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STEADY-STATE ROCKET COMBUSTION OF  
 GASEOUS HYDROGEN AND LIQUID OXYGEN  
 PART I: EXPERIMENTAL INVESTIGATION

By  
 L. P. Combs and F. W. Hoehn

RESEARCH REPORT

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PART I: EXPERIMENTAL INVESTIGATION  
Research Report 64-24

By

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## FOREWORD

The steady-state combustion studies reported here were conducted largely under U.S. Air Force Contract AF49(638)-817, monitored by the Air Force Office of Scientific Research, of the Office of Aerospace Sciences. Simultaneous unstable combustion experimental work was supported by Rocketdyne liquid propellant combustion IR&D funds, as was the continued analysis carried out subsequent to the end of the AFOSR contract.

## ABSTRACT

Combustion of gaseous hydrogen and liquid oxygen has been studied experimentally under rocket conditions in an uncooled transparent-walled two-dimensional combustion chamber which simulated a 1-inch-wide diametrical section of a conventional cylindrical rocket combustor. Tests were made with three injector types using hydrogen chilled to simulate regenerative rocket engine injection temperatures. Photographic data were obtained which yielded considerable qualitative insight and quantitative information concerning the propellant combustion processes.



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## SUMMARY

An experimental program is described which was undertaken to provide a foundation for the formulation of physically realistic analytical models for steady-state rocket combustion with the liquid oxygen-gaseous hydrogen propellant combination. Experiments were conducted with three different injector types in a transparent two-dimensional rocket combustion chamber:

1. Coaxial Jet. The injector had 38 injection elements, spaced approximately uniformly 0.53 inch apart in a single row along the injector face. Each element formed a cylindrical LOX stream with an annular gaseous hydrogen flow surrounding it.
2. Triplet. Spaced nearly the same as the coaxial jet injector elements; 36 triplet elements each had two gaseous hydrogen streams impinging at a 60-degree included angle on a single LOX stream spaced midway between them.
3. Fuel Showerhead-LOX Doublet. Eighteen cylindrical fuel holes were spaced alternately with eighteen oxidizer self-impinging doublets.

All three injectors were designed for approximately 100 ft/sec LOX and 1000 ft/sec hydrogen (250 R) injection velocities. Gaseous hydrogen was chilled (by a liquid-nitrogen-jacketed heat exchanger and propellant flow system) to injection temperatures ranging from 180 R to ambient (about 500 R). Chamber pressure ranged from 420 to 520 psia; injection mixture ratio varied from about 3.8 to about 7.1 lb LOX/sec per lb H<sub>2</sub>/sec among the various tests. Difficulties in controlling the test conditions



arose because the hydrogen temperature and pressure decreased continually during each test and because the pyrex chamber liner melted so that the chamber contraction ratio gradually decreased throughout the 400-millisecond tests.

The test results of interest in this paper are largely photographic. High-speed motion pictures and luminous streak films were obtained using standard techniques. The motion pictures gave indications of the liquid oxygen spray shapes, liquid jet penetration lengths, locations where melting of the pyrex walls become important (and why) and, occasionally, vague, hazy clouds led to inferences concerning condensation of water vapor from recirculating combustion products. The streak films were analyzed to obtain maximum and minimum luminous streak velocities over the entire chamber length; velocity profiles are presented graphically for at least one test with each of the three injectors. In addition, static pressures at several positions along the length of the chamber were measured to complement the velocity data.

Experimental velocity profiles obtained with the coaxial jet and triplet injectors were similar and differed from those with the third injector. With those injectors forcing immediate intimate contact between the high-velocity hydrogen and liquid oxygen streams, all visible streaks had low velocities (100 to 400 ft/sec) until, at about the position of disappearance of the LOX jet in the motion pictures, a nearly discontinuous jump in gas velocity (maximum streak velocities) to about 2000 ft/sec was indicated. By contrast, the third injector permits liquid oxygen atomization to proceed without forced contact with the hydrogen stream; the streak velocities here indicate a more gradual, continuous buildup of gas velocity. The results are discussed in terms of differences in atomization and combustion processes.



## INTRODUCTION

This research report is the first of a series presenting the results of a combined experimental and analytical study of the processes that transpire during steady-state rocket combustion with gaseous hydrogen and liquid oxygen propellants. The study, initiated in 1962, was patterned after similar work, performed earlier with liquid oxygen-kerosene propellants (Ref. 1 and 2): experimental observations were obtained so that the formulation of analytical descriptions (models) for the entire propellant combustion field could be guided along physically realistic lines. Conversely, the same experimental techniques may be used for providing quantitative evaluation of predictions derived from analytical models.

Emphasis was placed, in the prior work (Ref. 2), on the essential interdependence between analysis and experiment: "..... the acquisition of experimental data can ..... encourage the development of improved spray combustion models. With sufficient supporting data, a model can be developed which is nearly free of unfounded simplifying assumptions. Since the model is based on specific data, however, it must be recognized as a specific model for the particular propellants, injector type, and operating conditions employed in obtaining the data". The emphasis is still appropriate.

The experimental observations mentioned are acquired from model rocket motors especially designed for high-speed photography of the combustion processes. Both motion and streak photographic techniques are employed; in addition, conventional rocket test instrumentation provides nonphotographic data. Information is sought concerning propellant spray formation,



geometric spray distributions, axial velocities of combustion gases and of accelerating spray elements, propellant injection rates, chamber pressure along the length of the combustor and such peripheral phenomena as whether combustion gas recirculation near the injector appears to be of much importance, whether chamber pressure "noise" is random or appears to be ordered, and whether the combustion gas flow is characteristically uniform across the chamber width, or striated.

The rocket combustion processes of hydrogen and oxygen are of particular interest for several reasons: (1) it is the first propellant combination in which both fuel and oxidizer are cryogenic liquids, (2) the first of practical importance in which a propellant used to regeneratively cool the combustor walls and nozzle is gasified prior to its injection, and (3) is thus one in which the combustion rate might be controlled by the liquid-to-vapor conversion process of the oxidizer. These phenomena, unique to hydrogen/oxygen combustion, could conceivably cause the combustion processes to differ markedly from those accepted as the controlling processes with earlier conventional propellant combinations.

When the current study was begun, it was thought it would be possible to pattern both the experimental and analytical approaches after the preceding LOX/kerosene work. A straightforward, expeditious combustion model development was envisioned. Accordingly, the work was started by designing and testing propellant injectors of three different styles. Evaluation of the experimental results strongly suggested, however, that the combustion processes (for at least two of those injection systems) were so different from the processes characteristic of systems studied earlier that complete reformulation of the combustion model was in order. The experimental observations for all three injector types, whether or not they have been used for combustion model formulation, are included in this paper. The analytical formulation for the coaxial jet injection type will be presented in the second paper of this series.



## EXPERIMENTAL EQUIPMENT

## COMBUSTION CHAMBER

All experiments were conducted in a transparent two-dimensional research model combustion chamber\*. The combustion space represents a 1-inch-wide diametrical slice of a typical high-thrust engine combustor with flat transparent side walls for the cutting planes. The side walls of the chamber, made from 4-inch-thick Plexiglas with a 3/16- or 1/4-inch-thick pyrex liner to protect the inner surface, are held apart by uncooled copper spacers. These spacers are machined to provide combustion space cross-sectional area vs length profiles that simulate particular conventional rocket combustor shapes and chamber contraction ratios. A steel structural frame is used to clamp the combustion chamber tightly together and to provide required wall rigidity for relatively high chamber pressure operation (Fig. 1). Except for areas obscured by the structural members, the combustion field from the injector to the nozzle throat is visible for photographic observation.

For all tests discussed in this report, the combustion space had a constant 1.00- by 21.63-in. cross section from the injector face to 12.5-inches downstream of the injector, then converged to a 1.00- by 13.50-inch cross-section nozzle throat at 22.7 inches downstream of the injector.\*\* The initial chamber contraction ratio was thus 1.60, which

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\*Several tests were also made using combustion chambers having uncooled copper side walls; the results of those tests are not included in this paper.

\*\*The combustion space width, while nominally 1.00 inch, is dependent upon both individual spacer bar and pyrex wall plate thicknesses. For some tests, the width was as low as 0.93 inch.



corresponds closely to those of several high-thrust engines. During the mainstage portions of the experiments with hydrogen/oxygen propellants, however, melting of the pyrex walls began a few milliseconds after full chamber pressure was achieved. Small globules of molten glass were continuously shed from the chamber exhaust so that the nozzle throat area gradually increased throughout each test and the contraction ratio gradually decreased. It will be shown in Part II that the contraction ratio had decreased to approximately 1.30 to 1.40 within the first 300 milliseconds of some tests.

#### INJECTORS

Existing propellant injectors, previously machined for other propellant combinations, were reworked for the LOX/hydrogen experiments. Three different injection schemes were selected for evaluation:

1. Coaxial Jet (Fig. 2). This injector had 38 individual coaxial jet elements equally spaced, 0.531-inch center to center, on the basis of 39 elements--the center space was machined for hypergolic liquid igniter injection. Each coaxial jet element consisted of a 3/16-inch-OD by 0.132-inch-ID tube centered in an 0.291-inch-diameter hole through the injector face. Liquid oxygen was injected through the cylindrical tube; gaseous hydrogen was injected through the annular space surrounding the tube. The ends of the tubes protruded approximately 0.12 inch beyond the injector face.
2. Triplet. Spaced the same as the coaxial jet injector elements, except for a blank element space on each side of the central hypergol injection port, 36 triplet elements each had two gaseous hydrogen streams impinging, nominally at a 60-degree



included angle, on a single LOX stream spaced midway between them. The LOX stream was from a 0.136-inch-diameter hole drilled normal to the injector face, while the hydrogen streams were from 0.152-inch-diameter holes whose centerlines were 0.486 inch apart at the injector face. The hydrogen streams thus nominally impinged on the liquid oxygen streams about 1/2-inch from the injector face.

3. Fuel Showerhead-LOX Doublet. Eighteen cylindrical fuel injection holes, each of 0.302-inch diameter and drilled normal to the injector face, were spaced 1.063 inch apart, linearly along the injector face. Midway between each pair of these fuel showerhead holes was an oxidizer self-impinging doublet injector element; two 0.136-inch-diameter holes drilled at 70-degree angles from the face to form two liquid streams impinging at a 40-degree angle at about 1/2 inch resulted in a more or less flat propellant spray fan parallel with the chamber walls.

The two latter injector types are illustrated in Fig. 3. The total injection hole areas for both fuel and oxidizer were kept approximately the same among the injectors so that all would have approximately 100 ft/sec LOX and 1000 ft/sec fuel injection velocities at a mixture ratio of 5.0 and with 250 R hydrogen injection temperature.

#### GASEOUS HYDROGEN SUPPLY

Rocket systems employing liquid hydrogen as a regenerative chamber coolant typically may have hydrogen injection temperatures ranging from 150 to 350 R during mainstage, depending upon the combustor geometry and



operating mixture ratio and chamber pressure conditions. For that reason, a chilled gaseous hydrogen supply system was used for the transparent two-dimensional combustion chamber experiments. Gaseous hydrogen, obtained from approximately 2500 psig, ambient-temperature supply, was flowed through a coil of high-pressure, 1/2-inch-OD stainless steel tubing immersed in a 250-gallon tank of liquid nitrogen, then into a 400-gallon liquid-nitrogen-jacketed run tank. Flow from this tank to the combustor injector was through a 3-inch liquid-nitrogen-jacketed pipeline. The line included an orifice meter installation. The same system was used without liquid nitrogen in the jackets to supply ambient-temperature hydrogen to the combustor.

The chilling coil exhibited a very high pressure drop so it was not possible to maintain the chilled run tank pressure during a test by flowing cold hydrogen into the tank as it was being exhausted.\* The run tank was thus used as a blowdown reservoir. The weight flowrate of fuel during the mainstage portions of the experiments with chilled hydrogen amounted to about 4 to 10 percent of the initial weights of hydrogen in the storage system; comparable values of system pressure decay during mainstage were observed.

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\*One attempt at maintaining tank pressure by bypassing the chilling coils and flowing warm hydrogen into the tank as the chilled gas was being removed demonstrated that the warm gas short-circuited through the tank and raised the discharge temperature excessively.



## INSTRUMENTATION

Normal steady-state rocket motor static test instrumentation was used to record propellant tank pressures and discharge temperatures, injection manifold pressures and temperatures, and liquid oxygen flowrate. Gaseous hydrogen flowrate was measured with an orifice meter installation.\* Chamber pressure was measured at several positions along the combustion chamber length. For increased measurement accuracy, differential pressure transducers were used and a precise reference pressure slightly below the anticipated chamber pressure was applied to the low-pressure sides of those transducers.

In addition, at least one high-frequency-response Photocon pressure transducer was installed in each of the propellant manifolds and one was flush-mounted in the combustion chamber near the injector face. The Photocon outputs were recorded on FM magnetic tape; their main purpose was to monitor attempts to induce combustion instabilities not discussed in this report (Ref. 3). They are also useful in discriminating between random combustion noise and oscillatory combustion of such low amplitude that it is not considered unstable.

## COMBUSTION PHOTOGRAPHY

Photographic records of the combustion processes in the transparent chamber were obtained with a number of 16mm Fastax cameras. High-speed motion pictures were taken (using techniques described in detail in

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\*With orifice/pipe diameter ratio of 0.85, orifice tap pressure differentials of 5 to 50 psi were measured. In view of these extreme values, together with questionable precision of hydrogen temperature measurement, hydrogen flowrate measurement accuracy of about  $\pm 10$  percent was estimated.



Ref. 4) of the entire combustion chamber for observation of phenomena that might affect the validity of the test (chamber leakage, pyrex wall disintegration, nozzle erosion) and of specific local areas immediately downstream of the injector for observation of LOX jet atomization, spray geometries and interactions, recirculation, and other characteristics of the injection region. Color films were used almost exclusively for motion photography.

Modified 16mm Fastax cameras were used to obtain streak photographs simultaneously with the motion pictures. By removing the framing prism from the camera and placing a 0.002-inch-wide slit at the film plane, perpendicular to the film edges, the rapidly moving film was continuously exposed to the luminous emission from a long, narrow field of view along the chamber length. This is illustrated in Fig. 4. The resulting films are continuous time records of the luminosity along the length of the chamber.

With oxygen/hydrogen propellants the luminous emission from the combustion processes is not very intense. Further, the physical and transport properties of the combustion gases enhance heat transfer to the walls so that an intense yellow-orange emission is radiated from hot pyrex wherever high-velocity combustion gases contact the walls. The luminosity of the reacting combustion elements is discernible under these conditions only because of their motion. As a consequence, two streak photographs were taken during most of these tests: an injector-end film extended over the first 12 inches downstream of the injector and the exposure was set to reveal the least luminous region very near the injector; a nozzle-end film extended from 6 inches from the injector to the chamber exhaust and was exposed through a Wratten No. 39 filter to reduce the over-exposing effect of pyrex emission. Kodak Plus-X film was used for streak photography. A short segment of one of the injector-end films appears in Fig. 5.



### EXPERIMENTAL PROCEDURE

A special start sequence was developed which avoided excessive start transient damage to the pyrex lining of the chamber and provided a moderately long prestage for cooling both propellant systems and the injector before entering the mainstage portion of a test. The importance of the propellant system being well chilled derives from the limited useful mainstage duration imposed by a decaying hydrogen supply pressure and by nozzle-throat melting and erosion.

Prestage oxygen, at about half the mainstage flowrate, was turned on about 2.0 seconds before mainstage; about 1.0 second later a flow of triethylaluminum through the center element of the injector ignited hypergolically with the oxygen and burned continuously until after the hydrogen flow was established. The hydrogen valve was opened very slowly starting about 0.5 seconds before mainstage;\* fuel manifold pressure increased nearly linearly to approximately 90 percent of its mainstage value in approximately 250 milliseconds. Prestage combustion, then, was characterized by a gradually decreasing mixture ratio and increasing chamber pressure until values about half those of mainstage conditions were obtained.

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\*The gradual increase of gaseous hydrogen flowrate assured both complete ignition while the flow was very low and a continuous positive chamber pressure. In an early test, impulsive initiation of full flow apparently introduced so much jet momentum that a momentary vacuum was applied to the walls and the pyrex-to-Plexiglas bond was destroyed.



The step to mainstage was accomplished by rapidly opening an oxidizer main valve. Chamber pressure increased to its mainstage equilibrium value in about 50 milliseconds. The tests were terminated after about 400 milliseconds of mainstage by simply closing the liquid oxygen valves. Hydrogen flow was continued for an additional 1 second to prevent hardware burning by bursts of residual LOX entering the chamber during the shutdown transient.



## EXPERIMENTAL RESULTS

The conditions for, and some results from all the transparent two-dimensional combustion chamber experiments with liquid oxygen/gaseous hydrogen are given in Table 1. Additional results from selected experiments are shown in Fig. 6 through 8.

Static pressure data, measured at various distances from the injector face, are plotted in Fig. 6e\*, 7c, and 8e. The decrease in static pressure along the chamber length is due to the combustion gas expansion and acceleration. Calculated values for nozzle-end stagnation pressures indicate a decrease from the injector-end values and represent a loss of available energy by heat addition.

The most pertinent results of transparent chamber experiments at rocket operating conditions are photographic. Careful, detailed study of high-speed motion pictures can yield semiquantitative understanding of the combustion processes in depth that is not attainable by any other current means. These results are sometimes quite difficult to transmit by publication, however. In reproducing one frame or a few frames for publication, little (if any) of the dynamic quality is transmitted. Worse, some film sequences that are fairly informative when projected in motion may lose all meaning when reproduced as still photographs; that is, photography with grainy films, through badly cracked (yet geometrically intact) pyrex, or with marginal lighting or exposure, may result in such

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\*The chamber pressure data for run 417 appear high, probably due to a human error in manually setting the pretest differential reference pressure applied to the transducers. Comparing the flowrate and chamber pressure data to those from the other tests, an error of 100 psi is indicated.



loss. The experimenter thus learns much more than he is able to illustrate. For these reasons, only a few illustrative enlargements of single frames have been reproduced from the motion pictures; some of the results stressed in the Discussion section may appear not to be illustrated.

The streak photographic results are presented as velocity vs chamber-length plots. These were obtained by careful, detailed analysis of a 10-millisecond-long section of each streak film; usually this period was approximately 160 to 200 milliseconds after the establishment of full mainstage chamber pressure. A Vanguard Motion Analyzer was used to establish the maximum and minimum slopes of the luminous traces at various distances from the injector face. Knowledge of the chamber-camera geometric arrangement and of the instantaneous film velocity permitted determination of luminous particle velocity from those slopes. On the plots, the triangles are data from the injection-end films and the circles are data from the nozzle-end films.

Because of its important bearing on interpretation of streak velocity data plots from liquid propellant combustion experiments, a set of velocity data obtained from a recent experiment using gaseous hydrogen and gaseous oxygen propellants\* is included as Fig. 9. The coaxial jet injector was used; because the injection pressure drop was so high with gaseous oxygen, a chamber pressure of only 188 psia was attained. Four streak cameras were used with a wide latitude of exposure settings among them. Even so, none of the streaks in the neighborhood of the injector were reducible.

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\*The oxygen was injected cold, having been gasified just before the test by flowing a metered weight of liquid oxygen into the run tank, closing the vent and dropping the liquid into a warm, uninsulated pipeline to the test stand. Hydrogen was supplied at ambient temperature. Injection temperatures of 345 and 406 R were measured for the oxygen and hydrogen, respectively.



## DISCUSSION

Definitive combustion process and mechanism information may be discerned by careful examination of the experimental results of this work. The high-speed motion pictures reveal, for the most part in a qualitative manner, propellant spray densities and geometries, liquid jet penetration distances, relative steadiness of the injection, atomization and spray-spreading processes, geometric uniformity and stability of the combustion field, and the occurrence of combustion gas recirculation near the injector. Streak photographic results pertain to a more limited range of process phenomena than motion pictures, but frequently yield quantitative data. The interpretation of those results is thus crucial to the validity of the derived information.

A detailed discussion of the streak velocity data interpretation is developed in the Appendix. There, an upper boundary surrounding velocity data points is equilibrated to combustion gas velocity. Phenomena that could account for the lowest velocities are discussed at length, these include: large oxygen droplets persisting far down the chamber, combustion gas turbulence (Ref. 5), striations or "bubbles" of dense oxygen-rich gases in the combustion gas stream (Ref. 6), side-wall boundary layer effects (Ref. 7), and condensation of water vapor in the neighborhood of the injector. It is concluded that there is insufficient evidence to permit unequivocal assignment of the lowest streak velocities to any one of these phenomena.



## COAXIAL JET INJECTION

Approximately half of the experiments made in this study were with the coaxial jet injector. Some duplication of test conditions was made necessary by frequent failure to obtain streak films with reducible exposures. In particular, the film exposures over the first 12 inches of chamber length were erratic and unpredictable. Perhaps some of this resulted from changes in backlight placement in attempts to achieve improved quality with the Fastax motion pictures of the injection region.\*

During prestage operation at about half the mainstage chamber pressure and mixture ratio, the liquid oxygen jets were visible for only about  $1/2$  to  $3/4$  inch from the injector. Intense combustion close to the injector and strong combustion gas recirculation between jets was visible in the motion pictures. Excessive heat transfer to the walls was not a problem; only occasionally was pyrex wall melting observed during prestage with this injector.

The transition from prestage to mainstage, accomplished by opening the main oxidizer valve, was very apparent in the motion pictures. It was characterized by a smooth, continuous increase in the depth of penetration of the LOX jets into the chamber from the prestage values of less than 1 inch to depths ranging from  $3-1/2$  to 5 inches. The visible LOX jet lengths, among the mainstage portions of the several tests, appeared to be more a function of mixture ratio than of chamber pressure or hydrogen injection temperature. In all but the latest tests (No. 452 and 454),

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\*Eventually, a semibacklight, semisidelight technique was evolved. The lights were moved about 15 to 20 degrees away from being perpendicular to the liquid oxygen streams being illuminated. The streams usually appeared rosy-white against a dark blue-green to black background.



gross variations in liquid jet penetrations were seen to result from reed-like vibration of several individual liquid oxygen injection tubes. (The tubes had no lateral support over the last 2-1/2 inches of their length.) This condition, while it involved only about 15 to 20 percent of the tubes, gave a rather erratic, ragged appearance to the combustion field, since the jets concerned alternated in penetration from about 60 to 110 percent of those from steady tubes, and interacted to some extent with neighboring jets. Three short pieces of 3/64-inch-diameter wire were spaced 120 degrees apart around the outside of each tube and brazed in place to restrain the tube motion prior to test No. 452.

The LOX jets were observed to spread, presumably because of at least partial atomization, to about two to three times their initial injection diameters. Most of the spread was accomplished within the first inch of travel within the chamber. The outer boundaries of the LOX jet/sprays were predominantly smooth for about 1 to 1-1/2 inches; further downstream, rather large scale ruffles or eddies frequently disrupted the boundaries. The jet/spray's decrease in apparent diameter and disappearance was usually quite abrupt. Occasionally, the end of a jet would appear to be shorn off and swept downstream; these wispy fragments were very short-lived.

The position of the visual disappearance of the LOX jet/sprays corresponded reasonably well with the occurrence of an abrupt increase in the maximum velocities reduced from the streak photographs. Melting of the pyrex wall, as indicated by surface flow and intense emission (presumably from the sodium D line), frequently began less than an inch downstream of those occurrences. The molten pyrex seen in Fig. 6b beginning ] upstream of the ends of the LOX sprays was a result of LOX injection tube vibration earlier in the experiment.



The three phenomena just noted, abrupt disappearance of the LOX jet, abrupt increase in maximum observed velocity, and pyrex wall melting, are apparently interrelated. They give the implication that, once combustion becomes possible within the central oxygen-spray-bearing core of the system and flame penetrates that core, the rate of conversion of reactants to combustion products is very high and the combustion channel rapidly becomes filled with those products. The possibility of a plane flame front standing at a fixed position across a previously nonburning heterogeneous gas-spray mixture thus presents itself.

A schematic representation of the coaxial jet combustion processes associated with such a standing plane flame front is shown in Fig. 6f. The conditions upstream of the flame front are depicted as nonburning because a portion of the gaseous hydrogen stream is presumed not to be drawn into (nor "contaminated" by) the expanding liquid oxygen spray zone and can thus expand to fill the combustion channel and prevent recirculation of combustion gases. The observation of recirculation and its probable importance will be considered after discussing the LOX jet/spray zone.

A coaxial jet injection element is characterized by a relatively low-velocity liquid oxygen stream being completely surrounded by a higher velocity gaseous hydrogen flow. As long as the hydrogen stream presents a barrier, insulating the contained LOX stream from its surroundings, the jet atomization, spray acceleration, spreading, and evaporation processes will remain nonburning. At least two criteria must be satisfied before a flame can penetrate the spray zone and combustion can be sustained: first, enough oxygen must have evaporated so that the gases within the spray zone are flammable (perhaps 5 to 7 volume-percent oxygen), and second, the axial gas velocity must be equal to or less than the turbulent flame speed, or else an established combustion would be swept downstream.



The axial gas velocity within the spray zone should be lowest next to the atomizing LOX jet and that gas (having flowed through outer oxygen spray to get in against the liquid jet) might well have the highest oxygen content. Thus, there is a possibility of flame "creeping" upstream along the LOX stream and burning the spray from inside out. But if such combustion were not quenched (by excessive radiant heat loss due to its small size, or by excessive heat loss to a high population of evaporating LOX drops), it should be expected to expand radially and to engulf more and more of the spray while doing so. Eventually, however, its outward propagation would be delayed by encountering spray-gas mixture with a velocity greater than the turbulent flame speed. It is possible, then, to envision a hollow cone of nonburning spray surrounding a region of intense combustion. There is no evidence of such structure in any of the photographic data, so it seems reasonable that a further requirement is the existence of some stagnant or eddy regions for providing ignition energy from a stabilized flame source (Ref. 8). In the current experiments, these must lie outside the spray zone.

These observations suggest that the apparent insensitivity of the position of intense combustion to changes in chamber pressure and hydrogen temperature may reflect a complex tradeoff among the three criteria just discussed. For example, with warm gaseous hydrogen the oxygen spray might evaporate fairly rapidly but the hydrogen injection velocity would be so high as to keep the heterogeneous spray zone velocity from decelerating to the turbulent flame speed for some inches while, with cold gaseous hydrogen, the velocity requirement might be met well before enough oxygen had evaporated to render the gases flammable.

If the entire hydrogen stream were ingested into the expanding spray zone, combustion gases might be circulated upstream and drawn into the spray zone as well. Conceivably, enough thermal energy could thus be



introduced to accelerate appreciably the oxygen spray evaporation which would, in turn, lead to earlier satisfaction of the flammable oxygen concentration. Further, such circulation would undoubtedly react with the hydrogen-rich outer edges of the spray zone and provide a stabilized ignition source for the main body of the spray zone whenever it became ready to combust. Heidmann (Ref. 9), in photographing coaxial LOX/gaseous hydrogen jets injected radially into a windowed pancake motor, observed this type of phenomenon as a pale blue mantle surrounding the LOX spray. After viewing his films, the motion pictures from the experiments reported here were again reviewed; in a few cases, a very faint blue haze could be seen or imagined to surround a LOX spray downstream of about 1-1/2 to 2 inches from the injector. In no case was it possible to identify definite upstream motion of combustion gases but, significantly, local fogging of the pyrex walls by what appeared to be condensed water vapor was occasionally observed; usually, these occurrences came fairly early in mainstage and cleared later in the experiments. Some minor circulation appears to be going on.

Recognition that water vapor is a major portion of the combustion products and that both reactants are injected at temperatures far below the saturation temperature, suggests that gross combustion gas recirculation should be indicated by visible vapor clouds. The fact that none were seen further implies that only minor combustion gas circulation occurred during these experiments.

Some recirculation was seen in the neighborhood of the injector in test No. 452. Noticeable only during motion projection as a vague nonluminous upstream motion between jets, it was confined to about 1 to 1-1/2 inches from the injector.



The structure of the oxidizer-rich combustion gas flow, surrounding hydrogen or hydrogen-rich gas flow and reliance upon turbulent mixing for completion of combustion indicated in Fig. 6f, comes from earlier remarks about the meaning of the range of observed streak velocities and the gradually increasing upper-bounding velocities from the streak films.

With twisted-ribbon swirlers inserted in the liquid oxygen tubes, the visible LOX jet/sprays were approximately one-half the length without swirlers. The imposed angular liquid momentum effects a forced, intimate gas-liquid contact that should increase both the atomization rate and the exchange of momentum from the hydrogen stream to the oxygen spray. Earlier deceleration of the heterogeneous spray mixture to velocities below the turbulent flame speed and higher total rate of spray evaporation would rationally account for the observed shortening of the LOX jets with swirlers.

#### TRIPLET INJECTION

Prestage combustion with the triplet injector was different from that with the coaxial jet injector in that atomization and apparent consumption of the liquid oxygen stream occurred more rapidly, and oxygen-rich combustion gases were apparently forced out of the combustion regions toward the walls. Fairly severe wall melting and erosion were experienced during prestage; as a result, the quality of the motion pictures was somewhat degraded.

Combustion under mainstage conditions, however, was similar in many respects to that with the coaxial jet injector. The main characteristic-- that of an abrupt increase in gas velocity indicating a quasi-standing



flame-front combustion mechanism--was the same. The forced momentum exchange resulting from impinging two gaseous hydrogen streams on each LOX jet enhanced the atomization rate and perhaps the spray vaporization rate so that combustion apparently became possible at about 2 to 2-1/2 inches from the injector. This forced momentum exchange interpretation is similar to that in the preceding section regarding swirlers in the coaxial jet LOX supply.

Steady-state combustion with the triplet, however, was not entirely steady; the motion pictures clearly showed that lengths of the visible LOX sprays oscillated axially between about 1-1/2 and 2-1/2 inches. Evidence of the oscillations could be found on the streak films; in Fig. 7b the upper left boundary encloses a few data points reduced at a time when the visible sprays were shortest. The spray length oscillations, as seen by motion projection of the high-speed motion pictures, appeared to occur with a reasonably constant period but neighboring sprays were sometimes in phase and at other times out of phase and no general phase relationship across the width of the chamber could be discerned. Pressure records, obtained with a Photocon whose sensing diaphragm was flush with the inside of the chamber and 1-3/4 inches from the injector face, showed very mild fluctuations with periods corresponding to frequencies ranging from 1200 to 1600 cps. Oscillation amplitudes were approximately 10 psi (peak to peak) which is only 2 to 3 percent of the static chamber pressure. While the apparent frequency of the pressure fluctuations was close to the calculated frequency of the chamber's longitudinal acoustic mode (1150 cps) and the observed frequency of the first transverse acoustic instability (1500 to 1600 cps), the very low amplitudes and lack of well-defined phase relationships suggest that the oscillations were combustion phenomena not coupled with the chamber



acoustics. Perhaps something like the disruption and re-establishment of combustion gas recirculation could cause a modest change in the LOX spray vaporization rate which would, in turn, be reflected in the position at which a flammable gas mixture was established. The motion pictures did not show such details, however.



## FUEL SHOWERHEAD-LOX DOUBLET INJECTION

The combustion processes observed with this injection scheme were distinctly different from those delineated and discussed in the two preceding sections. Here, the liquid oxygen atomization proceeds without direct forced momentum exchange with the high-velocity gaseous hydrogen stream. A corollary of this is that the hydrogen stream expansion and deceleration transpire without gross transfer of momentum to accelerating spray droplets; the hydrogen stream momentum is available for inducing voluminous circulation of combustion gases upstream where they can be ingested into both the hydrogen stream (page 608 of Ref. 7) and into the oxygen spray.

Liquid spray droplets are formed, therefore, in the presence of hot combustion-product gases. Since the oxygen vapors of an evaporating droplet are capable of further oxidizing the circulated combustion gases (thus, maintaining relatively high reaction temperatures), individual spray elements would appear to be surrounded by a reaction front continuously from their formation to complete consumption. The energy and momentum for completing the liquid stream atomization and accelerating the resultant spray would thus be supplied by the local combustion processes.

Ample evidence for such a phenomenological description were found in the experimental data. The circulation of combustion gases was particularly clear in the test with ambient-hydrogen injection temperature; its volumetric rate apparently increased with increasing hydrogen injection momentum as theory predicts (Ref. 7). The circulation was strong enough to be revealed on the streak films as upstream-directed flow (negative velocity data points, Fig. 8c). The unchanged visible length of the LOX



sprays, between tests with chilled and ambient hydrogen, would seem to corroborate the additional circulation caused by and, thus, being mixed with the hydrogen stream. It is interesting that comparison of the upper-bounding combustion-gas velocities in Fig. 8c and 8d suggests that mixing more circulated combustion gas with the hydrogen stream might result in a more rapid approach to complete combustion.

There was no evidence of a general nonburning region with this injector. A realistic physical model for LOX/GH<sub>2</sub> with this injection scheme would, thus, be more closely related to work previously published concerning LOX/RP-1 propellants (Ref. 2) than to that discussed above for coaxial jet and triplet injection of LOX/GH<sub>2</sub>.



APPENDIX

**STREAK VELOCITY DATA INTERPRETATION**

The luminous traces recorded on the streak films are undoubtedly caused by variations in intensity of the radiant energy emitted from neighboring incremental elements reacting with each other as they flow in the combustion field. If the flow is approximately one-dimensional and in a direction along the streak camera's field of view, each burning element is observed during its passage over the entire length of the field of view. Differences in emission between one element and neighboring elements can persist only if the elements contain different chemical species, are at different temperatures, are exposed to differences in external excitation, or are interacting with other neighboring flow elements in unlike manners. Some phenomena that could conceivably account for the luminous traces on the streak film are: chemical reaction fronts in the vicinity of evaporating propellant droplets; small-scale, but appreciable variations in gas-phase composition (apparent fuel/oxidizer mixture ratio) even though temperature and pressure might be uniform; and emission from droplets, concentration striations, or recombination reactions in the decelerated flow within the wall boundary layer.

In interpreting previous experimental results with liquid oxygen/kerosene, one-dimensional spray combustion analysis was used to advance a strong argument for attributing the luminous traces to evaporating, reacting propellant droplets (Ref. 1). The highest velocity streaks were related to combustion field elements (gases or very small droplets) traveling at or nearly at the local combustion gas velocity, while the lowest velocity streaks were related to the largest, slowest moving kerosene droplets. Further support for that interpretation was offered by a successful



extension of the analysis to both propellant species and into the non-uniform injection region (Ref. 2).\*

As the streak data presented in Fig. 6c, 6d, 7b, 8c, and 8d for LOX/gaseous hydrogen were accumulated and reduced, it became increasingly apparent that the combustion fields downstream of 8 to 10 inches from the injectors were remarkably similar. This led to a strong suspicion that some phenomenon other than emission from large oxygen droplets might be responsible for the nearly constant 1000 ft/sec range of streak velocities, and eventually led to a decision to conduct an experiment with both propellants injected as gases. As seen in Fig. 9, the velocity data reduced from streak films exposed to the combustion field with coaxial jet injection of gaseous oxygen and gaseous hydrogen have a range not appreciably different than those observed in experiments using liquid oxygen. Immediately, one must conclude that the lower velocity data with LOX/hydrogen cannot be interpreted, unequivocally, as evidence that large liquid oxygen droplets penetrate far down the combustion chamber. This does not imply that there are not large droplets evaporating and accelerating in the combustion field but simply that, if such droplets exist, they are small enough to travel at higher velocities than the minimum streak velocities.

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\*An alternative interpretation of the observed range of streak velocities, that true mean axial combustion gas velocity is represented by some median value of the streak data, has been advanced (Ref. 5); those velocities above and below the mean were ascribed to turbulent fluctuations in velocity. This hypothesis fails to account for the fact that a boundary enclosing the maximum streak velocity data approximates closely the attributes of a one-dimensional burned gas flow (sonic velocity at the throat, acceleration from the proper geometrically prescribed velocity at the nozzle inlet) while lower values are too low to satisfy these attributes.



Some other phenomenon or mechanism that can account for the lower streak velocities must be sought. The evidence here is apparently not sufficient to provide a definitive choice between concentration striations in the combustion gas stream, emission from the decelerated flow in the boundary layer, and emission from visible water droplets. The following paragraphs present some ideas on this subject; it will be discussed more fully in a subsequent report which will include data and observations with other propellant combinations.

The behavior of gas "bubbles" of different densities than an accelerating gas stream which contains them (Ref. 6) provide qualitative evidence that the range of streak velocity data might reasonably result from the dynamics of pockets or striations in the combustion gas flow field. Such striations might come from the propellant distribution inherent with a particular injector, such as: the gases axially downstream of a coaxial jet or a LOX doublet might be grossly oxidizer-rich as compared with gases midway between such axes; or they might come from much more local sources such as the sudden conversion of a large liquid oxygen droplet to a vapor pocket (perhaps due to aerodynamic shattering, droplet heating through the critical temperature or condensative heat transfer). Gas pockets with densities higher than the surrounding combustion gas flow will experience lower accelerations than their surroundings. How much lower depends upon the ratio of densities, the shape of the pocket, and how much of the available translational energy is lost to vorticity of the pocket (Ref. 6). The inverse, higher acceleration of less dense gases, also occurs but in a rocket combustion flow field even pure hydrogen would have to undergo considerable heating before it would be lighter than the high temperature combustion products.



If the behavior of a cold, dense gaseous oxygen pocket in a combustion gas flow is assured, then at the time of its formation, it probably has a velocity somewhat, but not greatly, in excess of the axial LOX injection velocity. Thus, it may already be several hundred feet per second slower than the surrounding gases. Its acceleration, based upon the analysis of Ref. 6, might range from approximately 80 percent of the combustion gas acceleration for very dense oxygen vapor to approximately 95 percent for an oxygen-rich gas pocket with twice the gas stream density. One might expect then, as radiant and convective heat transfer heated the pocket and as turbulent mixing gradually converted it to an oxygen-rich combustion gas striation, that its rate of acceleration would approach that of the surroundings. Having accelerated from a lower initial velocity in the injection region, however, its velocity would always remain below the surrounding gas stream velocity.

The lower boundaries, enclosing the streak velocity data in the first 3 or 4 inches from the injectors, approximate for the most part, LOX injection velocities. The inflections to increasing lower boundary velocities probably correspond with completion of LOX jet atomization. For a short distance downstream of that point, the lower boundary must reasonably be attributed to large LOX droplet trajectories. The vapor pocket mechanism being discussed here would be evident only downstream of that region where droplets accounted for the lower boundary. To illustrate this, two sets of velocity calculations, each based upon 90 percent of the upper boundary velocity acceleration, but starting at different distances from the injector, are shown as dashed curves on Fig. 6d. Of course, the phenomena in the combustor are not nearly so simple as the conceptual discussion here implies. Things have been ignored, such as the superposition of combustion energy release around the pocket, the possibility that the summation of pockets may contain



more of the propellant mass flowrate than the combustion gas stream and momentum exchange, both between the gas streams (acceleration of the lower velocity pocket even if the combustion gas velocity is constant) and between gases and spray droplets contained within them.

Next, consider the possibility that the range of observed streak velocities might be associated with the wall boundary layer; this discussion is based in large part upon information from chapter XX of Ref. 7. The velocity boundary layer in a rectangular pipe can be related to that in a cylindrical pipe through the hydraulic radius; the equivalent hydraulic radius of the two-dimensional chamber is just under 1 inch. The highest gas velocity occurs at the center of the flow channel, while the gas velocity at the walls must be zero. At equivalent hydraulic distances of 0.05 and 0.10 inch from a smooth wall, the gas velocities should be approximately 70 and 76 percent of the highest centerline velocity, respectively. Existing with the velocity boundary layer is a thermal boundary layer with a radial temperature profile which usually drops to the wall temperature more sharply than the velocity profile falls to zero.

One possibility is that the gases closer than some critical distance to the wall are so cool that their emission is too weak to expose the streak films, while those gases further out in the channel would have strong enough emission to expose the films but, being within the velocity boundary layer, would have relatively low velocity. A major argument against such an interpretation arises from the similarity between streak velocity data with continually smooth pyrex walls (gas-gas test) and melting-roughened pyrex walls. The velocity boundary layer should be thickened by two to three times the distance from the wall for a given intermediate gas velocity, while the thermal boundary layer would be



only slightly thickened. Thus, a streak velocity range perhaps as much as 50 percent wider should be expected with molten pyrex walls. Further, exposure of the streak films by the lowest-velocity visible gases within a decelerated boundary layer flow should occur continuously while, in the actual data reduction, they must be carefully sought and are almost always found displaced in time from one another.

Another possibility is that the lowest streak velocities are caused by migration of droplets into the decelerated boundary layer flow. In the case of the gaseous oxygen-gaseous hydrogen experiment, the only possible source of droplets is condensation of water vapor.

The recirculation and mixing of combustion product gases with unreacted propellants near the injector could conceivably result in cooling large volumes of water vapor below the saturation temperature (905 R at 400 psia). Appreciable condensation from the gas phase could thus occur, but the droplets would probably be very small (perhaps even submicron) in diameter. Either continued circulation or direct condensation on the chamber walls could, however, result in wetted walls, from which aerodynamic shear forces could strip sizable droplets. Compared to liquid oxygen, small water droplets would evaporate very slowly, due mainly to a high latent heat of vaporization, high critical pressure, and lower molecular weight. Water droplets are, therefore, more likely candidates for revealing boundary layer velocity gradients than are oxygen droplets.

Although no direct observation of water droplets can be cited, there is indirect evidence of condensation. In tests with the coaxial and triplet injectors, motion pictures showed an occasional haziness of the transparent walls in the region near the injector. Similarly, freezing of condensate on the walls was reported in Ref. 3. On the other hand,



recirculation of combustion gases is known to have occurred with the fuel showerhead-LOX doublet injector and no evidence of condensation was observed.

The interpretation of the lower boundary enclosing the streak velocity data thus remains an enigma over a large part of the chamber length.



## REFERENCES

1. Lambiris, S. and L. P. Combs: "Steady-State Combustion Measurements in a LOX/RP-1 Rocket Chamber and Related Spray Burning Analysis," Detonation and Two-Phase Flow, Volume 6 of the ARS Progress in Astronautics and Rocketry Series, Academic Press, New York, N.Y., 1962, 269-304.
2. Lambiris, S., L. P. Combs, and R. S. Levine: "Stable Combustion Processes in Liquid Propellant Rocket Engines," Combustion and Propulsion, Fifth AGARD Colloquium: High Temperature Phenomena, The MacMillan Company, New York, N.Y., 1963, 569-634.
3. Hoehn, F. W. and R. B. Lawhead: "Combustion and Combustion Instability in Liquid Oxygen/Hydrogen Rocket Systems," (U), Bulletin of the Fifth Liquid Propulsion Symposium, Chemical Propulsion Information Agency, Silver Spring, Maryland, November 1963, 243-308, CONFIDENTIAL.
4. Lawhead, R. B.: "Photographic Studies of Combustion Processes in Liquid Propellant Rockets," Eighth Symposium (International) on Combustion, Williams and Wilkins Co., Baltimore, Maryland, 1962, 1140-1151.
5. Baker, P. D., R. G. Peoples, and T. R. Mills: Two Dimensional Motor Program, Aerojet General Corp. Report No. 2185, Azusa, California, January 1962.
6. Rudinger, G. and L. M. Somers: "Behavior of Small Regions of Different Gases Carried in Accelerated Gas Flows," Journal of Fluid Mechanics, Vol. 7, 1960, 161.



7. Schlichting, H.: Boundary Layer Theory, McGraw-Hill Book Co., New York, N.Y., 4th Edition, 1960.
8. MacCallum, N. R. L.: "Flame-Spreading Characteristics in Combustion," Combustion Researches and Reviews, 1957, Butterworths Scientific Publ., London, 1957, 31-39.
9. Heidmann, M. F.: Informal presentation of technical films at 15th AFOSR Contractors' Meeting on Liquid Rocket Combustion Research, Chicago, Illinois, June 1962.



TABLE 1

## SUMMARY OF EXPERIMENTAL RESULTS

Injector	Test No.	Injector End $P_c$ , psia	Mixture Ratio, o/f	Hydrogen Injection Temperature, R	Propellant Flowrate, lb/sec	
					LOX	Fuel
Coaxial Jet	417		4.9	~500	22.5	4.6
	418	516	5.0		26.4	5.3
	419	516	5.0		24.7	4.9
	431		7.1	315	24.9	3.5
	432	516	4.1	205	24.8	6.1
	433	522	5.2	210	25.7	4.9
	452	459	5.8	200	26.8	4.6
	454	523	3.8		20.0	5.3
Triplet	445	504	4.8	203	24.1	5.0
	446	479	4.4	228	24.6	5.6
	450	490	4.8		23.4	4.9
	451	460	5.7	273	23.2	4.1
Fuel Showerhead- LOX Doublet	447	427	7.5		21.0	2.8
	448	450	6.8	346	22.3	3.3
	449	525	4.0	225	21.1	5.3
	453	418	6.3	~500	22.7	3.6

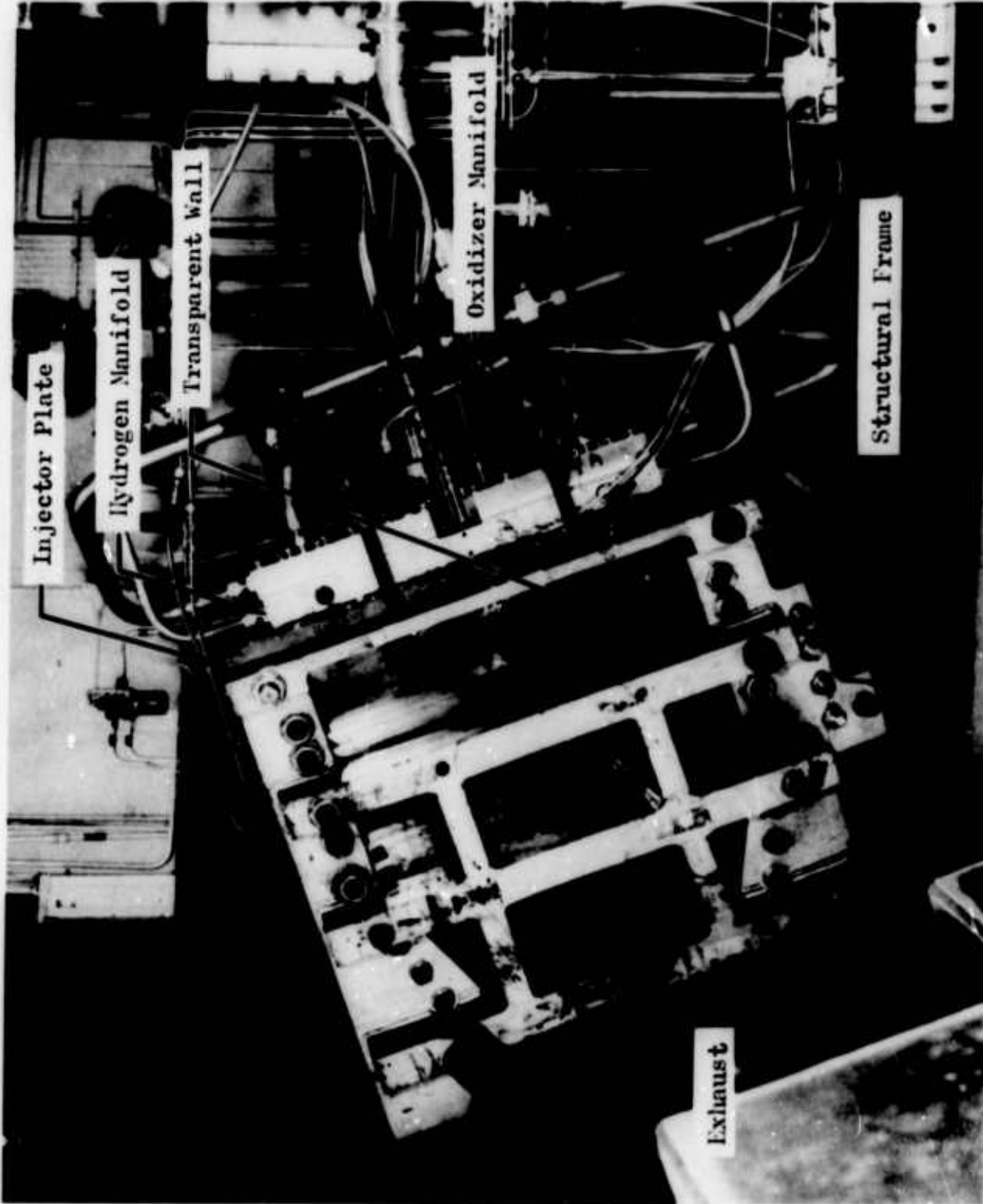


Figure 1. Transparent-Walled Two-Dimensional Research Combustion Chamber

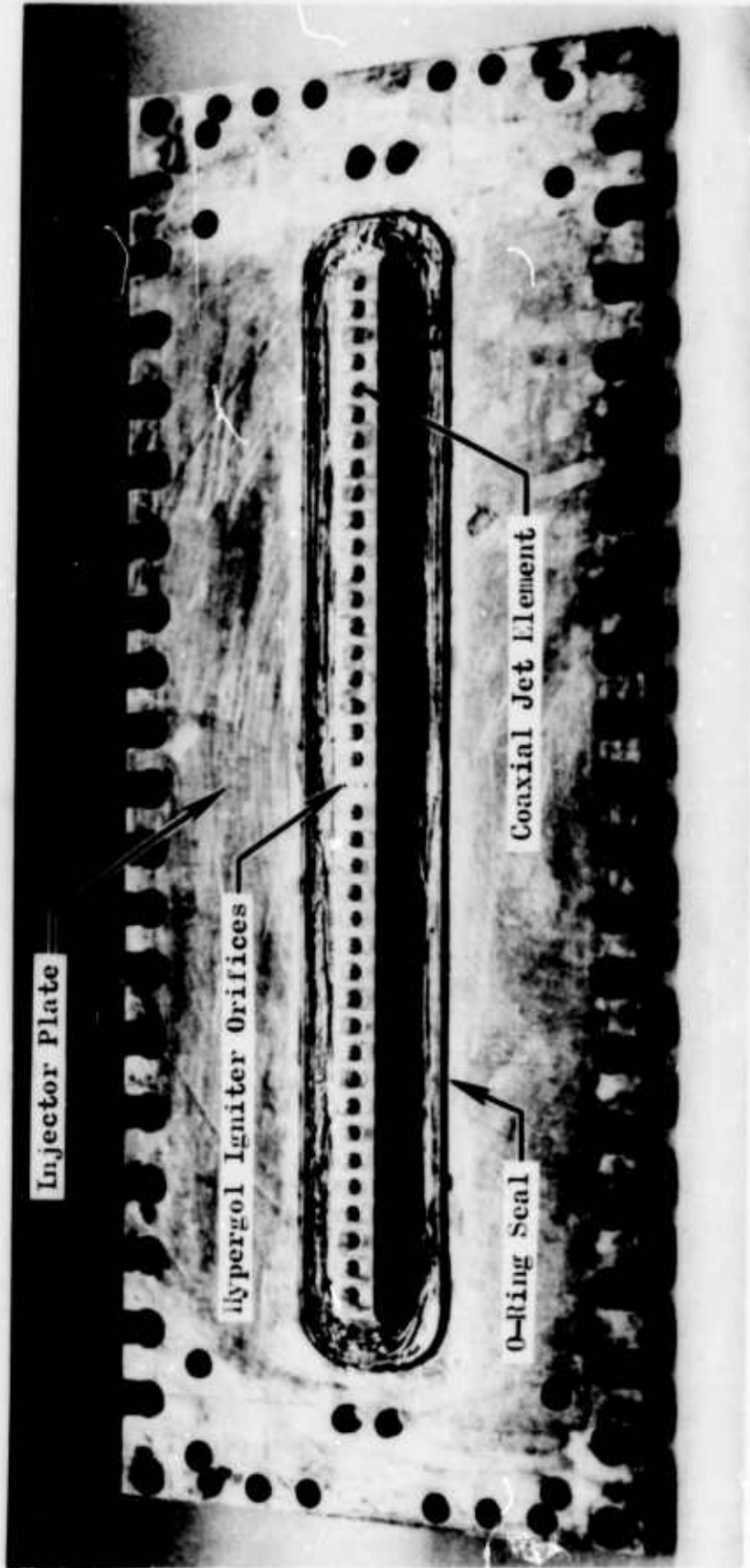
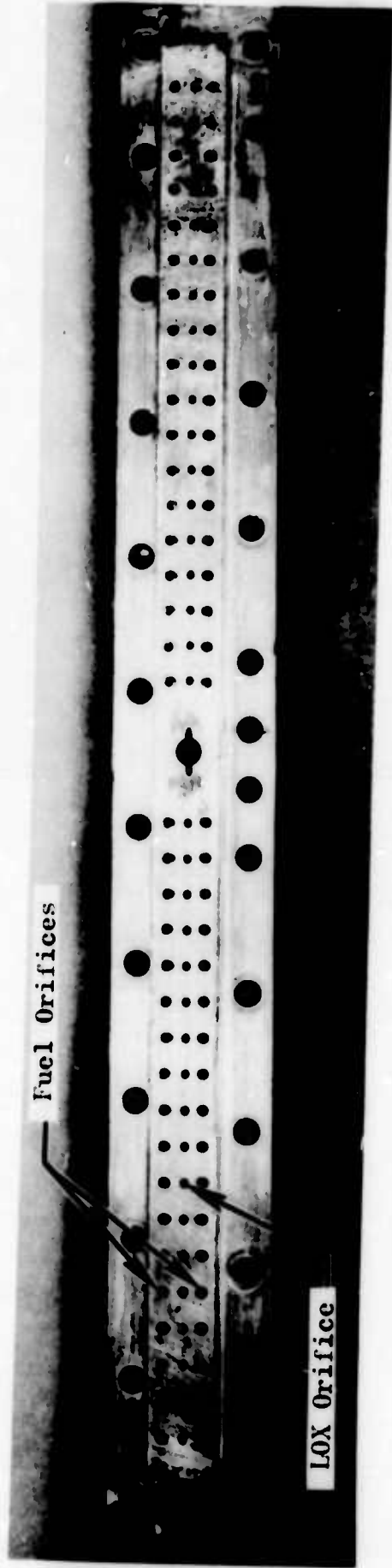
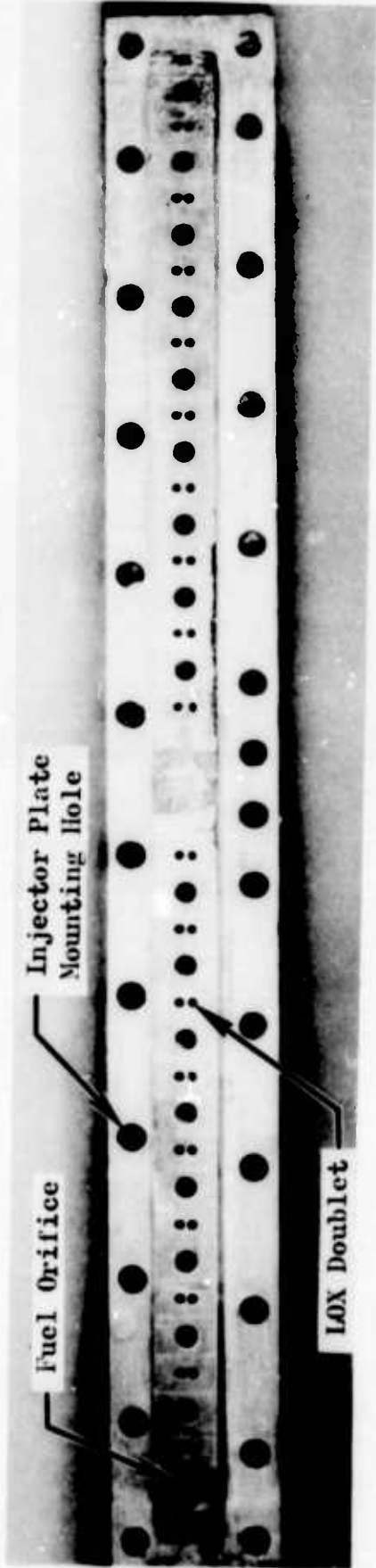


Figure 2. Coaxial Jet Injector for Two-Dimensional Research Combustion Chamber



Triplet Injector



Fuel Showerhead/LOX Doublet Injector

Figure 3. Triplet and Fuel Showerhead/LOX Doublet Injectors for Two-Dimensional Research Combustion Chamber

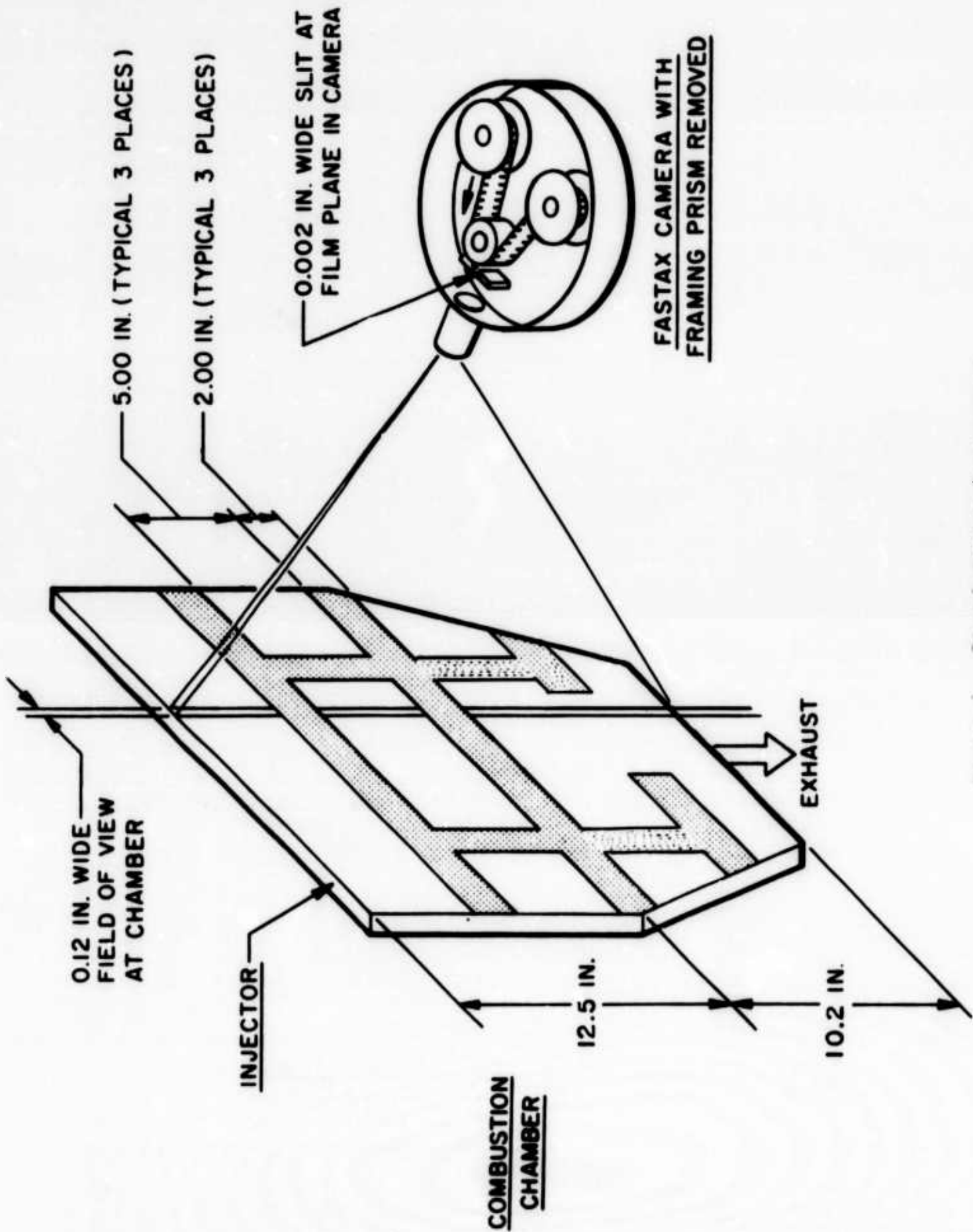


Figure 4. Streak Camera Arrangement

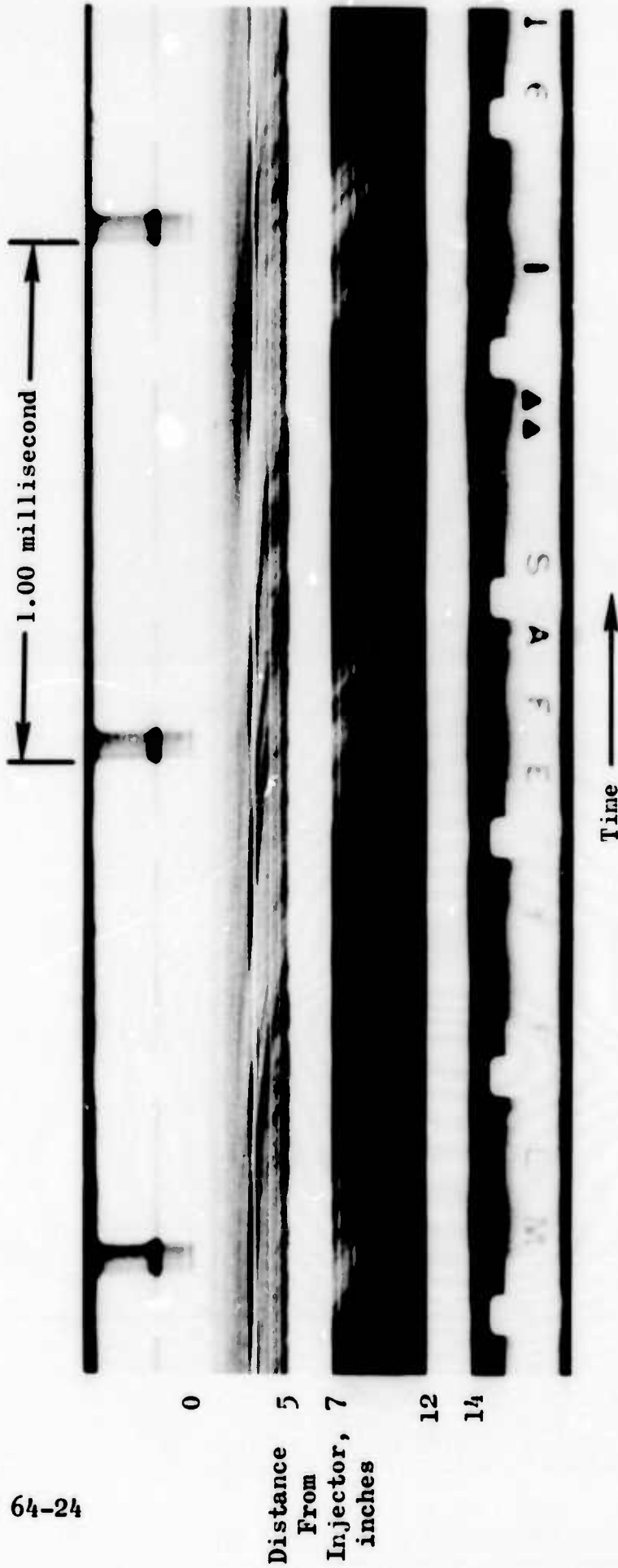


Figure 5. Enlargement of Typical Streak Photograph From LOX/GH<sub>2</sub> Combustion; Coaxial Jet Injection (Negative Print)

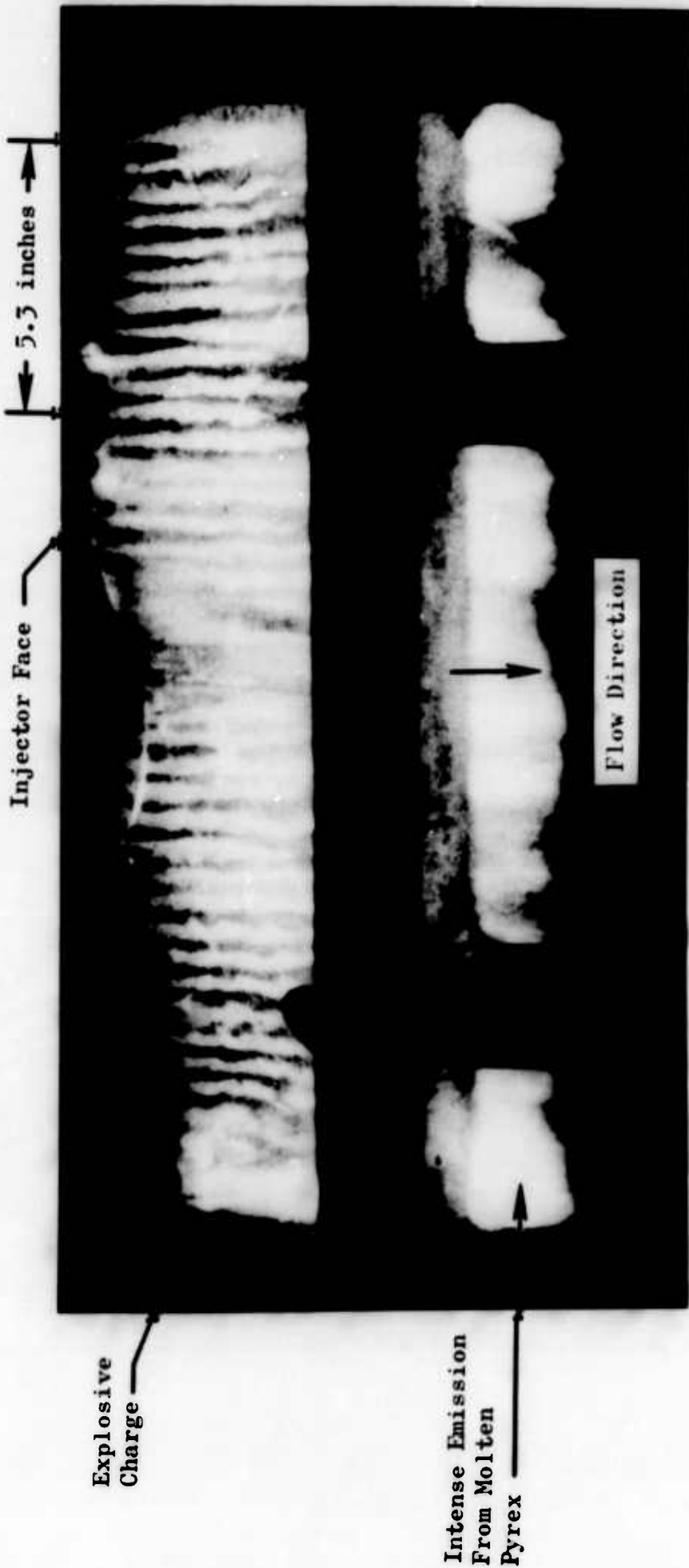


Figure 6. Experimental Results With Coaxial Jet Injection:  
(a) Full Width Photograph of Injection Region,  
Test No. 452 Approximately 200 R Hydrogen  
Temperature and 5.8 Mixture Ratio

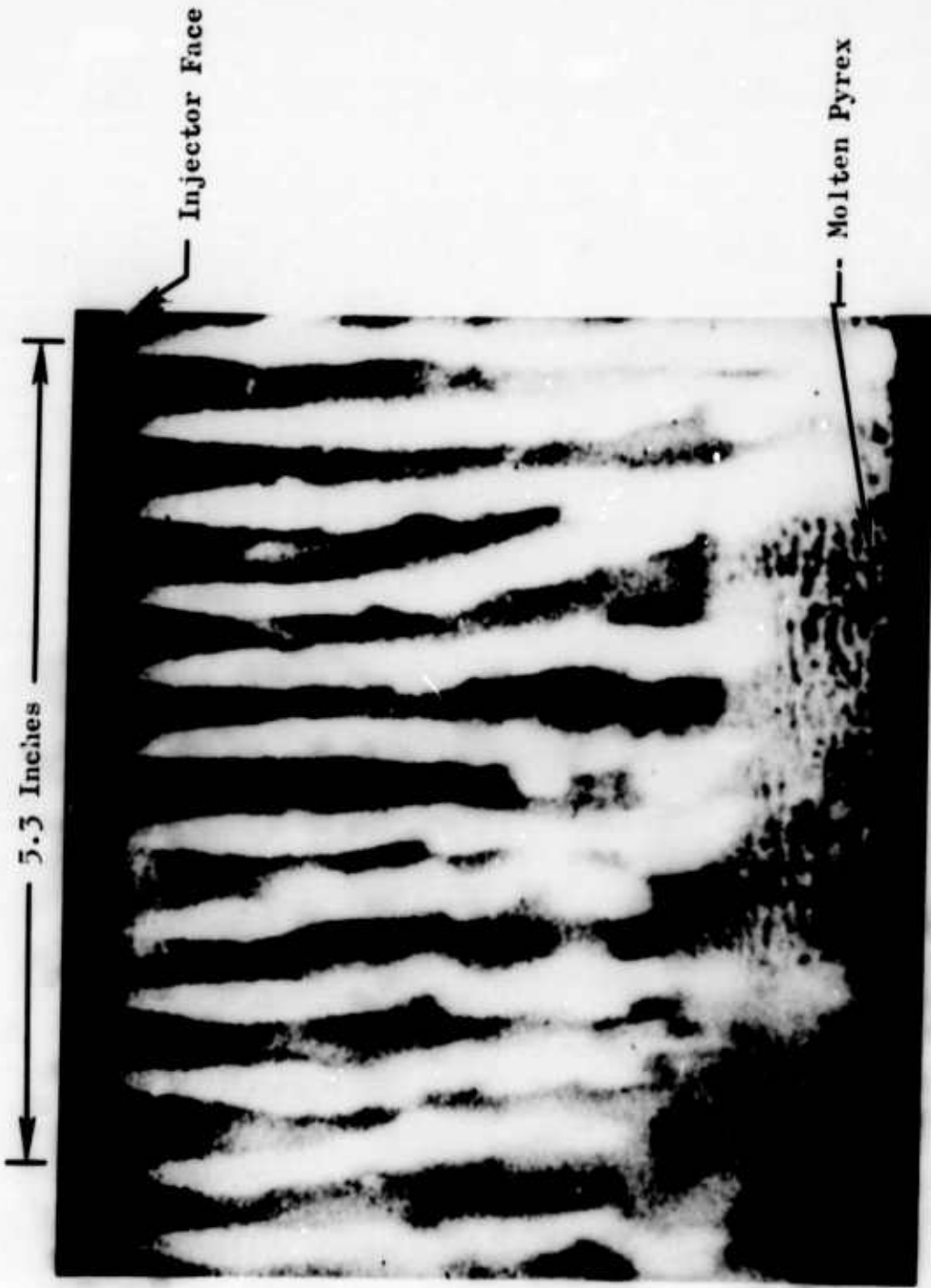


Figure 6. Continued. (b) Closeup Photograph of Injection Region, Test No. 431, 315 R Hydrogen Temperature and 7.1 Mixture Ratio

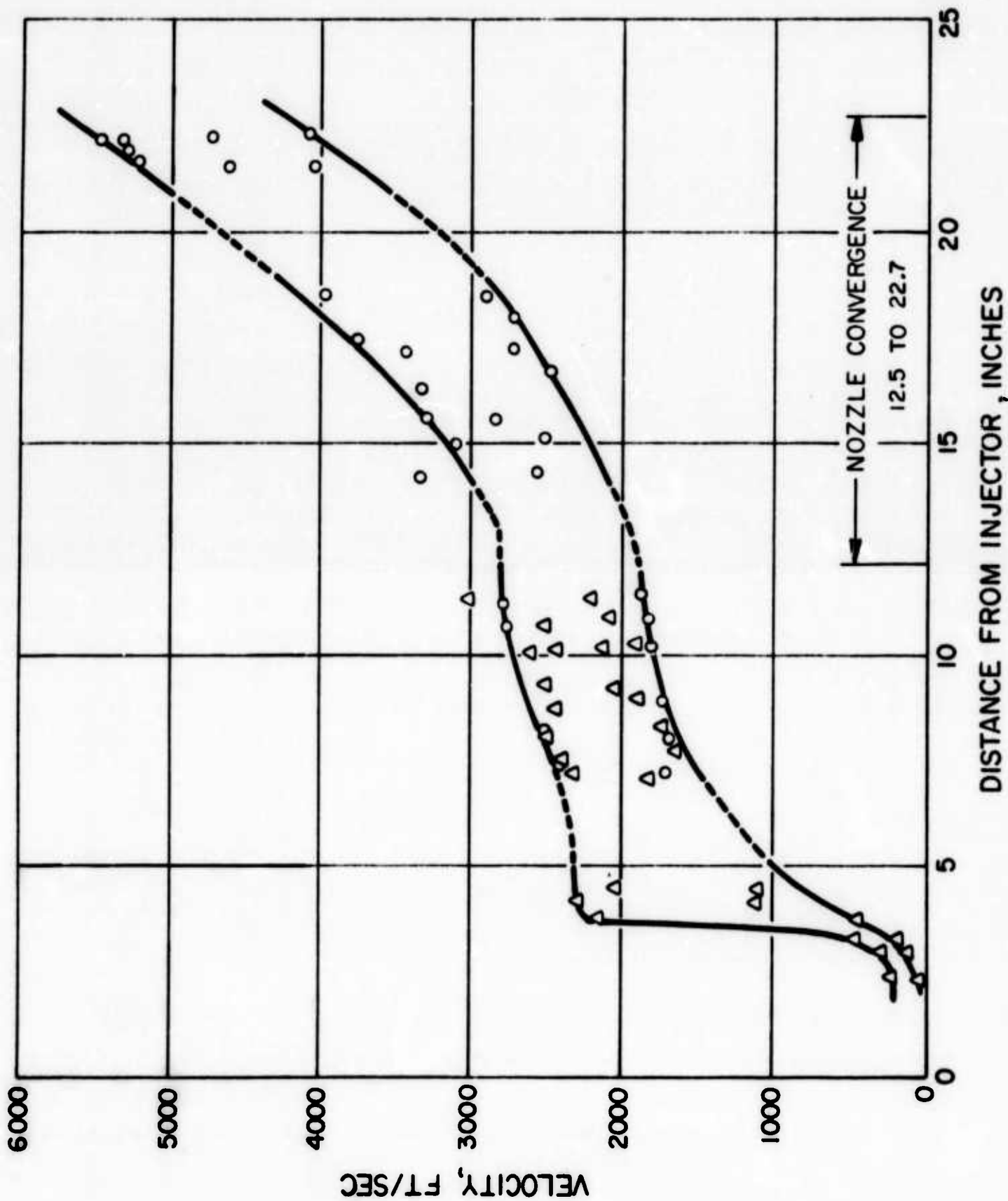


Figure 6. Continued. (c) Velocity Data Reduced From Streak Photographs, Test No. 417, Approximately 500 R Hydrogen Temperature and 4.9 Mixture Ratio

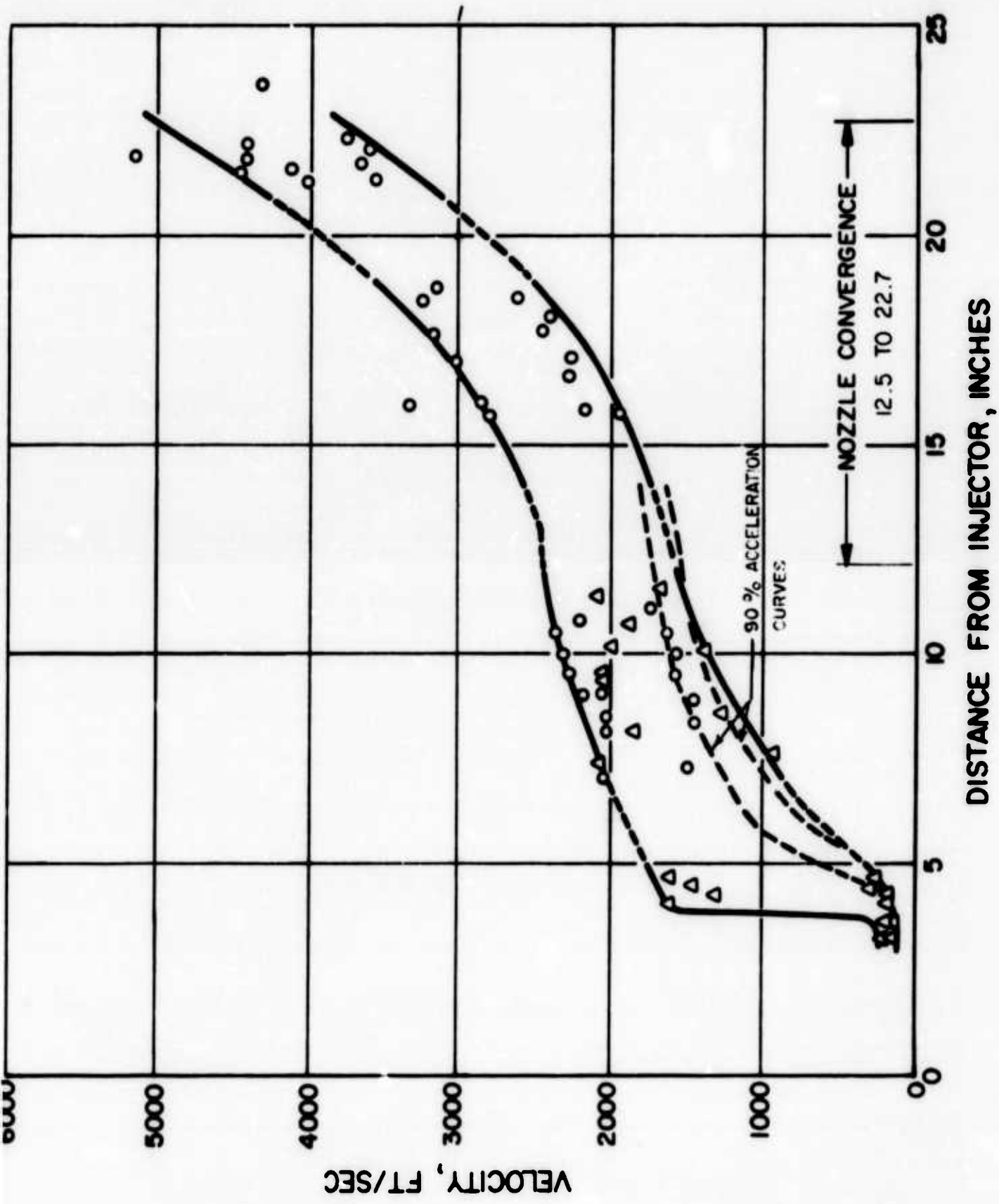


Figure 6. Continued. (d) Velocity Data Reduced From Streak Photographs, Test No. 451, 515 R Hydrogen Temperature and 7.1 Mixture Ratio

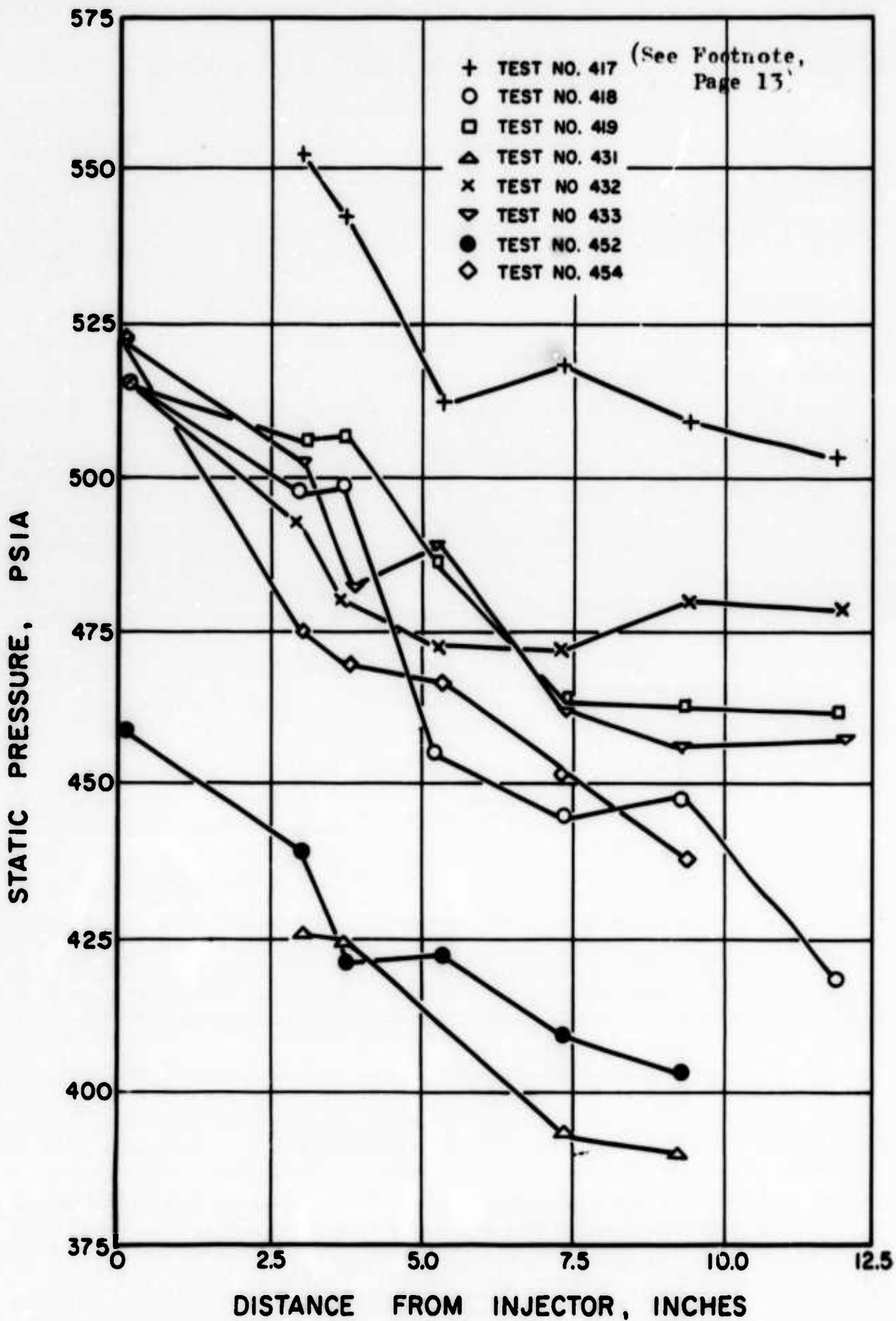


Figure 6. Continued. (e) Chamber Pressure Data

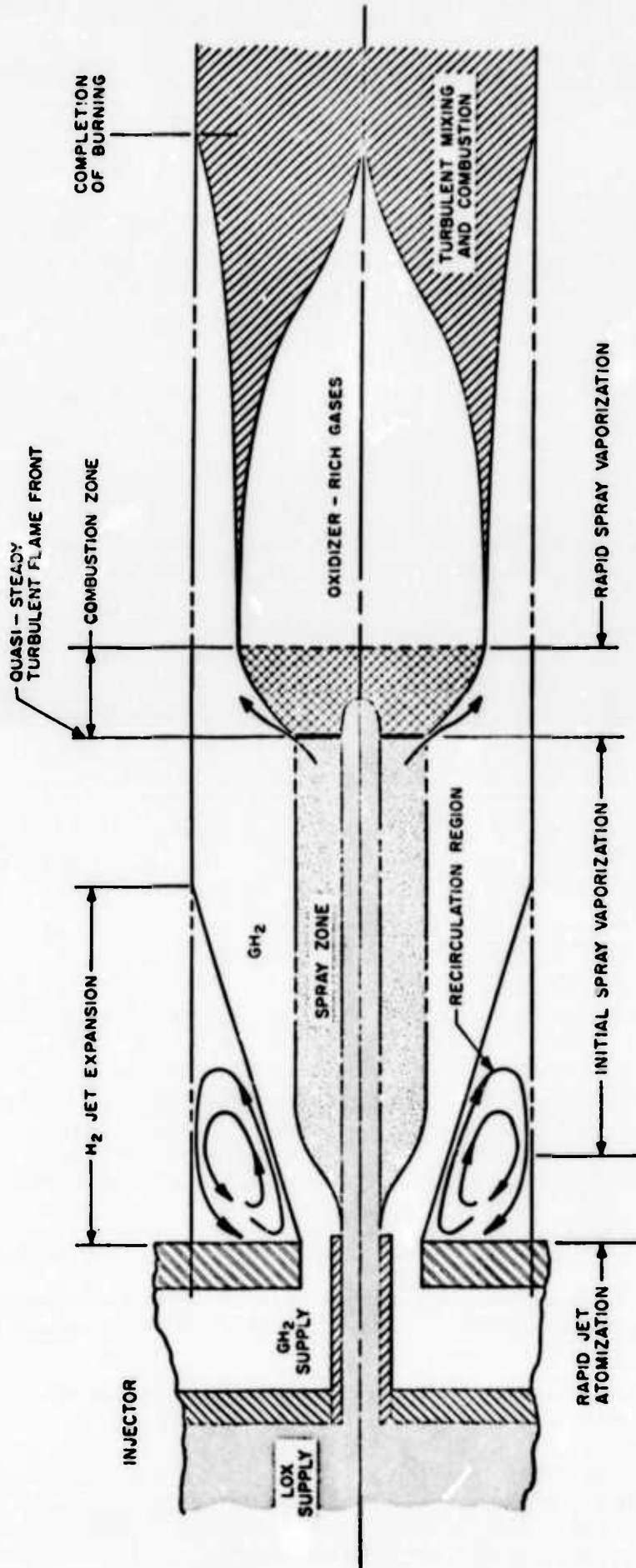


Figure 6. Continued. (f) Schematic Representation of the Combustion Processes

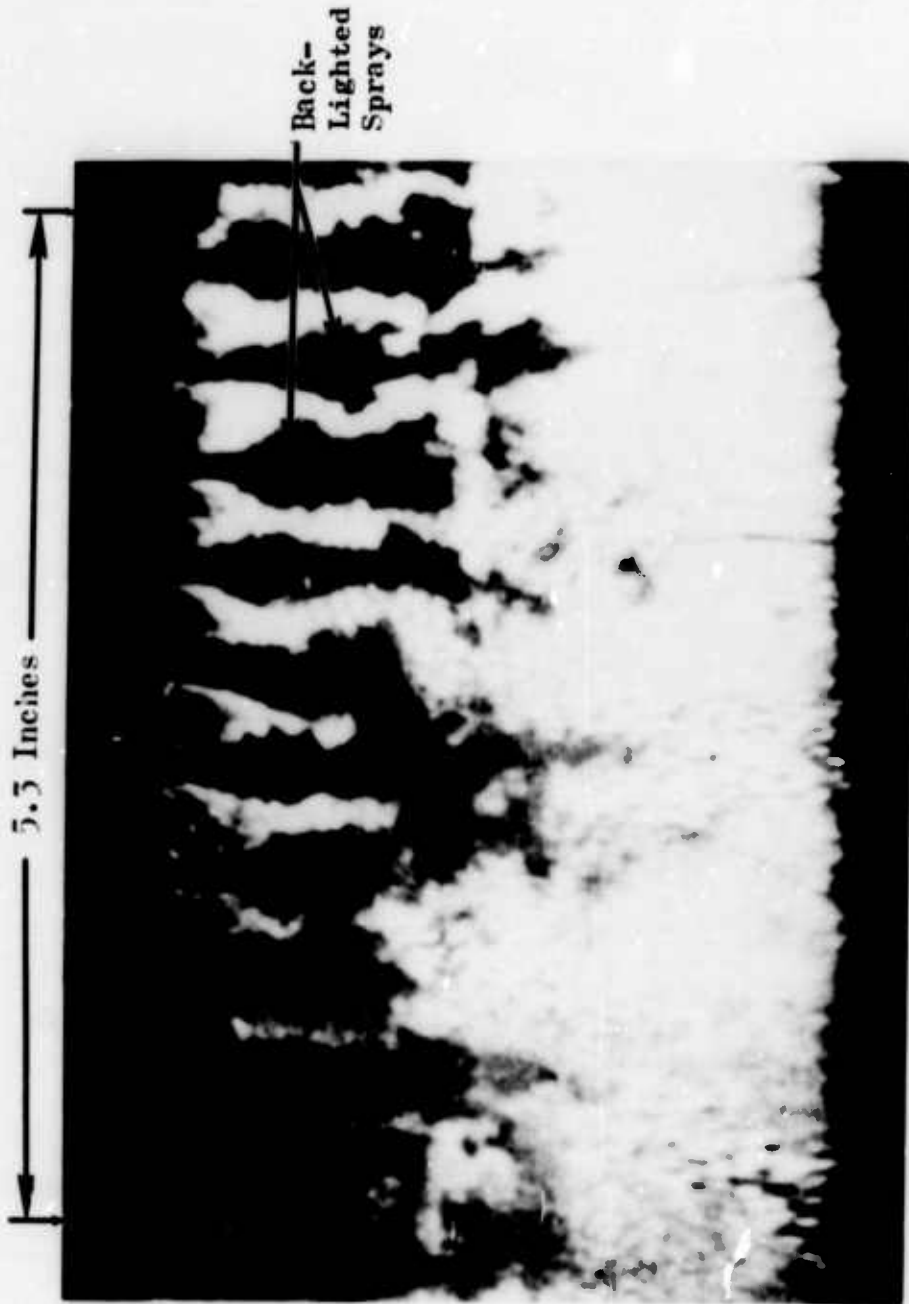


Figure 7. Experimental Results With Triplet Injection:  
(a) Closeup Photograph of Injection Region,  
Test No. 446, 228 R Hydrogen Temperature  
and 4.4 Mixture Ratio

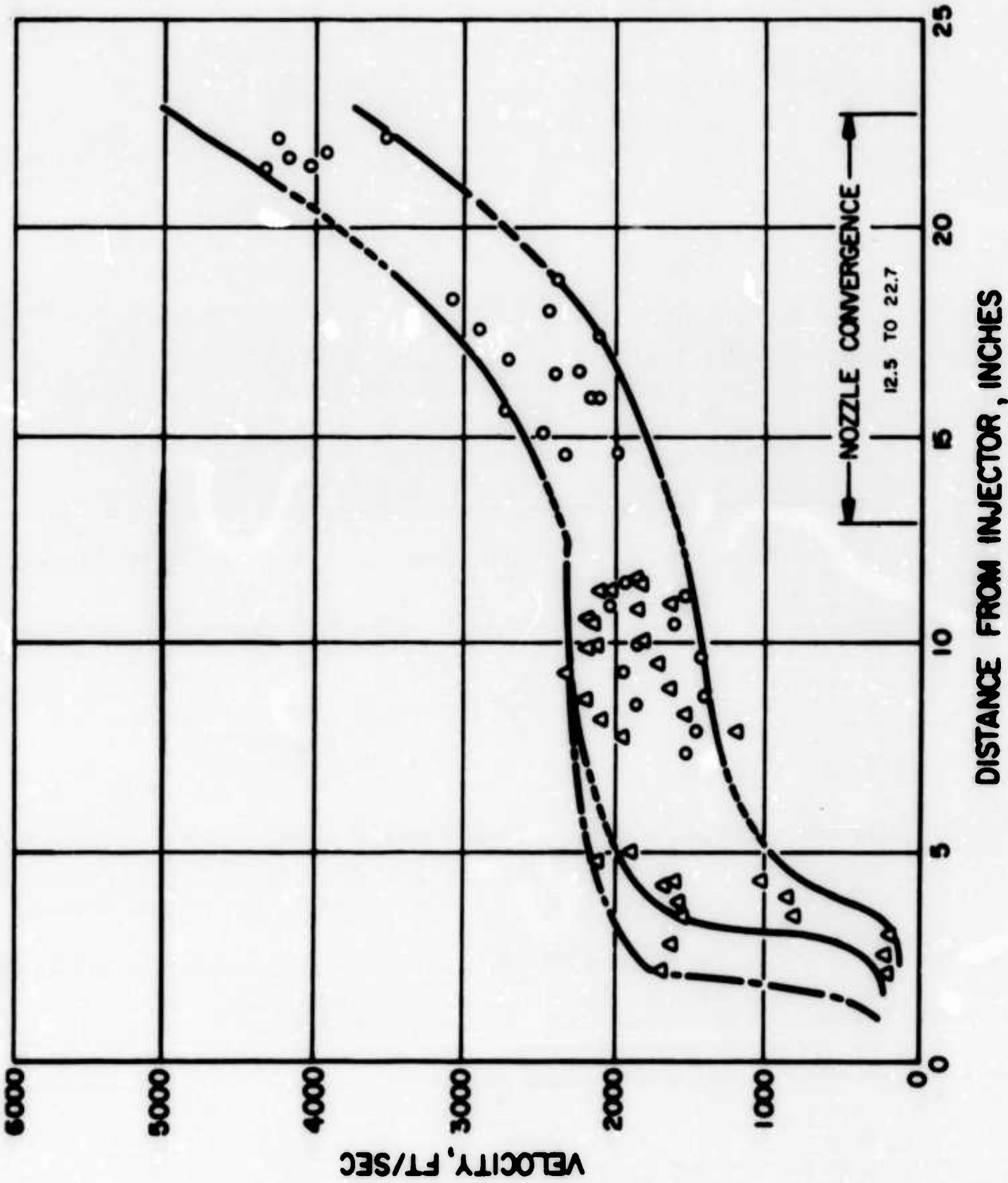


Figure 7. Continued. (b) Velocity Data Reduced From Streak Photographs. Test No. 451, 275 k Hydrogen Temperature and 5.7 Mixture Ratio

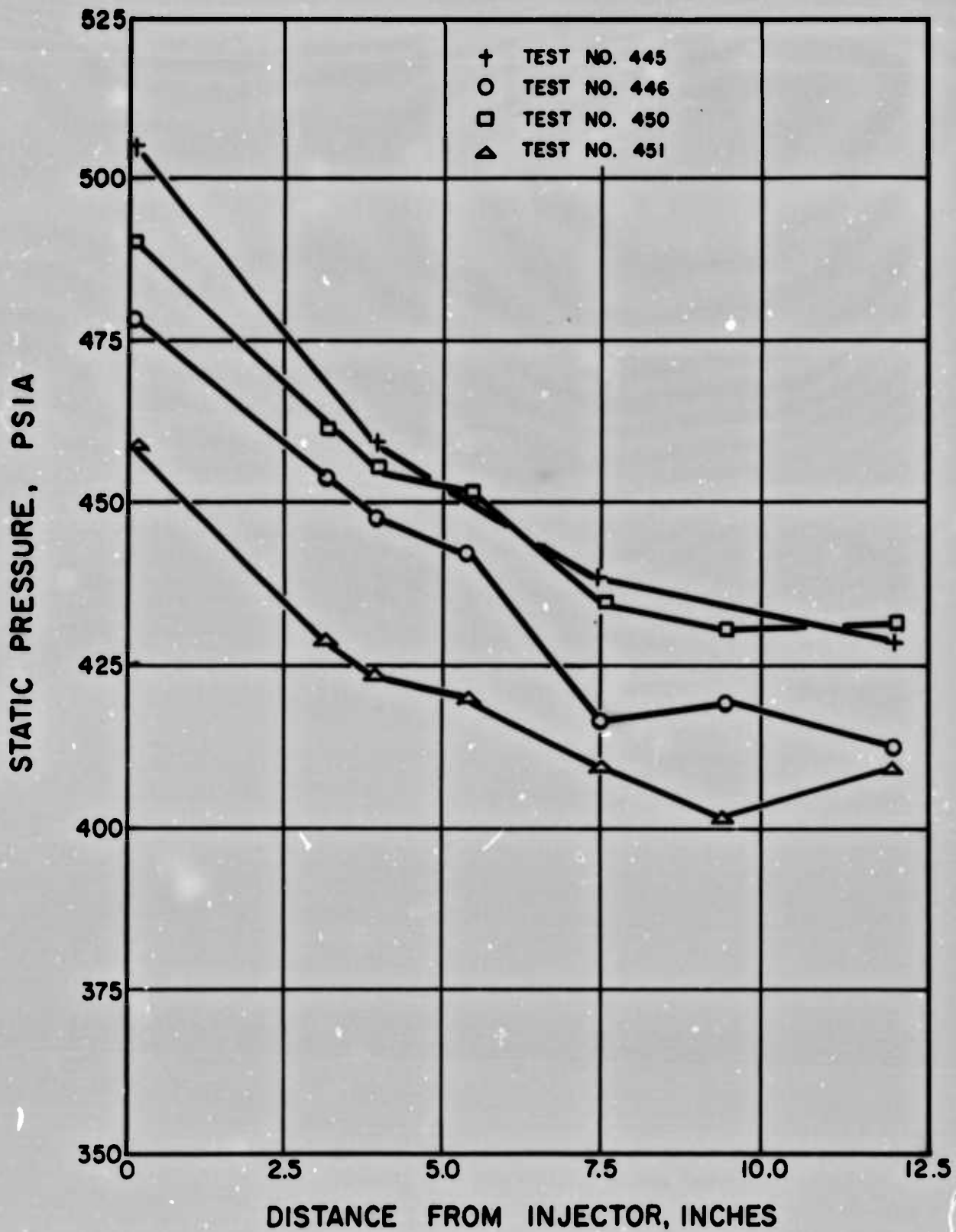


Figure 7. Continued. (c) Chamber Pressure Data



Figure 8. Experimental Results With Hydrogen Showerhead/LOX Doublet Injection: (a) Full-Width Photograph of Injection Region, Test No. 453, Approximately 500 R Hydrogen Temperature and 6.3 Mixture Ratio



Figure 8. Continued. (b) Closeup Photograph of Injection Region, Test No. 448  
346 R Hydrogen Temperature and 6.8 Mixture Ratio

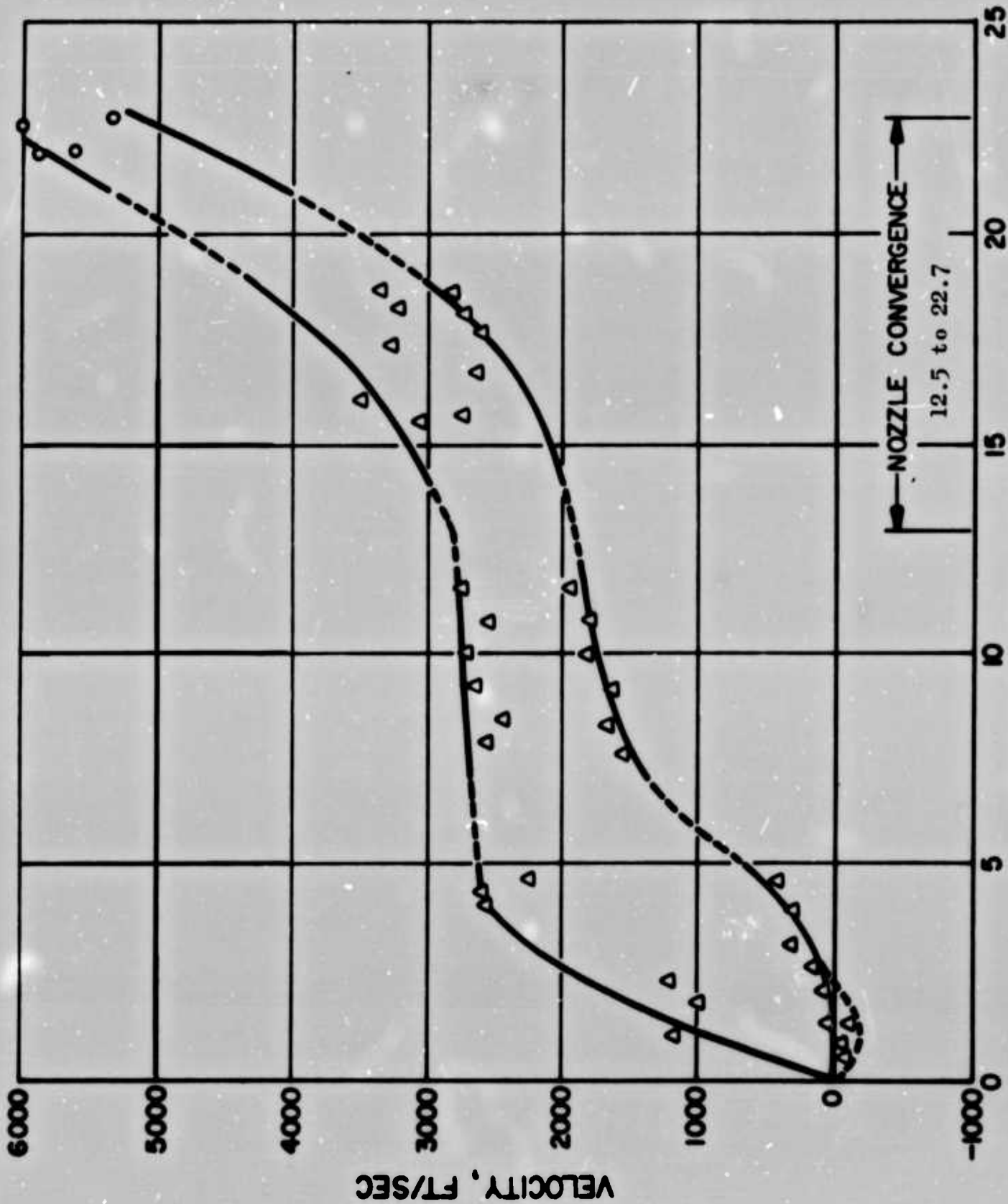


Figure 8. Continued. (c) Velocity Data Reduced From Streak Photographs, Test No. 453, Approximately 500 R Hydrogen Temperature and 6.2 Mixture Ratio

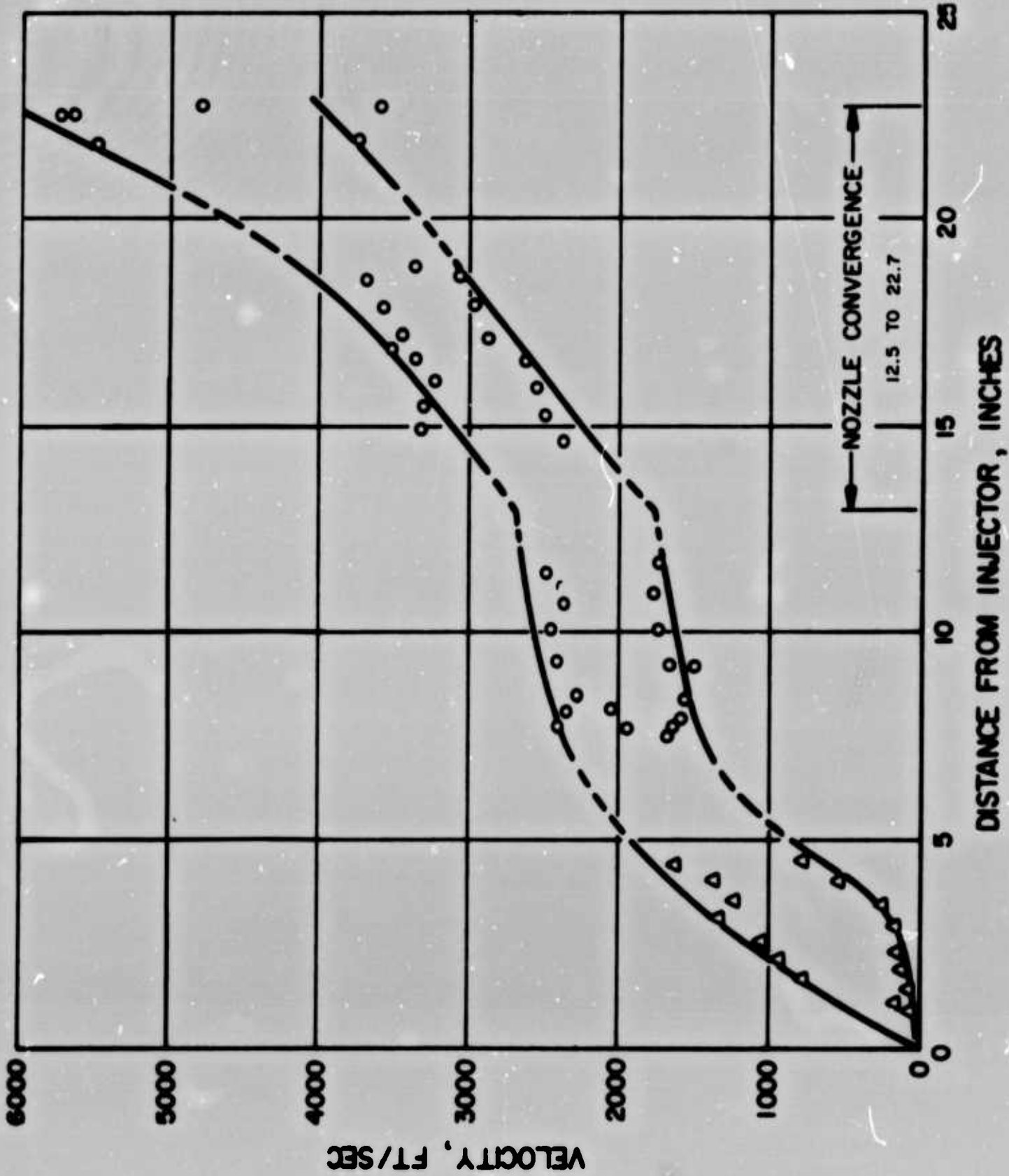


Figure 8. Continued. (d) Velocity Data Reduced From Streak Photographs, Test No. 449, 225 R Hydrogen Temperature and 4.0 Mixture Ratio

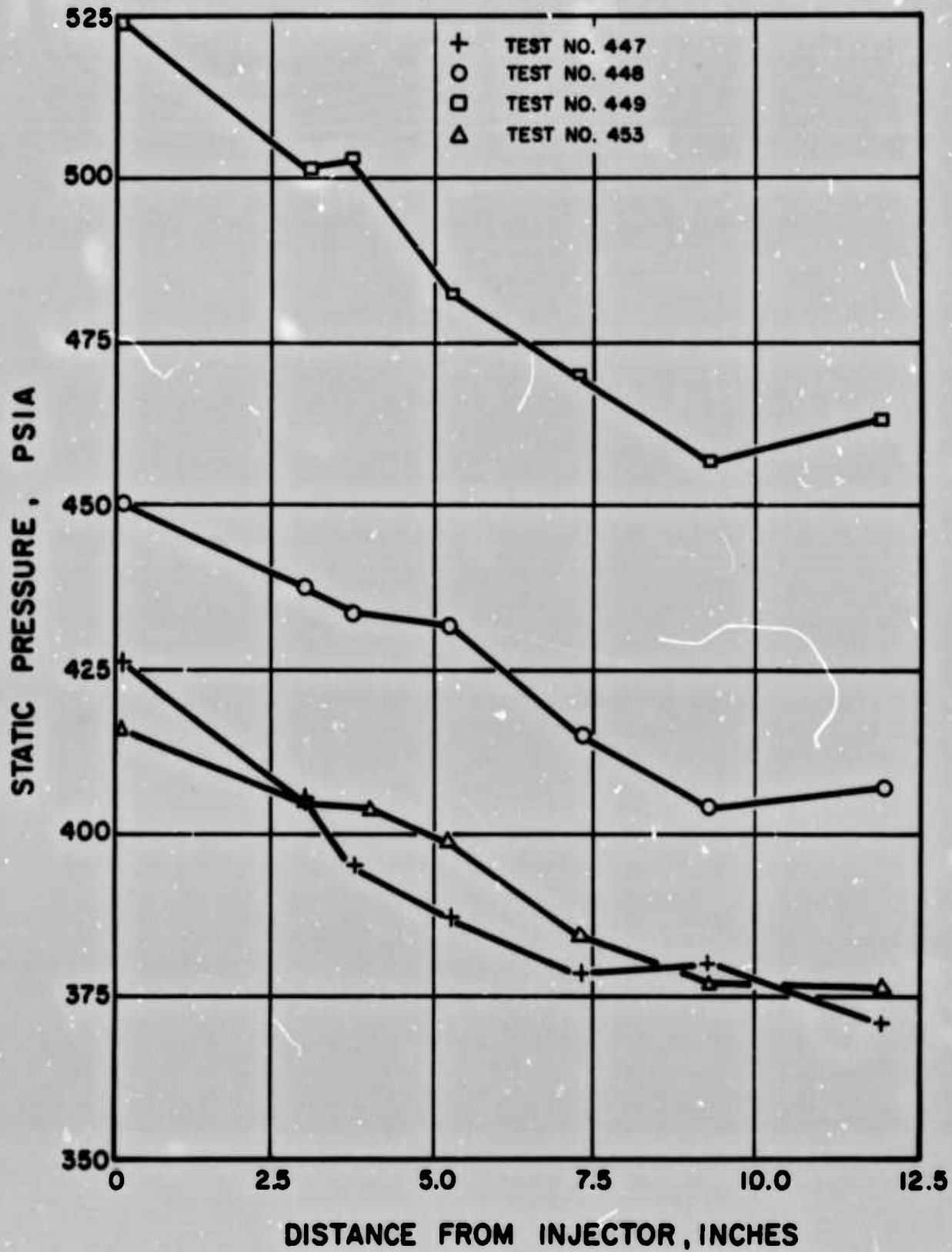


Figure 8. Continued. (e) Chamber Pressure Data

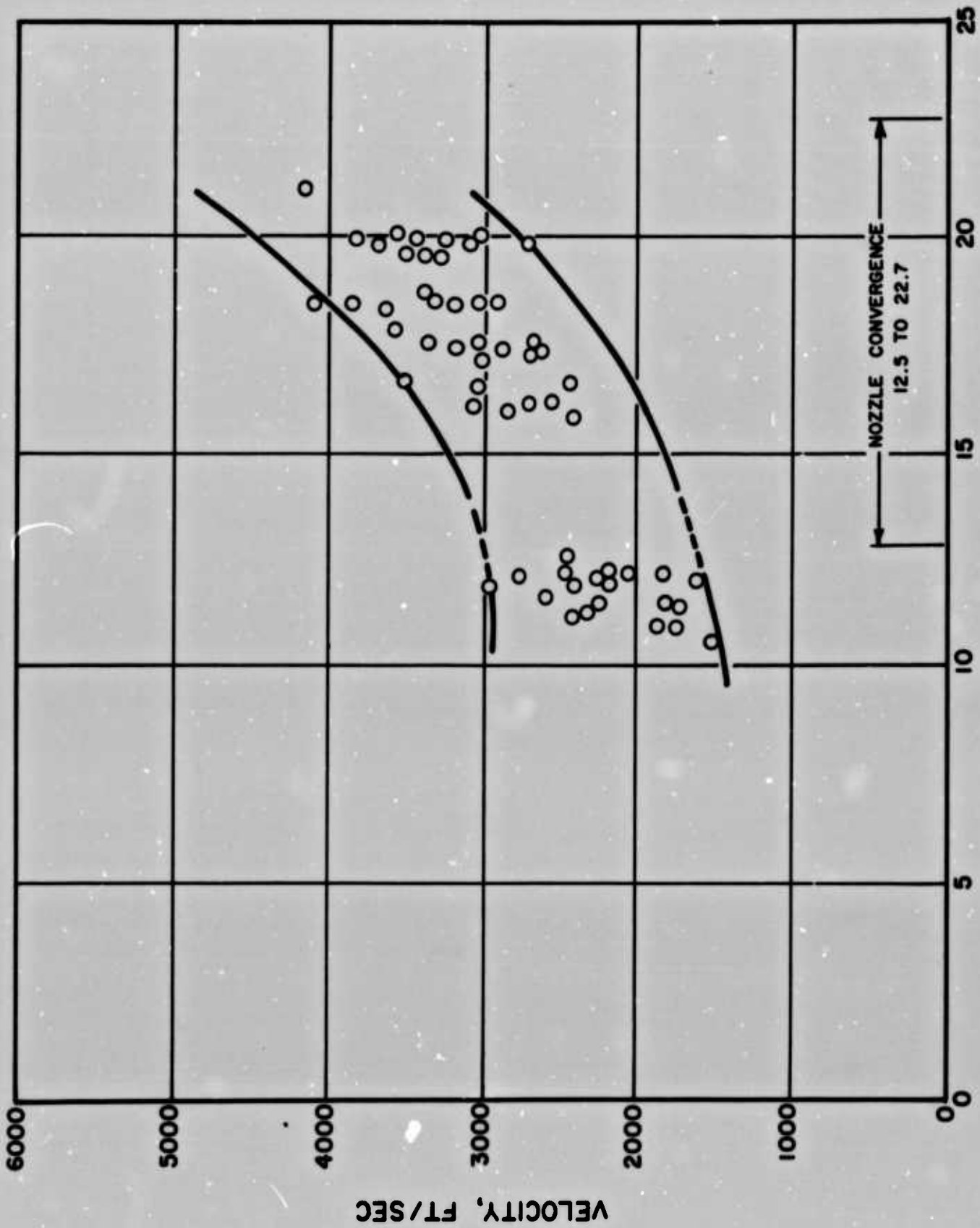


Figure 9. Experimental Results With Coaxial Jet Injection Using Gaseous Oxygen and Gaseous Hydrogen