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Illumination of 80 Inch Bubble Chamber *

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It is possible to design a cylindrical condensing system whose geometry allows light to be collected along the length of narrow tubular sources and to pass through a restricted port area. The quantity of light collected is many times that possible to obtain with axially symmetric lenses. This system has been applied to the illumination of the Brookhaven 80 inch bubble chamber. The optical arrangement is described. Other unique features include the use of plano reflectors to extend optically the flash tube and condenser lengths and the provision of a spot plate to eliminate surface reflections from the chamber window.

*Work performed under the auspices of the United States Atomic Energy Commission.

Before discussing the problems associated with the illumination of the chamber, a short description of the entire system is indicated.

The phenomena to be photographed are viewed through the chamber window whose free aperture dimensions are 193 cm wide by 63.5 cm high. The thickness of the window is 16.5 cm and the overall depth of the chamber, including window is 91.5 cm. The chamber tapers back, as shown, so that at the rear the dimensions are 233 x 84 cm. The arrangement is shown in Fig. 1.

Particles from the Brookhaven 33 Bev Alternating Gradient Synchrotron (A.G.S.)[1,2,3] are introduced into the chamber from the side as shown. A momentary reduction in pressure above the hydrogen is created producing bubbles along the particle trajectories. After a short interval during which the bubbles grow to a size approximately equal to the diffraction limit of the photographic lenses recording the event, the chamber is flash illuminated and the pictures recorded on film.

The type of illumination specified is of the retrodirective dark field type. The illumination diverges from a port of limited area some 182 cm from the chamber window and proceeds through it to the rear of the chamber. If a spherical mirror lined the rear of the chamber of radius equal to the apparent distance between it and the port, the rays would be sent back upon themselves and reenter the port from which they emerged. Four cameras simultaneously photograph the chamber at each flash. These are situated in a square array 63.5 cm on a side symmetrically disposed about the port and facing the chamber. If the rays on their return paths are undeviated they cannot enter the cameras. However, if perchance they strike something such as a bubble they can be diverted into the cameras and be recorded. Thus the tracks show up as bright streaks on a black background. It is obvious that the amount of light used in recording the tracks is extremely small as compared with that emerging from the port and great quantities of light must emerge from the port in order to obtain sufficient film exposure.

The word picture drawn above is somewhat simplified. It is clear that scattering from the bubbles could take place on the forward path of the rays, strike the spherical mirror and be reflected back into the cameras. These would show up as duplicate tracks in the image of the chamber in the spherical mirror, leading to confusion in the interpretation of the event. It is thus necessary to suppress the photographic recording of scattering on the forward path of the rays. Therefore the mirror is replaced in some other form of retrodirective device, one which retains the property of returning light in the same direction from which it came, but does not have image forming properties.

Several such have been proposed and that chosen is known by the term "coat hanger assembly"[4]. Nothing more will be said here concerning the nature of this device, except that it is quite effective in suppressing the unwanted track images.

All of the factors associated with the geometrical arrangement above, together with data available from Xenon flash tube characteristics and experience derived from the 20 inch chamber at Brookhaven and the 72 inch chamber at Berkeley were analyzed[5,6] in detail, including estimates for optical transmission and film sensitivity. The final estimate for the requirements for desired levels of illumination was given by F. Anderson[6] and his calculations set the desired illumination port area at 145 square centimeters of effective Xenon source image. Furthermore, upon laying out the geometrical arrangement with care it was determined that the beam spread required from the port to the chamber amounted to a numerical aperture of .167 in the vertical direction and to .42 in the horizontal ($19^\circ\ 15' \times 50^\circ$).

Thus, to recapitulate the requirements, it was necessary to provide at the port an illuminating area of 145 cm^2 and brightness essentially equal to the source and to provide the beam with angular spreads of N.A. = .167 vertically and N.A. = .42 horizontally. All this operating from a source whose diameter is a mere 4mm!

Let us assume for the moment that we set as the upper limit of practicability the provision of a condenser system which is able to collect a numerical aperture of .75 from the source, corresponding to a semi-angle of about 48.6°. To increase the numerical aperture above this figure can obviously be done only at great effort and for relatively small gain. If it works at 4.5x magnification, it will deliver a numerical aperture of .167, just sufficient to cover the small dimension of the chamber, but far from sufficient to cover the large dimension. For the latter purpose three such systems would be needed, each covering approximately one third of the chamber horizontally.

It is indeed just this threefold system that is in use at Berkeley to illuminate the 72 inch chamber. According to F. Anderson[6], the effective illuminating port area in the Berkeley system is 18.5 cm^2.

It is a reasonable assumption that the threefold Berkeley arrangement squeezes the utmost that can be expected out of conventional optical condensing systems and that to obtain the many-fold larger desired port area and corresponding illumination increase for the Brookhaven chamber which at the same time has sufficient beam spread requires an entirely new approach.

Conventional condensing systems use axially symmetric optical components to form a magnified image of the source somewhere else in the optical train which is coherent. This, however, is not a necessary requirement. Suppose for the moment that we have succeeded in our task of providing 145 cm^2 of port area acting as an effective Xenon source to illuminate the chamber. Each and every point of this area must send rays of illumination to all points in the chamber.

The requirement for the condenser system is that each and every one of these rays must have the original luminous source as origin, and if this condition is fulfilled, it does not matter in the least whether or not a coherent image of the source is produced.

The arguments given above indicate implicitly that when only a limited length of tube can be used, the luminous flux is insufficient. But Xenon flash tubes, while limited in diameter to 4mm are not so limited as to length, and if the condensing system were designed so as to take full advantage of the length, much more luminous flux could be made available.

The procedure adopted is given schematically in Fig. 2. In (a) we see a cross section through the vertical. The source S delivers a beam of high numerical aperture to the cylindrical lens L. The image of S is formed at the port P and is shown magnified into S', from which the beam spreads out vertically to illuminate the chamber C. The magnification chosen is such as to deliver the finally required vertical beam spread. However, in (b) lens L has no power, and an image of S is not formed at P. In this schematic representation, the source length required to illuminate the full chamber width is GK, and rays delivered to point B of the chamber may arise anywhere between H and K. A similar length of tube will serve to illuminate any other point of the chamber.

Let us examine for the moment the effect of adding spherical power to the system at the port P. Referring first to the vertical (a), it is to be noted that no effect will occur in the vertical meridian. However, in the horizontal (b), the effect of spherical power at P will be to alter the interval KH about the point M. If the power be gradually increased from zero, the points K and H will approach M, becoming coincident when the points M and B are conjugate. For this condition the required length of source will be a minimum. For still greater power, point H will move to the outside of M, and the required length will again increase.

It is to be noted that the system in no instance forms a coherent image of the source. Even in the case where M and B are conjugate, any point corresponding to B receives rays from all points of the source at M transverse to the source length, so that irregularities in the source in this direction are smoothed out. However, if the source should have irregularities along its length, the conjugate position will show bars of illumination variation in the chamber. In the present application, as will be seen later, spherical power has been added to the system at P substantially greater than that required for the conjugate condition, and is used for other purposes. For this reason, local irregularities in the source do not show up in the chamber.

The fact that we have chosen to use a cylindrical system affords favorable geometrical circumstances for source increase through duplication. In spherical condensing systems, there often is provided behind the source a spherical mirror which either images the source back upon itself or alongside itself so that the effective area is increased. Theoretically this increase can be as high as 2x, but in practice is usually considerably below this. There is no prospect of increasing source area through the provision of additional sources because of the mechanical interference of such sources with each other or with the spherical mirror and condensing system.

The cylindrical system affords freedom from this limitation. The modified FX-1 flash tube[7] to be used has an internal diameter of 4mm and the brightness is fairly uniform across this cross section[8]. The walls are 1mm in thickness. Two such tubes are used in conjunction with a cylindrical reflector in an arrangement illustrated in Fig.3.

The two Xenon flash tubes are shown at A and B with their outer walls separated by 4mm. A cylindrical reflector at M is so situated that tube A has its center 2.5mm below the mirror axis and tube B 7.5mm above the axis. Under these circumstances the effective inner 4mm of tube A is imaged by M at A' which is mutually tangent to both tubes as shown, and the effective inner 4mm of tube B is imaged at B' tangent to tube A. The result is a source area which is physically 19mm high, of which 16mm is effective. The radius of M is relatively unimportant, except that it be large compared to 19mm to minimize aberrations. The central axis of M should of course be in the plane of the tubes. The dimension of M in the plane of the figure should be somewhat larger than that needed to cover the source numerical aperture required (.75) and it should be roughly as long as the tubes. A photograph of the actual apparatus is shown in Fig.4. Means are provided for quick insertion of a new source system including tubes and mirror in case of tube failure. Fig. 5 is an exposure of a flash taken directly from the source system (attenuation needed required the use of two sets of crossed polarizing plates). In this picture the four component sources (two real and two imaged as explained) are readily apparent.

We turn now to a consideration of the design of the cylindrical condenser system itself. As stated before, we will collect a wedge of rays whose numerical aperture is .75 and transfer this into another at the port of N.A. ≐ .167, with therefore a magnification of 4.5x. It is implicit in our discussion that since we have expressed our beam spreads in terms of numerical aperture that we intend, in addition to correction for spherical aberration, to effect a high degree of agreement with the sine condition in our design. It is well known that for infinite magnification, fulfillment of the sine condition is needed to insure even illumination in the exit bundle. In a recent paper[9], Wallin ascribes to some unpublished notes of R.K. Luneberg the criterion for uniform illumination of an axially symmetric system, the equation

$$\sin u = m \tan u'$$

where u is the entrance angle (at the source), u' the exit angle (at the port) and m is the magnification. Since this presupposes a planar source (which ours is not), a plane surface to be illuminated (which ours is not, since the retrodirectors are curved) and a spherical system (which ours is decidedly not), this expression will not strictly hold. It is to be noted that in any case the Luneberg criterion is equal to the sine condition for large m. The development of an exact criterion for even illumination of our system poses a difficult problem in analysis, particularly in view of the curved image line resulting from a point object, to be discussed later. The development of such a theory would be interesting and perhaps should be done, but it is quite certain that whatever criterion results, it cannot be much different from that given by satisfaction of the sine condition. Thus the optical design problems associated with our system take on some of the same characteristics as those of designing a microscope objective.

Fig. 6 and Table 1 give the resultant design. The first three lenses nearest the source are aplanatic, that is, the entering surfaces are normal to the axial bundle while the exit surface is aplanatic. The lens nearest the source is made of fused quartz because of the heat. Thus each of these lenses reduces the numerical aperture by a factor equal to its index of refraction, until it is small enough to be turned into a convergent bundle with the required .167 N.A. The radius of the innermost surface is 39mm, while the next surface actually extends more than 180°. While no attempt is made to correct for chromatic aberration, the scale is small enough so that it is unimportant for our purposes.

At this point it seems appropriate to consider a serious aberration of this system which has no counterpart in spherical or axially symmetric systems. In a vertical meridian a point object at the source is imaged at the port. Ordinary Gaussian calculations are sufficient to determine the position and the magnification of a small object at the source. However, in actuality, a point source is not imaged as a point but as a line. If this line were straight and normal to the axis at the port with constant N.A., no difficutly would result. But this is very far from the case. This line is very strongly curved concavely to the lenses as illustrated in Fig.7, and this curvature is accompanied by a severe reduction in magnification and corresponding increase in numerical aperture at its outer portions which would lead to an intolerable reduction in illumination at the horizontal ends of the chamber if left uncorrected. However, it will be shown that provision of spherical power at the port serves to correct this defect so that the final overall illumination at the chamber is remarkably uniform. The writer has not explicitly met up with this aberration in his experience, nor does he recall it from the literature. It is hoped that some reader will be able to point out such a reference, or, failing this, to suggest an appropriate name for it.

In order to assess the magnitude of this effect, consider a ray originating at the source and lying in the plane containing the cylindrical axes of all of the lenses. This ray, assumed incident at an angle different from zero, can be traced through the cylinders as if they were a series of parallel plates. Consider the Coddington equations, namely --

$$N' \cos^2 I'/t' = N \cos^2 I/t + (N' \cos I' - N \cos I)/r_t$$

and

$$N'/s' = N/s + (N' \cos I' - N \cos I)/r_s$$

In these equations $r_t = \infty$ and r_s is the stated radius of curvature of the surface in Table 1. We are not concerned with the first of these equations in our system but only with the second, since we are interested only in the magnification of a small element of the source normal to the plane containing all of the cylindrical axes. In this calculation s_1 is the oblique distance of the first surface from the source along the ray. The magnification at each surface is given by

$y'/y = Ns'/N's$. The position of the point along the curved image line is determined by the final s', and the magnification by the product of the magnifications at each surface. Experimental verification of these calculations was afforded by setting up a high intensity point source in the proper postion. The curved image line was readily discerned on a screen placed not quite parallel to the cylindrical axes and the locations of each point on the curved line corresponded with the calculations as closely as could be measured. A screen placed normal to the exit beam well beyond the line demonstrated a strong pincushion effect as illustrated in Fig. 8. The smallest vertical section at the center corresponds to the vertical N.A. = .167 as desired, but the much larger sections at the ends reflect the effect of the greater N.A. associated with the outer parts of the curved line, resulting in corresponding reduced illumination. This latter would have amounted to a factor of approximately 2 at the ends of the chamber if left uncorrected.

The nature of the effect and the means for its correction are shown in Fig. 9 which is schematic in nature, showing the Xenon Source, the cylindrical system and the port. The chief ray to the center of the chamber originates at S_1 and passes through S_1' at the port. The chief ray to the end of the chamber originates at S_2. Other rays from S_2 normal to the plane cross the plane of the paper at S_2' because of the curved line aberration described above. A small element of the source at S_1 normal to the paper is imaged at designed magnification at S_1' while a small element at S_2 is imaged at a much lower magnification at S_2'. Now if spherical power is added at the port, no effect is produced on the position of S_1', and S_{1F}, its image in the lens, is shown coincident with it. However, the off axis image S_2' occurs before the port, and the effect of the spherical power at the port is to displace it still further away to S_{2F}. However, at the same time it will be magnified, reducing the numerical aperture and restoring the illumination at the chamber ends. The results are shown in two graphs, Fig.10 and Fig. 11. Fig. 10 shows the positions of the images above referred to, the upper curve referring to the image position S_2' after the cylindrical system, and the lower to that after passing through the spherical power introduced at the port, the latter designated by the term "aspheric lens" for reasons to be apparent later. Fig. 11 gives the same data for the magnification. The results show an actual increase in source magnification with field angle, but since the source image is physically further away from the chamber as given in the preceding graph, the illumination is no greater. But neither is it less, except for a normal $\cos^3 \theta$ fall off.

There is one minor difficulty with this arrangement, and a means for ameliorating it. The vertical port dimension is only moderately larger than the images S_{1F} or S_{2F}. Since there is a substantial displacement between the port and S_{2F}, vignetting of S_{2F} by the port will result in reduced illumination in the corners of the chamber. If we were to reduce the distance between S_{2F} and the port, this vignetting will be lowered. This can be done at the expense of separating S_{1F} from the port by moving the Xenon source closer to the cylindrical system. This situation is illustrated in Fig. 12. This procedure will introduce more magnification of the source for both S_1' and S_2', which are both shown larger than before. However, spherical lens L will tend to operate upon S_1' to pull it back and reduce the magnification, while the magnifying effect on S_2' is smaller than before because it is closer to L. The effect of L in this regard is to act as an optical balance wheel or governor of the system. Of course if this procedure is carried too far, while it would be possible to eliminate vignetting at the chamber ends, one could introduce it at the center. Practically it is advisable to make the position of the source adjustable so as to bring it empirically to the most favorable distance.

We turn now to a discussion of a major disability of all dark-field retrodirective systems and means for its elimination. Referring now to Fig. 13 we see a schematic of the system as we have built it up so far. A tremendous amount of light leaves the port toward the chamber and is returned by the retrodirectors. However, a portion of this light is reflected from each of the two surfaces of the window and these reflections may be seen directly by the cameras. The camera apertures approximate a point (they are only about 6mm in diameter). The net result of this is that each photograph is completely fogged over an area whose linear dimensions in relation to the chamber picture are approximately half those of the port. While this area is small related to the entire picture, it is large enough to be quite objectionable. One solution of this problem is to set the large window at an angle so that the reflected rays are thrown out of the field of view of the cameras. This has obvious geometrical disadvantages. It had been decided at Brookhaven to keep the window perpendicular to the axis, although the angled window arrangement is employed at Berkeley.

Consider the system in reverse. Rays from the camera apertures strike the window and are reflected from either surface back through the port. As we have seen, spherical power exists at this position. Consequently there must exist a plane conjugate to the camera apertures on the illumination side of the port, as shown in Fig. 13. Ideally the four camera apertures would image as four tiny dots in this conjugate plane. If now we set up a plate of glass at this position and opaque the area corresponding to the dots, no light will proceed from the illumination system and be reflected by the window into the cameras.

The system described above is complicated somewhat, so that the dots are more than infinitesimally small. Firstly, two systems are involved, corresponding to each of the two window surfaces so that the opaque areas must be large enough to cover dots in two slightly separated conjugate planes. Secondly the images are far from Gaussian and subject, because of their off axis position, to aberration, particularly astigmatism. Since the port lens turns out to have a high relative aperture, aberration spread is large. Spherical aberration for this reflected system is taken care of by making the port lens strongly aspheric, but astigmatism cannot be controlled because of the pupil of this system is at the lens and the astigmatism is determined, as is well known, by the power of the lens alone. The most favorable position for the spot plate is to place it in the sagittal focus, and the spots themselves are roughly lines pointing generally towards the axis.

It was decided to make the port lens from a single aspheric surface in front, to make its rear surface plano, to join, by cementing, the rear face of this lens to a large glass block, on the rear face of which the spots are located. In this way the number of air glass surfaces is reduced and the contrast in the images of the spots maintained high. Another advantage of this arrangement arises from the fact that the sides of the block can be optically polished, and use made of the internal reflection at these sides for the high angular rays (see Fig. 14) thus reducing substantially the required length of the cylindrical lenses and the Xenon tubes.

Returning now to the spots themselves, certain other properties are required. Since the system is such that a large amount of light flux is redirected back into the port, there is a danger that this light can illuminate the spot area from behind and again be reflected forward whence it will reemerge from the port and be reflected back by the window precisely into the camera apertures which are conjugate to the spots. To eliminate this, the spots are made of wafers of highly absorbing dark glass of index of refraction equal to that of the block, and cemented thereto by cement of the same index so as to eliminate the possibility of Fresnel reflection at the joint. The outside of the wafer is coated with an opaque layer of protected aluminum, preventing direct light from passing through the wafer. The dimensions of the wafer are determined finally by a mockup of the camera-window-port-block system and observing the image of the camera aperture, illuminated from behind, as seen by a microscope at the end of the glass block. Every vestige of light should be eliminated by the wafer. Whether or not the spot system will be completely successful is not known at the time of this writing, but a system mockup is encouraging.

The system has not yet been installed, but careful mockups have been made. Fig. 15 is a photograph of the port area (front of the aspheric lens) when the source was actuated, showing the image of the source as produced by the optical system. Two pairs of crossed polaroids again attenuated the light. It may be compared with Fig. 5. The corresponding four components are easily discernible and the vertical magnification quite apparent.

The system was turned towards a screen upon which was traced the chamber outlines. Fig. 16 shows a flash of the screen. Flash photometric measurements were taken at various positions on the screen and the relative intensities at different points are shown in Fig. 17. The uniformity is quite good for a system of this angular size and seems to reflect little more than the natural $\cos^3 \theta$ fall-off*

The apparent area of the source presented to the chamber at the port is approximately 8 cm vertically x 18 cm horizontally. Preliminary estimates of the actual intensity at the chamber distance indicate it to be as expected from this area, allowing for reasonable transmission and other losses.

Fig. 18 shows a photograph of the cylindrical lens system and Fig. 19 that of the aspheric lens and glass block.

Table 2 is a set of values giving pertinent dimensions and optical data.

Fig. 20 is an overall sketch of the entire system.

It is obvious that a project of this magnitude and importance required the contributions of several individuals and contractors.

*The photometer was turned toward the port in making the measurement, eliminating one cosine of the usual $\cos^4 \theta$. This was thought more realistic for the measurement of spherical bubbles.

For the sake of space many of the detailed points have either not been discussed or only lightly touched upon in this article.

Dr R. Ronald Rau (BNL) is responsible for the overall performance and thus guided the project, making all of the hard decisions required. Dr S.S. Yamamoto (BNL) made important measurements on the lateral and transverse source brilliance, and on tube lifetime. Mr. Irving Winters (BNL) solved many important problems relating to the mechanical assembly. Dr Robert B. Palmer (BNL) worked closely with the writer throughout the project in consideration of basic factors of design and execution. In particular, Dr Palmer is responsible for the concept of the glass block with its attached aspheric, while the writer's chief contribution is the concept and design of the cylindrical system.

As to contractors, Edgerton, Germeshausen & Grier, Inc. supplied the tubes of their FX-1 type but modified into a length over three times the normal 6 inches. Schott and Gen., Mainz supplied the raw glass for the large glass block to a tight bubble specification, required for important reasons not discussed. J.W. Fecker Division of American Optical Co., Pittsburgh, supplied the cylindrical lenses, which, because of their size and general requirements are unique in the optical art. The large glass block and the aspheric lens were fashioned to tight specifications by Photronics Corp., Flushing, N.Y.

The illumination arrangement as described in this article will no doubt be installed and used to illuminate the 80 inch chamber for the investigation of nuclear phenomena between the time of writing (January 1963) and that of publication (October 1963). It is hoped that a further account of its performance will be made available later.

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Figure Captions

List of Tables

TABLE 1

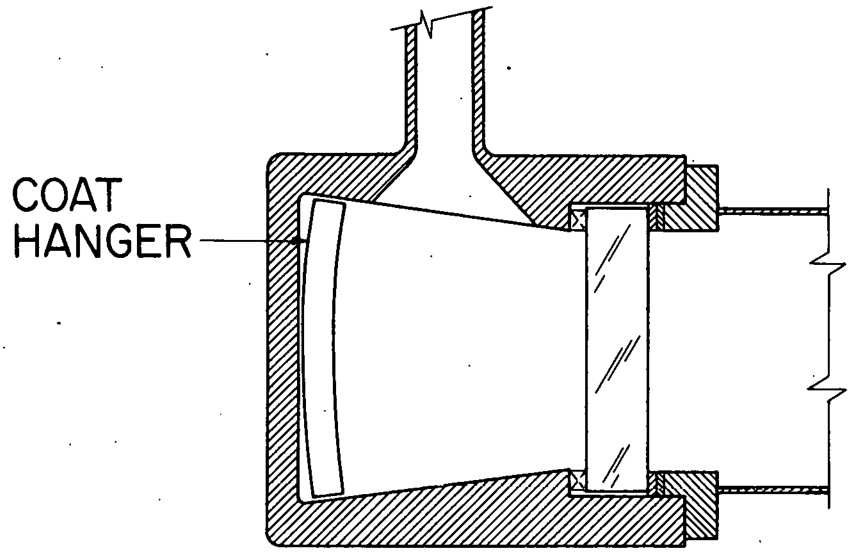
E.F.L.	70.00	Lens Purpose	Condensing
Image Distance	39.00	Lens Type	Cylindrical
N.A.	.750	Object Distance	(-379.5)
Stop Height	140	Object Size	85.6
Magnification	.2193	Instrument	80 inch bubble chamber
Image Size	19	Dimensions in mm	

Radius of Curvature	Separation	Height	N_F	Material
734.7				
	20.0	140	1.57952	LBC2
-258.4				
	3.0			
205.3				
	20.0	140	1.57952	LBC2
∞				
	1.0			
115.14				
	13.0	130	1.57952	LBC2
175.03				
	1.0			
67.467				
	17.0	116	1.57952	LBC2
93.180				
	1.0			
37.423				
	24.0	74.846	1.46318	QUARTZ
39.000				

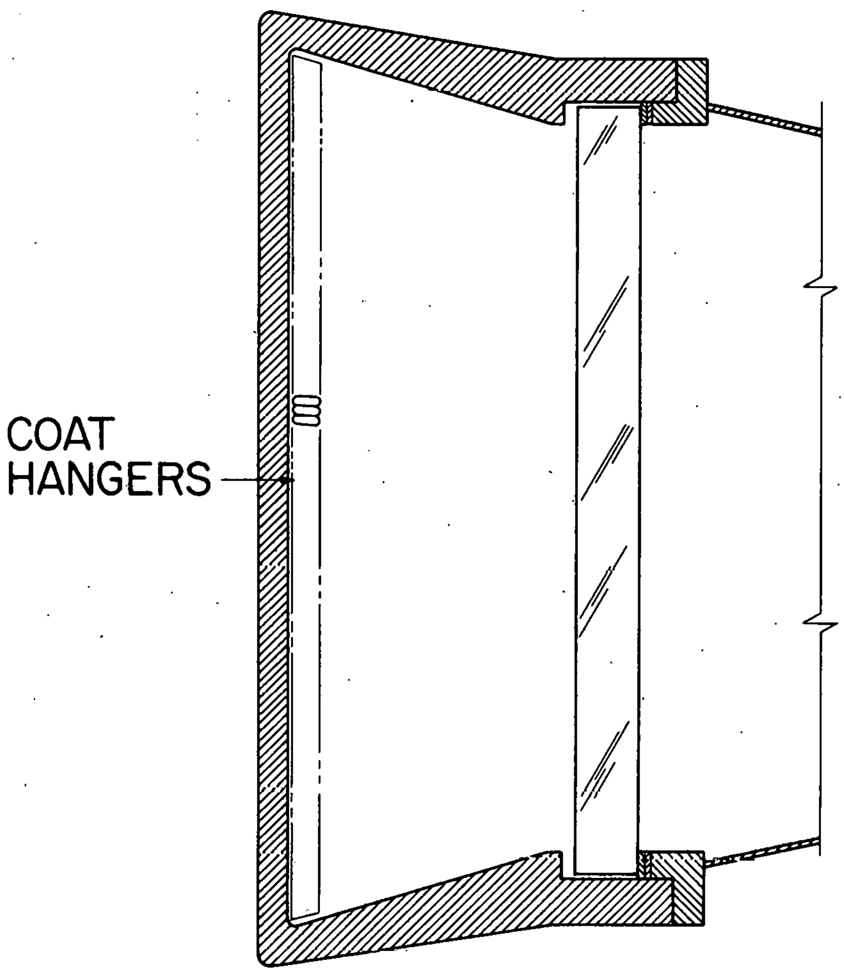
Length of Cylinders 406.4

TABLE 2

Optical Distance - From Field Lens to Inside of Window	190.5 cm
Window Free Aperture, Inside	193 cm x 63.5 cm
Angles from Field Lens	25° x $9^\circ 38'$
Numerical Aperture	.42 x .167
Numerical Aperture at Source	.75
Magnification Condenser System	4.56x
Source Height	1.9 cm
Image of Source Height	8.6 cm
Image of Source Length	18 cm (arbitrary)
Effective Image of Source Area	146 cm^2
Field Lens Free Aperture	19.7 cm x 10.8 cm (corners rounded)
Field Lens to Retrodirector	257 cm (air)
Camera Lens to Field Lens (reflected by surface 1/2 way between 2 window surfaces)	380 cm
Field Lens to Spot Plate	37.5 (air)
Sagittal Field Curvature Displacement (at height 3.12 cm)	.175 cm
Clearance Last Condenser to Spot Plate	.62 cm
Equation of Aspheric Surface (approximate)	
$x = 2.804 \times 10^{-2} y^2 + 1.043 \times 10^{-5} y^4$ (cm)	
Sagitta at Corner of Aspheric (y = 11.2 cm)	3.10 cm
Length of Glass Block (BK7)	56.8 cm
Magnification of Camera Apertures at Spot Plate	.0982 x
63.5 cm Square → 6.23 cm Square on Spot Plate	
Size Retrodirector	234 cm x 83.8 cm

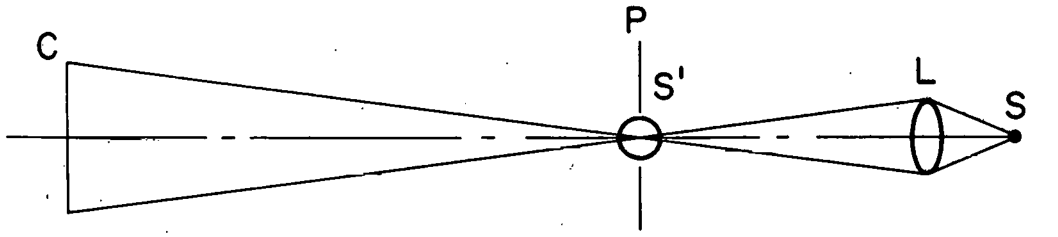


VERTICAL SECTION

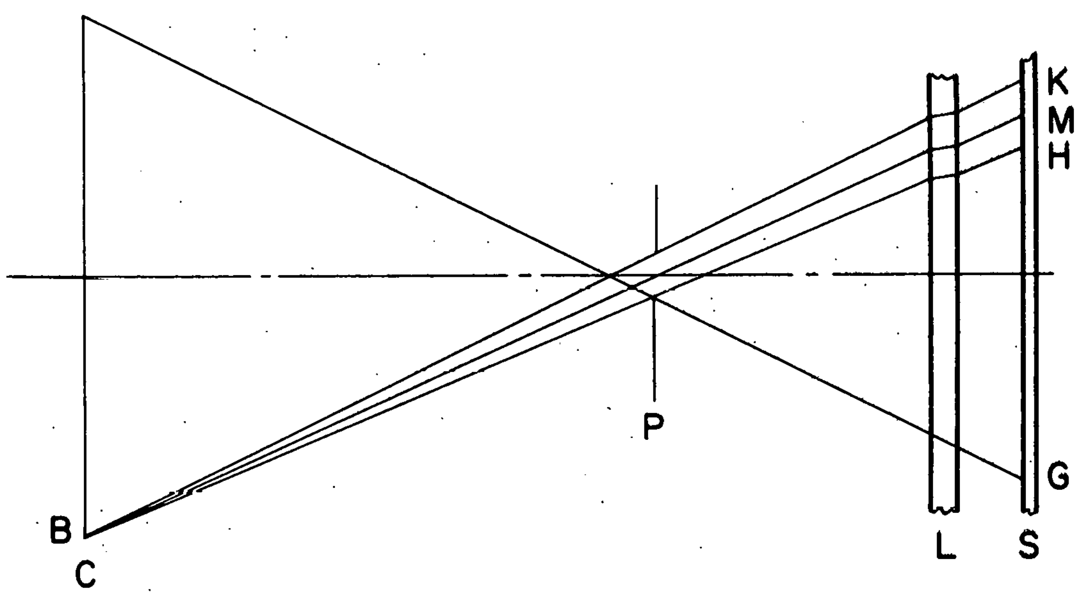


HORIZONTAL SECTION

FIGURE 1

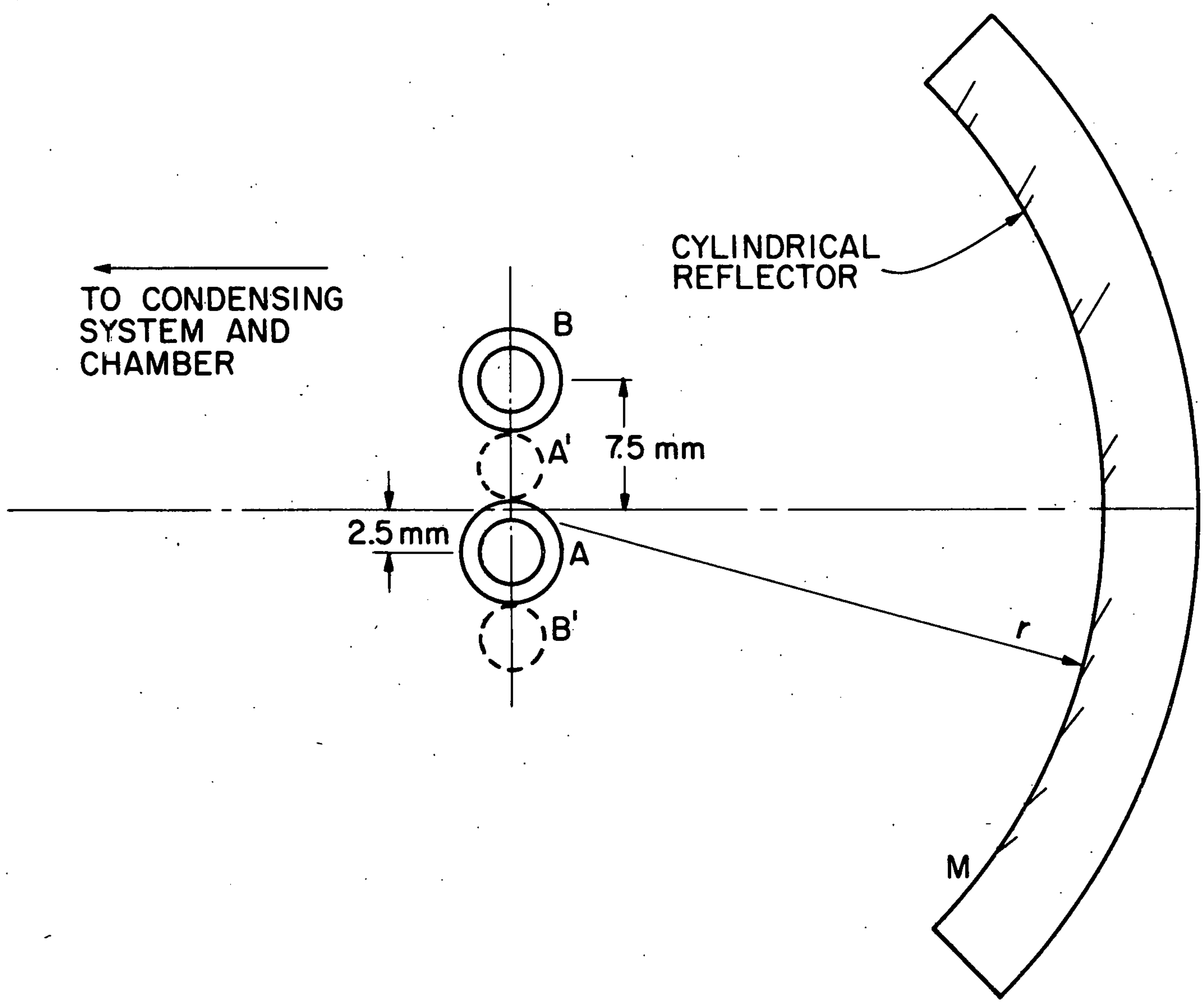


a) VERTICAL SECTION



b) HORIZONTAL SECTION

FIGURE 2



TO CONDENSING
SYSTEM AND
CHAMBER
CYLINDRICAL
REFLECTOR
B
A'
7.5 mm
2.5 mm
A
B'
r
M

FIGURE 3

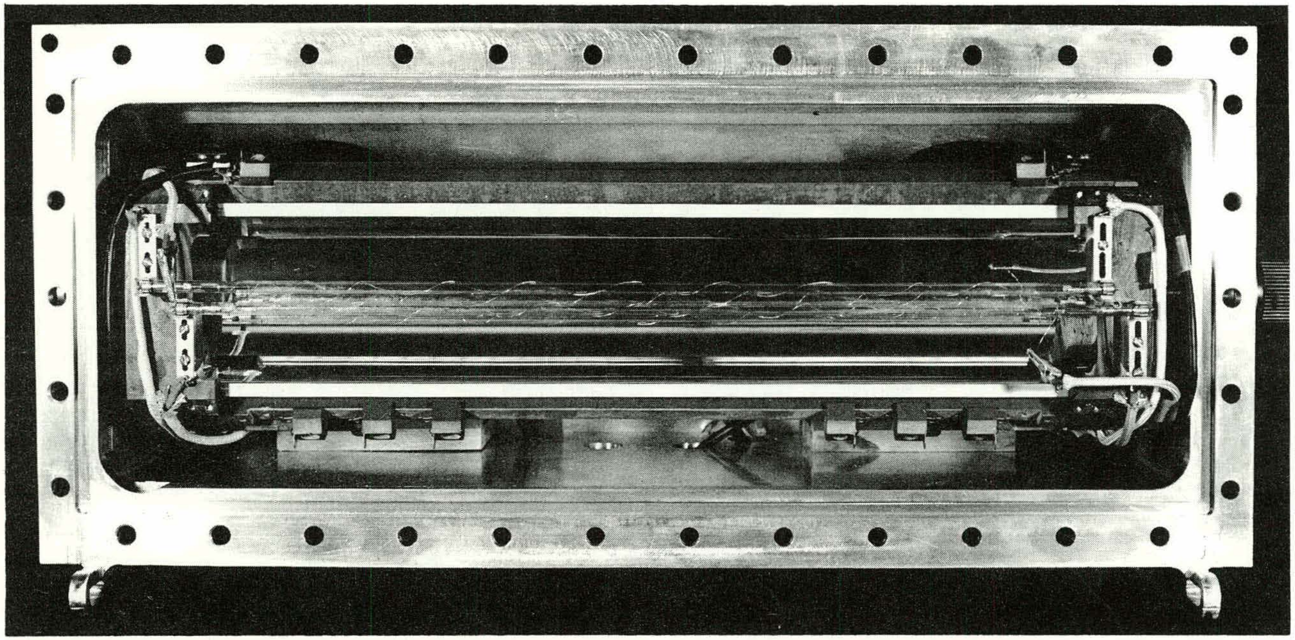


FIGURE 4

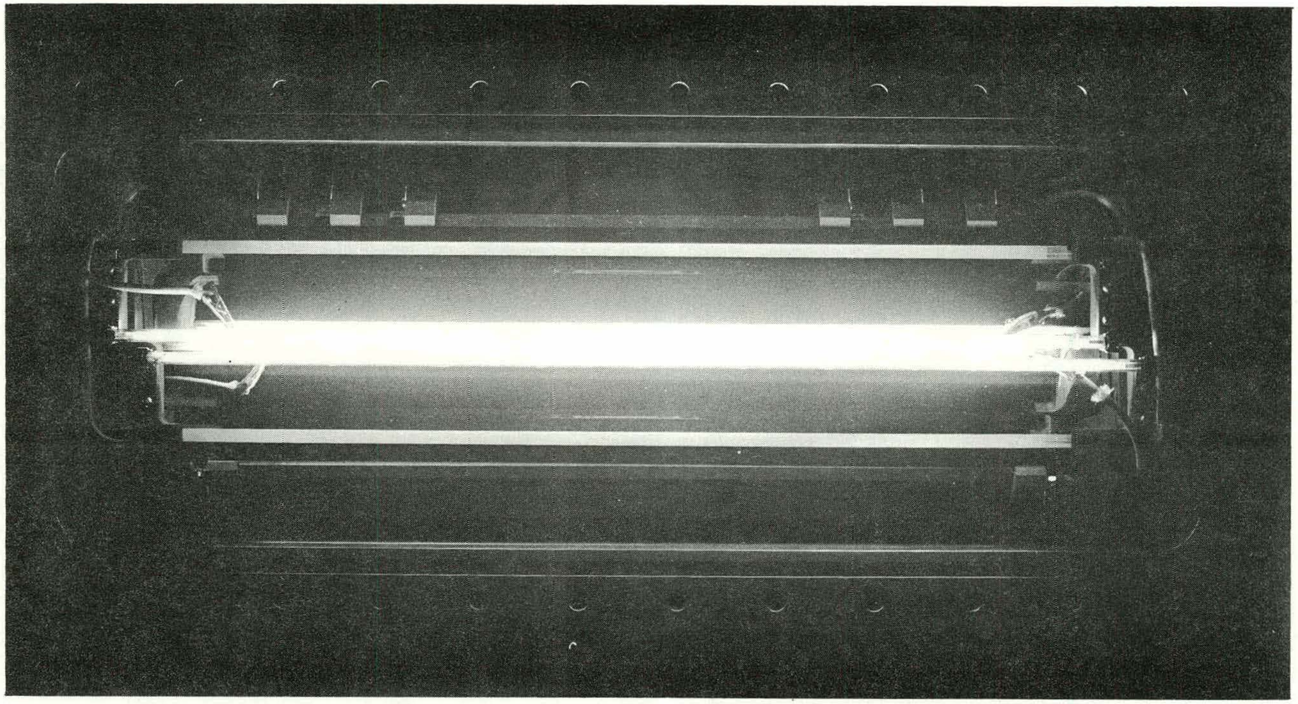


FIGURE 5

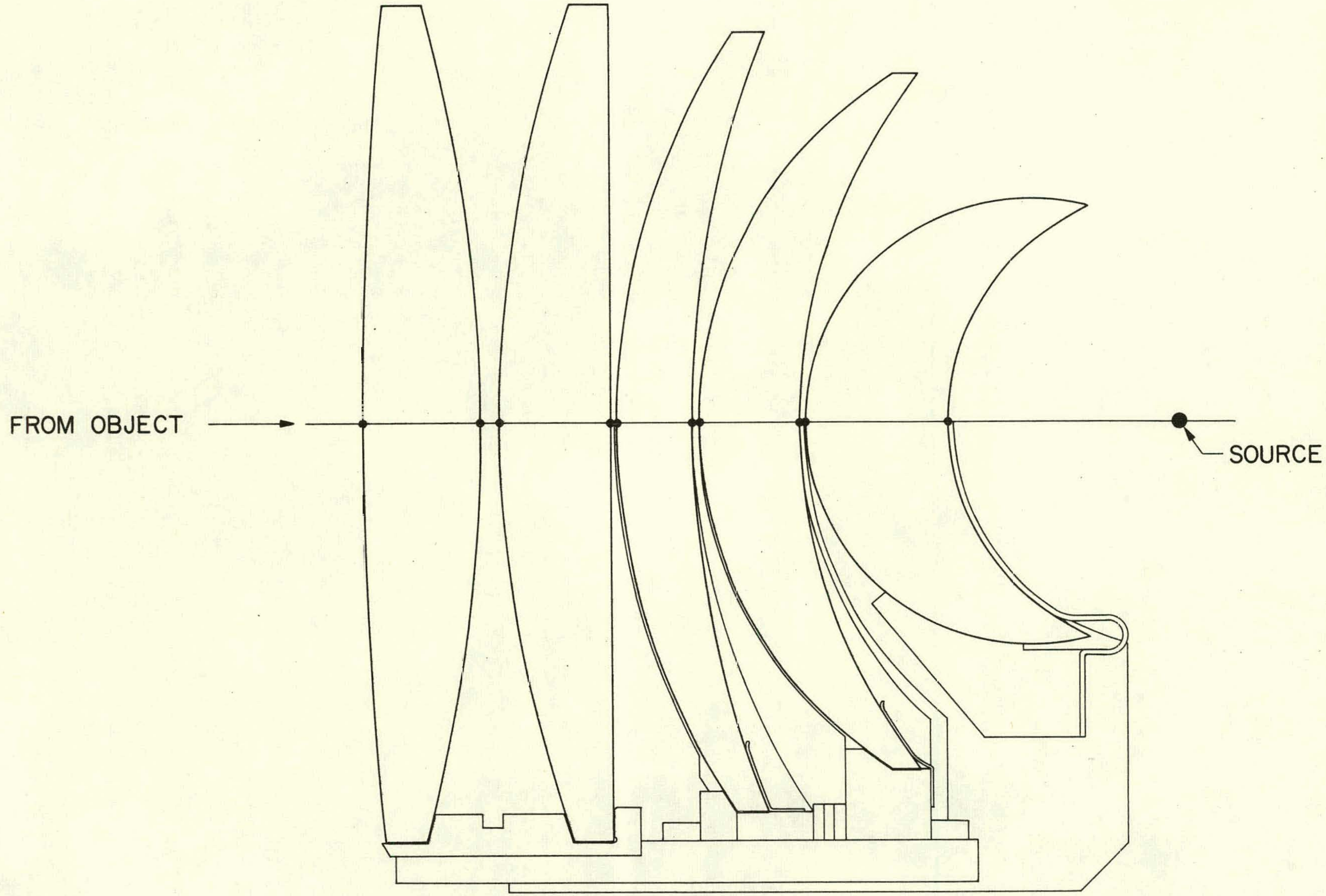


FIGURE 6

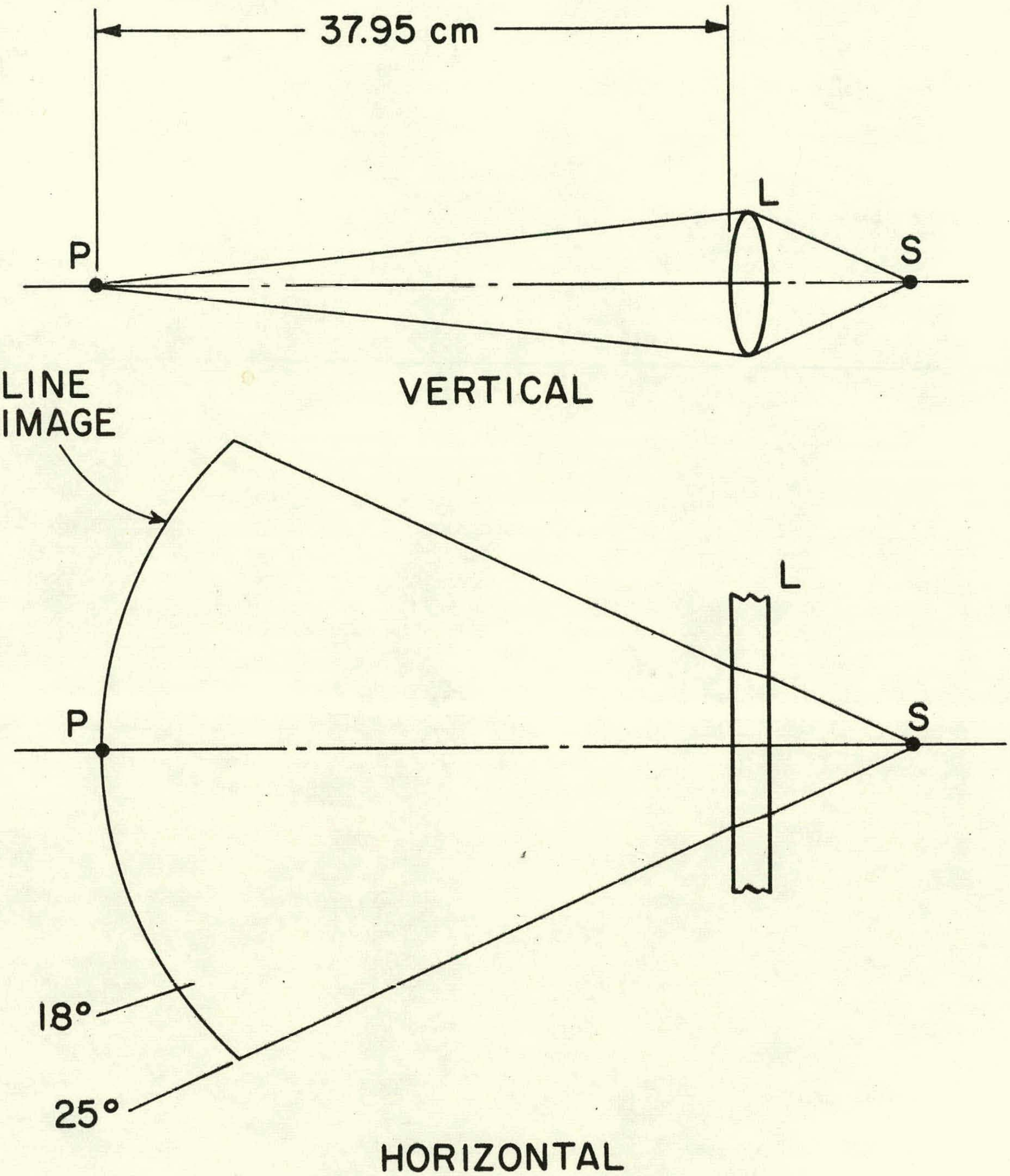


FIGURE 7

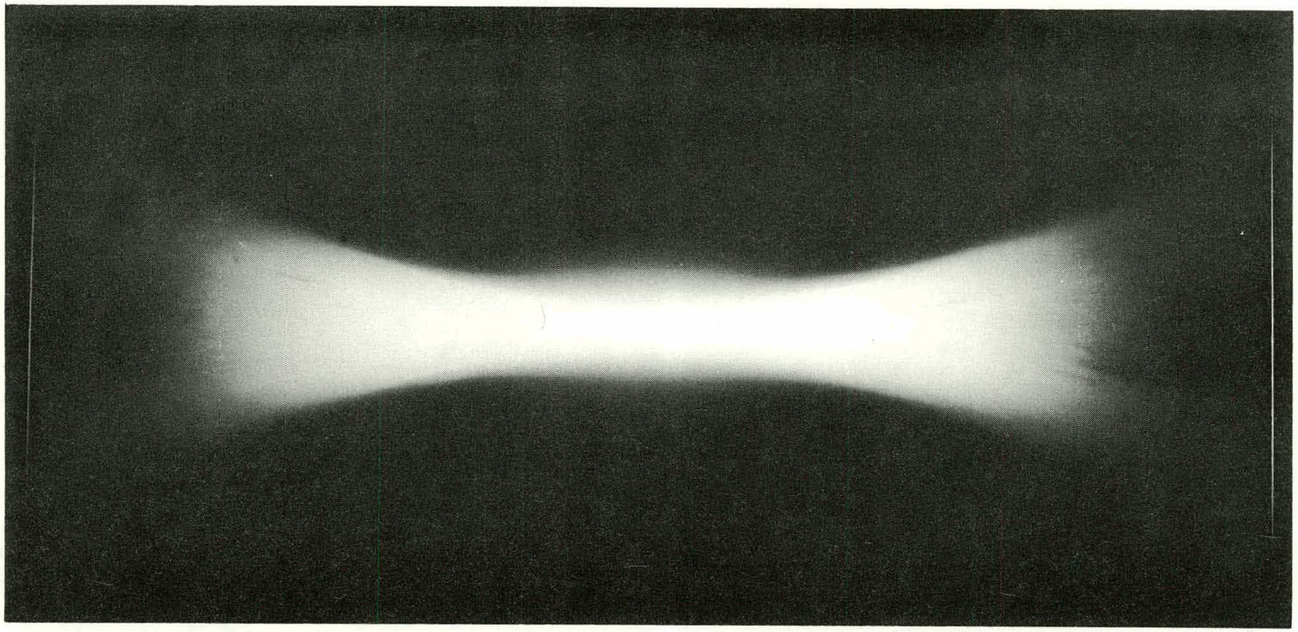
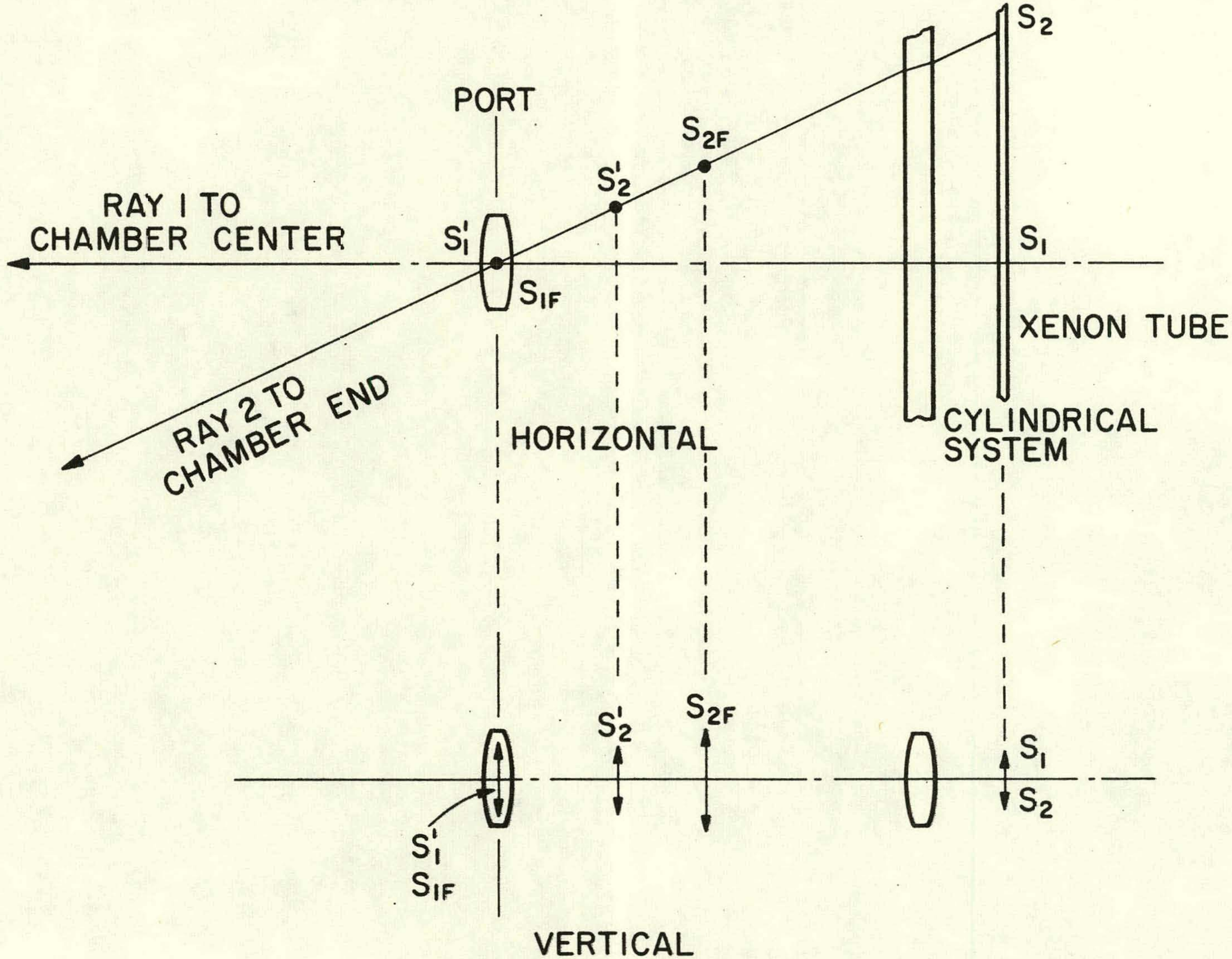
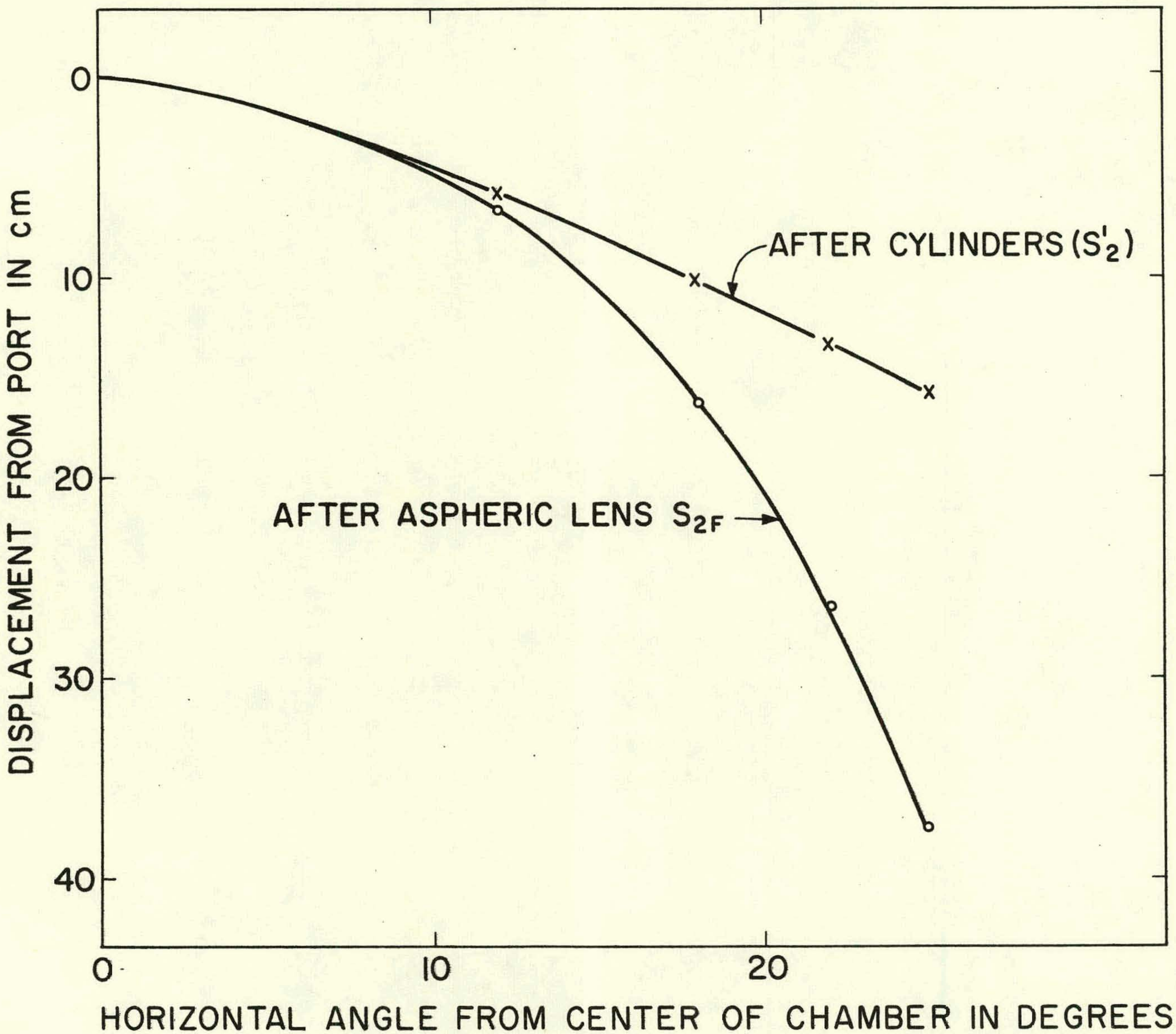


FIGURE 8



PORT
S_{2F}
S_2'
RAY 1 TO
CHAMBER CENTER
S_1'
S_{1F}
S_2
S_1
XENON TUBE
RAY 2 TO
CHAMBER END
HORIZONTAL
CYLINDRICAL
SYSTEM
S_2'
S_{2F}
S_1
S_2
S_1'
S_{1F}
VERTICAL

FIGURE 9



0
10
20
30
40
0
10
20
DISPLACEMENT FROM PORT IN cm
HORIZONTAL ANGLE FROM CENTER OF CHAMBER IN DEGREES
AFTER CYLINDERS (S'_2)
AFTER ASPHERIC LENS S_{2F}

FIGURE 10

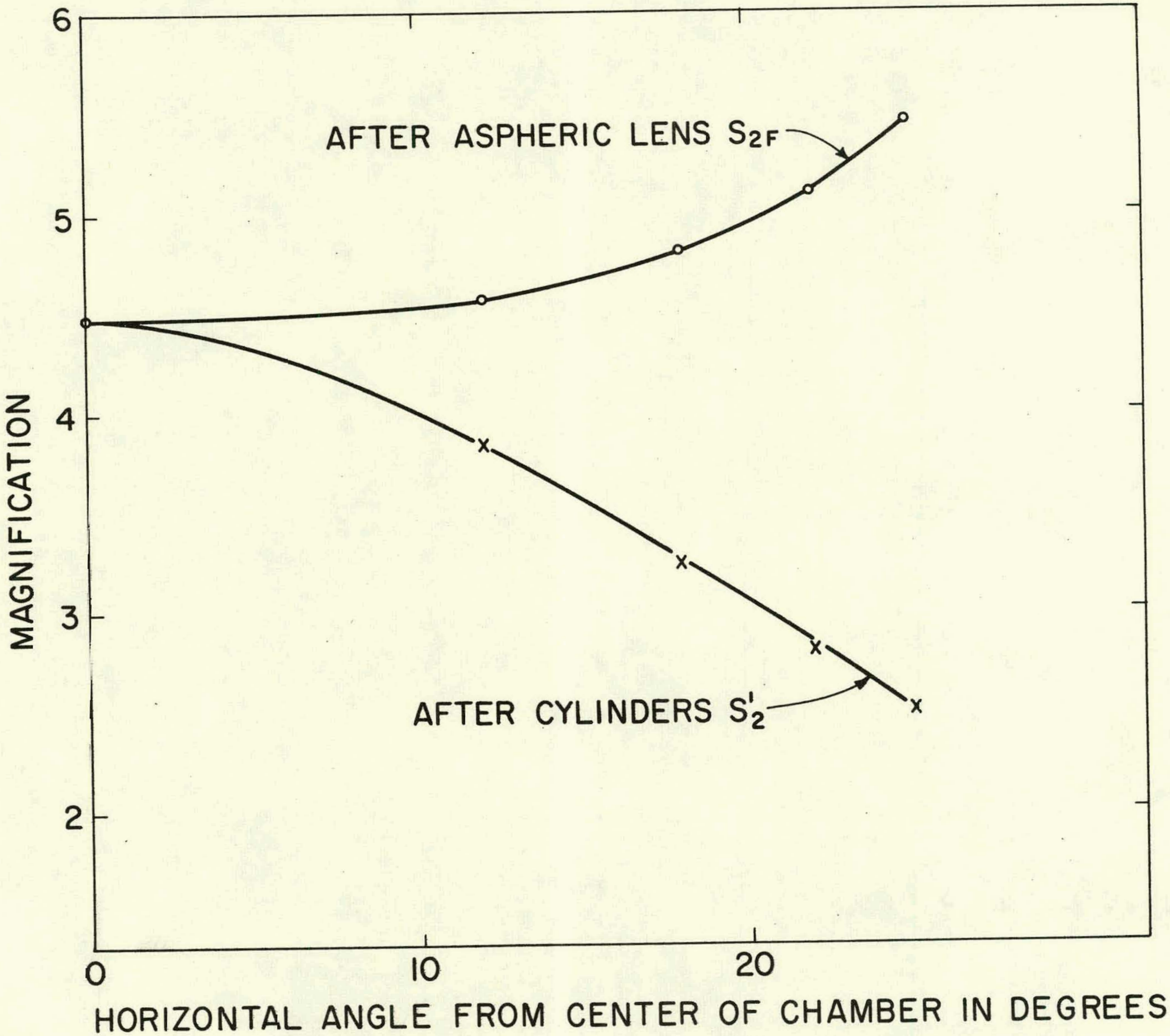

AFTER ASPHERIC LENS S_{2F}
AFTER CYLINDERS S'_2
MAGNIFICATION
6
5
4
3
2
0
10
20
HORIZONTAL ANGLE FROM CENTER OF CHAMBER IN DEGREES

FIGURE 11

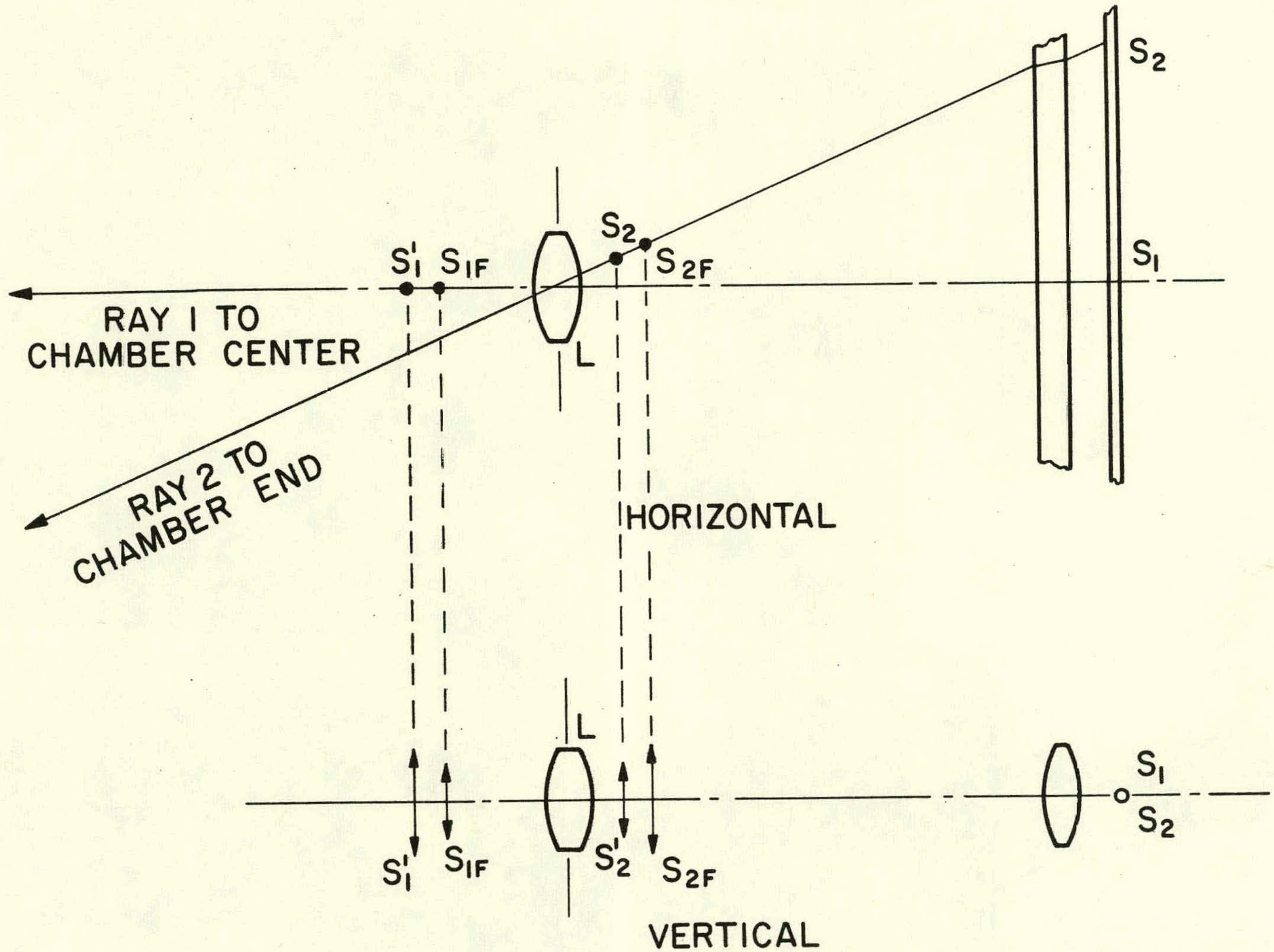

S2
S2
S2F
S1
S'1
S1F
RAY 1 TO
CHAMBER CENTER
L
RAY 2 TO
CHAMBER END
HORIZONTAL
L
S1
S2
S'1
S1F
S'2
S2F
VERTICAL

FIGURE 12

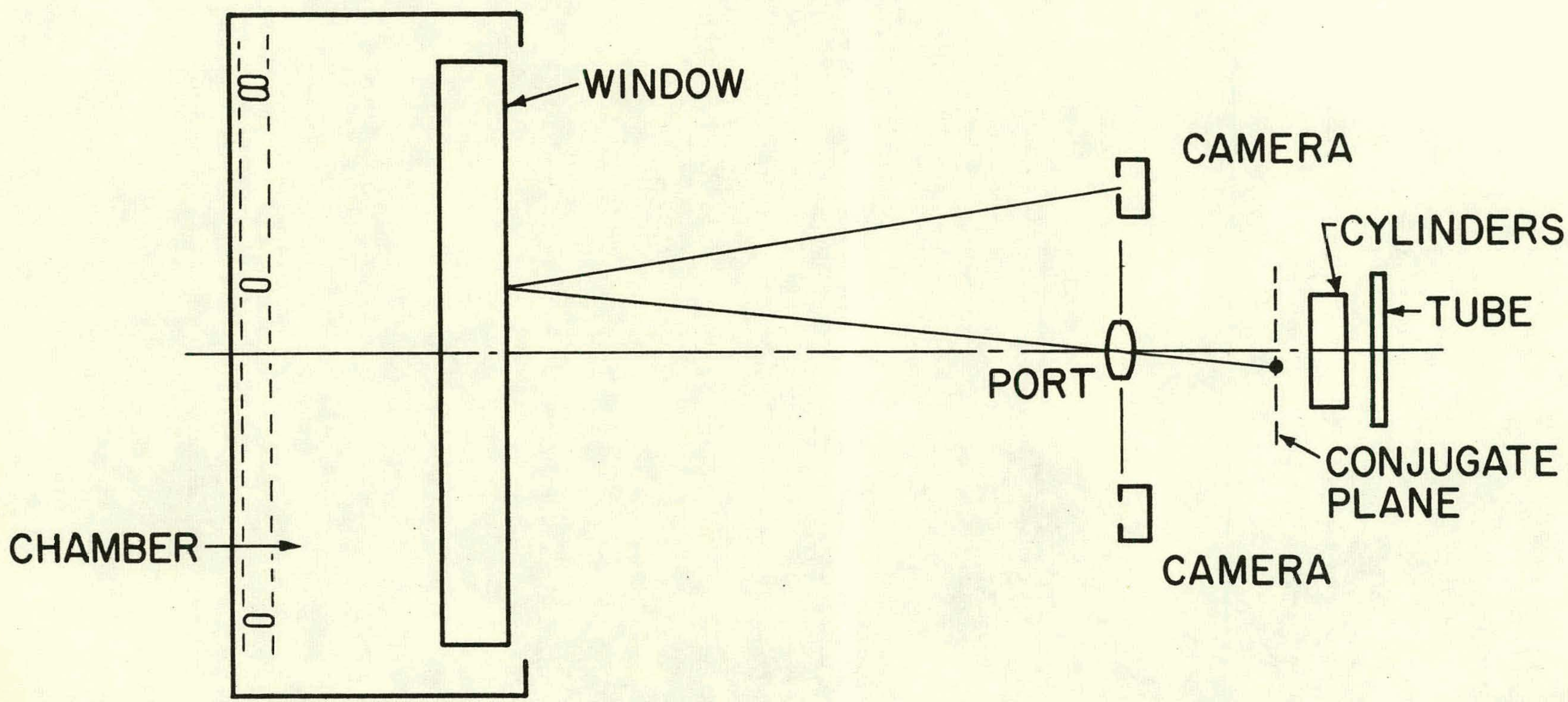

WINDOW
CAMERA
CYLINDERS
TUBE
PORT
CONJUGATE
PLANE
CHAMBER
CAMERA

FIGURE 13

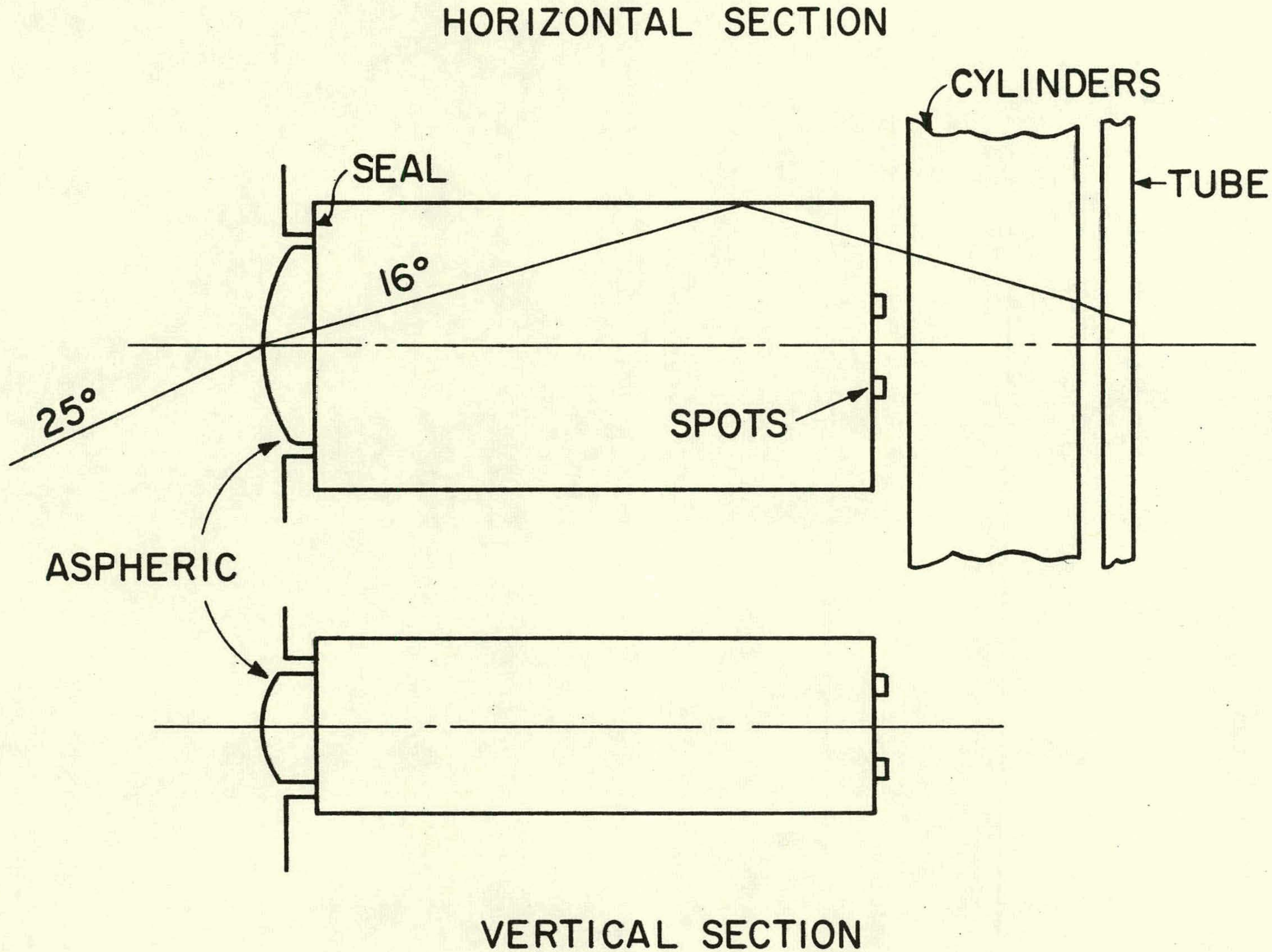

HORIZONTAL SECTION
CYLINDERS
SEAL
TUBE
16°
25°
SPOTS
ASPHERIC
VERTICAL SECTION

FIGURE 14

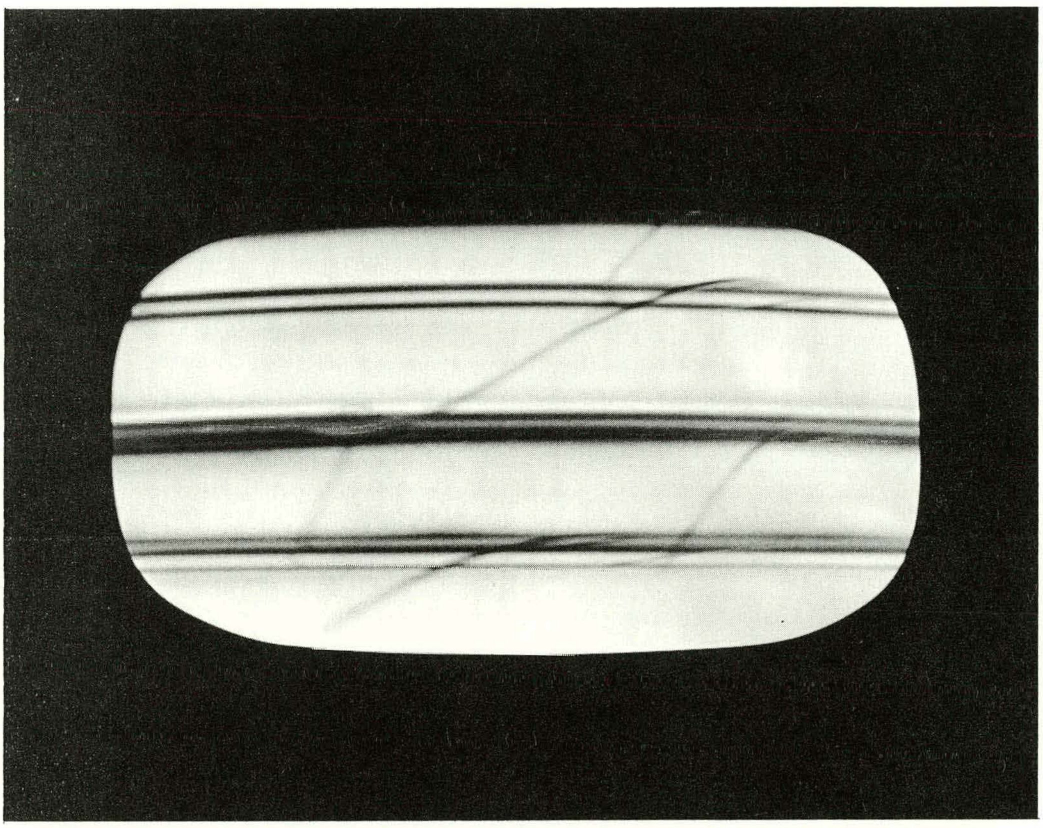


FIGURE 15

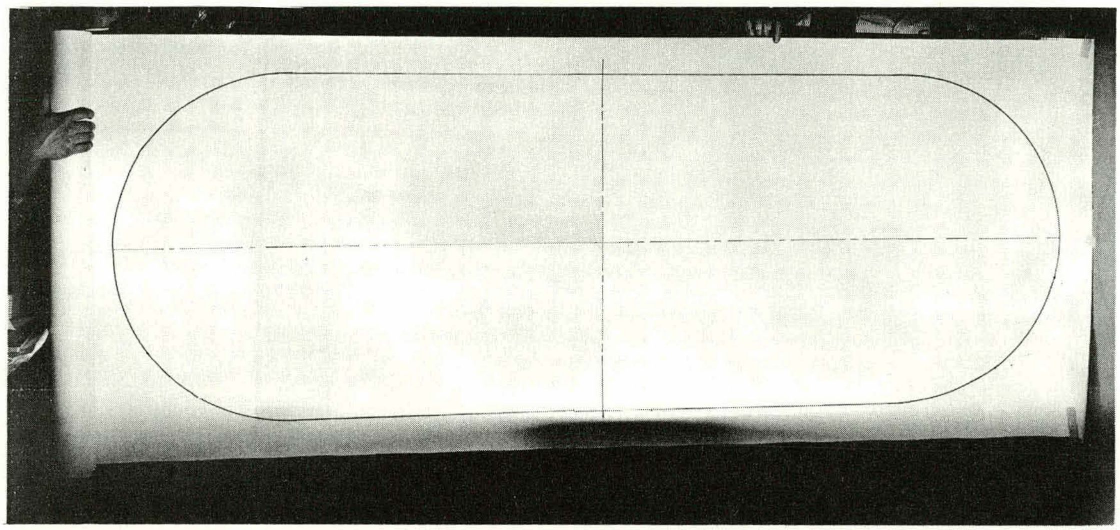


FIGURE 16

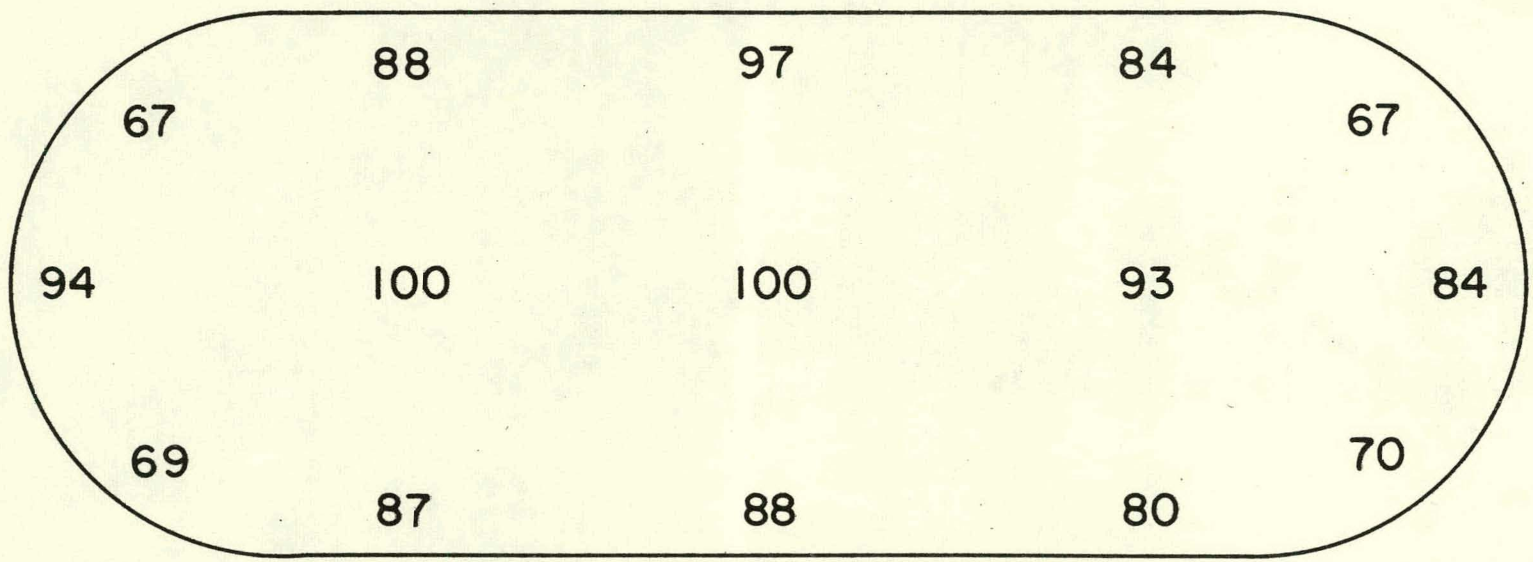


FIGURE 17

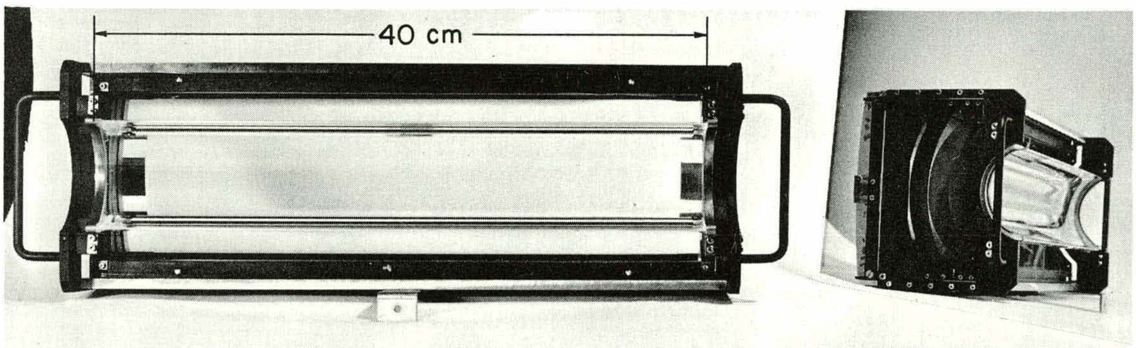


FIGURE 18

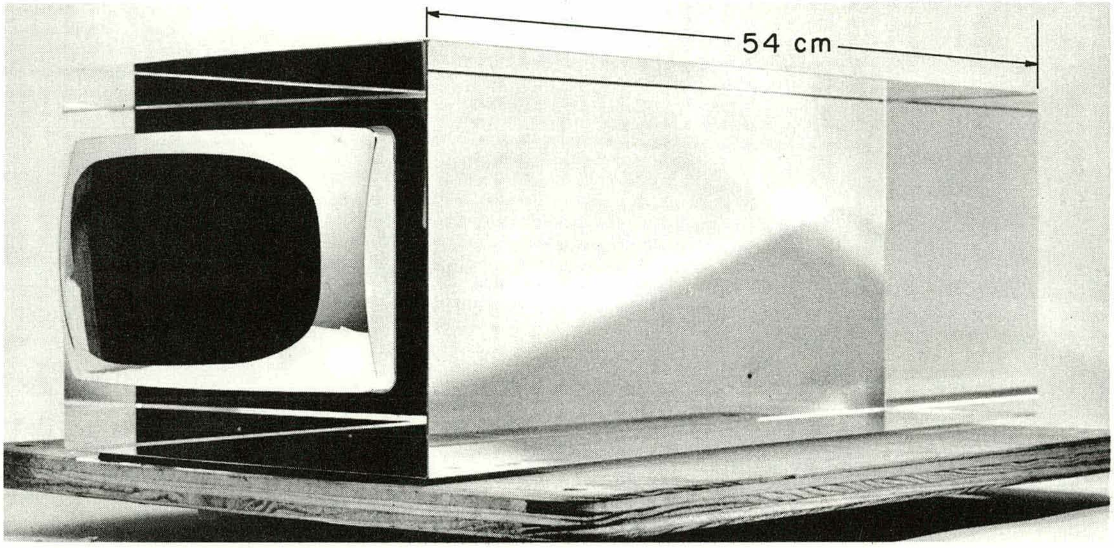
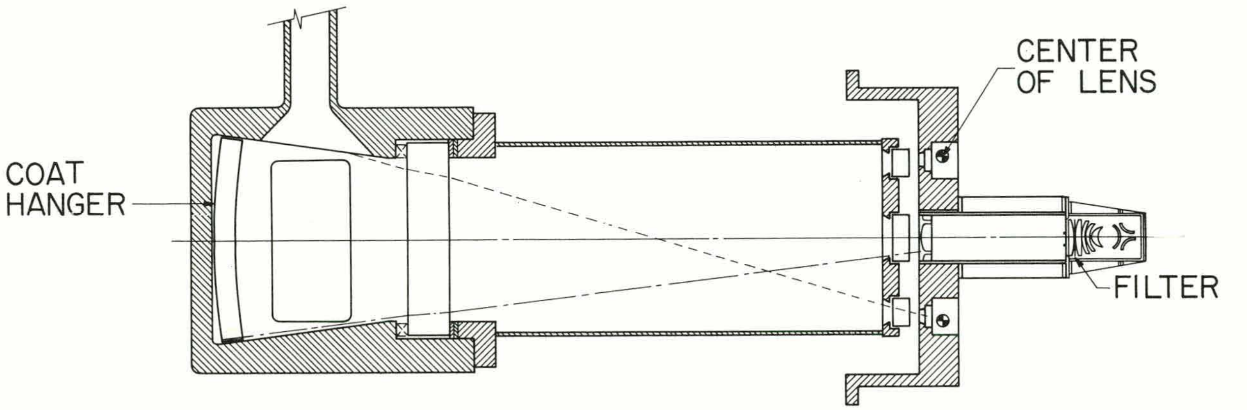
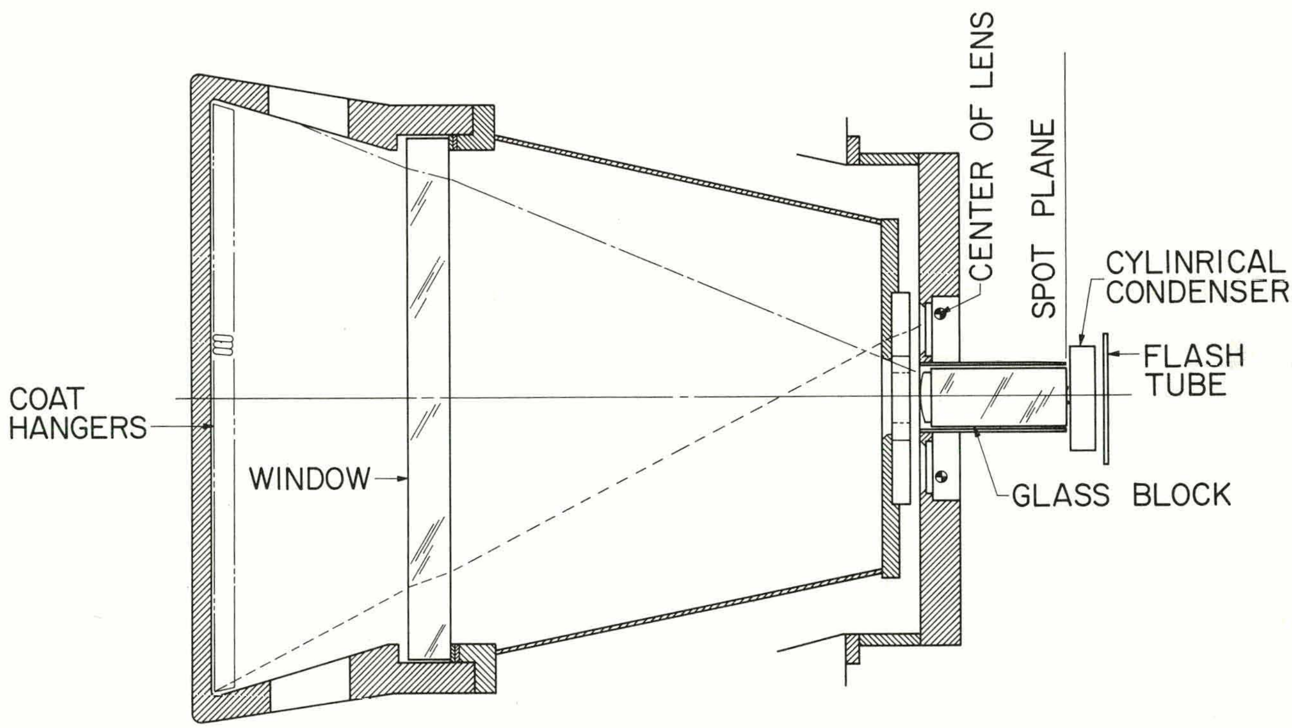


FIGURE 19



VERTICAL SECTION PLANE



HORIZONTAL SECTION PLANE

FIGURE 20