ARTICLE A,2

SHADOW AND SCHLIEREN METHODS

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A,2.1. Introduction. The function of both the schlieren and shadow methods is to determine small variations in the index of refraction of transparent materials. It can be shown that to a rough approximation the schlieren method measures the first derivative while the shadow method measures the second derivative of the refractive index [*1*,*2*,*3*,*4*].

The basic idea of the schlieren method was originated by Foucault [*5*] for testing lenses and other optical parts, but Töpler [*6*] greatly developed the method and applied it to the study of various air disturbances produced by sparks, explosions, air flows, etc. For the study of rapidly moving shock waves and other transient phenomena Töpler devised a spark light source which could be timed to illuminate a moving air disturbance at the desired instant. As a result "snapshot" pictures of the order of ten microseconds duration could be taken of the phenomena. Following Töpler a large number of workers have applied the schlieren method in various forms to the study of explosions, shock waves, and sound waves. R. W. Wood [*7*, p. 93] in a series of experiments beginning in 1899 photographed the reflection of compression waves from plane and concave mirrors, spherical aberrations, the diffraction produced by an obstacle, the refraction of a CO_2 lens, etc. The pictures graphically illustrate the change in shape of the wave front as it is brought to focus by a lens or concave mirror. The schlieren method has been applied also to the visualization and study of turbulence and convection due to hot wires or surfaces, the air flow around projectiles, jets, sound waves in air and in liquids, electrophoresis boundaries, diffusion boundaries, sedimentation in ultracentrifuges, etc. In recent years, especially, the method has been widely used in investigations of the air flow around bodies placed in high speed wind tunnels.

The shadow method, experimentally, is much simpler than the schlieren method and, since it depends upon the second derivative of the refractive index, is suitable for studies of such phenomena as intense shock waves or where the index of refraction changes very rapidly. The development of the method is usually attributed to Dvorak [*8*] who in 1880 used it to photograph air disturbances. Boys [*9*] in 1893 and Foley

[*10*], beginning in 1905, used the method to obtain beautiful photographs of the reflection, refraction, and diffraction of compression waves produced by sparks. The shadow method also has been used for investigating air jets, air flow around bodies in high speed wind tunnels, turbulence, the air flow and shock waves produced by high speed projectiles, sound waves in gases, liquids, and solids, etc. An excellent review of various shadow and schlieren arrangements, their theory, sensitivity, experimental details, and applications with many characteristic pictures has been written by Schardin [*2*]. The application of the schlieren and shadow methods to the aerodynamics of compressible flow has been discussed by Liepmann and Puckett [*11*, pp. 89–101].

A,2.2. Schlieren Systems.

Description of Schlieren Methods. The general principle of the schlieren system is illustrated by Fig. A,2.2a which is essentially the

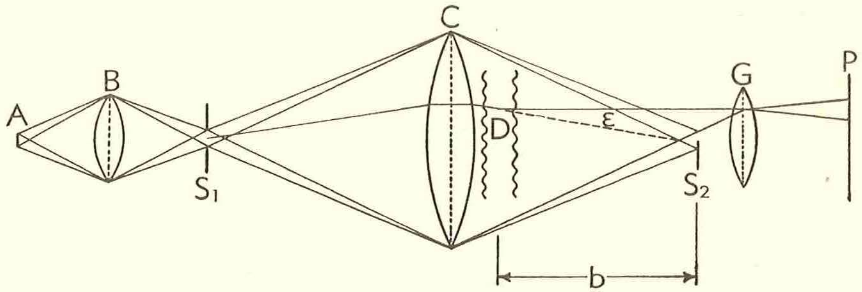

Fig. A,2.2a. A simple schlieren system. Lens *G* forms image of *D* on *P*.

arrangement used by Töpler, Wood, and others. Light from a source *A* such as a straight or ribbon filament perpendicular to the page is focused by the lens *B* on the slit S_1 so that it is uniformly illuminated. The light passing S_1 is focused on the knife edge S_2, which is parallel to the image of S_1, by the long focus, large diameter, so-called schlieren lens *C*. If now the knife edge S_2 is moved upward into the beam until it just blocks out the image of S_1, no light will reach *P* (neglecting diffraction effects) provided the lens *C* is of good optical quality, is free of chromatic and spherical aberration and of astigmatism, and if there are no index of refraction gradients in the air traversed by the light beam. On the other hand, if the air is disturbed in the region *D*, say by a shock wave, some of the light rays are bent so that they pass above the knife edge S_2 and are focused by the lens *G* upon the screen or photographic plate *P*. Consequently, an image of the disturbance is formed on *P*. It will be noted that, with this arrangement, only the light which is deflected upward by the disturbance passes S_2 so that the regions in which the refractive index gradient is such as to deflect the light rays downward or to right or left do not appear on P. In order to bring out the regions where downward deflections occur, it is common practice to adjust the knife edge S_2 to cut off the major portion but not all of the uniformly illuminated image of S_1. To observe the regions which deflect the light to the right or left, the whole optical system may be rotated through a right angle or other shapes of sources and knife edges, such as a point or disk-shaped source or slit at S_1, and a circular light stop at S_2 may

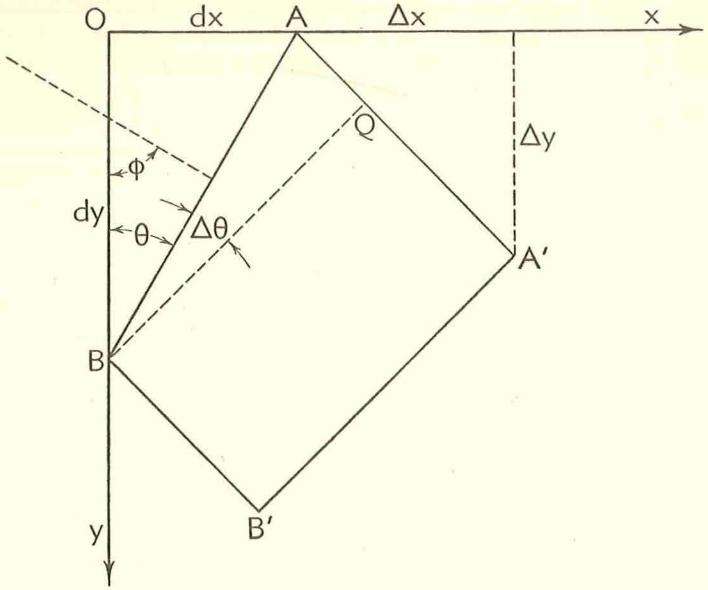

Fig. A,2.2b.

be used. If at D a light ray is bent through an angle ϵ by the disturbance as shown (exaggerated) in Fig. A,2.2a, the intensity of illumination on P may be considerably increased. Let a be the unobscured width of the uniformly bright image of the slit S_1 at S_2 perpendicular to the knife edge and b the distance from D to S_2. Then the proportional change in the light intensity I at P is approximately [*2,3,11*]

$$\frac{\Delta I}{I} = \frac{\epsilon b}{a} \tag{2.2-1}$$

as long as ϵb is smaller than the obscured image perpendicular to the knife edge. It will be noted that the sensitivity is increased by decreasing a and increasing b as long as diffraction effects can be neglected. Although reference must be made to more comprehensive treatments for the exact determination of the path of a light ray in a medium where the index of refraction varies in three dimensions [*1,2,3,4,12*], the case where it

varies in one dimension only (y direction) is illustrated in Fig. A,2.2b [*13*, pp. 253–273]. Consider a very small segment AB of the wave front of a light wave which makes an angle of θ with the y axis. If now at A the index

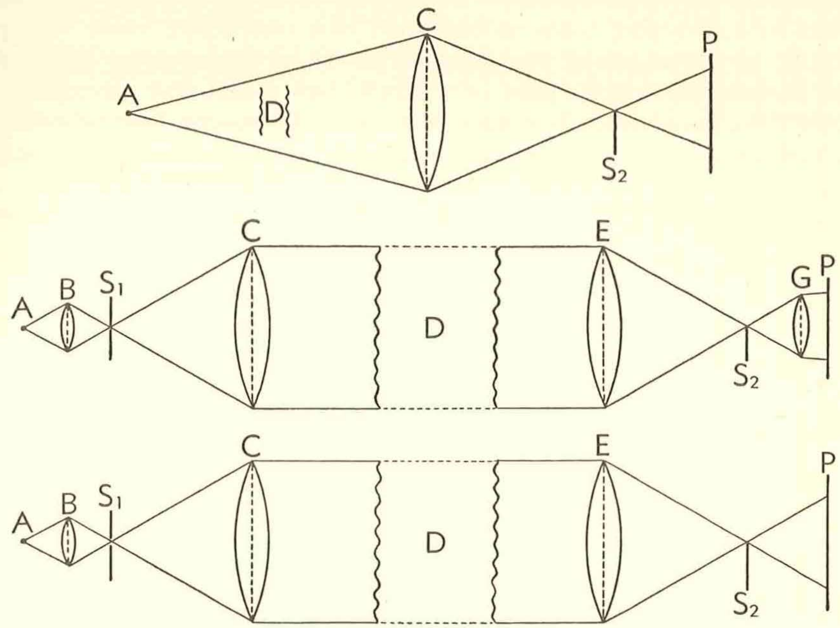

Fig. A,2.2c. Typical schlieren systems.

of refraction is n and at B it is $n + dn$, then, after a time Δt, the wave will move to $A'B'$ then

$$AA' = \Delta l = \frac{\Delta L}{n}$$

and

$$BB' = \frac{\Delta L}{n + dn}$$

where ΔL is the optical path of the wave front. Consequently,

$$\Delta\theta = \frac{AQ}{AB} = \frac{\Delta L}{n}\frac{1}{n}\frac{dn}{dy}\cos\theta = \frac{1}{n}\frac{dn}{dy}\Delta x \tag{2.2-2}$$

or

$$\epsilon = \int_0^l \frac{1}{n}\frac{dn}{dy}\,dl\sin\phi$$

where ϕ is the angle between the direction of the ray and dn/dy, i.e. the schlieren method measures the gradient of the refractive index. Since the work of Töpler, many variations of the method have been used by different workers. Three typical arrangements are shown schematically in Fig. A,2.2c. At the top is shown a scheme which utilizes only a single lens C. This arrangement requires a point or line source at A, and the distance from the region under investigation D to the schlieren lens C must be greater than the focal length of C so that the image of D is focused on the screen P. It will be observed that the disturbance takes place in a diverging beam as compared to a converging beam in Fig. A,2.2a. In the middle of Fig. A,2.2c is shown an arrangement in which the disturbance D takes place in a parallel light beam. For quantitative work there are several advantages in having D in parallel light, especially if its dimension parallel to the light beam is appreciable. At the bottom of Fig. A,2.2c is shown another arrangement in which D is in a parallel beam and the image of D is focused directly on the plate P by the lens E. In this assembly the distance from D to E must be greater than the focal length of E.

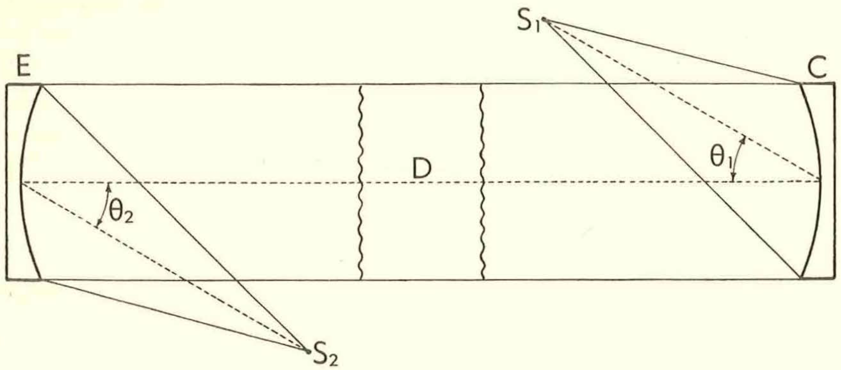

Fig. A,2.2d. Twin concave mirror schlieren system.

It will be noted that for any of the above schlieren arrangements the schlieren lenses C and E not only must be of the highest optical quality but also must have large diameters and long focal lengths. The large diameter is necessary because the cross section of the disturbance D is limited by the cross section of the lens. The long focal length is necessary in order to get the requisite precision and image size. As mentioned before, the schlieren lens should be free of chromatic and spherical aberrations. Also the astigmatism must be small, but it is not as critical as the other properties because of the axial symmetry. (See Art. 2.4.)

In experiments where the region under investigation D has a large cross section as in the case of many modern wind tunnels, it is very difficult to obtain lenses of sufficient diameter and focal length, and at the same time with the requisite optical properties and corrections, without almost prohibitive expense. As a result concave mirrors have been widely used. They are completely free from chromatic aberration and in large diameters and long focal lengths are much easier to grind and correct than lenses. Fig. A,2.2d shows a twin mirror system that

gives good resolving power. The schlieren mirrors C and E are a carefully matched pair. Usually they are made of glass and their front surfaces are parabolized to better than one tenth of a wavelength of light. The excellence of their optical quality cannot be overemphasized. Also due to their size (more than a foot in diameter) and weight they must be carefully mounted to avoid distortions [*14*]. The angle θ_1 must be approximately equal to angle θ_2 and they should be made as small as possible although angles up to about 7° are used successfully [*11*]. The distance between the mirrors C and E is not critical, but it is good practice to make it greater than twice the focal length of the mirrors. Also the optical system beyond S_2 is simplified if the distance from the disturbance to be observed at D to the mirror E is greater than the focal length of E. The parallel rays entering the region D are bent by the refractive index gradient and are no longer parallel to the beam and, hence, cannot be focused by the second mirror unless the distance from D to the second mirror E is greater than the focal length of E. Also it will be observed that for the case where the disturbance is in parallel light, Eq. 2.2-1 becomes

$$\frac{\Delta I}{I} = \frac{\epsilon f}{a}$$

where f is the focal length of the mirror or lens. (See Fig. A,2.2d.) Because the source slit or knife edge S_1 is off the axis of the mirrors, some astigmatism and coma are introduced, but this is reduced to a minimum by keeping S_1, the axis of the mirrors, and S_2 in the same plane. This plane may be horizontal, vertical, etc., depending upon the direction of the refractive index gradients in D to be observed. With this arrangement the coma is compensated almost completely and the astigmatism lengthens the image of S_1 at S_2 in the direction of the knife edge rather than perpendicular to it so that no appreciable troubles are introduced. Occasionally it is necessary to observe the refractive index gradients in all directions at the same time. This may be accomplished with a point or disk source of light at S_1 and a disk light trap at S_2 which just blocks the image of S_1. This light mask at S_1 may be made, for example, by exposing, say, a lantern slide plate in the position of S_2, then using the developed plate for a light mask. For proper adjustment the knife edges or slits S_1 and S_2 should be of high quality and should be mounted so that they can be raised and lowered, rotated, or moved forward or backward by micrometer adjustments [*2,14*]. Also the mirrors should be accurately adjustable. The mountings of all of the components should be rigid. When properly adjusted for maximum sensitivity, the above system of Fig. A,2.2d responds to very small convection currents and temperature gradients in the light beam as well as the disturbances under investigation at D, i.e. they produce an undesirable background disturbance. Consequently, the distance between the mirrors should not be larger than necessary and care must be taken to prevent room disturbances. Temperature differences of 1°C in air which corresponds to refractive index changes of one part in 10^6 are readily observable [*14*].

Fig. A,2.2e shows a double traverse coincident schlieren system. Light from the source A is focused on the knife edge mirror S_1 by the condensing lens B. The light then goes to the large schlieren concave mirror C where it is returned to the knife edge S_2. The camera lens G is focused on the disturbance D or the region under investigation. In most of the experiments C is a spherical mirror of very long focus and very high quality.

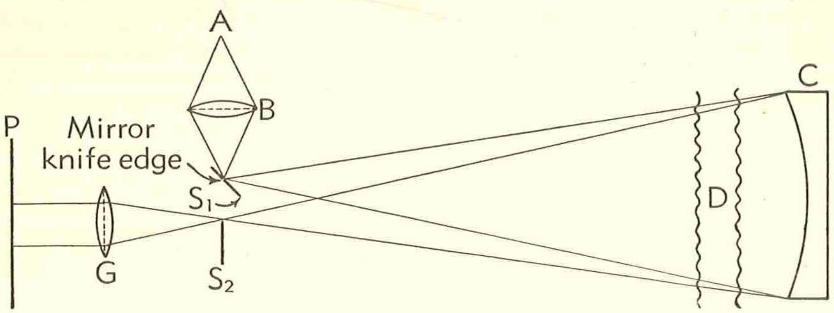

Fig. A,2.2e. Double traverse coincident schlieren system.

It will be observed that the light traverses the disturbance D under investigation twice so that the sensitivity is doubled. On the other hand one beam is converging and the other diverging. Since the two paths through D are not identical, there is a slight blurring or doubling (in case of a shock) of the image which may reduce the resolving power [*15*]. However, in practice this system is especially used to observe very weak disturbances where the light is refracted only a very small amount in one traversal. It can be shown that the sensitivity is

$$\frac{\Delta I}{I} = \frac{4\epsilon f}{a}$$

where f is the focal length of the mirror and the other quantities have the same meaning as in Eq. 2.2-1 [*11*]. This type of schlieren system has been used, for example, in observing phenomena in hypersonic low pressure wind tunnels by McLellan, Williams, and Bertram [*16*]. With a spherical mirror 1 ft in diameter and a radius of curvature of 20 ft they observed density changes across a shock of 1.3 per cent of the free stream density, which was only 6 or 7 per cent of an atmosphere. Optical distortion in the windows of their tunnels limited the precision of their observations.

In Eq. 2.2-1 the refractive index gradient is determined by measuring

the light intensity changes on the photographic plate. Often it is more convenient to determine small displacements. One such method is shown in Fig. A,2.2f. (The top diagram gives a side view and the bottom, a vertical projection.) It is known as the Thovert [*17*], Philpot-Svensson [*18,19*] inclined slit method and measures the refractive index gradient in one direction [*20*]. A is a light source, preferably monochromatic, such as a high pressure capillary mercury arc with filters [*14*] to give the green line, B a collimating or projection lens, S_1 a narrow horizontal slit, C the first schlieren lens, D the region under investigation, S_2 an inclined slit, G a camera lens, I a cylindrical lens with a vertical axis, and P the

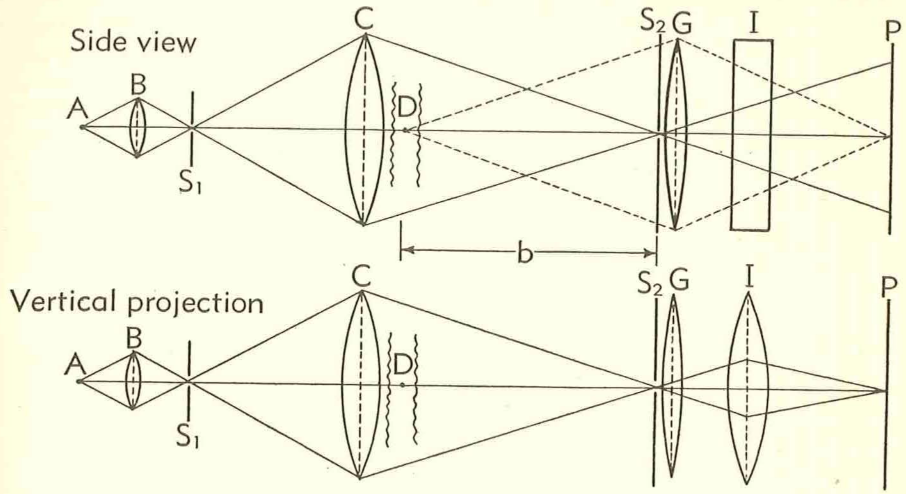

Fig. A,2.2f. Thovert, Philpot-Svensson inclined slit system.

photographic plate or viewing screen. Three principal adjustments must be made: first, the image of the horizontal slit S_1 must be thrown on the inclined or diagonal slit S_2, which is just in front of G; second, the image of the region D must be focused on the photographic plate or viewing screen P; and third, an image of the inclined slit S_2 is formed on the photographic plate P. The cylindrical lens I with vertical axis has no focusing effect on light in the vertical plane, so that each vertical coordinate y in the region D corresponds to a vertical coordinate Y on P or $Y = K_1 y$ where K_1 is the optical magnification of the region D on P. In the horizontal plane G and I focus S_2 upon P with a magnification factor K_2. If no gradient of the refractive index exists in D, a straight vertical line is formed on P. On the other hand, in the presence of a gradient the image of the light source on the inclined slit S_2 is displaced either up or down by an amount ϵb where ϵ and b have the same meaning as in Fig. A,2.2a. This causes the image to be horizontally displaced a distance $K_2 \epsilon b \tan \varphi$, where φ is the angle the inclined slit S_2 makes with the vertical. Consequently, a curve is automatically recorded on P which gives the refractive index gradient versus the vertical height in the region D. The absolute value of the refractive index is obtained from the integral or area under this curve. If the disturbance D has a large dimension perpendicular to the paper, Fig. A,2.2f (top), and if the vertical refractive index gradient is not uniform perpendicular to the paper across D, then a wide vertical slit should be placed in front of C. The vertical refractive index gradient in the region of D illuminated by the parallel beam is then recorded. The entire region D may be investigated by moving the wide slit across C. The horizontal gradient of the refractive index can be obtained by rotating the whole optical apparatus through a right angle. Also schlieren concave mirrors, Fig. A,2.2d, may be used in place of the schlieren lens. Some experimenters prefer to use a small inclined solid bar at S_2 instead of a slit [*21*]. This gives a dark line on a light background rather than a light line on a dark background. The method was designed originally for observing sedimentation in ultracentrifuges and moving boundaries in electrophoresis where it has wide application, but it is extremely useful in any experiment where quantitative data are essential. Angular deflections ϵ of 10^{-5} radians can be measured with a schlieren mirror of 60 in. focal length and 12 in. diameter.

A number of different optical arrangements may be used with the above method such as shown in Fig. A,2.2c. In fact it is usually preferable to have the region D in parallel light. Also attention should be directed to the Longsworth slit method [*22*] and the Lamm scale method [*13*], as they both give precision comparable with the above methods. The latter method, which essentially consists of photographing a scale or rectangular network through the disturbance and measuring the distortion of the image, is capable of high precision although the reduction of the data is laborious.

In the above schlieren methods the region D under investigation may be of considerable length in the direction of the light beam and still be focused on the photographic plate P, i.e. there may be a comparatively large depth of focus. However, it is often desirable to record only the phenomena which occur in a plane perpendicular to the light beam in D. For this purpose a sharp-focusing schlieren system has been devised recently by Kantrowitz, Trimpi, and Miller [*23*]. The method employs multiple sources and slits (knife edges) with each source and corresponding slit acting as an ordinary schlieren system. The light rays through the region under investigation are approximately parallel but the different beams are oblique to the axis. In this way the disturbances in a given plane in D are accentuated with respect to the other planes with the result that a sharp focus is obtained.

Another method [*1,2,24*] of recording the angular deviation ϵ consists in placing a series of parallel slits in front of or behind the image plane

of S_1 at S_2 (Fig. A,2.2a) with the knife edge removed [*32*]. Usually the slits (Ronchi plate) are equally spaced and the distance between the slits is equal to the width of the slits. The slit S_1 is narrowed until the width of its image is not larger than the distance between the slits [*32*]. With this arrangement the background of the schlieren lens (or mirror) and hence the plate or screen at P is covered with straight lines if there is no disturbance at D. However, any refractive index gradients in D will cause the lines to be curved in the region of the disturbance. From the displacement of these lines the angular deviation ϵ can be determined. Diffraction apparently sets the lower limit of the width of the slits that can be used. Darby [*24*] found that 100 lines per inch was about the limit for his apparatus, which had a sensitivity of about 10^{-4} radians per line.

In general the schlieren method is used either for the detection of small refractive index gradients or for the quantitative measurement of these gradients. For the detection of small gradients the apparatus described above, in which the deviation of the light ray ϵ gives rise to the relative light intensity change $\Delta I/I$ on the photographic plate, is almost universally used for studying phenomena in aerodynamics and ballistics. The method also may be made quantitative, but attention must be given to the several variables in the experimental arrangement. If the disturbance is to be photographed, the arrangement must give a maximum contrast between the images of the undisturbed and disturbed regions and at the same time the photograph must be dense enough to be measurable by photometric means. In most cases high contrast photographic plates are preferable even though they are somewhat slower. In order to calibrate the system, a known refractive index gradient such as a small glass prism may be inserted in some corner of the median plane of the disturbance D which allows a check on the formulas used for the optical system. The sensitivity, i.e. $\Delta I/I$, depends directly upon the brightness of the image of S_1 at S_2 and upon its uniformity of illumination. This of course requires as bright and uniform a source as possible to start with and an optical system which sacrifices no more light than necessary. Rectangular sources are usually superior [*11*] and, if they are wide or high enough (for example, a General Electric type H6 lamp) [*14*], they may be placed directly back of the slit S_1 with the elimination of the lens B [*22*]. It is also clear that if the unobscured width a of the image at S_2 is reduced, the sensitivity is increased. However, there is a practical minimum for the width which is set by the diffraction pattern at S_2 and the intensity and size of the source. The sensitivity also increases directly with the focal length of the schlieren mirror or lens, while a large aperture gives high aperture to disturbance ratio which increases the contrast and density on the plate. Shafer [*4*] especially has analyzed theoretically the above factors and has concluded that the effective f ratio of the optical system should be as large as possible, consistent with the brightness of the light source and the availability of the optical parts. He gives a value of $f/10$ for the schlieren system to be used with a Charters [*25*] 1-mm diameter source through which an energy of 5 watt sec is passed in 10^{-6} sec. He also concludes that in general the optimum position of the knife edge should be near the optic axis although the exact position must be determined by the size and brightness of the image of S_1 at S_2. Shafer gives the optimum size of the light source as one whose geometrical image in the focal plane of the objective (schlieren lens) is equal to the width of the "Airy disc" of the objective [*26*].

Suppose the above method is applied to the study of disturbances such as density gradients in a wind tunnel in which the flow is two-dimensional. That is, if the flow is in the x direction and the light beam is in the z direction, the component of the gradient of the refractive index vanishes in the z direction. The index of refraction in air for sodium light can be expressed in terms of the density ρ by the relation

$$n = 1 + 0.000293 \frac{\rho}{\rho_{\mathrm{NTP}}}$$

where ρ_{NTP} is the density at 1 atm and 0°C. As a result Eq. 2.2-2 gives for the components of the angular deflections ϵ_x and ϵ_y in the x and y directions, respectively, as

$$\epsilon_x = \int C \frac{\partial \rho}{\partial x} dz, \qquad \epsilon_y = \int C \frac{\partial \rho}{\partial y} dz$$

where C is a constant.

When the component of the density gradient in the direction of the light beam does not vanish, the interpretation of the pictures is more complicated.

THE SENSITIVITY OF THE SCHLIEREN METHOD FOR STUDIES OF SHOCK AND EXPANSION WAVES. As shown in Art. 2.2, Fig. A,2.2a and Eq. 2.2-1

$$\frac{\Delta I}{I} = \frac{\epsilon b}{a}$$

If now we assume (following references [*2,11,27*]) that we can determine a 10 per cent change in $\Delta I/I$ and set $b/a = 10^4$ (for example $a = 0.006$ in. and $b = 60$ in.), then $\epsilon = 10^{-5}$ radians (about 2 sec of arc).

Of special interest is the question: Under what condition will an oblique shock become visible [*27*]? Assuming the knife edge to be parallel to the front of the oblique shock and, as a typical value, the angle between the shock and the optic axis $\theta = 1° = 0.0175$ radians, it can be shown that all the light incident upon the shock is refracted and the amount of light reflected is negligible. If index 0 characterizes the stagnation conditions at 20°C, index 1 the free flow on the upstream side of the

shock, and index 2 on the downstream side, Snell's law of refraction leads to the relation

$$1 + 0.000293 \frac{273}{293} p^0 \left(\frac{\rho_1}{\rho^0} - \frac{\rho_2}{\rho^0}\right) = 1 - \epsilon \tan \theta$$

or for $\epsilon = 10^{-5}$

$$\rho_2 - \rho_1 = \rho^0 \frac{\tan \theta}{27.3 p^0} \tag{2.2-3}$$

where p^0 is the stagnation pressure in atm.

If the knife edge is, as usual, parallel or perpendicular to the flow and the shock makes an angle β with the flow, the right side of Eq. 2.2-1 has to be multiplied by $\cos \beta$ or $\sin \beta$, respectively.

More useful than the density difference is the difference between β and the Mach angle μ which is a measure of the shock strength. If M_1 is the Mach number of the flow upstream of the shock, M_n the component of M_1 normal to the oblique shock

$$\sin \beta = \frac{M_n}{M_1} = M_n \sin \mu$$

Furthermore

$$\frac{\rho_1}{\rho^0} = \left(1 + \frac{M_1^2}{5}\right)^{-\frac{5}{2}} \quad \text{if } \gamma = \frac{C_p}{C_v} = 1.40$$

and

$$\frac{\rho_2}{\rho_1} = \frac{6M_n^2}{M_n^2 + 5}$$

$$\frac{\rho_2 - \rho_1}{\rho^0} = \frac{\rho_2 - \rho_1}{\rho_1}\frac{\rho_1}{\rho^0} = \frac{5(M_n^2 - 1)}{M_n^2 + 5}\frac{\rho_1}{\rho^0} = \frac{\tan \theta}{27.3 p^0} \tag{2.2-4}$$

provided the knife edge is parallel to the shock wave front. Therefore, at given values of θ, p^0, and M_1, also M_n and therefore the minimum difference $\beta - \mu$ which will give a visible schlieren effect is determined.

If the density change across the oblique shock is small, also $\beta - \mu$ is small, $M_n^2 = 1 + \delta$, with $\delta \ll 1$

$$\beta - \mu = \frac{3}{5}\frac{\rho^0}{\rho_1}\frac{\tan \theta}{27.3 p^0 \sqrt{M_1^2 - 1}}$$

if $\epsilon = 10^{-5}$ and the knife edge is parallel to the front of the shock wave. For $\theta = \beta - \mu = 1°$ the following table gives the minimum stagnation pressure at which shocks will be visible by schlieren at the assumed rather favorable condition.

M	$p^0_{\min}$ atm
2	0.055
3	0.102
4	0.205
5	0.396
7	1.21
10	4.46

If θ is 5° instead of 1°, the minimum pressures given are approximately five times as large.

A similar consideration will give the conditions for visibility of expansion waves [*27*].

A,2.3. Shadow Methods. As pointed out above in Art. 2.1, the shadow method depends upon the second derivative of the index of refraction and therefore is best suited to recording sudden changes. The apparatus used in the shadow method is much simpler than that used in the schlieren method. Fig. A,2.3a shows a typical arrangement. A is a point light source, D is the region under investigation, and P is a photographic plate or viewing screen. Usually the distance AD is greater than 10 ft while DP is of the order of 1 or 2 ft, depending upon the

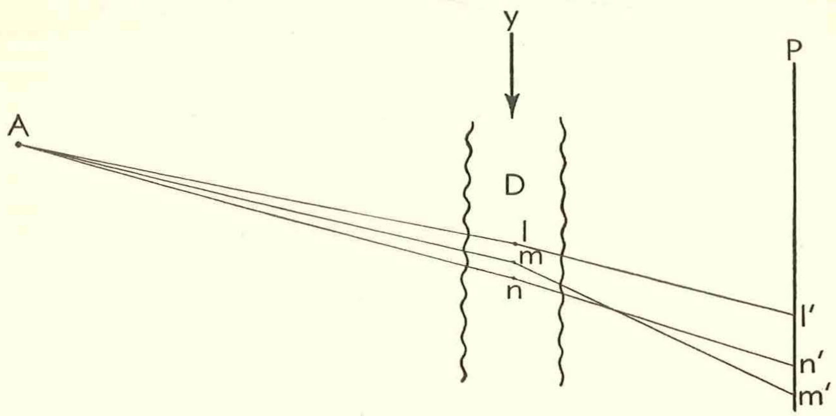

Fig. A,2.3a. Simple shadow system.

magnification desired. The light from A in passing through the disturbance D is refracted and bent out of its path. If the refractive index gradient, say $\partial n/\partial y$, is constant along the length of D, then all the rays are bent by the same amount and no change in the light intensity I occurs on the screen or plate P. On the other hand, if $\partial n/\partial y$ varies and hence $\partial^2 n/\partial y^2$ is not zero, then the deflection of the rays is not constant. For example in Fig. A,2.3a, if the gradient $\partial n/\partial y$ at m is greater than at l and n, the rays will be deflected by different amounts and n' will lie between l' and m' and a darker region will occur between l' and n' while a lighter region will occur between n' and m'. For example in a shock wave the density increases rapidly to a peak and then approaches a constant value [*11*] so that the image on the plate consists of a dark and light band adjacent to each other [*28*]. As the plate P is moved back, this region broadens and becomes more distinct. However, there is usually an optimum distance of a foot or so which gives the best contrast. The distance from the light source A to D is determined by the intensity of the source and by its size. If A is very small as in the case of, say, a concentrated arc lamp or small hole illuminated by a focused spark, the

distance AD may be made much less than shown in Fig. A,2.3a. The distances of light source A and plate P from the region D under investigation are especially critical if the turbulent nature of the flow is to be studied (see [*45,52*] and F,3).

The above discussion has been limited to one dimension, but for two dimensions [*2,3,11*] the increase of intensity

$$\Delta I = k\left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2}\right)$$

where k is a constant and x and y are the coordinates in a plane normal to the light path.

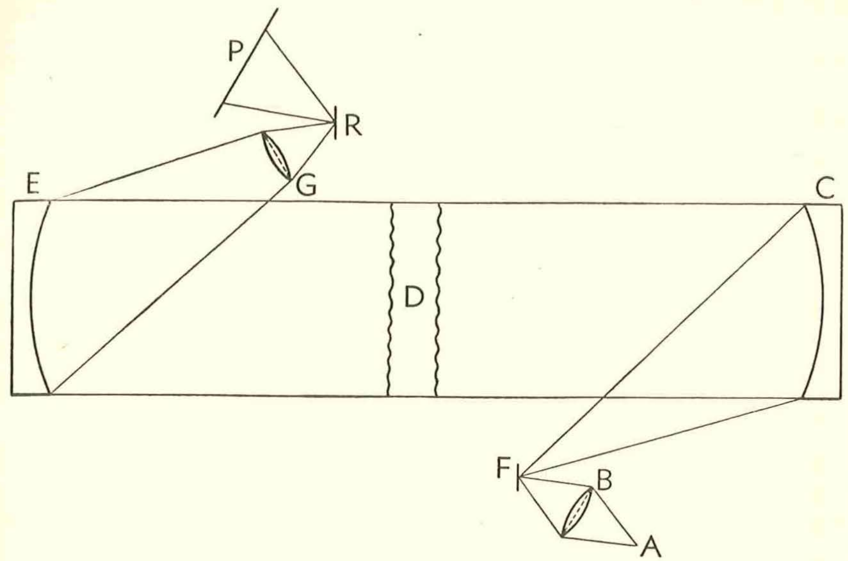

Fig. A,2.3b. Shadow system using parallel light.

Shadowgraphs may be taken in parallel light as shown in Fig. A,2.3b. A is the light source, B a lens, F a flat front surface mirror, C and E the large concave mirrors such as used in Fig. A,2.2d, D the region or plane of the disturbance, G a lens, R another front surface mirror, and P the photographic plate or viewing screen. All of the optical parts should be of first quality and carefully corrected as in the schlieren apparatus. The lens G is so adjusted as to bring the plane of D "in focus" on the photographic plate P. It is therefore possible to obtain "focused" shadowgraph pictures [*29*]. Or if the disturbance is weak, greater shadow effects are obtained by throwing the system slightly out of focus.

Since the shadow method is sensitive to sudden changes in the refractive index, it is often used to study transient phenomena in high velocity jets, the flow of air around rapidly moving bodies, sound waves, shock waves, etc. Consequently either the shutter at R or at F (Fig. A,2.3b) should operate very quickly or the light source at A (Fig. A,2.3a and Fig. A,2.3b) must be made of very short duration to prevent blurring of the image. Rapidly rotating mirrors have been used [*29*] at R or at F and spark light sources are often used at A. These light sources are discussed in Art. 2.4. The shadow method gives the position of the disturbance as well as that of the object which produces it with high precision. It also gives the Mach angles and peak density of the shock waves. As an illustration of the clarity with which the shadow method brings out air disturbances and flow, special reference should be made to the beautiful shadow photographs of projectiles in flight made by Charters and his associates [*25,28*] and to Plate F,1.3. In quantitative studies of the density distribution in air disturbances great care must be given to the proper photographic procedure as well as the photometric measurement of the plates. Usually shadow photographs of shock waves are made at two distances from the disturbance and measurements are made of the width of and intensity across the dark band. Keenan and Polachek [*30*], Clippinger [*31*], and others [*2*] have developed methods of evaluating shadowgraphs and have concluded that they are most useful in determining the density distribution near the front of the shock wave, the slope of the wave, and the peak intensity.

A,2.4. Light Sources, Optical Parts, and Photography. The type of light source required for either the schlieren or shadow method is determined by the type of problem under investigation. In general the schlieren and shadow methods are used to study two kinds of phenomena. The first kind is stationary or changes very slowly with time while the second kind is transient, moving or changing very rapidly.

For the first type of problem almost any kind of light source which is intense enough is satisfactory. The carbon arc and the incandescent lamp especially have been widely used for the first type of phenomenon. In many cases a straight filament or ribbon incandescent lamp may be used without a condensing lens or slit. When monochromatic light is required the mercury lamp with filters is used. For most experiments a high pressure "capillary" mercury arc is suitable since it has both high intensity and a slitlike shape. Also the spectral lines are well spaced and efficient filters are available for isolating the various spectral lines. The spectral lines of course are broadened in the high pressure arc, but it is seldom that the schlieren or shadow methods require highly monochromatic light. A number of investigators have found the H4 and H6 mercury lamps [*14*] especially suitable for their experiments. Because of its very small cross-sectional area and high intensity, the zirconium concentrated arc light is an excellent source, especially when a point

source is required. It may be obtained in various sizes depending upon the light intensity requirements [*34*]. Many other light sources are commercially available. Finally, in considering a "white" light source, the sun should not be overlooked because of its high intensity parallel light.

For investigation of the second type or transient phenomenon mentioned above, the experimenter must resort to a fast-acting light shutter or must employ a light source of short duration. In their early experiments, Töpler, Wood, Ferry, and others used a condenser discharge through an electric spark gap. Wood [*4*] developed a slit type intense spark light source by enclosing two sheets of metal between glass plates. The condensed spark takes place between the edges of the two thin metal plates and the light is viewed "edge on." With magnesium sheets as electrodes, Wood obtained extremely intense spark light especially in the spectral region of the 4481A spark lines of magnesium. Condensed discharges through enclosed capillaries or small channels have been developed in recent years for light sources, especially by Charters [*25*], Ladenburg [*35*], and their associates [*36*]. In most cases, the light source is viewed "end on" and is very intense. As long as the phenomena under investigation will permit exposure times of one microsecond or longer, no special care must be taken with these spark sources. However, for the study of the air flow around bodies in supersonic wind tunnels, around high speed projectiles, for the study of turbulent boundary layers, etc., blurring occurs unless the exposure time is reduced well below one microsecond. In general, minimum duration of the spark light source is determined first by the difficulty of getting sufficient energy into the spark and then cutting it off, and second, by the die-away of the light in the spark after the electric current in the spark is stopped. In most practical cases, this die-away time is roughly between 0.01 and 0.1 microsecond. In any type of condensed electric discharge, the resistance of the spark gap changes from almost infinity before the breakdown to a comparatively small value after complete breakdown occurs. That is, the current in the spark must build up from practically zero to a large value in a few hundredths of a microsecond. Consequently, in order for this to occur, the effective inductance in the circuit feeding the spark must be very small and the capacity should be comparatively large. A number of special noninductive condenser spark gap arrangements have been developed which have reduced the effective duration of the spark light to a few tenths of a microsecond [*37*]. Since the principal difficulty with a lumped capacity-resistance-inductance circuit is in matching the impedance of the source to the spark gap, a low impedance transmission line may be employed to considerable advantage [*38*]. In practice the transmission line is open-ended at the output end and shunted at the input end by the spark gap in series with a noninductive resistance equal to the surge impedance of the line. If the line is charged to the desired potential, the spark discharge impresses a discharge wave upon the line. This surge travels to the open end, is reflected, and returns to the input end where it reduces the potential across the spark to zero. The potential across the spark gap is maintained only while the discharge wave is traveling twice the length of the transmission line, and consequently the time can be varied by changing the length of the line. The maximum current in the spark is determined by how small the surge impedance of the line can be made. This can be reduced by using several lines, say RG8/U cable in parallel. Recently Fitzpatrick, Hubbard, and Thaler [*39*] have developed a barium titinate coaxial transmission line (which now can be obtained commercially), with the order of a few ohms surge impedance, which increased the spark light intensity over an RG8/U cable by 1,000 times for 0.1 microsecond flashes. As a result the die-away time of the excited gases in the gap is probably the principal limiting factor on the minimum time of duration of the spark light.

It is clearly possible to take short schlieren or shadow photographs by using a rapidly rotating mirror or a Kerr cell as a light shutter. With the present techniques of rotating mirrors the only limiting factor on the rotational speed obtainable in practice is the strength of the mirror [*40*]. With good highly polished steel mirrors, light flashes or exposures from 10^{-9} to 10^{-10} sec duration can be obtained. These mirrors may be magnetically suspended and driven electromagnetically or they may be air driven [*41*]. Usually they are spun in a vacuum or light gas such as helium in order to reduce optical distortion by shock waves arising from the rapidly moving mirror edges. Kerr cells also may be used as light shutters, although their time of observation is limited by the time constants of the electric circuit of which they represent a minimum of the circuital capacity. However, light flashes of the order of 10^{-9} sec duration can be obtained. The light source used with a rapidly rotating mirror or Kerr cell should be as intense as possible and should be roughly synchronized with the mirror or cell. Consequently high intensity sparks or small exploded metal wires with large capacities across them serve as good light sources.

For quantitative work the optical parts preferably should be as nearly perfect as possible. It can be shown that the difference in the lengths of the light paths of any two rays in an optical system containing lenses or mirrors need not be smaller than $\frac{1}{4}$ wavelength of the light used [*26*]. However, this is often difficult (though not impossible) to obtain and in practice a few wavelengths can usually be tolerated. This also applies to any wind tunnel window through which the light passes. However, it should be pointed out that perfect lenses or mirrors if used in a manner for which they are not constructed give rise to difficulties. For example, a portrait objective should not be used for parallel light, etc. For each

system careful calculations should be made using the well-known methods of optics (*2,26,42*). The slits and knife edges must not only be accurately adjustable but also they must be precisely made [*1,2,14*]. For example, an error of one mil in the knife edge would introduce a change in intensity on the plate of about 16 per cent in the problem discussed in Art. 2.2. Because of the long optical paths, diffraction patterns formed by the slits and knife edges are sometimes gross enough to be readily visible. In the case of a slit the diffraction pattern is symmetrical, but for a knife edge the pattern consists of "a system of fringes of decreasing width, outside the edge of the geometrical shadow, while within the edge the illumination falls off rapidly without however passing through maxima and minima" [*42*]. Consequently, a knife edge gives a relatively sharp image. On the other hand, the position of the edge of the image of a knife edge will appear to shift on the photographic plate with exposure time (assuming a constant intensity source) while the central line of the slit image will be relatively independent of the exposure time [*22,43*]. In all quantitative work the photographic procedures must be carried through in such a way as to give an accurate recording of the light intensity.

A,2.5. Comparison of Schlieren and Shadow Methods. As pointed out in Art. 2.1 above, theory shows roughly that the schlieren method depends upon the first derivative while the shadow method depends upon the second derivative of the refractive index. Consequently, in phenomena where the refractive index varies relatively slowly, the schlieren method is to be preferred to the shadow method, other things being equal. On the other hand, the shadow method brings out very beautifully the rapid changes in the index of refraction. The shadow method also has the advantage of greater simplicity and somewhat wider possible application. The two methods therefore supplement each other and both should be used whenever possible. Fortunately, in many cases the same apparatus or optical parts can be used for both methods by simple rearrangements and without too much effort on the part of the experimenter. In addition to the first and second derivatives, the refractive index itself can of course be obtained by integration. However, whenever possible, it is preferable to measure a quantity directly rather than obtain it from its derivative. For this reason it is clear that the shadow and schlieren methods should be supplemented by the interference method, which gives the refractive index directly. The complete information which can be obtained by these three methods supplementing one another is beautifully demonstrated by the recent work of Ladenburg and his associates [*35,36,44,45*]. The interference method is taken up in detail in the following article. Recently several experiments have been described which utilize essentially the same optical parts for the schlieren, shadow, and interference methods [*44,45,46,47*]. For additional illustrations of the application of the shadow and schlieren methods, reference should be made to the following articles: for axially symmetric jets [*1,2,11,35,36,38,48,49*]; for two-dimensional channel flow and wind tunnels [*1,11,16,51,52,53,54*]; for projectiles [*1,25,28,29,50,55,56,57,58,59*]; for shock tubes [*60,61,62*].

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ARTICLE A,3

INTERFEROMETRY

R. LADENBURG

DANIEL BERSHADER

A,3.1. Introduction. The importance of interferometry for the study of high speed aerodynamics is due to the fact that interferometers allow quantitative measurements of density and subsequent calculation of the pressure, temperature, and velocity in a flowing gas without introducing any disturbance into the phenomena to be investigated. In order for the interferometric method to apply, the velocity of the gas stream has to be of the order of, or larger than, the sound velocity. (See Table A,3.1.)

Table A,3.1. M = Mach number; ρ = density.

M	0.2	0.5	0.7	1.0
$\Delta\rho/\rho$	0.02	0.13	0.26	0.58

Then compressibility effects become noticeable and local changes in density and in refractive index occur. Such changes can be measured to a high degree of accuracy by interferometry. A suitable arrangement is the division of amplitude of the light from a monochromatic source by a glass plate, the so-called "beam splitter," into two coherent beams which when reunited may give interference fringes. Fringe maxima occur if the difference in optical path length between the two beams—that is, the product of refractive index n and geometrical path length l—is an even multiple of a half wavelength. Assuming, for simplicity, that the index is constant over each path, there results for the maxima

$$n_1 \cdot l_1 - n_2 \cdot l_2 = 2N\left(\frac{\lambda}{2}\right) \qquad N = 0, 1, 2 \ldots$$

Minima occur if this difference is an odd multiple, $(2N + 1)\lambda/2$. (See for example [*1*] or [*2*].)

Changes of the density ρ of the gas are proportional to changes of its refractive index n. With one beam undisturbed, a change in optical path

VOLUME IX

HIGH SPEED AERODYNAMICS

II AND JET PROPULSION

PHYSICAL MEASUREMENTS IN GAS DYNAMICS AND COMBUSTION

EDITORS

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FOREWORD

On behalf of the Editorial Board, I would like to make an acknowledgement to those branches of our military establishment whose interest and whose financial support were instrumental in the initiation of this publication program. It is noteworthy that this assistance has included all three branches of our Services. The Department of the Air Force through the Air Research and Development Command, the Department of the Army through the Office of the Chief of Ordnance, and the Department of the Navy through the Bureau of Aeronautics, Bureau of Ships, Bureau of Ordnance, and the Office of Naval Research made significant contributions. In particular, the Power Branch of the Office of Naval Research has carried the burden of responsibilities of the contractual administration and processing of all manuscripts from a security standpoint. The administration, operation, and editorial functions of the program have been centered at Princeton University. In addition, the University has contributed financially to the support of the undertaking. It is appropriate that special appreciation be expressed to Princeton University for its important over-all role in this effort.

The Editorial Board is confident that the present series which this support has made possible will have far-reaching beneficial effects on the further development of the aeronautical sciences.

Theodore von Kármán

Press and of the staff of this office has been noteworthy. In particular, Mr. H. S. Bailey, Jr., the Director of the Press, and Mr. R. S. Snedeker, who has supervised the project at the Press and drawn all the figures, have been of great help. Special mention is also due Mrs. H. E. H. Lewis of this office who has handled the bulk of the detailed editorial work for the program from its inception.

Joseph V. Charyk
General Editor

PREFACE TO VOLUME IX

This volume is concerned with physical measurements in gas dynamics and with the corresponding measurements in combustion processes. It records the varying techniques which can be employed to measure density, pressure, velocity, and temperature in gaseous systems. It deals with the measurements of shock waves, turbulence, condensation studies, and analogue methods. The second half of the volume is concerned with techniques and the measurement of properties in materials undergoing combustion processes.

The first 340 pages of the present volume represent the original proposal for a single volume. To secure a greater uniformity in the size of each volume in the series the second part was added to the first. Professor R. Ladenburg, with a rare editorial initiative and skill, assembled his contributors' material more rapidly than any other editor. Unhappily, he did not live to see the fruits of his effort through the processes of printing and publication. That duty has been most efficiently discharged by his former pupil and colleague Professor Daniel Bershader. Together they have provided an authoritative document in the field of measurement in gas dynamics. The list of their authors and the articles are at once a guarantee of the authority of the work and a tribute of devotion to their late editor. The volume becomes in this way a memorial to Professor Ladenburg's unique abilities in the area in which he so conspicuously excelled.

The second part of the volume will, it is hoped, not be found unworthy to be included with the material assembled by Professor Ladenburg. It has been the writer's responsibility mainly to secure this in respect to Part 2, and to provide a summary of the techniques and measuring tools that can be employed in flames and in combustion processes generally.

The results achieved would not have been possible without the loyal effort and cooperation of some twenty-two authors, the General Editor and his staff, and the Princeton University Press. To them I extend sincere appreciation and thanks.

Hugh Taylor
Volume Editor

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EDITOR: R. LADENBURG

A. DENSITY MEASUREMENTS