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13. ABSTRACT (Maximum 200 words)

Experiments concerning the details of combustion in large vortices in the Caltech Unsteady Combustion Facility, using simultaneous measurements of pressure, shadowgraphy, and chemiluminescence are now about 50% complete. The detail of these results document a very different ignition mechanism and combustion pattern than previous experiments have suggested. Shock tube studies of shock enhanced mixing of helium into air, utilizing the Rayleigh scattering technique have been completed. Because of their greater sensitivity in the low concentration range, these measurements are significantly more accurate than those obtained with laser induced fluorescence and demonstrate that mixing is considerably more rapid and more complete than reported previously. Preliminary results have been obtained from experiments on the interaction of shock induced mixing with shear layers in the GALCIT M = 2.5 supersonic wind tunnel. These indicate a significant interaction between streamwise vorticity produced by shock enhancement and cross-stream vorticity in the shear layer.

14. SUBJECT TERMS
Supersonic Combustion, Vortex Combustion, Shear Layers, Vorticity Generation, Hypervelocity Mixing, Shock Enhanced Mixing

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1. RESEARCH OBJECTIVES

This report describes the second year of Grant AFOSR-90-0188 which is essentially a continuation of three year University Research Initiative Contract F49620-86-c-0113. This latter investigation aimed to demonstrate the high degree of mixing enhancement between hydrogen and air that could be induced through the appropriate interaction of relatively weak shock waves with the interface between the two gases. This interaction generated strong streamwise vorticity at the interface which, in turn, led to a rapid distortion of the interface and correspondingly rapid mixing between the hydrogen and air. The experimental and computational investigations were sufficiently successful that an injector mixer suitable for a scramjet was designed. With NASA support, models were built and tested in a Mach 6 wind tunnel at Langley Research Center with very satisfactory results. An invention disclosure was made and the patent claim is being pursued by the U.S. Air Force.

There were, however, several aspects of the shock enhancement that were not understood. The two most important of these were the later stages of mixing and the scaling of the process with both size and shock Mach number. In addition, we saw the possibility of utilizing the shock interaction mechanism to control the distribution of heat release along the direction of flow. These items formed the basis of the grant which is the subject of this report.

Shock Tube Experiments. - Because of the very accurate correspondence of the time-dependent development of the two-dimensional vortex structures with the streamwise development of the three-dimensional field, shock tube experiments have proven exceedingly useful. Under the present grant, experiments in the GALCIT 17-inch Shock Tube are being employed to examine the scaling of the mixing process with shock Mach number and the influence of multiple shock impingement. These are being carried out using vastly improved optical techniques.

Combustion in Large Vortices. - The details of the combustion process within the vortex structure is being investigated using our Unsteady Combustion Facility. This facility is capable of producing large reacting two-dimensional vortices, of three-inch diameter periodically. The size, repetition rate, and two-dimensionality provide excellent access for chemiliminescence, shadowgraph, and laser-doppler velocimetry techniques. It is the aim of this task to complete the bridge between the non-reacting mixing experiments and their reacting counterpart.

Computational Study of Shock Enhancement. - The experimental research is both expensive and time consuming, and, as a consequence, we must assure that each of the experimental points addresses a well-defined issue. From the beginning of this project we have made extensive use of computations to explore conditions that merit experimental effort. Fortunately most features of the interfacial instability and the rolling-up process can be modelled with an inviscid code, an economy of both time and expense which has allowed a wide and revealing examination of shock interface interactions. The results have proven successful, not only to pinpoint valuable experimental conditions but also as a considerable aid in studies of Mach number and geometric scaling.

Interactions with a Shear Layer. - The interactions of shock waves with a strong density discontinuity, which is the main focus of this project, seldom occurs in the absence of shear layers. The vorticity generated by the shock interaction is almost entirely aligned with the direction of free stream flow, while the shear flow generated, for example, by the presence of a combustion chamber wall lies largely normal to the stream direction. The complex mutual interaction of these two vorticity fields is the subject of experiments in the small GALCIT supersonic wind tunnel. Although the tunnel Mach number of 2.5 is lower, and the size of the working section is smaller than one would wish, it does give a very convenient opportunity to explore the interaction between the shock-enhanced mixing of a helium jet in air and a thickened wall boundary layer of the wind tunnel.

2. STATUS OF RESEARCH

Investigations in the Galcit 17-inch Shock Tube

The experiments in the shock tube of the time-dependent mixing of helium into air correspond accurately to the steady spatial mixing process of technological interest through the correspondence illustrated in Figure 1. This relationship, generally known as the "slender body approximation", is described

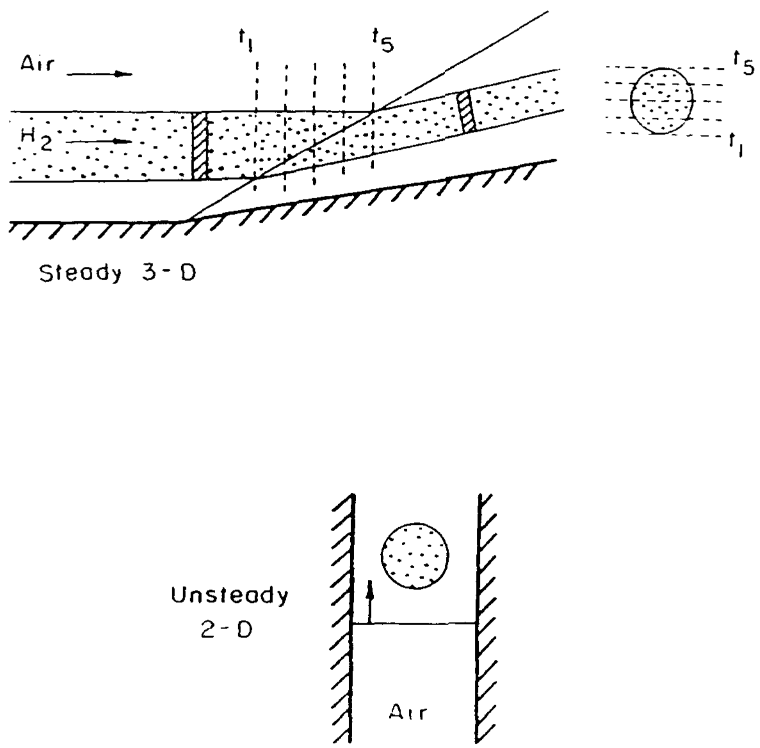

Figure 1. Comparison of 3-D Steady with 2-D Unsteady Flows

in more detail in Marble et al.(1986a). The configuration of the shock tube and the arrangement of the instrumentation shown in Figure 2 allows time-resolved "prints" to be obtained through application of pulsed laser induced fluorescence.

The initial experiments, Marble et al. (1990), Jacobs (1990), Jacobs (1991), employed biacetyl as the dye and the results were extremely important in establishing the mechanism of shock enhanced mixing. As the quantitative accuracy of the experimental results assumed greater importance, two features of this experiment were of concern. First, there is a considerable difference between the diffusion rates of helium and biacetyl and second, the camera we were using had a very non-linear sensitivity at low intensity levels. This led us to implement the Rayleigh scattering technique, the use of which we had anticipated from the beginning of the effort.

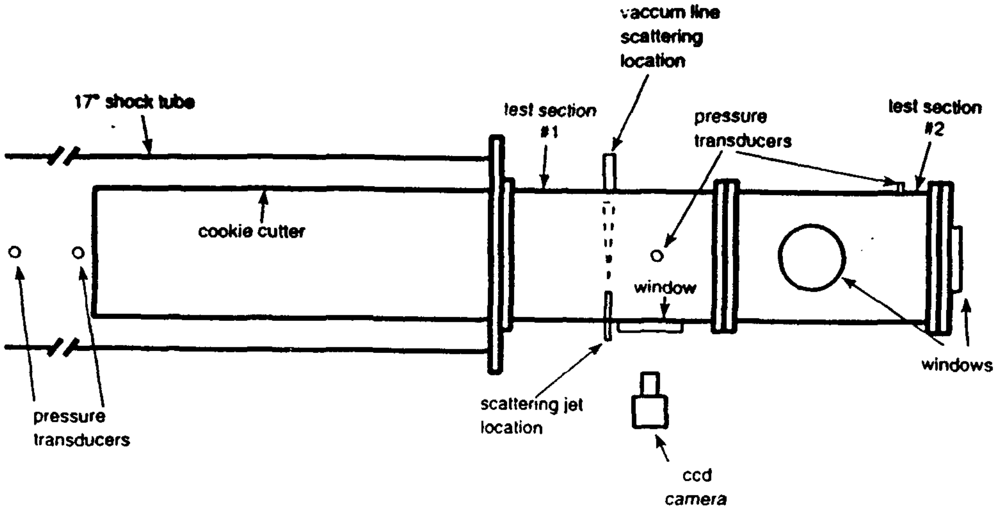

Figure 2a. Side View of Shock Tube Mixing Experiment

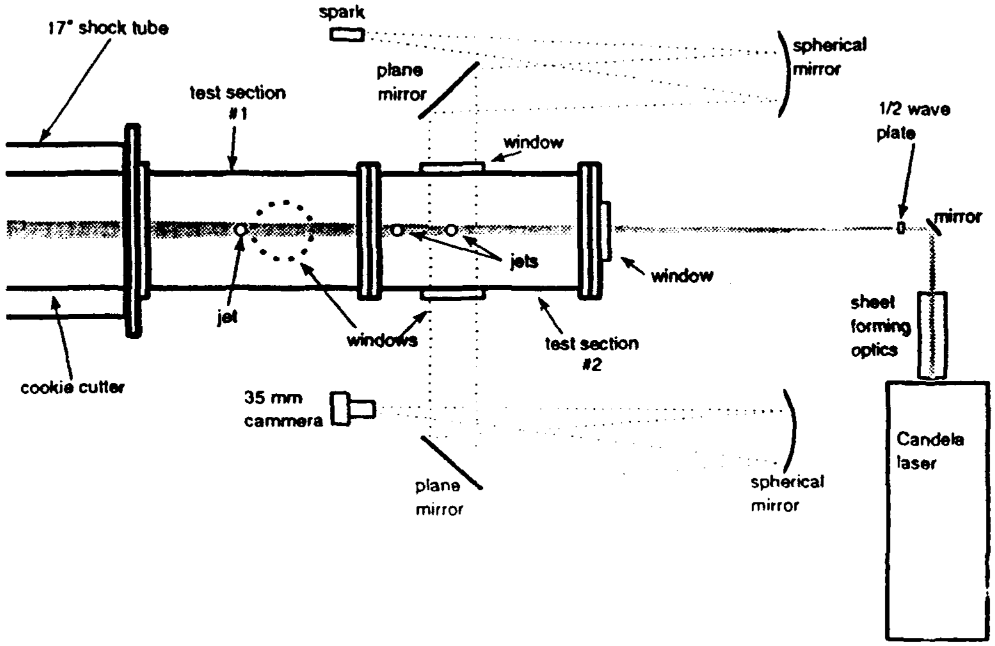

Figure 2b. Top View of Shock Tube Mixing Experiment

The weaker signal resulting from Rayleigh scattering necessitated significant modification to our optical setup. The power of the laser was increased by a factor of more than ten through employing a different dye, a new camera with linear response was acquired, and an extensive calibration of each camera pixel was undertaken. The results were rewarding in that they revealed aspects of the shock enhanced mixing that were not apparent from our earlier work.

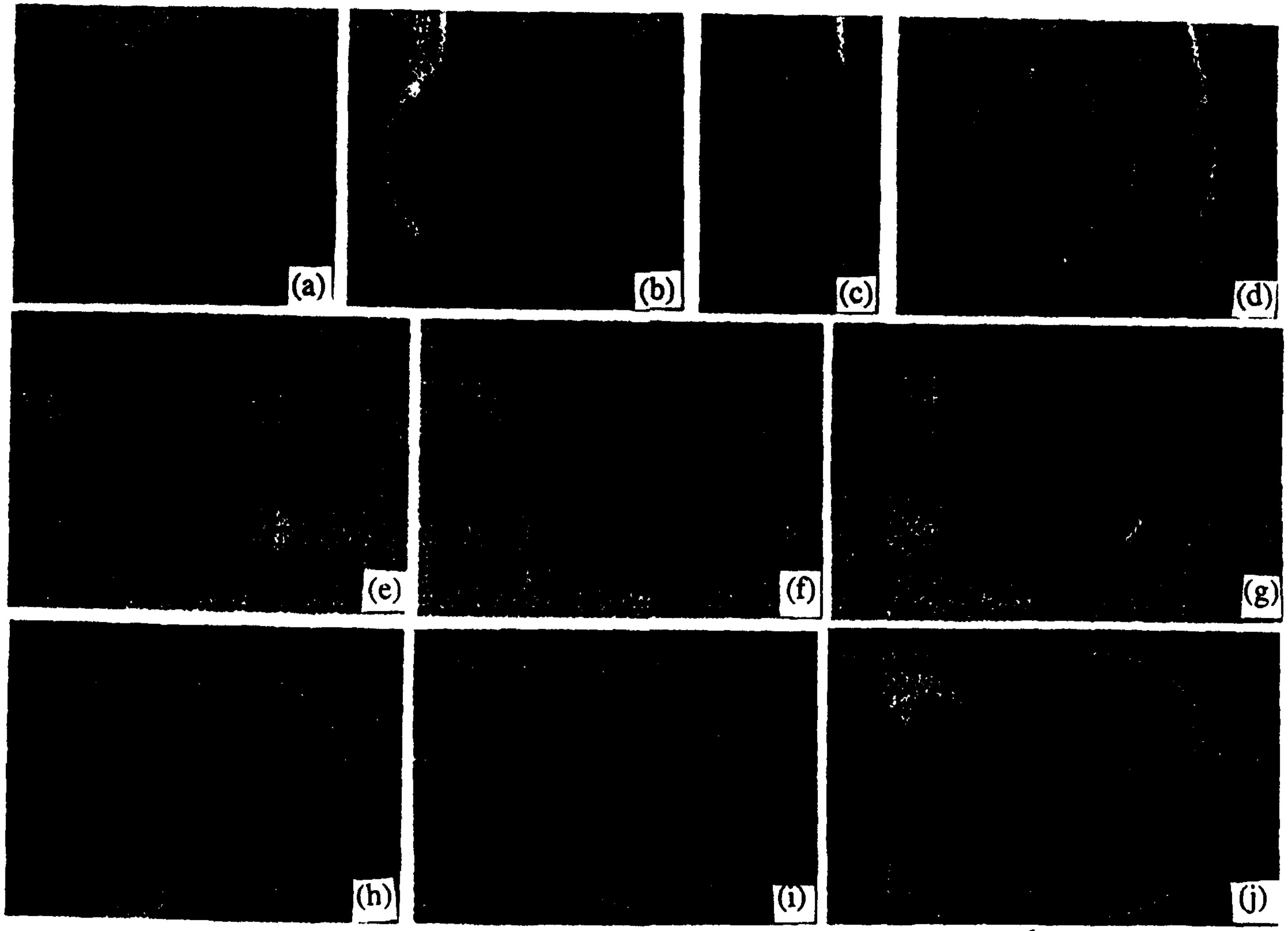

Figure 3. Rayleigh Scattering Images,
Shock Mach Number 1.142

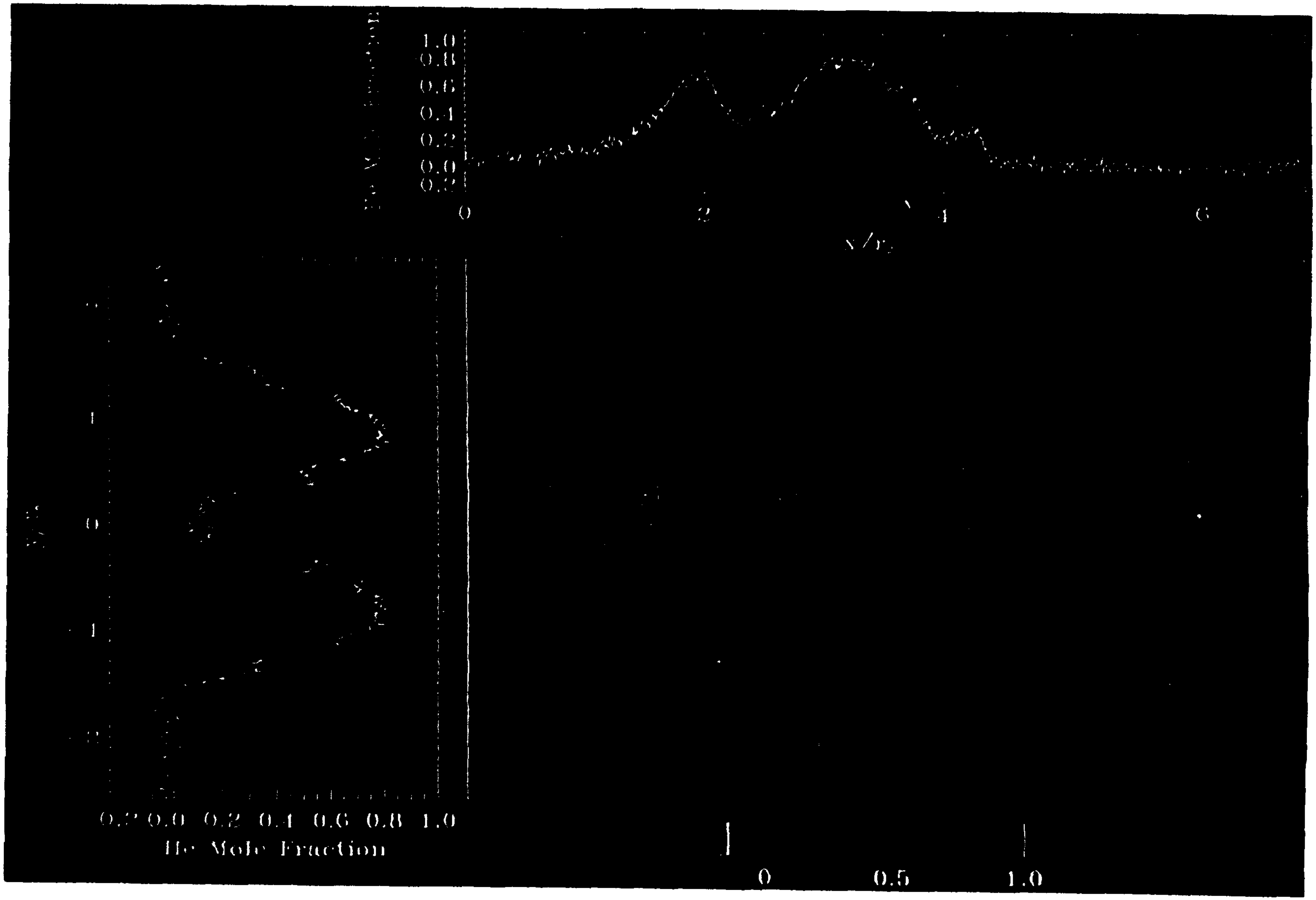

Figure 4. Detailed Rayleigh Scattering Image with Mole Fraction Sections, Shock Mach Number = 1.06

The shock tube study of shock induced mixing has now been completed; the final portion of that effort, completed this last year is reported in detail by Budzinski (1992). Results are given for shock Mach numbers of 1.066, 1.14 and 1.50 which were examined in great detail, in particular, the progress of molecular mixing was determined. Figure 3 shows Rayleigh scattering images of the interaction of a 1.142 Mach number shock wave with a helium jet where the initial pressure was one atmosphere. The photos in the first row show the initial jet and process of shock passage through the helium. The remaining photographs detail the progressive distortion and mixing of the helium into air. This type of photograph was used to determine the degree and rates of mixing. Figure 4 shows one detailed photo for a shock Mach number of 1.06, together with the helium mole fraction distributions along the two cuts shown. Such results, with equal excellent accuracy, form the basis for our integrated mixing rate determinations.

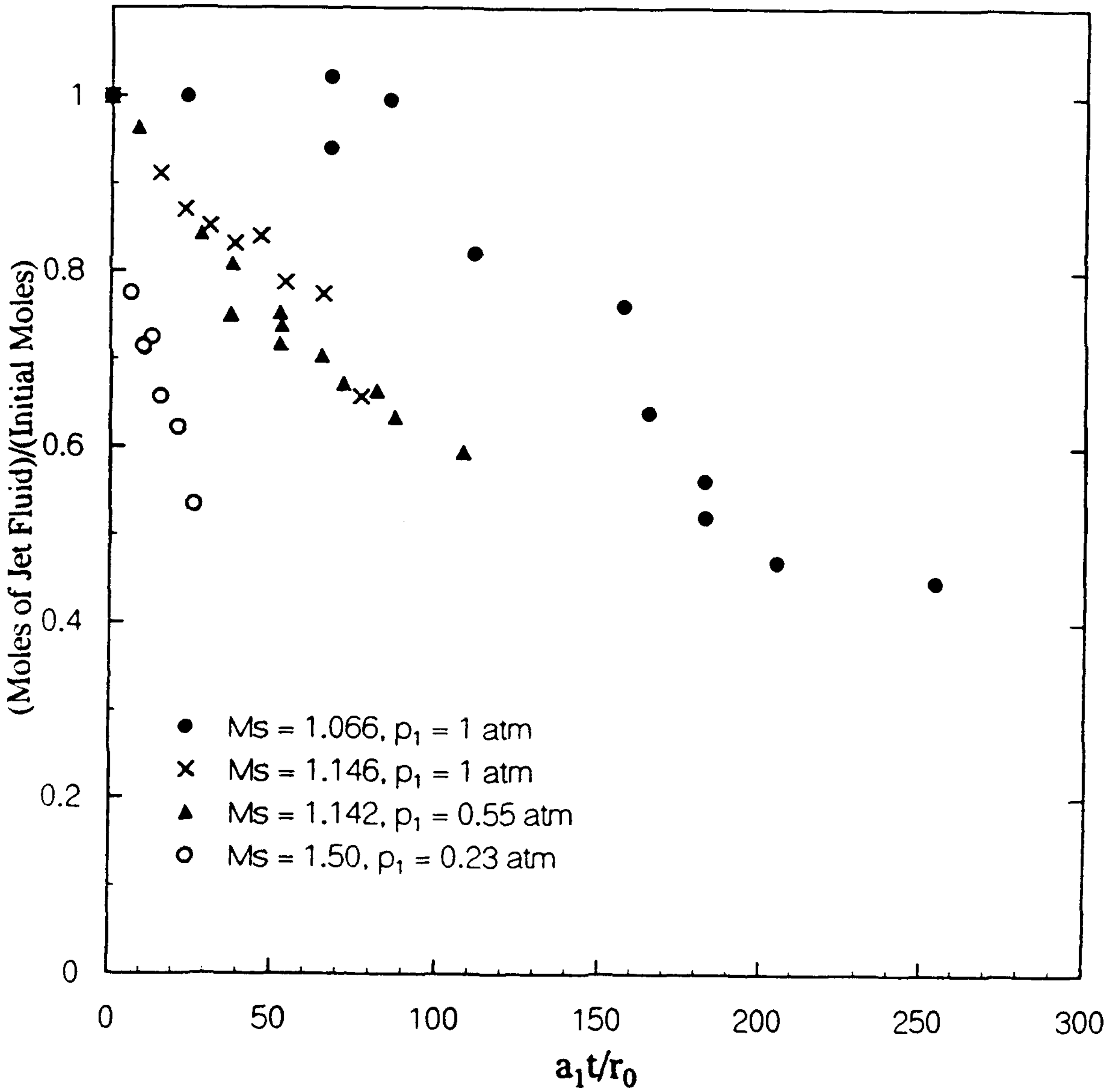

Figure 5. Mass of Helium in Regions With More Than 50% Helium

Figure 5 summarizes the integrated degree of mixing, represented by the fraction of "unmixed helium", that is, helium mass in regions containing greater than 50% helium, and shown for three different shock Mach numbers and three different levels of initial pressure. The horizontal scale is time after shock impingement, made dimensionless by the acoustic velocity a of air in the initial shock tube state, and the initial radius r of the helium jet. The increased rates of mixing with increased shock strength, that is increased shock Mach number, is obvious from the results. An elementary analysis shows that for weak shocks, such as those in question here, the slope of this mixing line scales as M -1, where M is the shock Mach number, and application of this result to the data shows that it holds quite accurately. It is important to recall when thinking about scramjet combustors, that this Mach number corresponds to that of the weak shock generated in the combustor rather than to the throughflow Mach number of the burner.

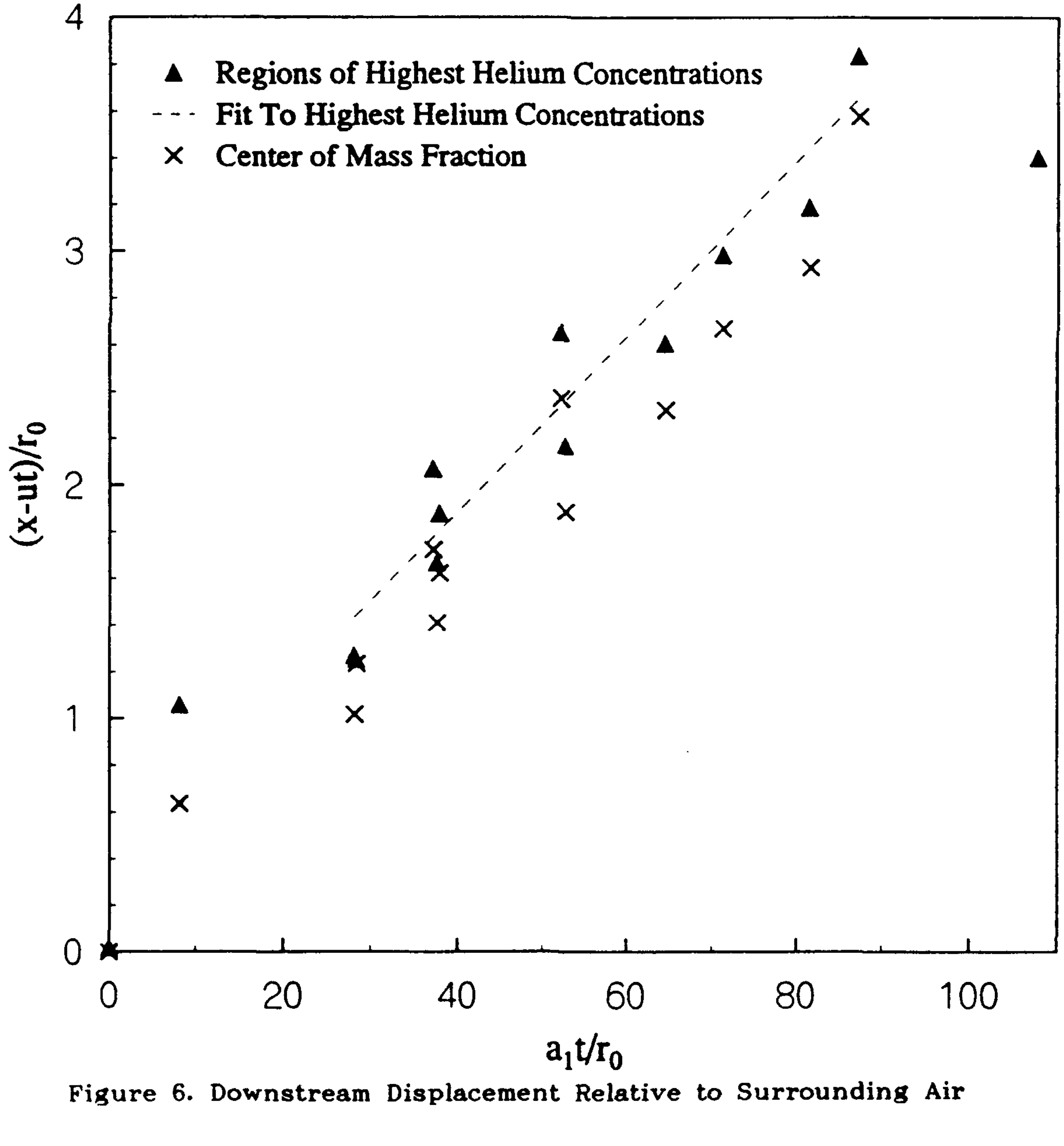

Figure 6. Downstream Displacement Relative to Surrounding Air

Another feature that is of both gasdynamic interest and technological importance is the motion of the vortex pair with respect to the motion of the surrounding air after passage of the shock. Results for the shock Mach number 1.142 are shown in Figure 6 where the numerator of the vertical scale, $x - Ut$, is the displacement of the vortex pair with respect to the background air stream moving with a constant velocity u. This displacement, which according to the results shown in Figure 6 proceeds at a constant rate, represents the distance the helium mass is transported through the ambient air as it mixes. In a combustor, this motion may represent the distance the fuel is transported away from the surface where it was injected.

Investigation of Combustion in Large Vortices

The large vortices being studied are generated in the Caltech Unsteady Combustion Facility shown in Figure 7. The vortices are formed at the sharp lower lip of the combustor chamber entrance and the periodic shedding process is sustained by the interaction of the unsteady heat release in the vortices, the subject of our study, and the resonant acoustic oscillations of the duct system. In this apparatus several acoustic modes are typically excited simultaneously and this dual mode operation makes the use of phase averaging difficult.

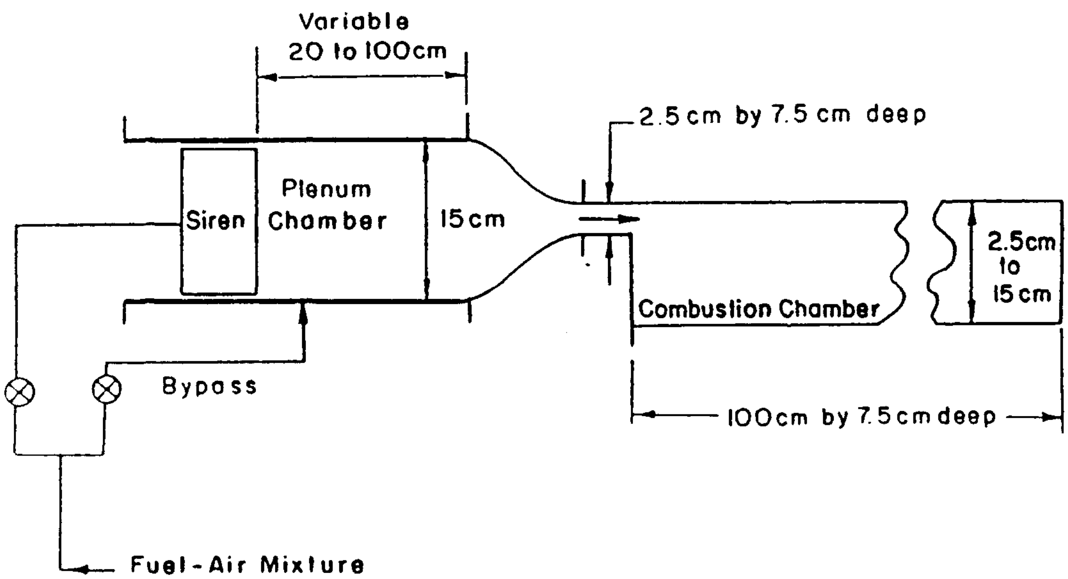

Figure 7. Unsteady Combustion Facility

The combustion process in vortices produced as described above is being investigated by measuring the chemiluminescence that results from the combustion process. In doing this we are using the proportionality between intensity and heat release to obtain a measure of the local chemical reaction rate of the fuel-air mixture. In the past we have been able to produce schlieren movies of the vortex shedding process at rates of 5,000 frames per second, more than 20 frames per cycle of vortex shedding, which is enough to allow detailed analysis of the temporal development of the density field. Measurements of the chemiluminescent

radiation produced by the chemical reactions were restricted to video camera rates of about 30 frames per second which is far too low to allow more than a rough analysis of the combustion process. We have not been able to obtain a refined picture of the combustion process, even through use of phase averaging techniques.

During the past year, however, we have found that the Kodak-Spin Physics video camera system can be used to obtain digitized photographs of the chemiluminescent radiation at rates up to 3,000 frames per second. The arrangement of the instrumentation is as shown in Figure 8 where the Spin Physics camera replaces the intensified video camera. These photographs allow

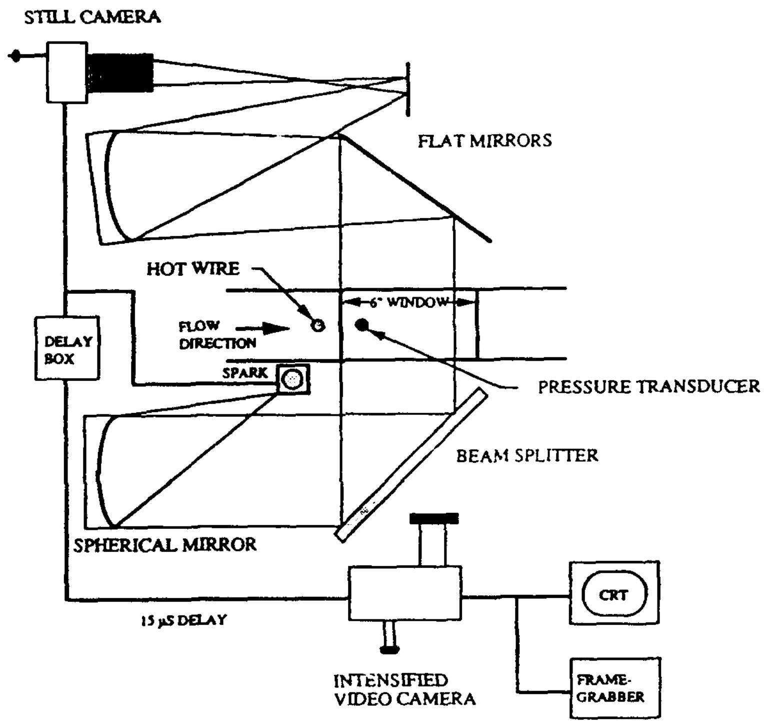

Figure 8. Arrangement for Simultaneous Chemiluminescence and Spark Shadow images

us to make detailed studies of the development of the chemical reactions within the vortices. Several preliminary experiments have been carried out with this system; an example of several cycles is shown in the (false color) images of Figure 9a,b,c.

The inlet flow is a fuel rich mixture of air and methane, equivalence ratio of 1.3, which enters the chamber with an average velocity of 21 m/s. The photographs of the radiation pproduced by the chemiluminescence were taken at a frequency of 3000 frames per second and the vortices were being shed at 230 Hz. **Thus about 13 photographs correspond to one vortex shedding cycle. In these photographs, the inlet to the combustion chamber is shown as a slot located at the upper left-hand corner of each photograph and is 0.64 cm high. The chamber is 7.62 cm high by 7.62 cm deep and the view covers the upstream 30 cm of the duct. The flow is approximately two-dimensional.**

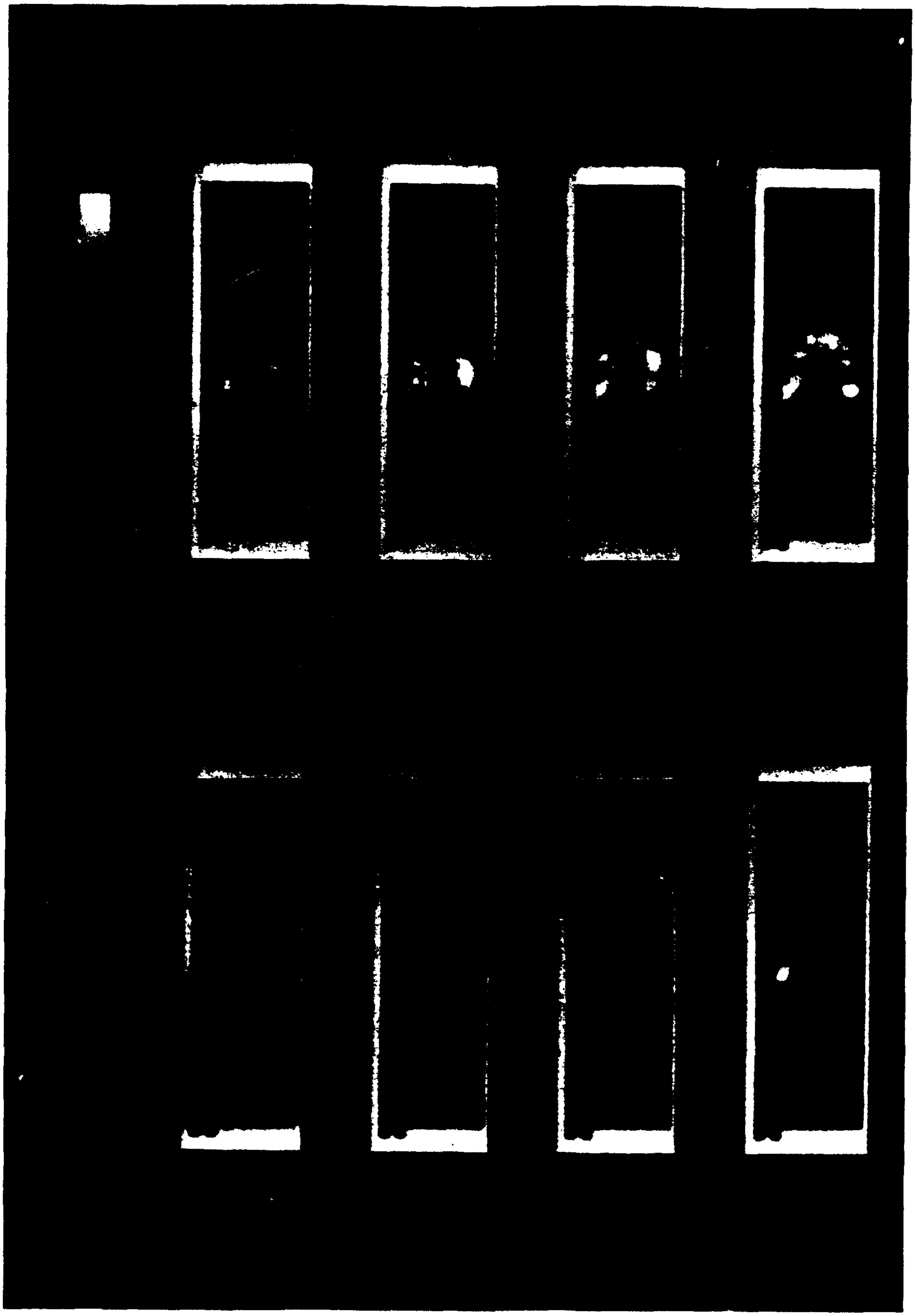

Figure 9a. Color Enhanced Chemiluminescence Images of Vortex Burning

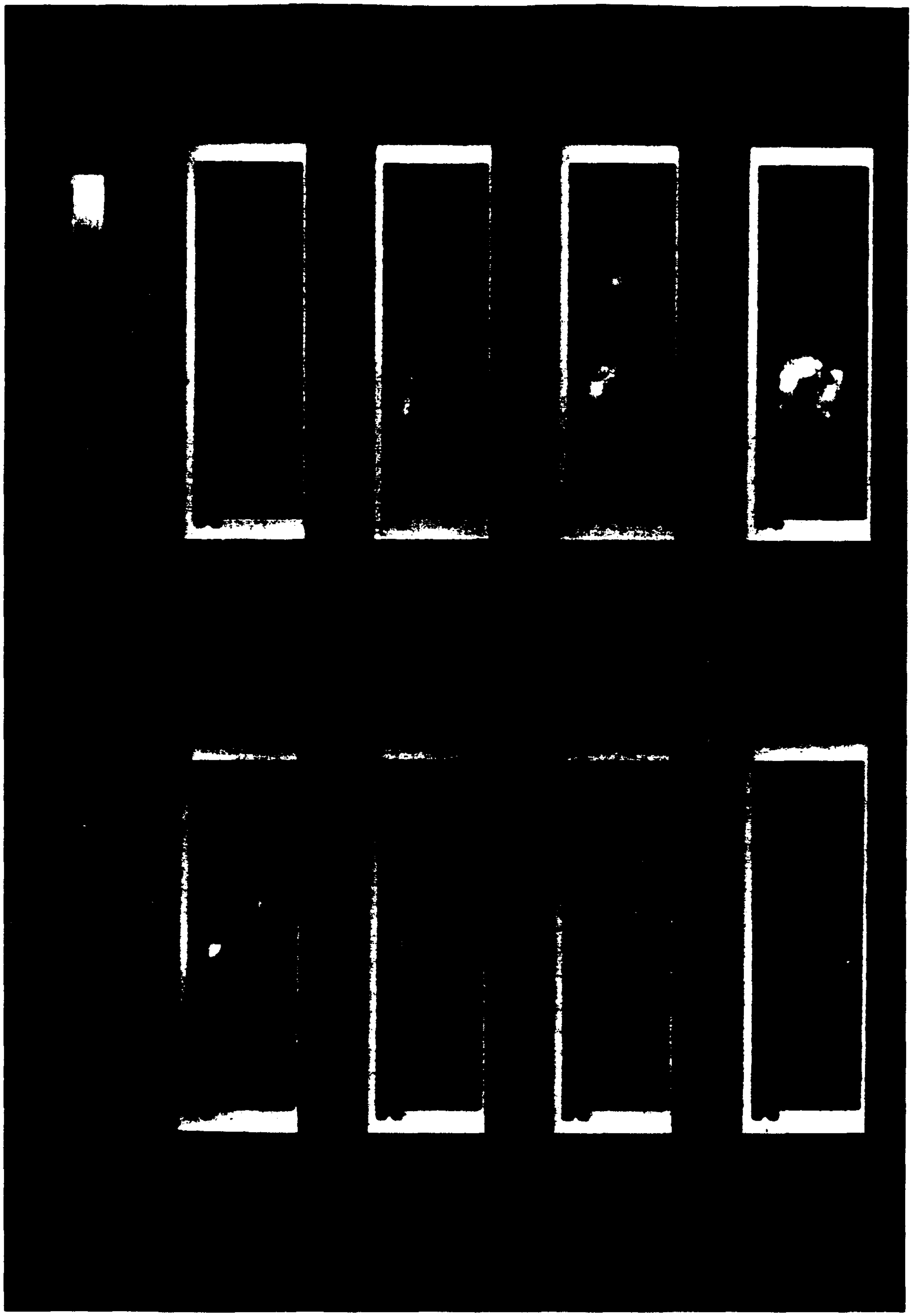

Figure 9b.

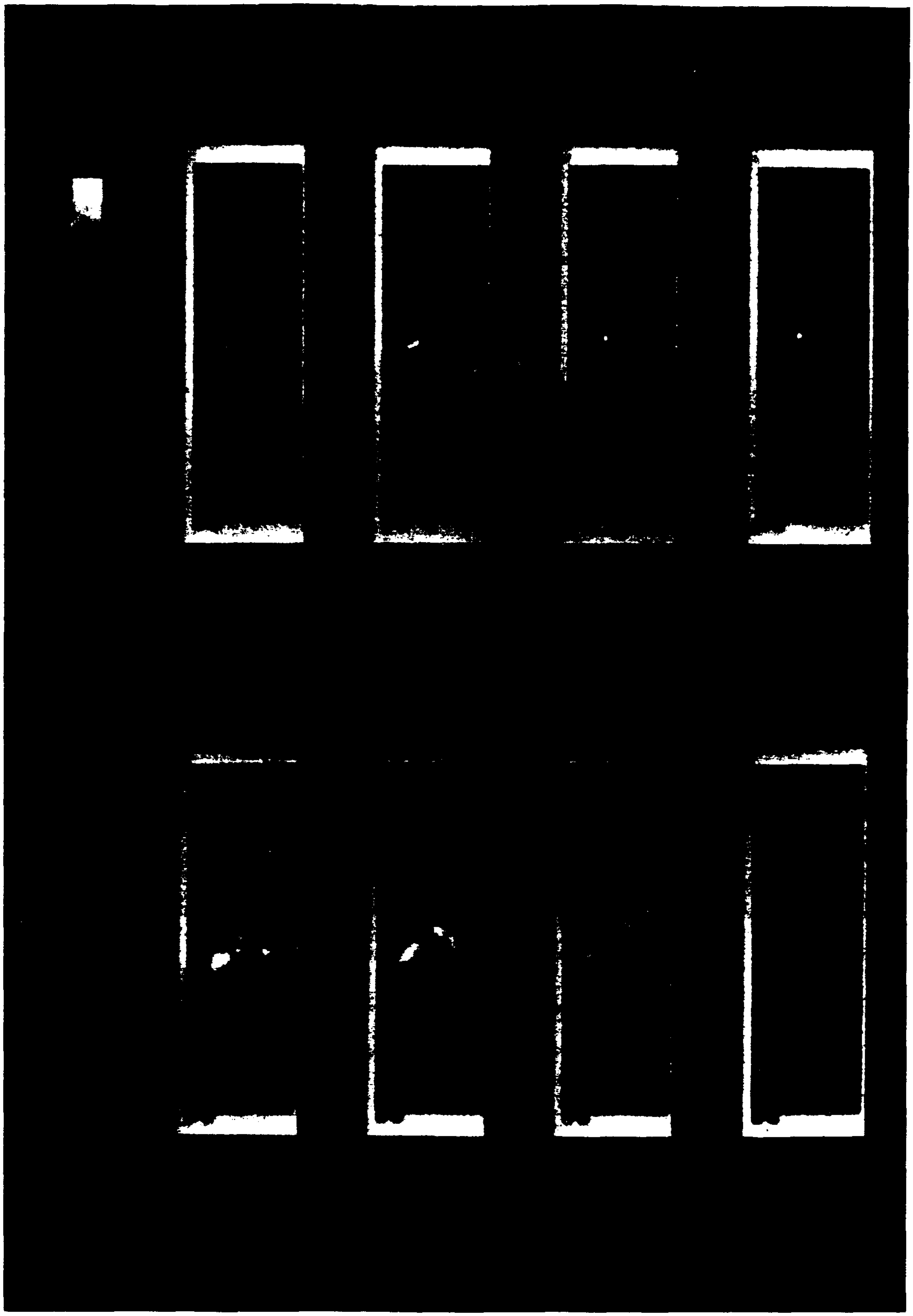

Figure 9c.

The contour map shown in Figure 10 corresponds to the first photograph of Figure 9a and will provide orientation to interpretation of the whole sequence of Figure 9. The first of the three vortices present appears as the shaded

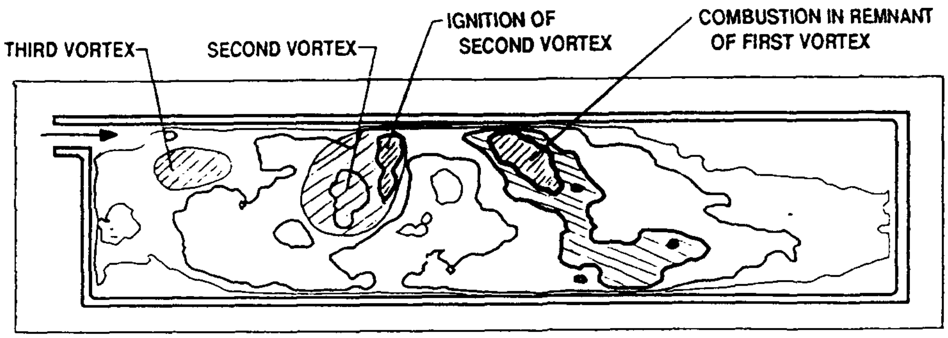

Figure 10. Contour Plot of First Photo in Figure 9a

region at the right in Figure 10. This mixture has moved downstream from the inlet and the combustion process is nearly complete. Combustion products and burning gas associated with this vortex have impinged on the bottom wall and spread laterally. The second vortex appears as the shaded region near the center. Combustion has been initiated on its right-hand edge and spreads rapidly throughout the structure in the subsequent 8 photographs of Figure 9.

The third vortex appears as the light green region just visible at the left edge of Photos 4 and 5 of Figure 9a. It is clearly visible in subsequent photographs. The circulation about the third vortex can be seen in photos 6 through 15 as reacting mixture is drawn around the less rapidly reacting gas in the center of the vortex. No combustion is associated with the third vortex until photo 9 or 10, about 2 milliseconds after it was shed.

Combustion in the second vortex, indicated by the intensity of chemiluminescence, reaches a peak in the fourth photo and dies off over the following 10 frames. Similarly, combustion intensity in the third vortex peaks in frames 15 through 20. The time delays between vortex formation and ignition, between vortex formation and the start of rapid combustion, and the duration of the rapid combustion phase are important features of vortex burning and quantifying their dependence on the geometric, gasdynamic and chemical parameters is a major aim of the study.

We are now obtaining a data set for 33 operating conditions which include the following ranges of parameters: duct heights of 2.54, 5.08 and 7.62 cm; fuels consisting of methane and a mixture of 10% hydrogen in methane; three gas inlet speeds, and 3 fuel-air ratios. This set of data will encompass the wide ranges of pressure amplitudes, vortex shedding frequencies, and characteristic chemical and fluid dynamic times required for completion of our study.

The time-resolved data being obtained in these experiments include: pressure amplitude measured at the walls of the combustion chamber, velocity measured at the entrance to the combustion chamber, shadowgraph movies of the density field for the first 30 cm of the combustion chamber at rates of 4 to 6000

frames per second, and video movies of the chemiluminescent radiation produced by combustion within the first 30 cm of the chamber at framing rates of 3000 frames per second. In addition, gas temperature will be measured at a number of positions within the combustion chamber using 25 micron diameter thermocouples. The shadowgraph movies have been obtained for about half of the test conditions and the high speed movies of chemiluminescence will be obtained later this year.

Studies in the GALCIT Supersonic Wind Tunnel

One of the important factors that becomes evident when attempting to make technological application of the shock enhanced mixing is the interaction of the streamwise vorticity induced by the shock enhancement with the boundary layer vorticity which is predominantly normal to the flow direction. In the studies of the hypersonic injector which we carried out at NASA Langley Research Center, Marble et al. (1990), Waitz et al. (1991), and Waitz (1991), this interaction proved to be important in choosing the physical configuration.

To examine this important issue in detail, plans were made to install a cylindrical jet injector in the 5 cm by 6.47 cm test section of the GALCIT Mach 2.5 supersonic wind tunnel; the installation is shown in Figure 11. The apparatus

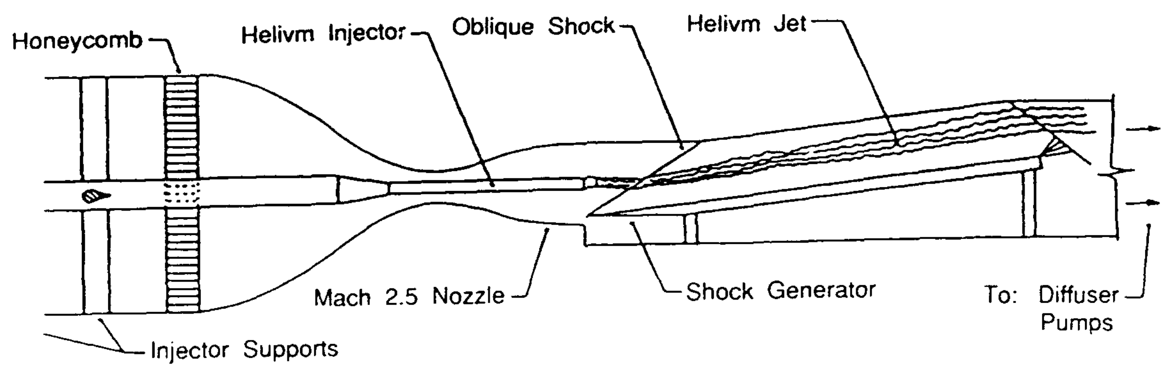

Figure 11. Shock Enhanced Mixing Experiment in GALCIT M = 2.5 Tunnel

for this investigation has now been completed. The system includes a sensitive schlieren system and a helium gas supply which can be used to inject a wide range of flows of helium at temperatures ranging from 150 K to 300 K and Mach numbers from subsonic to 2.50. Total temperature and pressure rakes and gas sampling probes traverse across the test region.

The chief diagnostic method for quantitative examination of the mixing process will be light scattering off ice crystals formed in the air stream as room air is accelerated to Mach 2.50 in the tunnel. A dye laser will be used to illuminate the ice crystals. This laser and accompanying optical equipment is the system which was the light source for the experiments in the 17 Inch Shock Tube; it has now been moved to a cart which allows its use for both the shock tube and the wind tunnel experiments.

Preliminary experiments with uncooled helium have been carried out. The limited light scattering data suggest that considerably more mixing occurs in the shock enhanced mixing process when shear between the helium jet and air is present than when it is not.

Notation for Section 2.

a_1	Acoustic velocity at the initial state in shock tube.
M	Mach number
M_s	Shock Mach number in shock tube
p_1	Initial pressure level in the shock tube
phi	Equivalence ratio; fuel-air ratio divided by stoichiometric fuel-air ratio
r_o	Initial radius of helium jet
u	Velocity of air following shock in shock tube
V	Mixture velocity entering chamber of Unsteady Combustion Facility
x	Distance measured from jet center, in flow direction

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4. PERSONNEL

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5. INTERACTION WITH INDUSTRY AND GOVERNMENT LABS

Professor Kubota has been in close contact with the high speed aerodynamics group at NASA Langley Research Center because of our experiments being carried out there in the Mach 6 High Pressure wind tunnel.

Professor Marble serves as a member of the Committee on Hypersonic Technology for Military Applications of the Air Force Studies Board, the Hypervelocity Mixing Advisory Group, NASA Langley Research Center, the NASA Committee for Generic Hypersonics Program, and the Peer Review Group for Turbomachinery, NASA Lewis. He is Chairman of the Propulsion Panel, Aeronautical Technologies Committee of the Aeronautics and Space Engineering Board, Member of the ASEB, and Member of the National Research Council Committee on Earth to Orbit Propulsion Options. Professor Marble has periodically given briefings to Pratt & Whitney and to Rocketdyne concerning the shock enhanced mixing study.

As a result of the completion of the GALCIT Piston Shock Tunnel, Professor Zukoski has maintained close contact with Rocketdyne, who is the heaviest user of the tunnel. Dr. Zukoski has been instrumental in carrying out experiments of shock enhanced mixing installed in the Rocketdyne Scramjet model at real conditions corresponding to a Mach number of 12. This is the closest we have been able to come to having the AFOSR research applied to NASP hardware. The results will be available to us in the near future. Dr. Zukoski has continued to stay in close contact with the Scramjet research group at NASA Langley Research Center.