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EXPERIMENTAL MEASUREMENT OF SHOCK
DETACHMENT DISTANCE ON SPHERES FIRED
IN AIR AT HYPERVELOCITIES

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To be Presented at
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U. S. NAVAL ORDNANCE LABORATORY
White Oak, Silver Spring, Maryland

EXPERIMENTAL MEASUREMENT OF SHOCK DETACHMENT DISTANCE ON SPHERES FIRED IN AIR AT HYPERVELOCITIES*

Introduction

Studies ^{were} ~~are being~~ made at the ~~Naval Ordnance Laboratory~~ of the shock detachment distance on spheres fired in a small aerophysics range. A second part of the experimental research program, not discussed in this paper, consists of measurements of radiation from the model surface and from the gas which envelops the model. Results of earlier studies made at this Laboratory are contained in References 1 and 2. This paper will present results from some of the recent shock detachment measurements obtained on spheres fired into air.

Investigations of this type can yield accurate information about the thermodynamic state variables of high temperature air in equilibrium as well as a check of the calculated values available in the literature. Moreover, if the density is sufficiently low, then the shock detachment distance becomes a measure of the lag in the exchange between the energy of translational motion and the internal modes and chemical reactions.

Experimental Equipment

The experimental program was conducted in a small aerophysics range, 30 feet long, equipped with a two-stage light gas launcher and

*The work reported was sponsored by the U. S. Bureau of Naval Weapons.

high-speed optical and radiation instrumentation. A schematic drawing of the range is shown in Figure 1.

Two launchers (1/4" and 1/2" caliber) were selected for these tests. The muzzle of the launchers extended into one end of a 30-inch diameter blast tank. At 15 feet downrange, the model entered a 5-inch inside diameter tube, passed through a velocity light screen and into the field of view of the rotating mirror camera.

Each light-screen system consisted of a light source which projected a 3-inch high by 1/16-inch wide beam across the flight path into a lens-phototube receiver arrangement. The phototube circuit was designed to provide a uni-directional signal regardless of the direction of the change in light input; therefore, the luminous gas caps rarely upset the timing system. A one-megacycle counter-timer recorded the time between light-screen signals from which the projectile velocity was calculated. The signals were also used to operate the proportional-delay units for triggering the spark light source for the rotating mirror camera.

A photograph of the rotating mirror camera setup is shown in Figure 2, and a schematic layout is shown in Figure 3. Basically the rotating mirror tracks the model for the duration of the spark light source and produces a single sharp image on the film rather than a blur. A 1/3 μ sec. barium titanate spark is used as a light source for the simple schlieren optical system and camera. The first lens collimates the light.

The second lens acts as the camera lens which is focused on the center of the range. It also serves to focus the collimated light at the knife edge position. The rotating mirror surface is located just aft of the knife edge, but close to it in order to keep the physical size of the rotating parts to a minimum. Eastman Kodak Tri-X film was used for photographing the models.

The films were read on a shadowgraph projector set at a magnification factor of 25. Many of the photographs were extremely sharp and the total variation in the measured shock detachment distance (Δ) for several readings was less than 5 percent. Other pictures were not quite so sharp, and the measurements of Δ varied up to about 10-percent.

It is interesting to note that the best negatives for reading correspond to the low pressure shots with weak shockwave lines. Unfortunately, much of the quality of these negatives is lost in the reproduction process. However, in spite of this difficulty two typical pictures are shown in Figures 4 and 5.

Shock Detachment Distance Calculations

The shock detachment distance on a sphere may be expressed approximately by the relation

$$\Delta = .41 \frac{\rho_1}{\rho_2} D$$

where $\frac{\rho_1}{\rho_2}$ is the density ratio across the shock on the stagnation streamline, and D is the diameter of the sphere. It can be seen that

Δ varies directly with the diameter and inversely with density in the shock layer. For a perfect gas with $\gamma = 1.4$, the density ratio across the shock wave has a minimum value of $1/6$. However, high velocity shock waves in air do not have such a limit, except at very low pressures where the relaxation times are large compared to the transit time for the air flowing over the model. The tendency is for the enthalpy to go into heat of formation in chemical reactions such as dissociation, rather than increasing the temperature of the gas. Dissociation may be looked on as a sink for the enthalpy and a constraint on the temperature rise. The effect of the constraint is to increase the density and to decrease the shock detachment distance as compared to the perfect gas result.

A more accurate prediction of the shock layer thickness can be made from the numerical solutions of the flow about blunt axisymmetric bodies given by Van Dyke and Gordon in Reference 3. Figure 6 is a plot of their calculated values of Δ/D (shock layer thickness/diameter) on a sphere for a range of density ratios and several values of γ . It can be seen that γ has a small effect on Δ for the density ratios that are plotted. In addition, from continuity considerations it can be shown that Δ is largely unaffected by a variation in the effective γ (the γ that satisfies the Rankine Hugoniot relationship) when "real gas effects" are present. Therefore, the assumption is made that the plot in Figure 6 is applicable for high enthalpy air in thermodynamic equilibrium.

Using the data given in Figure 6, along with the Hilsenrath and Beckett tables, Reference 4, we can now calculate the shock detachment distance on spheres fired in air at high velocities. Curves of Δ / D versus sphere velocity for air in chemical equilibrium are given in Figure 7.

Returning now to non-equilibrium flows, it is to be expected that the oxygen and nitrogen recombination will tend to "freeze" in the expanding flow away from the stagnation point. The flow here is similar to that experienced in high enthalpy wind tunnels. Calculations carried out at NOL and other laboratories have shown that appreciable freezing can be obtained in such a flow.

Still another, and perhaps more significant, effect on the shock layer thickness is the non-equilibrium flow that develops in the gas passing through the shock wave away from the stagnation streamline. The temperature, pressure and particle flow times are all lower than at the stagnation point. These effects tend to increase the departure from equilibrium; see for example Reference 5.

Results and Discussion

Before describing the data in detail, it should be pointed out that all of the results have been plotted for a 1/2-inch sphere. The data for the 1/4-inch sphere were applied to a 1/2-inch sphere by multiplying the pressure by a factor of 1/2. This implies the assumption that during the

relaxation processes, bi-molecular collisions are the important interactions and that the three-body recombination interactions can be neglected. Various shocktube studies provide a good justification for this assumption.

All of the data are plotted in Figures 7a and 7b. The first Figure indicates the accuracy or variation in the shadowgraph readings. The second Figure (7b) includes faired curves through the data for ambient range pressures of 2.5, 5, 10, and 20 mm Hg. Four curves showing calculated results are also shown. The upper one gives the shock detachment distance Δ / D for a perfect gas, with $\gamma = 1.4$. The lower three curves give Δ / D for air in full chemical equilibrium. A fifth line at the higher velocity end of the plot indicates the shock detachment for the case where the nitrogen dissociation is frozen out and the remainder of the air is in equilibrium.

The data in the velocity range 8,000 to 15,000 ft/sec exhibit a pronounced frozen flow effect at the lower speeds and at an ambient air pressure of 5 mm Hg. This same effect was observed in earlier experiments by Eckerman, see Reference 1. It is interesting to note that for equilibrium conditions the degree of dissociation of oxygen in air is higher than in pure oxygen for the same velocity because the gas temperatures in this range are considerably higher for air. That is, the undissociated nitrogen dilutes the dissociating oxygen and raises the temperature above that achieved in oxygen alone. For example, at 15,800 ft/sec and 5 mm Hg, the dissociation of O_2 in air is roughly 96% complete, whereas in oxygen

alone, at the same conditions, the dissociation is only 10 percent complete.

For velocities near 16,000 ft/sec, it appears that the air is approaching thermodynamic equilibrium, especially at the highest pressures of 20 mm Hg. We see here a demonstration of an accurate experimental technique for determining the thermodynamic state variables of high temperature gases in equilibrium. The pressure of the gas in the shock layer can be calculated accurately, the enthalpy is known, and now the density can be determined directly from the shock layer thickness. (Information of this type is needed for high pressure gases where intermolecular forces are significant and the calculated state variables are subject to error.)

At still higher velocities the 2.5 mm Hg data lie considerably above the equilibrium curve. (Note that for the equilibrium case the Δ/D decreases as the pressure decreases.) Based on the results at lower speeds, it can be assumed that the oxygen dissociation is essentially complete -- particularly at a velocity in the vicinity of 20,000 ft/sec. Therefore, the departure from equilibrium is probably due to an appreciable amount of "frozen" molecular nitrogen. Here again, as the pressure is increased, the detachment distance decreases.

In the experimental results discussed above there is one consideration apart from "real gas effects" which might tend to decrease the shock detachment distance and also the gas radiation. As the Reynolds number

is decreased the boundary layer thickens and will eventually merge with the shock wave. Moreover, for highly cooled bodies the displacement thickness can become negative, and the shock wave will move closer to the surface. Fortunately, in the present experiments the wall temperature is such that the displacement thickness is practically zero, even though the thermal boundary layer is about $1/5$ of the shock layer thickness, see Figure 8.

An additional possible source of error is the removal of surface material by ablation. Heating calculations indicate that for most cases this effect is negligible. However, they do indicate that the depth of material removed from a $1/4$ -inch nylon ball fired at a velocity of 20,000 ft/sec into a range pressure of 5 mm Hg is 8 percent of the shock detachment distance. No allowance was made for a heat of fusion, the flow of the ablated material, or a rotational velocity for the model.

Of course, the best estimate of this effect can be made by measuring the photographs of the model in flight. The contours of most models appeared to be little affected by the high heating rates. In fact, it was often possible to observe that a particular model was rotating by the location of the luminosity on the surface. As a final check, some magnesium "low temperature heat sink" models were fired. The data from these models fell in the midst of the data from the nylon spheres.

The above results for non-equilibrium flow can be applied to a body in hypersonic free flight. For example, the flow over a 1-foot sphere at 20,000 ft/sec and an altitude of 210,000 feet should be similar to that for a 1/2-inch sphere in the range at 20,000 ft/sec and at a pressure of 2.5 mm Hg.

The recent paper by Hall et al, Reference 6, seen by the author after the completion of this work, presents some calculated detachment distances which include the effects of non-equilibrium processes. The calculated values were applied to a 1/2-inch sphere by adjusting the ambient pressure, and are plotted in Figure 7b.

Acknowledgements

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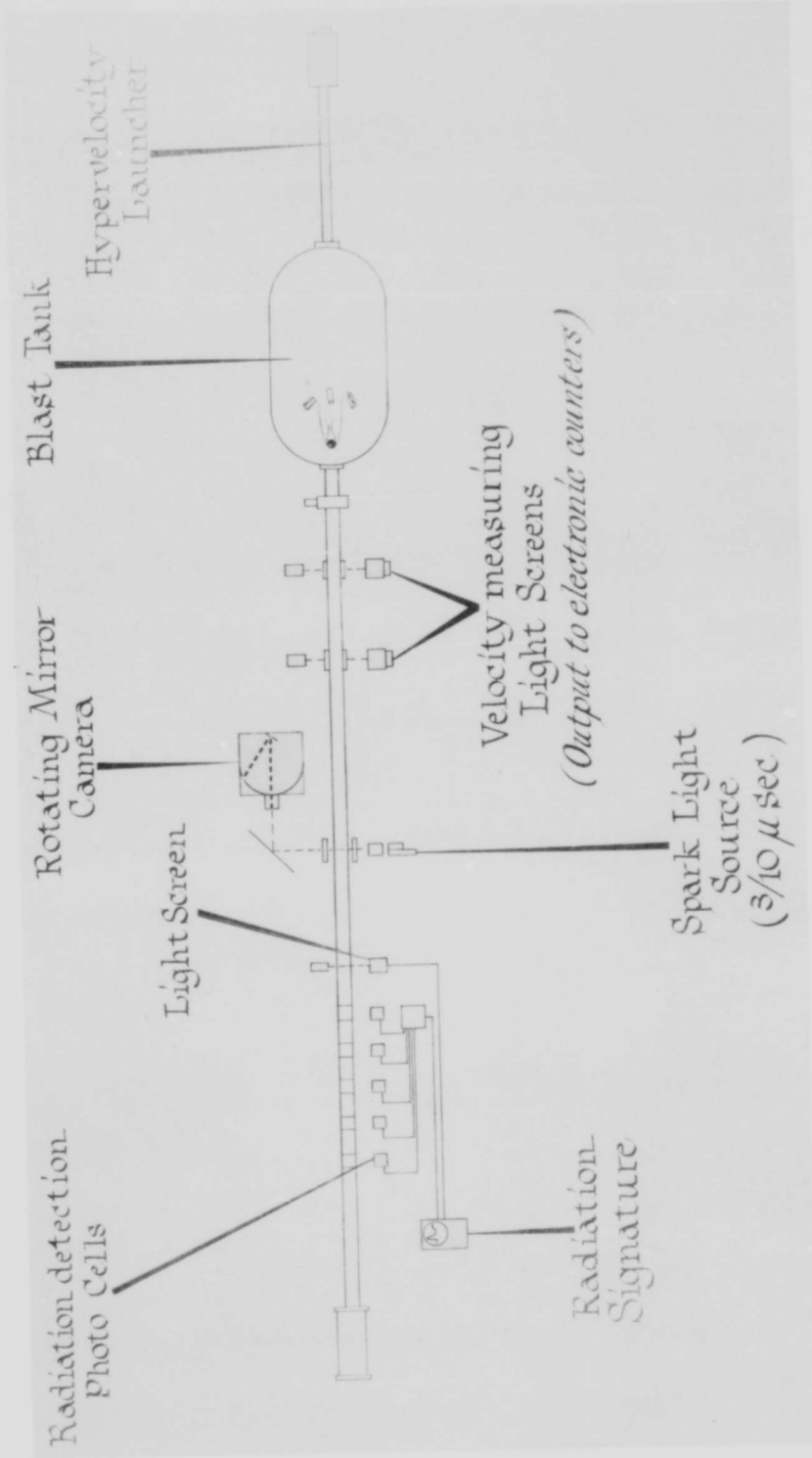


FIGURE I - NOL AEROPHYSICS RANGE

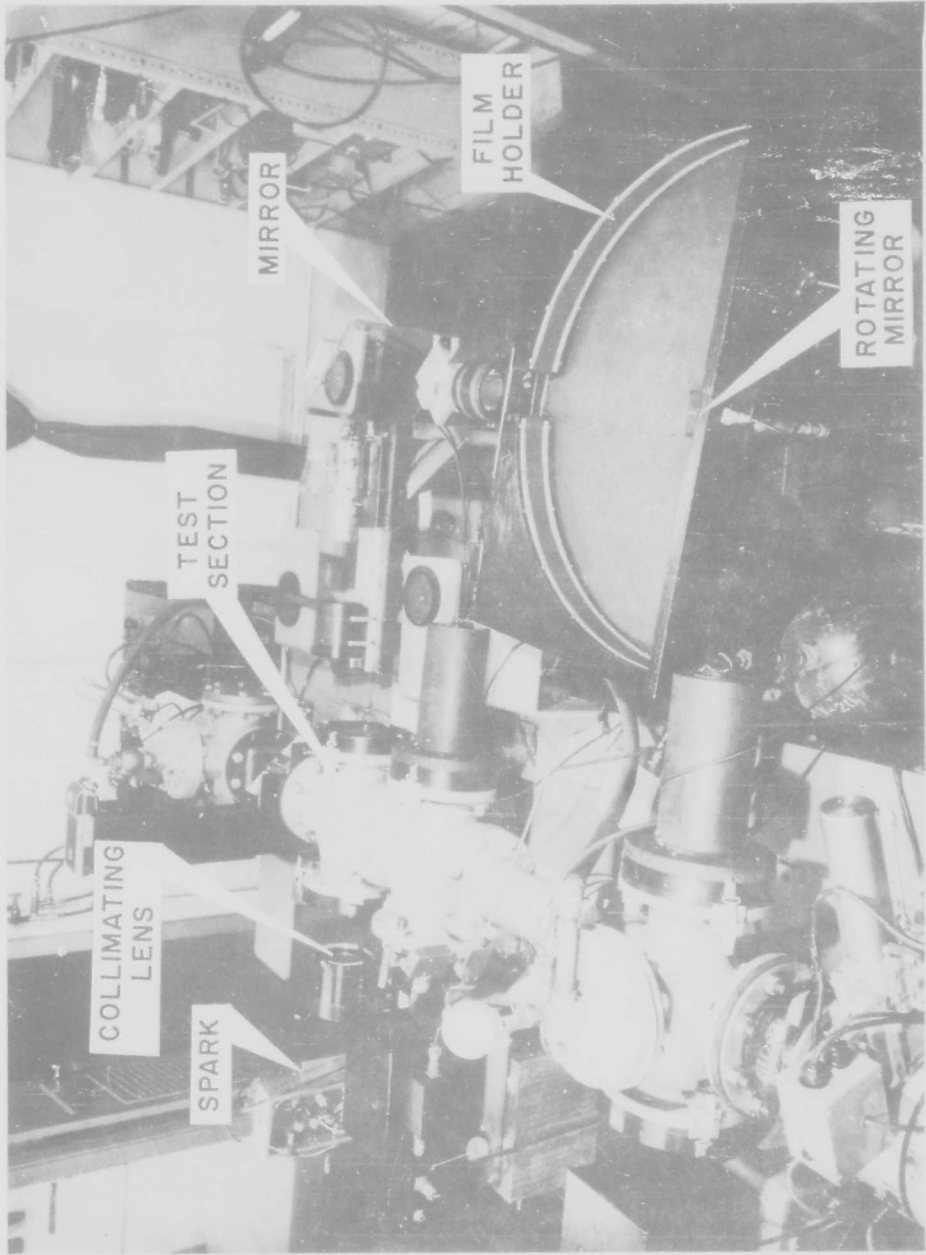


FIGURE 2 - ROTATING MIRROR CAMERA AND AEROPHYSICS RANGE

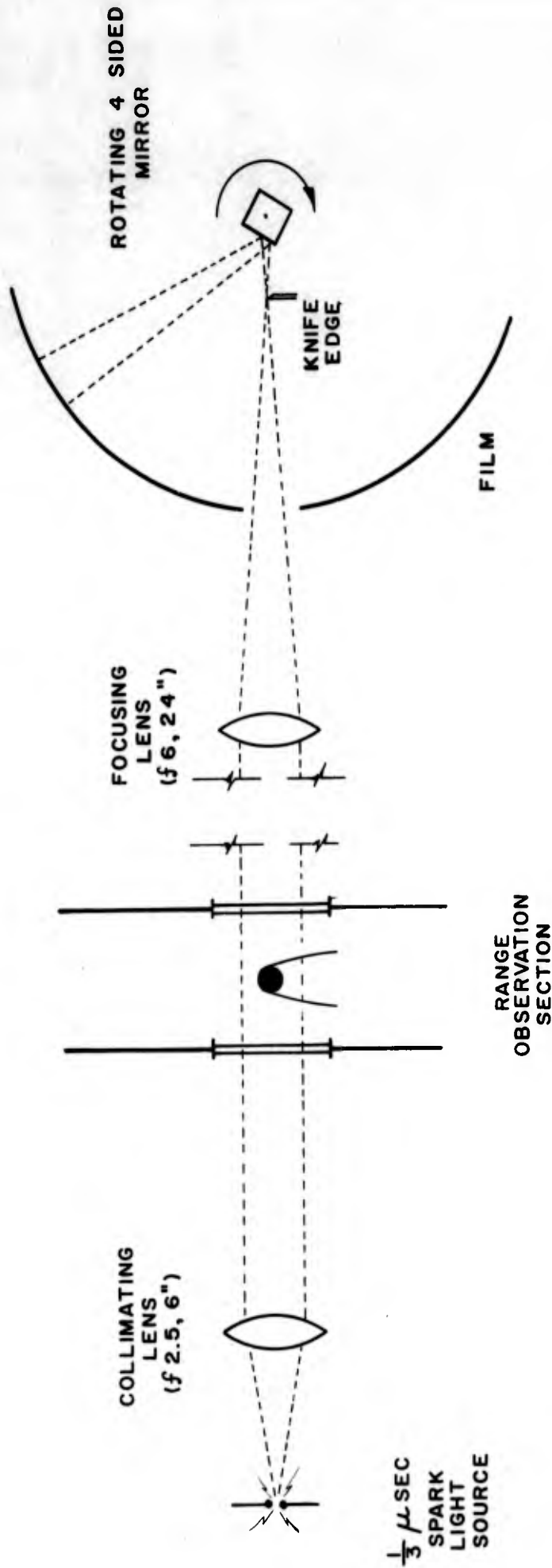


FIGURE 3 - SKEMATIC DIAGRAM OF ROTATING MIRROR CAMERA
 AND SCHIEREN OPTICAL SYSTEM

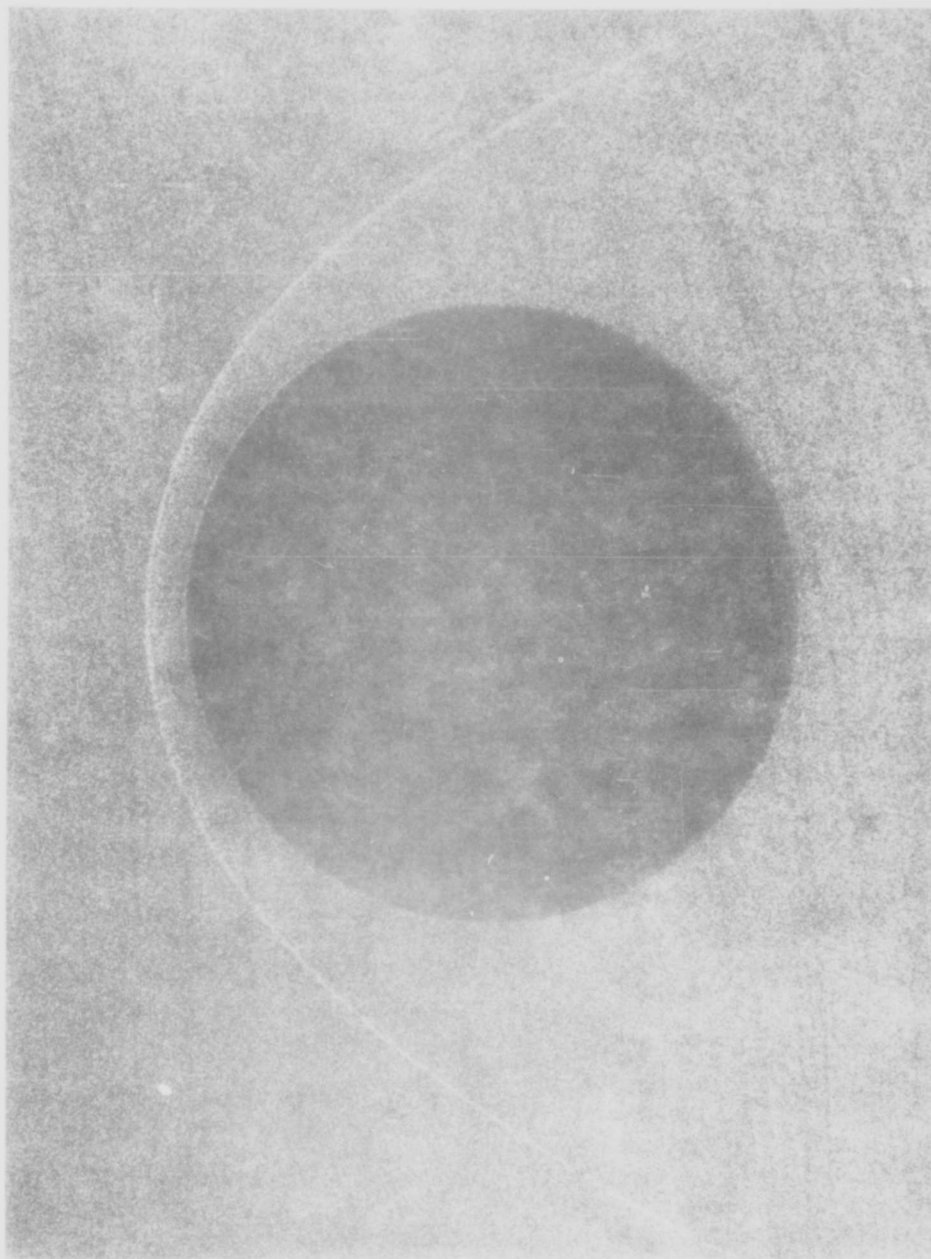


FIGURE 4 NYLON SPHERE IN AIR. DIAMETER = $\frac{1}{2}$ "
VELOCITY = 8,020 ft/sec, PRESSURE = 10mmHg.

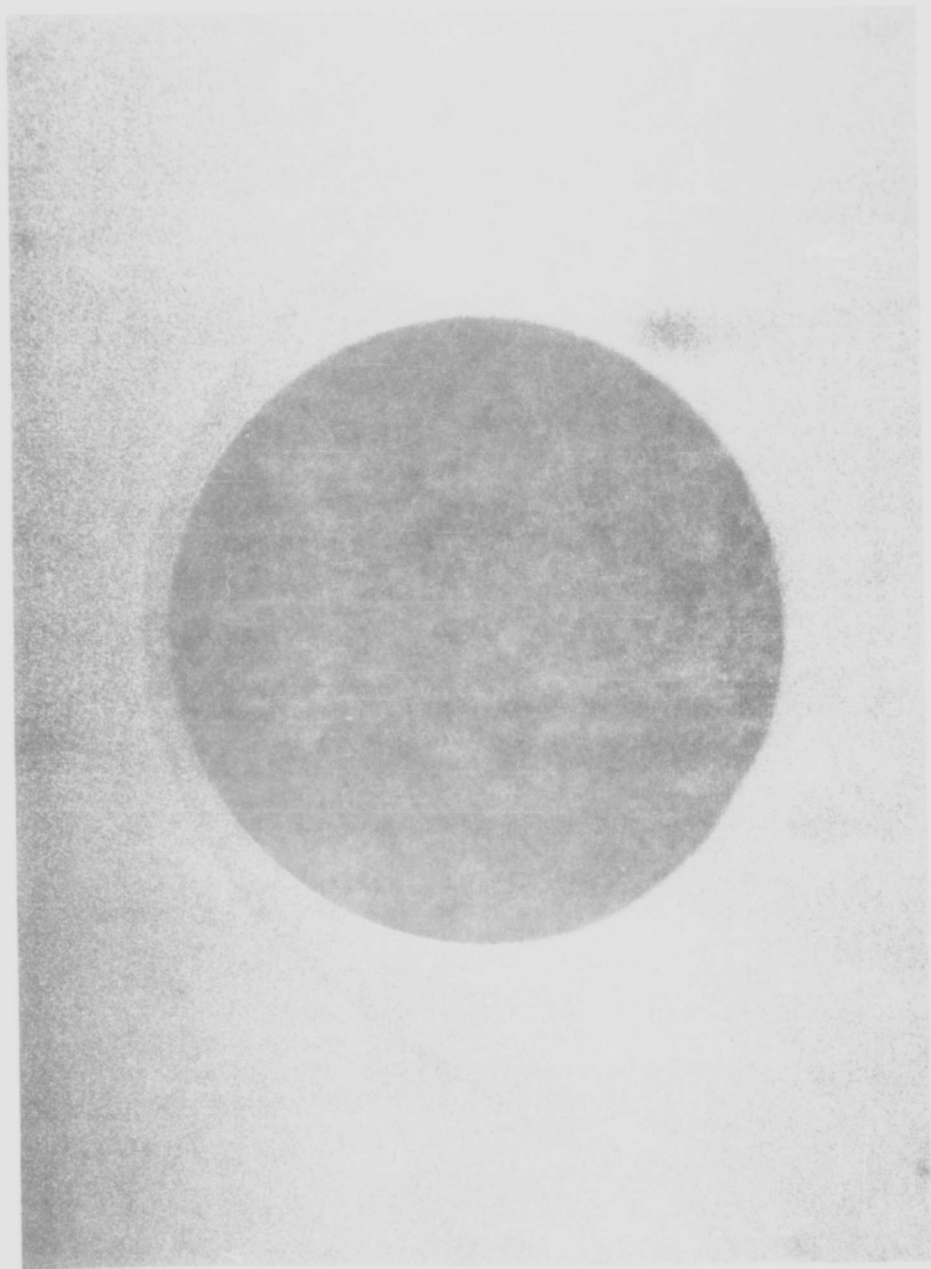


FIGURE 5 NYLON SPHERE IN AIR. DIAMETER= $\frac{1}{2}$ "
VELOCITY=17,315 ft/sec, PRESSURE=5mmHg.

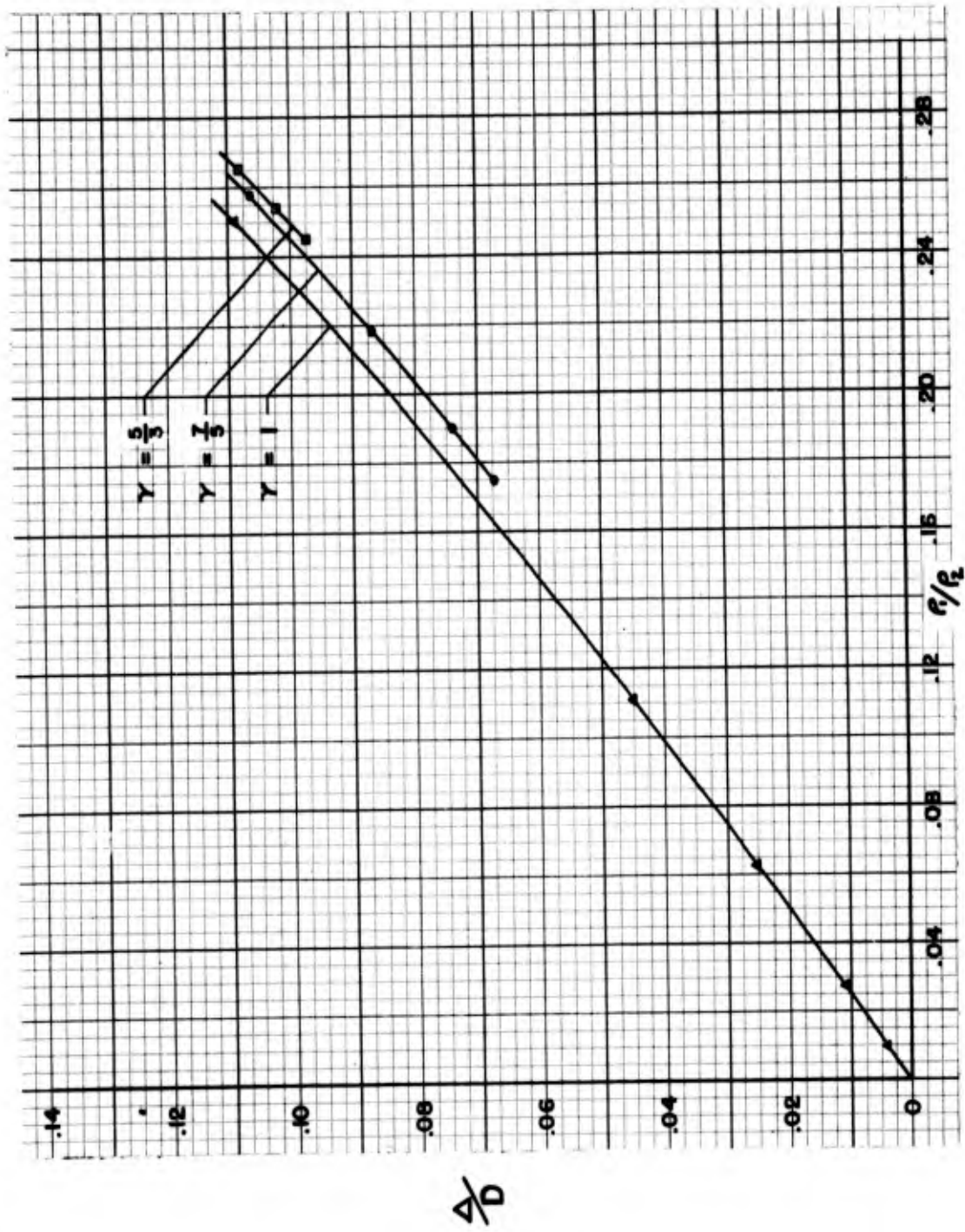


FIGURE 6 - STAND-OFF DISTANCE ACCORDING TO DENSITY RATIO ACROSS NORMAL SHOCK WAVE (REF. 3)

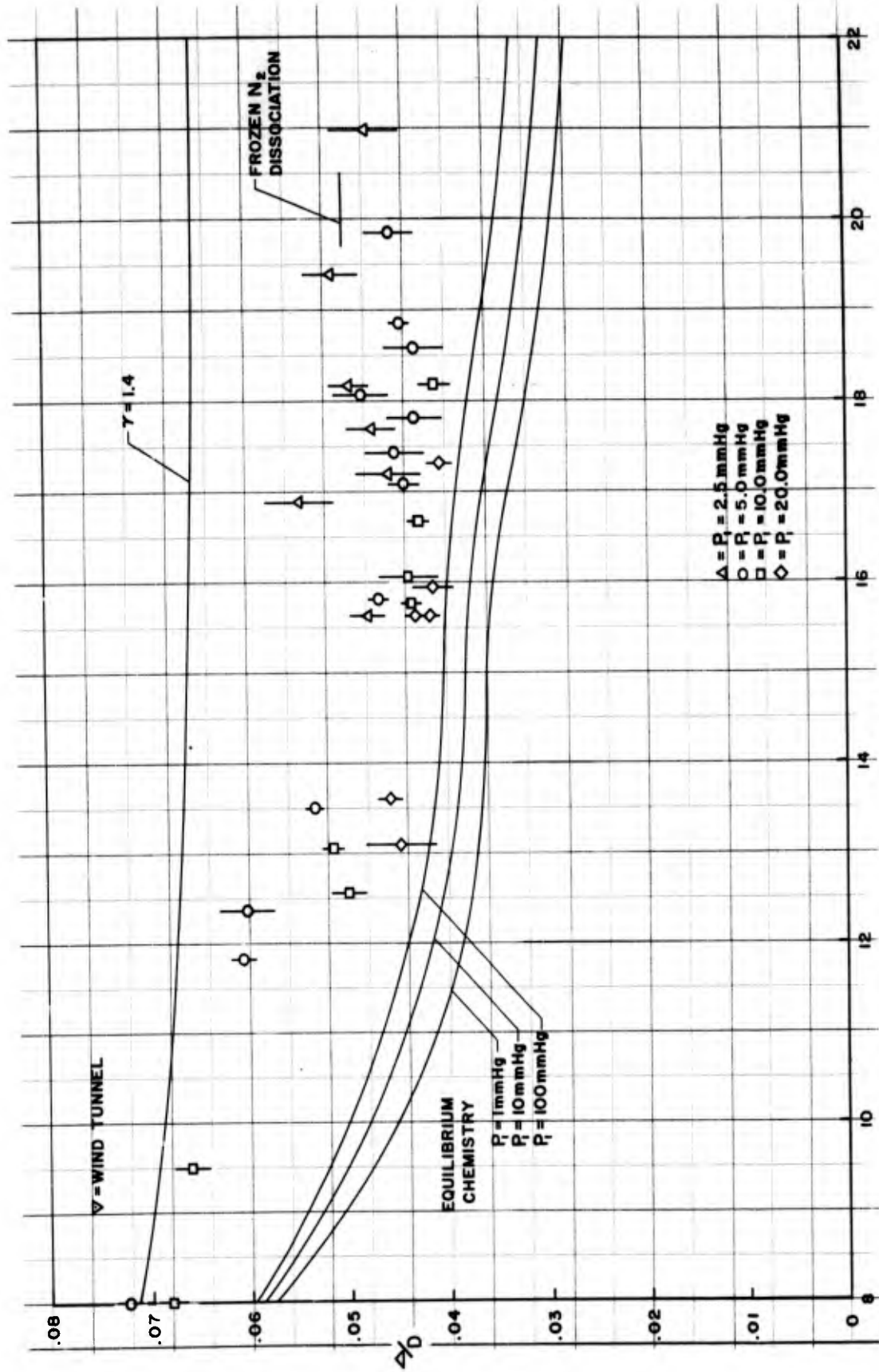
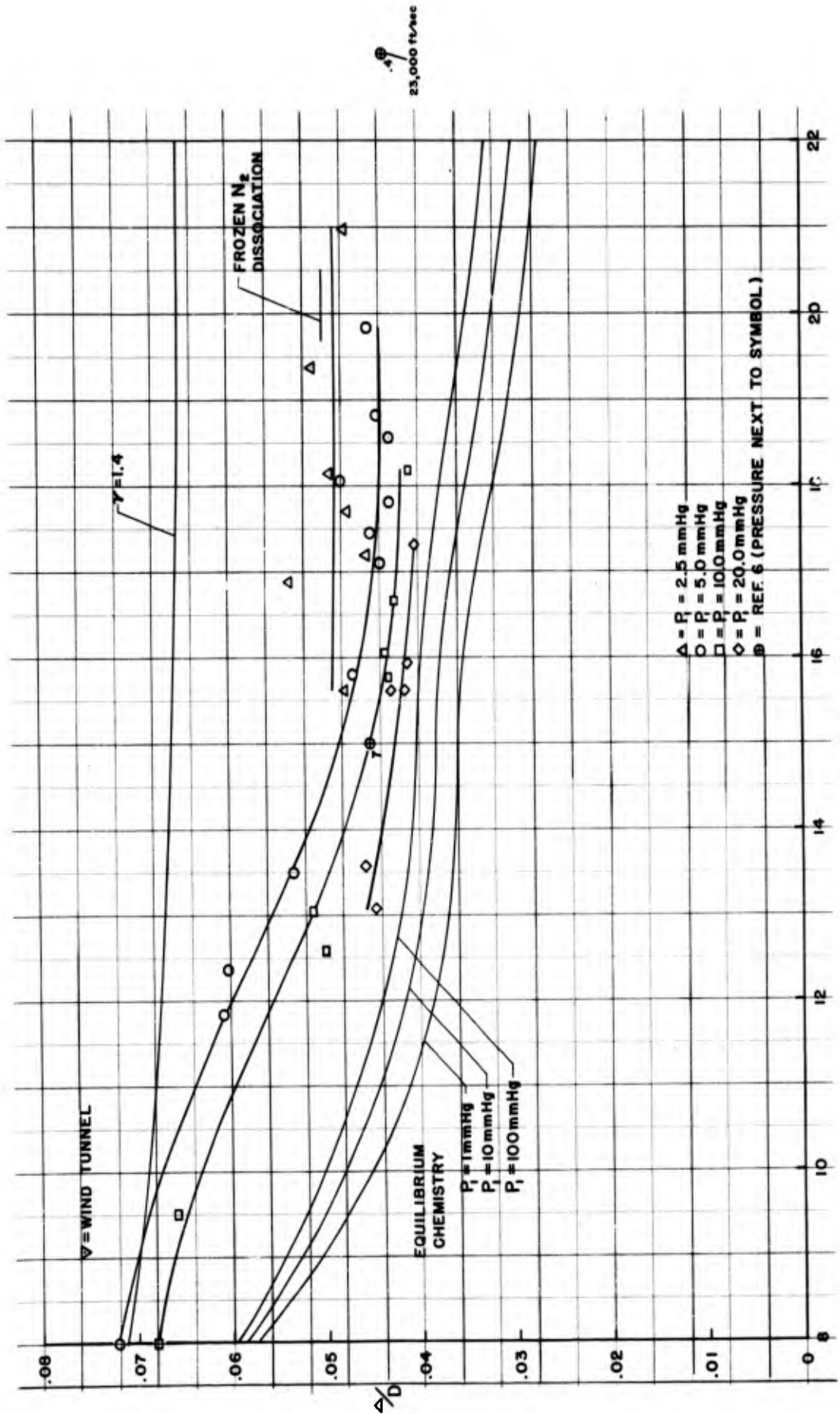


FIGURE 7a - SHOCK DETACHMENT DISTANCE ON A 1/2" DIAMETER SPHERE IN AIR. (SHOWING ACCURACY OF DATA) TEMPERATURE = 293° K



VELOCITY x 10^{-3} ft/sec
 FIGURE 7b - SHOCK DETACHMENT DISTANCE ON A 1/2" DIAMETER SPHERE IN AIR.
 TEMPERATURE = 293°K

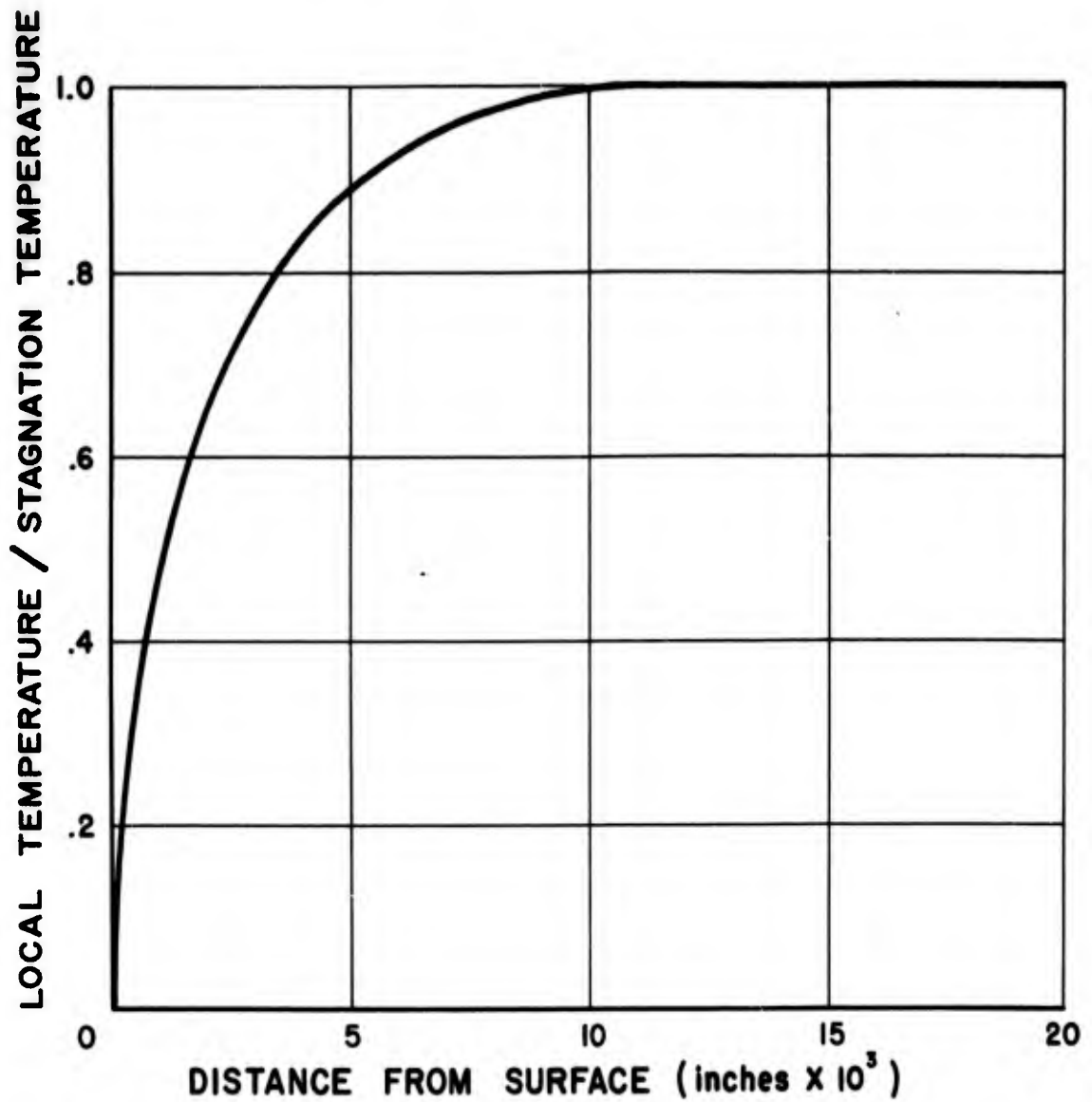


FIGURE 8 TEMPERATURE DISTRIBUTION IN BOUNDARY LAYER AT STAGNATION POINT, FROZEN FLOW, 1/2" SPHERE, 20,000 ft/sec, 5 mm Hg, $\Delta \approx .025$ "

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