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ABSTRACT

Various techniques developed at the Avco-Everett Research Laboratory for observing the flow field behind hypervelocity bodies in ballistic ranges are discussed. These techniques fall into two categories: (1) photoelectric instruments for measuring the radiation intensity and its distribution in the wake, and (2) instruments for visualizing or photographing the flow field.

In the first category a photoelectric recorder is discussed. This instrument measures the radiation intensity as a function of distance downstream in the wake. Also, a wake scanner is described by which it is possible to repetitively scan the wake every few microseconds and obtain profiles of the radiation distribution in a plane nearly perpendicular to the flight direction.

In the second category drum camera techniques including a "race track" adaptation are described for photographing the self-luminous flow field. Data available from these drum camera techniques include gas particle velocity in the wake, shedding frequency of turbulent eddies, and width and rate of growth of the luminous wake. A schlieren technique is discussed in which the refractivity of the test gas is increased by using a small partial pressure of sodium vapor in the gas and taking the schlieren photograph with light of wavelength close to the sodium resonance line at 5896 Å. Good quality schlieren photographs have been obtained at densities less than 1% of atmospheric. The use of an image converter to take snapshot photographs of the self-luminous wake is discussed. Pictures showing the details of the luminous flow field in the base region have been obtained.

The description of these instruments is given, typical data are shown, and the types of information obtainable from the data are illustrated.

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TECHNIQUES FOR RADIATION MEASUREMENTS AND FLOW VISUALIZATION OF SELF-LUMINOUS HYPERSONIC WAKES

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INTRODUCTION

This paper describes several techniques developed at the Avco-Everett Research Laboratory (AERL) for investigating the wake generated by hypervelocity projectiles in a ballistic range. The importance of the study of the hypersonic wake rests in the fact that most of the energy dissipated by an object re-entering the atmosphere goes into the wake. The processes occurring during the redistribution of this energy into the random thermal motion of the air molecules produce the re-entry observables, such as optical emission and radar signature. The observable phenomena of the wake are a complex interaction of aerodynamic effects, chemistry, ionization, and radiation. Experimental study of these observables is needed in order to guide the development of analytical descriptions of the wake.

The ballistic range is the primary laboratory facility which has been used to simulate the wake phenomena of re-entry (1). Because of the low level of radiation intensity and the short times involved in these experiments, detailed, quantitative measurements of the self-luminous flow field behind the body have been difficult to obtain (2). Also, visualization of the flow field by ordinary shadowgraph and schlieren techniques has been difficult at the low densities required for simulation (3). The techniques described in this paper fall into two general categories: (a) photoelectric instruments for measuring the radiation intensity and its distribution in the wake, and (b) instruments for visualizing (photographing) the flow field. The instruments are described, typical data are shown, and some of the information available from the data is discussed. Other papers (4), (5), (6) illustrate the importance of these data in guiding the understanding of wake phenomena.

The experiments described herein were carried out either in the AERL ballistic ranges, using arc-heated light gas guns, or at the Canadian Armament Research and Development Establishment (CARDE) ballistic range facility.* The models were unsaboted plastic spheres of 0.22, 0.55 and 0.88-inch-diameter fired at Mach numbers of 15-25. In most cases air at controlled

*The authors wish to thank Mr. George Tidy, Superintendent, Aero/Physics Wing, and Dr. Andre Lemay, Section Leader, Radiation Physics Section, for their assistance and cooperation in the CARDE program.

density and ambient temperature was the test fluid. For some experiments, argon, nitrogen, or xenon were used to change the flow conditions or to increase the optical radiation. The optical radiation observed in these experiments is due predominately to ablative impurities in the viscous core of the wake (7).

PHOTOELECTRIC INSTRUMENTS

Photoelectric Recorder

Two photoelectric techniques have been devised for obtaining quantitative measurements of the radiation intensity from selected volume elements of the self-luminous hypersonic wake. In the simpler of these instruments, the photoelectric recorder, the radiation from the projectile and its wake is monitored by a photomultiplier tube looking through a thin slit oriented perpendicular to the flight direction. A schematic of this instrument is shown in Figure 1. A slit, positioned in front of the photomultiplier tube, is imaged into the range by a spherical mirror. The dimensions of the slit and the optical magnification control the area in the test section from which the radiant intensity is integrated by the instrument. At AERL, a 10" focal length mirror is used to give an optical magnification of about one. Thus the image size is nearly the slit size, typically 1.0" x 0.020". The photomultiplier used has S-11 response giving it a spectral sensitivity from 3200-6200 Å. No filters have been used in obtaining data discussed here. The electronics and oscilloscopes employed with this instrument are sufficiently fast that the response of the instrument is the transit time of events across the slit—approximately 0.1 μ sec for a projectile flying at 15,000 ft/sec.

A sample oscillogram from the photoelectric recorder for a firing of a 0.22-inch-diameter nylon sphere into air at a pressure of 7.0 cm Hg is shown in Figure 2. The projectile crosses the slit about 6 μ sec after the scope has been triggered. The first sharp rise in intensity results from the stagnation point radiation. The gas cools as it expands around the body, and the radiation intensity falls. A few microseconds later, a second but less abrupt rise in intensity occurs. The timing of this rise is consistent with the position of the recompression shock as seen in schlieren or shadowgraph photographs. Following this second peak, the radiation gradually decays downstream in the wake. The fluctuation in intensity associated with the decay can be correlated with turbulent eddies in the wake. The photoelectric recorder, together with the streak drum camera technique discussed below, achieved the first experimental evidence of transition from laminar to turbulent flow in the viscous core of the hypersonic wake (4).

Wake Scanner

The second of the photoelectric techniques developed at AERL is the wake scanner. This instrument makes it possible to repetitively scan the wake and obtain profiles of radiation intensity across the flow field, i.e., in a direction perpendicular to the flight path. The instrument is shown schematically in Figure 3. The optical system images the 17 fixed mirrors, each of which is masked to form a rectangular slit, into the range. As the turbine-driven

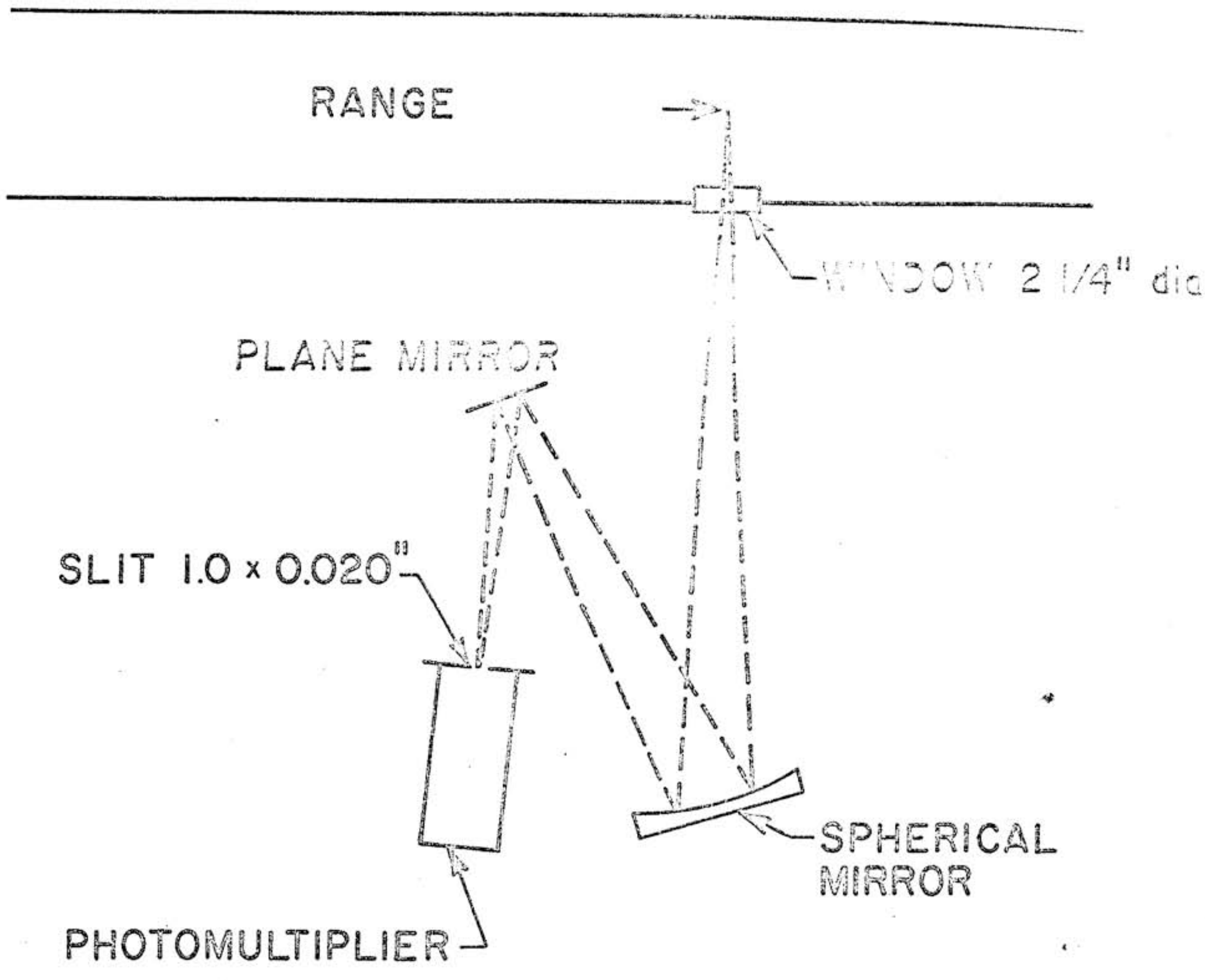


Fig. 1 Schematic of photoelectric recorder. View is from the top. The arrow in the range indicates a model moving from left to right across the test station. The dimensions shown here are for the AERL range.

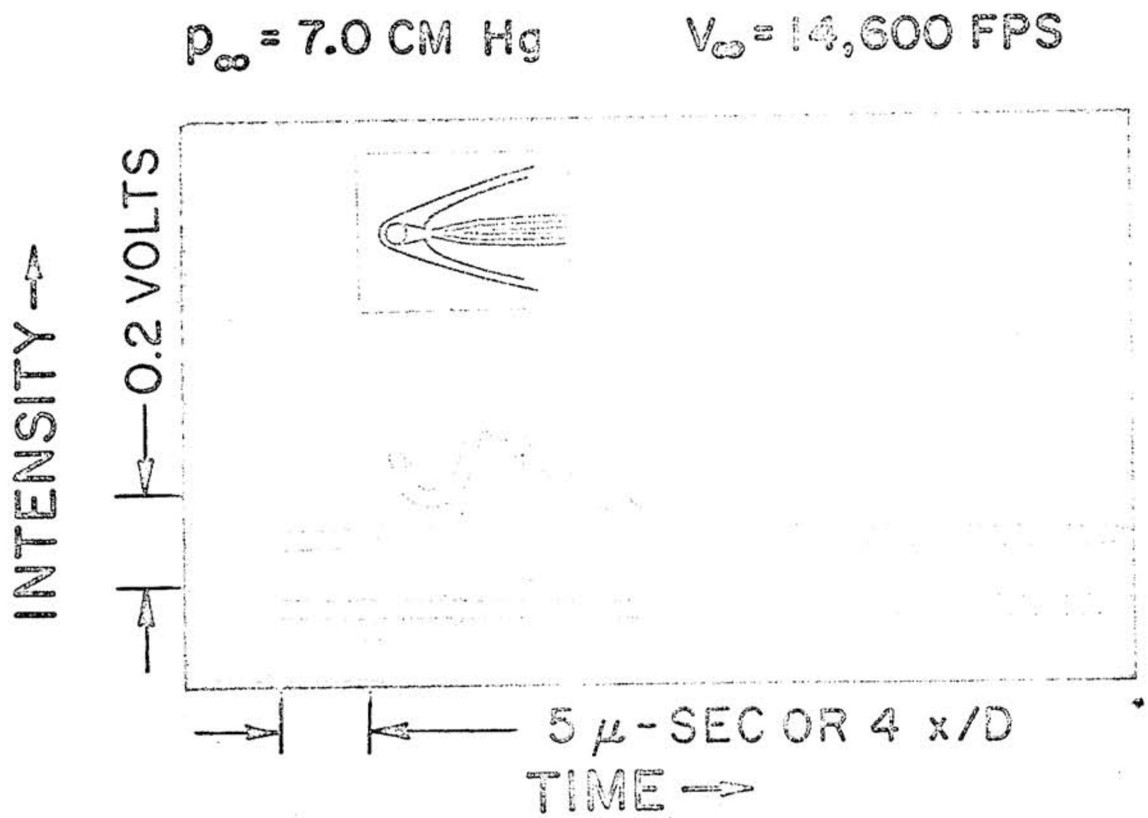


Fig. 2 Sample oscilloscope record of photoelectric recorder output. The sketch at the top of the photograph has been drawn approximately to scale to aid in correlating the recorder signal with the flow field events. The data were taken on the AERL range firing 0.22-inch-diameter nylon spheres. Note that the horizontal scale, time, may be converted into distance downstream of the stagnation point in body diameters, x/D.

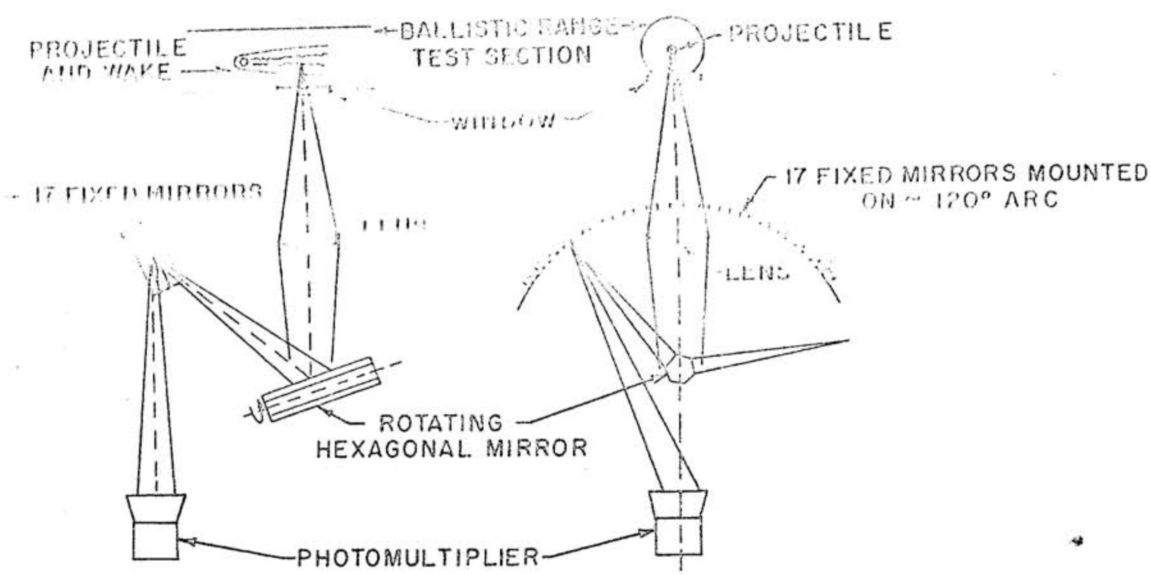


Fig. 3 Schematic of wake scanner instrument. The left-hand view is from the top, the right-hand view from the side.

hexagonal mirror is rotated the image of each slit is moved across the range from top to bottom. The intensity of radiation seen by an image as it traverses the range is monitored by a photomultiplier tube and displayed on an oscilloscope. A photomultiplier tube with S-11 response is also used in this instrument. The wake scanner is designed so that the 17 fixed mirrors are seen sequentially by each of the six faces of the rotating mirror. Thus 102 equidistant scans across the wake are made per revolution of the rotating mirror. At a mirror speed of 1500 revolution/sec* a scan of the wake can be made every 6.5 μ sec. Increasing the scanning frequency may be achieved by increasing the mirror speed. Conversely, the scanning frequency may be decreased by masking off intermediate fixed mirrors or decreasing the rotational speed of the mirrors.

As used on the AERL range (firing 0.22-inch projectiles) with a 7-inch focal length, f/2.5 lens, the image of each slit in the range is typically 1/4-inch long by 1/16-inch high. Therefore, normal to the wake axis in the scanning direction the instrument resolves about 1/4th of a body diameter, while its resolution axially is about one diameter. The distance between images is about 1.2 inches (measured normal to the wake axis). This distance can be increased at a sacrifice in the number of scans per mirror revolution by masking off some of the fixed mirrors. With the conditions listed above and with the rotating mirror driven at 1500 revolutions/sec, the linear velocity of each image traversing the range is about 15,000 ft/sec.

A sample of data from the wake scanner is shown in Figure 4 from a firing of a 0.22-inch-diameter nylon sphere into argon at a pressure of 2.0 cm Hg. In the left-hand oscillogram the upper beam displays the signal from the photoelectric recorder while the lower beam records the wake scanner output. The two instruments are observing the same position in the range. The display of the photoelectric recorder is seen to be qualitatively somewhat different than that in Figure 2. This is a result of the facts that the test gas in Figure 4 is argon, and that the wake is laminar under these flight conditions. It can be seen that as the model passes the test station the wake scanner records a large signal and drives the oscilloscope off scale. The sensitivity of the instrument has been set high in order to observe radiation in the far wake and, therefore, details around the body have been lost. The instrument soon recovers, and scans across the wake are obtained about every 7 μ sec. On the right-hand oscillogram three of the scans are presented at a faster sweep speed illustrating the detail available by this technique. An interesting feature of this data is that it can be interpreted to indicate that the laminar wake is either a luminous axisymmetric shell with a darker center core or a multiple filament structure.

Besides this interesting qualitative feature, quantitative results can be obtained from this data. For example, from pictures such as Figure 4 the

*The rotating mirror is manufactured by Avco Research and Advanced Development Division, Wilmington, Mass. and can be operated up to 3000 revolutions/sec.

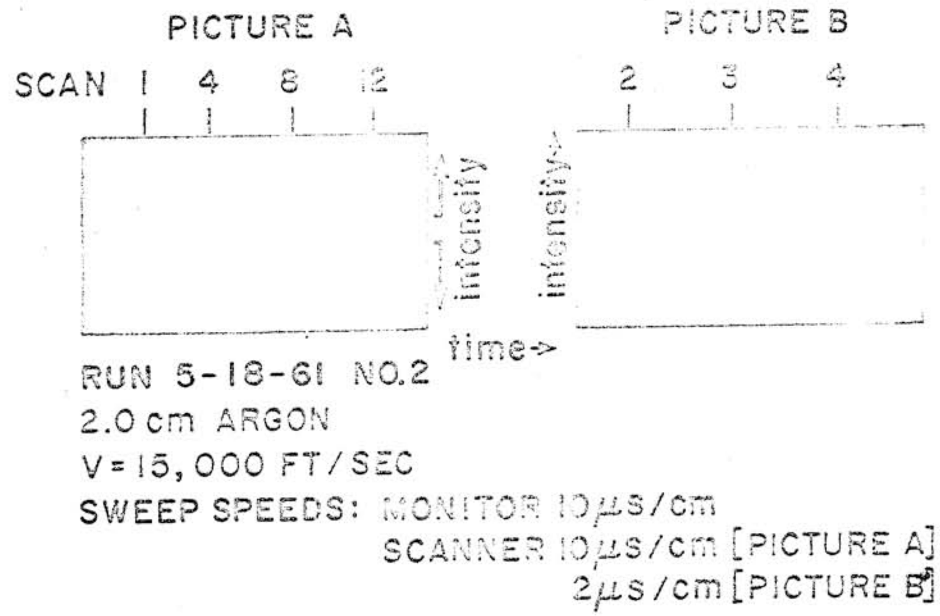


Fig. 4 Typical wake scanner data for the firing of a 0.22-inch-diameter nylon sphere into argon. Picture A shows both a photoelectric recorder signal (top beam) and the wake scanner output (lower beam). Note that the sense of increasing signal (radiation intensity) is opposite for these two signals. Picture B displays three wake scans in greater detail.

width of the luminous wake and its growth downstream of the projectile can be determined. Such information is now available for a number of runs in air, argon, and xenon for a range of free stream pressures and velocities. Wake width measurements made with the wake scanner have been compared with such data from other techniques; e.g., shadowgraph and race track pictures.

A reconstruction in projectile coordinates of the wake scanner data is shown in Figure 5. The intensity profiles obtained in the individual scans are displayed at their proper positions downstream of the model. From such a reconstruction the real time development of the luminous wake can be observed. The results in Figure 5 are for a firing of a 0.22-inch-diameter lexan sphere into xenon at 1.0 cm Hg pressure; for such conditions the wake is turbulent. The asymmetric pattern of the intensity profiles is indicative of large scale turbulent motion in the luminous wake.

FLOW VISUALIZATION TECHNIQUES

Streak Drum Camera

In early attempts at AERL to visualize the wake by its own luminosity, a streak drum camera (8) was used to photograph the flow field at low pressures. The experimental arrangement is shown in Figure 6. The drum which carries the film is pneumatically driven and rotates the film at a velocity of up to 0.1 mm/μ sec at the focal plane. The optical system of the camera (f/2.5) images the motion of the model and its wake on the film. As the model and its wake move down the range, their image moves transverse to the motion of the film, producing on the film an x-t diagram of the flow field events. The film used in these studies was Royal-X-Pan developed to obtain the highest film speed.

Figure 7 shows typical streak drum camera records for nylon spheres fired into argon. Figure 7 (a) is an x-t diagram to aid in interpreting the pictures. The bright diagonal streak across each photograph is caused by the luminosity in the stagnation point region. The luminous flow field shows up as a family of curved streaks in Figure 7 (b). These streaks are interpreted as being luminous, large scale turbulent eddies which start out with the model velocity and slow down as the gas expands and flows back into the wake. In Figure 7 (c) the wake appears as luminosity without structure. This is interpreted as a laminar wake. The two vertical dark lines at the left in each picture are calibration masks placed on the window about one inch apart. Each picture shows about 18 inches of flight path. The drum camera photographs, such as Figures 7 (b) and (c), together with the photoelectric recorder data described earlier are used to differentiate between laminar and turbulent wakes (4).

From photographs such as Figure 7 (b) the velocity of the luminous eddies can be determined. Such data are shown in Figure 8 where the eddy velocity in a coordinate system fixed in the model, V_s, normalized by the model velocity, V_∞, has been plotted against distance downstream in the wake, for several pressures of air and argon. It can be seen that for air

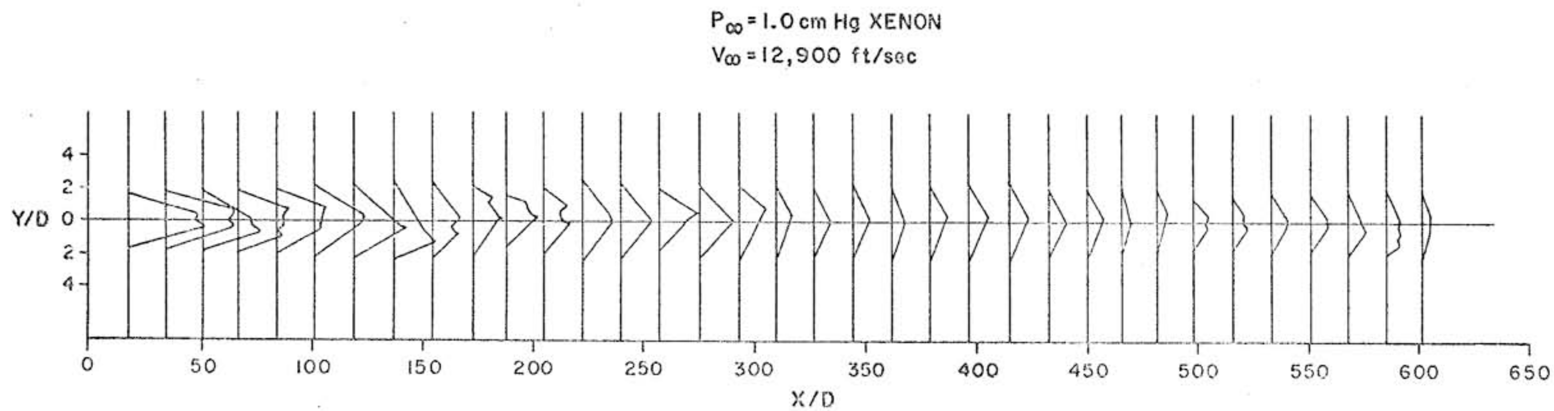


Fig. 5 Display of wake scanner profiles for a firing of a 0.22-inch-diameter lexan sphere into xenon. The individual intensity profiles have been placed along a scale of distance downstream in the wake from the stagnation point in body radii, X/R_N. The vertical scale gives the width of the profiles in body radii, Y/R_N.

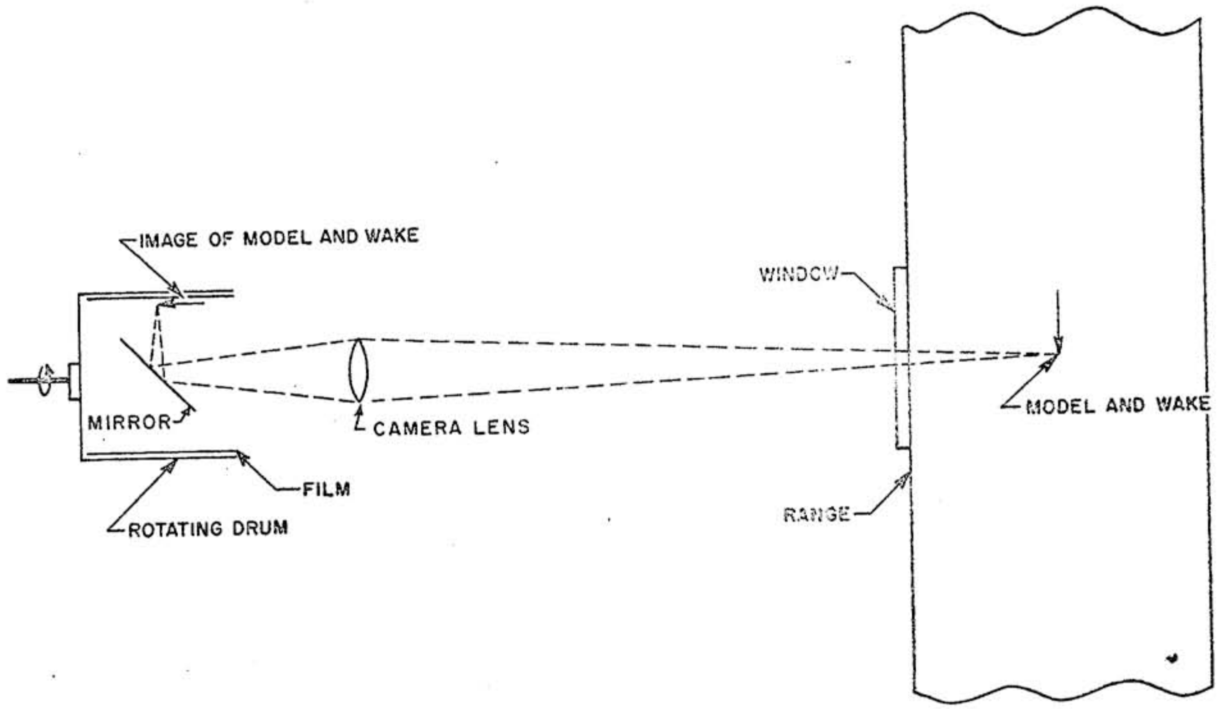


Fig. 6 Schematic of drum camera. View is from the top. The arrow (projectile and wake) is flying from top to bottom in the sketch while its image on the film moves from right to left.

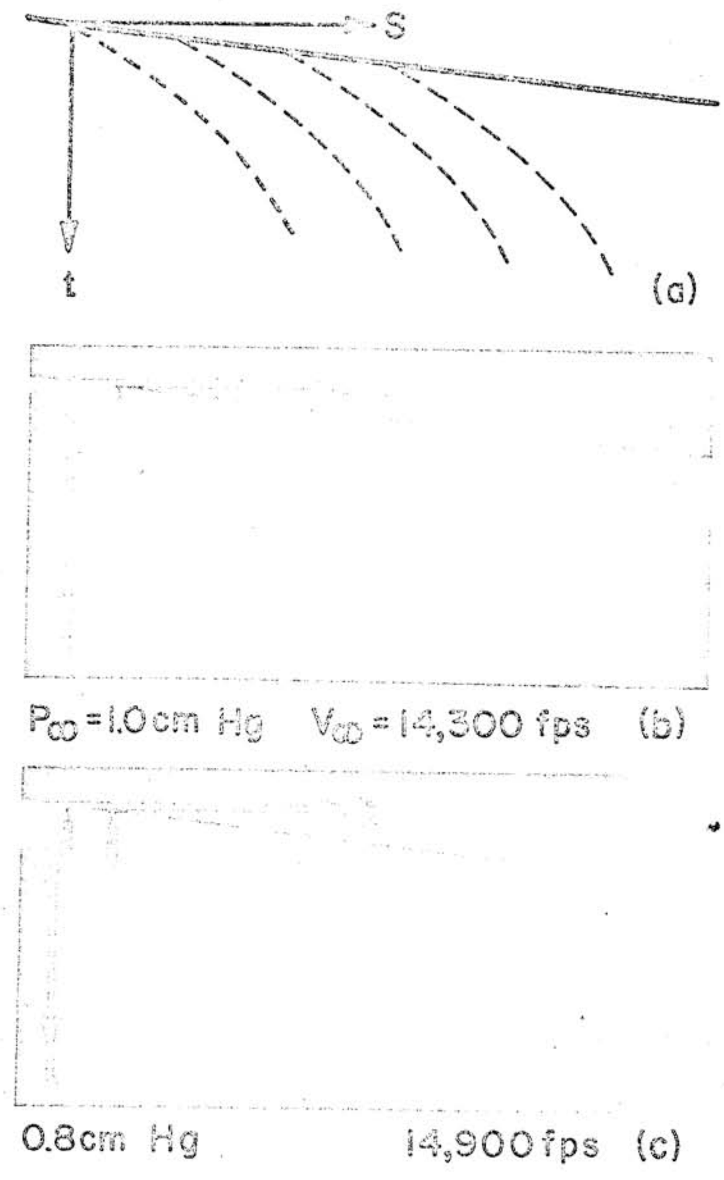


Fig. 7 Typical streak drum camera data. (a) An s-t (distance-time) diagram to aid in interpreting the photographs. The diagonal heavy line represents the projectile and stagnation point radiation. The dashed, curved lines represent luminous eddies which start out with the projectile velocity but, as they flow downstream in the wake, slow down eventually coming to rest. (b) and (c) Streak drum camera photographs of 0.22-inch-diameter nylon spheres fired into argon. In (b) the luminous streaks are interpreted as luminous large scale disturbances in a turbulent wake. In (c) the diffuse, structureless luminosity of the wake is interpreted as caused by a laminar flow field.

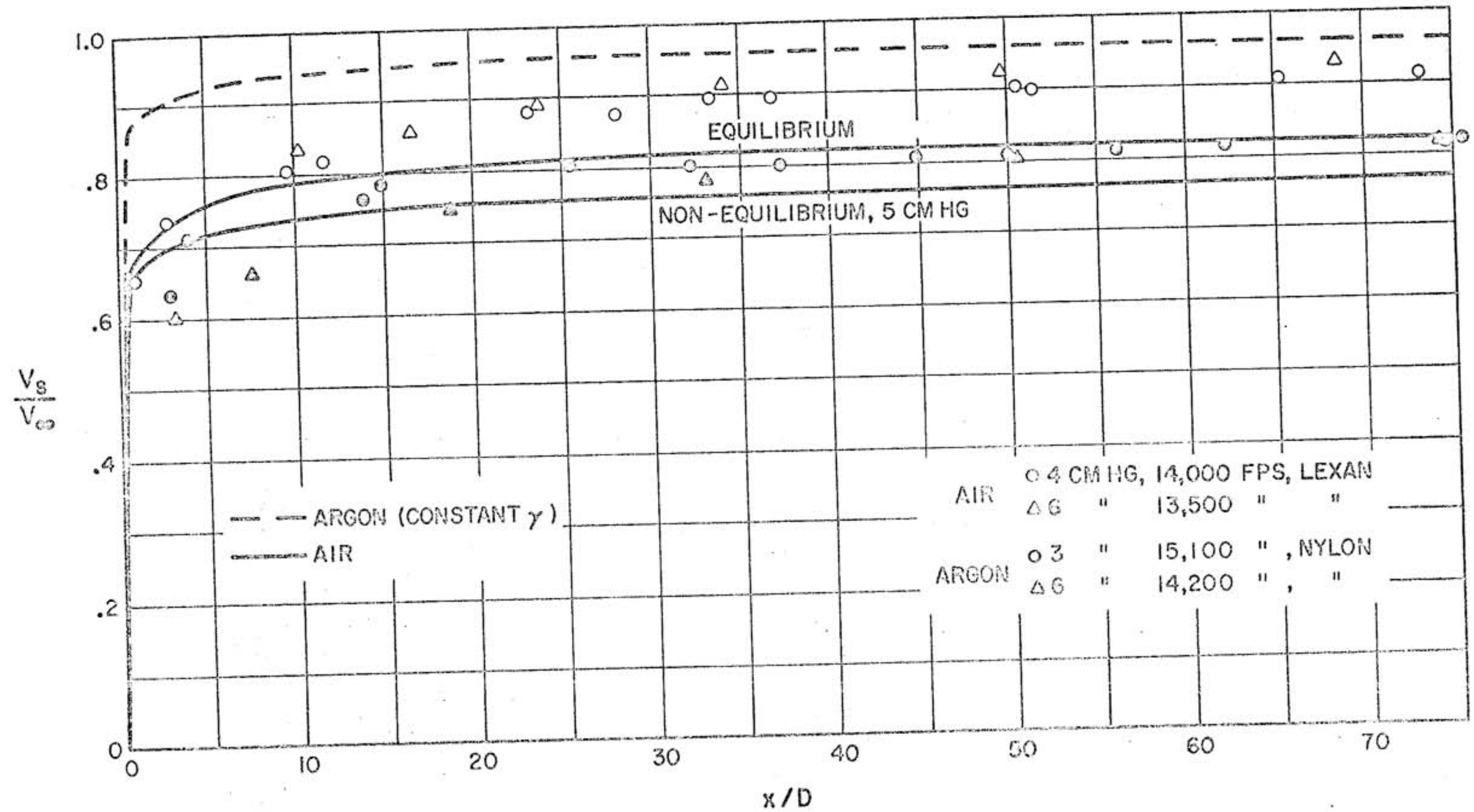


Fig. 8 Eddy velocity as obtained from drum camera photographs, such as Fig. 7 (b), for firings of 0.22-inch-diameter spheres into air and argon. The eddy velocity, V_s, is given in the steady state (body fixed) coordinates, normalized by the model velocity, V_∞. The solid curves are theoretical calculations which show good agreement with the experimental data.

the velocity of the turbulent eddies has decayed to about 0.2 of the model velocity as close as 15 body diameters downstream in the wake. The solid lines on Figure 8 are theoretical calculations of the gas velocity in the wake at the edge of the viscous core, as discussed in Reference (4). Besides yielding information on eddy velocity in the wake, these drum camera pictures can also be analyzed for the shedding frequency of the eddies. [illegible] have been useful in drawing comparisons between the wake behind hypersonic models and the wake behind bluff bodies in incompressible flow (6).

Race Track Flow Visualization Technique

The race track method is a technique of flow visualization (8), (9) which enables self-luminous events in the wake to be photographed when the illumination is too low and the motion is too fast for conventional high speed movies and snapshots. The basic principle of the method is as follows: A drum camera is used to form an image of the object on a moving film strip. The orientation of the moving image and the rotating film is 90° different from the streak drum camera technique described previously, in that the film is moved parallel to the projectile motion. By adjusting the drum speed to match the image speed, the action is effectively stopped and longer exposures may be employed without blurring the image. The exposure is determined by the time, t_e, it takes the object to cross a slit placed in front of it, perpendicular to its motion. Of course, tracking is possible in only one direction and some resolution is lost if the event to be photographed does not move parallel to the film motion. The amount of blurring which results from miss-tracking is $(\bar{V}_i - \bar{V}_f)\, t_e$, where $\bar{V}_i$ is the vector velocity of the image and $\bar{V}_f$ is the vector velocity of the film. For the hypersonic wake the radial motion is expected to be a small fraction of the axial motion, and, therefore, the loss in resolution resulting from miss-tracking can be kept small. In any event the resolution and the exposure are controlled by the slit width.

A schematic diagram of a race track set-up is shown in Figure 9. It consists of (a) an f/2.5 drum camera, (b) a row of 3 vertical slits 0.2 inches wide mounted on the range window 0.67-inch apart, and (c) an array of mirrors to preserve a constant optical path from each slit to the film. The purpose of the multiple slits is to produce several images for studying the spatial correlation of luminous events as they move downstream in the wake. The array of mirrors displaces vertically the image from each slit so that the successive images do not write over each other on the film. A different arrangement of the slits and optical system is used to allow orthogonal viewing of the wake. By using slits of different widths, the dynamic range over which the luminosity can be recorded may be greatly increased.

In the present work the system was adjusted to track luminous events far downstream of the model. The wake velocity was determined from streak drum camera data such as Figure 8. For projectile velocities of about 15,000 ft/sec, the effective exposure times were about 5 μ sec. Since a tracking accuracy of about 10% was achieved, the image quality is the same as that which would be obtained in a snapshot at one-tenth the exposure.

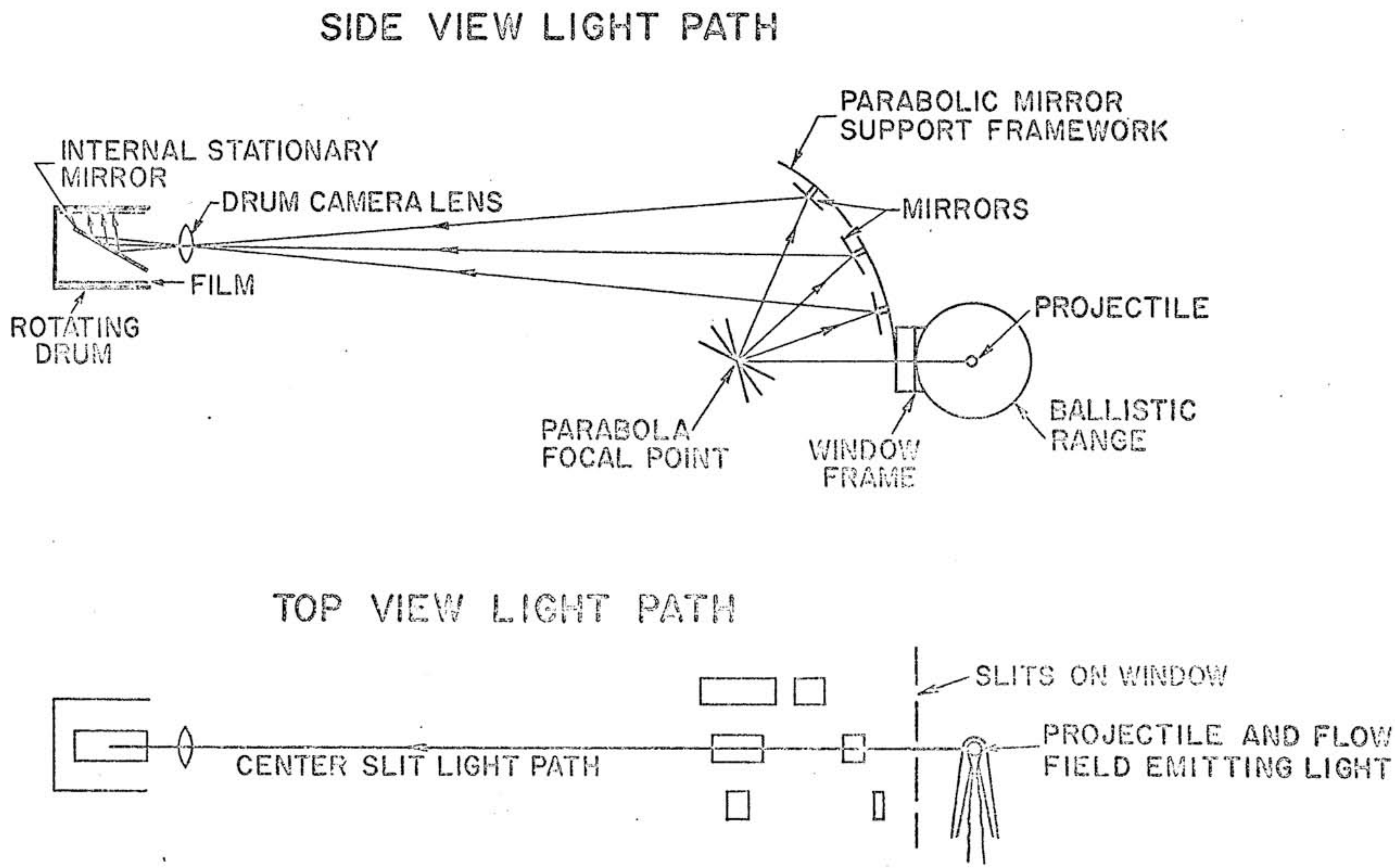


Fig. 9 Schematic of the race track flow visualization technique. In this arrangement the motion of the luminous wake as seen through the slits is tracked by the film on a rotating drum.

Some typical race track photographs are shown in Figures 10 and 11. Figure 10 shows photographs taken at AERL of 0.22-inch-diameter lexan spheres fired into xenon and argon. Both turbulent and laminar wakes are shown. The pictures in Figure 11 were taken at CARDE firing 0.55-inch-diameter lexan spheres into air. The development of the turbulent wake as the free stream pressure (Reynolds number) increases is evident. Note that the region close to the pellet where the difference between the gas velocity and film speed is large is not tracked and no detail is evident in this portion of the picture.

In interpreting these photographs it is important to keep in mind that they are not snapshots. As in the case of focal plane shutters, different parts of the picture are exposed at different times. This leads to a distortion of the photograph in which, although the apparent length of the wake is shortened, the structure of the events which are being tracked is correctly reproduced. The scales shown in Figure 10 give the distance between the projectile and an event at the instant that the event is photographed. However, that scale does not represent the true distance between events in the wake (9).

Besides providing information about the development of the turbulent wake these race track photographs can be analyzed for the growth of the luminous wake. In this respect the technique complements the wake scanner. Orthogonal race track photographs have also yielded evidence of asymmetries in the hypersonic wake (6).

Sodium Schlieren

In attempting to use schlieren photography for the study of transition from laminar to turbulent flow in the wakes of high speed projectiles, it has been found necessary to reduce the gas density to levels close to the limits of sensitivity of current techniques. Under these conditions, when one looks at a set of photographs of decreasing pressure, it is exceedingly difficult to determine whether the disappearance of the characteristic pattern of small scale turbulence in wakes results from laminar flow or from loss of sensitivity. The present work was undertaken in an attempt to remove this ambiguity by achieving at least an order of magnitude improvement in schlieren sensitivity (10).

At the time the work was begun, it was felt that refinement of the optics had already been pushed to the point of diminishing returns. Since the sensitivity of a schlieren system is directly proportional to the refractivity of the test medium, it was decided to explore the possibility of enhancing the refractivity of the gas by using radiation close to a resonant transition. One advantage of enhancing the refractivity is that spurious refractive variations in the windows become less important. Calculations using the dispersion formula of classical radiation theory (11) show that the absolute value of refractivity of a gas close to a resonance line can be many orders of magnitude larger than that of air in the visible portion of the spectrum, far from its resonance in the vacuum ultraviolet. Since the technical difficulties associated with working in the vacuum ultraviolet are very substantial, it appeared more attractive to attempt enhancement of the refractivity by using a gas with strong resonances in the ultraviolet or visible region. Sodium vapor with

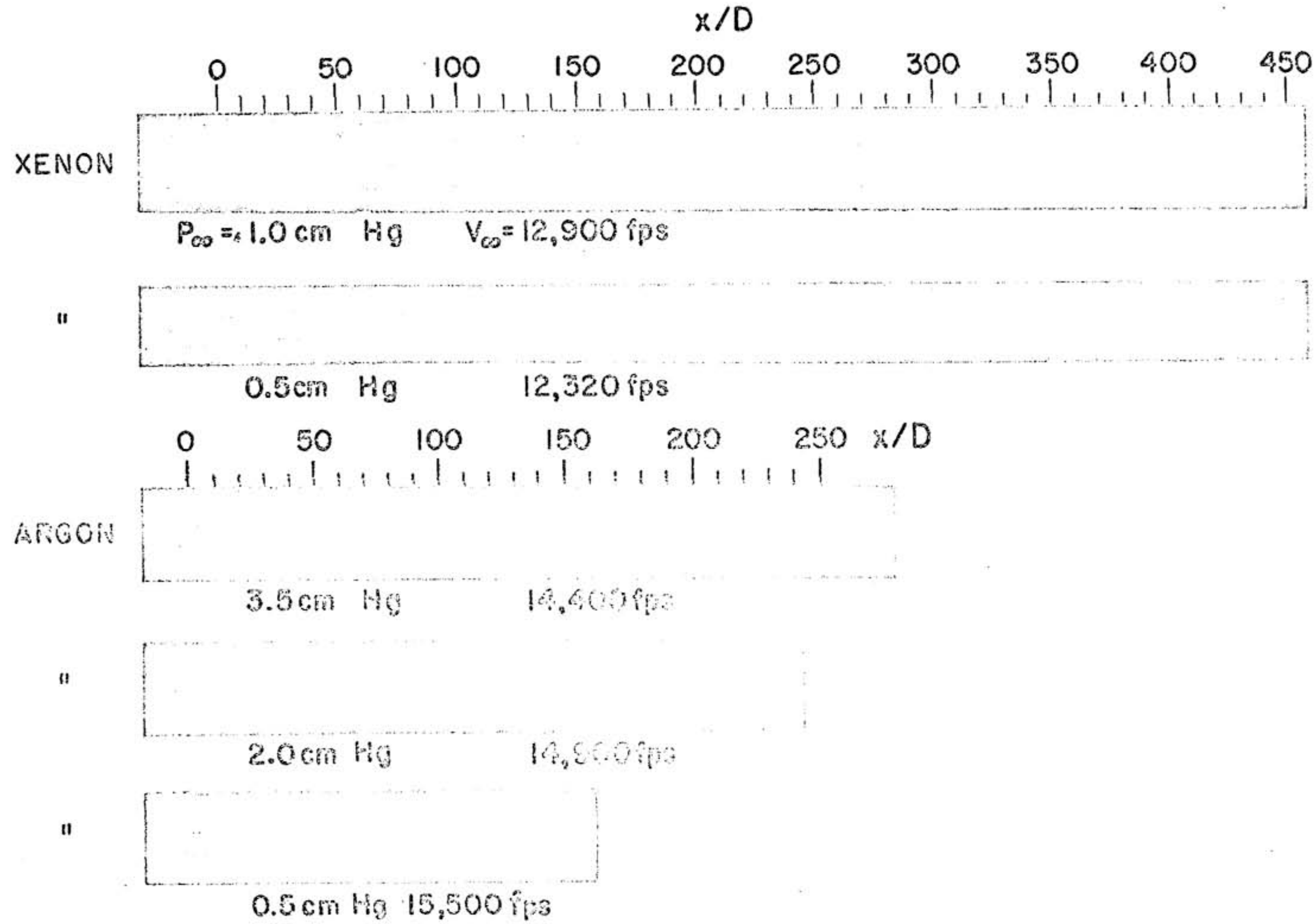
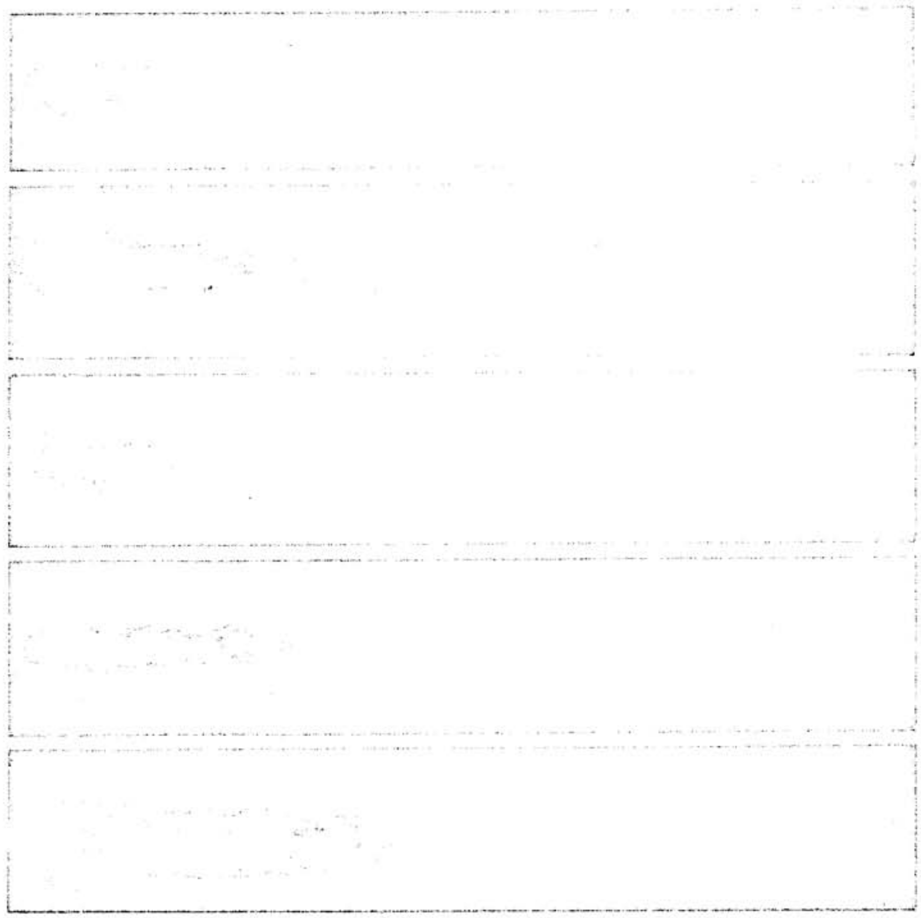


Fig. 10 Typical race track photograph. The top two pictures are for 0. 22-inch-diameter lexan spheres fired into xenon. The large-scale turbulence of the top photograph is to be compared with the laminar flow of the picture beneath it at a factor of two lower pressure. The lower three photographs are for nylon spheres fired into argon. Although the radiation intensity is lower than for the xenon runs, the character of the flow field is evident from the pictures.



0.70 cm Hg AIR
18,450 f.p.s.

0.90 cm Hg AIR
19,250 f.p.s.

1.5 cm Hg AIR
18,825 f.p.s.

4.0 cm Hg AIR
18,190 f.p.s.

10.0 cm Hg AIR
19,700 f.p.s.

Fig. 11 Race track photographs of 0.55-inch-diameter lexan spheres fired into air for a range of free stream pressure. The development of the turbulent wake as the pressure (Reynolds number) is increased is evident.

its strong resonance lines near 5896 Å seemed the most convenient choice for an initial experimental study. The radiation is in the visible range of the spectrum, so that standard light sources and schlieren instrumentation can be used, and for which appropriate narrow band filters are readily available.

The absolute value of the refractivity of sodium (12) as a function of pressure for various wavelengths close to its resonance lines is compared with that of air in Figure 12. It can be seen for example, that if one operates with light 20Å from resonance one obtains with sodium vapor a refractivity more than two orders of magnitude larger than is obtained with air at the same pressure.

A schematic of the apparatus used in the present work is shown in Figure 13. The optical system is the usual schlieren off-axis parabolical mirror arrangement with a narrow band interference filter placed just in front of the knife edge. The remainder of the apparatus consists of an oven constructed of two 30" lengths of 2" diameter pipe in the form of a cross which is placed inside the test section of the ballistic range. The central 6" of the cross can be heated to temperatures of 500°C to maintain the required partial pressure of sodium vapor (Figure 12). The arms of the cross are water-cooled to keep the sodium vapor from condensing on the windows. Sodium is placed in the center of the cross and the total pressure is fixed with the working fluid of either argon or nitrogen.* The absolute vapor density of sodium is determined as a function of wall temperature by measuring the percent transmission through the vapor of light selected by an interference filter and comparing with similar test cell transmission calibrations (12). The sodium level reached in the central region has been observed to be close to the equilibrium vapor pressure for the measured wall temperature.

Figure 14 shows six wake photographs taken using a filter 70Å wide with the peak transmission 20Å toward the red from the resonance line, and an exposure of one microsecond. These are photographs of 0.22-inch-diameter nylon spheres fired into nitrogen with 0.1% of atmospheric density of sodium vapor added. The three pictures in the right-hand column, taken at about the same velocity, represent a transition sequence as the free stream density (Reynolds number) is increased. The photographs at constant pressure (top row, middle row and lower left) indicate decreased structure as the free stream velocity increases. Sodium schlieren pictures have now been obtained at densities of 0.51 to 10.0% atmospheric and at velocities between 1,300 and 13,000 ft/sec for 0.22-inch-diameter nylon spheres. The results of this study are contributing to the understanding of the aerodynamics of the wake (5).

*Air cannot be used with sodium vapor at these temperatures because of the reaction of sodium with oxygen.

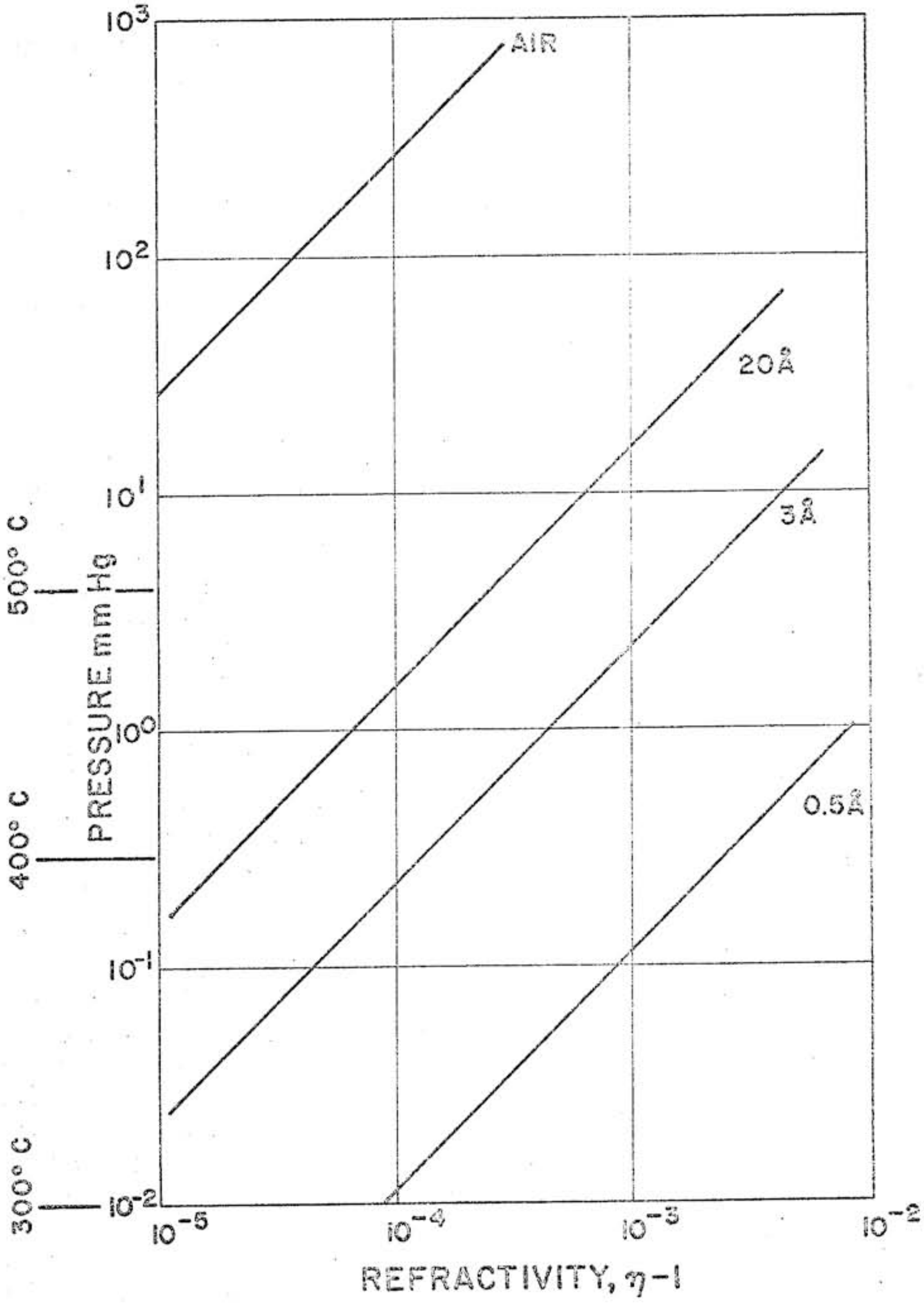


Fig. 12 Refractivity of sodium vapor and air as a function of pressure. The three curves labeled 0.5Å, 3Å and 20Å are the refractivity of sodium vapor measured with light 0.5Å, 3Å and 20Å, respectively, from the resonance line at 5896Å. The temperature scale indicates the heating necessary to produce the corresponding equilibrium vapor pressures of sodium.

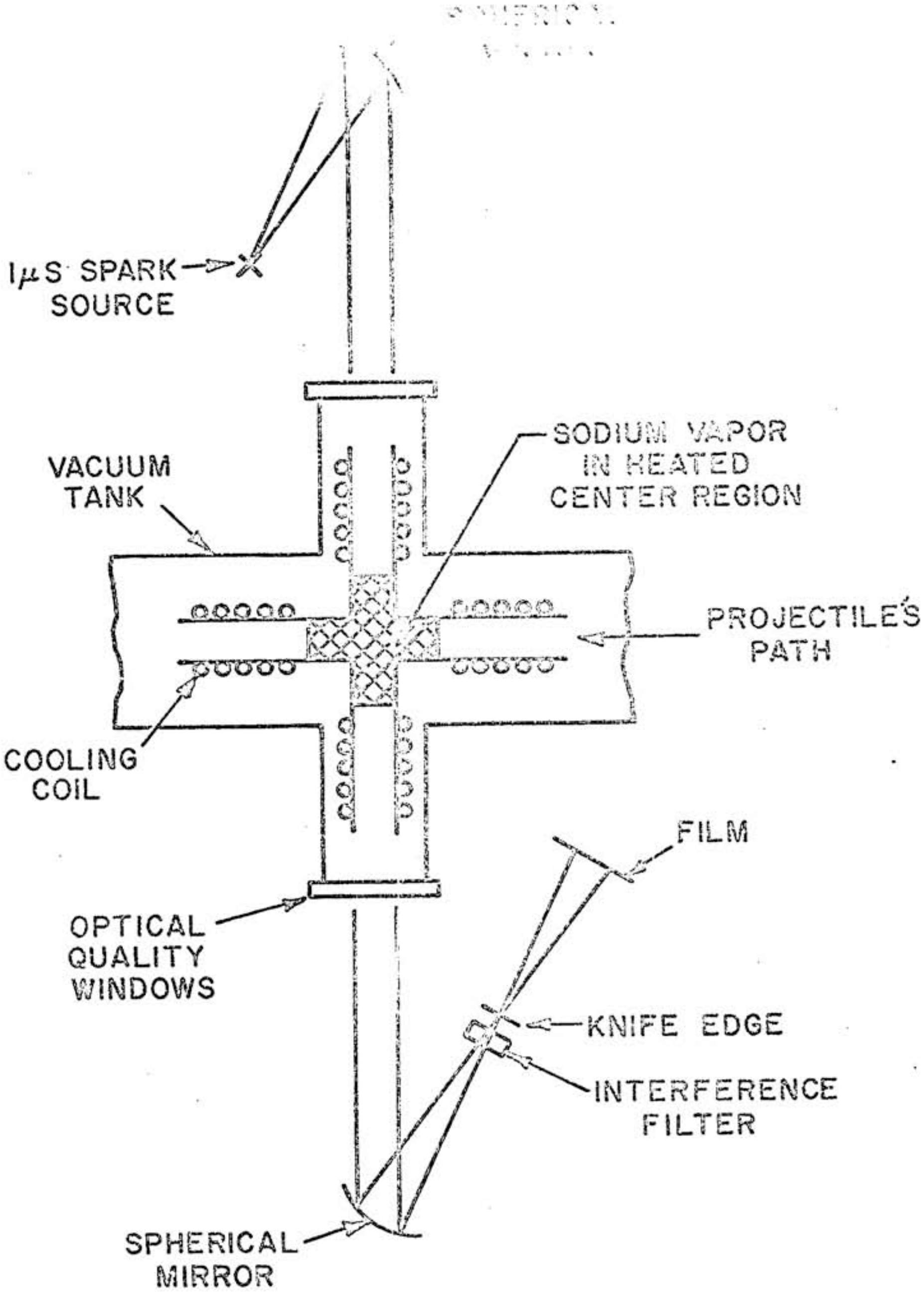


Fig. 13 Schematic of sodium schlieren apparatus. The cross in the center of the system is an oven to produce a controlled partial pressure of sodium vapor in the working fluid.

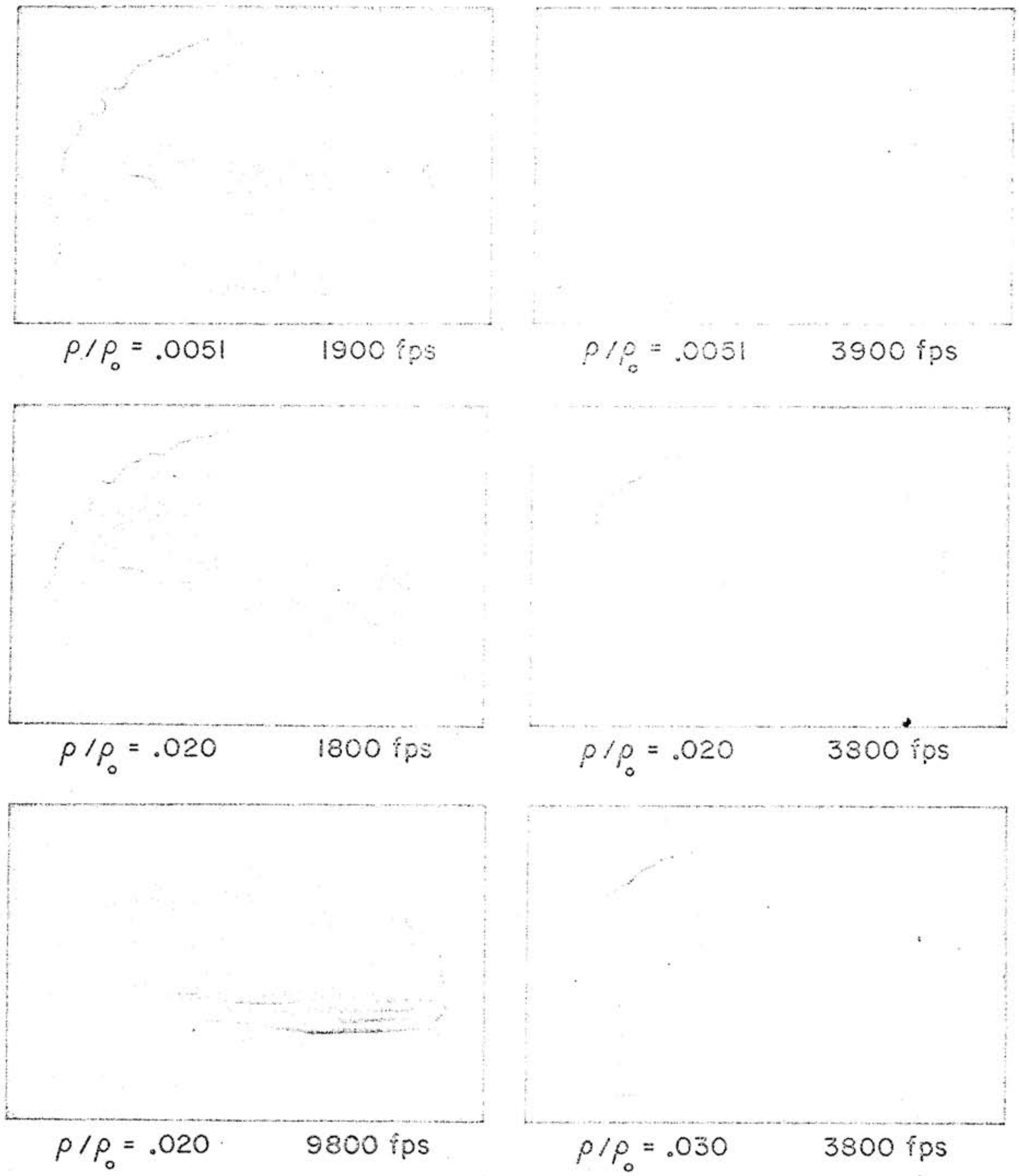


Fig. 14 Schlieren photographs of 0.22-inch-diameter nylon spheres fired into nitrogen at indicated density with 0.1% ρ/ρ_o of sodium vapor added. The free stream speed of sound under these conditions is about 2000 ft/sec, so that the top two pictures at the left are subsonic.

Image Converter

Although the low levels of luminosity and short exposure times necessary for taking snapshots of the hypersonic wake have led to the development of the race track technique discussed previously, the recent development of the image converter camera has brought about re-examination of the direct photographic technique. The image converter camera (13) is an instrument in which both electronic light amplification and fast shuttering are available. An image converter camera* was recently purchased by the laboratory and installed on the AERL range to photograph the base region of the flow field. This instrument utilizes an RCA tube with S-11 response and has a light gain of about 50 from the photocathode to the photoanode. A framing unit is available which allows three consecutive exposures to be made with independently adjustable intervals between frames. The frames are electronically deflected on the photoanode face to prevent double exposures.

Photographs by this technique for 0.22-inch-diameter lexan spheres are shown in Figure 15 for three gases air, argon, and xenon. In all cases the free stream pressure is sufficiently high so that the wakes are turbulent. Considerable detail is evident in these pictures, and it is hoped that this data may provide information on the mechanism of vortex shedding and the onset of turbulence in the wake.

SUMMARY

This paper has discussed a variety of techniques that have been developed for obtaining data on the wake behind hypersonic projectiles in the ballistic range. Photoelectric instruments, the recorder and wake scanner, are now available for measuring the intensity of radiation from selected volume elements of the wake. The streak drum camera and its race track adaptation allow the self-luminous flow field to be visualized. The sensitivity of the schlieren photographic technique has been increased by the use of resonance radiation to the point where pictures showing wake structure at densities less than 1% of atmospheric density can be obtained. The development of the image converter camera has made it possible to take snapshot photographs of the self-luminous flow field with exposure times sufficiently short that details of the base flow region are now available.

The types of wake data available from these instruments are: (a) rate of decay of radiation, (b) transverse profiles of radiation, (c) eddy velocity history, (d) eddy shedding frequency, (e) width and growth of the luminous wake, (f) Reynolds number for transition from laminar to turbulent flow, and (g) statistical structure of the turbulent wake. These data are having a significant effect upon the development of the understanding of the wake behind blunt bodies flying at hypersonic Mach numbers.

*Model C Image Converter Camera manufactured by STL Products, Inc., Los Angeles, Calif.

AIR	ARGON	XENON
P_∞ = 3.0 cm Hg	6.0 cm Hg	1.5 cm Hg
V_∞ = 14,800 ft/sec	14,300 ft/sec	14,000 ft/sec

LENS - f/2	f/2	f/2
EXPOSURE - 0.2 μ sec	0.1 μ sec	0.1 μ sec
TIME BETWEEN FRAMES - 5 μsec	5 μ sec	10 μ sec (BETWEEN 1st AND 2nd) 5 μ sec (BETWEEN 2nd AND 3rd)

Fig. 15 Image converter photographs of the base flow region of 0.22-inch-diameter lexan spheres in air, argon and xenon. There are three frames per picture, the time sequence running from top to bottom. The projectile is moving from left to right in each photograph. The range conditions are given at the top of the pictures and the image converter camera conditions at the bottom.

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