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INFLUENCE OF DEAD ZONES AND TRANSONIC  
SLEWING ON THERMAL BLOOMING

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United Aircraft Research Laboratories

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13 ABSTRACT

An experimental research program is being carried out to investigate two particular aspects of the thermal blooming problem. Thermal blooming is the self-induced effect which results from refractive index variations in the path of a laser beam caused by absorption of laser beam energy. The two aspects being investigated are the effect of transonic flow and also dead zones on the thermal distortion. When heat is added to flow at near sonic velocities severe density gradients and even shock waves can result. An experiment involving a CO<sub>2</sub> laser and a blow down wind tunnel are being used to investigate this problem and a pulsed schlieren system is used to observe the density gradients. The dead zone problem occurs when a beam is being slewed in a direction opposite to the motion of the vehicle carrying the laser. There is a region of the air path where there is no relative motion between the air and the beam and under these conditions severe thermal blooming can occur. This problem is being simulated in the laboratory using a low power CW CO<sub>2</sub> laser and a seeded gas cell which is rotated about a pivot point creating a dead zone at the pivot. The experimental apparatus and technique are described and preliminary data are reported on both of these experiments.

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Influence of Dead Zones and Transonic Slewing  
on Thermal Blooming

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## SUMMARY

The subject contract is concerned with two particular problems associated with self-induced thermal distortion of laser beams. Self-induced thermal distortion is the result of heating of the air in the path of the laser (by absorption of laser beam energy) which changes the index of refraction and therefore causes beam distortion. The two specific problems that are being investigated under the present contract are the influence of transonic flow and also the effect of dead zones on thermal distortion. With transonic or near sonic flow, the addition of heat by absorption can lead to extremely strong density gradients, stronger than those normally encountered in the subsonic flow case. The dead zone problem arises when there is a region of the propagation path where the relative motion of the beam with respect to the air is zero. This occurs when a beam is being slewed from a vehicle moving in a direction opposite the slewing motion. The progress made in investigating these two problems is described briefly in the following paragraphs.

The laboratory simulation of the transonic slewing conditions has been completed and we are now in the process of analyzing the data. The apparatus used in this experiment consisted of a 500 watt CO<sub>2</sub> laser, a blow down wind tunnel, and a pulsed schlieren system for observing the density gradient. The high intensity 10.6 $\mu$  beam passed through the transonic flow of air which was seeded with a small portion of SF<sub>6</sub> for simulation of atmospheric absorption conditions, and the density gradients were recorded with a schlieren system coaxial with the laser beam. In addition, the near field and far field patterns of the CO<sub>2</sub> laser beam were examined after passing through the transonic flow. Based on a simple one-dimensional heating, the experimental conditions were chosen to give an interaction which would result in a shock wave. In the experiments, however, no shock was observed on the schlieren photos which undoubtedly is the result of the two-dimensional nature of the flow in the vicinity of the beam. The laser induced gradients are found primarily in the wake of the beam, are primarily in a direction orthogonal to the beam and flow directions, and show that the laser absorption causes a density decrease rather than a density increase as would be expected for one-dimensional simple heating theory. Detailed analysis of the data will be carried out during the remainder of the contract period.

The influence of a dead zone or region of the beam path with zero transverse velocity is also being investigated experimentally. A 10-20 watt cw CO<sub>2</sub> laser and detector system have been made available by the Research Laboratories. The absorption cell to be used to simulate a slewed beam with a dead zone has been constructed. The dead zone is simulated by pivoting the cell at various axial positions and translating one end of the cell. By moving the pivot point the influence of the position of the dead zone can be evaluated. Qualitatively the dead zone can be looked upon as a transient effect. Immediately after turning on

the beam the dead zone literally extends from the target to the source. As time progresses energy is deposited in the beam path and, as a greater fraction of the path satisfies the condition for steady state blooming, the dead zone shrinks in length from the target back toward the point of pivot. Thus the problem must be looked at as transient blooming plus slewing and experimentally the intensity will be monitored as a function of time until some form of heat transfer limits the experimental observation. Our preliminary experiments indicate that the limits on observation time are thermal conduction and natural convection or buoyancy. The length of observation time can be increased, if necessary, for simulation of more realistic propagation conditions, by increasing the cell pressure or by a vertical orientation of the cell to reduce conduction and convection effects. A short high pressure cell has been constructed to examine the relative effect of a stagnation zone at various points in the propagation path. In addition, by pivoting this cell about its center it should be possible to test various interpretations of the effective length of the dead zone. During the remainder of the contract period experimental data on the dead zone problem will be taken and analyzed to determine the magnitude of the effect on atmospheric propagation of high energy laser beams.

## SECTION I

## INTRODUCTION

The United Aircraft Research Laboratories are conducting an experimental study of two specific problems associated with the self-induced thermal distortion of laser radiation propagation through the atmosphere. One is the so-called dead zone problem which arises when there are regions of the propagation path where the relative motion of the beam with respect to the air is zero. This occurs when a beam is being slewed from a vehicle moving in a direction opposite to the slewing motion. The second problem is the effect of transonic or near sonic flow where the addition of heat by absorption can lead to the formation of extremely strong density gradients and possible distortion of the beam.

Self-induced thermal distortion, commonly called thermal blooming, has been treated in detail and the result of these investigations have been widely published, but in most instances the problem treated was the steady-state distortion arising from a uniform wind or a slewed beam with a velocity varying linearly with range.<sup>1-4</sup> The steady-state temperature profile is obtained in a straight forward manner by balancing the convective heat transfer against the absorption from the laser beam. The two specific problems being treated under this research contract are more complicated in that a straight forward analysis is not possible and no complete analytic solution has been developed. Hayes<sup>5</sup> has analyzed the dead zone problem qualitatively by dividing the propagation path up into regions where the beam undergoes steady state slewing and a region of zero wind. His analysis shows the problem to be serious in some specific circumstances. The problem of transonic slewing has been analyzed<sup>7,8</sup> and the density gradients obtained in closed form. However, both the analysis of dead zone and transonic slewing have trouble handling the propagation of the laser radiation through the disturbance. The basic problem is not knowing the axial length of the dead zone or the effective path length of the transonic zone. It therefore is difficult to evaluate these two effects even qualitatively. Under this research program, we are attempting to study these problems experimentally and determine if they are a serious threat to high power laser applications.

The experiments have been set up in the laboratory and a description of the apparatus is given in the following sections. Data on the transonic slewing experiment have been taken and a detailed analysis of the results is currently being undertaken. The dead zone experiment has been initiated, but the data so far have been exploratory in nature. No conclusions have been drawn relative to the severity of these problems.

## SECTION II

## TRANSONIC BLOOMING

## 1. INTRODUCTION

In this section experiments designed to simulate the propagation of high-intensity cw laser radiation through an absorbing, transonic flow are described. This problem would be encountered at high slewing rates, where a point along the beam is traveling at mach one with respect to the surrounding air. Theoretical studies of this problem<sup>7,8</sup> have indicated that under such conditions, the non-linear interaction between the laser energy and the flow can cause rather severe density variations and that for flow velocities just slightly greater than mach one, can cause shock waves in the flow.

The approach being used in the present study is to pass a high-intensity  $10.6\mu$  beam through a transonic flow of air which has been made absorbing at  $10.6\mu$  by adding a small fraction of SF<sub>6</sub>. The density gradients induced in the flow are recorded with a schlieren system coaxial with the laser beam and the effects of these density gradients are measured by looking at the transmitted beam in the near and far fields. The experiments are being carried out under very strong interaction conditions in order to establish a lower bound on the laser intensity required for this effect to be a significant propagation problem.

## 2. EXPERIMENTAL APPARATUS

The apparatus being used in these experiments is shown schematically in Fig. 1, and a photograph of the experimental arrangement is shown in Fig. 2. The supersonic nozzle is operated as a blowdown wind tunnel by charging a fifty-liter vessel with a mixture of compressed air and SF<sub>6</sub>. The flow is switched on with a solenoid valve and the system provides quasi-steady flow in the nozzle for several tenths of a second. The flow channel is a two-dimensional converging-diverging nozzle with a throat height of  $\sim 3.0$  mm, with a width in the laser beam direction of 5.0 mm and with an exit mach number of  $\sim 1.3$ . A typical schlieren photograph of the nozzle flow is shown in Fig. 3, along with the corresponding trace of nozzle stagnation pressure. The schlieren photo was taken 0.2 sec after the opening of the solenoid valve. The expansion fans at the nozzle throat can be seen in Fig. 3, as well as the strong normal shock at the nozzle exit.

The CO<sub>2</sub> laser being used in the experiments is a pulsed, low-pressure, coaxial electric discharge laser and is shown in Fig. 2. A typical trace of the laser output, as measured with an AuGe detector is shown in Fig. 4. The peak power of the laser is  $\sim 500$  W and, as seen from Fig. 4, is effectively constant for  $\sim 0.1$  msec. The laser output is focussed into the flow channel with a 25 cm fl lens which gives

a 1.5 mm diameter focal volume which is nearly cylindrical over the 5 cm width of the flow channel. Since the flow velocity in the experiments is  $\sim 3.6 \times 10^4$  cm/sec., the laser intensity is constant for  $\sim 24$  flow times (based on the beam diameter), and the laser-flow interaction should reach steady-state during the laser pulse. The relative position of the laser beam in the flow channel (and hence the mach number at the beam location) can be varied by translating the nozzle relative to the beam. The relative positions of the laser beam and the schlieren field are fixed.

The flow is photographed using a high-speed schlieren system as shown in Fig. 1. The schlieren light source is a small air spark with a duration of  $\sim 2$   $\mu$ sec. The schlieren source was monitored with a photo-detector and the signal can be seen superimposed on the laser signal in Fig. 4. It can be seen that the schlieren photos give an instantaneous record of the quasi-steady density distribution due to the laser-flow interaction.

In addition to the schlieren photos, various measurements of the transmitted laser radiation are being made. The near-field beam intensity is measured, with and without absorbing flow, by removing one of the schlieren mirrors and placing an AuGe detector in the beam. This measurement gives a time-resolved record of the beam attenuation. Measurements of the far field beam intensity are made by placing a lens in the transmitted beam and focussing the beam on to thermal sensitive paper or on to a pinhole placed in front of the AuGe detector.

### 3. EXPERIMENTAL PROCEDURE

In order to adequately simulate transonic slewing of a high-intensity beam propagating through the atmosphere, the conditions of the experiment must be chosen to give an interaction which is at least as large as that expected under actual conditions. We can make a rough estimate of the effect of the laser flux on the flow by assuming that the energy absorption process results in simple one-dimensional heating with a corresponding increase in the stagnation temperature.\* For this case the increase in stagnation temperature is given by the relation<sup>9</sup>

$$Q = c_p \Delta T_0, \quad (1)$$

where  $c_p$  is the specific heat,  $T_0$  is the stagnation temperature, and  $Q$  is the

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\*In the actual case, the heating and flow processes are two-dimensional and a rigorous treatment would involve the non-linear fluid equations for two-dimensional flow.

energy addition per unit mass. In the case of laser absorption, the energy addition can be written as

$$Q \approx \frac{\alpha I_0 d}{\rho u} \quad , \quad (2)$$

where  $\alpha$  is the absorption coefficient,  $I_0$  is the incident laser intensity,  $d$  is the beam diameter,  $\rho$  is the mass density, and  $u$  is the flow velocity. Thus, we have

$$\Delta T_0 \approx \frac{\alpha I_0 d}{\rho u c_p} \quad . \quad (3)$$

From one-dimensional flow considerations, we expect that if the calculated change in  $T_0$  is larger than that necessary to reduce the flow to  $M = 1$ , the flow will be choked locally, and some sort of shock structure will result.

In the experiment, the quantities  $\rho$ ,  $u$ , and  $c_p$  are comparable to those that would be encountered in the atmosphere. As mentioned previously, the peak laser intensity is  $I_0 \approx 5.0 \times 10^4$  W/cm<sup>2</sup> and the focussed beam diameter is  $d \approx 1.0$  mm. Thus, the remaining parameter to be determined is the absorption coefficient  $\alpha$ . In the actual situation, typical values would be  $I_0 = 1.0 \times 10^4$  W/cm<sup>2</sup>,  $\alpha = 5.0 \times 10^{-6}$  cm<sup>-1</sup>, and  $d = 1.0 \times 10^1$  cm, giving  $\alpha I_0 d = 0.5$  W/cm<sup>2</sup>. For the experimental values of  $I_0$  and  $d$  mentioned above, this would correspond to an absorption coefficient in the experiment of  $\alpha = 1.0 \times 10^{-4}$  cm<sup>-1</sup>.

A second consideration in choosing the experimental value of  $\alpha$  is the stagnation temperature rise required to produce shocking for a given initial mach number. Taking  $M = 1.2$  as a typical initial mach number in the experiment, one obtains the value  $T_0/T_0^* = 0.9787$  for Rayleigh flow. For  $T_0 = 300^\circ\text{K}$ , this implies  $\Delta T_0 = 6^\circ\text{K}$ . For typical experimental conditions; i.e.,  $\rho = 1.7 \times 10^{-3}$  gm/cm<sup>3</sup>,  $u = 3.6 \times 10^4$  cm/sec, and  $c_p = 1.0$  J/gm-<sup>o</sup>K, this in turn corresponds to  $\alpha = 0.07$  cm<sup>-1</sup>.

Another parameter of importance in the experiments is the laser path length through the flow. In the present experiments the major emphasis is on detecting the presence of laser-induced shock waves, and the 5.0 cm channel width was determined primarily by considering the path length required to give good resolution in the schlieren photographs. If shocks are present, this path length should be sufficient to produce strong effects in the beam itself. If shocks are not present, the expected effect on the beam can be estimated from conventional thermal blooming theory.

In the simulation experiments the strength of the interaction can be chosen by setting the concentration of SF<sub>6</sub> and hence setting the value of  $\alpha$ . In running

the experiments, the blowdown vessel is evacuated and back-filled with a few torr of SF<sub>6</sub>. The vessel is then filled with air to a pressure of ~ 90 psia, and the mixture is allowed to mix for several hours. The optimum SF<sub>6</sub> fraction was determined by measuring the transmitted laser energy with and without flow in the channel. Most of the data have been taken at  $\alpha = 0.2 \text{ cm}^{-1}$ , this being the largest value for which conditions would be relatively uniform across the flow channel. Therefore, in the simulation the value  $\alpha I_0 d \approx 1.0 \times 10^3 \text{ cm}^{-2}$  is obtained. Thus, as mentioned previously, the present experiments are being carried out under extremely strong interaction conditions.

As mentioned above, the laser pulse time is such that quasi-cw conditions are obtained during the pulse. In the experiment, the laser is set to fire at a pre-set delay after the opening of the flow solenoid valve (typically 0.2 sec) to allow the flow to become fully established, and the schlieren spark is pre-set to fire during the peak of the laser pulse, as shown in Fig. 4.

#### 4. EXPERIMENTAL DATA

Typical schlieren photos, with the  $10.6 \mu$  beam located at  $M \approx 1.17$  in the flow channel, are shown in Fig. 5. The corresponding transmitted laser pulses are shown in Fig. 6, and show that a value  $\alpha \approx 0.2 \text{ cm}^{-1}$  was obtained in these experiments (~ 4 torr of SF<sub>6</sub>). Figure 5-a shows the schlieren field with no density variations. Figure 5-b was obtained by firing the laser into the flow channel with no flow, but with a slight amount of residual SF<sub>6</sub>, and serves to locate the position of the  $10.6 \mu$  beam in the flow channel. Figures 5-c and 5-d are photos of the laser-induced density gradients under the conditions outlined in Section 3 above.

While detailed analyses of the schlieren data have not yet been conducted, two major comments concerning the photos can be made. (1) No laser-induced shock waves are seen on the photos. (2) The laser-induced density gradients are found primarily in the wake of the beam, are primarily in a direction orthogonal to the beam and flow directions, and show that the laser absorption causes a density decrease rather than a density increase as would be expected for one-dimensional simple heating theory.

These effects are contrary to the simple estimates made in Section 3 above, but are undoubtedly related to the two-dimensional nature of the flow in the vicinity of the  $10.6 \mu$  beam. This two-dimensional character can be seen clearly in Fig. 5.

Additional schlieren photos, with the beam located at a higher mach number, are shown in Fig. 7. These flow conditions would potentially lead to stronger shocks (i.e., greater net change in mach number) with a sufficiently strong interaction. The photos show a weaker density change than in Fig. 5, even though the calculated  $\Delta T_0$  is larger than that required to decelerate the flow to mach one. This effect again is probably due to the two-dimensional nature of the flow.

Additional schlieren photos, under various conditions, as well as various beam measurements have been made; however, these data have not yet been analyzed.

5. Future Program

During the remainder of the contract period, detailed analyses of the experimental data will be carried out, and additional measurements will be made, as necessary. The analyses will include estimates of the magnitudes of the laser-induced density variations, analyses of the near-field and far-field beam patterns, and correlations of the laser-induced effects under different flow conditions.

## SECTION III

## THERMAL BLOOMING OF A SLEWED BEAM WITH A DEAD ZONE

## 1. INTRODUCTION

A potentially serious problem in the propagation of high intensity laser beams through the atmosphere arises when there is a region of the path where there is no motion of the medium relative to the beam. The stagnant region of the path is conveniently referred to as a dead zone. This situation can occur under certain circumstances when a laser beam is being slewed from a vehicle which is moving in a direction opposite to the slewing motion. The propagation of a slewed laser beam having a dead zone has been treated analytically (Refs. 5, 6) and the models predict that severe thermal distortions will result in some specific cases. The purpose of this study is to experimentally assess the problem and, if possible, to relate the experimental results to the longer scale propagation in the atmosphere. A laboratory simulation is made by pivoting an absorption cell about a point, which then physically locates the position of the dead zone. The use of an absorbing gas, such as  $\text{CO}_2$  at a pressure in the range of 1-10 atm, gives an absorption over a 1-m path comparable to that experienced by a 10.6- $\mu\text{m}$  beam over a several kilometer range in the atmosphere. The experimental apparatus has been set up and preliminary data taken to evaluate the performance of the equipment. Based on these results and a study of the analytical models, future plans for this investigation are being formulated.

## 2. EXPERIMENTAL APPARATUS

The experimental arrangement, illustrated in Fig. 8, consists of a 1-m long, 4.3-cm I.D. absorption cell, attached to a pivoted beam, which is driven by a linear reciprocator and synchronous motor. The anti-reflection coated germanium windows have a 4-cm aperture; and, together with the  $\sim 1$  cm beam diameter of the entering laser beam, this aperture limits the sweep to 3 cm. The laser beam is turned on and off at the ends of the travel by a microswitch controlled solenoid. A 10-msec shuttering time is obtained with the present arrangement; however, by placing the shutter in the focussing telescope, this time could be reduced an order of magnitude. The laser beam intensity is measured with a gold-doped germanium detector (Santa Barbare Au:Ge-HS) and displayed on a Tektronix 536 or 454 oscilloscope.

The laser used in the experiments is a 2-m long, 15-W, stabilized  $\text{CO}_2$  laser. When properly alligned and adjusted a  $\text{TEM}_{00}$  beam is obtained and persists for several hours of running time. The diameter of the beam is approximately 1 cm, giving a divergence of 3 mrad. If focussed by a 1.5-m focal length mirror, the

beam diameters at the entrance and exit windows of the absorption cell would be 0.7 cm and 0.45 cm, respectively, which does not represent a very satisfactory focussing arrangement. Therefore, the beam is expanded by a two-fold Galilean telescope, which is also used to give a focus at 2 m. This arrangement should give 1/e-beam diameters of 1.0 cm and 0.25 cm at the entrance and exit windows of the cell. Power-in-the-bucket measurements of the beams at these locations showed 95% of the power was contained in a fundamental gaussian beam with 1/e-beam diameters of 1.0 and 0.25 cm, respectively. A scan of the beam at the exit window, made with the Au:Ge detectors and a 600- $\mu$  pin hole, is shown in Fig. 9 and verifies the integrated intensity measurement of the 1/e-beam diameter.

### 3. EXPERIMENTAL RESULTS

The experimental data obtained to date has been largely exploratory in nature, directed toward an evaluation of the performance of the apparatus and an understanding of the basic parameters involved in the study.

In the experiments the direction of the laser beam and the position of the detector are fixed and the medium is moved relative to the beam by pivoting the cell. A small problem involving the intensity normalization was anticipated with this arrangement. At the center of the travel the cell windows are normal to the direction of the laser beam and the beam passes through undeflected. At either end of the travel the windows make an angle of  $1.7^\circ$  relative to the normal and the beam is deflected 0.01 cm from the intended path. Since a 0.06-cm aperture is used to monitor the beam intensity the 0.01-cm displacement could result in a noticeable change in the intensity over the 3-cm travel. However, the focussed beam profile, Fig. 9, is fairly broad and, together with other effects such as the finite angle of the beam cone and wedging of the windows, the beam intensity is nearly constant over the 3-cm travel, as shown in Fig. 10(a).

The effect of an absorbing gas on the propagation of the focussed, slewed beam having a dead zone at the center of the path is shown in Figs. 10(b) and (c). CO<sub>2</sub> gas at a pressure of 30 psig (3 atm) is used, giving an absorption coefficient of 0.2 m<sup>-1</sup> and an 82% transmission over the 1-m path length. The laser beam intensity averaged over the 0.06 cm aperture is also initially 82%, but then decreases with time as heat is deposited in the medium and the beam spreads. After approximately 1 sec this average intensity levels off as natural convection and thermal diffusion balance the heat input and give rise to a steady state. The data shown in Figs. 10(b) and (c), were made with velocities of 0.2 cm/sec and 2 cm/sec, respectively (slew rates of 0.004 sec<sup>-1</sup> and 0.04 sec<sup>-1</sup>); and the intensity minima occur at 0.75 sec and 0.3 sec, respectively. Figs. 11 (a) and (b) show how the medium has moved relative to the beam for these two slew rates and elapsed times. In both cases a long portion of the path is essentially stagnant during the transient time interval and the dead zone is not well defined. To obtain a good definition of the dead zone it will be necessary to employ slew rates an order of magnitude faster.

For instance, Fig. 11 (c) shows the movement of the medium for a slew rate of  $0.2 \text{ sec}^{-1}$  and an elapsed time of  $0.1 \text{ sec}$ . For this slew rate the 3-cm sweep is completed in  $0.3 \text{ sec}$ , that is, the whole sweep is within the transient time regime; and, for all but the central 20 cm of the path, the velocity due to the beam slewing exceeds the natural convection velocity. As a result, a fairly well defined dead-zone would be expected. A speed of  $10 \text{ cm/sec}$  is approximately the upper limit of the apparatus as the use of higher speeds gives rise to undesirable motions and vibrations of the optical table.

#### 4. DISCUSSION

Hogge and Butts (Ref. 6) have performed numerical calculations for the thermal distortion experienced by a slewed, high power beam having a dead zone in the center of the path. The parameters used in the numerical study and typical laboratory values are given in Table I. The calculations predict that the normalized intensity will decrease to 0.79 and 0.22 for elapsed times of  $0.01 \text{ sec}$  and  $0.1 \text{ sec}$ , respectively. The point of maximum irradiance on the wind axis and the location of the power centroid only move a small fraction of the beam diameter from the target point, because of the spherical symmetry of the negative lens at the dead zone and the approximate cancellation of the beam motions relative to the wind occurring before and after the dead zone. A greater amount of spreading occurs transverse to the wind axis with an eccentricity increasing from 1.3 to 2.4 as the time goes from  $0.01 \text{ sec}$  to  $0.1 \text{ sec}$ . An interesting feature of the calculations is that the intensity distribution at  $0.1 \text{ sec}$  shows two peaks symmetrically positioned above and below the wind axis.

The non-dimensional parameter,  $N_t$ , characterizing the distortion arising from a stagnant zone in a beam path is given by

$$N_t = \frac{-n_T \alpha P t R \Delta}{\pi \rho_0 c_p a^4} \quad (4)$$

where  $n_T$  is the temperature derivative of the index of refraction of the medium,  $\rho_0$  is the density,  $c_p$  is the specific heat at constant pressure,  $\alpha$  is the absorption coefficient,  $P$  is the beam power,  $a$  is the beam radius at the dead zone,  $R$  is the range,  $\Delta$  is the length of the dead zone, and  $t$  is the elapsed time. The relative intensity resulting from a dead zone located at a fractional position  $x = z/R$  in the propagation path is given by

$$I_{REL} = 1 - \frac{2N_t(1-x) - \left(1 - \frac{a_R}{a_D}\right) + \left[\left(1 - \frac{a_R}{a_D}\right) - N_t(1-x)\right]^2}{\left[\frac{a_R}{a_D} + N_t(1-x)\right]^2} \quad (5)$$

where  $a_D$  and  $a_R$  are the laser beam radii at the dead zone and the target, respectively. All of the variables required to evaluate the distortion parameters are known, except for the effective length of the dead zone. Two possible definitions might be employed. First, one might imagine that the length of the dead zone is determined at any instant of time by that portion of the path which does not meet the conditions for steady state blooming, namely,  $V(z) \cdot t \geq 2a(z)$ , where  $V(z)$  and  $a(z)$  are the velocity and the laser beam radius at the point  $z$ . For a slewed beam  $V(z) = \Omega(z - z_D)$ , where  $\Omega$  is the slew rate and  $z_D$  is the position of the dead zone. Using this definition and the parameters of Hogge's calculations, the length of the dead zone is 140 m at 0.01 sec, giving a distortion parameter of 0.55 and a relative intensity of 0.03. This reduction is over an order of magnitude greater than that predicted by Hogge, and indicates that this definition overestimates the length of the dead zone.

Hayes (Ref. 5) has examined the dead zone problem and gives a rather restrictive definition of the stagnation zone. When heat is deposited in a gas, there is an effective radial expansion velocity given by

$$V_R = \frac{(\gamma - 1) \alpha P}{\pi e \rho_0 a C_s^2} \quad (6)$$

where  $\gamma$  is the ratio of specific heats at constant pressure and constant volume and  $C_s$  is the speed of sound. Hayes defines the length of the dead zone,  $\Delta$ , by

$$\Omega \frac{\Delta}{2} = \delta V_r \quad (7)$$

where  $\delta$  is on the order 10 or greater. Using this definition and Hogge's parameters, the thermal distortion from the dead zone is found to be two orders of magnitude smaller than the net distortion predicted by the numerical calculations.

Thus it would appear that some definition intermediate between the two is appropriate, and well-planned experiments together with some analytical insight may help to resolve this problem. Physically one can describe the problem of slewing in the presence of a dead zone as follows. At the instant the beam is turned on, the whole propagation path is within the transient regime; however, the heat input is infinitesimal and no distortion is seen. At some later point in time, three regions can be distinguished: (1) regions which satisfy the condition for steady state blooming; namely,  $\Omega(z - z_D) t \geq 2a(z)$ , (2) intermediate zones where there is some heat removed by forced convection due to slewing, and (3) the true dead zone where the forced convection velocity due to slewing is comparable to the radial convection velocity, thermal conductivity, or other local disturbance. As time increases and greater portions of the beam satisfy the steady state conditions the portion of the path occupied by the intermediate

zones and the dead zone shrinks in size; however, a proportionally greater amount of heat has been deposited in these combined zones. In theory, we can define at any instant of time an effective length of the "dead zone", using this term loosely to stand for the combined zones. This length would be expected to decrease somewhat with an increasing time and to decrease with increasing slew rate. The goal of the experimental program is to determine the effective length for the laboratory case and, by varying available parameters, to scale these findings to atmospheric propagation situations.

## 5. FUTURE PLANS

In the light of the previous discussion the following experimental program has been formulated. First, a short high pressure cell of 20-cm length has been constructed. By placing this cell in the beam and monitoring the intensity as a function of time the transient distortion due to a 20-cm dead zone at a given point in the path can be assessed. The intensity will decrease with time until natural convection and thermal conductivity of the medium establish a steady state level. By varying the gas pressure the relative contributions of these two effects can be separated, as thermal conductivity displays a stronger pressure dependence. The use of high pressures is desirable in these experiments as the conduction and convection times for the beam diameters used in long path atmospheric propagation situations will be long. By moving the cell to various positions along the propagation path, the relative severity of a dead zone at a given point can be determined. Finally, the effective length might be determined in the following way. For a given point in the path the distortion introduced by a 20-cm long dead zone can be determined with the stationary cell as described above. A record is then made of the intensity as a function of time with various slew rates as the short cell is pivoted about its center. The contributions of the portions of the beam meeting the steady state blooming conditions will be small; thus comparing the distortion at a given time for a certain slew rate with the distortion of the fixed cell for that same elapsed time will allow the effective length for the given set of conditions to be specified. Through a variation of the experimental parameters, such as beam power and focussing conditions, an attempt will be made to scale these findings to larger scale propagation situations. Having completed the studies described above the thermal blooming of a slewed beam with a dead zone will be studied. As the separate parts of the problem should then be well understood these experiments will provide a final test of the experimental modeling. The location of the dead zone can be changed by moving the position of the pivot and special attention will be given to the case of a dead zone close to the source.

TABLE I.

Parameters in Dead Zone Studies: (A) Numerical Calculations of Hogge and Butts, and (B) Typical Laboratory Simulation Parameters.

Parameter*	(A)	(B)
R	1 km	1 m
$\alpha P$	100 W/m	4 W/m
$\Omega$	0.27 sec <sup>-1</sup>	0.2 sec <sup>-1</sup>
a(o)	35 cm	0.35 cm
a(R)	1.9 cm	0.085 cm

\* Key:

R: Range  
 $\alpha$ : Absorption Coefficient  
P: Beam Power  
 $\Omega$ : Slew Rate  
a(o): Beam Radius at Source  
a(R): Beam Radius at Target

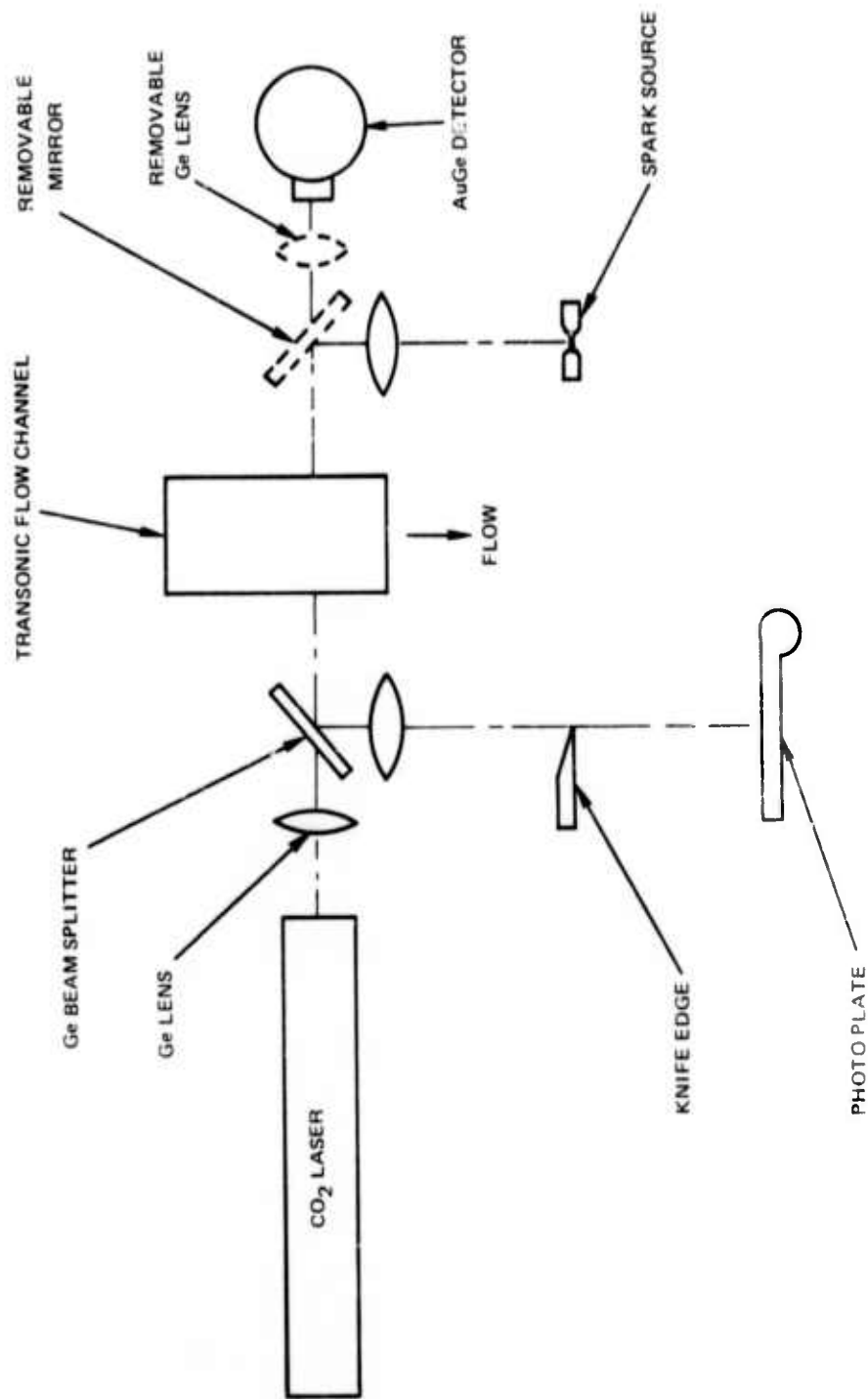
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1. F. G. Gebhardt and D. C. Smith, "Effects of Wind on Thermal Defocusing of CO<sub>2</sub> Laser Radiation", Applied Physics Letters, Vol. 14, No. 2, pp. 52-54, January 1969.
2. D. C. Smith and F. G. Gebhardt, "Saturation of the Self-Induced Thermal Distortion of Laser Radiation in a Wind", Applied Physics Letters, Vol. 16, No. 7, pp. 275-278, April 1970.
3. F. G. Gebhardt and D. C. Smith, "Effects of Diffraction of the Self-Induced Thermal Distortion of a Laser Beam in a Crosswind", Applied Optics, Vol. 11, No. 2, February 1972.
4. J. Wallace and M. Camac, "Effects of Absorption at 10.6 $\mu$  on Laser-Beam Transmission", Journal Optical Society of America, Vol. 60, pp. 1587, December 1970.
5. J. N. Hayes, Private communication.
6. C. B. Hogge and R. R. Butts, "Propagation Effects of a Slewed Beam with Transverse Wind Null Spots", AFWL-TR-73-76, May 1973 (Unpublished).
7. J. N. Hayes, Private communication.
8. C. B. Hogge and J. E. Brau, "Optical Effects of Transonic and Supersonic Winds on High-Energy Laser Beams", AFWL Laser Digest, RT-73-131, 129, 1973.
9. A. H. Shapiro, The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol. 1, The Ronald Press Co., New York, 1953, pp. 195.

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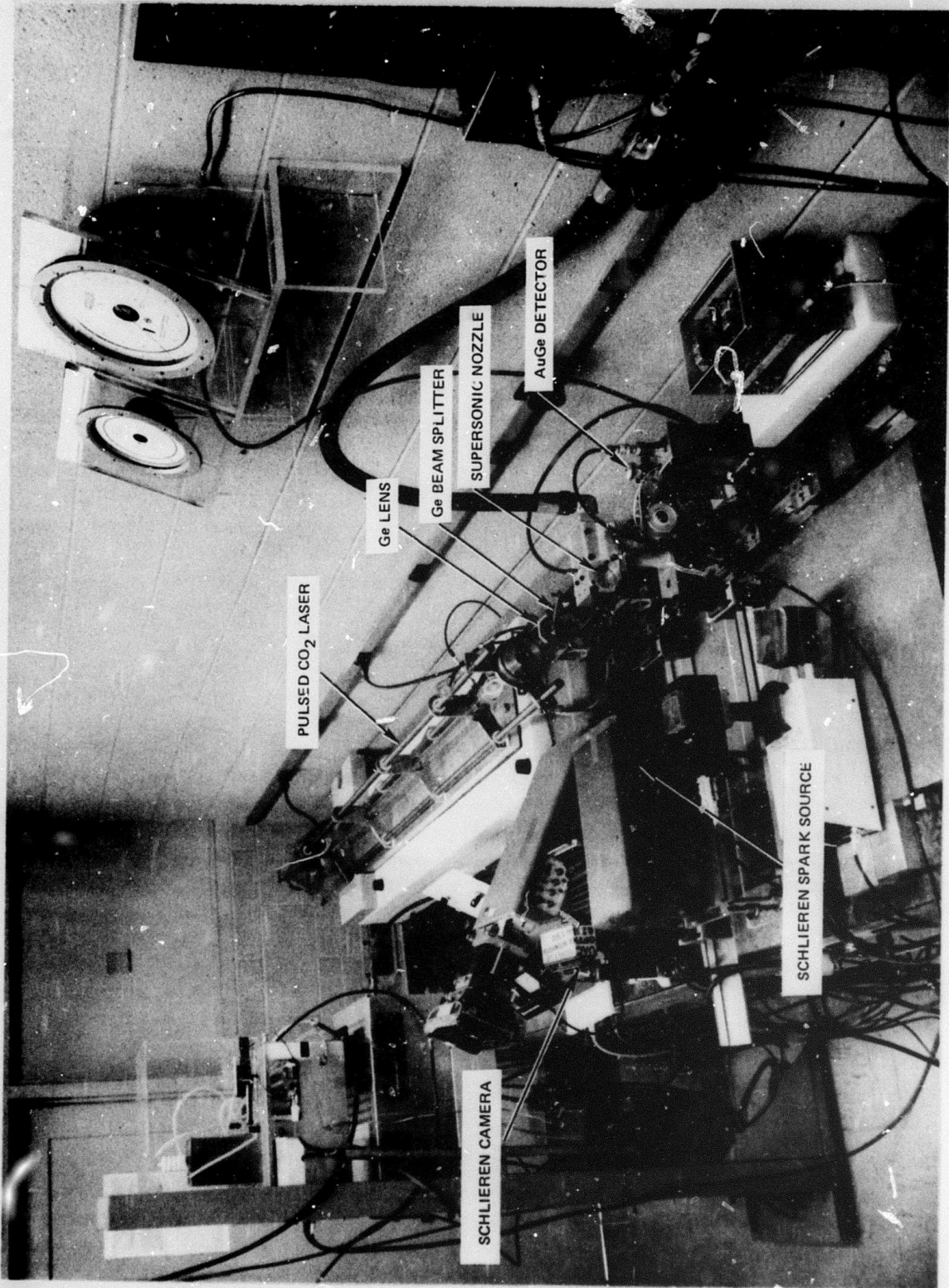
1. Transonic blooming experimental setup.
2. Photograph of transonic blooming experiment.
3. Transonic channel flow. (a) Photograph of fully-developed flow. (b) Stagnation pressure trace.
4. Pulsed CO<sub>2</sub> laser characteristics. (a) Laser power, (b) Laser discharge current.
5. Schlieren photographs of laser-induced density variations in transonic flow ( $M \approx 1.17$ ).
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8. Experimental Arrangement for the Dead Zone Study.
9. Pin-Hole Scan of the Focussed Beam.
10. Transient Blooming Observed with Pivoted Cell and Slow Slew Rates.
11. Movement of the Medium Relative to the Beam for Various Slewing Cases.

TRANSONIC BLOOMING EXPERIMENTAL SETUP

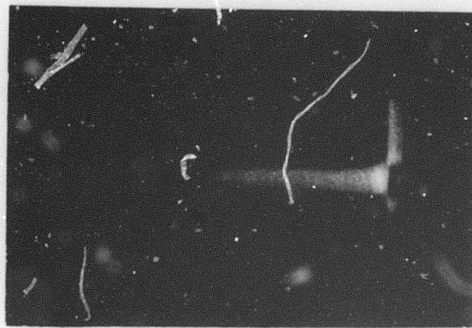


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for all Pictures**

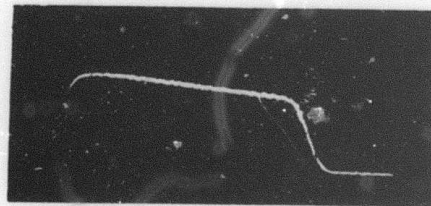
TRANSONIC BLOOMING EXPERIMENT



TRANSONIC CHANNEL FLOW



(a) NOZZLE FLOW

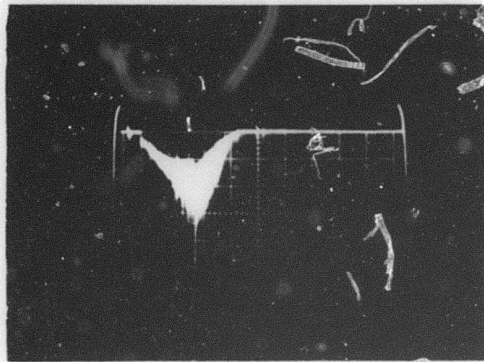


10 psi / Div

b) STAGNATION PRESSURE

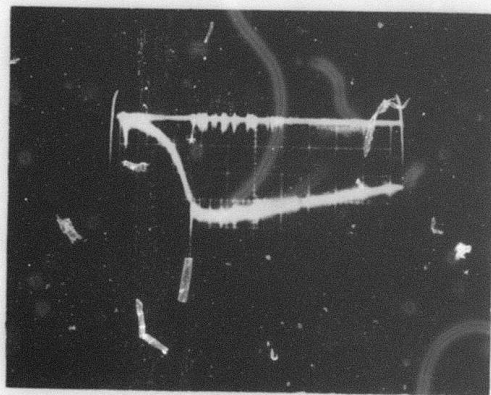
PULSED CO<sub>2</sub> LASER CHARACTERISTICS

Arb Units



(a) LASER POWER

300 ma/ Div

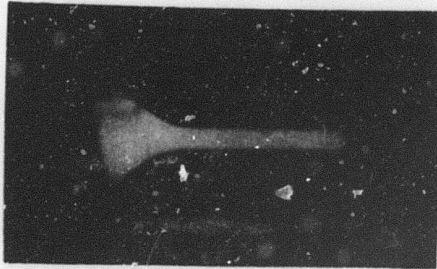


(b) LASER DISCHARGE CURRENT

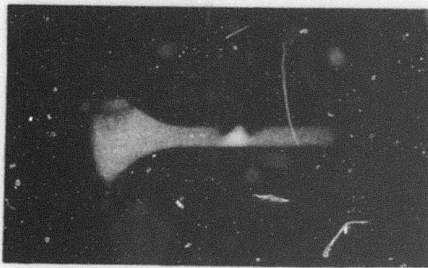
0.1 msec/ Div

SCHLIEREN PHOTOS OF LASER-INDUCED DENSITY VARIATIONS

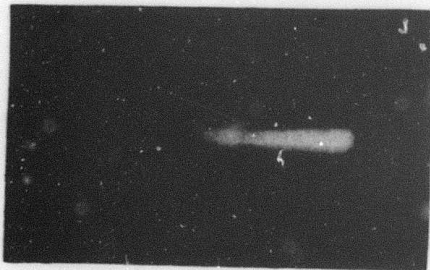
(M=1.17 AT BEAM LOCATION)



(a) NO FLOW, NO 10.6  $\mu$  LASER FLUX



(b) NO FLOW, WITH 10.6  $\mu$  LASER FLUX



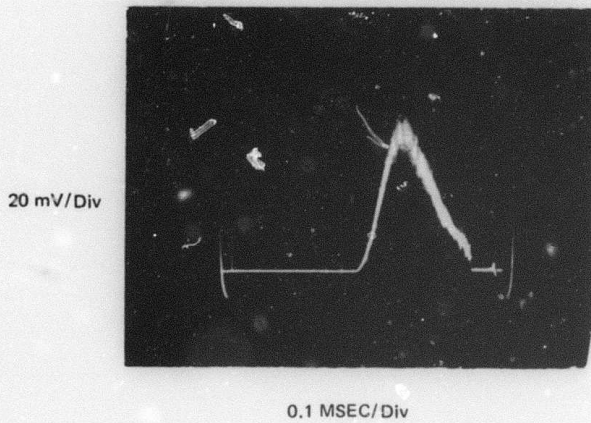
(c) FLOW AND 10.6  $\mu$  LASER FLUX  
(KNIFE EDGE VERTICAL)



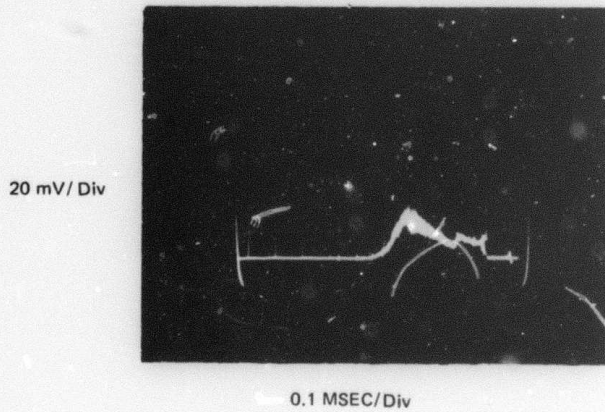
(d) FLOW AND 10.6  $\mu$  LASER FLUX  
(KNIFE EDGE HORIZONTAL)

TRANSMITTED 10.6  $\mu$  LASER POWER

(CENTER PORTION OF BEAM SAMPLED WITH AuGe DETECTOR)



(a) TRANSMITTED LASER POWER  
(NO ABSORPTION IN CHANNEL)



(b) TRANSMITTED LASER POWER  
(FLOW IN CHANNEL)

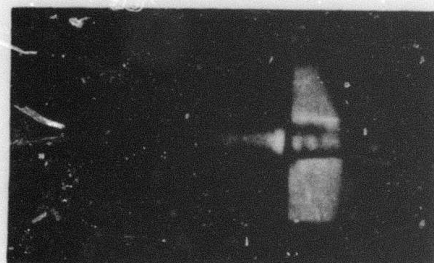
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SCHLIEREN PHOTOS OF LASER-INDUCED DENSITY VARIATIONS

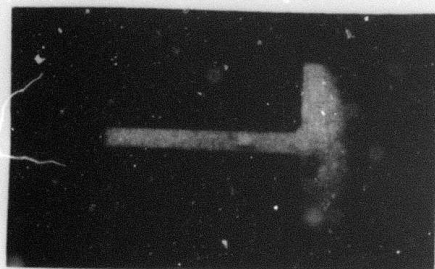
(M=1.28 AT BEAM LOCATION)



(a) NO FLOW, WITH 10.6  $\mu$  LASER FLUX

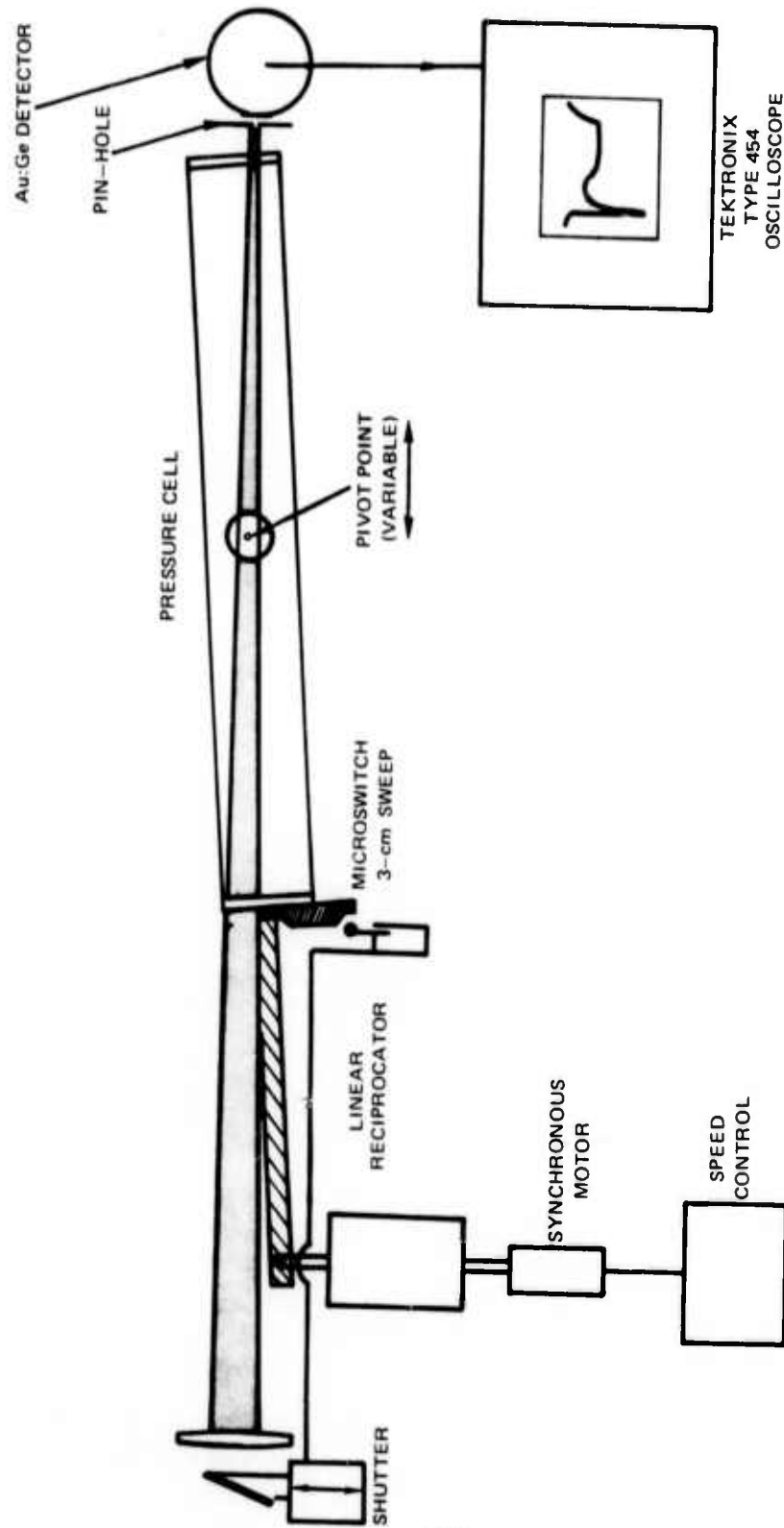


(b) FLOW AND 10.6  $\mu$  LASER FLUX  
(KNIFE EDGE VERTICAL)



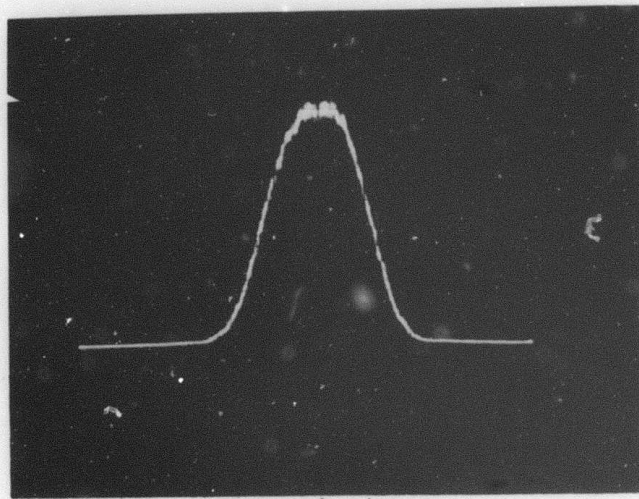
(c) FLOW AND 10.6  $\mu$  LASER FLUX  
(KNIFE EDGE HORIZONTAL)

DEAD ZONE EXPERIMENT

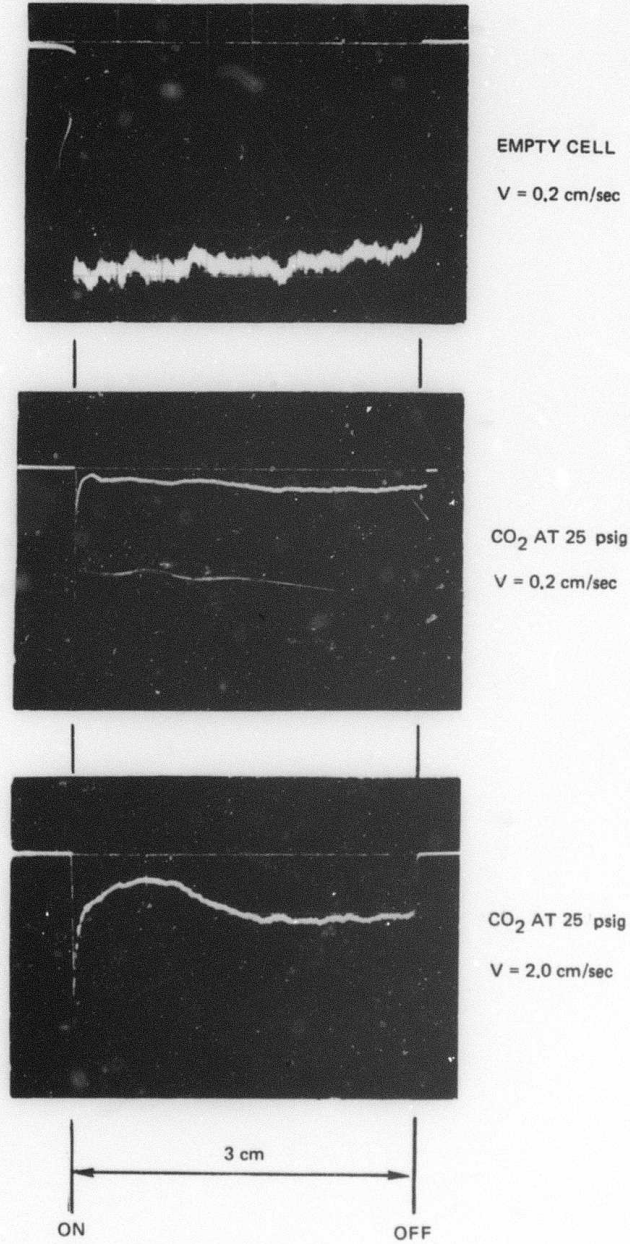


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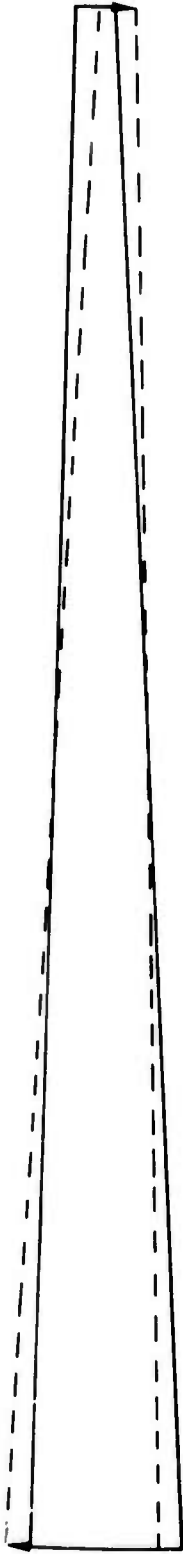
LASER BEAM PROFILE



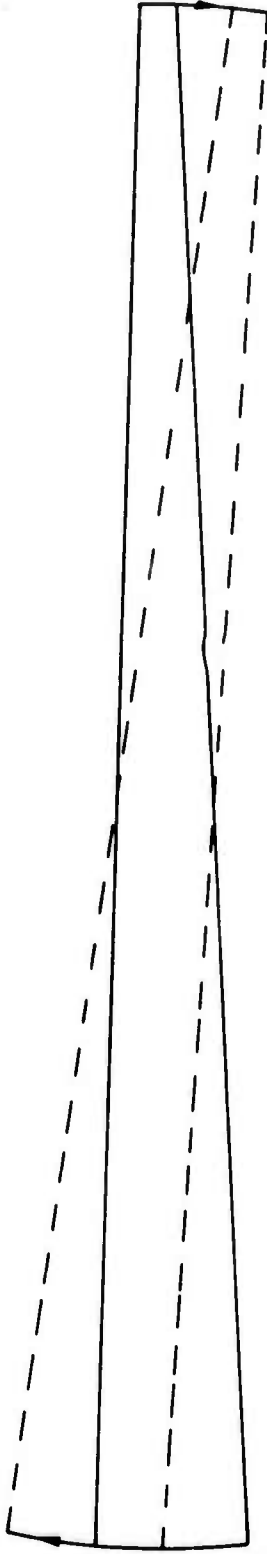
TRANSIENT BLOOMING - SLOW SLEW RATE



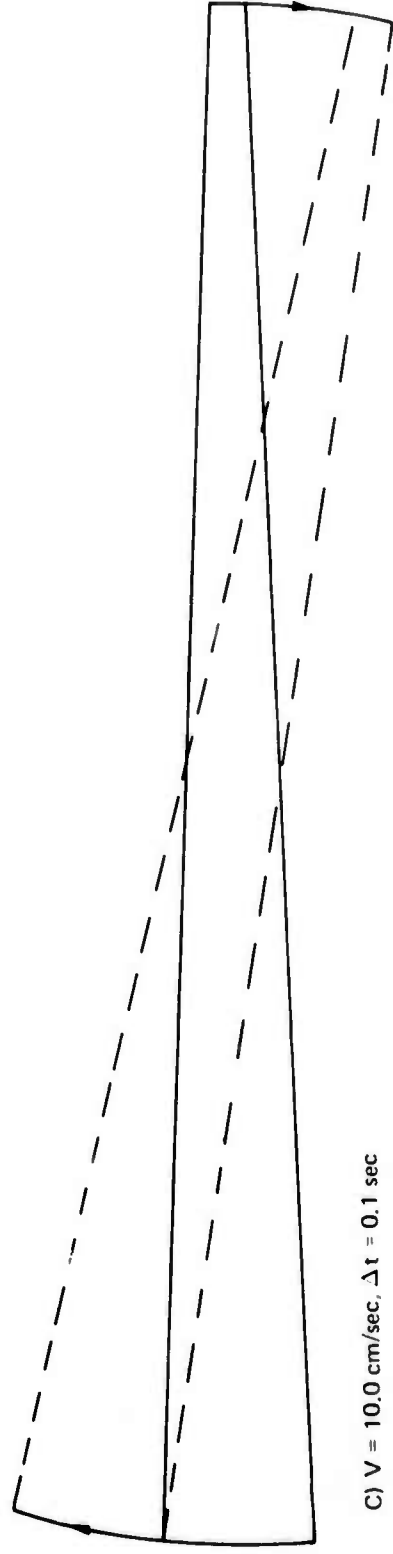
MOVEMENT OF MEDIUM FOR VARIOUS SLEWING CASES



A)  $V = 0.2 \text{ cm/sec}$ ,  $\Delta t = 0.75 \text{ sec}$



B)  $V = 2.0 \text{ cm/sec}$ ,  $\Delta t = 0.3 \text{ sec}$



C)  $V = 10.0 \text{ cm/sec}$ ,  $\Delta t = 0.1 \text{ sec}$

29.