion mechanism was constructed which accounts for many of the observed phenomena, and which explains the very rapid combustion characteristics.

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# PART I

By Simon Slutsky and
Jose Tamagno

## I. INTRODUCTION

The principal effort of this research to date has gone into the study of techniques for understanding, predicting, and then controlling the processes of gas phase combustion for a supersonic or high subsonic flow. In the course of such studies it was observed how crucial the various gas transport processes are in the analysis of the combustion mechanism. Thus it was concluded that the rate coefficients of the various elementary gas phase reactions were coupled with the generally turbulent diffusion, heat conduction and viscosity characteristics of the flow, and that together, they determined whether or not the mixture would react chemically, and the distances characterizing ignition and complete combustion.

It is the purpose of the present study to extend the philosophy of the previous efforts to the combustion processes characterizing high speed liquid fuel-air systems and ultimately to more general multiphase fuel oxidizer systems (e.g., slurries, gels, etc.).

Such combustion processes could be of considerable significance in many advanced hypersonic airbreathing vehicle applications, especially where the structural cooling function of the liquid fuel is not essential for mission feasibility and the system is volume limited. The advantages of compact lightweight, low pressure fuel storage facilities, unemcumbered by heat exchanger or vaporizer weight penalties makes the subject of direct liquid fuel injection for high performance systems one of great interest at flight Mach numbers between 3 and 8 and at altitudes between 60,000 and 150,000 feet.

Such a study must involve the formulation of analytical models to describe the interaction between the liquid fuel droplets and the surrounding supersonic airstream. The analytical representation of the turbulent mixing and finite rate combustion in high speed flows is, for the homogeneous gas phase case, quite far advanced (Reference 1). Substantial progress has been made as well in the analytical description of the turbulent mixing and combustion of gas flows containing cryogenic evaporating liquid components (Reference 2). The analytical goal of the present study is to extend this work by adapting the previous experience to the two-phase (gas-liquid) system of interest. This involves the extension and adaptation of existing mixing and combustion analyses to the case of liquid fuel injection, and the incorporation of generalized models of droplet diffusion and combustion. A second task of the study is to investigate experimentally the combustion process associated with liquid fuel injection into a supersonic airstream.

## II. EXPERIMENTAL PROGRAM

The first phase of the experimental program was a preliminary attempt to investigate the feasibility of achieving combustion of a cold liquid fuel injected into a supersonic stream. In particular, we started with an experimental configuration, Figure 1, in which liquid hexane was injected normally from the wall into a square test section. The fuel flow distribution was made uniform across the duct, insofar as possible, so that instruments and photographs could be interpreted two-dimensionally.

Figure 1 is a cross-section of the test section including the viewing windows and the wall injectors, and Figure 2 is a schematic longitudinal section showing the Mach 2 nozzle, the test section, and an extension section in which pressure taps were installed at one inch spacing.

Combustion was achieved in this apparatus, with remarkably little difficulty. In fact, the heat release was so rapid, and local temperatures so high that the main problem was the

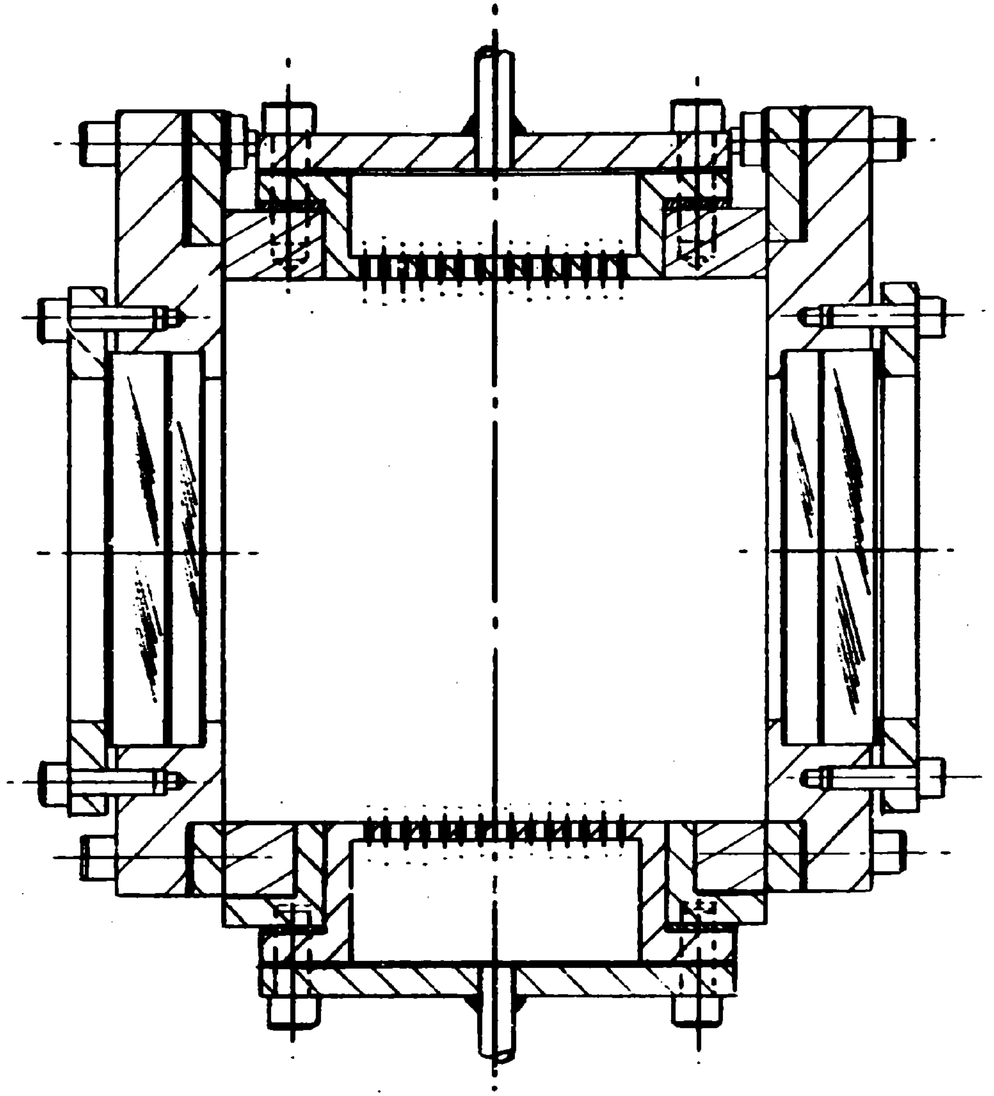


FIGURE 1 - SUPERSONIC COMBUSTION OF LIQUID HEXANE - FLUSH MOUNTED WALL INJECTOR

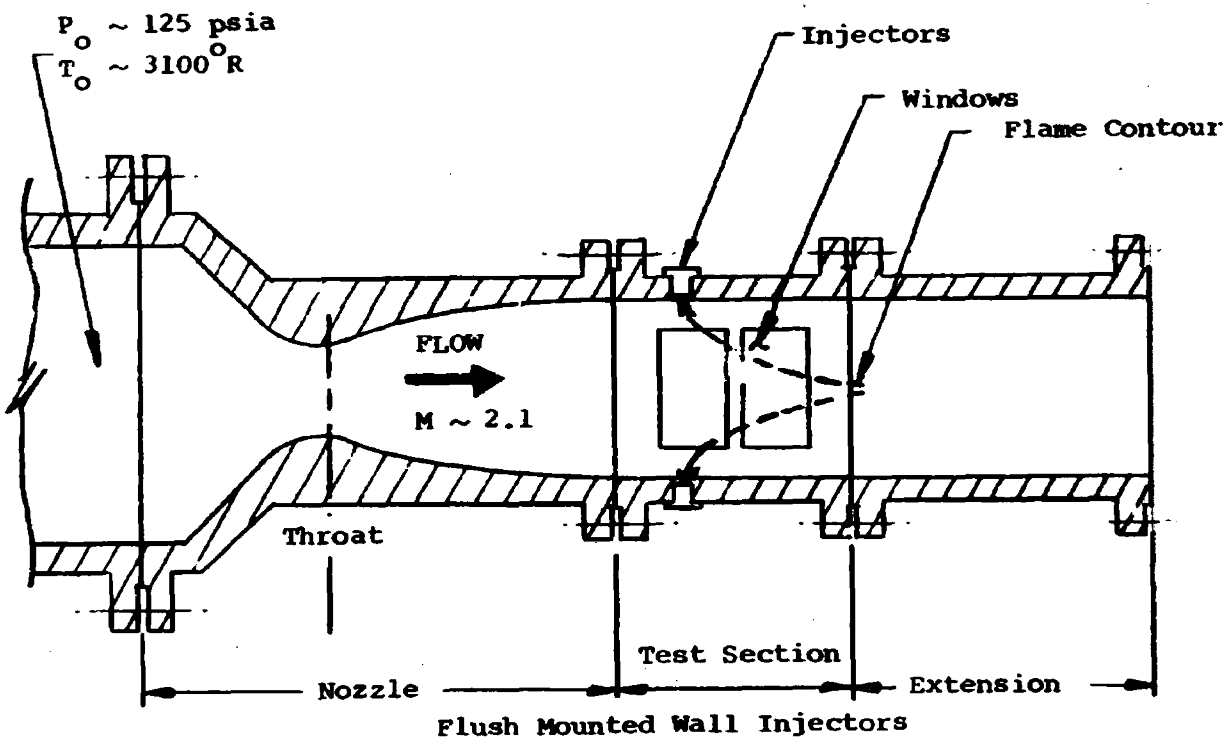


FIGURE 2 - SUPERSONIC COMBUSTION OF LIQUID INJECTED FUEL SCHEMATIC OF EXPERIMENTAL APPARATUS

burnout of midstream instrumentation. This loss of instrumentation occurred twice, so that the decision was made to delay this type of measurement.

Figure 3 is a photograph of a flame resulting from a very low rate of fuel mass flow injected along one wall, corresponding to 4 percent ($\phi = .04$) of the stoichiometric fuel air ratio. Figure 4, by contrast, is an example of very intense combustion in a configuration with high rates of fuel flow ($\phi = .442$) injected along both walls. Figure 5 shows the pressure distribution measured along one wall. The lowest curve was made without any fuel injection, whereas the middle and upper curve are for equivalence ratios of .183 and .211 respectively. One-dimensional calculations of fuel air mixtures corresponding to these conditions show that Test 26 would not choke, but that Test 25 should. It is,therefore,very interesting to note that in Test 25 there seems to be only a small amount of upstream influence of fuel injection and combustion on the wall pressure distribution (as expected), whereas the pressure distribution of Test 25 shows that a large upstream region is affected. The one-dimensional flow calculation for Test 26 conditions also indicate an equilibrium $p/p_{t_\infty}$ which, when corrected by adding the no burning (Test 23) rise of about 0.04, caused by boundary layer growth

$P_o$ = 115 psia

$T_o$ = 3200°R

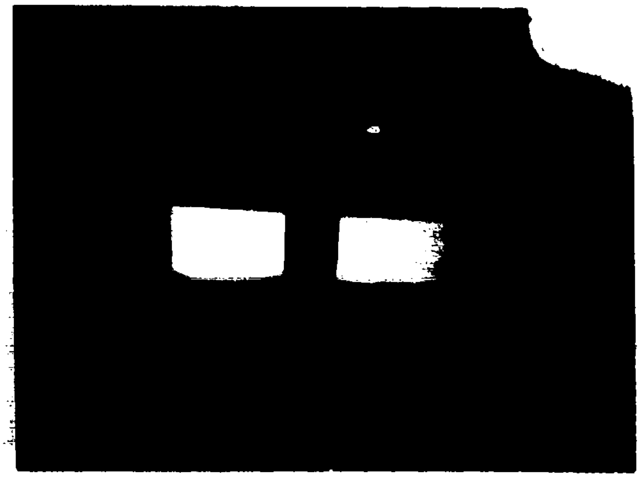
Injector: Flush mounted to bottom wall

Fuel Mass Flow: .03 lb/sec

$\varphi$ = .040

Air Mach Number: 2.0

FIGURE 3 - SUPERSONIC COMBUSTION OF LIQUID INJECTED HEXANE



$P_o$ = 128 psia

$T_o$ = 3000°R

Fuel Mass Flow: .386 lb/sec

$\varphi$ = .442

Air Mach Number: 2.0

FIGURE 4 - SUPERSONIC COMBUSTION OF LIQUID INJECTED HEXANE

| TEST 23 | TEST 25 | TEST 26 |
|---|---|---|
| Air Total Pressure: 125 psia | Air Total Pressure: 123 psia | Air Total Pressure: 125 psia |
| Air Total Temperature: 3000°R | Air Total Temperature: 3100°R | Air Total Temperature: 3120°R |
| Air Mach Number: 2.12 | Air Mach Number: 2.15 | Air Mach Number: 2.13 |
|  | Fuel Mass Flow: .175 lb/sec | Fuel Mass Flow: .154 lb/sec |
|  | Equivalence Ratio: .211 | Equivalence Ratio: .183 |

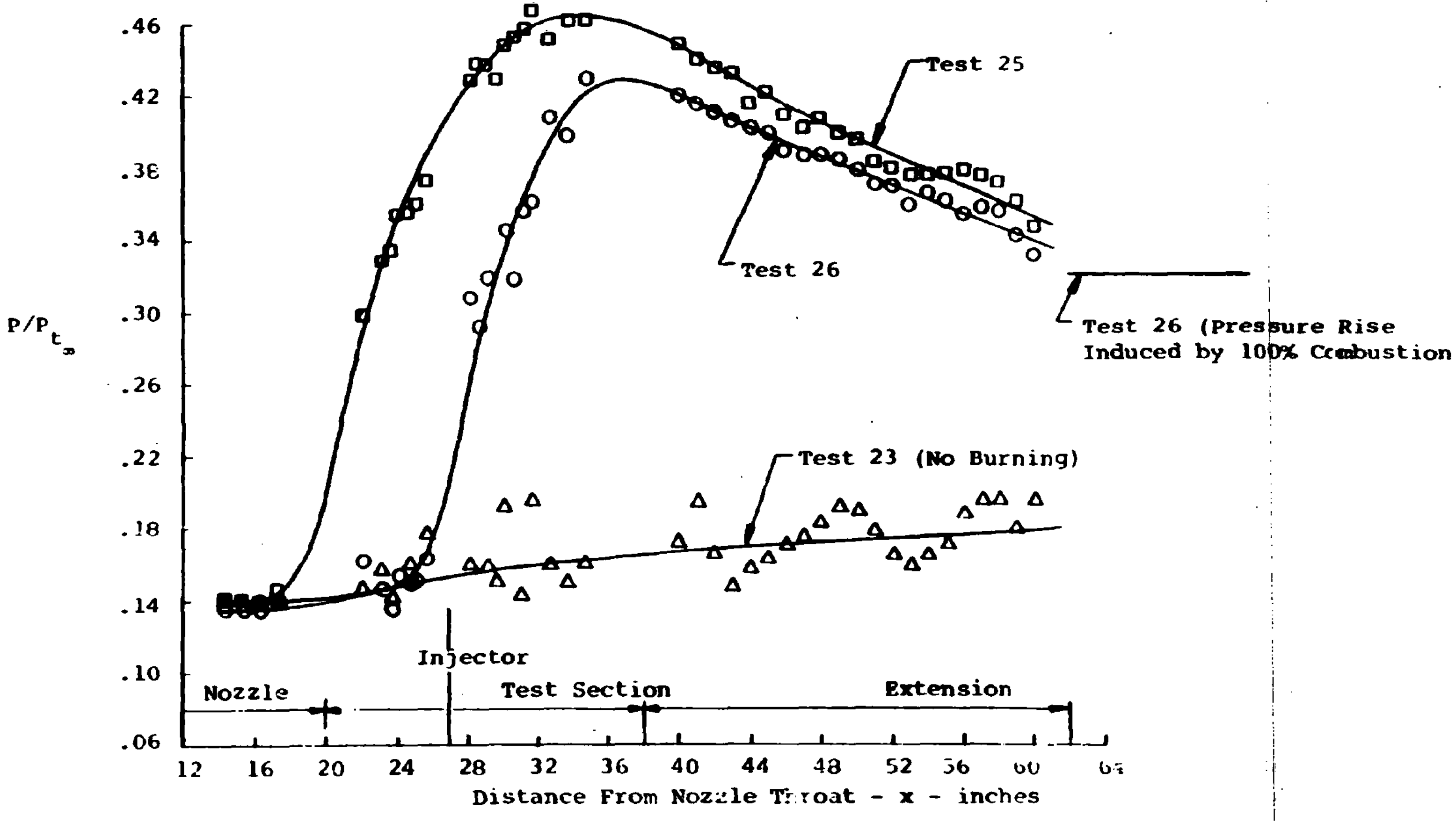


FIGURE - PRESSURE RISE INDUCED BY COMBUSTION OF LIQUID HEXANE to station 60", results in a theoretical pressure corresponding to 100% combustion. This theoretical value of $p/p_{t_\infty} = .32$ is remarkably close to that being approached by the distribution of Test 26.

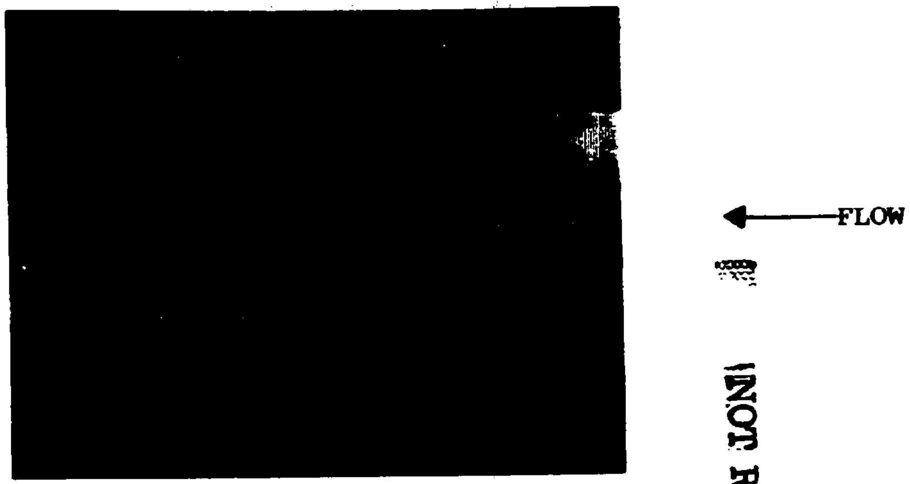
The large pressure rise from station 26 (inches) to about 38 for Test 26 suggests a strong pressure interaction mechanism between the region of intense heat release and the surrounding main air flow. This conception is discussed below in connection with the central injection system. The wall pressure rise is thus seen to be quite rapid, but so smooth that the occurrence of extensive strong shock structures can be considered unlikely.

Tests were then carried out with this configuration to determine the effect of air temperature on ignition characteristics. Combustion was obtained with values of total temperature as low as 2700°R. However, when the total temperature was further decreased to 2500°R, no flame generation was observed. Instead, a photograph (Figure 6 ) of the fuel injection region showed an initial region of luminosity which had a sharp front at the line of injection and which faded rapidly as the flow moved downstream, and disappeared in a distance of about 1-1/2 inches. It is believed that this photograph represents flame ignition and quenching and will be discussed below.

In the next phase of this exploratory sequence, a test series was carried out with a midstream injector. Longitudinal and cross-sectional views of this configuration are shown in Figures 7 and 8. A piloted midstream injector was also designed for low temperature operation (Figure 9), but use was postponed until later.

Very rapid combustion was achieved in the system with air total temperature in the neighborhood of 3000°R. In fact, heat transfer rates in the neighborhood of the injector were so great that several injector rigs were burnt out, and configurations with cooling ultimately had to be built and installed. A typical photograph of the system is shown in Figures 10a and 10b.

Several resulting wall pressure distributions are shown in Figure 11. A no-burning case, Test 40, was run in order to obtain an estimate of wall boundary layer and injector drag effects on the pressure distribution. The (spatially) oscillatory character of the pressure distribution is due to the presence of multiple reflections of the induced pressure wave field. These wave structures, although quite well defined, are clearly of low intensity and may be regarded as isentropic compressions.



$P_o$ = 118 psia
$T_o$ = 2500°R
Injector: Flush Mounted in Top Wall
Fuel Mass Flow: .14 lb/sec

FIGURE 6 - IGNITION WITH SUBSEQUENT FLAME QUENCHING OF LIQUID HEXANE IN SUPERSONIC AIR STREAM

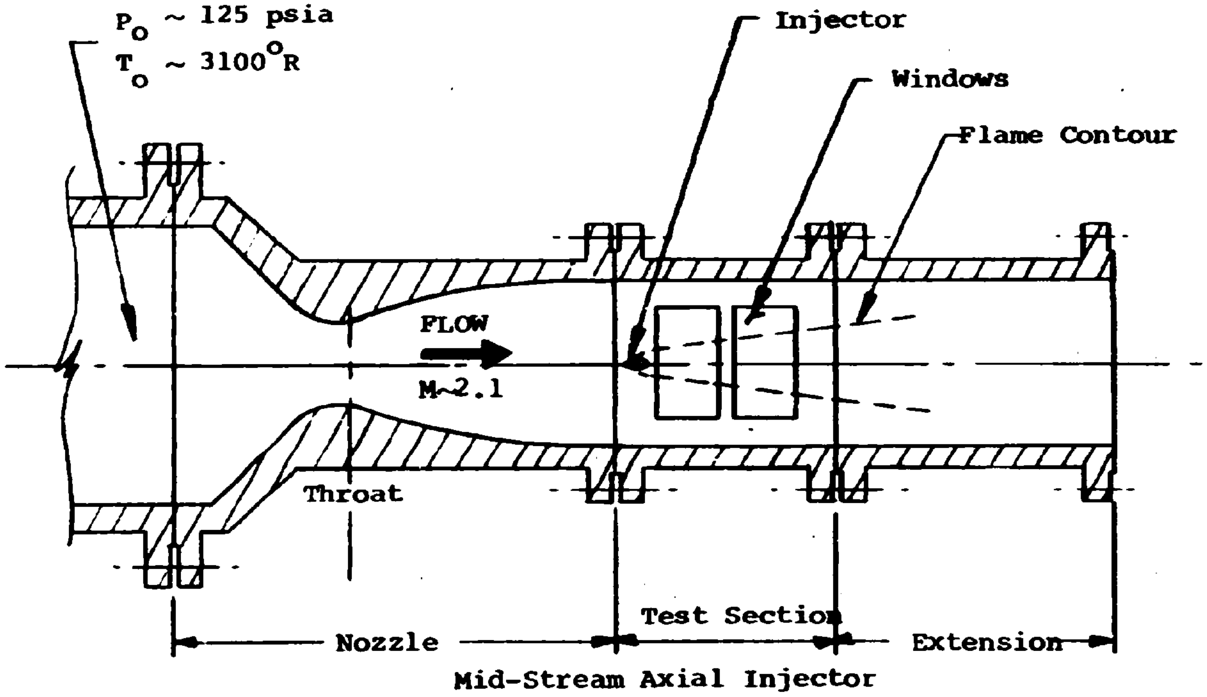


FIGURE 7 - SUPERSONIC COMBUSTION OF LIQUID INJECTED FUEL SCHEMATIC OF EXPERIMENTAL APPARATUS

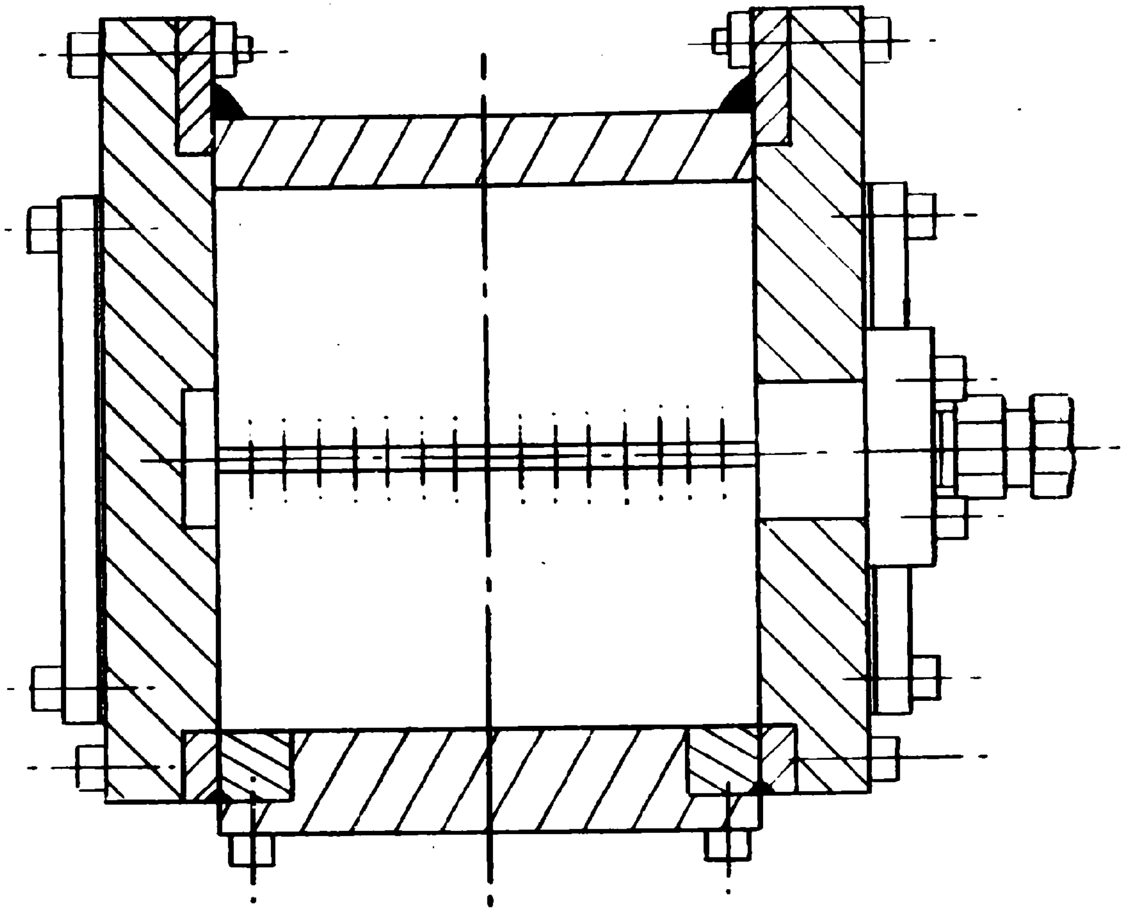
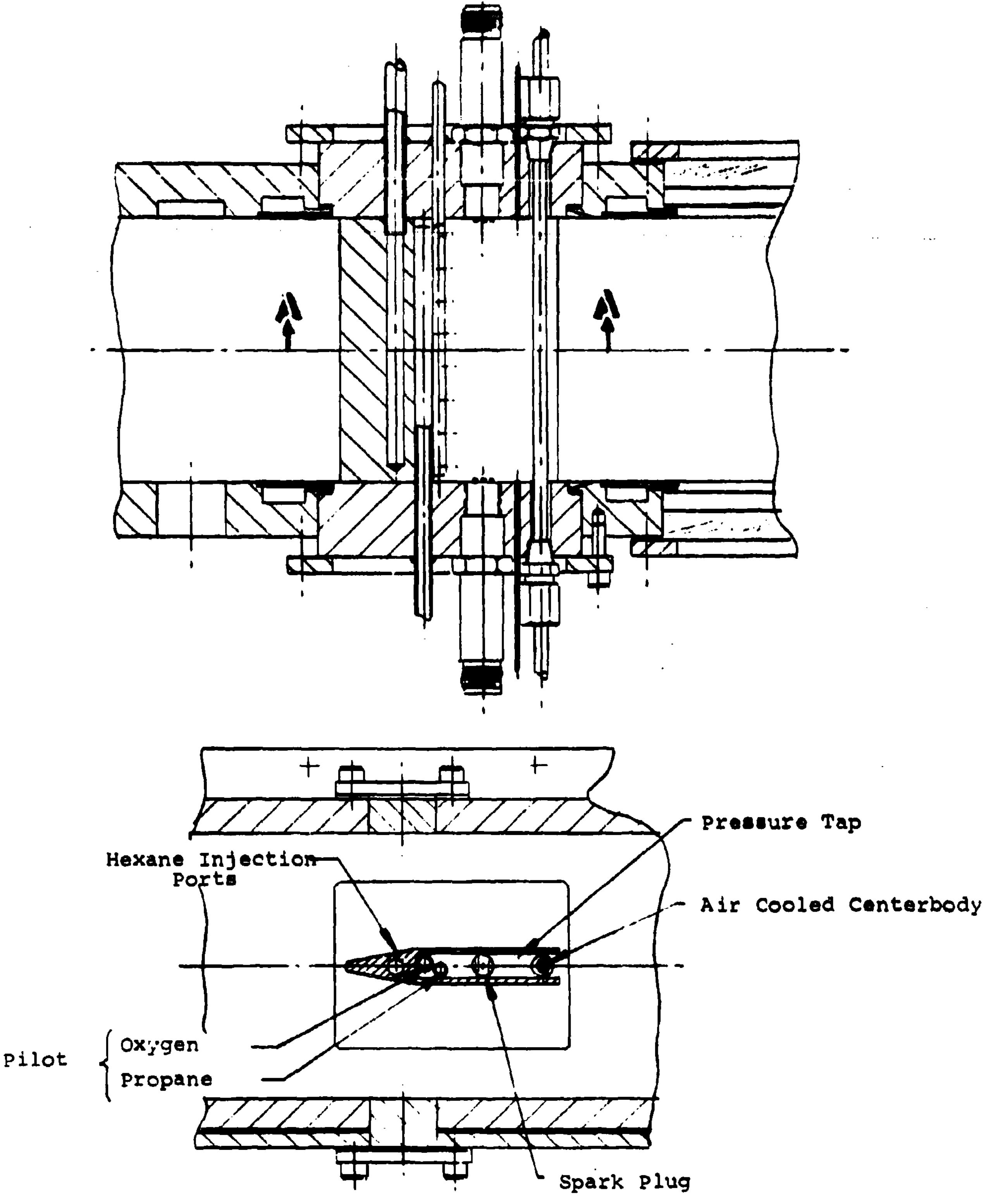
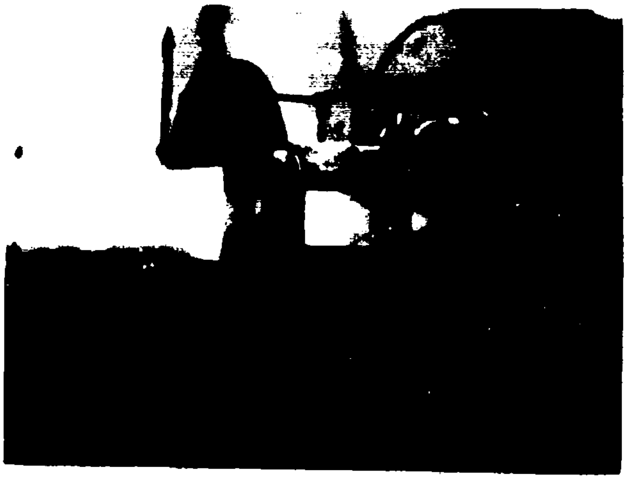


FIGURE 8 - SUPERSONIC COMBUSTION OF LIQUID HEXANE - MID-STREAM AXIAL INJECTOR



SECT. A-A

FIGURE 9 - MIDSTREAM AXIAL INJECTOR WITH ETHYLENE-OXYGEN PILOT



$P_o$ = 120 psia

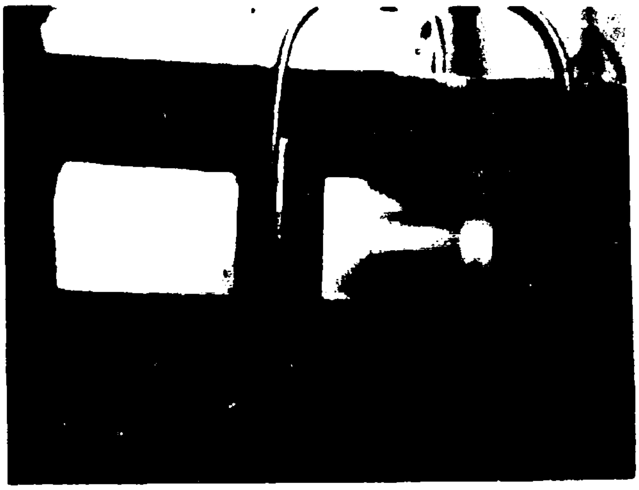
$T_o$ = 3000°R

Injector: Single Wedge Mid-Stream

Fuel Mass Flow: .106 lb/sec

$\omega$ = .13

FIGURE 10a -- SUPERSONIC COMBUSTION OF LIQUID INJECTED HEXANE



Air Total Pressure: 134 psia

Air Total Temperature: 3000°R

Fuel Mass Flow: .071 lb/sec

Equivalence Ratio: .088

Injector Type: Mid-Stream Axial Injector

FIGURE 10b - SUPERSONIC COMBUSTION OF LIQUID INJECTED HEXANE

| TEST 34 |
|---|
| Air Total Pressure: 123 psia |
| Air Total Temperature: 3230$^{\circ}$R |
| Air Mach Number: 2.02 |
| Fuel Mass Flow:.11 lb/sec |
| Equivalence Ratio:.153 |

| TEST 40 |
|---|
| Air Total Pressure: 130 psia |
| Air Total Temperature: 3060$^{\circ}$R |
| Air Mach Number: 2.00 |
|  |
|  |

| TEST 42 |
|---|
| Air Total Pressure: 120 psia |
| Air Total Temperature: 2970$^{\circ}$R |
| Air Mach Number: 2.01 |
| Fuel Mass Flow:.07 lb/sec |
| Equivalence Ratio: .103 |

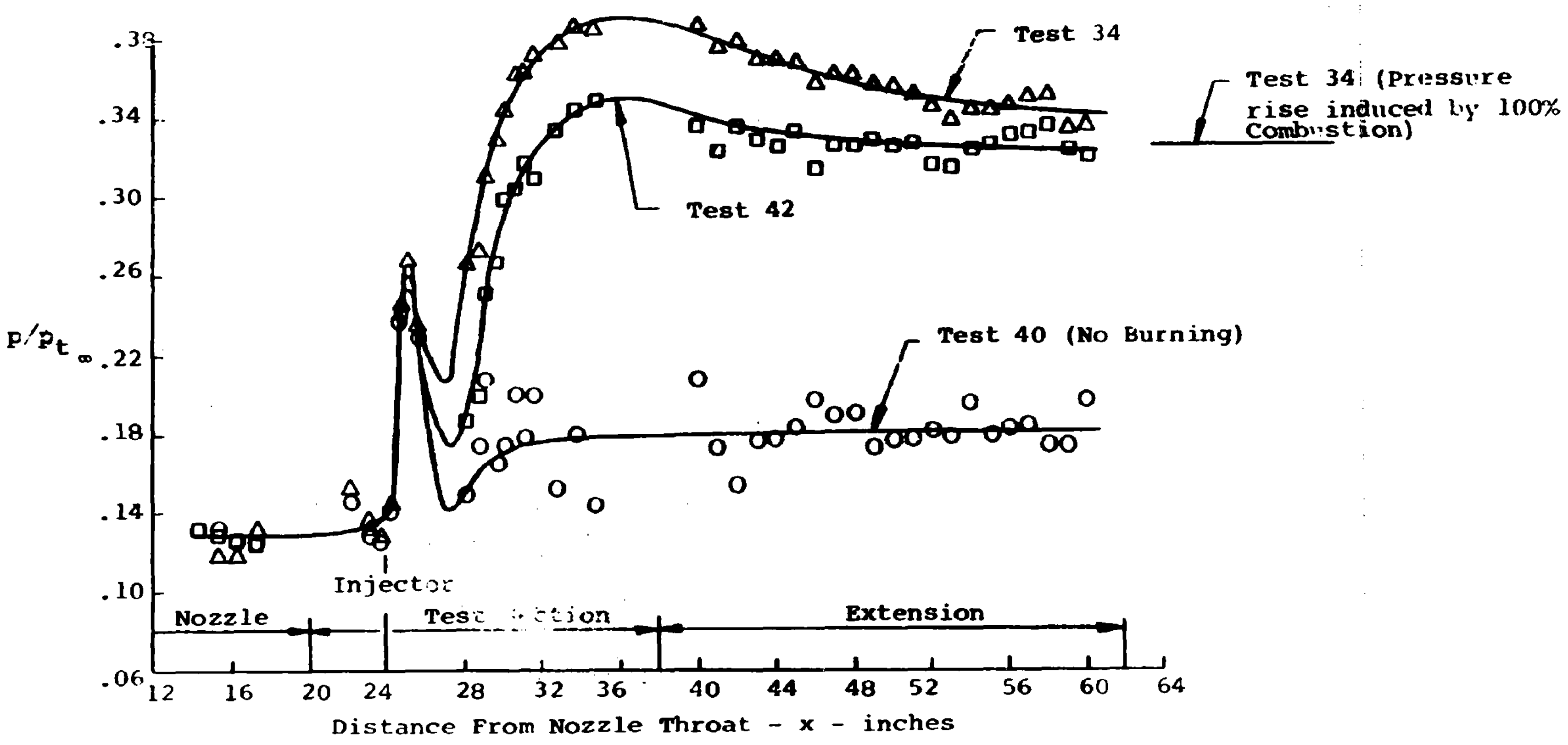


FIGURE 11 - PRESSURE RISE INDUCED BY COMBUSTION OF LIQUID HEXANE

Tests 42 and 34 are very interesting. These flows are supersonic throughout, the pressure never reaching the choking ratio which is at $p/p_{T_\infty} \approx .5$ (as discussed later). An equilibrium chemistry one-dimensional stream tube calculation was carried out assuming adiabatic walls to determine the equilibrium pressure which the physical flow should ultimately approach. This was done, neglecting the pressure effect of the boundary layer growth and of the injector drag. When the latter "tare" pressure rise is superimposed upon the "ideal" combustion pressure rise corresponding to the air and fuel flow conditions of Test 42, it is found to agree almost identically with the pressure actually experienced. In addition, a boundary layer calculation was carried out and was used to calculate the effective area change of the duct. This area change was then used to calculate the associated rise. This rise was found to be quite consistent with that observed in Test 34.

These are encouraging and exciting results since they imply that essentially complete combustion of the liquid hexane fuel was achieved in about two feet of duct at velocities of about 3000 fps. This kind of effective kinetic response is comparable with the best that is achievable with high performance gaseous fuels and is comparable even to hydrogen.

It is still more remarkable that the static temperature of the airstream in the test section is quite low, i.e., about $1650^{\circ}R$ when $T_t = 3000^{\circ}R$ and $M = 2.0$. Hydrogen introduced by means of a parallel flow injector could not be ignited under these conditions without a pilot or a shock inducing flame-holder. Gaseous hexane and the JP fuels do, of course, ignite at this and lower temperatures, but ignition delay times of the gas phase hydrocarbons are normally considered excessively long for flight engine application unless accelerated by means of pilot flames.

Clearly the mechanism of ignition and combustion is not simply that of evaporation from a droplet surface into an oxidizing atmosphere followed by ignition. A model for description of the observed phenomena is discussed in the next section.

Before we proceed to that section, however, it is of interest to understand the mechanism of the static pressure rise in Tests 42 and 34 and of the subsequent static pressure falloff. This mechanism can be clarified by means of the two-dimensional flow field calculation which had been carried out assuming that hydrogen gas, (fuel air ratio $\omega = 0.04$) was injected into a Mach 2 airstream and was ignited by a pilot flame. The heat release rate from the hydrogen combustion was first computed using a mixing plus finite rate chemistry program at constant pressure (Reference 3 ) to calculate the shape of the equivalent displacement thickness, δ*, of the body. The concepts of equivalence between heat release and volume displacement as developed in Reference 4 , was then used to calculate a modified supersonic flow field (Figure 12), and the corresponding wall pressure distribution (Figure 13). A pressure correction to the δ* distribution was then made and a correspondingly corrected flow field computed. It should be noted that the simplest formulation of the equivalent volume concept assumes that the flow field affected is that of an infinite free field, and that any wall and viscous effects require appropriate modification. However, analysis of the initial region, including the neighborhood of the pressure maximum, is appropriate within the framework of this uncoupled model.

The resulting figures show the rapid pressure rise due to initial heat release, and the subsequent pressure drop due to re-expansion of the flow as combustion approaches completion. Thus, the characteristic dependence of $d\delta^*/dx$ with $\frac{1}{\sqrt{x}}$ results in maximum pressure rise in the near region of the injector. Incidentally, the small extent of the equivalent displacement

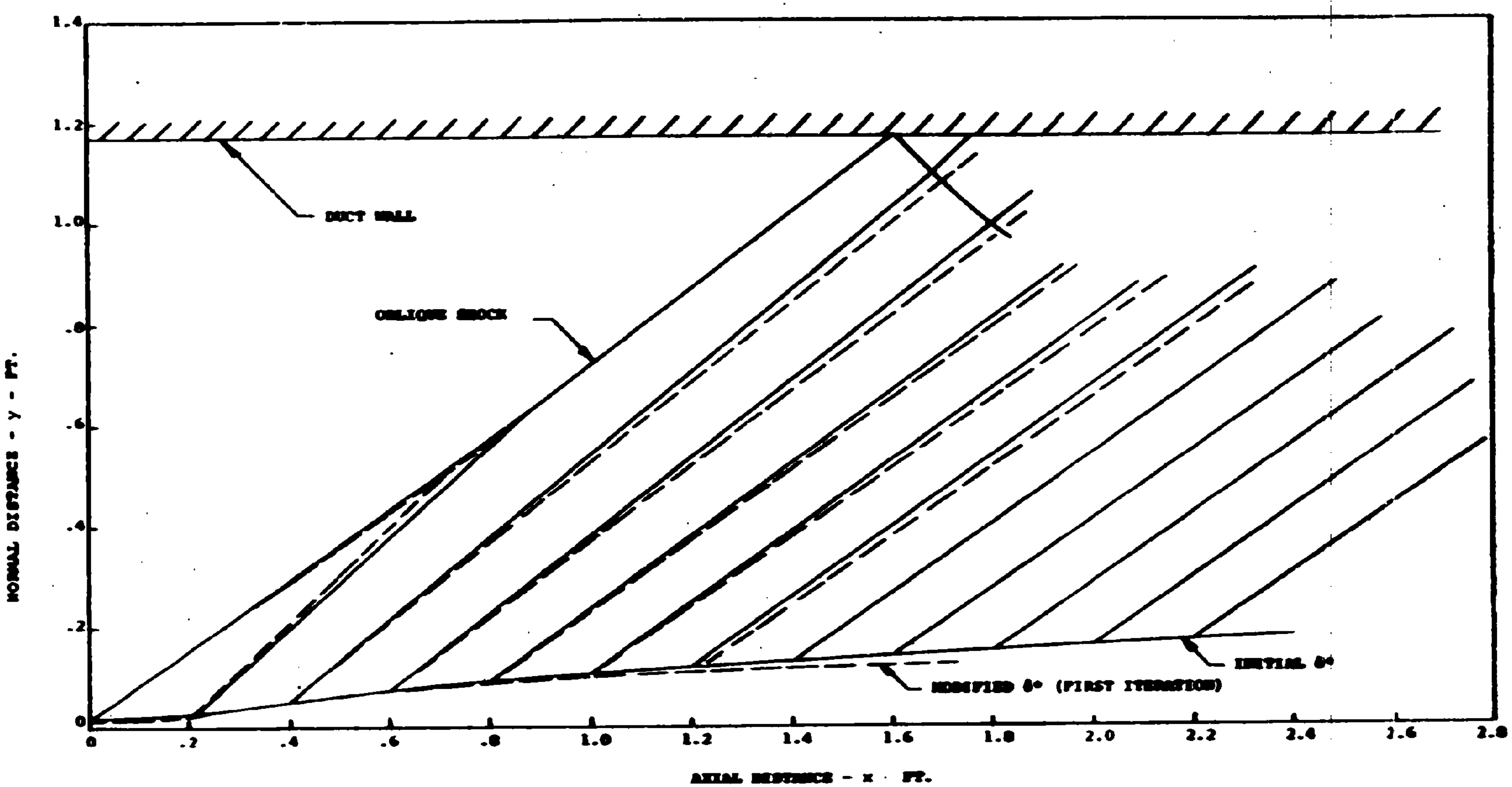
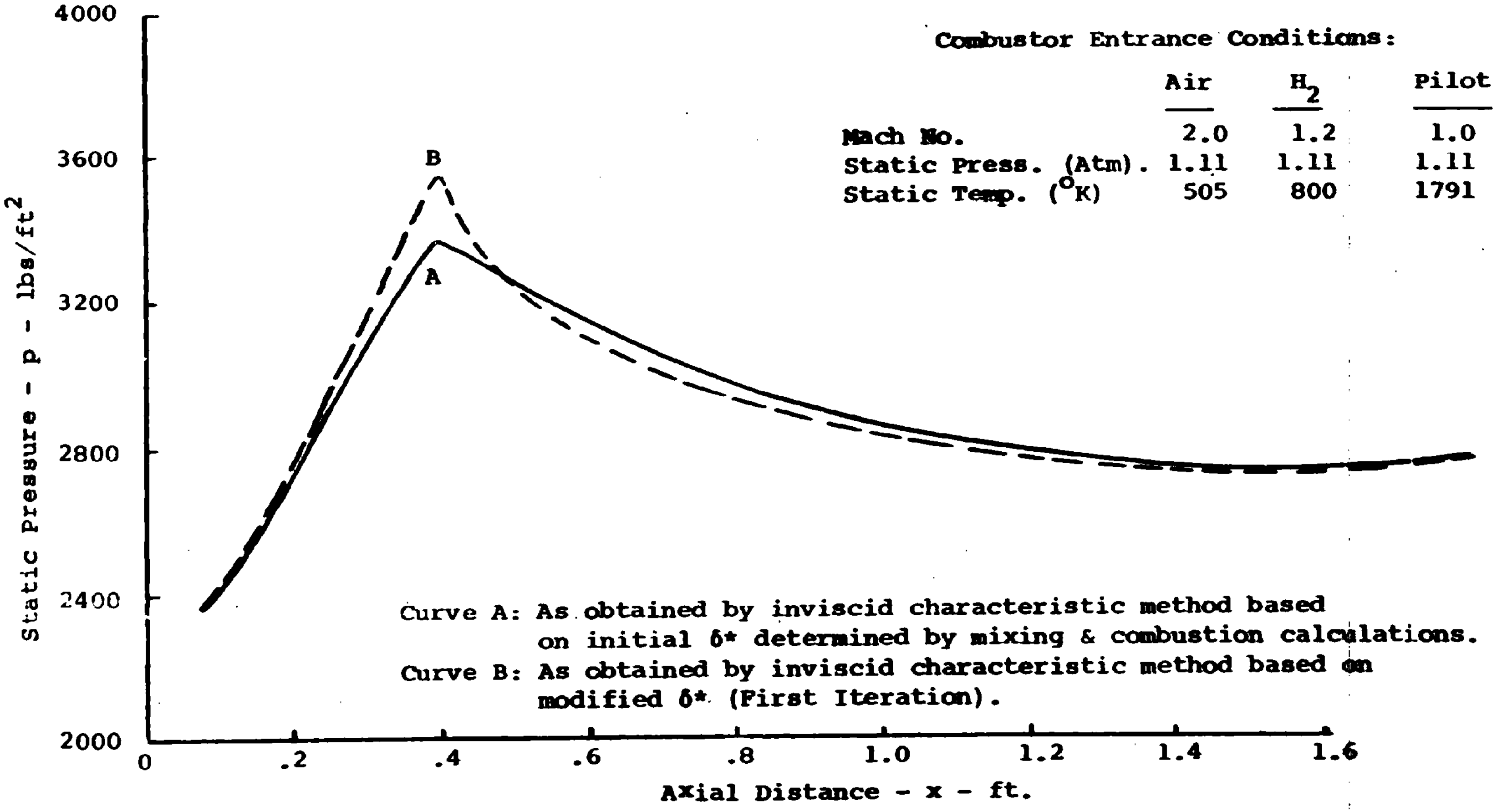


FIGURE 12 – TYPICAL WAVE DIAGRAM FOR TWO-DIMENSIONAL CONSTANT AREA COMBUSTOR, $\varphi_e$ = 0.04



Combustor Entrance Conditions:

| | Air | $H_2$ | Pilot |
|---|---|---|---|
| Mach No. | 2.0 | 1.2 | 1.0 |
| Static Press. (Atm). | 1.11 | 1.11 | 1.11 |
| Static Temp. ($^oK$) | 505 | 800 | 1791 |

Curve A: As obtained by inviscid characteristic method based on initial $\delta^*$ determined by mixing & combustion calculations.

Curve B: As obtained by inviscid characteristic method based on modified $\delta^*$ (First Iteration).

FIGURE 13 - COMPARISON OF AXIAL PRESSURE DISTRIBUTION ALONG THE EFFECTIVE BODY FOR TWO-DIMENSIONAL CONSTANT AREA COMBUSTION, $\phi = 0.04$

volume should not be confused with the extent of the mixing region, which is large. Furthermore, the two-dimensional aspect of the flow shows that the maximum pressure ratio $p/p_{t_\infty}$ of .39 for Test 34, indicates supersonic flow (it would be sonic at $\frac{p}{p_{t_\infty}} \approx .35$ for fully mixed one-dimensional flow with heat release). Since the mixing boundary has not yet reached the wall, the stagnation pressure at the wall locations in the neighborhood of maximum pressure station is still essentially that of the reservoir. Consequently, the wall flow there is supersonic at pressure ratios below about .5.

## III. QUALITATIVE DISCUSSION OF COMBUSTOR MECHANISMS

It is believed that the following sequence of events, as illustrated in Figure 14, occurs in the combustor which explains qualitatively the observed ignition and combustion phenomena. These are initiated with the injection of the liquid fuel streams, normally to the airstream, whether from the wall or central injector arrangement. This stream very quickly becomes unstable and breaks into droplets. At the same time the flow must decelerate to the stagnation conditions on the droplet surface, so that shock fronts must be generated.

The relative velocity between the particle and airstream is of the order of magnitude of the injection velocity divided by the sine of the angle between the particle direction and the

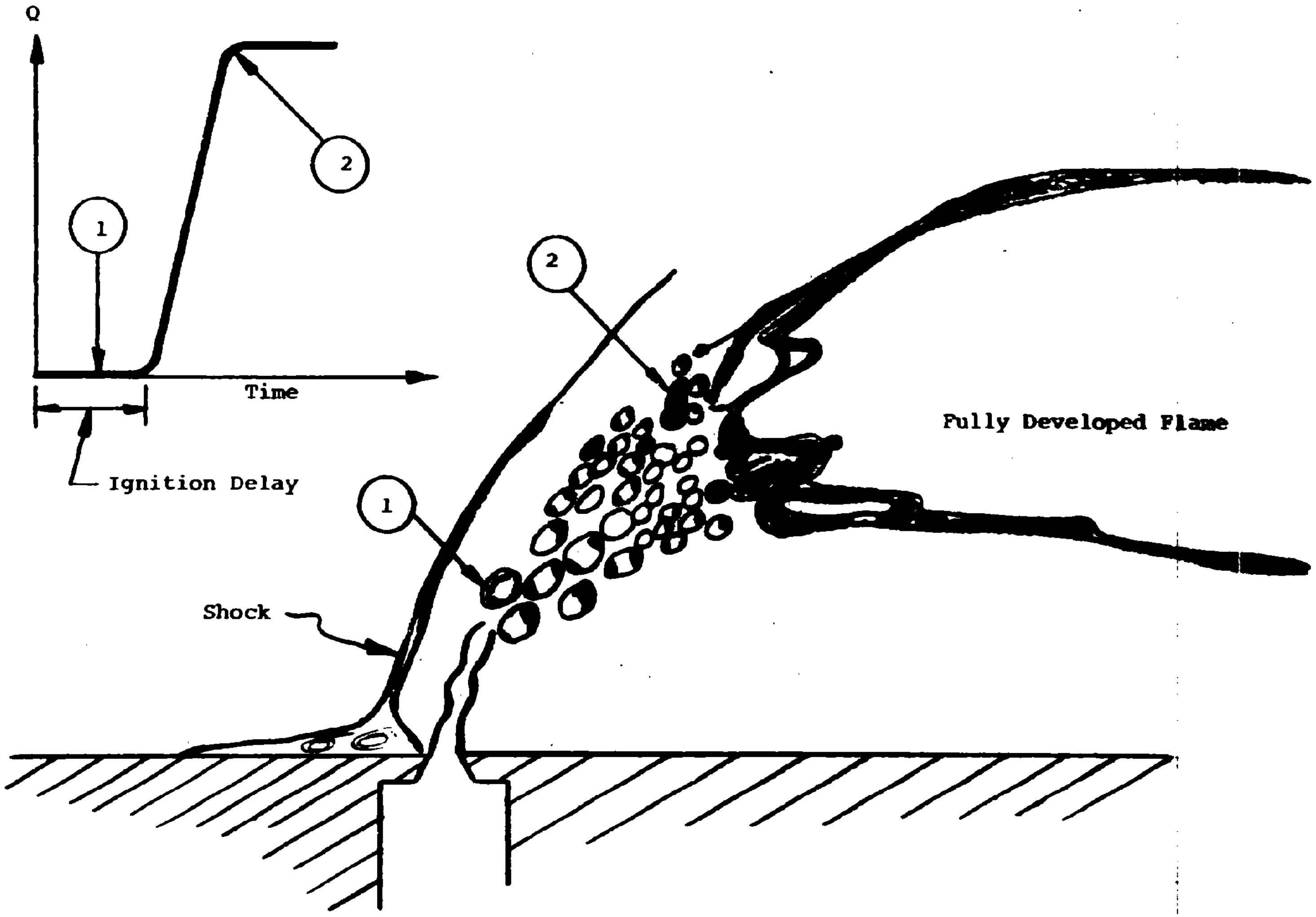


FIGURE 14a - SCHEMATIC OF SEQUENCE OF EVENTS OF A LIQUID JET INJECTED INTO SUPERSONIC AIRSTREAM

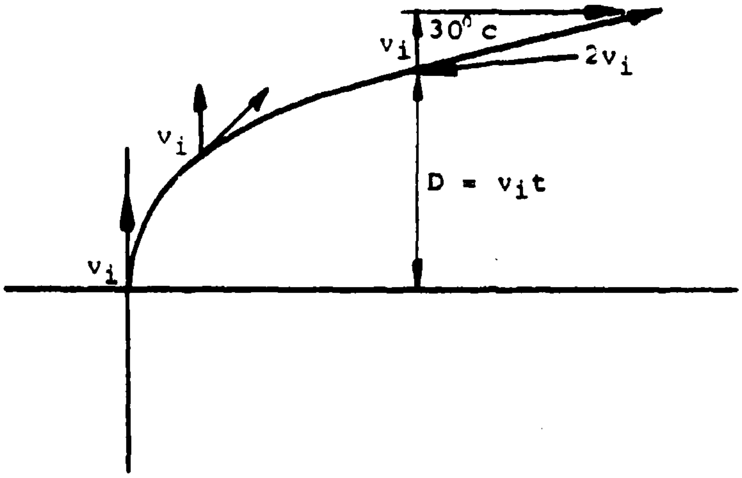


FIGURE 14b - SCHEMATIC OF VELOCITY REPRESENTATION OF THE LIQUID JET free stream direction. With this high relative velocity the rate of particle breakup is extremely high. At the same time, the minimum time spent by the particle in a region where the absolute velocity is equal to or less than twice the initial velocity estimated from Figure 15 is estimated to be of the order of $D/v_i$, where D is the measured penetration distance to the point on the path where the particles are moving at 30° to the initial free stream and $v_i$ is the initial injection velocity. From Figure 15,which is a photograph of hexane injection into a Mach 2 stream under conditions of the current tests, we estimate that this low speed residence time is of the order of one millisecond.

A period of one millisecond is quite adequate for ignition of a hexane atmosphere provided the static temperature of the gas phase fuel air mixture is sufficiently high. For the configuration of Figure 14 the static temperature experienced by the vapor layer around the droplet will be somewhat (but not very much) less than the full total temperature of the incoming flow.

In view of the foregoing, it is very important to study the system response as the stagnation temperature of the incoming flow is decreased. In this way it was found that the lower stagnation temperature limit for ignition and combustion was about 2600° R.

NOT REPRODUCIBLE

$P_o$ = 115 psia

$M_o$ = 2.05

Fuel Flow Mass: 0.226 lb/sec

FIGURE 15- INJECTION OF LIQUID HEXANE USING MID-STREAM AXIAL INJECTOR

In terms of the preceding hypothesis, it may be concluded that below that critical temperature the combustible mixture does not remain long enough within the region of high relative velocity and high static temperature to experience the necessary ignition delay time required for full combustion. The photograph of the injector during Test 30 (Figure 6) is particularly interesting in this connection. This shows the wall injector during injection, with the stagnation temperature of the incoming airstream at 2500° R. The line of initial luminosity followed by fading is interpreted as ignition in the region of highest static temperature on the droplets followed by quenching as the particles accelerate and the maximum surface static temperature drops.

It should follow from this interpretation that optimum combustor design will not be obtained by injection of the smallest possible droplet size or by injection of vapor phase. The contrary should be true since the residence time at static temperatures of the order of free stream stagnation will be very short for the latter. Furthermore, in the case of droplets there is always a region in the film about each droplet having a fuel-air mixture ratio with optimum combustibility (minimum ignition delay) which is in the neighborhood of the stagnation point of each droplet.

For a corresponding gas jet this conjunction of high static temperature and optimum mixture ratio can only occur close to the injection point. Furthermore, the spatial distribution of gas fuel at favorable conditions for ignition is more limited than for the liquid. Thus, the liquid jet breakup and droplet formation provides a larger contact area with the environment and as indicated above each fragment or droplet has its own optimum ignition source.

Finally, it is concluded that the optimum choice of liquid fuel jet diameter should be such as to result in residence time in a high static temperature environment sufficient to exceed the ignition delay time for the most favorable gas phase mixture at that temperature.

In order to quantify these hypotheses and determine the feasibility of the proposed mechanisms, estimates of the ignition characteristics of the liquid jets have been made. In addition, some theoretical considerations are in order regarding the losses in combustion efficiency associated with vaporization and with stagnation pressure losses. These considerations are undertaken in Part II of this report.

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# PART II

By Forman Williams

## I. INJECTION AND ATOMIZATION

### A. Introduction

For simplicity, attention will be focused initially on normal (transverse) injection of a single cylindrical liquid fuel jet into a uniform supersonic airstream. Of interest are jet penetration distances, droplet size distributions produced by atomization, temperature and gaseous fuel concentration distributions in the vicinity of the jet and fuel residence times in the high-enthalpy region. The preliminary theoretical considerations presented in this section will refer only to nonreacting conditions; the connection with ignition criteria will be made in a later section.

### B. Literature Review

Numerous studies have been made of liquid disintegration in gas streams. Most of this work has been concerned with low-velocity conditions under which, for example, a large spherical droplet will become oblate, will develop into an extended cup-shaped sheet or "bag" with its rim on the upstream side, and eventually will burst into a large number of small droplets and a circular ligament from the rim which contracts into a number of somewhat larger droplets. These low-velocity atomization studies are not directly relevant to high-speed conditions; at higher speeds the disintegration mechanism is quite different, typically involving stripping of very small droplets from the surface of the liquid. There have been fewer studies of high-velocity disintegration. It is of interest to review very briefly some of the literature on breakup of liquid jets in air streams.

Studies on techniques of fluid injection in deLaval nozzles for achieving thrust vector control motivated much research, purely theoretical[1] as well as experimental[2-6] with theoretical interpretation, on injection of liquids into supersonic streams. Since the objective in thrust vector control is merely to produce a side force, atomization and penetrations are not directly relevant. Therefore, although these studies reveal many characteristics of the influence of injection on the supersonic stream, they yield very little information on the behavior of the liquid jet itself. Experimentally observed jet penetration distances can be found in some of this work,[4] but information on other jet characteristics was not obtained. Data on liquid jet penetration distances in supersonic streams have been obtained in other studies[7,8] that were more fundamentally oriented, and theories of jet penetration have been presented.[8,9] One of these studies,[8] against which unfortunately a number of objections can be raised on technical grounds, was in fact motivated by the supersonic combustion problem. To develop an accurate theory for even so gross a jet parameter as penetration distance is difficult,[9] because complex breakup phenomena influence penetration.

Very few studies have considered the fuel concentration and temperature fields that develop in the vicinity of a liquid jet for transverse injection. Apparently, data of this type are available only for subsonic gas streams.[10]

Abundant data on jet breakup mechanisms and resulting droplet size distributions have been accumulated for liquid jets in subsonic gas streams,[11-18] but very limited experimental results are available for mean droplet sizes and droplet size distributions produced in supersonic streams.[19-22] A few theories have been advanced for liquid jet breakup in subsonic (References 9, 17-18, 23-25) and supersonic (References 9,23-25) gas streams, the last[25] yielding theoretical expressions for the mean droplet size in the atomized spray. The theories differ greatly in their physical assumptions and invoke at least three distinct physical mechanisms for disintegration, as discussed below (Section I.C). Thus, differences between theories and paucity of reliable experimental data cause estimates of disintegration characteristics of liquid jets in supersonic gas streams to be highly uncertain.

Some ideas concerning liquid jet disintegration may be derived from a long series of careful experiments[26-36] on the breakup of liquid droplets in gas streams. Typically, droplets of controlled size are produced and suspended in shock tubes by various ingenious techniques, and photographic observations of the droplets are recorded after passage of a shock wave. Only the last two[35-36] of these studies achieved supersonic flow of the gas behind the shock wave relative to the droplet, and even in these two cases no data are reported for convective Mach numbers based on relative velocity behind the shock in excess of 1.5. However, the results reveal no startling differences between breakup mechanisms for supersonic Mach numbers and breakup mechanisms for higher subsonic Mach numbers; droplet flattening into a lenticular shape followed by some type of surface stripping always appears to occur. Aside from the minor difference arising from cylindrical versus spherical geometry, jets will differ from droplets in the presence of a convective liquid flow transverse to the gas stream, in the probable presence of a much higher intensity of turbulence of the liquid, and possibly in the presence of enhanced vaporization rates for volatile liquids. Nevertheless, one would expect that at least there would be a tendency for liquid jets to exhibit the phenomena observed for droplets. This expectation is demonstrated by the fact that theoretical descriptions of disintegration mechanisms for droplets in high-speed flows invoke the same physical phenomena that have been used in discussing jet disintegration (for example, the analysis in Reference 36 is based on a viscous shearing disintegration mechanism whose fundamental attributes closely resemble those of the analysis in Reference 17).

### C. Disintegration Mechanisms

It is of interest to look more closely at disintegration mechanisms for liquid jets because the physical mechanism of disintegration affects the functional dependence of jet breakup time on liquid and gas properties and because, as will be argued in Section II, the jet breakup time is directly relevant for ignition criteria.

Three different physical processes that can lead to disintegration have been identified clearly in the literature.

One mechanism, for which an analysis was first given by G. I. Taylor in a study of the dynamics of droplets subjected to air flows, involves merely the theory of steady viscous flows, without consideration of any instability phenomena. This mechanism is analyzed in Reference 17 for liquid jets in subsonic flows and in Reference 36 for droplets in supersonic streams. The flow in a steady-state two-phase viscous boundary layer on the windward side of the liquid is described by simplified versions of the boundary-layer equations. The azimuthal component of mass flow rate in the liquid phase, induced by the surface shear, is calculated at a position 90 deg from the forward stagnation point, and it is postulated that because of the flattened shape of the liquid, the liquid boundary layer separates from the bulk of the liquid at this point, so that the calculated mass flow rate equals the rate at which mass is stripped from the liquid surface. Obviously, the velocity of the gas relative to the liquid and the viscosities of both the liquid and the gas will appear as parameters affecting the breakup time in these theories; surface tension will be irrelevant. We shall identify this type of disintegration mechanism as the steady-shear mechanism.

A second disintegration mechanism emerges from the well-known fact that wind blowing over a liquid surface generates surface waves. The flow of the gas relative to the surface of the liquid jet may therefore be expected to generate surface waves on the jet by the same type of instability phenomenon. Droplet formation will occur when the ratio of amplitude to wavelength for these waves becomes too large for the crests to remain an integral part of the jet. Although the theoretical foundations for describing this type of wave generation were laid long ago by H. Jeffreys and others, the application to jet disintegration was carried out by E. Mayer.[23-24] Breakup times predicted by this kind of theory will depend on the relative gas velocity and on the surface tension of the liquid; the viscosity of the liquid enters only secondarily, as a damping effect, and the viscosity of the gas does not enter at all. We shall call this type of disintegration mechanism the capillary-wave mechanism.

Analysis of the third type of disintegration is also traceable to G. I. Taylor;[37] this is the well-known "Taylor instability." When a fluid is accelerated either by gravity or by inertia in a direction perpendicular to an interface across which there is a discontinuity in density, waves grow on the surface provided that the body-force vector, in a coordinate system moving with the undisturbed interface, is directed from the more dense fluid into the less dense fluid. The upstream face of a liquid jet is subject to breakup by means of this type of instability. Adelberg[9,25] was the first to include this mechanism in an analysis of jet disintegration; it has never been applied to droplet breakup. The resulting breakup time depends on the relative velocity of the gas and the mass of the liquid but not on either surface tension or gas viscosity; liquid viscosity enters only in a relatively minor way by producing damping. This type of disintegration mechanism will be termed the acceleration-wave mechanism, a nomenclature which is more precise than the more conventional "gravity-wave" label.

The analyses referenced above are necessarily quite imprecise. It is understandable that phenomena so complex as finite-amplitude wave development on surfaces of complex geometry cannot be analyzed accurately. The results constitute at best order-of-magnitude estimates and at worst dimensional analyses. Moreover, the analyses do not take into account various phenomena, such as vaporization of the liquid or turbulence in the liquid jet, which certainly will modify the results quantitatively and some of which might produce jet disintegration in the absence of the proposed mechanisms. There may be ways to account approximately for some of these phenomena; for example, although arguments to the contrary can be given, it may be reasonable to try to describe the effects of liquid turbulence by using a turbulent viscosity coefficient in place of the molecular viscosity of the liquid. However, for the purpose of obtaining a rough estimate of the disintegration time for use in an ignition theory, it seems best to avoid imposing further complications on existing theories and instead to attempt to select the mechanism that appears most likely to occur under the conditions of interest in supersonic combustion, and to employ as simple a respresentation as is possible for describing the implications of this mechanism.

Accordingly we observe that for a liquid of given dimensions, as the velocity of the gas relative to the liquid increases, the acceleration-wave mechanism progressively becomes relatively more important than either of the other two mechanisms that have been considered. This result is demonstrated by Adelberg[9,25] in comparison with the capillary-wave mechanism and can also be demonstrated in comparison with the steady-shear mechanism. It appears that under the high-velocity conditions of interest in supersonic combustion, the acceleration-wave mechanism will be dominant for liquid jet disintegration. Since droplets are typically less massive than jets and can therefore be accelerated more easily, it would follow from this observation that the breakup of droplets in supersonic streams should best be treated by the acceleration-wave mechanism, in spite of the fact that Ranger and Nicholls[36] developed a steady-shear theory for correlating their experimental results. The photographs shown in Reference 36 for the higher Mach numbers (convective Mach number relative to droplets $\gtrsim 1.4$) appear to demonstrate clearly the development of rather long liquid "fingers," reminiscent of Taylor instability, extending upstream on the windward face of the droplet, as would be expected for an acceleration-wave mechanism but not for a steady-shear mechanism. Thus, it would be of interest to attempt to correlate the high-speed results in Reference 36 by means of an acceleration-wave theory. In our present considerations of supersonic combustion, we shall restrict our attention to the acceleration-wave regime.

### D. Jet Breakup Time and Penetration Length from Acceleration-Wave Theory

The growth time for acceleration waves is of the order of[37]

$$\tau_g = \sqrt{\ell/a} \qquad (1)$$

where $\ell$ is the wavelength of the disturbance and a is the acceleration. A force balance for an element of the liquid jet of diameter d and length $\Delta x$ in a stream of air (of density $\rho_a$) with relative velocity component v normal to the axis of the jet, can be written as

$$\Delta m \ a = \frac{1}{2} \rho_a v^2 C_D (\Delta x \, d) \quad , \qquad (2)$$

where $\Delta m$ is the mass of the element of the liquid jet and $C_D$ is the drag coefficient of the jet. Since

$$\Delta m = \frac{\pi}{4} d^2 \Delta x \ \rho_\ell \qquad (3)$$

where $\rho_\ell$ is the density of the liquid, we find from Equations (1) and (2) that

$$\tau_g = \left[\left(\frac{\ell d}{v^2}\right)\left(\frac{\rho_\ell}{\rho_a}\right)\left(\frac{\pi}{2\ C_D}\right)\right]^{1/2} \qquad (4)$$

If $\ell$ is of the order of d and if $C_D$ is of the order of $\pi/2$, then Equation (4) reduces approximately to

$$\tau_g = (d/v)\ \sqrt{\rho_\ell/\rho_a} \qquad (5)$$

This characteristic growth time for acceleration waves can be interpreted as the jet breakup time that would result from an acceleration-wave breakup mechanism.

If $\tau_g$ is the breakup time of the jet, then the penetration distance $x_p$ of the liquid, measured along the axis of the jet, is given approximately by

$$x_p = v_\ell \tau_g = d\ (v_\ell/v)\ \sqrt{\rho_\ell/\rho_a}\ , \qquad (6)$$

where $v_\ell$ is the injection velocity of the liquid. This formula neglects such phenomena as further penetration of droplets after atomization, the change in v between the injection point and the tip of the jet arising from curvature of the jet axis, and the decrease in d with increasing x due to atomization. The equation is useful only for obtaining the order of magnitude of $x_p$ . Since the mass rate of injection through a single orifice is given by

$$\dot{m} = \frac{\pi}{4} d^2 \rho_\ell v_\ell \quad , \tag{7}$$

noticing that $\pi/4$ is of the order of unity we can write Equation (6) in the alternative form

$$x_p = \dot{m}/(dv \sqrt{\rho_\ell \rho_a}) \tag{8}$$

Equations (6) and (8) are presented here only for general interest and will not be needed in the ignition analysis.*

A more accurate theory which removes many of the approximations that are implicit in the equations given here may be found in References 9 and 25. The improved theory uncovers a number of additional parameters for which approximations must be introduced due to the complexity of the phenomena involved. It also leads to considerably more complicated equations. However, the results do not appear to differ in order of magnitude.

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* Recently rather extensive data on jet penetration distances have been taken [M.A.Koplin, K.P.Horn and R.E.Reichenback, AIAA J. 6, 853 (1968)]. The resulting correlations are in good agreement with the present theory over nearly three orders of magnitude in gas-to-liquid dynamic pressure ratio, in the acceleration-wave regime.

## E. Mean Droplet Size in Acceleration-Wave Regime

For analyzing the two-phase spray-combustion processes occurring after atomization, one must know the drop-size distribution produced during atomization. No experimental data at all on size distributions are available in the acceleration-wave regime, and apparently only the rudimentary data of Reference 21 are available for mean droplet sizes in this regime. A theoretical result for the number-weighted average drop diameter $\delta$ in the acceleration-wave regime is derived in Reference 25; it is

$$\delta = 65.3\,[\mu_\ell \sqrt{\sigma_\ell/\rho_\ell}/(\rho_a v^2)]^{2/3} \qquad (9)$$

where $\mu_\ell$ and $\sigma_\ell$ are the viscosity and surface tension of the liquid. Many questions can be raised concerning the analysis that leads to Equation (9). It is not clear that the proper physics of the process has been taken into account; a cascade mechanism of multistage droplet breakup may be involved in the real atomization process, turbulence in the liquid jet may be of importance, or a gas-phase shearing off of instability-generated protuberances may be dominant so that the viscosity of the gas affects $\delta$. Moreover, at this stage it appears that balance arguments comparable in simplicity to those of Section I. D cannot yield a numerically reasonable formula for $\delta$, such as Equation (9). Therefore for the purpose of supersonic combustion analyses it seems best at present to treat droplet sizes and size distributions as adjustable parameters that are assigned values which lie in a reasonable range but are varied to obtain correlation with experimental data on combustion. It would be of interest to make experimental observations of the atomization process and of droplet sizes under these high-speed conditions as aids in discovering the relevant physical mechanisms and in providing input data for combustion analyses.

### F. Vaporization in the Vicinity of the Liquid Jet

For the jet to participate in the ignition process, some vaporization of the fuel must occur in its vicinity, since the boiling point of the fuel typically is well below the "ignition temperature." It is obvious that some vaporization will occur because of the high stagnation temperature, and it is also obvious that because of the complicated three-dimensional flow and the complex and unknown atomization processes occurring, an accurate description of the temperature and concentration fields consequent to vaporization cannot be obtained. Simplified models must be developed. The most pertinent simplified model appears on physical grounds to be vaporization in a two-dimensional stagnation-point boundary layer on a flat plate of liquid fuel. For the purpose of ignition analyses, it is appropriate in describing this flow field to neglect chemical heat release in the first approximation and therefore to employ a theory applicable to nonreacting flow. This nonreacting stagnation-point boundary-layer problem with coupled heat and mass transfer is relatively simple and has been analyzed previously.[38-41] Results are available for temperature and concentration profiles. The principal predictions are that there is a smooth concentration profile in which the concentration of vapor decreases from a peak value at the liquid surface to zero at the edge of the boundary layer, and that the temperature profile rises smoothly from the boiling point at the liquid surface to the stagnation temperature at the edge of the boundary layer. The significance of these results for ignition theory is that an extended region of gas with concentrations lying within the flammability limits is exposed to temperatures that are only slightly below the stagnation temperature.

## II. IGNITION

### A. Approach to Ignition Analysis

It is apparent from the preceding observations that conditions conducive to ignition exist in the vicinity of the injected liquid jet. Since an accurate theoretical description of this flow region is unattainable, approximate physical concepts are necessary in ignition analyses. Ample background material is available on the theoretical development of approximate ignition concepts.[42-53] For the present problem, it seems best to divide the overall combustion reaction into two parts--an energetically neutral ignition reaction in which radicals are formed through a chain mechanism, followed by an exothermic combustion reaction in which the radicals recombine. Then the ignition reaction will not affect the temperature field. Moreover, it appears reasonable at this stage to neglect any differences between kinetic mechanisms in premixed and nonpremixed systems for the ignition reaction and to assume that during the ignition process the gas-phase region in which the fuel-air mixture ratio lies within the flammability limits remains sufficiently broad in spatial extent for diffusional losses of radicals to be negligible. The ignition reaction is then unaffected by concentration gradients in the flow field, and special consideration of quenching processes[53] is not required. Under these conditions, one can ascribe to each point in the combustible gas mixture an ignition delay time $\tau(T)$ which depends only on the local static temperature. If hydrogen were the fuel, then one could calculate $\tau(T)$ from available data on rates of elementary reactions by using the known kinetic mechanism; for liquid fuels such as hydrocarbons the elementary rates and kinetic mechanisms are not well known. However, extensive data is available[54-55] and attempts at formulating reaction mechanisms for hydrocarbons have been made and successfully applied to these data.[56,57] Thus, we obtain the function $\tau(T)$ from these studies and use this result along with the preceding assumptions to obtain an ignition criterion as described below.

## B. General Ignition Criterion

An element of combustible gas, moving at the local mass-weighted average velocity, will be exposed in the vicinity of the injector to temperatures which change rapidly with time. We are therefore faced with the problem of applying ignition delay data, obtained under isothermal conditions, to a flow in which the temperature varies. If it is assumed that the overall ignition reaction can be approximated as a one-step zero-order chemical kinetic process with reaction rate $\omega(T) = 1/\tau(T)$, then the kinetic equation for the overall reaction is

$$dY/dt = \omega(T) = 1/\tau(T) \quad , \qquad (10)$$

where Y is a reaction progress variable which goes from zero at the beginning of the reaction to unity at its completion. Integration of Equation (10) yields

$$\int_0^{t_i} [dt/\tau(T)] = 1 \qquad (11)$$

as the equation for the ignition time $t_i$ of an element of combustible gas exposed to a specified time-dependent temperature T(t). Equation (11) can be used as an ignition criterion for the present problem in the following way.

In the steady-state flow field established in the vicinity of the injector and downstream, we trace the path followed by each element of combustible gas, from the time the element is formed until it leaves the motor. On the assumption of nonreacting flow, we calculate the convective velocity of the element and also the static temperature to which it is subjected, over this entire history for each element. If Equation (11) is satisfied at any point inside the combustion chamber, for any element of combustible gas, then we conclude that spontaneous ignition occurs in the combustion chamber. An ignition criterion thereby is obtained from Equation (11).

### C. Approximate Ignition Criterion

Since the flow field is too complicated for accurate calculations of temperature and velocity histories to be completed, it is of interest to resort to rough physical ideas for making an approximate application of Equation (11). It is well known that $\tau(T)$ is generally expressible in the form

$$\tau = A \exp (E/RT) \quad , \qquad (12)$$

where R is the universal gas constant, E is the (constant) overall activation energy, and A is also a constant. It therefore follows from Equation (11) that regions of high temperature and regions of long residence time are most effective for producing ignition; regions where the temperature is low or the velocity is high will produce relatively small contributions to the integral in Equation (11). Thus, combustible gases blown downstream from the injected liquid jet will tend to be ineffective in producing ignition on two counts--first because of their reduced residence time and second because of their reduced temperature. The same comment applies, to a lesser extent, to combustible gases surrounding atomized droplets, because the droplets are probably so small that they are accelerated rapidly [Equation (9) yields $\delta \sim 20\ \mu << d$]. Thus, we are led to the conclusion (neglecting wall effects) that residence of combustible gases on the upstream side of the liquid jet produces the principal contribution to the integral in Equation (11). A rough ignition criterion can therefore be obtained by applying Equation (11) only to a gas element in the boundary layer on the upstream face of the liquid jet.

In Section I.F it was argued that combustible gases are subjected to temperatures only slightly below the stagnation temperature $T^{\circ}$ on the upstream face of the liquid jet. To complete the application of Equation (11) to a fuel element in this location, one need only estimate its residence time in this region of high static temperature. To avoid a complicated three-dimensional boundary-layer calculation, we observe that the velocity of this critical gaseous fuel element is directed parallel to the axis of the liquid jet and is approximately equal in magnitude to the velocity of the liquid. Therefore the residence time of the critical element of combustible gas, in the region where $T \approx T^{\circ}$, is simply the jet breakup time derived in Section I.D. In view of Equation (5), application of Equation (11) therefore yields the following approximate ignition criterion:

$$\tau^{\circ} \equiv \tau(T^{\circ}) \leq (d/v)\sqrt{\rho_{\ell}/\rho_{a}} \qquad (13)$$

From the derivation, it is clear that Equation (13) represents an extremely rough result. Taken literally, the derivation would predict that the (exothermic) flame would be attached to the tip of the injected liquid jet. Experimental observations seem to show, on the contrary, that the flame develops some distance downstream from the injection region. On the basis of the present theoretical ideas, this observation can be explained by saying that the jet is not quite sufficient to cause ignition under the experimental conditions, but instead the continuing ignition reactions in the vicinity of droplets atomized from the tip of the jet eventually cause Equation (11) to become satisfied at some distance downstream before the droplets leave the combustion chamber. An alternative explanation of the observed behavior would be that oblique shocks from the walls increase the temperature in the vicinity of the droplets, thereby providing a step in the contribution to the integral in Equation (11) which rapidly produces ignition.

A few aspects of Equation (13) may contribute to its usefulness as a practical ignition criterion in spite of the lack of rigor in its derivation. Since $T$ is somewhat below $T^\circ$ in the critical gas-phase ignition zone, the use of $T^\circ$ tends to underestimate the ignition time and thereby provide an overoptimistic ignition criterion. On the other hand, since continuation of the ignition reactions in the vicinity of shed droplets is neglected in Equation (13), an underoptimistic ignition criterion would tend to be obtained. Thus, cancellation of competing effects may contribute to the practical accuracy of Equation (13).

### D. Design Criteria

Equation (13) has a very simple interpretation as an injector design criterion. It predicts that only the injector orifice diameter influences ignition of a given fuel in a given air stream. The equation therefore can be used as a formula for the critical orifice diameter that assures ignition. In design, first the orifice diameter can be chosen according to this formula, then other injector characteristics (e.g., the injection rate per injector element) can be chosen in order to achieve other desirable aspects of injector performance (e.g., jet penetration).

## E. Comparison with Experiment

It is of interest to compare the predictions of Equation (13) with experiment. Using GASL data, we find that typically, in the experiments where burning occurred, $\sqrt{\rho_\ell/\rho_a}\,(d/v) \approx 70$ µsec. The predicted ignition delay time for the appropriate test conditions is $\tau^\circ \approx 10$ µsec. Hence, ignition is predicted and observed. At a Mach number of 2.13, Equation (13) predicts that the minimum stagnation temperature for ignition is approximately 2600°R for the GASL experiments. In the experiments of Mestre and Viaud,[58] although the injection geometry is considerably more complex, we can use the wall-injector orifice size to estimate that $\sqrt{\rho_\ell/\rho_a}\,(d/v) \approx 10$ µsec and the stagnation temperature to show that $\tau^\circ < 1$ µsec, thereby again obtaining agreement between the prediction of Equation (13) and the experimental observation that ignition occurred.

Finally, it should be emphasized that if improved accuracy is needed or if other injection geometries are of interest, Equation (11) should be used in place of Equation (13).

## III. SPRAY COMBUSTION

Although injection and atomization processes are so complex that the relevant conservation equations cannot be solved numerically, it is quite possible that the spray combustion processes occurring downstream from the atomization region can be analyzed accurately by such numerical approaches. The relevant conservation equations for steady flows have been given in Reference 59. To include the gas-phase ignition process in the analysis may prove difficult, but in the region downstream from the position at which ignition is completed, it should be possible to treat a single heterogeneous combustion reaction and thereby simplify the calculations. Much theoretical work remains to be done in analyzing how the mathematical properties of the spray equation[57] modify the usual characteristic calculations for supersonic flow; studies of this kind should be completed before attempts are made to program the full equations. However, there appears to be nothing in principle that would prevent the performance of calculations with the full equations.

In view of the probable existence of nonuniform fuel distributions, it does not seem desirable to restrict one's attention to quasi-one-dimensional forms of the equations, as was done in the applications given in Reference 57. At the very least, characteristic analyses for steady-state two-dimensional flows should be performed. However, other approximations, such as the assumption of a monodisperse spray and the assumption that the droplets and gas travel at the same velocity, may introduce useful simplifications without impairing accuracy severely.[60] Work on the solution of steady-state two-dimensional conservation equations for sprays must certainly be initiated if useful calculations of combustion efficiency are desired.

A very rough approximation for combustion efficiency can be obtained by substituting suitable numbers into Equation (34) of Reference 59. For a velocity of 4000 ft/sec and a combustion chamber length of 4 ft, if the square of the droplet diameter decreases linearly with time, then for a burning rate constant of $10^{-2}$ $cm^2$/sec, an initial mean droplet diameter of 30 $\mu$ and a Rosin-Rammler size distribution with exponent 4, we find a combustion efficiency of 98%.

## IV. STAGNATION PRESSURE LOSSES

Calculation of losses in stagnation pressure should be performed for comparing liquid-injection and gaseous-injection supersonic combustion. In the absence of such calculations, preliminary thought leads one to believe that the losses associated with heat release in supersonic flow are likely to be comparable in the two cases. However, the probable lower rate of heat release (after ignition) with droplet combustion may provide the designer with greater opportunities for changing motor geometry to alleviate losses. Also, it is quite clear that the stagnation pressure losses associated with injection of a liquid fuel are much less than those associated with injection of the same mass flow rate of gaseous fuel. Therefore, from the viewpoint of reducing the stagnation pressure losses, use of liquid injection may prove to be attractive.

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13. ABSTRACT

An experimental study was carried out to investigate the combustion of a liquid hydrocarbon (hexane) injected into a supersonic stream. Injection modes included wall and central injection configurations. Extremely rapid and intense heat release phenomena were obtained. It was concluded that this mode of combustion could be made to compete with that of pure gas phase combustion for many technological applications.

A preliminary theoretical model of the combustion mechanism was constructed which accounts for many of the observed phenomena, and which explains the very rapid combustion characteristics.

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| Ram Jet Engines |  |  |  |  |  |  |
| Viscous & Diffusive Mechanisms |  |  |  |  |  |  |
| Shockless Transition |  |  |  |  |  |  |
| Turbulent Transport Coefficient Models |  |  |  |  |  |  |
| Eddy Viscosity |  |  |  |  |  |  |
| Diffusivity |  |  |  |  |  |  |
| Conductivity |  |  |  |  |  |  |
| Mixing |  |  |  |  |  |  |

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