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A series of experiments has been conducted using schlieren apparatus at low gas pressures. The experience here gained will be applied in the design of optical equipment for a projected Mach 5 wind tunnel. Lenses and mirrors of various focal lengths and aperture ratios were employed for collimating the beam and for collecting the deviated light. Among other experiments, a trial was made with mirrors in which an axial secondary mirror was used similar to the diagonal in the Newtonian telescope. The test phenomena were shock waves produced in a partially evacuated gas chamber either by passage of a condenser discharge across a gap or by air flow from a special nozzle. The beam of the schlieren system crossed this chamber to display the refractive effects upon the screen of a camera.

The first such system used two concave mirrors having diameters of 10 inches and focal lengths of 40 inches, with an aperture ratio therefore of f/4. The illumination was, at choice, either an incandescent light for adjusting the system and observing steady-state conditions, or a Libessart spark gap of APL style for observing transient phenomena. The illuminants were imaged on a spectrometer slit (Gaertner) for defining the width of the source. The schlieren stop was a knife-edge slide with a delicate screw movement for adjusting the cut-off. This system was arranged with the light source axis and camera axis perpendicular to the common axis of the two concave mirrors. Small diagonal or secondary mirrors placed on this main axis at the intersections with the light source and camera axes reflected the light into the first or collimating mirror and into the camera from the second or collecting mirror. The arrangement worked satisfactorily, subject to the qualification that the superimposed silhouette of the two diagonals appears in the middle of the field. Adequate refinement of adjustment could be obtained as is evidenced by Fig. 1, a photograph of a candle flame used as a test object. The convection stream above the candle was observed to contain interference fringes similar to those observed by one of the authors (ELG) and reported in Ref. 1.

The original purpose in using the on-axis secondary mirror was to gain the sensitivity from a 40-inch optical lever available with the long focus mirror and yet avoid the astigmatism associated with the Z-axis arrangement of mirror. For example, with such a Z-arrangement, the distance between the vertical and horizontal image lines using a 12-inch-diameter mirror of f/6 ratio is 1.3 cm (Ref. 2). The use of a point source is precluded because the image of a point becomes a vertical line, and if a horizontal slit image is desired, it is

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[1] E. L. Gayhart and R. Prescott, "Interference Phenomenon in the Schlieren System," Journal of the Optical Society of America, Vol. 39-7, July 1949, pages 546-555.

[2] R. Prescott and E. L. Gayhart, "A Method of Correction of Astigmatism in Schlieren Systems," Journal of the Aeronautical Sciences, Vol. 18-1, January 1951, page 69.

necessary to refocus the knife edge. The minimum Z-angle is approximately 7° for the f/6 system; for an f/4 system, the angle is greater and the astigmatism increased. This aberration and the inconveniences necessary to escape the same are avoided by the on-axis arrangement.

The entire cone or solid angle of light flux coming from the source is contained in the cylindrical collimated beam of the system and is condensed by the collector lens to an image having the same light intensity as that which comes through the slit, but this only if the collimated beam is unobstructed. Any obstruction of the beam results in a reduction in brightness in the slit image in the proportion of the reduction in clear cross-section of the beam. The windows of the evacuated chamber were 4 inches in clear diameter, reducing the effective aperture of the mirrors from f/4 to f/10, with so great a reduction in illumination that the spark gap lighting became marginal.

A change was now made in the optical arrangement by substituting for the 10-inch collimating mirror a mirror 4 inches in diameter but of 16 inches focal length (still f/4). The same cone or solid angle of light from the slit is collimated as with the 10-inch mirror but the light is now concentrated into a 4-inch beam. The illumination was now ample for the spark photography but two other considerations assume importance:

1. The silhouette of the diagonal mirrors now blocks a relatively greater portion of the collimated beam (although except for the reduced radius, no more of the real field is obscured than before).

2. The image of the slit at the knife edge, instead of being in a 1:1 ratio, is magnified in the ratio of 40:16. While this effect increases the range of the schlieren response, the sensitivity is decreased because a greater refractive gradient is required to deviate the slit image through the increased width.

With respect to light intensity, there is a saving feature in the use of the smaller collimating mirror. The light intensity in the beam is increased in the ratio of the inverse squares of the mirror diameters, here 100 to 16. If the slit width is reduced in the ratio of the focal lengths, namely 16 to 40, to maintain the earlier image width, the light passing into the exit cone from the slit is reduced in this ratio, but the net effect on the illumination at the camera is a gain in light intensity in the ratio of 100 to 40 (provided the height of the slit image is allowed to remain at the magnified size).

There are shown in Fig. 2 views of shock waves produced in the evacuated chamber at a delay of 30 microseconds and at chamber pressures of 265 mm, 126 mm, and 42.4 mm, respectively. At the last-named pressure, the sensitivity of the system was marginal and could barely show the shock sphere (which appears as a ring in the photograph). The pressure of 42.4 mm therefore corresponds to the limiting density for which this system, as set up, can demonstrate a shock wave. At pressures less than this level, no shock could be seen. In addition to the lack of sensitivity, a further limitation developed on the spark method of inducing shocks, namely, that instead of producing a spark, the discharge became of the glow type. An interesting phenomenon occurred in this connection.

The spark gap was between a pair of fine brass wires, about 0.005 inch in diameter (B.&S. 36) with a gap length of about 1/16 inch. The arrangement appears in Fig. 2. It appeared that the limited surface available for carrying electricity into the spark discharge column caused the voltage drop to rise to a level such that the discharge occurred in a sheet across the entire electrode system including the parallel leads.

When the spark gap failed as a source of discernible shock waves at low pressure, the arrangements were changed to use the electrodes as supports for exploding wires. The wire was Number 40 B&S (0.0031-inch diameter) nickel. This metal was used because the wire was at hand. The wire in a length of 1 inch fired satisfactorily at pressures down to the levels at which the spark gap became ineffective. The discharge was produced by a 1 microfarad condenser charged to 8000 volts. At the lower pressures, there was a combination of melting the wire without disruptive effect and a glow discharge, and at still lower pressures (below 25 mm) the wire remained intact and practically the entire discharge took place across the supports for the wire. Since the object of the procedure was not to explode wires in a vacuum but to produce a shock wave by the application of only a moderate output of energy, this line of investigation was dropped when it appeared that the disruptive effect dropped off at low pressures.

There was available a dioptric schlieren system having a collimated beam diameter of 3 inches and aperture ratio of f/5. The light source was arranged for use of a steady incandescent lamp with possibility of convenient substitution of a Libessart spark gap. The knife "edge" was a fine wire of 0.006-inch diameter, used to give bilateral symmetry in the schlieren image. A deviation of the beam by a refractive gradient in either direction will give rise to a schlieren display, in which the gradients are displayed equally well, whether their direction is to the right or to the left. When a wire is used as the schlieren stop in the slit image plane, the degree of cut-off is adjusted by the relation of the slit image width to the wire diameter. Obviously, if the image is wider than the wire, the field will be illuminated even in the absence of disturbance. If the image is narrower than the wire, the disturbance must be sufficient to deviate the beam across the overlap before any image-forming light passes to the camera screen. This statement and the following, namely, that if image and stop are equal and exactly centered the field will be dark, must be qualified by the phrase "except for light diffracted around the sides of the wire."

Because of the shorter optical lever, this dioptric system using the collector lens of 15-inch focal length is less sensitive than the mirror system having a 40-inch focal length for the same slit width. Moreover, the reduction in slit width to approximately 0.006 inch to fit the 0.006-inch wire used as a stop caused the illumination to be weak. Improvement to overcome these two disadvantages was accomplished by application of the same principle for building up the illumination as was used with the mirror system, namely, the substitution of a collimator of the same aperture ratio but of smaller diameter. A well-corrected lens of f/4.5 aperture and 114 mm (4.5 inches) focal length (a telephoto objective for a 16 mm film camera) was substituted for the 3-inch-diameter, 15-inch collimating lens previously used. But there now developed the same situation as discussed earlier involving increase in magnification of the slit image, in the ratio of 15 to 4.5. To increase the sensitivity, a narrower wire was substituted 0.003 inch in diameter, and the slit reduced to a width of 50 microns. As to sensitivity, note that a deviation of the image amounting to 0.003 inch is sufficient to change from dark field to full brightness. The equipment was now capable of satisfactory schlieren adjustment for photographic results with a nozzle which will next be described.

At this point there should be reported the results of a slight digression from the schlieren experiments. It was mentioned that the 4-inch mirror was substituted as a collimator and that the change resulted in adequate illumination when using the spark. However, a certain degrading of the schlieren effect was one of the reasons for going over to the dioptric system. When opportunity offered, the 4-inch mirror was set up for a knife-edge test, and focograms were made of this mirror as well as of another of the same size, and of a third mirror, 6 inches in diameter. These three mirrors, which were intended for spectrometers, have zonal imperfections serious enough to make them useless for image-forming purposes. For their intended use as condensers to concentrate light upon a slit, they are suitable, but for schlieren use they are entirely unacceptable. The mirrors appear in Fig. 3. This experience points out the need to check the mirror figure when used in a schlieren system. It also suggests another comment. If the mirror is used to collimate a beam, it should have a parabolic figure; otherwise the field will not be flat or uniform. If a spherical mirror is so used, the field will show a shadow pattern similar to the familiar pattern observed in the Foucault test for parabolic mirrors. On the other hand, if a single mirror is used, with the light making a double pass through the phenomenon, the mirror should be spherical. A parabolic mirror would display the familiar Foucault pattern.

When the spark proved to be an inadequate source of discernible shock waves at low pressures, a nozzle, fed by atmospheric air flowing into the vacuum chamber, was designed to produce supersonic flow. The "wind tunnel" so formed was essentially of the "blowdown" variety, as the operating time is limited by the rapid rise of pressure in the small volume of the vacuum chamber. The table of isentropic parameters for several Mach numbers appears below:

TABLE I

	M=2	M=2.5	M=3	M=3.5
A/A^*	1.688	2.637	4.235	6.790
p/p_t	0.1278	0.0585	0.0272	0.0131
T/T_t	0.556	0.444	0.357	0.2899
T for T_f = 520°R	289°R	232°R	186°R	151°R
p for p_t = 76 cm	9.70	5.84	2.06	0.995

From this table, a Mach number of 3 was selected as being the highest that could be utilized without the complication of heating the inlet. (The highest Mach number was desirable to give the maximum cross-sectional free jet area for a given mass flow.)

A miniature nozzle was made, fitting the above conditions (at M = 3) on the basis that T_t = 520°R and p_t = 76 cm (room conditions of temperature and pressure). The contour of the two-dimensional nozzle was developed on only one side of its plane of symmetry. This scheme was adopted in order to halve the mass flow and so stretch out the available blowdown time. The nozzle, mounted in the side of the vacuum chamber, extended into the path of the schlieren beam to place the exit on the optical axis. The thickness of the jet in the schlieren path, 0.053 inch, was made small in order that the mass flow, with a height of jet of 0.25 inch, be kept down (consistent with the vacuum chamber size). The profile of the nozzle, cut into a septum separating the two side cheeks, was developed by the method of characteristics. A table of ordinates for stations at intervals of 0.05 inch from the throat follows:

Station	Ordinate	Station	Ordinate
0	0.058	18	0.207
2	0.065	20	0.218
4	0.081	22	0.227
6	0.099	24	0.233
8	0.119	26	0.239
10	0.139	28	0.244
12	0.159	30	0.246
14	0.177	32	0.250
16	0.194		

It was shown that the dioptric schlieren system used here can display shocks produced by the M = 3 nozzle. This was demonstrated by photographing shocks at a density corresponding to a pressure of 20 millimeters. The projected M = 5 supersonic tunnel will operate at a density corresponding to 7 millimeters or one-third of the pressure here used. It is expected that a schlieren system of the characteristics used here will be adequate for showing the aerodynamic phenomena of the M = 5 tunnel. Such a conclusion is based upon the consideration that the jet from the M = 3 nozzle had a thickness of only 0.053 inch whereas the thickness of the jet or phenomenon in the M = 5 tunnel will be many times as great. On the other hand, the relative density ratio for the M = 5 tunnel will be only 1 to 3.

Operation of this nozzle was accomplished by closing the outer end with a stopper and pumping down the pressure in the vacuum chamber. Upon removing the stopper, the nozzle discharged into the chamber. To demonstrate the flow, a blunt body, the head of a household pin, was mounted in front of the nozzle. This operation, in a darkened room, was carried out with camera shutter open. Immediately upon removing the plug, the illuminating spark flashed in the schlieren system to record the blunt body shock. Examples are shown in Fig. 4.

One of the examples shown in Fig. 4 was made under the conditions of p_t = 76 cm and p = 2.0 cm. The resulting detached shock appears in the photograph. However, for the case when p_t = 38 cm and p = 1.0 cm, the schlieren system could not show the shock at a density so much lower.

RECOMMENDATIONS

Considering that the M = 5 tunnel in its prototype form has two windows 7 inches in diameter, separated by a space of 1 inch, it is recommended that the collimating mirror be 8 inches in diameter and have an aperture ratio of f/4. The geometrical considerations of the occulting of the field and resulting effect upon the equivalent aperture ratio for the case of a 7-inch mirror and of an 8-inch mirror are shown in the accompanying diagram, together with suggested arrangements (Figs. 5 and 6). From the estimate in Fig. 5 it appears that the effective aperture of the f/4 8-inch-diameter mirror will be f/5. It is expected that this aperture, which is approximately that of the 3-inch dioptric system used in the preliminary experiments, will be found adequate.

The scheme shown in Fig. 6 represents the input or collimating half of the optical system. The output or camera end will be arranged similarly. In this arrangement, the use of secondary mirrors makes it possible to place the light source and camera axes parallel to the wind tunnel and reduce the over-all lateral dimensions of the system. The secondary mirror for the knife edge is placed below the beam to give Z-symmetry. Because of the 90° rotation of the astigmatism pattern, the Z-arrangement in the vertical plane now necessitates a horizontal slit and knife edge. Note that the proposed rolling or sliding support allows the mirrors to serve either window equally well. It is expected that if the support is sufficiently rugged, the system can be moved from one window to the other with but slight effect upon adjustment.

APPENDIX

An Auto-Collimating Schlieren System

Subsequent to the preparation of the foregoing report, the attention of the authors has been brought to a variation of an auto-collimating optical system in which the advantages for use in the M-5 wind tunnel are so marked as to justify the addition of its description. This system is an application of the method of testing concave mirrors at the principal focus by the use of a flat. Conversely, the method is also used to test a flat, provided the concave mirror is good.

To describe the system briefly: assume an optical axis upon which there are placed a concave mirror (paraboloid), a plane mirror, and a 90° prism, front-surface-silvered on the two side faces, mounted with the hypotenuse toward the plane mirror, and parallel to the same. This prism, or its pair of reflecting surfaces at a 45° angle to the axis, is placed near the focus of the paraboloid. If we select a parabolic mirror of 8-inch diameter, the distance would be 4 inches, bringing the focal point to the edge of the collimated beam of the concave mirror. A light source at this point will cause a parallel beam of light to be projected upon the plane mirror. The parallel rays, which are returned to the paraboloid, will converge again, falling upon the reflecting prism. This time, because of a slight angularity of adjustment, the rays converge upon the other face of the prism and are reflected to the other side of the beam. They come to a focus at the edge of the beam, at which point the schlieren stop is placed, with the camera on beyond on the same cross-axis.

There are several features of this arrangement worthy of note. The region of observation is in the parallel beam between the reflecting prism and the plane mirror. The phenomenon is therefore traversed twice with a doubling of the sensitivity. Differing, however, from other single-mirror systems using a double pass, this arrangement has no parallax, because the entering and emerging beams are (substantially) perpendicular to the plane mirror. The phenomenon and its reflection are superimposed. There is then no doubling of the lines in the image. In contrast to the single-mirror system, where the light source is at the center of curvature with consequent halved aperture ratio, the light source here is at the focus, and the mirror works at its full aperture.

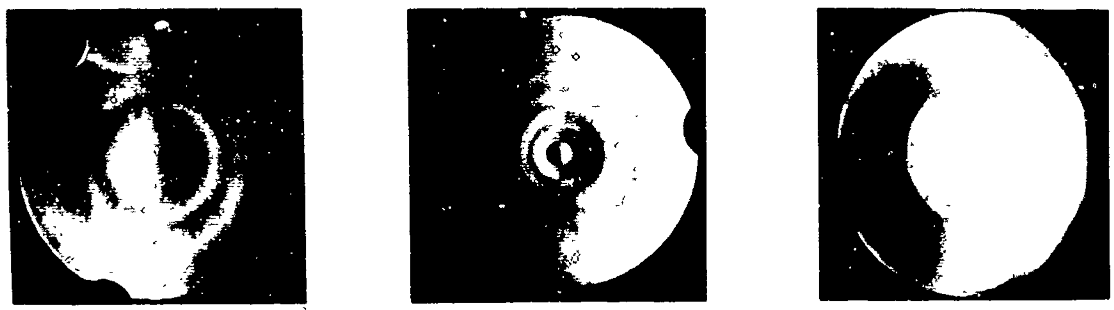
A mechanical feature of the auto-collimation arrangement which is of advantage is that the light source, camera, and concave mirror are all on the same side of the wind tunnel, where their location may avoid the electrical leads and pressure taps necessary for the tunnel instrumentation. Nothing but a plane mirror is required on the opposite side.

Figure 1

Figure 2(a)

Figure 2(b)

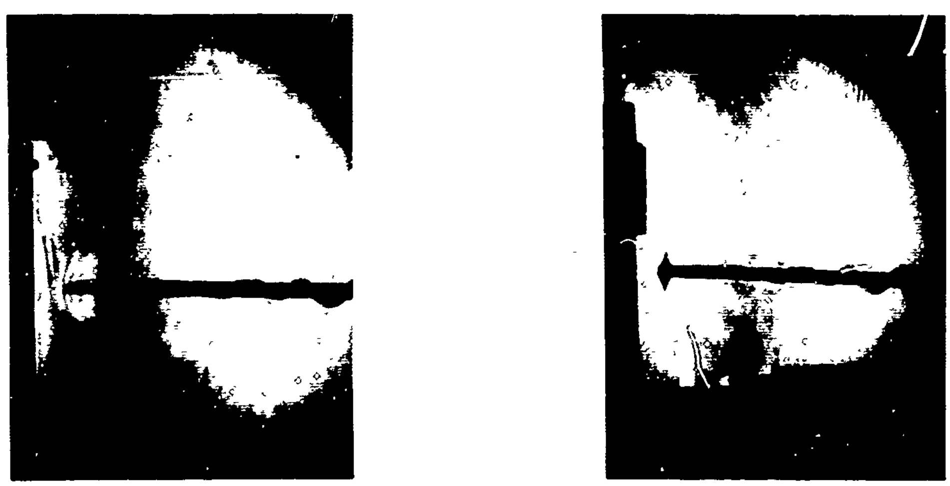
Figure 2(c)



(a) (b) (c)

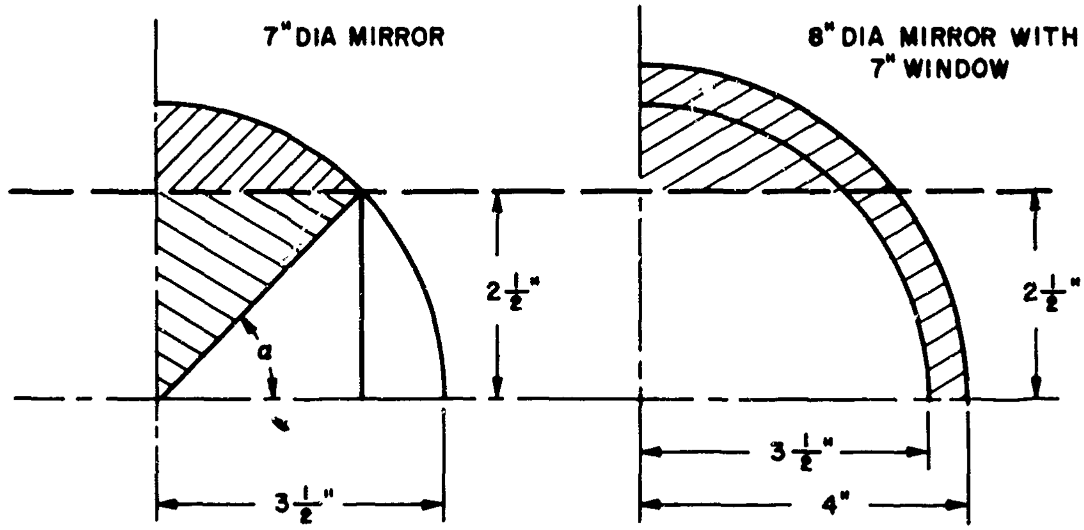
6 inch mirror
(reduced scale)

Figure 3



(a) (b)

Figure 4

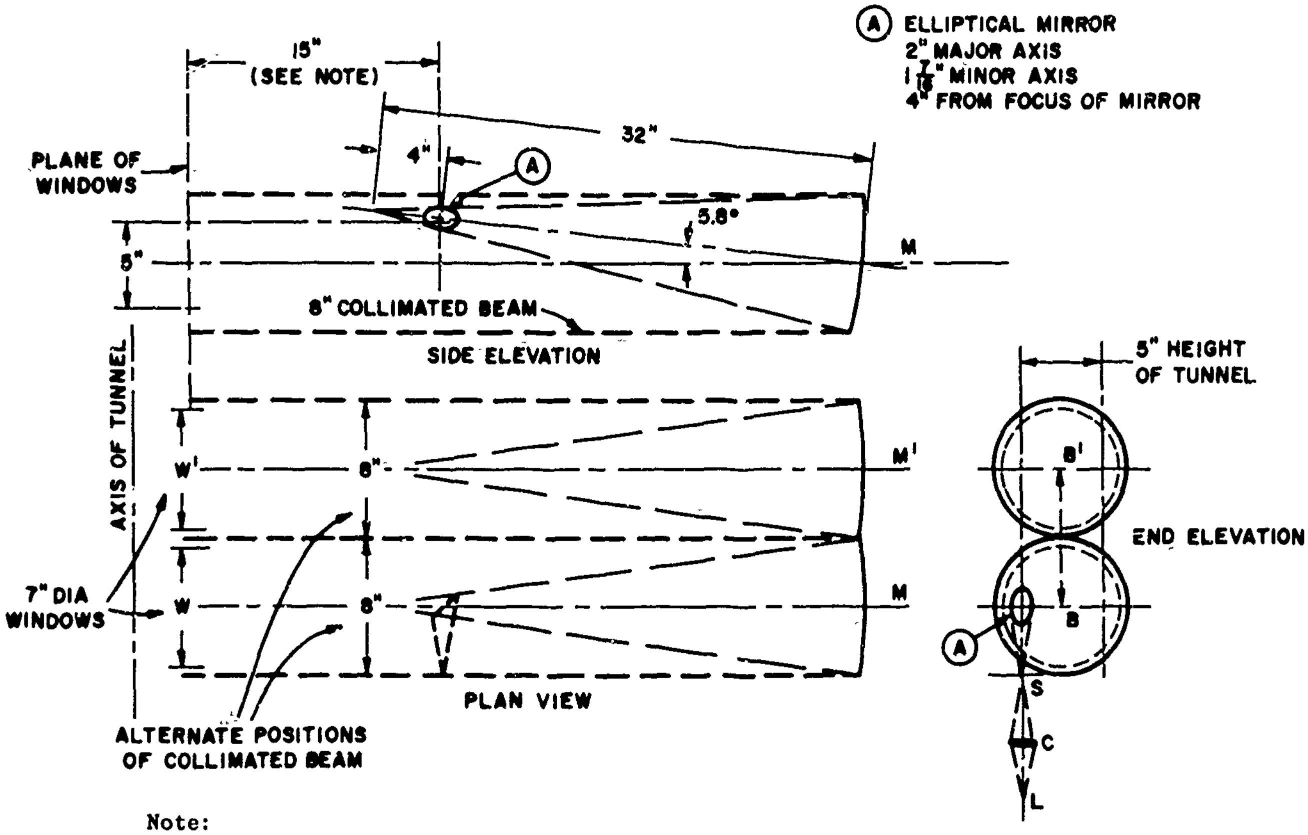


$\alpha = \sin^{-1} \frac{2\ 1/2}{3\ 1/2} = 45°.6$

Cos α	.700
3 1/2 x cos α	2.45
$\frac{2.45 \times 2.50}{2}$ (shaded triangle)	3.08
angle of sector 90° - 45°.6	44°.4
$\frac{44.4}{90}$ (fraction of quadrant)	0.493
$\frac{\pi\ \overline{3.5}^2}{4}$ (area of quadrant)	9.62
x 0.493 area of sector	4.74
area of segment	$\frac{3.08}{1.66}$
$\frac{9.62 - 1.66}{9.62}$ unobstructed fraction =	0.827
$\sqrt{\frac{1.00}{.827}}$ = equivalent dia. ratio	1.10
xf/4 equivalent f/number	f/4.4

7" circle	
quadrant	9.62
segment	1.66
Unobstructed area	7.96
8" circle	
quadrant	12.57
$\sqrt{\frac{12.57}{7.96}}$ = equivalent dia. ratio	1.25
xf/4 = equivalent f/number	f/5.00

Figure 5



Note:
The main mirror, M, and secondary mirror A are mounted on a rigid frame to hold a constant relative position. The frame rolls on tracks to move from position B to B' and thus project the collimated beam through either window W or W'. The light source L, condenser C, and slits are supported from the same frame. The 15" dimension represents a desirable separation of tunnel window and diagonal mirror.

The collecting mirror, secondary mirror, knife edge, and camera are in a similar group opposite, with secondary mirror below axis. Slit and knife edge are horizontal.

Figure 6

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