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UNUSUAL APPLICATIONS OF THE SCHLIEREN PRINCIPLE

BY

J. M. HOLEMAN

REPORT NO. 60GL197

OCTOBER 12, 1960

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GL-254A

Introduction

In 1945 Norman Barnes of G.E.L. published an article on schlieren equipment which has become a classic. At that time the Company's interest in the process was as a tool to make visible aerodynamic and heat transfer phenomena.

Fifteen years later the interest has changed to the schlieren projector, otherwise known as the light-valve projector. This device converts an electronically written image into an enlarged visible image through the medium of a "control layer", usually a fluid or thermoplastic. It is a means to project a display of any kind of information that can be produced electronically. Ideally, there should be no limit to the size of the projected image or its illumination. The source of light is a continuously burning lamp and the display is produced by modulating this light by the control layer.

The idea of the light-valve projector is not new. Baird in 1927 gave it serious thought and after some experimentation abandoned it as a technology ahead of his time. Dr. Gretener of Switzerland patented the idea in 1942 and developed a version of it which he called the "Eidophor" process. The word in Greek means "Image-bearer" and is the name he gave to the control layer. The Eidophor process was demonstrated in New York City in 1950 when closed circuit T.V. pictures were projected on a theatre screen with complete success. The viewers of the demonstration including G-E representatives were much impressed with the resolution and tone range of the large image, and arrangements were made with Gretener to purchase a projector and develop the process in this country.

Two factors delayed development. While the demonstration had been a success, the equipment was not. The machine was large, expensive and extremely temperamental. At that time there did not appear to be any way to reduce the cost or complexity of the device or to improve its reliability. A second reason was that in 1950 there was no demand for large-screen T.V., all the interest was in small home sets.

Between 1950 and 1958, several technological advances changed the equipment aspect very considerably and at the same time there arose a persistent demand for large-screen and brilliant displays of electronic information.

Among the advances which made the present equipment possible were:

1. Development of enclosed arc lamps to replace the carbon arc originally used. Actually, enclosed concentrated arc lamps have been available since 1936, but they were laboratory curiosities and showed a number of features which made it difficult to apply them to the schlieren projector.

2. Development of the multiple-layer interference heat filter. This device had been made as early as 1948, but only recently became commercially available.

3. Development of a silicone oil to replace the hydrocarbon oil used in the Eidophor process. Silicone oils had been made since 1939, but had not been applied to this purpose.

4. Development of new and simpler optical systems to replace the large and expensive Eidophor elements. These systems, incidentally have lead to better optical efficiency and higher screen brightness.

A most important technological development in the G-E Company was the patenting of the "Cross-modulation color" process by Dr. Glenn of the Research Laboratory. The idea had been tried by Wood and Ives as long as fifty years before as a means to make color photographs, but it had been beyond their technological abilities. It is interesting that Glenn first succeeded in making the process work with photographs rather than an electronic device. The cross-modulation color process is a potential means for creating the most faithful color pictures ever made. It is at the same time a possible means to make stereoscopic or other multiple-image displays.

This report is concerned only with the optical features of the process. The general properties of schlieren systems and their many variants are considered. These examples will show some of the forms future projectors may take. This is followed by descriptions of the Eidophor and several G-E projectors. The final pages describe a schlieren device for an entirely different purpose which had been included because it shows the solution to a number of unusual problems.

The chief purpose for writing this report is that there is no information on the optics of schlieren projection in literature.

While the electronics and theory of the Eidophor process are described at great length in German and Swiss publications and appear in some English translations, their references to optics are few and vague. We have read the published articles and feel that none of them has value to the understanding of the optical problems and hence the Eidophor literature is not included in our references. The translated articles were written by persons unfamiliar with optics who confused "refraction" and "diffraction" and contribute little enlightenment.

This report summarizes what had been accomplished in the art up to January 1960. Still newer types of schlieren projectors are being designed and built so that the value of this writing is mainly as historical and background material. A report on the current design and theory is yet to be written.

BACKGROUND INFORMATION

Definition

A schlieren apparatus is one which makes visible refractive variations in a transparent medium. Since changes in refraction can be caused by changes in temperature, pressure, composition or variations in the slope of the interface between two transparent media of different refractive index; schlieren equipment is a means to detect relatively small amounts of these parameters.

Classical applications for schlieren apparatus are to study the streamlining of projectiles or high speed aircraft models where the bow or compression wave can be seen as well as turbulence and other flow effects. Further applications are to photograph explosive compression waves and destructive reflection effects of these waves. In chemistry the equipment has been used to study the diffusion of gases and liquids, the mechanism of solubility, and electrode effects.

The above are probably the most important and well-known uses, this report will cover less well-known applications.

History

Schlieren effects can be observed without any equipment. Examples are the distorted view obtained when looking at the ground through the heated and turbulent exhaust of an airplane engine or the wavy effects produced when sunlight is refracted when passing through air over a hot object.

The first apparatus designed to utilize schlieren and make small refractive index gradients visible was described by Toepler in 1864. Toepler was a chemist and defined "schlieren" as the optical effect produced when two liquids of different refractive index such as water and sulphuric acid are mixed in a transparent container and viewed against a uniform light source.

The word "schliere" means "veil" in German and refers to the appearance of the phenomenon described by Toepler which is "like a gauze veil waving in the wind" or "the movements of a patch of eel grass in a rapid current of water". We have come to use the word "schlieren" to describe any aspect of the phenomena or the equipment in English, and this practice will be followed. Writers with German background refer to the phenomena as "schliere", in French they are called "striae" and the equipment is called a "strioscope".

The original Toepler schlieren apparatus has the layout shown in Figure 1 and this principle is used in all schlieren equipment. Light from a uniform source such as a ribbon filament lamp is focused on a small aperture. This aperture acts as the effective source for the system and is a small circular and well defined spot of light. This source is then focused by lenses or mirrors (called schlieren optics) back to an image. If the schlieren optics are of good quality and the magnification unity, the image will also be well defined and the same size as the source plus some slight enlargement due to unavoidable aberrations and diffraction. In the example given where the aperture is .040 inch in diameter, the source image should not be over .044 inch. If a stop in the form of a thin opaque metal disc this size or slightly larger is placed in this image plane, then no light will pass beyond, and the image produced by the photographic lens will be totally dark. Optically this is called a "dark-field" system meaning that no direct rays reach the final image field. If a refraction or deviation of the rays occurs anywhere in the path between the aperture and its stop, some of the rays will miss the stop, enter the photographic lens and form an image of this phenomenon.

Sensitivity

The sensitivity of a schlieren system is defined optically in two terms: the full range sensitivity and the ultimate sensitivity. The full range sensitivity is the angle which the rays must be bent so that the source image moves completely off the stop. In the example given in Figure 1 with a .044 inch spot falling on a stop of the same size and a schlieren lens of 24 inch focal length the full range sensitivity is:

F.R. sensitivity equals the angle whose tangent is .044/24 or 6-1/2 minutes.

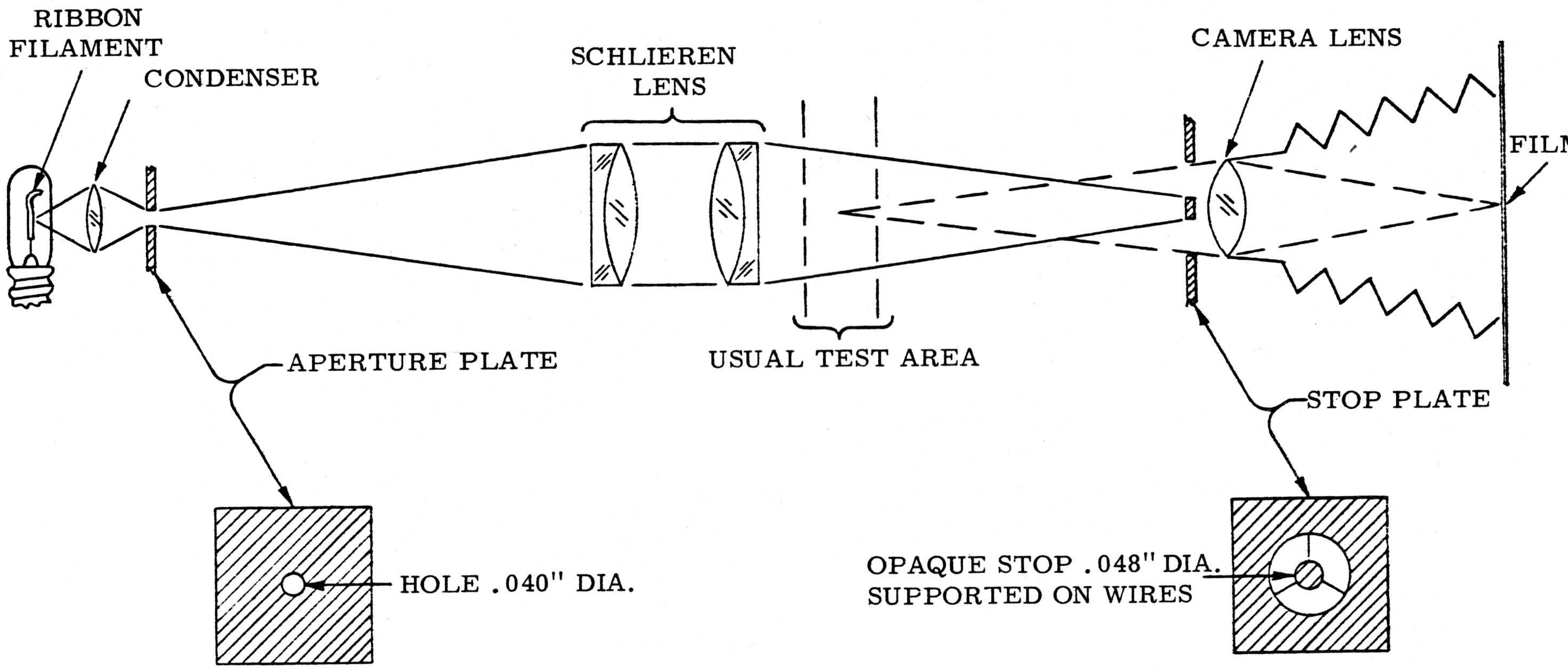


FIG. 1 TOEPPLER SCHLIEREN SYSTEM

The ultimate sensitivity is the smallest variation in deviation of the light beam that can be detected visually or photographically and depends on the quality and design of the optics, for good optics it should be about .01 the full range sensitivity or about 3.9 seconds of arc for the case described. With less ideal equipment the ultimate sensitivity may be only .1 to .02 of the full range.

By suitable design the sensitivity can be adjusted to meet the intended use and the ultimate value may be anywhere from several degrees of arc to a fraction of a second. It is a great mistake to overdesign a schlieren system as too much sensitivity may make visible effects which are not wanted and the cost of the high quality optics can be considerable.

The sensitivity of a schlieren system may be increased by making the aperture and its image smaller or the focal length of the optics longer. There is a practical minimum to the size of the aperture before the light in the system becomes vanishingly small and the adverse effects of diffraction set in. Increasing the focal length of the optics makes the system physically large which may result in a space problem.

The functional sensitivity is the smallest amount of temperature, pressure or other gradient that can be detected and may be as low as one degree of temperature in air, a fraction of a pound per square inch or the refractive index difference between .001 percent solution and an .002 percent solution of salt.

A common test for sensitivity of aerodynamic schlieren equipment is to determine if it will make visible the heat rising from a person's hand in a normally heated room. To pass this test the ultimate sensitivity must be in the neighborhood of one second. We prefer as a test object a piece of glass containing a calibrated striation. Striae are caused by refractive index variations in the glass and may be found anywhere. Over a period of years we have collected a number of pieces of glass and measured the refractive index gradients and these have been used to test the sensitivity of schlieren systems.

The three factors normally considered in calculating sensitivity are the size of the light aperture, focal length of the schlieren optics and their image quality. This method has been used for many years to compare the relative sensitivity of two systems, but it is not theoretically sound. In "A Physical Optical Analysis of the Schlieren Method", H. Shafer, Physical Review, Vol. 75 (1949), p. 1313, reported that an analysis of the conventional schlieren system on the basis of diffraction theory shows that for a point source illuminator, the sensitivity is independent of the focal length of the optics. This case is of academic interest only since there are no point sources. For a finite source the sensitivity is determined by the relative sizes of the source image and the Airy diffraction disc. In practical terms this brings us back very closely to the first definition because the size of the source image is largely determined by the aperture and focal length while the Airy disc is determined by the quality of the lenses and their relative aperture. This conclusion points to the interesting fact that in some cases it may be possible to trade focal length for aperture and thereby make a more compact system with better illumination. So far as known this has never been given any serious consideration because of the economic fact that it is cheaper to buy focal length than aperture at the same quality. Schlieren mirrors are rarely faster than f/8 because of the severity of off-axis aberrations, Maksutov systems as fast as f/4 can be used, but lenses in the conventional single-aperture high-sensitivity system are usually limited to f/11 which is the highest aperture that will allow full correction of chromatism and spherical aberration in an achromat. If compactness were more important than cost, then high quality complex fast lenses could be used and speeds of f/2 or greater might be obtainable. Assuming "perfect" lenses could be made, increasing the relative aperture from f/11 to f/2 would allow the length to be reduced to one-fifth.

Slit-Type System

Another form of the equipment uses a slit and a knife-edge instead of a round aperture and disc, and is called the slit-and-bar system. This arrangement has several advantages, for one, the slit transmits many times more light than a small aperture and this means the slit width can be reduced and the sensitivity increased while still producing enough light for microsecond exposures of such fugitive phenomena as those caused by the passage of a bullet. Also the adjustment of the knife-edge is far simpler than any other form of stop. Assuming that it is parallel to the aperture slit and in the proper focal plane, then a knife-edge requires only one fine motion to precisely align it with the slit image. In the case of the circular aperture, anything that changes the magnification of the system requires the manufacture of a new stop and to position this stop requires two fine motions.

A possible objection to the slit-type system is that it favors refractive gradients parallel to the slit. Normally, this is no problem as the slit can be oriented to the most favorable angle to make the desired effect visible. The circular aperture system is said to have omnidirectional sensitivity while the slit-type has one-directional sensitivity.

COMPOUND SCHLIEREN SYSTEMS

Approximately fourteen variations of the classical schlieren system have been invented. Several of these are combinations of a schlieren device with some other kind of optical equipment with the intention of producing higher sensitivity than can readily be attained in the classical arrangement. In the paragraphs below several of these will be described in general terms. Later, under the heading of "Variant Systems" we will return to the details of some of them.

1. Interferometer Schlieren System

By combining an optical interferometer, usually of the Mach-Zehnder type with a schlieren system, it is possible to obtain extremely high sensitivity, so much so that any piece of glass will show defects and the normal air currents in a room are quite visible. This device was the first of the high-sensitivity schlieren systems but is little used today because of its high cost and difficulty of adjustment. A new type called the "Crystal Interferometer" is used today where high sensitivity is required, or often the same results can be obtained with the simpler phase-contrast system.

2. Phase-Contrast Schlieren System

A phase-contrast microscope is one which makes visible very small differences in refractive index in transparent objects. It does this by means of an annular stop in the illuminating system and an annular semi-transparent stop plate in the objective which retards and changes the phase of part of the light. The result is an interference of phases and a high sensitivity to refractive index variations. When the phase-contrast principle is added to a schlieren system, the sensitivity is greatly increased so that it becomes one of the few devices we have that will measure optical path length variations as small as .2 angstrom, which is to say atomic dimensions. This device is little known today, but promises to become an important industrial device for many kinds of testing due to its relatively low cost and insensitivity to vibration.

3. Color Schlieren

If the entrance slit of a spectroscope or monochromator is used as the slit aperture of a schlieren system and the prism or grating is used as a dispersing medium, it is possible to view schlieren in color instead of shades of gray. All workers report that the addition of color increases the apparent sensitivity of the system and reduces the possibility of confusion of a schlieren artifact with an image defect. Color schlieren finds its chief value where it is necessary to determine whether a particular area is of higher or lower refractive index. In a black and white image, it is usually only possible to say that changing shades of gray represent changing refractive index and it is rarely possible in a complicated situation to say in which direction it has changed. In color schlieren it is usual to set up the apparatus so that the knife-edge cuts the green rays in the center of the spectrum and the undisturbed field will then appear a pale uniform green. When disturbed, areas which show an increase in refractive index will be bright yellow, orange or red while areas of decreased index will be blue or violet.

4. Multiple-Slit Systems

There is no reason why a schlieren system has to be confined to the use of a single slit and knife-edge. One refinement is the use of a double-edge knife which is just wide enough to obscure the slit image. With this arrangement refractions in either direction perpendicular to the knife-edge will cause light to pass the stop and there will be twice as much light in the image. Thus, it is also possible to use two or more parallel slits and an equal number of parallel double knife-edges or "bars" as diagrammed in Figure 2. The chief advantage of the multiple-slit-and-bar system is the increased light in the final image. One precaution that has to be taken is that the maximum possible refraction does not exceed the full range sensitivity or else the refracted image may be deviated so far it will fall on the next bar and not pass through one of the slits.

It is also possible to use multiple apertures, usually a circular array of holes in a square or hexagonal pattern. The multiple-aperture system transmits less light than the multiple-slit system because it has less open area, but it has the advantage of being omnidirectional.

There are three well-documented ways to design the illumination system for a multiple aperture system:

a. For ordinary schlieren tests of materials, a diffuse source consisting of a bank of lamps and a ground glass diffuser behind the slit plate will be satisfactory. This is diagrammed in Figure 3a. The ground glass scattering angle is usually sufficient to allow the light from the slits to fill the aperture of the schlieren optics as it should. The objections to this system are that only a small portion of the source flux passes through the slits and can be utilized and secondly, scattering is a poorly controlled process. This system though inefficient is simple to build and is the most common type of multiple-source illumination.

b. For schlieren projection something more efficient is required and a typical system using high aperture condensers to collect light from a concentrated arc source is shown in Figure 3b. The condensers form an enlarged image of the source on the slit plate and thus the slits are much more brightly illuminated than in the diffusing system described above.

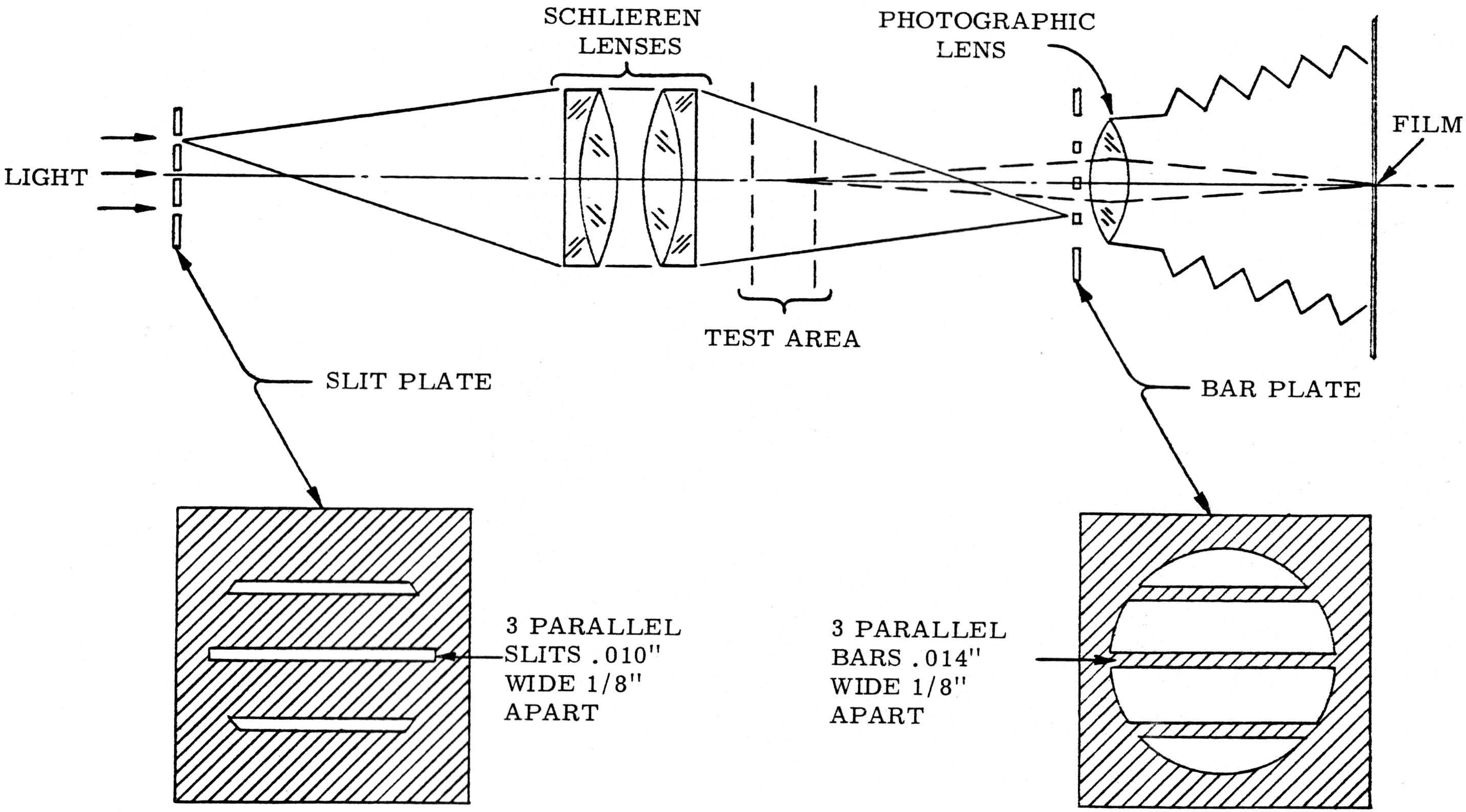
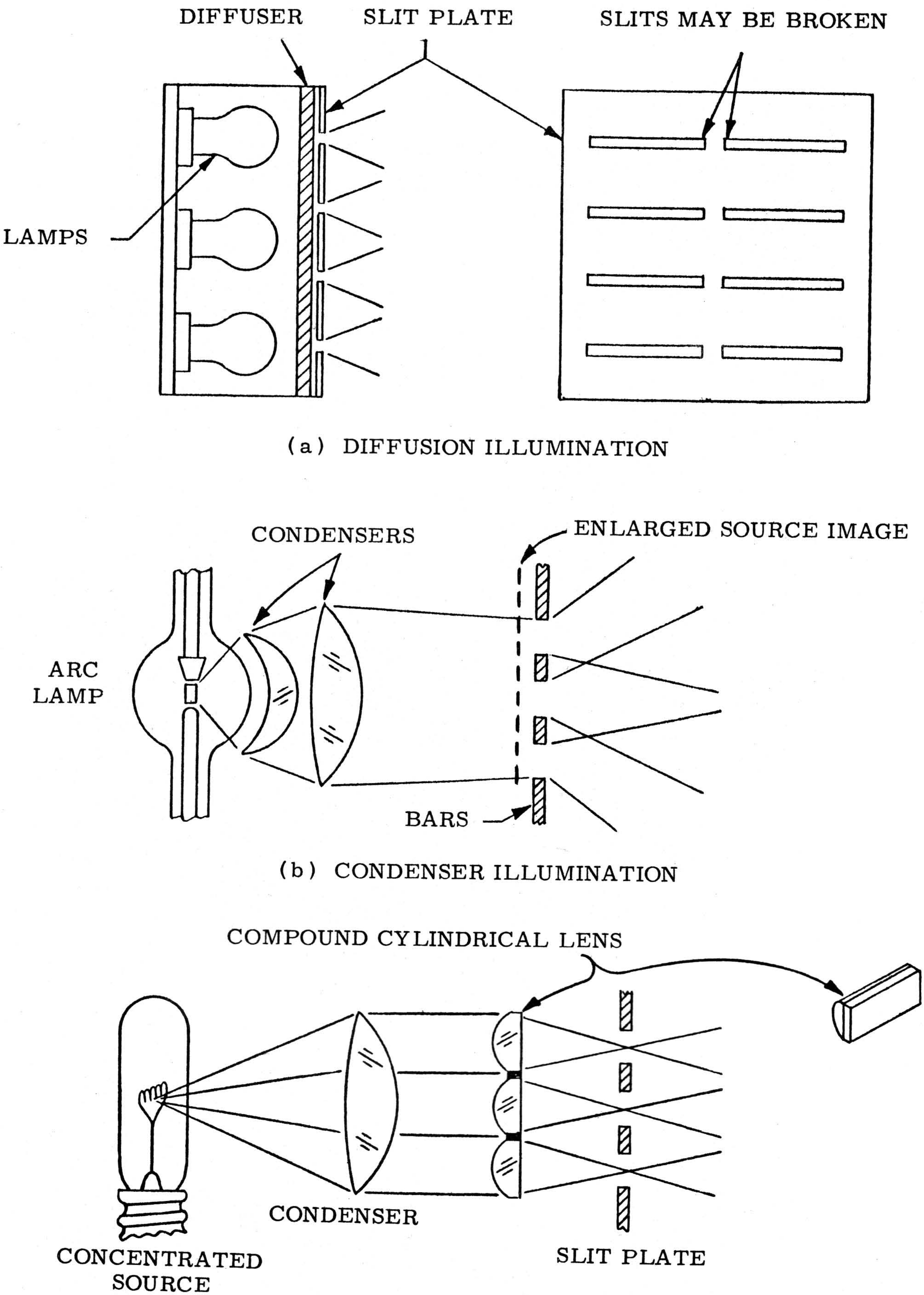


FIG. 2 MULTIPLE - SLIT SCHLIEREN SYSTEM



(a) DIFFUSION ILLUMINATION

(b) CONDENSER ILLUMINATION

(c) COMPOUND - LENS ILLUMINATION

FIG. 3 ILLUMINATION SYSTEMS

Dr. Gretener, inventor of the Eidophor process contributed a new element to the improved illumination of the multiple-slit system. This device he called "staggered mirror bars". It can be seen in Figure 3b that if plain opaque bars are used between the slits that they will take out half the light. If, instead we use a set of staggered mirrored strips as in Figure 4, nearly all the light from the condensers will be used. The mirrors as seen from the source fill the aperture, but as seen from the schlieren system are separated by non-luminous spaces or bars. The condenser-illuminated system is capable of projecting a much brighter picture than the diffusion-illuminated system, but it is more difficult to design, build and adjust.

c. The third system is the compound-lens type, first suggested by Dr. Glenn and diagrammed in Figure 3c. A single source, preferably a concentrated arc is placed at the focus of a condenser to produce collimated light, in this light and behind the slit plate is placed a compound lens which in the case of slits is an array of parallel cylindrical lenses. The two effects of the cylindrical lenses are to focus the collimated light on the slits increasing the efficiency of their illumination and providing a cone of rays which will fill the schlieren optics. In the case of multiple apertures it is possible to use a device known as "honeycomb" lens, which is a hexagonal array of spherical lenses molded into a glass or plastic plate. Systems using 80 and 160 lens elements and corresponding apertures have been built. The compound-lens illuminating system can produce a higher efficiency than either of the other illuminators. The optics of compound-lens illuminating systems is the subject for a separate report mentioned in the bibliography.

LIMITATIONS OF CLASSICAL SYSTEMS

All the above designs and several others not mentioned at this time are "classical" schlieren systems in that they are obvious modifications of the original Toepler device and they all suffer from two limitations which can be extremely serious in aerodynamic research; one of these is field of view and the other is window quality.

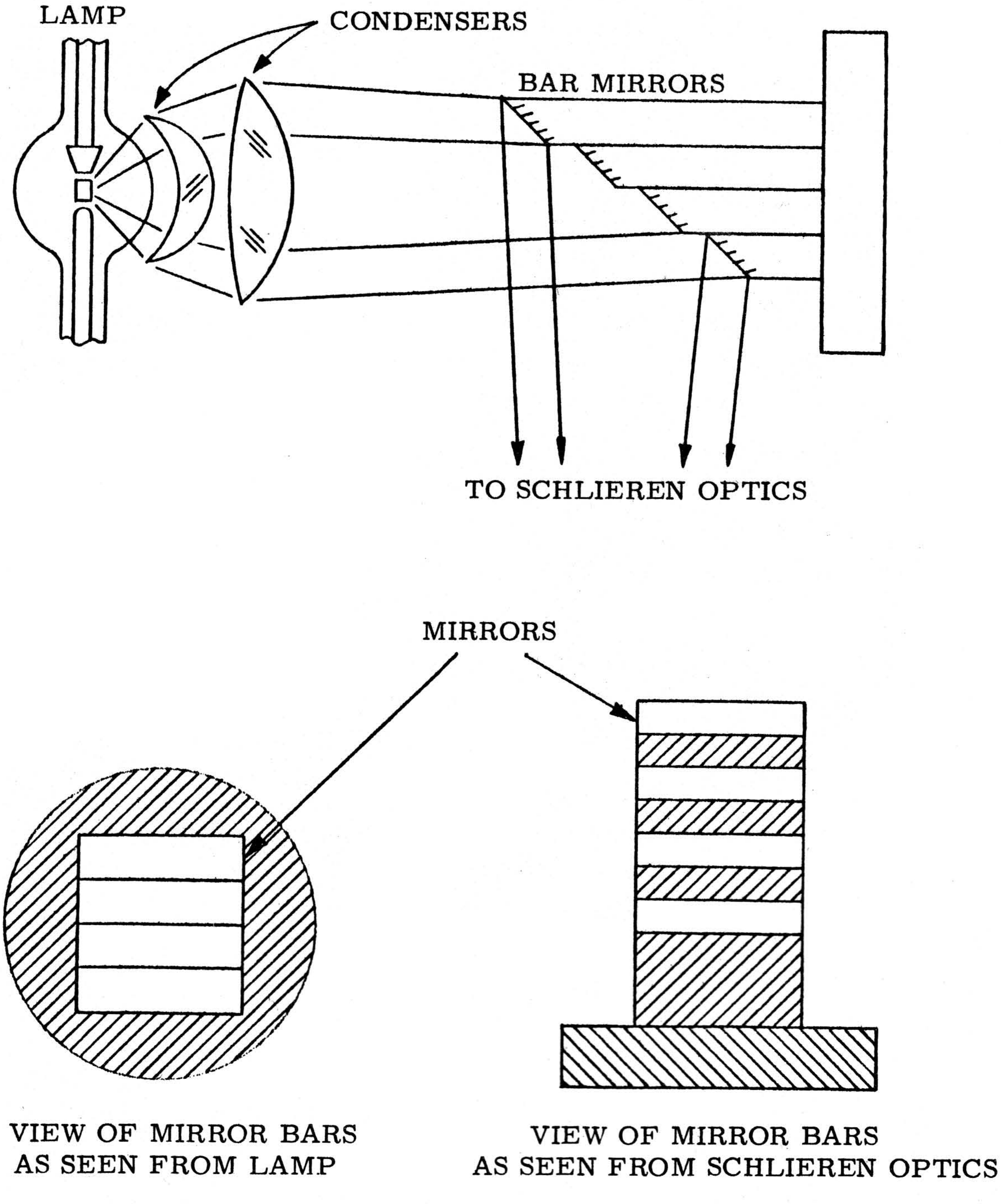


FIG. 4 STAGGERED MIRROR BARS

The maximum object area that can be viewed in the classical systems is no greater than the diameter of the schlieren lenses or mirrors. The sensitivity usually requires that the schlieren optics be of very high quality and since large diameter high quality optics are difficult to obtain, this imposes a limitation on the field of view. In testing airplane models in wind tunnels, it would be desirable to have a field of view six feet or larger in diameter, but three feet is maximum diameter to which schlieren optics have been made so far as we are aware.

The second limitation is that of window quality. In wind tunnels and other pressure vessels, it is necessary to have flat pieces of glass (called "windows" in optics) which are as large as the aperture of the schlieren optics. Since the schlieren system is extremely sensitive to refractive index variations, this means that the windows have to be optically homogenous to a greater degree than is normally available. Glass, or any other material free from refractive index gradients in the range of .00001 or less is difficult to find, expensive to buy and unavailable in large pieces. Since a good schlieren system will detect refractive index variations of one part in a million, "perfect" windows are a virtual impossibility and even usable windows are a problem. The largest schlieren windows known to have been made are three feet in diameter and while their cost is not known, similar glass blanks are currently selling for $40,000.

In the classical schlieren systems the aperture of the photographic lens is limited by the exit pupil of the schlieren optics so that in the example shown in Figure 1, if the source image is .048 inch in diameter and a four-inch photographic lens is used, the effective aperture of this lens would be f/80 for the strongest schlieren it could detect and much less for weak schlieren where the source image is barely deviated from the stop. The slit system behaves in practically the same way and effective apertures of f/200 are common. With such small aperture ratios, the depth of field of the photographic portion is practically infinite and all scratches, dirt and refractive index variations on the surfaces and in the interiors of the optics and windows will appear in all the pictures. If the windows contain visible schlieren of their own, these will greatly interfere with the detection and interpretation of schlieren in the test area.

Sharp-Focusing Schlieren System

This name is given to multiple-source schlieren systems that have the general layout shown in Figure 5. It will be noticed that only one schlieren lens is normally used, but because the slit plate and its image may have considerable area and therefore produce large field angles, it is usual to employ a photographic type lens as a schlieren lens.

The layout consists most often of a diffusion illuminated slit plate, the light then passing through the test area after which the single schlieren lens forms a reduced image of the slit plate. In this plane is located the cut-off plate which acts as a multiple-bar system. Behind this is the photographic lens and camera.

There is no practical limit to the field of this system because the slit plate is a simple mechanical part and can be made as large as desired while the schlieren lens retains a moderate size. As the area of the source array increases, more lamps have to be placed in it, but this is only a minor problem involving power and cooling. Since the cut-off plate can be made photographically, it automatically compensates for distortion in the schlieren lens and does not limit the number of slits that can be used, nor is there any requirement for high accuracy or straightness in the source slits.

Fairly poor windows can be used with the sharp-focusing system because the light from different sources (slits) passes through the windows at different angles and these effects average out if the number of sources is large enough. In most cases ordinary plate glass or even plastic sheet can be substituted for costly schlieren windows.

Since the cut-off plate has considerable area, the light passing the bars largely fills the aperture of the photographic lens and allows the use of fast lenses with high effective speeds and shallow depth of field with the result that only one plane, that of the test object is

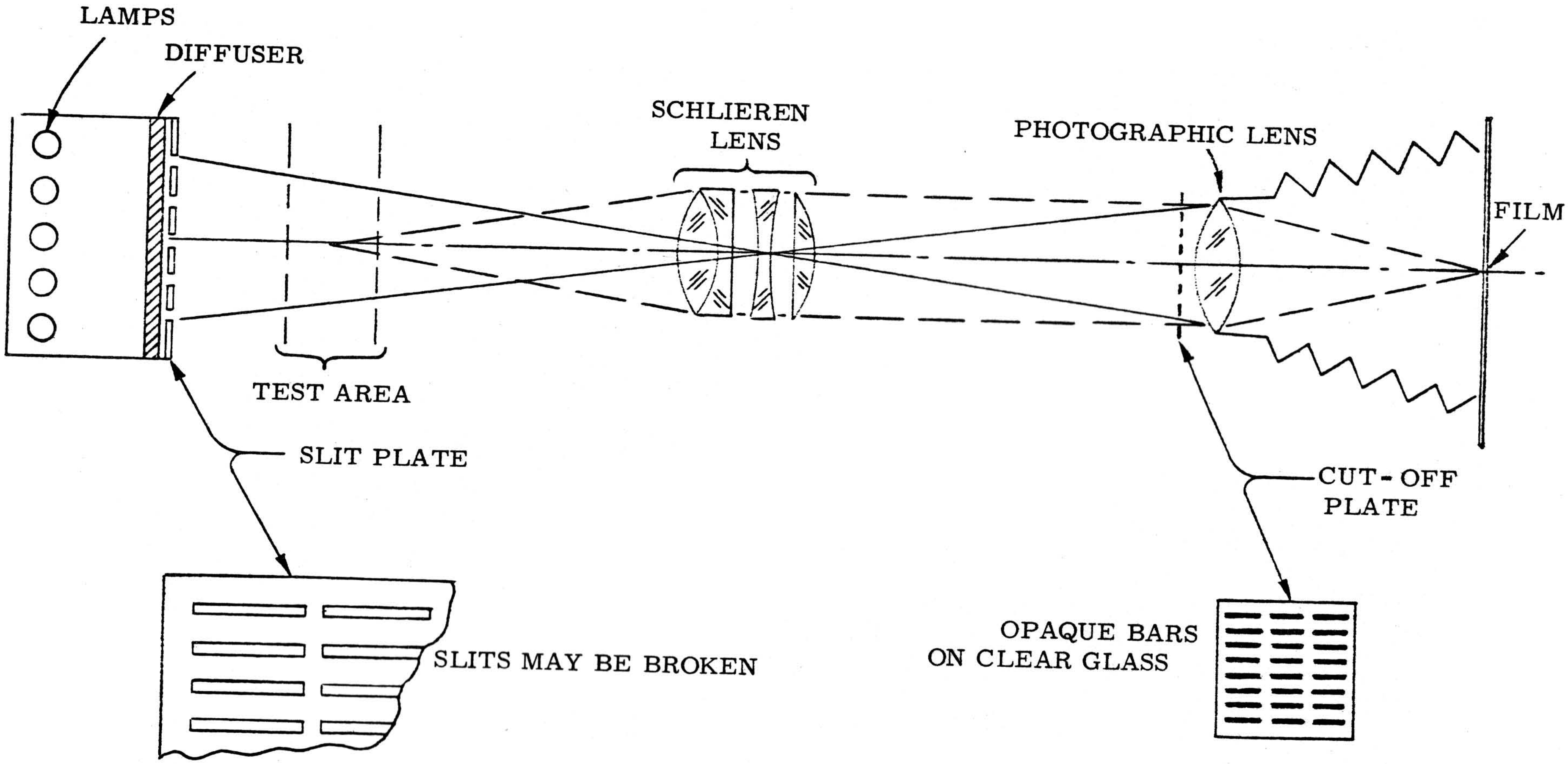


FIG. 5 SHARP - FOCUSING SCHLIEREN SYSTEM

in sharp focus, hence the name "sharp-focusing" schlieren system. In general, the shallow depth of field tends to make scratches and defects in the windows invisible or at least unobtrusive.

DESIGN FEATURES OF SCHLIEREN ELEMENTS

The previous section described the chief types of schlieren apparatus and their limitations with no particular attention to their design. This section considers the design and selection of individual components.

Source Uniformity

The classical and condenser illuminated systems work best with a uniform source and a condenser that makes a uniform source image. In a sharp-focusing system such as a projection device it may be enough to have uniform illumination of the condenser aperture. Non-uniform illumination results in shading of the image field and a non-linear relation between the refraction and image brightness. In aerodynamic work this is serious because it becomes impossible to calibrate such a system or assign values to the results. In a schlieren projection system where the illuminated screen is an enlarged image of the source, non-uniformity will result in uneven screen illumination. This is particularly serious in the case of gaseous arcs which may be bright in the center and surrounded by shells of lesser intensity and will produce a screen image that is bright in the center with dark edges and corners. What is more, a schlieren projection system is a chain of several complex lenses each with additive vignetting so that the central bright spot is barely attenuated while the edges of the screen are illuminated by marginal rays that have suffered considerable losses from vignetting and source non-uniformity.

The diffusion and compound-lens illuminated systems can produce a reasonably uniform screen level from a non-uniform source.

Source Brightness

Static or slowly changing schlieren phenomena can be observed and sometimes photographed using tungsten sources. Any dark-field system is an inefficient one, and where high sensitivity requires the use of small apertures, the efficiency can be extremely poor. To photograph transitory events, the brightest obtainable sources must be used and flashing sources can be employed for exposure times shorter than can be obtained with mechanical shutters. Typical sources for schlieren apparatus are ribbon filament lamps, tungsten arcs, high pressure gaseous arcs and exploding wires.

In a schlieren projector where every attempt is made to obtain the highest possible luminous efficiency, it has never been possible to get an efficiency above 6 percent at full range refraction. In practical terms this means that a schlieren projector will compare very unfavorably to a conventional projector and if the same lamp were used in both, the schlieren instrument would probably deliver only one-sixth as much light to the screen. The two features of dark-field illumination and the large number of optical elements are inherent limitations of existing instruments and successful schlieren projection has only become possible since new very bright sources have been developed.

Source Size

The classical single-aperture or single-slit systems require small sources, preferably not much larger than the apertures.

The condenser and compound-lens illuminated systems also require compact sources as will be described under condenser design.

The diffusion-illuminated source can be of any type, even fluorescent lamps.

In cases where it is desired to make continuous visual observations and take instantaneous pictures, it is possible to use a source which may be operated continuously at a low level of brightness and pulsed at a high level, or it may be possible to combine two separate lamps so they can be used interchangeably.

Source Spectral Distribution

A good choice of source for black and white photography is the mercury arc. For the projection of black and white or color schlieren images a white source such as the xenon arc is preferred. For color schlieren a white source with no strong spectral lines is required. Phase-contrast and interferometer schlieren are most effective with monochromatic light.

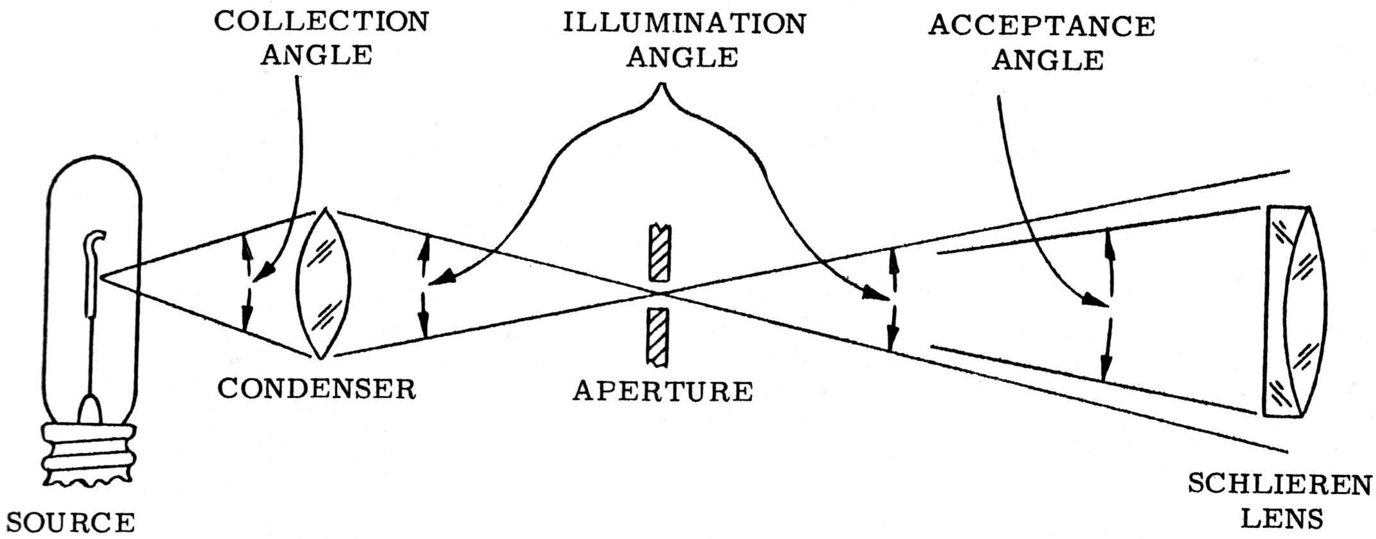
Condensers for Single Aperture Systems

The Toepler apparatus shown in Figure 1 uses a simple condenser and aperture plate (pinhole) to form a small sharply defined effective source for the system. A condenser for this serivce has only to meet the requirements of focal length and aperture so that the illumination angle provided by the aperture is greater than the acceptance angle of the schlieren optics. These terms are defined in Figure 6a where it will be seen that unless this condition is fulfilled part of the usable aperture of the schlieren optics will be wasted and part of the field lost. The other condenser requirement is that the image of the source be larger than the aperture, otherwise due to the aberrations of simple condensers the edges of the aperture will be poorly illuminated.

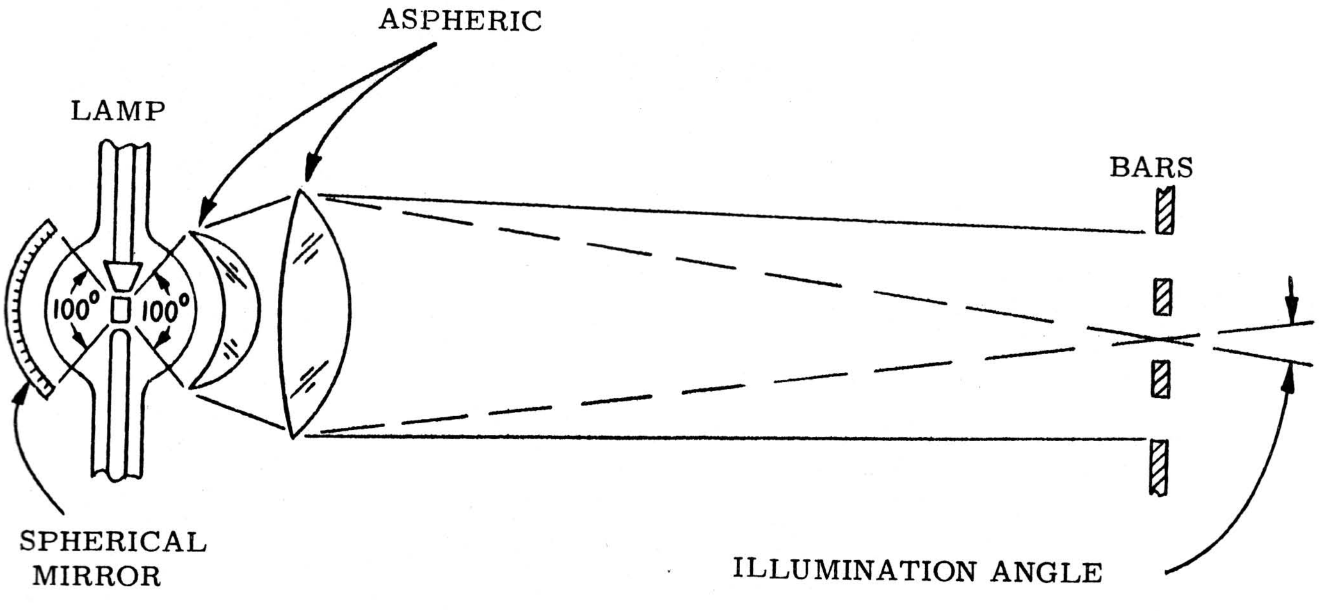
It is possible to eliminate the condenser and aperture plate where the source itself is suitably shaped, the required size and well defined. Lamps which may be used in this manner are tungsten and zirconium arcs and possibly concentrated mercury arcs. For a slit source the General Electric BH-6 capillary mercury arc which can be masked to a lesser width with knife-edges may be used. Flashing sources which can be used without condensers or apertures are the General Electric short arc xenon flash tubes and the Edgerton xenon-filled capillary flash tubes.

Condensers for Multiple-Slit Projection Systems

In order to produce the most light on the screen, these instruments require the brightest sources available such as concentrated arcs, and the condenser system should collect as much of the source flux as is compatible with the other requirements. A typical system is shown in Figure 6b which was designed around an Osram lamp. The light distribution of this lamp is in the form of a ring which extends about 50 degrees above and below the equator of the lamp and beyond these limits the light is shadowed by the electrodes. This odd light distribution means that the maximum practical condenser acceptance angle is 100 degrees, but even this is difficult to obtain. Condensers with an aperture ratio faster than f/1.0 are rare and this



(a) DEFINITION OF TERMS



(b) ASPHERIC CONDENSER SYSTEM

FIG. 6

represents an acceptance angle of only 60 degrees. Faster condensers such as have an acceptance angle of 90 degrees are usually aspheric and to obtain 100 degrees and produce a well-defined image with only two elements requires double aspherics. Since these lenses are very close to a 2 kilowatt heat source, they have to be made of fused silica or heat-resisting glass. An additional requirement of the condenser is that it produces an illumination angle that exactly fills the picture area since any excess means wasted light and any lack results in dark corners on the screen. If a rectangular picture is to be projected, we may as well use condensers that are rectangular in outline. It is rarely recognized how much light is lost in illuminating a rectangular area by a round beam. If the normal 2:3 aspect rectangular picture is inscribed in a circle which represents the area illuminated by a round condenser, 38 percent of the light collected by the condenser system is taken out by the film gate or aperture mask. In the compound-lens illuminating system, a rectangular source image is produced in a very simple manner.

Further requirements for the condenser are that it produces a minimum of chromatic aberration and a uniformly illuminated aperture. The condenser system shown in Figure 6b has no chromatic correction and this proved to be somewhat troublesome.

Condensing Systems for Compound-Lens Illuminators

The first commercial compound-lens illuminating system was marketed by Zeiss Ikon about 1957 for a 35 mm. cinema projector. Since the principle is little understood, it will be explained here in detail.

Compound lenses, also called raster, honeycomb or composite lenses or lenticular plates are used in nature for insect eyes and have been used for automobile headlamps, airport beacons, exposure meters, flash tube diffusers and as a ten thousand-lens element for the Courtney-Pratt high speed camera.

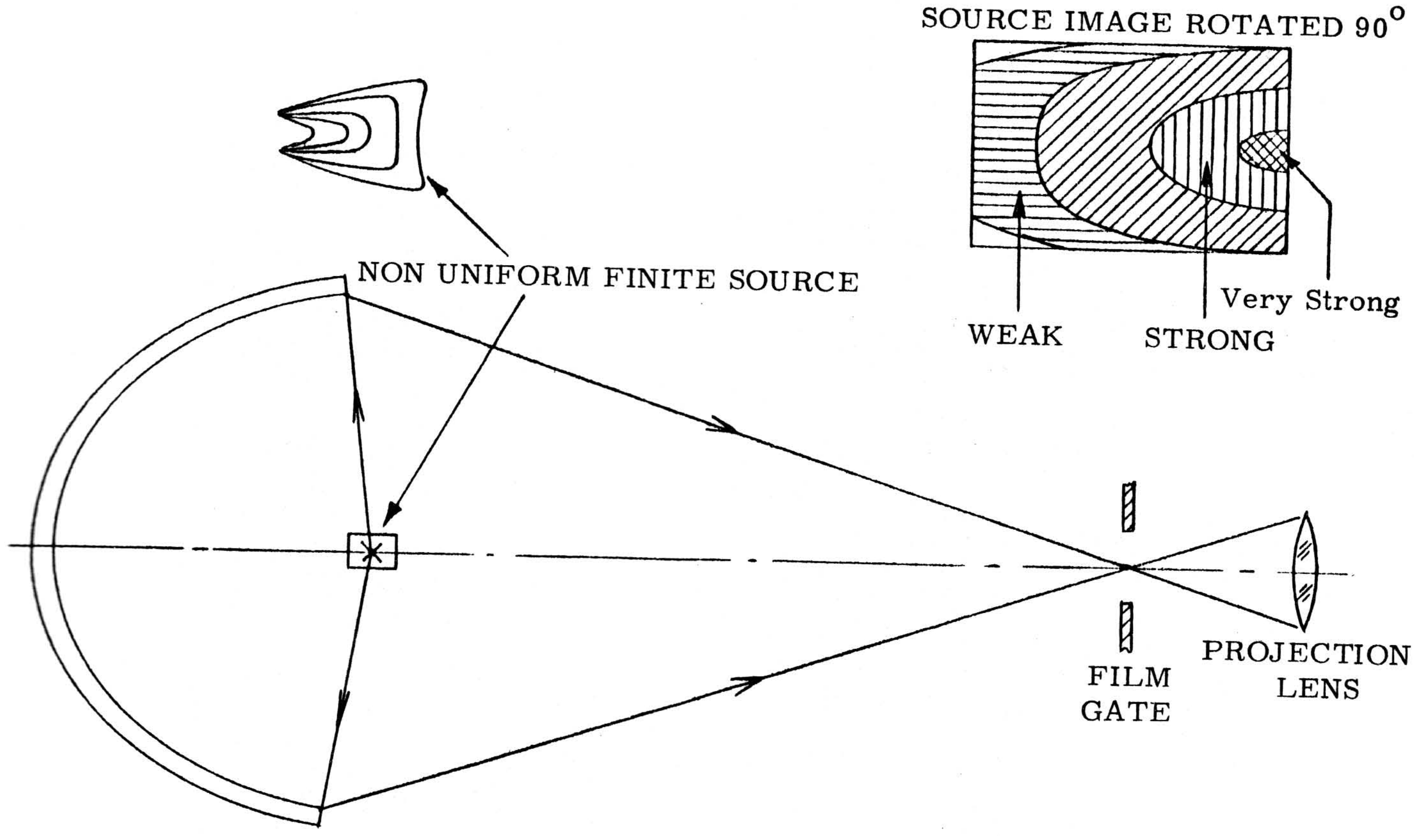
A fairly complicated example is the Zeiss Ikosol lamphouse for the Osram arc lamp. This device allows the very non-uniform arc to be used for 35 mm. motion picture projection. In a typical carbon arc or filament lamp projector an image of the source is formed on the film gate and the screen illumination is an image of the film gate through the projection lens. This system is not suitable for non-uniform sources because the screen will also be non-uniform. This is shown in Figure 7a where the source and source image magnified by the mirror are shown rotated in relation to the optical layout.

The Zeiss solution is to reconstitute the image by means of a honeycomb lens consisting of two plates, one with rectangular elements. These elements are spherical lenses cut to shape. The first plate is placed in the ray paths as shown in Figure 7b.

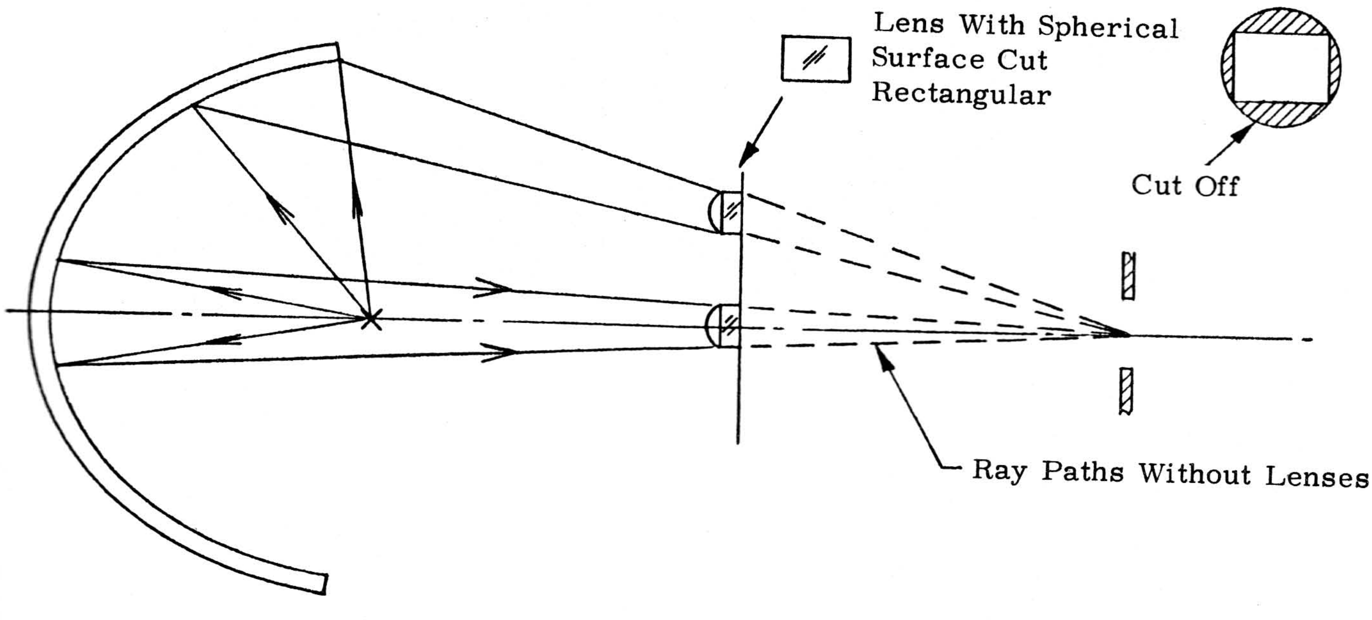
If we consider first a point source as shown in Figure 8, we see that the matrix of rectangular lenses "sees" the illuminated surface of the mirror and effectively divides it into rectangular elements. The film gate illumination is now not an image of the source but an image of the mirror element and will be more uniform. Actually, 163 lenses are used in the matrix. It will be seen in Figure 8 that all the images of the mirror elements automatically superimpose, regardless of their position on the mirror surface even though all the lenses in the matrix are the same focal length.

The rays shown in Figure 8 and Figure 9a are marginal rays. It is helpful to note what happens to the axial bundles shown in Figure 9b. Here we see that the real function of the matrix lenses is to image the mirror on the film gate. Dashed lines show an off-axis bundle of image-forming rays.

With a finite source marginal rays from the edge of the source take the paths shown in Figure 10a. A reduced source image is formed behind the matrix lens and these rays continue to form a displaced light image which is not on the film gate. The result of superimposing many elemental source images from a finite source would be a large fuzzy spot. The introduction of a field lens in the plane of the source images, as shown in Figure 10b, bends the off-axis rays back to the axis. The axial rays since they pass through the center of the field lens are not deviated.



(a) CONVENTIONAL PROJECTION SYSTEM



(b) ACTION OF FIRST HONEYCOMB LENS

FIG. 7

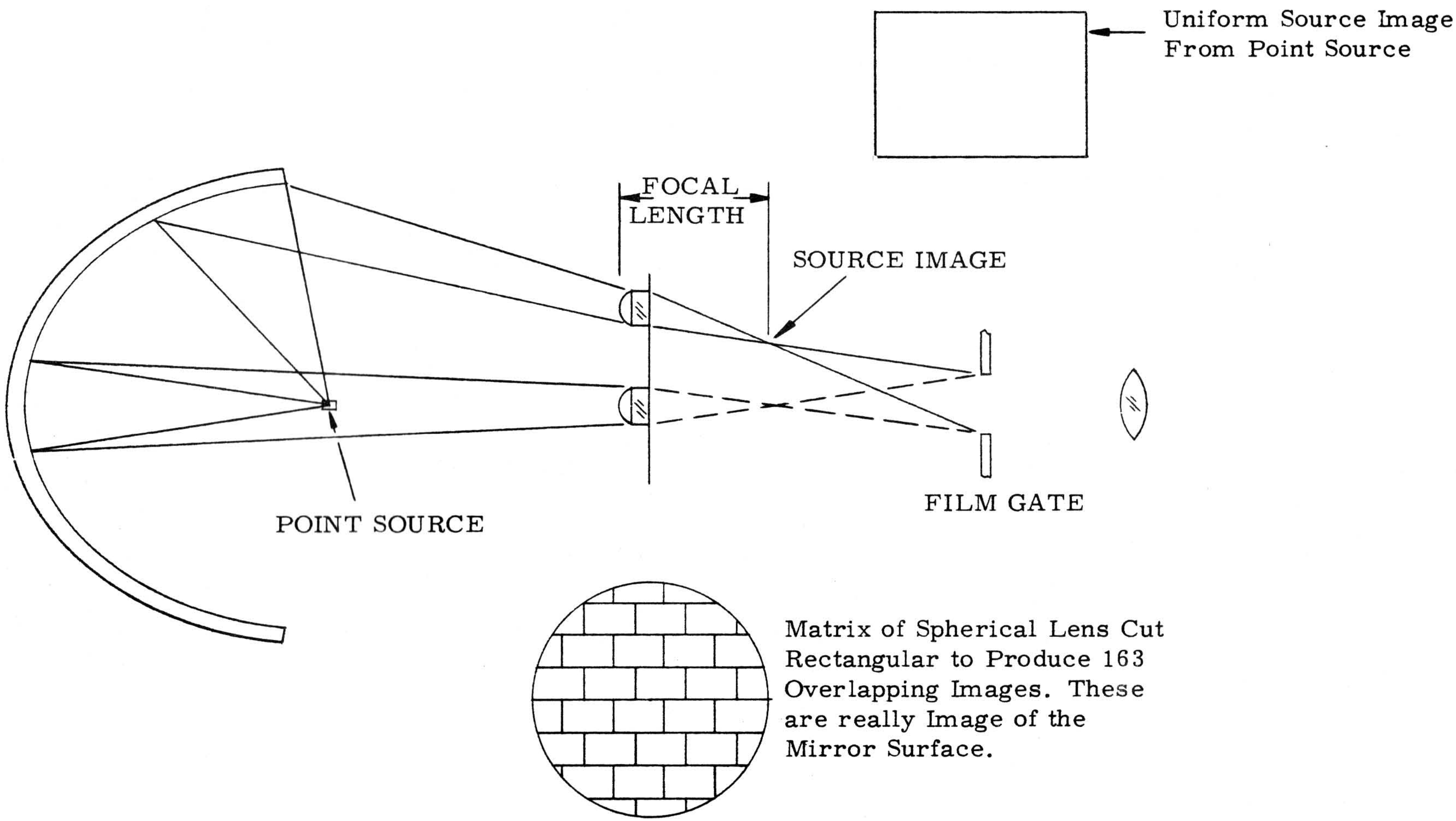
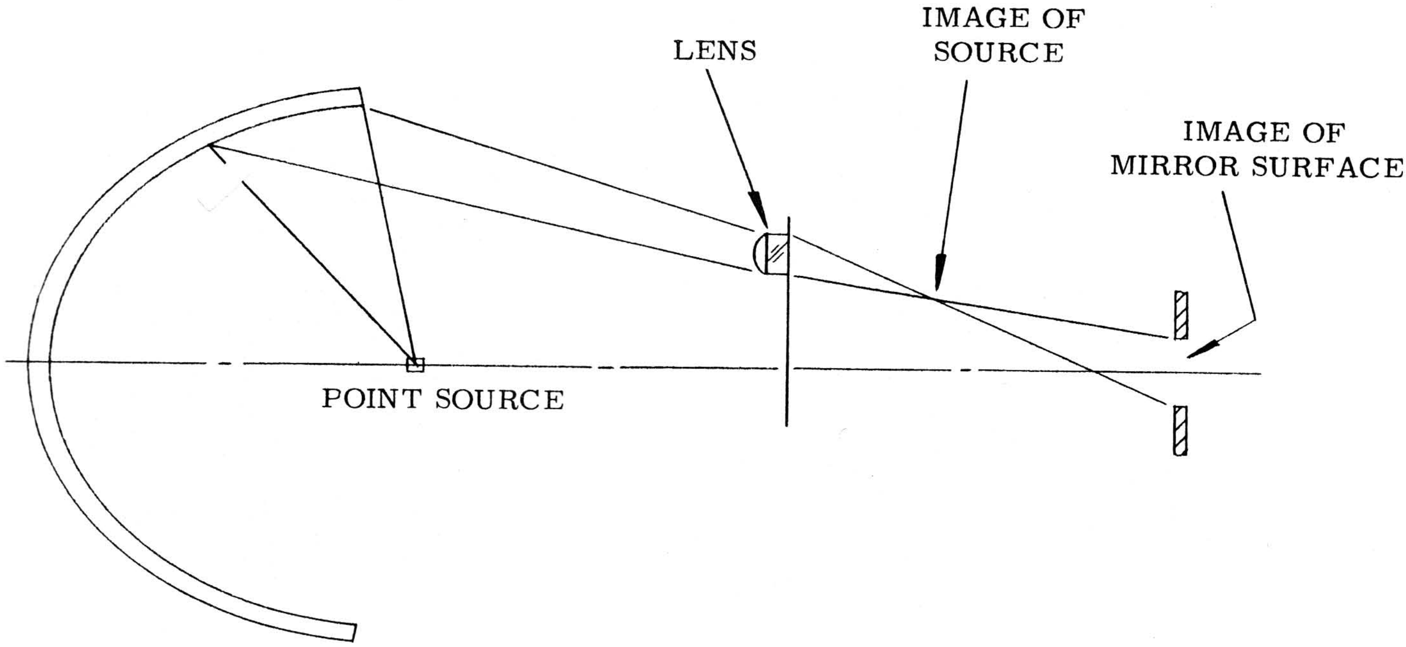
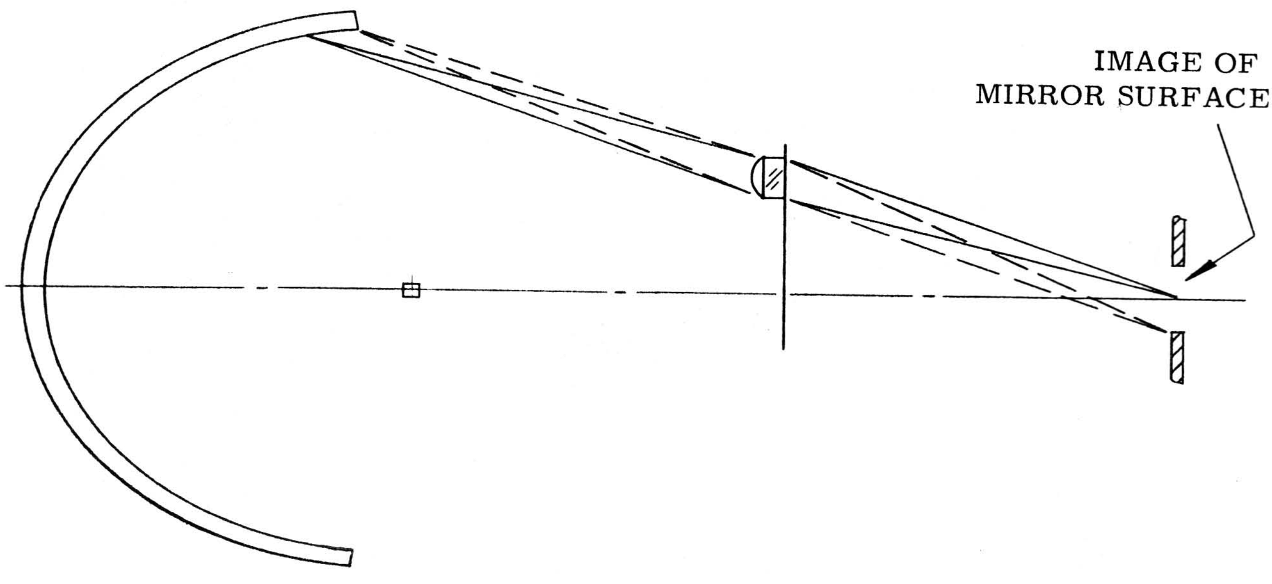


FIG. 8 HONEYCOMB LENS SYSTEM

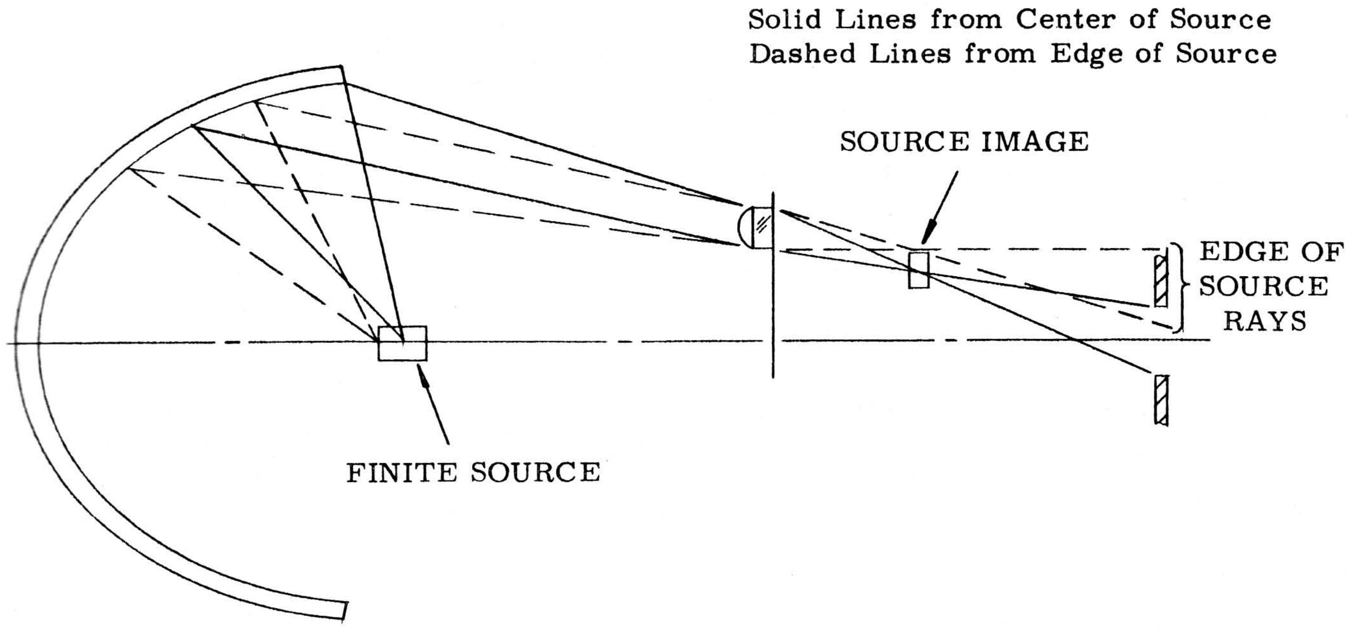


(a) MARGINAL RAYS

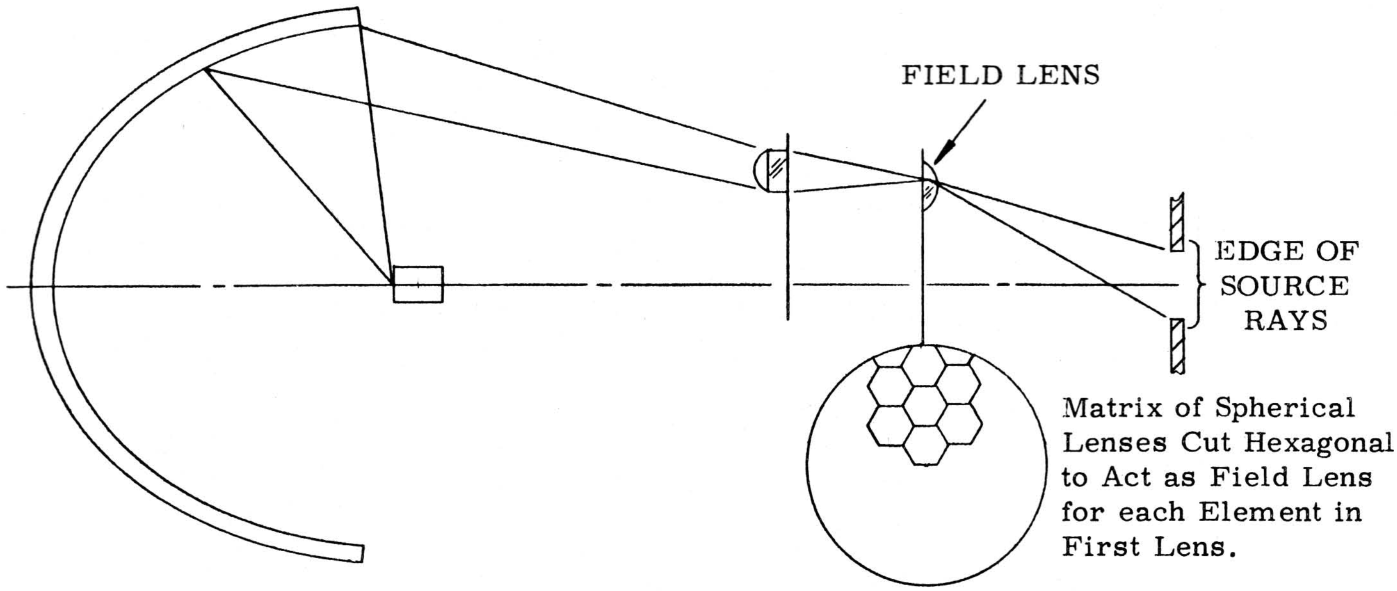


(b) AXIAL AND OFF - AXIS BUNDLES

FIG. 9 HONEYCOMB LENS SYSTEM



(a) WITHOUT FIELD LENS



(b) ACTION OF FIELD LENS

FIG. 10

The reason the illumination at the film gate is rectangular is shown in Figure 11 where it is shown that the field lens images the rectangular matrix lens and hence the image is sharply rectangular. Because there are three overlapping optical systems here, each with image forming and marginal rays and 163 matrix elements, it is difficult to make a single diagram which shows all the things that are happening.

The object of the Zeiss system was to provide a single uniform source image for cinema projection. For multiple-slit schlieren devices the object is to produce several uniform images which become the slits of the system. Where no high degree of efficiency is required and especially where the slits are not wide, the simple arrangement shown in Figure 3c is adequate. A condenser, preferably achromatic, collects light from a concentrated source producing a collimated beam which falls on a compound lens made of cylindrical elements. Each cylinder forms a separate line focus which becomes a concentrated slit source. In every case we have examined it has been necessary to employ a defining or slit plate to sharpen the images of the slit edges and remove unwanted spurious images. These spurious images arise from reflections inside the lamp enclosure and between the condenser elements. The defining plate is a somewhat difficult item to make because the slit spacing must be exactly the same as the spacing of the cylinder lens vertices and it must be adjusted so that the slits are exactly parallel to the axes of the lenses and in their focal plane. It is possible that two-element cylinder lenses corrected for spherical and chromatic aberration would produce slit images well enough defined to dispense with the defining plates. Whether or not this arrangement could be used will depend on the presence and strength of spurious images.

In the case of the multiple-aperture sharp-focusing schlieren system using round holes instead of slits, it is possible to use the Zeiss honeycomb lens as a source to simultaneously illuminate up to 163 apertures. Since the writer is the only known builder of this type of schlieren device, a brief description will be given of one of the methods used to make defining plates. As mentioned above,

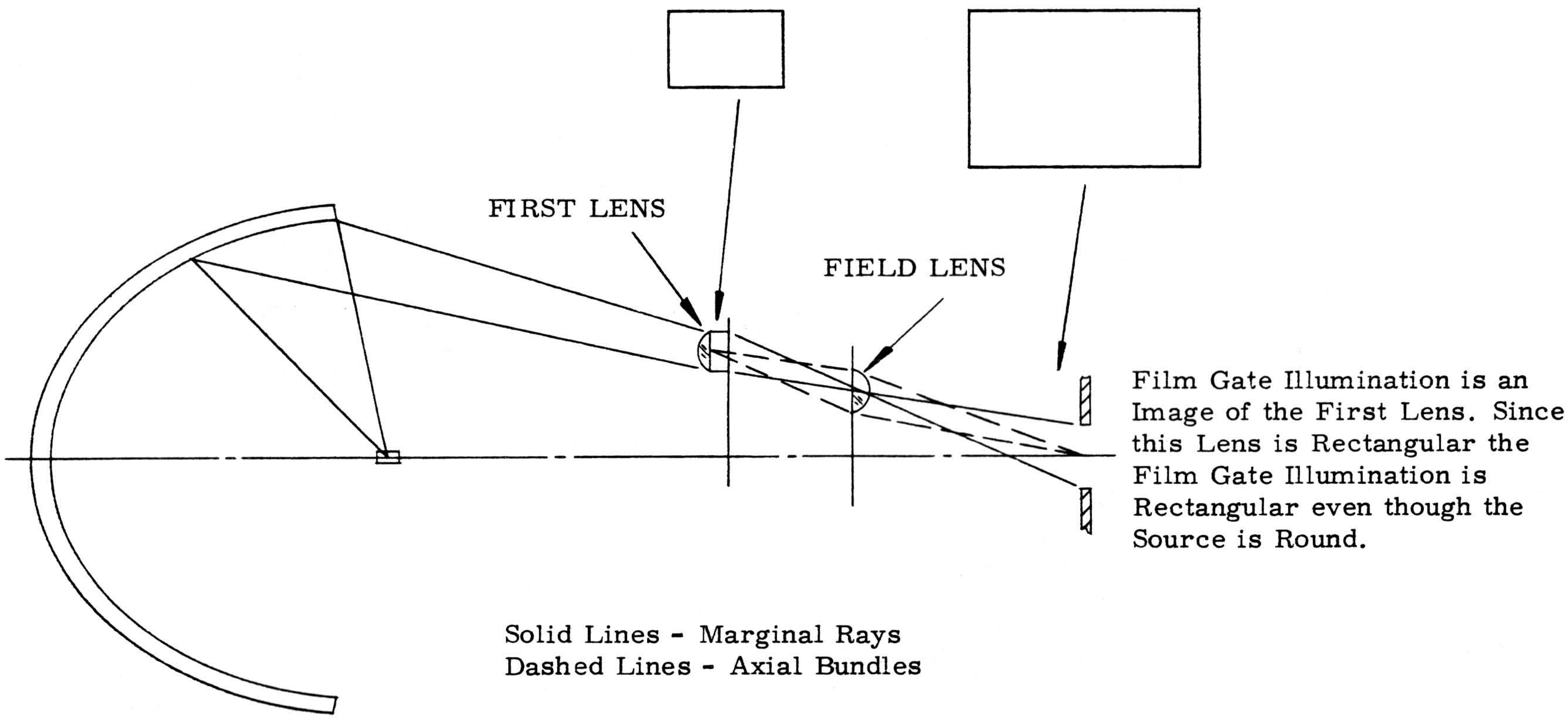


FIG. 11 HONEYCOMB LENS SYSTEM

it may be possible in cases where the lenticular plate is of high quality to eliminate the defining plate. The Zeiss honeycomb lens is of excellent quality for a molded lens, but considered as an optical element it has three serious defects:

1. Some of the facets are poorly formed and produce ill-defined images.

2. Irregularities on the lens surfaces produce "asterated" images with rays or spicules around them.

3. Concave fillets between the hexagonal elements act as negative cylindrical lenses and produce a hexagonal pattern of lines connecting all the image points.

Every one of the above defects is undesirable in a schlieren system where the source should be well-defined and the presence of these defects can be expected to result in loss of sensitivity, spurious optical artifacts in the final image and considerable difficulty in making a satisfactory cut-off plate.

In the sharp-focusing schlieren system where the cut-off plate is made photographically, it would be expected that the photographic process would automatically compensate for the source image defects. For example, it would be anticipated that the cut-off plate would contain a hexagonal pattern of lines which would take out the spurious hexagonal pattern in the image; and it is true that a carefully made cut-off plate will go a long way towards compensating for defects in the lenticular plate. The practical difficulty arises due to the mechanics of the photographic process and the great difference in intensity of the source images focused by the hexagon lenses and the relatively weak spurious images formed by the lens fillets. If the cut-off plate is exposed just enough to give good dense images of the virtual apertures, then the hexagonal pattern will barely show. If the exposure is enough to produce a hexagon pattern that is dense enough to be effective, then the source images will be "irradiated" or grown oversize by overexposure and sensitivity will be lost.

Another difficulty is that these spurious effects, even though stopped or attenuated by the cut-off plate still act to break up the diffraction pattern that would normally form in the aperture of the photographic lens. This can take several complex forms and can produce strange and difficult to explain light distributions in the final image. For example, the Zeiss honeycomb lens with its hexagonal pattern results in an image filled with inscribed squares and rectangles of different intensity. This is another case of a system in which the sensitivity varies over the field and while it does not keep the optical system from showing schlieren phenomena, it makes their interpretation very difficult. As mentioned before, all these spurious effects may be eliminated by the use of a defining plate in the source image plane. For the multiple-aperture system, the defining plate consists of an opaque foil with a circular hole for each source image.

We have used successful techniques to make defining plates, but before this is begun it is necessary to make a rigid assembly of the other illuminator parts - the source, the condenser and the lenticular plate. If this is not done and any subsequent readjustment of the system causes the slightest misalignment of these parts, the source images will no longer fall on their apertures and the result will be little or no light coming through the holes. Once the illuminator parts have been firmly mounted together, a precision holder is made for the defining plate. A typical defining plate is shown in Figure 12. The heavy metal support is for rigidity, the actual defining plate is made from a stretched piece of shim stock soldered to the support. The plate should be marked so that it is always inserted in the same position. It is simple to make the defining plate apertures by photo-engraving; coating the plate with Kodak Photo-resist, exposing to light through the honeycomb plate, developing and etching out the holes. Unfortunately, the resulting apertures will be perfect images of the lens defects and the holes will be badly asterated, that is to say, instead of being uniform round holes they will be star-shaped holes of assorted sizes. The

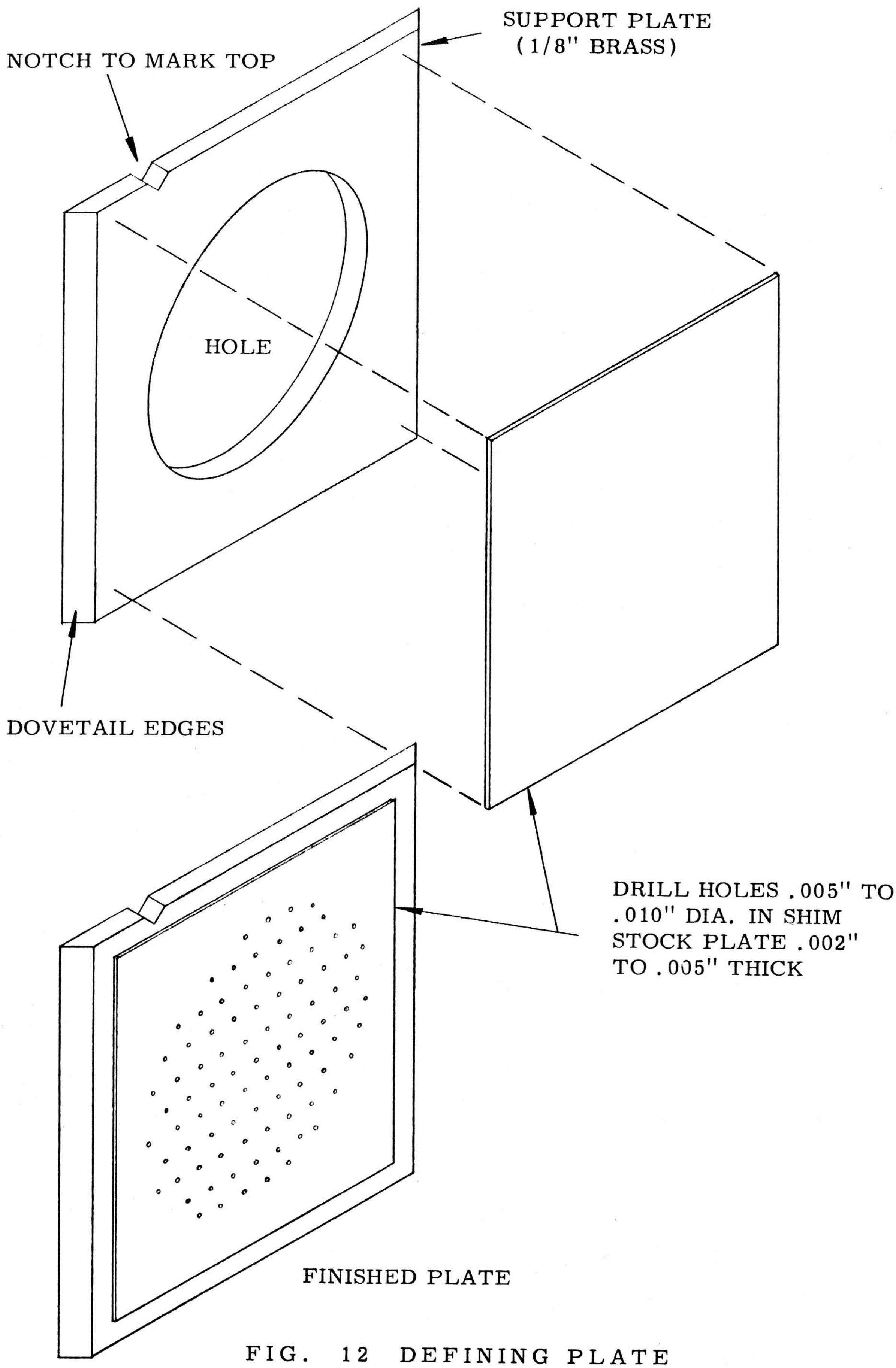


FIG. 12 DEFINING PLATE

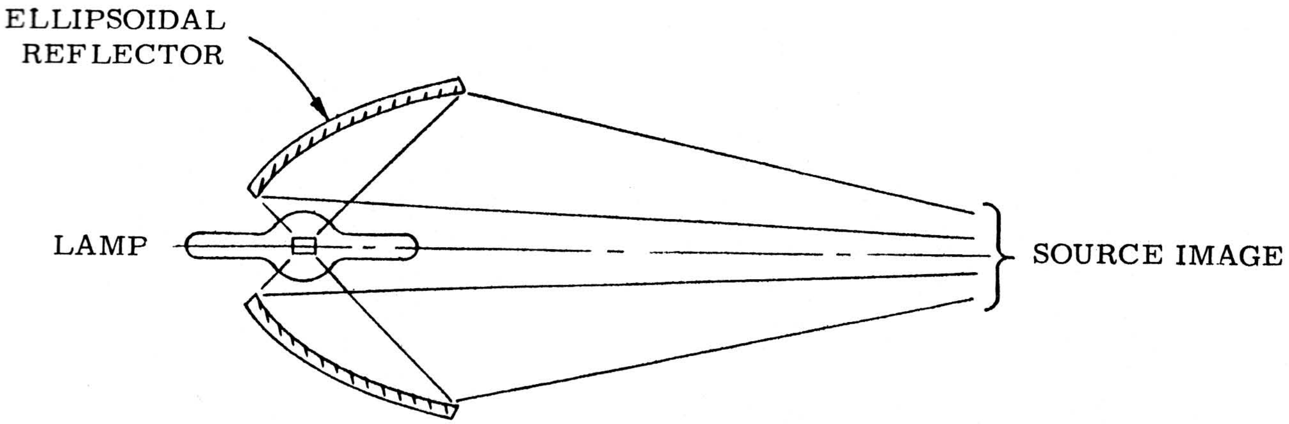
simplest means to obtain round holes has been to expose the Photo-resist coated plate, develop and dye the images and then using a precision micro-drill, mechanically drill out the images. If all this is properly done, the finished defining plate may then be dropped into its holder and the holes will line up perfectly with their images and the defining plate as seen from the schlieren optics will be a geometrical array of many perfectly round uniformly luminous apertures.

Compound Lens Illuminating Systems for Schlieren Projectors

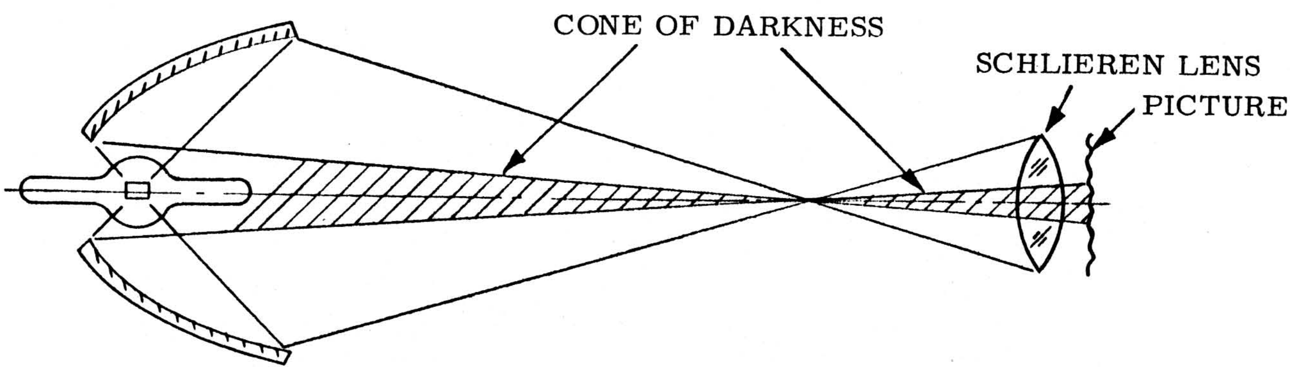
In the case described above it was assumed that the main condenser would collimate the collected source illumination and the compound lenses would be placed in collimated light. This means that the input bar plate will be as large as the condenser aperture. In our schlieren projectors this has been an impractical condition. Up until now we have been forced to use a fairly large working distance (separation of the condenser from the source) and this combined with the extremely wide collection angle results in a condenser aperture of 4 to 6 inches, but the design of the present projectors will not accommodate an input bar plate larger than about 2 inches.

One proposal has been to use a deep ellipsoidal reflector as suggested by Dr. Glenn and pioneered by the Dojun Koki Co. of Japan for theatre motion picture projectors and diagrammed in Figure 13a. One fault of this arrangement when used to illuminate a schlieren system is that the beam has a dark center due to shadowing of the electrodes and this, when imaged by the schlieren lens produces a dark center in the picture shown in 13b. One possible way around this is to use a deep paraboloidal reflector and cylindrical lenses which act to break up the dark center and "homogenize" the light something in the manner of the Zeiss honeycomb lenses. It is doubtful that this arrangement could be made small enough to illuminate the input bar plates in current use.

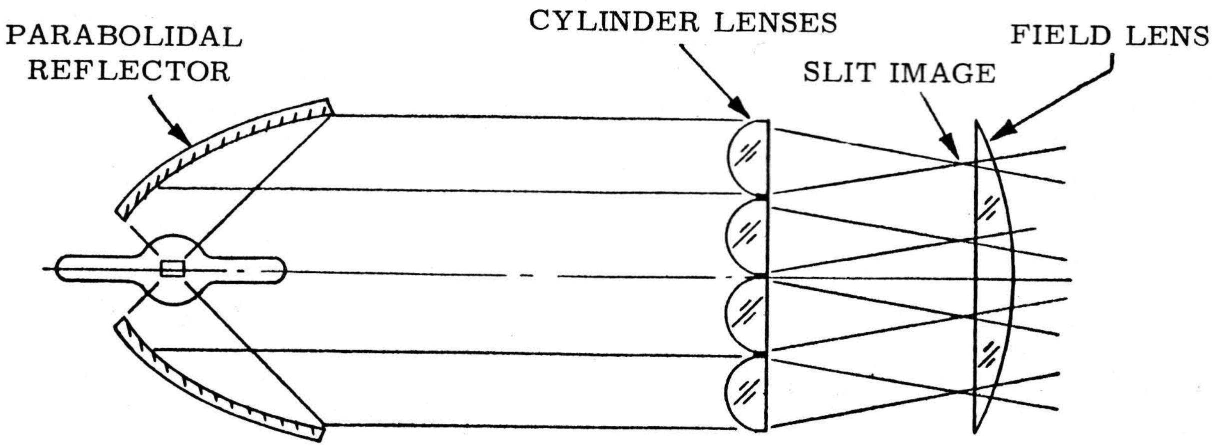
Another proposal is to use an ellipsoidal mirror and place the cylindrical elements in the converging beam either with or without a negative lens as shown in Figure 14. If the cylinders are of short



(a) ILLUMENATOR USED BY DOJUN KOKI, LTD.



(b) CENTRAL DARK SPOT PRODUCED BY AXIAL SYSTEM



(c) COMPOUND-CYLINDER SYSTEM

FIG. 13 MIRROR COLLECTION SYSTEMS

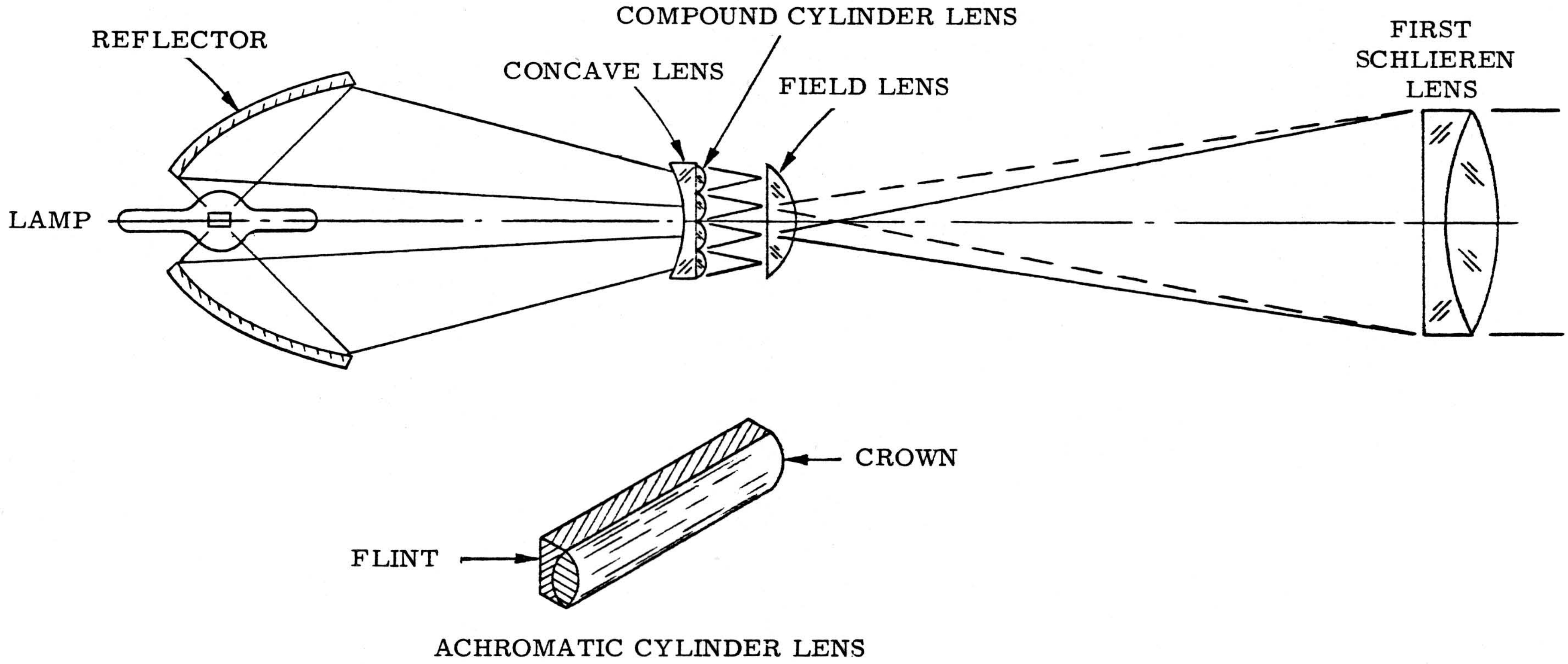


FIG. 14 COMPOUND - LENS PROJECTOR

focal length, they may produce color fringing unless they are achromatized. An optical analysis of this arrangement has been made in another report and in spite of its apparent simplicity it seems to have a number of serious limitations. For systems using a small input bar plate there is little advantage in using a compound lens device to focus the light on the slits or apertures. By using a condenser with high magnification it is possible to fill the bar plate with light having practically the same brightness as the source. Since it is impossible to make the source images brighter than the source, compound lenses cannot increase the screen illumination. At present it appears that the value of compound lenses is to dissect and spread apart the source images so that a small source can be used to illuminate a large bar plate. This is necessary if the available source is too small or it is impossible to produce the required high magnification with a condenser. There is no question that compound lenses properly applied will increase the efficiency of the system where efficiency is defined as the ratio of light on the screen to the light produced by the source, and this may allow the use of a smaller source. In a small system it may be more economical to use a "large" source than to involve the complications of additional parts and adjustments.

To summarize our conclusions, the addition of compound lenses will not produce a brighter screen image than a simple condenser which fills the bar plate with light at the proper illumination angle for the schlieren system. On the other hand, compound lenses can reduce the size of the source required to produce the same screen brightness and this results in an increase in efficiency as defined above. The cost of this efficiency is additional parts and adjustments.

Diffusion-Illuminated System

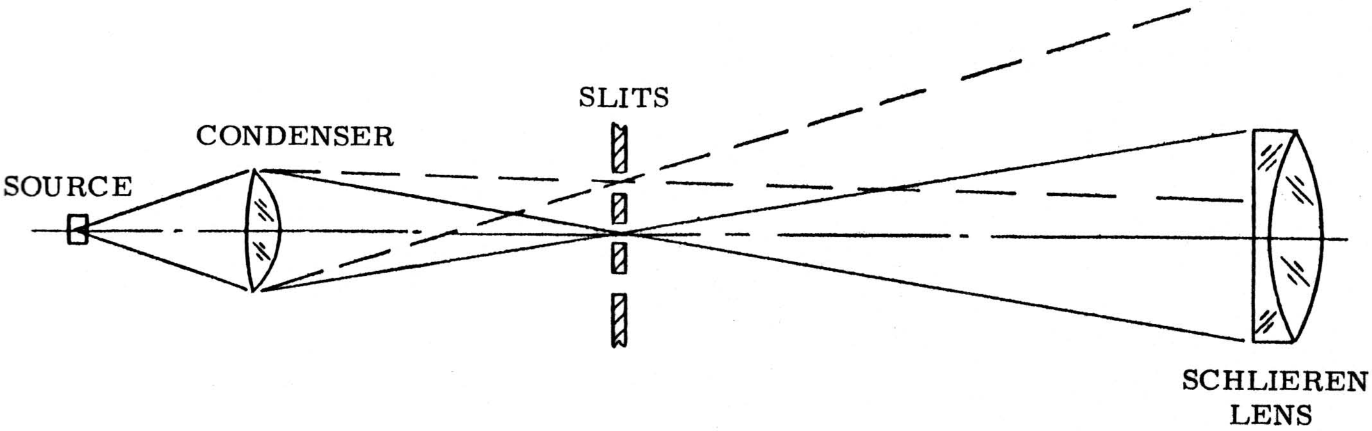
The diffusion-illuminated system diagrammed in Figure 3a uses a scattering medium such as ground glass to obtain the necessary illumination angle at the slits. The scattering function defined as the polar plot of the light distribution produced by the scattering of a collimated beam incident normally, varies with the material and typical curves for common materials can be found in Engineering Optics by Habell & Cox, p. 272 and the Jour. Soc. Mot. and Television Engr., Aug. 1959, p. 521. For most purposes ground glass (actually chemically frosted glass) is a good choice as it has a scattering angle that places most of the light within ten degrees of the axis and this angle is about right for schlieren optics with an aperture ratio of f/8 such as are frequently used in aerodynamic research.

Field Lens

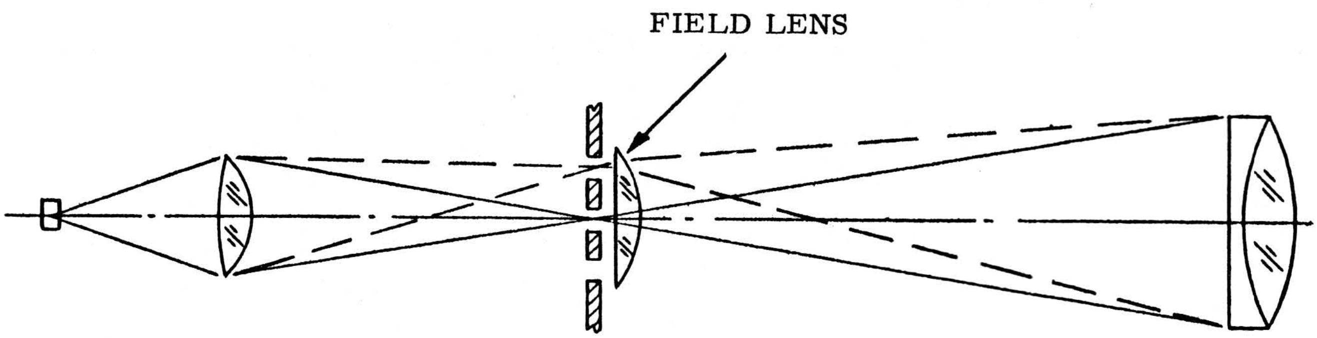
The condenser illuminated multiple-source system usually requires a field lens. Figure 15a shows a schlieren projector without a field lens and it will be seen that the light from the off-axis slits will usually fail to fall on the first schlieren lens resulting in inefficiency and non-uniform screen illumination. The addition of a simple field lens as in 15b is enough to correct this. The design of the field lens in its simplest aspect is simply the selection of a diameter that will cover the slit array and a focal length that will image the condenser on the schlieren lens.

Windows

Since a schlieren system is a dark-field system, it is sensitive to scattered light and the success of any of these instruments depends on clean optical surfaces and lack of internal reflections. It is easy to show that the efficiency of most schlieren systems is so low that the reflections from a single misplaced surface such as a flat window can introduce more stray light in the image than can be produced by the maximum refraction. One of the features of a well-designed system in the absence of refractions, is a field that is truly dark, or at most, only a fraction of a percent of the full-range brightness. Further, the field should be black, that is to say, free of spurious color and free from reflection artifacts. Among the worst offenders in this last category are field lenses and windows. It is usual for this reason to "bend" the field lenses to some shape which will result in two surfaces neither of which will produce a focus or reflection anywhere in the image. Windows can also be bowed though this may result in unwanted changes in the



(a) PATHS OF OFF - AXIS RAYS



(b) ACTION OF FIELD LENS

FIG. 15 FIELD LENS

aberrations and focal points. In general, the best results have been obtained by tilting flat windows so that the surface reflections are thrown out of the light path. This introduces some astigmatism in the image forming rays, but if the window is thin and the tilt angle small, the effect will not be noticed.

Schlieren Optics

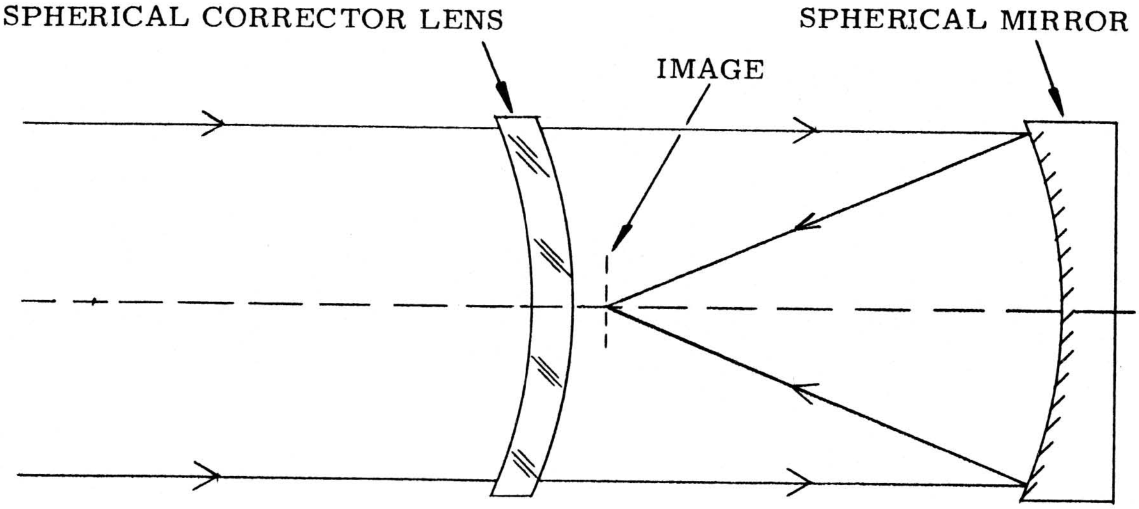
It has been stated many times in the literature that the schlieren optics for the conventional systems must be virtually free from spherical and chromatic aberration. The reason for this is that to obtain high sensitivity requires that the schlieren optics accurately image a narrow slit exactly on a knife edge. Spherical aberration is the defect of optics that causes paraxial rays striking the optical surface in different zones to come to different foci in space. If the optics have this fault, there will be no position where the knife-edge will cut the image cleanly. To obtain a dark-field with a system having this aberration, it will be necessary to displace the knife-edge, or if it be a bar to add "guard bands" or additional width to intercept the aberrant rays. These remedies allow the production of a dark-field, but at the expense of reduced sensitivity, and in the case of a continuous gray scale projector, an altered tone range so that a "gamma correction" circuit may be required. If the guard bands are so wide that they obstruct an appreciable area of the projection lens aperture, then the aberrations will reduce the efficiency and maximum obtainable screen brightness.

Chromatic aberration is the defect of lenses that causes light of different colors to come to different foci in space and its effects are similar to spherical except that the images are "chromatic" or colored. If the knife-edge or bars are placed where they intercept the red image, the blue image will be oversize and will pass the stop forming a blue dark field. If the bars are made with guard bands wide enough to stop the most aberrant color, then refraction will cause the first image that appears to be the color that forms the largest image on the bars. The color of the first refracted image in a single bar system can be predicted from the known aberration of the lenses and the position of the stop, but in the case of multiple bar systems the situation is difficult to analyze because off-axis images have both axial and lateral chromatic aberration which means that different colors not only come to focus in different planes in space but also in images that are different sizes in the same planes. In general, the result will be a more or less monochromatic screen image which may be red at the top and blue at the bottom, but it is also possible to have bands of color across the image, a circular halo of color around the image field, a circular colored spot at the center of the screen and even more complex effects.

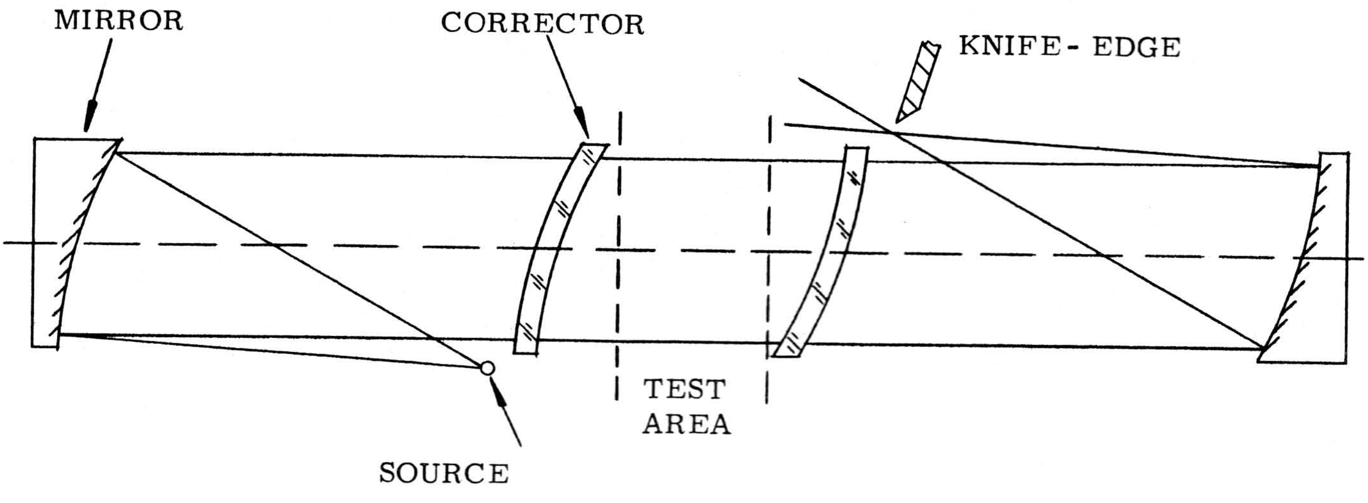
It should be mentioned that the requirements of no measurable amount of spherical or chromatic aberration is for high-sensitivity black and white systems such as those used for air flow studies, and hence practically all large schlieren equipments used in wind tunnels use paraboloidal mirrors which on the optical axis are free of these two aberrations. With lenses it is practically impossible to eliminate chromatic aberration. The term "achromatic" when applied to a lens means that two colors, usually particular wavelengths of red and blue, have been brought to the same spatial focus and it is normal to expect that other colors will not depart but a small fraction of the focal length of the lens from this focus. The axial chromatism of an achromat can be fifty times less than a simple lens with the same aperture and focal length. The residual chromatism, technically known as "secondary spectrum" in an achromat may cause trouble in a high-sensitivity system, particularly if the lens has a high aperture ratio or large diameter. So long as the diameter of an achromat can be less than three inches, residual chromatism is rarely troublesome, but it increases rapidly in large lenses. Spherical aberration can be largely corrected in an achromat by the choice of proper spherical curves, but it cannot be eliminated. The normal design is one in which rays through the center and edge come to a common focus. Rays through other zones may come to a focus ahead (or rarely behind) this focus. In the usual achromat the maximum spherical aberration is located in a zone having a radius .7 that of the lens and this maximum residual is usually termed "zonal" spherical aberration.

Depending on the application, even a small amount of zonal aberration may prove troublesome in a high-sensitivity system. Achromats can be hand-polished to slightly aspheric surfaces to show almost no zonal spherical aberration, but since this is a costly procedure, lenses with machine-made spherical surface are more common. Experience has shown that zonal aberration in an ordinary achromat is negligible so long as the aperture ratio is no greater than f/11. The two requirements of low residual chromatism and zonal spherical aberration largely restrict the use of achromats as schlieren optics in high-sensitivity systems to lenses less than three inches in diameter and aperture ratios not over f/11. These limitations are a large part of the reason why mirror optics are favored for large size and fast sensitive systems. These restrictions do not necessarily apply to our schlieren projectors which would not be classed as sensitive systems compared to the aerodynamic instruments.

Paraboloidal mirrors are made by hand-polishing a machine-made spherical surface until it is the proper contour. For a six-inch diameter f/8 mirror, this amounts to the removal of about 8 micro-inches of glass at the center and none at the edges and tapering the removal process so that there are no detectable transitions. This is not a difficult operation for an expert, but as the diameter grows larger so that the optician cannot easily perform the work manually, the time to perform the work may increase from days to years. If the aperture ratio becomes much less than f/8, then the amount of material to be removed is so great that the slow process of polishing is no longer practical and the tedious procedure of zonal grinding has to be used. Because of the great difficulty of making a true paraboloid faster than f/8, it is becoming increasingly common to use all-spherical catadioptric (lens plus mirror) systems such as the Bouwers or Maksutov design. The principle of the Maksutov design is shown in Figure 16a where all parts have spherical surfaces and can be machine-made to the fairly high aperture ratio of f/4. The spherical mirror alone would have intolerable spherical aberration but for the weak lens or "corrector plate" which compensates for this almost completely. The corrector plate is a very weak lens and produces some chromatism but this is negligible for speeds less than f/4.



a. MAKSUTOV SYSTEM



b. OFF - AXIS MAKSUTOV SCHLIEREN SYSTEM

FIG. 16 CATADIOPTRIC SCHLIEREN SYSTEM

It is often desirable to use a mirror system off-axis to keep the remainder of the optics out of the light path. A typical off-axis Maksutov system as made by the J. W. Fecker Company is shown in Figure 16b. In this case the mirrors and corrector plates look strange because only an outer portion of the total spherical surface is used. As will be seen later, it may be possible to apply the Maksutov system to the Gretener Eidophor projectors using the corrector plates as windows and improve the tone quality, efficiency and possibly the dark field.

The schlieren optics of the multiple-slit systems, particularly those used in the large wind tunnels have the additional requirement for a large angle of view to cover the source array. For this application a photographic type anastigmat is the only kind of lens that is suitable.

Low sensitivity projectors such as used in our projectors and the thermoplastic film process have entirely different requirements from those described for high sensitivity. In the Toepler system we may have a full range of refraction of one minute of angle and a sensitivity of a fraction of a second. In a light-valve projector we are able to produce refractions of 1 to 5 degrees and high sensitivity would be an undesirable feature because it would make visible the air currents in the projector, the striae in the lenses, variations in thickness of the oil film and would considerably worsen the problems of obtaining a dark field with existing electrically conducting films and fluids. Some of our experiments have indicated that if the refraction angle in the control layer could be made as large as 15 degrees that the problem of defects in the raster plate and dust in the fluid would practically disappear, assuming of course, that we do not have an excessive degree of magnification between the picture and its projected image.

While the sensitivity requirement for light-valve projectors is less than the classical schlieren system, there are additional optical requirements that more than make up for it. The input plate which becomes the "object" for the schlieren optics may be so large that it subtends 5 degrees or more, a rather severe requirement for an achromat or pair of achromats. This means that the off-axis aberrations become important, lateral chromatism, coma, astigmatism, curvature of field and distortion.

a. Lateral chromatism is the tendency of lenses to form images in different colors which are also different sizes. With the present 5 degree fields, this defect is unimportant.

b. Coma is the flare of light around the image, most of the stray light being distributed radially from the center of the image. Coma will usually be negligible for these small fields if spherical aberration and astigmatism are controlled.

c. Astigmatism is the property of an optical element that causes lines which are radial and tangential to the field of view to come to focus in different planes. In a bar system the bar that crosses the center of the field is said to be radial, the bar at the edge of the field is tangential and intermediate bars are a mixture of the two. To obtain a good focus on all the bars requires a difference of astigmatic foci which is less than the depth of focus. Astigmatism is doubly important because as mentioned under (b) it can also contribute to coma.

d. Curvature of field which is curvature of the image surface in relation to the object surface is impossible to control in the case of an achromat or a pair of positive achromats. In general the curvature of the image will be approximately spherical, actually ellipsoidal, with a radius about one and a half times the focal length of the lens. If two lenses are used, the curvature is additive and about the same fraction of the focal length of the combination. Thus for a pair of schlieren lenses each having a focal length of 6 inches, the approximate radius of the image surface is 4.5 inches concave toward the lens. If the bar system is over an inch in diameter, the curvature may make it impossible to get the image to focus on a flat output bar plate. Ideally, one set of bars should be bowed to the measured radius of curvature when the curvature exceeds the depth of focus of the lenses. The only lenses that produce flat fields are photographic anastigmats and they do this by means of a fairly strong negative element close to the nodal plane. Undoubtedly, it would be advantageous to adopt this type of construction for light-valve projector schlieren lenses, but it must be done with caution. One of the most important requirements of the schlieren lenses is that they do not cause light scattering or spurious images through reflections from their surfaces. We have found that these "ghost" images invariably fall in the spaces between the output bars and cause odd patterns of light in the dark-field. We have adhered to the principle that in a dark-field system it is best to use the simplest design and the fewest possible elements to avoid these artifacts. Our few experiments using a photographic lens as a schlieren lens have produced unsatisfactory dark-fields because the concave surface of the field flattening element acted as a spherical mirror for light reflected back from the raster plate and this light was focused between the bars and on the screen. It would appear possible to design or perhaps to discover among existing designs for photographic lenses one which would not show this defect, but to date, all our best results have been obtained with achromats in spite of their obvious shortcomings.

e. Distortion is the property of an optical system which forms an image that is not the same shape as the object. A pair of symmetrical achromats produce a negligible amount of distortion in the small fields normally used. If distortion is present, then one set of bars should be shaped appropriately.

The aperture ratio of the schlieren lenses used in projectors is unusually high, often about f/2 for reasons that will be described later. So far as we know there is no source of supply for achromats this fast with acceptably low values of the important aberrations. The General Electric Company has developed three designs which are in current use in several instruments. One, known as the "Jaegers" lenses are a symmetrical pair consisting of two identical three inch diameter, six inch focal length achromats. The second, known as the large "American Optical" lenses are an unsymmetrical pair of

3.8 inch diameter lenses having conjugates of 10 and 5 inches on the two sides. These are described more fully in the section devoted to detailed descriptions of the G-E projectors. The third is a scaled down set of American Optical lenses.

Output Bars

This plate, also known as the cut-off plate presents the following problems:

a. If the first set of bars is staggered as in the Gretener system, then the second set may have to be staggered also to stay in focus.

b. "Guard bands" or additional width may have to be added to the bars beyond their calculated dimensions if there is aberration in the system.

c. If the schlieren lenses produce a curved image, the bar array may have to be curved also.

d. If the schlieren optics produce distorted bar images, the bars may have to be shaped to fit the distorted image.

e. In the dark-field condition all the energy and heat collected by the condensers is focused on the second set of bars. If these bars are small and the energy input large, the bars may become distorted from the heat or even red hot. In the original Gretener system it was necessary to water cool the bars.

f. Means must be found to prevent the light incident on the output bars from being reflected back into the optical system where it can be re-reflected onto the screen. Sometimes black paint carefully maintained is adequate, better means is to make the bars slanted or triangular in cross-section to reflect the non-absorbed light out of the optical path. Probably a system of mirrored bars reflecting the light into a trap would be ideal but has not yet been used. The typical appearance of bar reflections is many small sets of light bars scattered over the screen, but since these images are usually out of focus, it is difficult to locate them and track down the source.

In the construction of a thermoplastic film projector, the bars should be focused with a slide in place as the thickness of the slide determines the optical path length and hence the position of the bar image. Changing the thickness of the slide may require refocusing of the bars to compensate, and this feature should be allowed for in the design of a slide projector.

Projection Lens

The optics of dark-field optical systems are different from a bright-field projector where the rule is that the condensers and projection lens are matched in relative aperture. In bright-field systems it is desirable to make the f number of all the optics approximately the same to obtain the best efficiency and prevent scattered light in the system. In dark-field systems this rule does not necessarily hold, a good example being the dark-field microscope. If a N.A. 0.6 objective (half-illumination angle 37 degrees) is used, it is necessary to have a condenser system which is considerably faster, about N.A. 1.0 (half-illumination angle 90 degrees) in order to get any light in the image since the central 0.6 is completely stopped by the central disc comparable to the Toepler schlieren stop. For the same reason, the aperture ratio of the schlieren projector lens may bear little relation to the aperture ratio of the other lenses in the system. The following requirements are noted:

a. The back focus must be adequate to cover the distance between the output bar plate and the raster plate.

b. The equivalent focal length must be adequate to give an image the desired size at the required distance. The back focus of the normal projection lens is about .7 its focal length. When it must be greater than this special designs can be used.

c. The aperture of the rear element of the projection lens must be as large as the output bar plate. This factor and the focal length determine the aperture ratio of the projection lens.

d. The image quality must be adequate. For narrow fields of 20 degrees or less, projection triplets such as slide projector lenses are satisfactory. For wider fields a more complicated lens such as a Tessar or other photographic lens should be used.

e. The lens must be capable of standing the heat absorbed when it is used as a projection lens. All camera lenses are not designed with this in mind and the glass elements may break from thermal shock or become separated if they are cemented.

f. In the Gretener system to be described, the picture is formed on a concave surface. To project this on a flat screen requires a special lens. Such lenses are not too difficult to design, but they are not commercially available.

g. The lens should show low distortion. This is partly to prevent the appearance of a distorted image which may be objectionable, but more important to prevent "double imaging". When an optical system shows appreciable distortion and its aperture is obstructed by bars or other stops and these stops are located asymmetrically in relation to the optical axis, then the lens will produce two separate differently distorted out of register images, an unpleasant defect. The double image should disappear when the bars are perfectly symmetrically located, but in practice this becomes difficult because of the additional requirements of alignment of the output bars with the images of the first set of bars. All reversed telephoto lenses show some distortion and should therefore be used with caution.

SYSTEM DESIGN

High Sensitivity Schlieren System

The design of classical schlieren systems is well covered in the articles of N. Barnes of G.E.L. which were published in Journal of the Optical Society of America, 1945, p. 497, and Society of Motion Picture and Television Engineering, October 1952, p. 500 and December 1953, p. 487. These articles not only discuss design features but also list a bibliography of over 200 items. The most recent bibliography which also covers multiple-source, sharp-focusing and interferometer schlieren is to be found in AGARDograph #23 published by the NATO Advisory Group for Aeronautical Research and Development and titled, "Optical Methods for Examining Flow".

The optical layout which Barnes and many others have favored for high sensitivity is shown in Figure 17. The two identical f/8

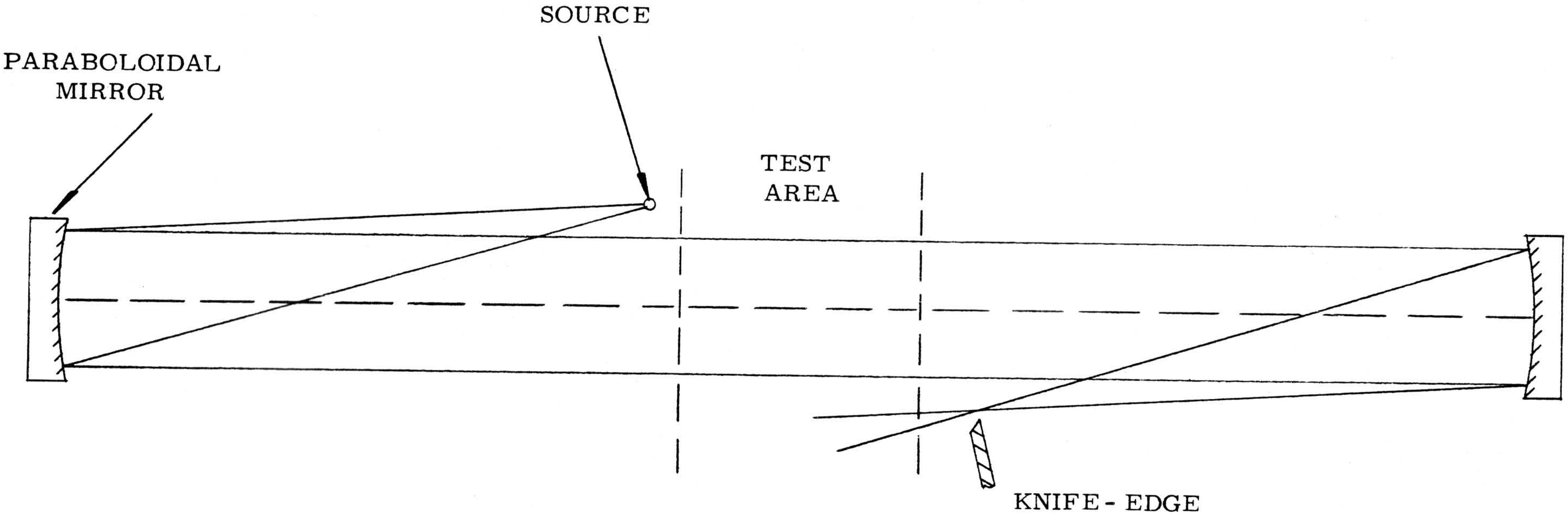


FIG. 17 TWO PARABOLOIDAL MIRRORS USED OFF - AXIS

paraboloidal mirrors are used off-axis. In a single mirror this would produce rather bad astigmatism, but a pair arranged as shown have aberration of the opposite sign and it is virtually compensating. Beyond five degrees the compensation is less perfect and this and the problem of making high aperture paraboloids largely limits the design to speeds not over f/8.

A faster off-axis system that is simpler to make is the Maksutov design as shown in Figure 16b where speeds of f/4 are obtained.

The design of the system is usually arrived at from consideration of the following parameters:

1. The required sensitivity is normally specified. If it is in terms of functional sensitivity such as minimum temperature change detectable, then it will be necessary to calculate the optical sensitivity. Assuming a single slit and knife-edge and "perfect" or diffraction limited optics, it is possible to calculate the focal length required to produce this sensitivity.

2. The size of the test area will determine the size of the optics. The diameter and focal length of the optics determines the relative aperture.

3. The minimum exposure time to take a photograph is often specified and from this, the film speed and relative aperture it is possible to estimate the required source brightness.

4. If the negative size is specified this will determine the focal length of the photographic lens. The aperture of this lens is determined by the length of the knife-edge illuminated by the source.

Schlieren Projector System

The requirements are different from above in that relatively low sensitivity in terms of degrees rather than minutes or seconds is in order, but the specification of high and uniform screen brightness is difficult in any dark-field system.

Detailed examples of specific designs will be given later, but the general procedure used by the writer is as follows:

1. The maximum refraction angle must be known. A white screen is produced when the entire raster is written at the maximum refracting angle and this angle is the same as the full-range sensitivity. The maximum refracting angle then becomes the angular subtense of the spaces between the bars.

2. The specified raster size determines the diameter of the schlieren lenses. When the raster is in contact with one of the schlieren lenses then the lens needs to be only slightly larger than a circle which will circumscribe the picture. If there is considerable separation then the lens may have to be considerably larger. The best illumination uniformity is usually obtained with the raster close to the schlieren lens and this condition will be assumed.

3. If the size and distance of the projected picture are specified, then the projection angle and focal length of the projection lens can be found. The back focus, defined as the separation between the rear lens elements and the raster for a conventional projection lens is about .7 the focal length, this determines the separation between the raster and the back of the lens. Usually the output bars are as close to the back of the projection lens as practical while leaving space for the lens to focus. Ideally, the bars should be inside the lens at its nodal plane, but this has several drawbacks:

a. It is difficult to arrange mechanically.

b. The bar images will be distorted by the rear elements of the projection lens and the bars will have to be distorted to match.

c. The location of the bars may result in a heat dissipation problem.

d. Reflections from the bars may be re-reflected in the rear lens elements.

e. A new means for focusing the projector lens will have to be found. The space between the lens elements is usually quite limited and the lens cannot be focused without moving the bars. This can be arranged by having a special lens in which the rear elements are stationary and focusing is accomplished by moving the front element only.

The output bars are assumed to be just behind the projection lens. If they are far from the lens they will show in the picture as dark bands. Assuming the raster is close to the second schlieren lens, the distance from the schlieren lens to the bars can be calculated. This will be the focal length of the second schlieren lens.

4. The diameter and focal length of the schlieren lens determine its relative aperture. Assuming a 35 mm. picture is to be projected with a 5 inch focal length lens, then the diameter of the schlieren lens should be about 1.9 inches and the focal length 3.5 inches which requires an f/2 schlieren lens. If the relative aperture of the schlieren lenses is unreasonable, it may be necessary to separate the raster from the schlieren lens or to use a reversed telephoto projection lens to gain more separation.

In light-valve systems it is also necessary to allow space between the raster and output bars for the electron gun. Assuming the gun is off-axis the distance required will depend on the maximum angle the gun can be placed off-axis and the size of the gun.

5. The actual width of the spaces between the bars can be calculated from their angular subtense and the separation of the raster and bars.

6. The permissible size of the bar array is determined by the usable field of the schlieren lenses. In the case of achromats it is limited to about 10 degrees total and certainly not over 15 degrees or there will be trouble with off-axis aberrations and image curvature. When the size of the bar array and width of the spaces is known, the output plate can be designed. The usual practice is to make the bars and spaces equal, this is inefficient but our best compromise at present.

7. The diameter of the rear element of the projection lens must be large enough to accept all the refracted light passing the output bars. The lenses for schlieren projectors are therefore chosen for the diameter of the rear element rather than relative aperture, though these two bear a close relationship.

8. The first schlieren lens will have the same diameter as the second, but not necessarily the same focal length. The advantage of a symmetrical system is that the two lenses and two bar plates are interchangeable, but this may be less important than the ability to utilize a larger source image. In a symmetrical system the source image has to be the same size as the output bar plate, but by making the focal length of the first schlieren lens twice that of the second, a larger source image can be used and the aperture ratio of this lens is reduced. In the example that follows a symmetrical system is assumed and the input bars will then be the same size as the output bars.

9. The collective system must produce a uniform spot of light which covers the input bars and the illumination angle must be the same as the acceptance angle of the first schlieren lens. In our example the lens is f/2 and the illumination angle is 28 degrees.

10. When the illumination angle and source size are known, it is possible to calculate the maximum collection angle at the source by the approximate relation:

$$\frac{\text{Tan } 1/2 \ \text{ Collective angle}}{\text{Tan } 1/2 \ \text{ Illumination angle}} = \text{Magnification source image}$$

In our example the illumination angle is 28 degrees. The source is assumed to be a 500 watt tungsten filament 8 mm. square and it will have to be magnified three times to fill the one inch diameter bar array. The resulting collective angle is 74 degrees which allows the use of standard slide projector condensers.

CALCULATION OF EFFICIENCY

Once a projector has been designed on paper it is possible to estimate the screen illumination. This is not as easy as it would appear, and without experience it is possible to err a hundred percent or more in either direction. Before undertaking the rather complicated calculation of a schlieren projector, the inexperienced reader should follow the method used by Osram in some of their early publications and explained below.

Figure 18 shows a cinema projector using a tungsten filament lamp and a condensing lens illuminator. The bars and figures under the diagram indicate the relative light flux at various points in the system. The source is a 1000 watt projection lamp with a filament 10 mm. square and an output of 28,000 lumens. The flux at the source is 100%. The projector lens is f/1.8 which means it will require an illumination angle from the condenser of 32 degrees. To enlarge the 10 mm. filament to .8 inch to cover a single 35 mm. frame requires 2.2 times magnification and the collective angle at the source then becomes about 64 degrees. While this angle is large enough to fill the aperture of the projection lens on axis, without a field lens the illuminating bundles at the edge of the film gate will be oblique and only partly fill the projection lens. There is a formula to calculate the excess illumination angle at the condenser to fill a known projection lens aperture, or it can be found by making a layout of the ray paths. In this case it was found to require a 70 degree collection angle and a 34 degree illumination angle to prevent vignetting at the film gate.

The first problem is to calculate the percentage of the source flux that will fall on the first condenser. For a point source this would be simple, but for a flat array of coiled filaments it can only be found by experiment or reference to the manufacturer's literature which sometimes shows polar curves. From these curves the energy in the solid 70 degree angle can be estimated and in this case it is 20%.

The condensers have four surfaces, each of which if uncoated will reflect and presumably lose about 5% of the light, or a total of about 20% for the four surfaces. There will also be absorptive losses, especially if the condensers are of Pyrex glass. Both losses can be measured in the laboratory, but in the example it is assumed that with non-coated Pyrex lenses 50% of the light incident on the first condenser will be transmitted by the second. This .5 times the 20% collected results in the figure of 10% for the illumination beam.

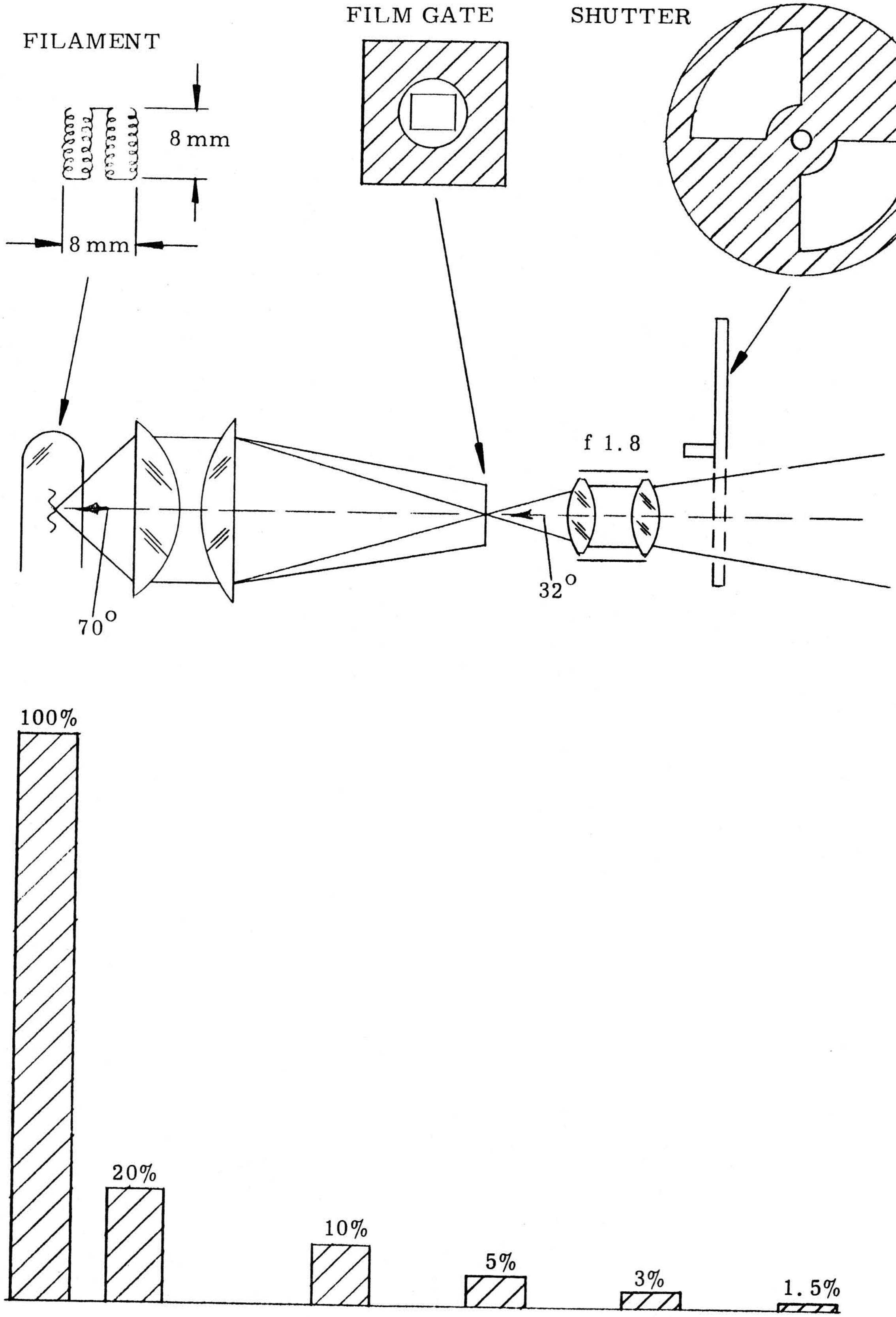


FIG. 18 EFFICIENCY OF CINEMA PROJECTOR

The spot of light falling on the film gate is round and somewhat larger than a circumscribed circle around the film aperture. The rectangular aperture has only half the area of the illuminated spot. If the illuminated spot were uniform, then the film gate would transmit half the light or .5 times 10% or 5%.

The reflection and absorption losses in the projection lens reduce the transmitted light to 3%.

The rotating projection shutter which is opaque over half its area reduces the projected light to 1.5%. All of this should fall on the screen. If the output of the lamp was 28,000 lumens, then the screen illumination should be 420 lumens. If the screen size is 40 square feet (5 by 8 feet) the illumination level would be 10.5 foot candles with no film in the projector - an acceptable value.

Since the screen image is an enlarged image of the source, the only three ways to make it brighter are to use a brighter source, use faster lenses or reduce the losses. An example of the first means is shown in Figure 19 in which a brighter carbon arc is used. Since the carbons are only 8 mm. diameter, the source is not only brighter but smaller. A larger collection angle can be used.

The calculation of efficiency of schlieren projectors follows the same procedure and examples will be given with the detailed descriptions of the instruments.

VARIANT SYSTEMS

This section is included to show some of the forms that schlieren equipment can take. All of these are too recent to be included in the classic Barnes' bibliography referred to earlier.

Stereoscopic

Three-dimensional systems have been built, though they appear to show few advantages. One is described as, "High Speed Stereoscopic Schlieren System", J. Hett, Jour. Soc. Mot. Pictures and TV Engineers, Feb. 1951, p. 214. This device is a conventional schlieren system using two parabolic mirrors except that the beam has been divided, separated and sent through the test area at two different angles where it is recombined at a single knife edge. Stereoscopic motion pictures of explosion phenomena have been made.

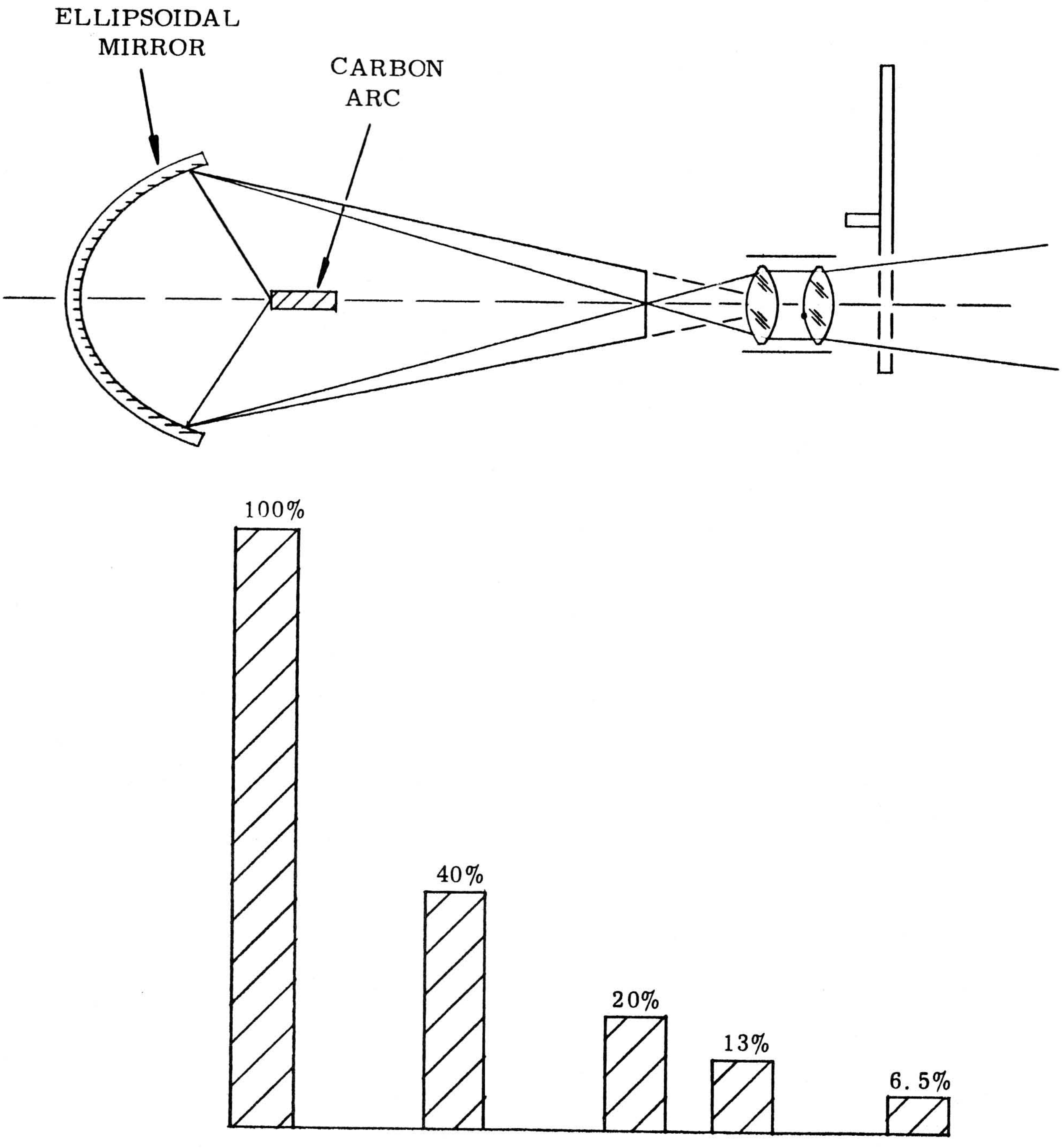


FIG. 19 EFFICIENCY CINEMA PROJECTOR

Wide Range

In the classical Toepler dark-field system shown in Figure 1 and described by H. Antweiler in Zeit. Fur Electrochemie, Vol. 44, p. 719, the dynamic range of the system is the range of refraction which exists between just barely perceptible movement of the spot of light off the stop to complete displacement. Further displacement produces no change as the dynamic range has been exceeded. In multiple-slit systems care must be taken that the range is not exceeded else the displaced light images may fall on the next set of bars. Several ways to increase the dynamic range are described in, "A Wide Range Schlieren System", H. Jefree, Jour. Scient. Inst., Jan. 1956, p. 29.

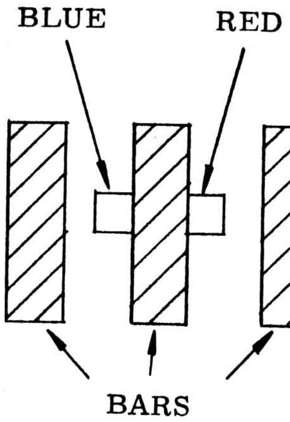
Two devices which extend the range of black and white photography are exponential instead of parallel slits and knife-edges that consist of neutral density wedges. The clear end of the wedge is near the knife-edge and the density increases with displacement of the image. Jefree also describes exponential multiple-slits and multiple-exponential multiple-slits.

The range can also be extended through the use of several color devices to be described under that head.

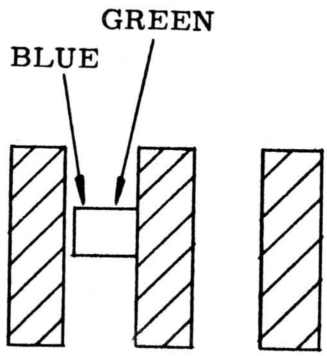
Color

Color can be introduced into a schlieren system in several ways and for several purposes. A color system which increases the dynamic range is described by Jefree as referenced under Wide Range systems.

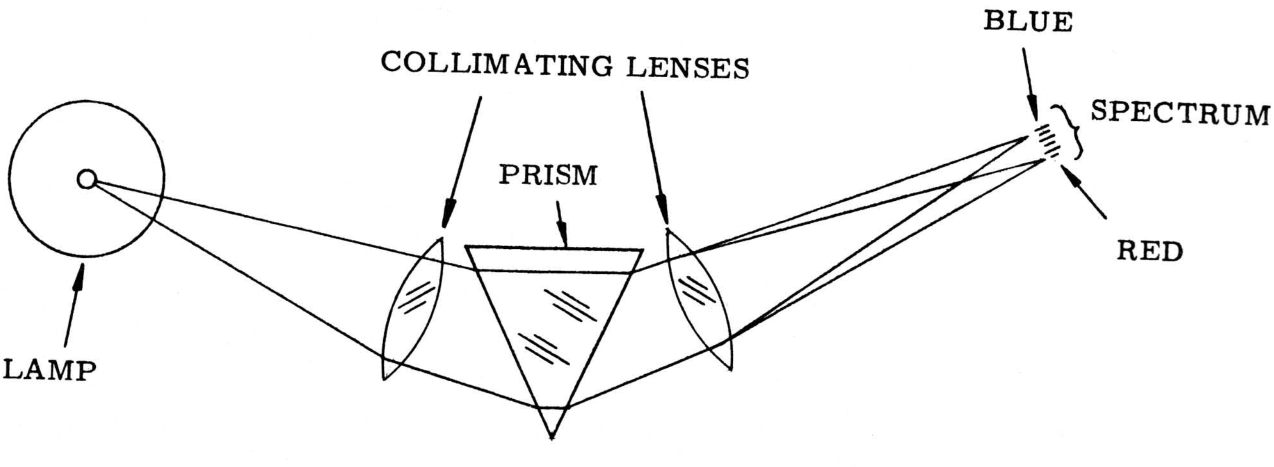
In one of these, a spectrum or other band of color produced by the source is normally centered behind the output bar as shown in Figure 20a. Under this condition the field is not dark, but filled with red plus blue or purple light. An event which causes a refraction which displaces the spectrum to the left as shown in 20b will cause the objects shown to change to blue-green. If the displacement is continued, the color will change in a predictable cycle until the spectrum is partly covered by the second bar and then the cycle will repeat. This gives a great dynamic range. If the displacement is to the right, similar cycles take place, but in different color



a. SPECTRUM - CENTERED



b. SPECTRUM DISPLACED TO LEFT



c. SYSTEM TO PRODUCE SPECTRUM

FIG. 20 COLOR SCHLIEREN

order. The combination of effects allows both range and direction to be recorded. Direction in this case is equivalent to increase or decrease in refraction.

One way to produce the spectrum is shown in 20c. A line source such as a .006" diameter straight filament sound exciter lamp is used with a simple spectroscope to produce a spectrum about one-sixteenth inch long. The complete apparatus is shown in Figure 21 which shows a telescope used to observe the effects.

The band of color can also be produced by combining three or more color filters such as red, blue and green or by using a photographic color transparency of a spectrum.

An unusual color system is described as "Color Schlieren System for High Speed Photography", G. Hays, Jour. Soc. Mot. Pictures and T.V. Engineers, June 1957, p. 355. The layout is shown in Figure 22a. The source is a 100 watt zirconium arc, the schlieren lenses are non-achromatic, but spherically corrected, the knife-edge is the camera lens iris specially mounted so it can be decentered. Since the schlieren lenses are simple lenses, they produce considerable axial chromatism so that red comes to a focus beyond blue. If the knife-edge is off center and arranged to cut off the blue light as shown in 22b, the undisturbed field will be bright and colored red plus green or a sort of tan color. A refractive change which moves the cone of light downward will cut off the blue and yellow leaving the background red. If the cone of light moves upward, the red will be cut off by the upper knife-edge and blue and yellow will pass giving a green background.

The value of this system is that color change will indicate the direction of refractive index variation and the addition of color makes it simple to distinguish between schlieren effects which occur in color and image defects such as flaws in the windows which will be in black and white.

A second color system similar in principle is described as "A Schlieren Apparatus Giving an Image in Colour" by Holder and North, Nature, March 15, 1952, p. 466. Their arrangement is shown in Figure 23.

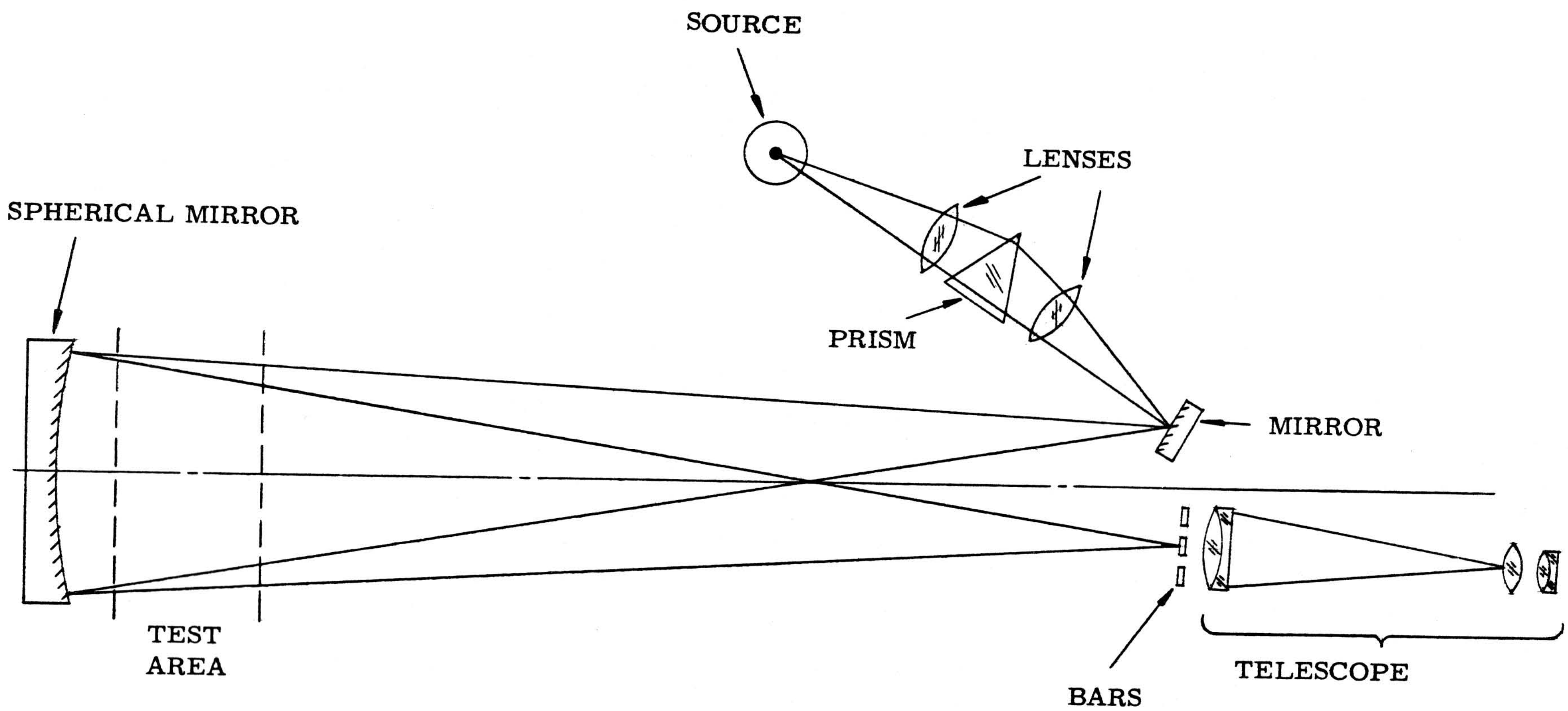
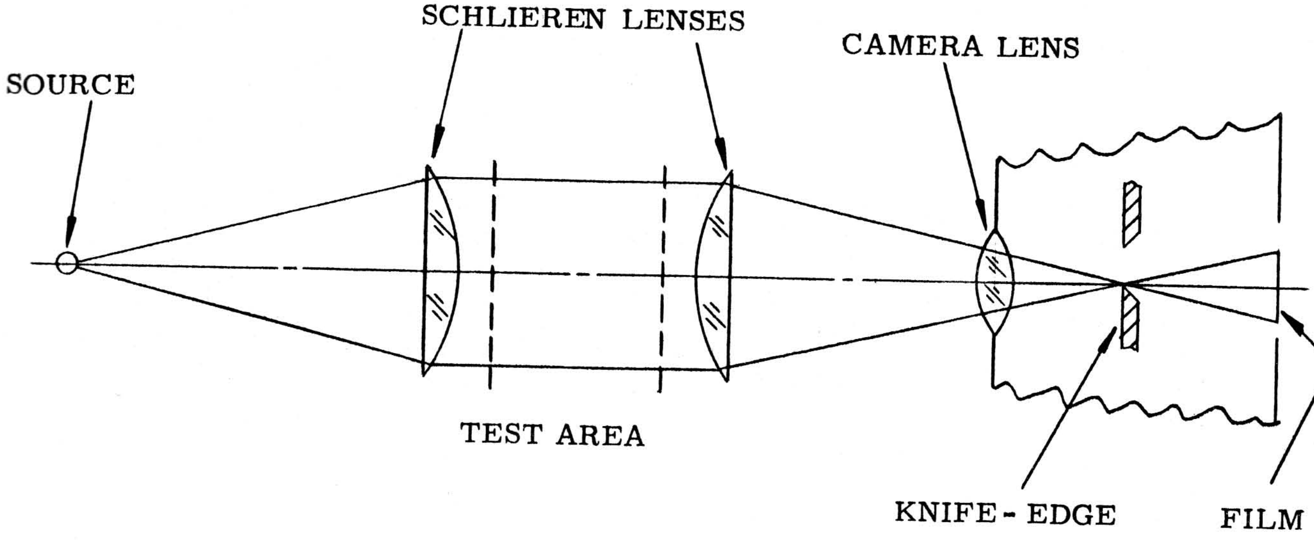
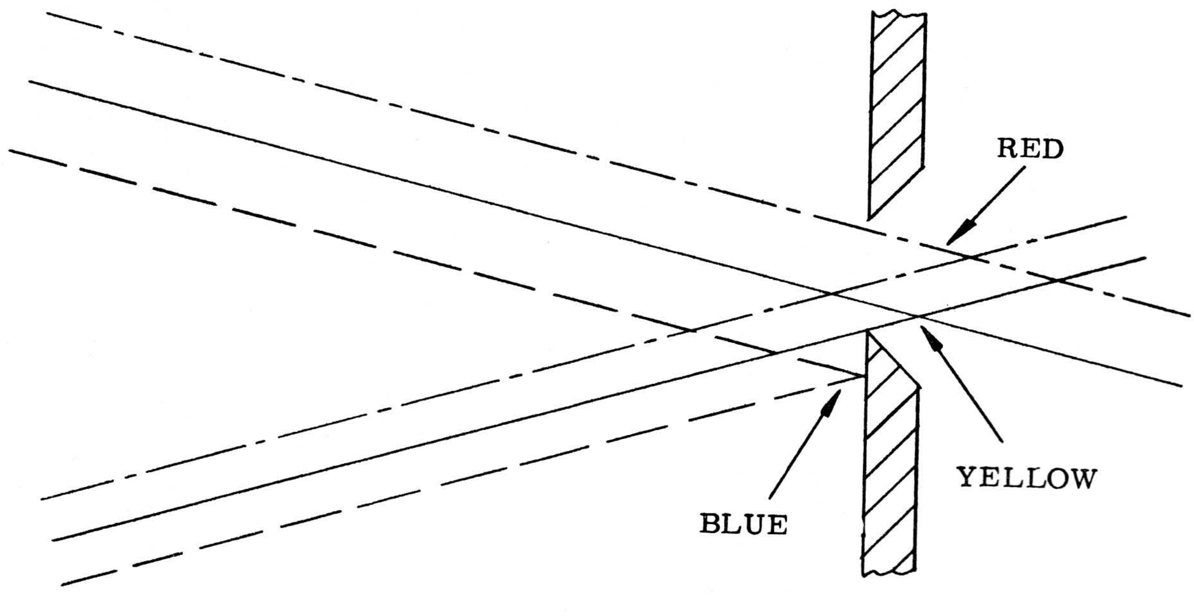


FIG. 21 COLOR SCHLIEREN SYSTEM



(a) LAYOUT OF COLOR SCHLIEREN APPARATUS



(b) KNIFE - EDGE (IRIS) ARRANGED TO CUT-OFF BLUE

FIG. 22 COLOR SCHLIEREN

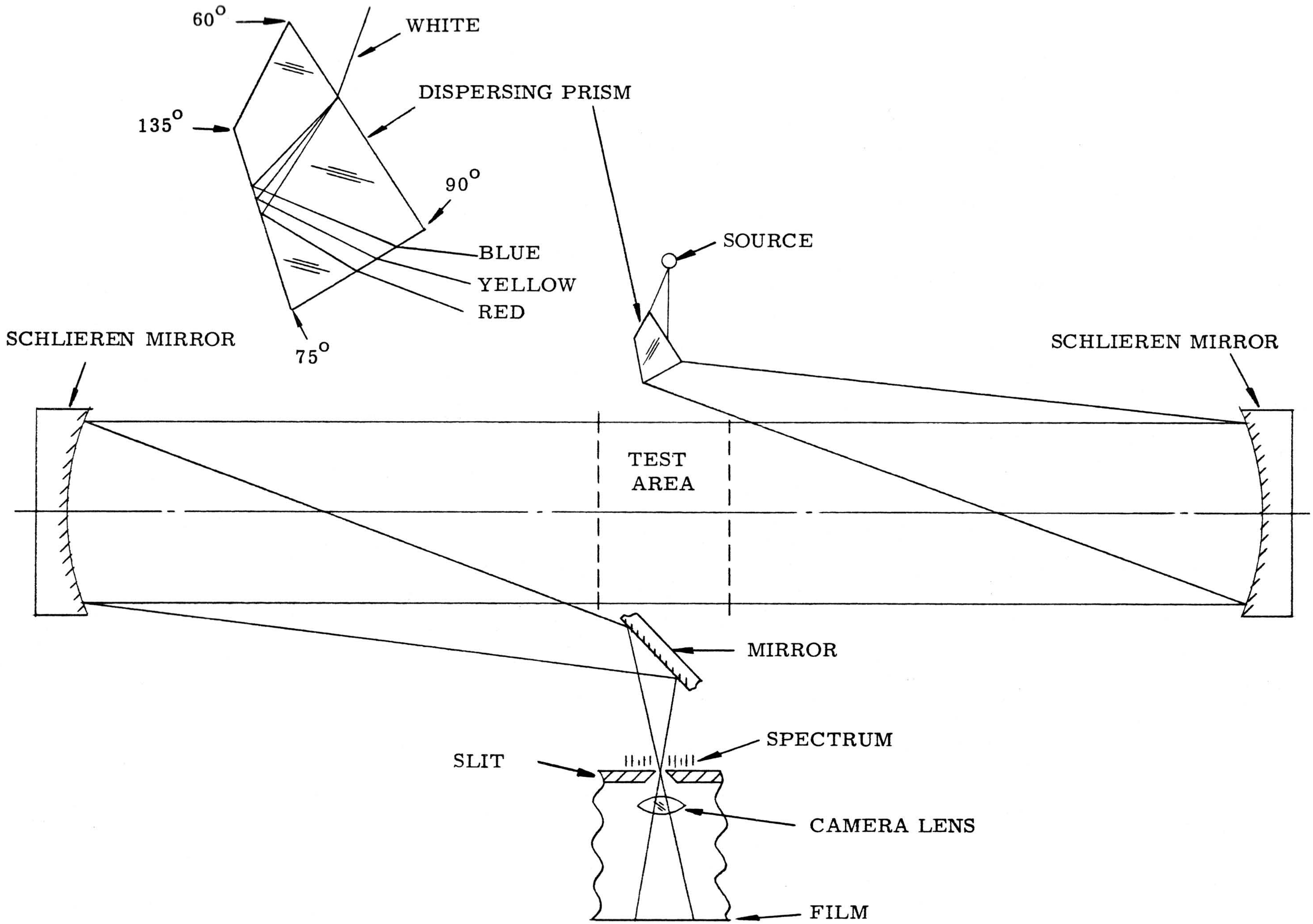


FIG. 23 COLOR SCHLIEREN SYSTEM

The dispersing element is a constant deviation prism and a single pass of the test area is obtained by using two paraboloidal mirrors off-axis. In this case the spectrum is long and a fairly narrow slit is used to pass one color, normally yellow. Holder and North claim that the addition of color results in higher sensitivity because the eye is more sensitive to changes of hue than to changes of illumination. They also believe that the bright field as opposed to the usual dark field provides better illumination of weak refractive disturbances.

It is also possible to produce color by interference and polarization methods.

Interference Methods

An early schlieren interferometer is described by H. Antweiler in Zeit. Fur Electrochemie, Vol. 44, 1938, p. 719 and shown schematically in Figure 24. The carbon arc source was focused by a single schlieren lens, the beam divided by the first beam-splitter and combined by the second, one path passing through the test area. No second aperture was required since interference will produce a dark or striped field when the optical retardation is properly adjusted in the two paths. An advantage of this method is that it is quantitative and can be calibrated. This feature is of particular value in hypersonic wind tunnels where it is necessary to know the relative pressure on each side of the shock wave.

Phase Contrast

The best description of this principle is in "Phase Contrast Observation of Flames" by Saunders and Smith in Jour. Appl. Physics, Feb. 1956, p. 115. The optical layout is shown in Figure 25. The system is a normal single slit system except that the bar is replaced by a bar-type phase-plate consisting of an etched area on a microscope slide. The article describes a method for making these phase-plates, but we have found it easier to make them by the more conventional techniques used in the manufacture of phase-contrast microscope objectives.

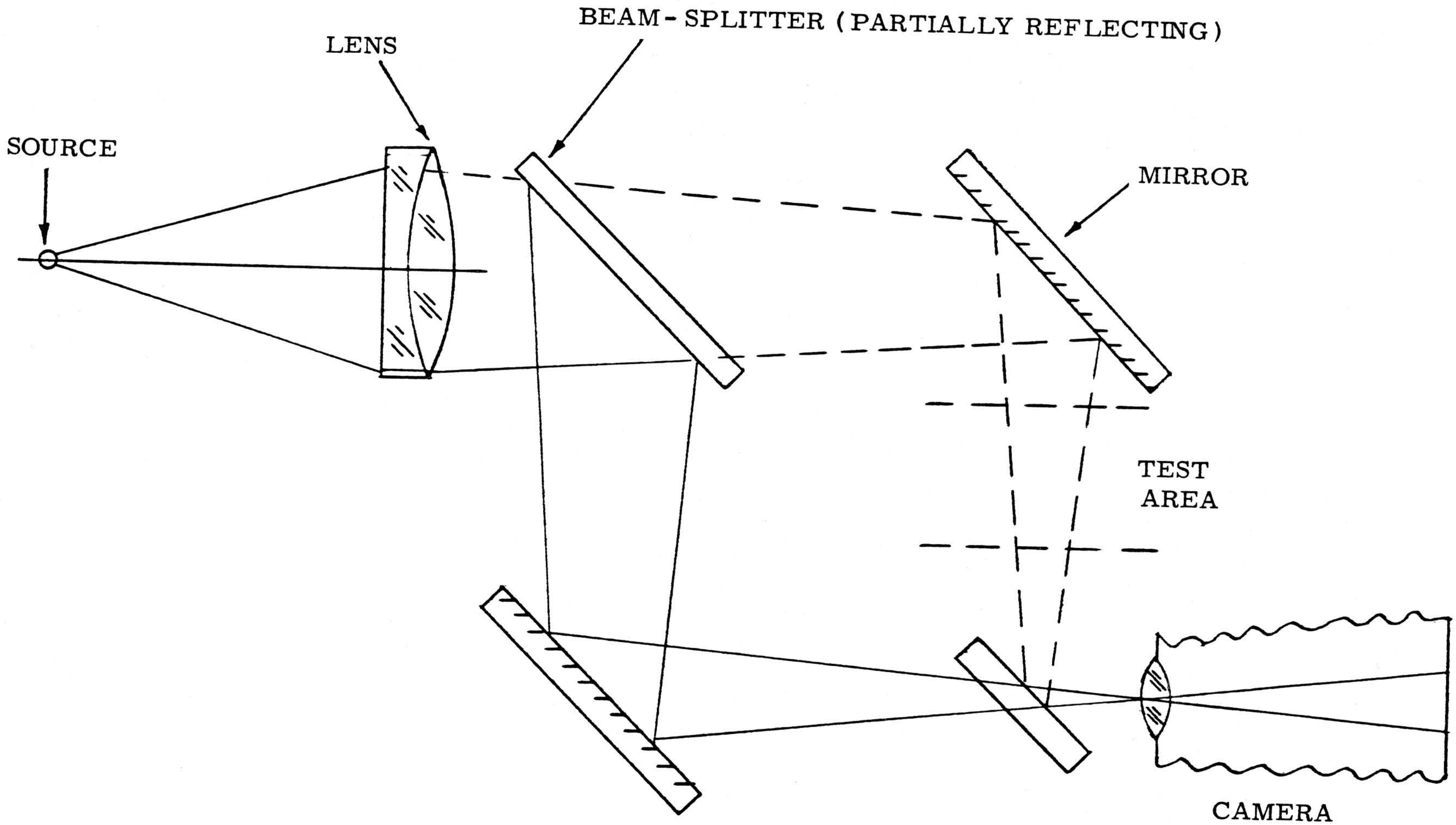


FIG. 24 SCHLIEREN INTERFEROMETER

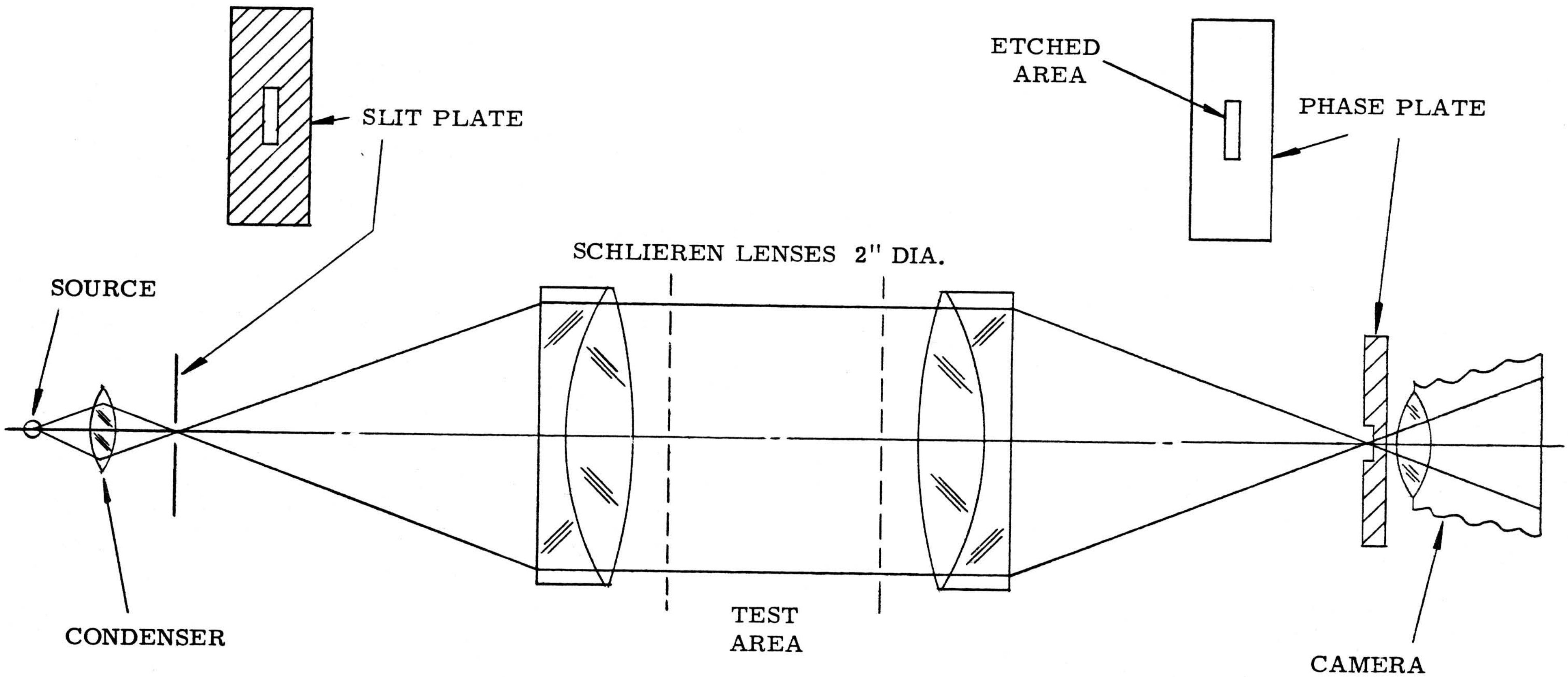


FIG. 25 PHASE - CONTRAST SCHLIEREN

The advantages of phase-contrast schlieren are:

1. The optical system can be extremely short and compact. The one described in the article is only 32 inches long and yet it has sensitivity equal to a Toepler system about 25 feet long. The addition of phase-contrast should increase the sensitivity at least ten times with no increase in size.

2. Relatively low precision and low-cost optics may be used to obtain high sensitivity.

3. There is more light in the image due to the fact that the phase-plate is partly transparent while the bar in the usual system is opaque.

4. The compact construction allows a high relative aperture to be attained at low cost. The system shown in Figure 25 uses f/6 lenses that are only two inches in diameter. To obtain the same sensitivity and relative aperture in a conventional system would require optics 20 inches in diameter.

5. The compact construction allows the construction of an instrument that has high sensitivity and yet is portable and relatively free from vibration effects.

Multiple Source

An early multiple-slit system is described as "Modified Schlieren Apparatus for Large Areas of Field", R. Burton, Jour. Opt. Soc. Am., Nov. 1949, p. 907. A diagram of the optical system is shown in Figure 26. This is a diffusely illuminated multiple-slit system in which no secondary lens is used. The schlieren lens must be a photographic type anastigmat in this case because the large field of the slit-plate must be accurately imaged on the cut-off plate. The source used in the article was an ordinary 100 watt frosted lamp, the diffuser, a sheet of ground glass and the slit-plate was an engraver's screen. The schlieren lens was an f/3.5 Tessar with a focal length of 20 cm. The apparent weaknesses of this system are the relatively weak illumination unless wide slits are used, the rather low sensitivity and the fact that without a secondary photographic lens the image is likely to be as large or larger than the test area. Burton mentions that in place of slits, round apertures or concentric circles may be used to produce an omnidirectional system.

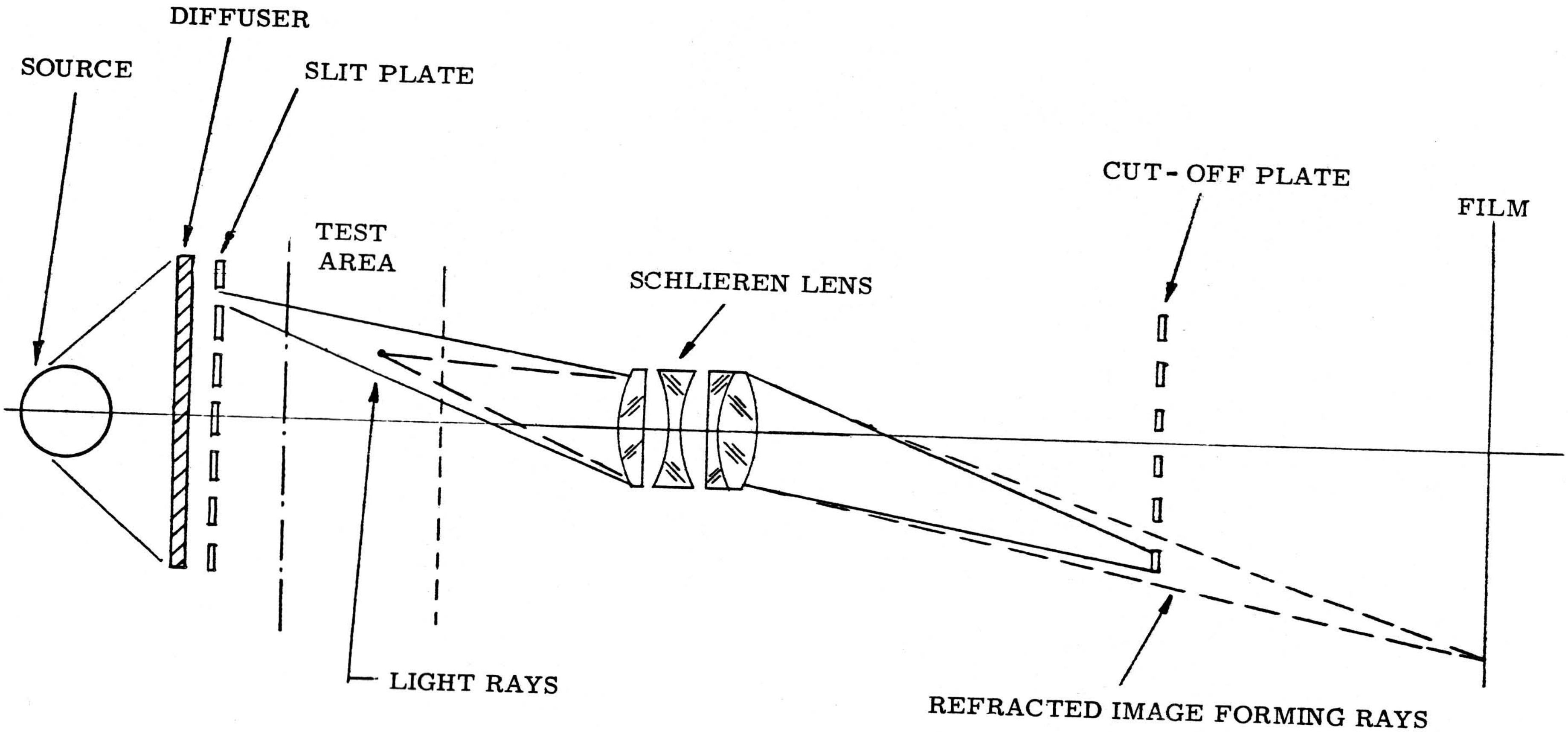


FIG. 26 MULTIPLE SOURCE SCHLIEREN

A somewhat more advanced arrangement is described as "Improved Schlieren Apparatus Employing Multiple Slit Gratings", T. Mortensen, Rev. Sci, Inst., Jan. 1950, p. 3. The optical layout is shown in Figure 27. This is a condenser illuminated system with an anastigmat used as the schlieren lens and an achromatic doublet used as the photographic lens. The source in this case was a carbon arc, the condenser consisted of a pair of 12-inch diameter lenses, the schlieren lens was an f/3.5 Tessar with a 13.5 inch focal length. The brighter source and condensers provided a high optical efficiency. The focal length of the photographic lens was chosen so that the test area would be reduced to fit 35 mm. film.

A still more sophisticated system was described as "Sharp Focusing Schlieren System", A. Kantrowitz, Jour. Aeronautical Sci., May 1950, p. 311. The layout is similar to Figure 27 except that a rather high aperture was used throughout the system to limit the depth of field. In this case an anastigmat was also used for the photographic lens and a field lens was employed in the illuminator. The term "sharp-focusing" as used by Kantrowitz means having limited depth of field. The conventional single aperture system has a very low effective aperture at the photographic lens, often f/200, and as a consequence has almost unlimited depth of field. This can be a disadvantage if it shows defects in the windows, stray air currents in the room or other unwanted schlieren effects that are impossible to eliminate. The slit-plate used had 82 slits of which only 50 were effective. These slits were 1.5 inches long, .004" wide and .036" apart. The author describes a good many methods of making the slit-plates and cut-off plates and while he succeeded in producing good results, we have used other techniques. Dr. Kantrowitz demonstrated that the sharp-focusing system was capable of photographing either of two simultaneous schlieren phenomena less than an inch apart in depth by selective focusing.

Anamorphic Schlieren

It is possible to produce an image of a schlieren phenomenon in which the relative dimensions have been altered. One of these is

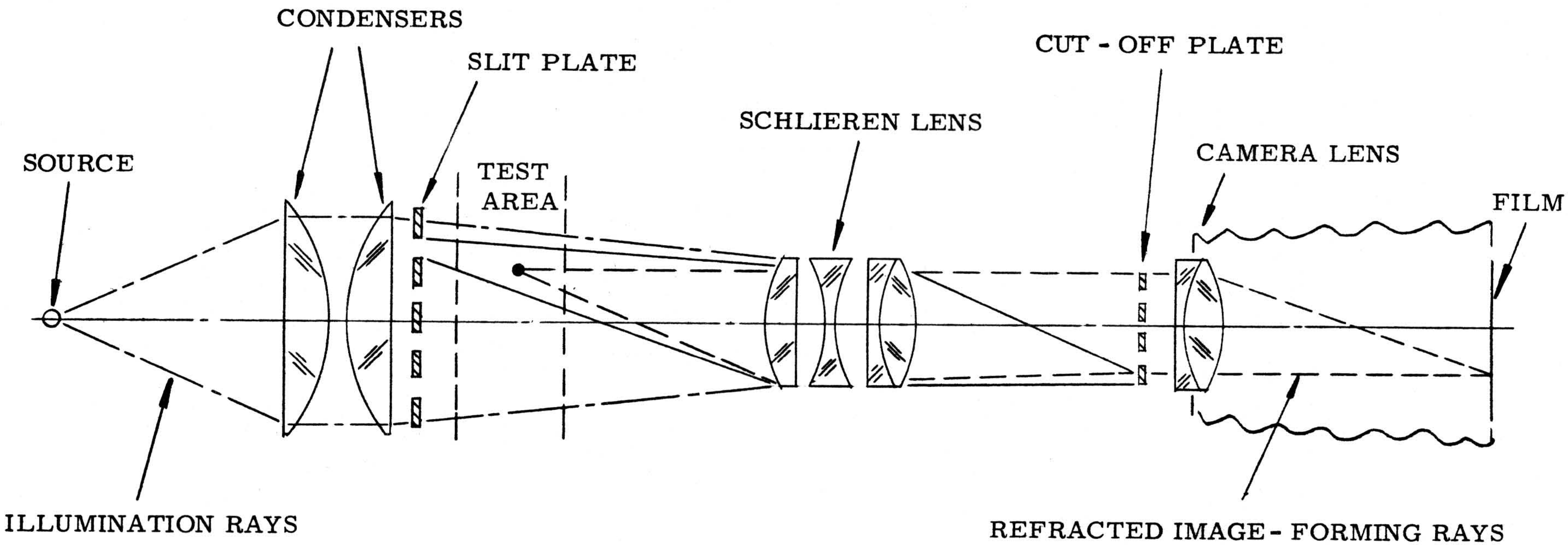


FIG. 27 SHARP - FOCUSING SCHLIEREN

described as "Lens System Producing Unequal Magnification in Two Mutually Perpendicular Planes", Buchele and Gossens, Rev. Sci, Inst., March 1954, p. 262. The system described images an area 1 inch wide and 20 inches long which would be awkward to place on a 16 mm. frame. The schlieren system is normal except that there are three cylinder lenses between the second knife-edge and the film. The result is 24 times magnification in height and no magnification in length.

Polarization Systems

No one, so far as can be found, has ever built the obvious polarizing system using as input bars alternate strips of differently oriented polarizing material and output bars consisting of crossed polarizers, there have been a number of polarizing systems built which used the more efficient crystal polarizers. These systems can be arranged to give color produced by the phase-retardation of polarized light, or without the addition of any of the usual interferometer parts they can become schlieren interferometers. One of the most sensitive instruments on which we have any data was built on this principle and served to show measurable schlieren in a low-pressure wind tunnel. The instrument proved to be so sensitive that all the space inside the optical system had to be evacuated to prevent stray schlieren effects.

Polarization and phase-contrast systems will be discussed at length in another report.

Development of Projection Systems

In concluding this section on variant systems, it is interesting to note how they can contribute to the projection system. Any schlieren system can be used as a projector, but the multiple-slit arrangements produce brighter images than single slit or multiple circular aperture devices. The condenser illuminator is much more efficient than diffuse types and so the first choice for a schlieren projector takes the form shown in Figure 28. The good feature of this design is that it can be built from low-cost commercially available and shop-made parts with the exception of the schlieren lenses. A 35 mm. slide projector cut in half will provide the source,

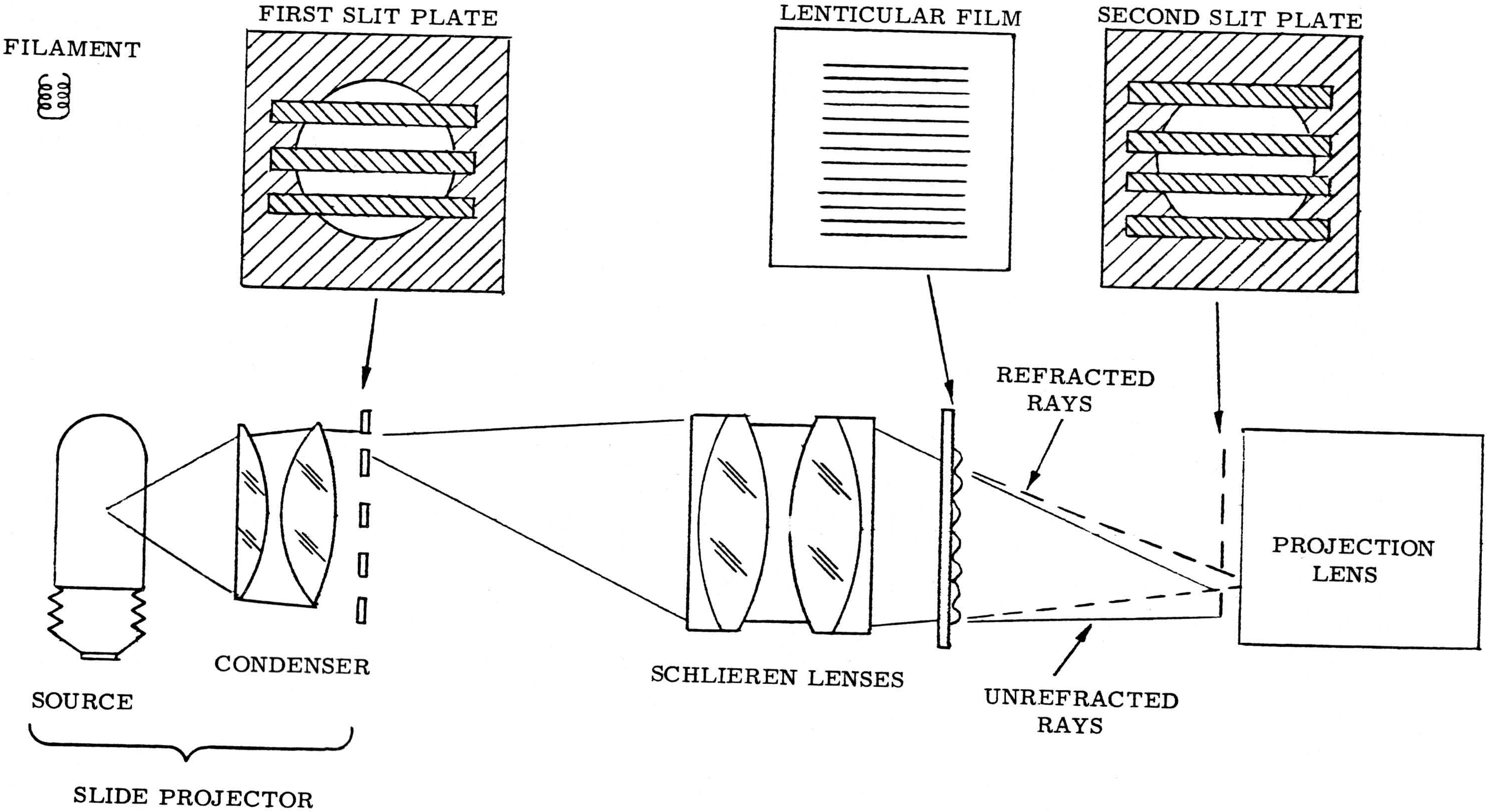


FIG. 28 SIMPLE SCHLIEREN PROJECTOR

condensers and projection lens. The three bars normally used are easily fabricated from sheet metal. The writer has built a number of these projectors for thermoplastic film and they are adequate for a two square foot image with a 500 watt tungsten lamp. In a totally dark room they will fill a 40 by 40 screen with acceptable illumination.

The bad features of this projector are the limited brightness of the projected image and the fact that it is difficult to obtain a uniformly illuminated screen image.

The causes of inefficiency are listed as follows:

a. The lens condensing system collects only about 6.5 percent of the source output.

b. The first set of bars take out at least half the light.

c. The condensers and schlieren lenses produce a round spot of light on the picture and usually only an inscribed rectangular area is used. The losses amount to 40-50 percent.

d. Some light is lost by the "guard bands" on the second set of bars.

e. Light is lost by reflection and absorption in the optical parts. This can amount to 50 percent.

The first improvement is to replace by the first bars by staggered mirror bars as shown in Figure 4. This will nearly double the efficiency.

The second step is to go to a smaller, brighter source which will allow a more efficient collection system and provide a higher brightness at the luminous slits.

The final stage, still in the future at the present time is a phase-contrast or polarization system in which the bars are either eliminated completely, are transparent phase-retarding bars or are semi-transparent combination phase and amplitude bars. In its simplest terms, a dark-field phase-contrast system is one in which the output bars are not opaque, but are made of a transparent or semi-transparent material such as an evaporated dielectric or metal which retards the phase of the light passing through the bars in relation to the light passing around the bars so that a phase cancellation or interference takes place. Since the system requires light passing around the bars as well as through them to produce the dark-field, it means that the output bars can be narrower then in existing designs and the need for guard bands is eliminated. Further, since the bars are not opaque, it is theoretically possible to make a system using this principle which is nearly as efficient as a bright-field projector, or in simpler terms, to obtain highlights that are nearly as bright as the existing projectors with all the bars removed. One of the limitations of a phase-sensitive system is that it requires a phase coherent source of light.

DETAILED DESIGNS

The Gretener Eidophor Projector

General

Historically, the Gretener system is the oldest schlieren projector and has many features to recommend it. It was the first to use the staggered mirror bars and it is unusual in using one concave spherical mirror as the entire schlieren optics. Dr. Gretener early learned that the fewer the optics the higher the efficiency and he was able to combine the first and second bars in one unit and combine the schlieren optics and raster plate. G.E. bought its first Gretener projector in 1950 and the optical design has not changed except for the light source and condenser in the modern Gretener or CIBA projector.

Optical Layout

The layout is shown in Figure 29 where no attempt has been made to draw it to scale or in the proper orientation. The source is an Osram 2 kw xenon lamp, the reflector is spherical, the two condensers form an enlarged image of the source on the mirror bars which are staggered so that they are a solid mirror as seen from the source. The dichroic mirror reflects light but is transparent to infrared and prevents a large amount of heat from getting into the vacuum system. The field lens is to prevent the loss of marginal rays and its use is explained in Figure 15. The raster is formed on the spherical mirror bowl. The bowl rotates continuously to renew the oil film. The metal coating on the glass bowl acts as both a mirror and as the electrically conducting surface which dissipates the electron charge. The electron gun is off-axis about 15 degrees. The spherical surface of the bowl acts as the entire schlieren optics on the principle shown in Figure 30a where a point at the center of a sphere is imaged on itself. The mirror bars which are the sources in this case are arranged about the center of the sphere and the images then fall back on the bars as in 30b. The image of the central bar (assuming three bars) fall on it, the top bar is imaged on the bottom bar and vice versa.

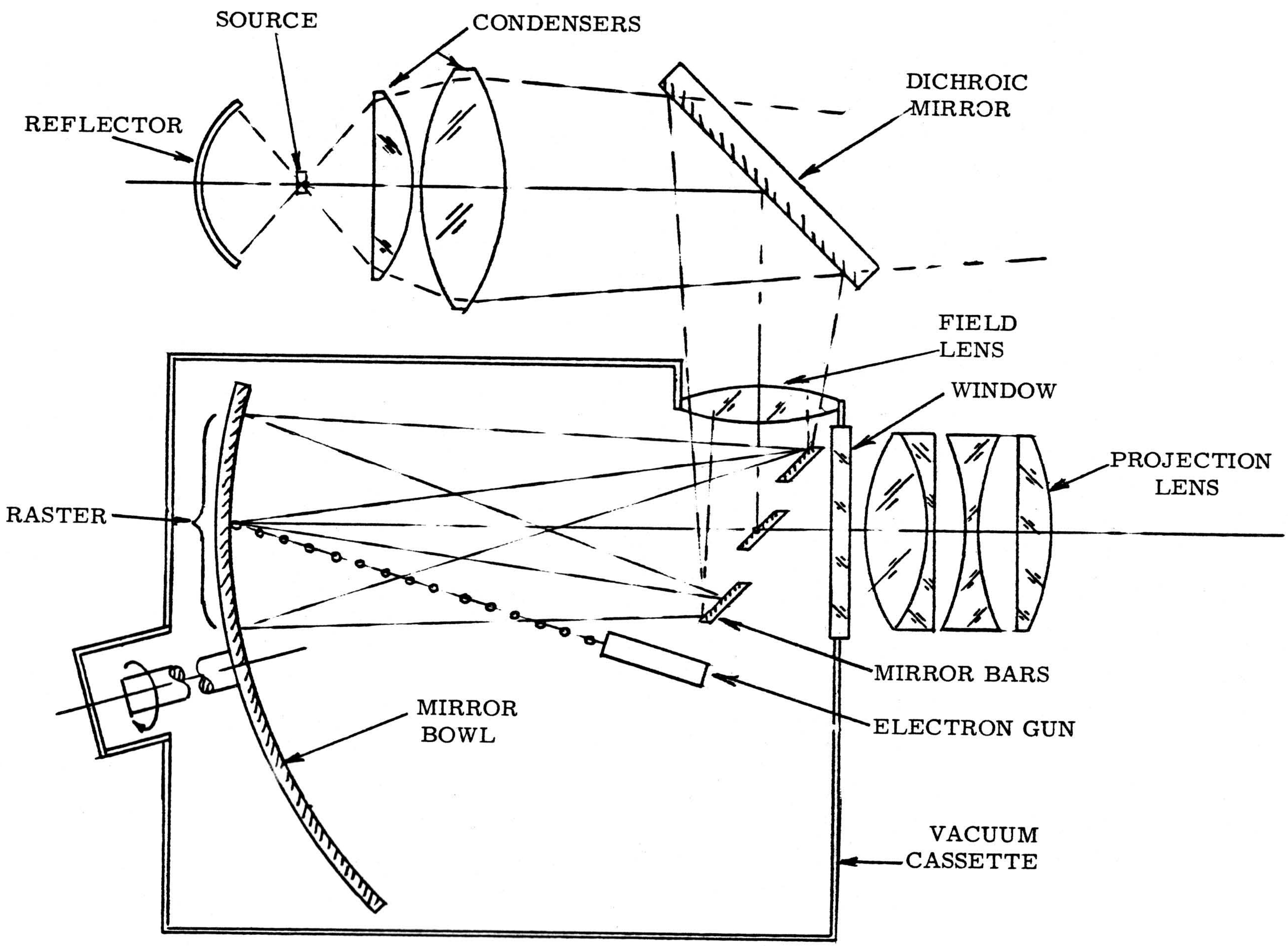
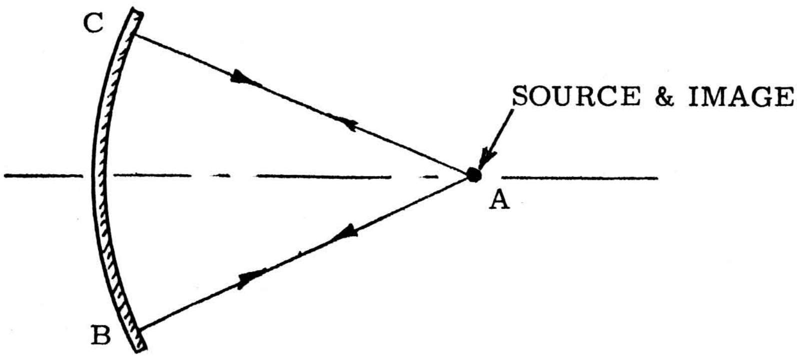
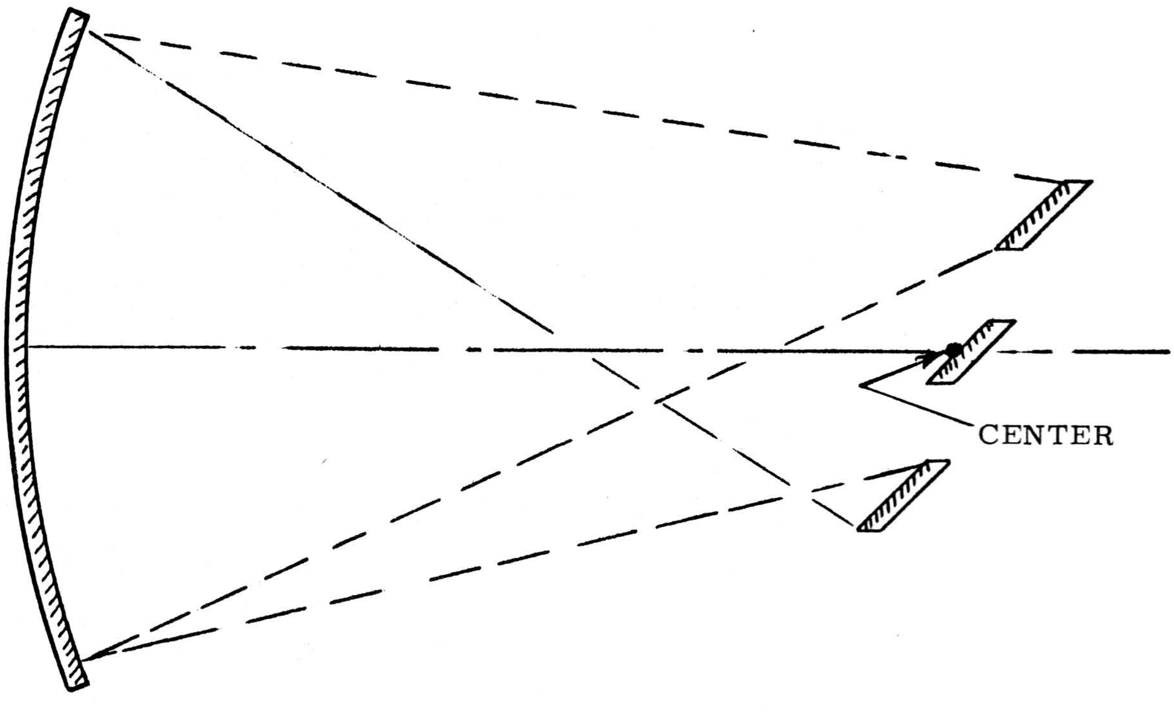


FIG. 29 GRETENER EIDOPHOR SYSTEM (SCHEMATIC)



(a) PRINCIPLE OF THE SPHERICAL MIRROR
(LINES AB & AC ARE RADII, HENCE NORMAL TO THE SURFACE)



(b) MIRROR BARS AT CENTER OF SPHERICAL MIRROR

FIG. 30 ACTION OF SPHERICAL MIRROR

When the oil film is modulated by the electron beam, the surface refracts the rays from the mirror bars and they no longer fall on their conjugates and some light passes between the bars. As seen from the raster, the spaces between the bars are equal to the widths of the bars. The light leaves through the vacuum window and the raster image is enlarged by the projection lens.

Detailed Design

The actual layout is as shown in Figure 31 where compared to the diagrammatic layout the light path is twisted between the dichroic mirror and the field lens. The reason for this is that the illumination on the screen is an enlarged image of the source. The Osram lamp must be operated in a vertical position and the arc has a greater vertical length, 4 mm. than width, 2 mm. The projected picture is always horizontal, so to lay the arc image on its side, it is necessary to have a right angle twist. This means that the enlarged source image falling on the bars will have its long dimension horizontal or running the length of the bars.

While it is possible to re-synthesize this projector using the principle of system design described earlier, it will be analyzed as it exists starting with the source. Some of the information here may be in error because we have never had detailed data on this system. Many of the figures quoted are guesses or crude measurements.

Source

The Osram XBO-2001 xenon source is described in the Osram bulletins, also in articles in the Jour. Soc. Mot. Pictures & TV Engrs., June 1958, p. 389 and 397. More detailed information is available in a series of twelve reports by the writer titled "Solar Simulator - Source".

The lamp requires 65 volt DC with low ripple at 70 amperes. The power supply is fairly large and expensive and includes a 40 kv transformer to start the lamp. Cooling of the lamp is required and some ozone may be produced. Baffling of the air exhaust is required unless the projector is to be installed in a booth.

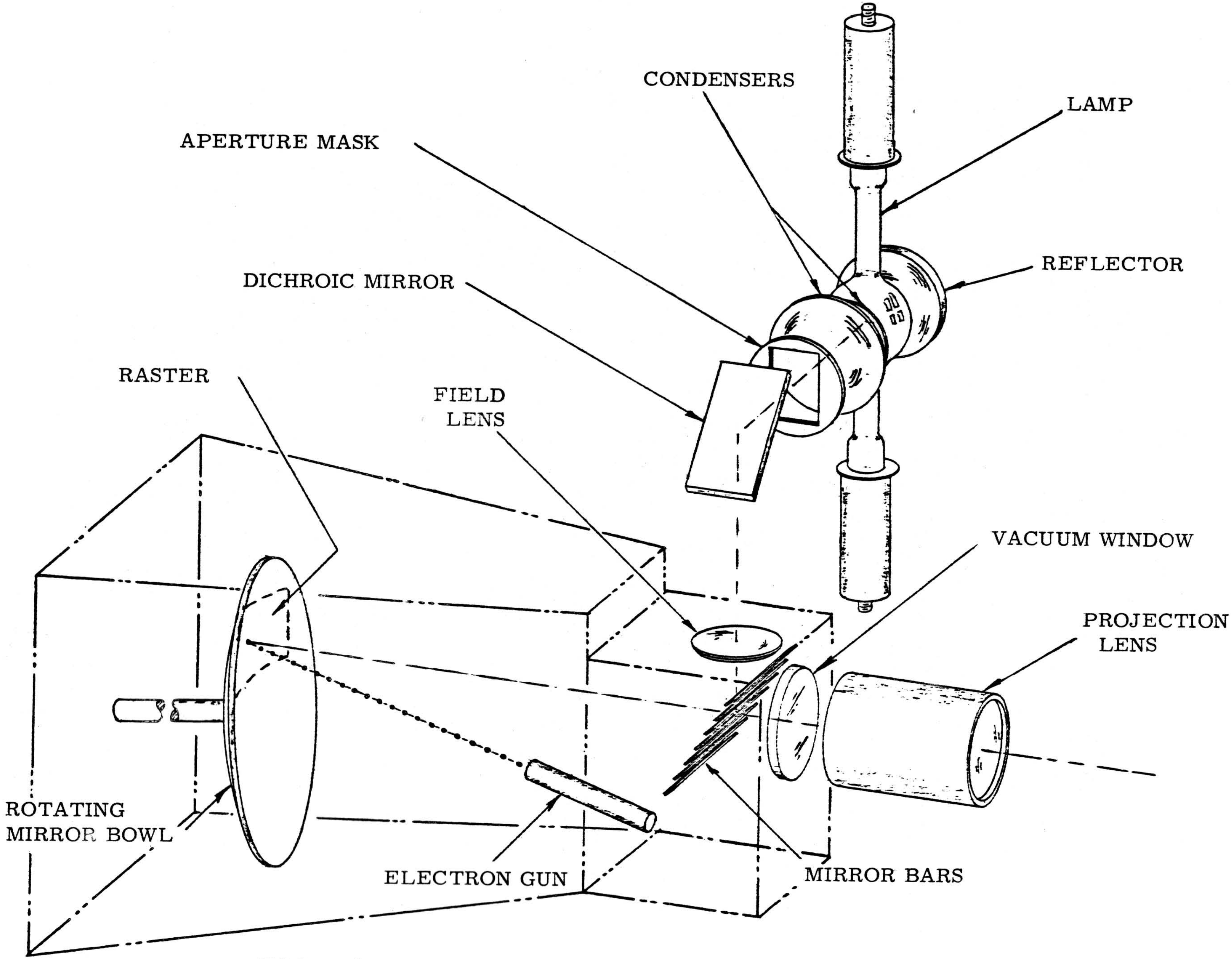


FIG. 31 GRETENER EIDOPHOR PROJECTOR

The source is a non-uniform bell-shaped arc with a very bright cathode spot. The shape of the arc and the intensity distribution are shown in the SMPTE articles mentioned above. The screen illumination is intermediate between an out-of-focus source image and a condenser aperture image. The spherical mirror helps form an inverted image of the non-uniform source so that there are two cathode spots and some overlapping of the different brightness shells. The resulting screen illumination uniformity is acceptable but follows an unusual pattern.

Spherical Lamp Reflector

As mentioned under Source above, the chief purpose of this reflector is to improve screen illumination uniformity. A spherical mirror images the source back on itself, but the image is inverted. The second purpose is to nearly double the screen illumination since this mirror receives an equal spherical angle of energy from the source and sends it back through the condensers. The illumination is not doubled because of:

a. Losses due to metallic reflection.

b. Losses due to transmission through the lamp envelope three times.

c. Absorption in the arc.

These arcs are not completely transparent but tend to show absorption of the same wavelengths they emit. An estimate of the gain that is possible by using a reflector is given in the SMPTE article referred to above.

The only properties required for this reflector are moderate spherical accuracy and high reflectivity. The obvious solution is an aluminized glass mirror, but it may have to be specially treated to stand the high temperature. The vertical polar distribution of the Osram lamp is shown in their bulletin and amounts to a total included angle of about 110 degrees of which the outer 5 or 7 degrees on each side is rather weak. The Gretener system we estimate to be designed for 96 degrees, hence this is the collection angle of the mirror. Normally these mirrors are placed as close to the source as possible to make a compact system and keep the mirror small. Figure 32 shows an approximate scale drawing of the condenser system in which the mirror is 45 mm. from the source and 70 mm. in diameter. It would be equally satisfactory optically to use a larger mirror at a greater distance and since the heat would be distributed over a larger area the service would be less severe.

The most important feature of the reflector is a good system for aiming it and preferably some means for telling when it is adjusted correctly. These adjustments should provide means for locating the mirror so that the source is at the exact center of the spherical surface. It is necessary to focus as much light as possible through the 4 mm. gap between the massive electrodes and anything less than a perfect adjustment can result in:

a. Poor screen uniformity.

b. Considerable loss of illumination.

c. Damage to the electrodes.

d. Possible lamp failure.

Damage to the electrodes may come from overheating. The electrodes operate at white heat and are designed to have enough surface to radiate at a rate which will keep them from melting. If their radiation is focused back on them and the lamp is running at full power, they can be melted or deformed. If the electrode gap is changed more than a few thousandths of an inch or the faces become asymmetric or non-concentric, the arc will become unstable and the lamp unusable.

Lamp failure could be caused if the reflector were displaced so that the source image were focused on the silica enclosure and the heat softened it. Since the pressure in the lamp is 300 lb./ sq. in. and the source temperature about 6000 degrees K, this is a possibility though unlikely. This type of failure, melting of the enclosure, frequently happens with tungsten projector lamps having soft glass bulbs. As a safety precaution the reflector should be mounted so that its adjustment is limited and its focus cannot fall on the envelope.

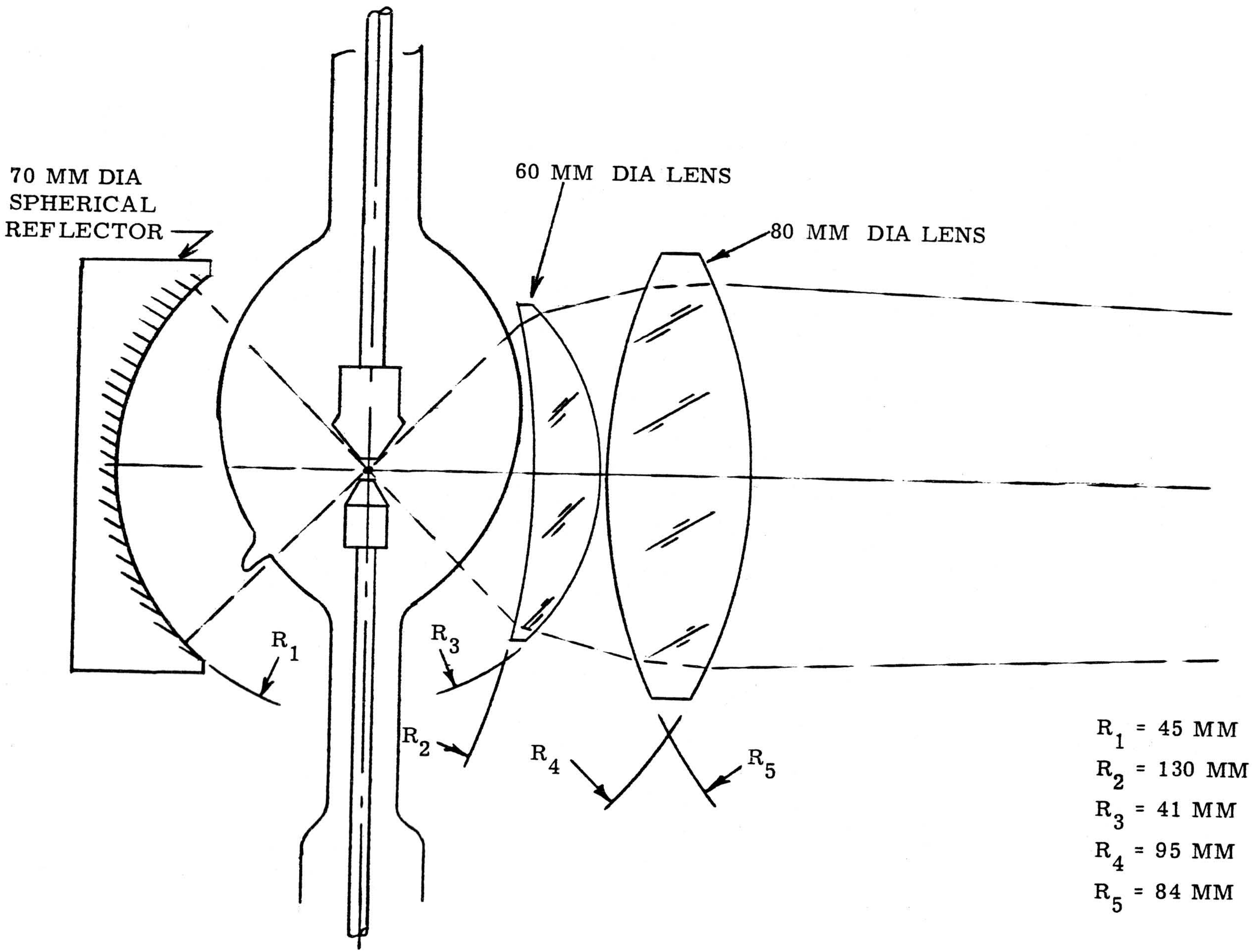


FIG. 32 CONDENSER SYSTEM

Alignment of the reflector can be done by observing the screen with the bars removed or displaced and adjusting until the direct and mirror image of the cathode spot are symmetrically located on the screen. The direct image will always be noticeably brighter. Another means is to use a very dark welder's glass, such as Willson Shade No. 10, to look in the projection lens where images of both the arc and its inverted reflection can be seen. The best way to align the mirror is to use a "focusing microscope" such as is built into the Zeiss Ikosol lamphouse for the Osram lamp.

Condenser Lenses

As mentioned under Reflector, the collection angle of the illuminating system appears to be 96 degrees. If our information is correct, the source image does not fall on the bars but on the field lens. To illuminate the mirror bar array requires a 20 mm. width spot. This represents a 10 times magnification of the source. The problem is to design a condenser with a collection angle of 96 degrees and a magnification of 10. It is not possible to do this with a single lens, two lenses are the minimum number. If the criterion is to make the system as compact as possible then the condenser should have the minimum focal length that will allow room for the lamp and at least one-eighth inch clearance. Note that the lamp is pear-shaped and the maximum diameter is not at the source. It is fairly clear that the nodal point of the condenser system will fall between the lenses and it is a matter of trial to fit this to the requirements. The focal length of the condenser then turns out to be 1.14 inches, though this is of less importance than the conjugates which measured from the nodal point are 1.25 inches on the short side and 12.5 on the long side.

The condensers used by Gretener are shown pretty much to scale in Figure 32. A further advantage of making the system compact is that it keeps the size of the condensers to a minimum. With the condensers very close to the hot lamp, they will have to be made of silica or low-expansion glass, such as Pyrex which has a fairly high absorption when made into thick lenses. Silica, on the other hand, is very transparent but has such a low refractive index the low-reflection coating is not very effective. There is not much choice between the two, but silica is slightly more efficient and appears to be used in the Gretener lenses.

The aperture ratio of the condenser is about f/0.7 as used, and it is impossible in this case to fully correct spherical aberration with only two elements having spherical surfaces. Some degree of correction is necessary because large amounts of spherical aberration in a condenser will produce a source image which would consist either of a bright central spot surrounded by a large halo of diffuse light, or a dark center with an annulus of light. These are both undesirable and a fair degree of correction is required to concentrate the source image into a moderately uniform spot close to its geometrical size. It has been our opinion that Dr. Gretener purposely allowed some aberration with the idea that it would prevent a sharp focus of the non-uniform source image and improve screen uniformity. This alternative to diffusion is a somewhat tricky thing as it requires the correct amount of aberration of the proper algebraic sign, but in this case the results are fairly good and in our estimation probably as good as can be obtained with a two-lens system. The screen illumination at the edges is about one-half the brightest area. With the intense cathode spots located where they are, the brightest area is not likely to be at the center of the screen. When the bars are displaced in the projector, the non-uniform arc images on the screen are apparent.

There is no provision for chromatic correction in the condensers and while the dispersion of silica is lower than glass, the red focus is about an inch beyond the blue focus. The only noticeable effect is that the screen illumination tends to be somewhat blue at the center and reddish around the edges. When the condensers are slightly out-of-focus, there will be a pink ring partly inscribed in the screen rectangle.

Aperture Mask

Located near the condensers is a rectangular metal mask which is imaged by the field lens on the raster as shown in Figure 33.

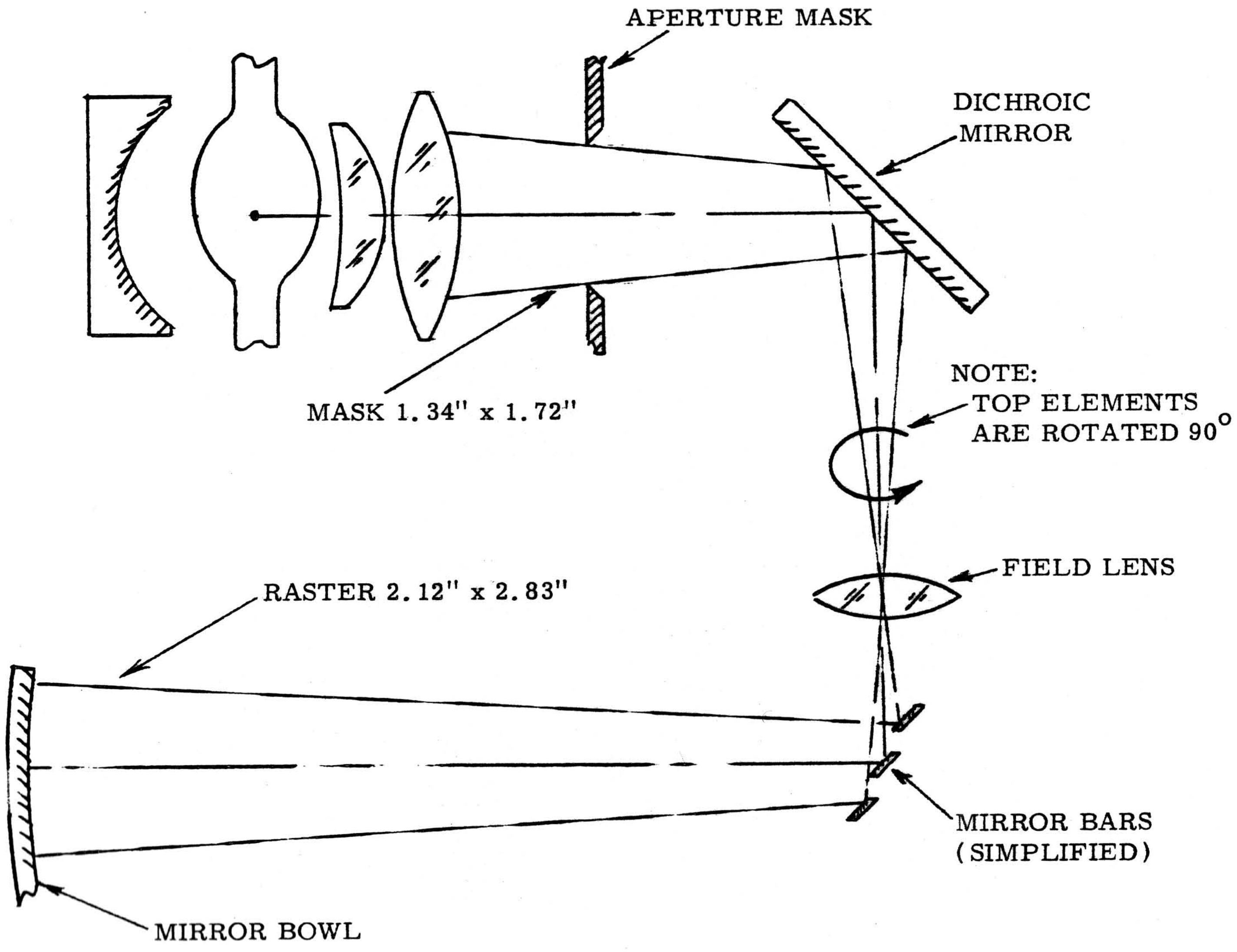


FIG. 33 ILLUMINATION SYSTEM

Without this mask a round spot of light, the image of the condenser would fall on the oil film. All the light outside the inscribed raster is unnecessary and it is better to take out stray light and heat before it enters the vacuum system. The conjugate from the lens to the raster by way of the mirror bars is 13.8 inches, therefore, the magnification is about 1.64. Since the raster size is 2.12 x 2.83 inches, the required size for the aperture is 1.34 x 1.72. This aperture plate gets quite hot because it intercepts nearly half the energy collected by the condenser system or about 300 watts and therefore it must be made of heavy material and be designed to radiate.

Dichroic Mirror

The dichroic mirror reflects visible light and transmits infrared. It is a multi-layer dielectric coating on glass. The Gretener mirror is probably a Balzer product and appears to be both efficient and durable. Similar mirrors are made by Fish-Schurman and others and appear to be of equally good. The transmission and reflection curves may be obtained from the manufacturer and have been checked at GEL. A good mirror will reflect about 94 percent of the visible, the loss occurring chiefly at both ends of the spectrum and will transmit about 80 percent of the infrared from .75 to 2.5 microns. A good dichroic mirror is therefore as efficient as the best metal mirrors and at the same time keeps most of the unwanted infrared out of the vacuum system.

Field Lens

In this instrument, the field lens serves three purposes:

a. Vacuum window.

b. Images the aperture mask on the raster.

c. Controls the marginal rays as shown in Figure 15.

The diameter of the lens is 50 mm. and for purpose (b) the focal length should be 5.2 inches, for the purpose (c) it should be 6.1 inches. This is a common compromise in field lenses and since (b) is probably the more important, we believe the focal length to be a little over 5 inches. Minimum spherical aberration is produced in a lens used at practically unit magnification when it is symmetrical and this design is apparently used. The aperture ratio of the field lens is about f/2.5 which is fairly fast. The lens has enough chromatism to produce a colored ring around the raster and this may be the cause of some of the color effects seen on the screen.

Since the source image falls on or nearly on the lens it should be made of low-expansion glass or silica.

One of the weaknesses of the Gretener system is that the undeviated light falls back on the mirror bars and then goes up through the illumination system. If there is any reflection from the field lens, it will probably produce light areas in the dark-field. According to what we have heard, Dr. Gretener was amazed by how serious this reflected light could be. When the first projector was assembled, it did not use a field lens, simply a flat window and because the window was not available, the projector was tested without it. The dark-field was good and the contrast ratio between the dark-field and the bright field obtained with the bars displaced was 1000 to 1. When the projector was later assembled with the window, the dark-field was poor and the contrast was only 60 to 1. Steps that can be taken to reduce reflections are:

a. Tilt the window.

b. If the window is also a lens and cannot be tilted, it can be "bent" which means that the two curves are changed while keeping the power constant until the reflections are defocused.

c. Low-reflection coating.

In this particular case, coating cannot be relied on because everything in the vacuum system soon becomes covered with a condensed oil film which destroys the optical properties of interference coatings. The lens must be designed to produce no reflection when oil is covered. Also because of the oil problem the lens mounting must be designed for easy removal for cleaning.

Mirror Bars

The system described actually uses seven bars though a lesser number is shown in the figures for simplicity. As described previously, the bar array is carefully adjusted so that as seen from the source the assembly appears as a solid mirror, but as seen from the raster the spaces between the bars are equal to the apparent bar widths. The edges of the bars are beveled so they will not obstruct the deviated light. To prevent the bars from overheating in the vacuum from absorbed energy, they should have as high reflectivity as possible. The bar assembly must be removable for cleaning. The assembly must have a micrometer adjustment for alignment of the bars and their images to produce a dark-field and this adjustment must be brought out through the vacuum. The individual bars must be accurately made, reasonably flat and free of nicks and chips along the edges. The other faces should be blackened. Early mirror bars were hollow and water-cooled, but the addition of the dichroic mirror reduced the heat input enough to allow this feature to be eliminated.

Mirror Bowl

This optical element gave Dr. Gretener more trouble than any other part. The optical requirements are bad, but combined with the physical requirements it proved a difficult part to make. Optically the surface should be an accurate sphere since it is the schlieren optical system and it must be mounted at its exact center so that it rotates without detectable wobble. The metallic coating must be as efficient a reflector as possible to prevent heating the mirror unduly and it is not possible to over-coat the surface with a non-conductor because it is also used as the discharge electrode. The surface should not be affected by the oil or scratched by the oil distributing system.

The optical difficulty of using a schlieren mirror as an imaging device, is that its good field is quite small and points more than three degrees off the axis will show considerable coma and astigmatism. The extreme bars in this array are more than six degrees off-axis and considerable aberration is produced in the images. The general effect is that the bars tend to produce images which are expanded at their ends, that is to say, the aberrations add to the dimensions of the image the further it is from the optical axis. Figure 34 gives an approximate idea of the effect and its magnitude. Of course, it would be impossible to obtain a dark-field with these aberrated and enlarged images spilling over the bars and through the slots. To prevent this, black metal "guards" were added to the bar array to intercept the aberrant rays. It would appear that these guards were made by trial and error and filing them from sheet metal and fitting to the bar array with screws. Since the actual array uses seven bars, there is a considerable number of guards to be made and they must be filed and adjusted until a satisfactory dark-field is produced.

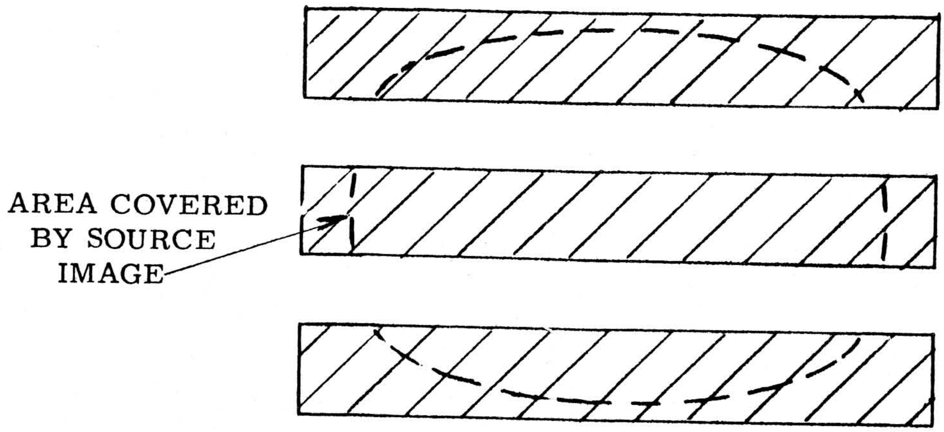
The radius of curvature of the mirror bowl was 11.81 inches or 30 cm. The raster size was 2.12 x 2.83 inches so that the relative aperture of the schlieren optics is f/3.7 which is high for a spherical mirror. The choice of the mirror curvature is the result of several compromises. If the radius were greater, it would help flatten the image surface and reduce the aberration of the bar images, but if the raster had to be kept the same size, it would reduce the illumination angle. Going back to the condenser it will be seen that the only way to decrease the illumination angle would be to increase the condenser magnification which would result in a larger source image and a larger bar array which would bring the aberration back to its original value and the larger set of bars would require a larger projection lens. Actually, there are several compromises in the bowl design, but most of them are of minor interest.

Vacuum Window

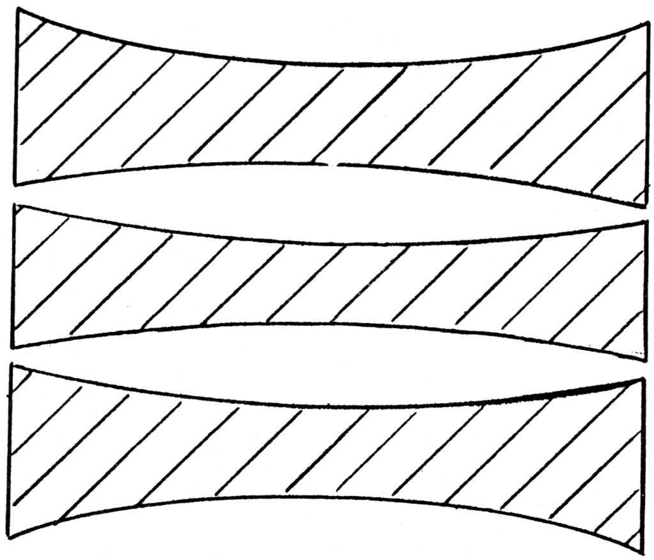
Since this window is beyond the output bars, reflections from its surfaces will probably not be troublesome.

Projection Lens

The raster surface is concave spherical and the picture is projected on a flat screen, requiring a special design of a lens. The back focus has to clear the mirror bar array and window which together amount to at least 12.5 inches. The resulting focal length is slightly over 13 inches and it can be seen that wide angle lenses will be very difficult to apply to a projector of this type.



MIRROR BARS AS SEEN FROM RASTER (SIMPLIFIED)



MIRROR BAR IMAGES

FIG. 34 ABERRATION OF BAR IMAGES

As mentioned before, the diameter of the rear element of the projection lens has to be large enough to cover the bar array so that light refracted above and below the bars will be utilized. This results in a diameter of about 3.5 inches which at 13 inches focal length is f/3.0, a fairly large but not extremely fast lens.

Good Features of the Gretener System

1. When the system was designed it was easier to produce a defect-free mirror than a transparent raster plate of comparable quality.

2. The efficiency of the schlieren system is high.

3. A mirror schlieren system has no chromatic or spherical aberration.

4. None of the optics except the condensers and field lens require high aperture ratios.

Bad Features of the Gretener System

1. The mirror bowl was an expensive and rather fragile item. They had great difficulty in finding anyone who could make them. The metallic coating had to be replaced at intervals which meant returning the mirror to the factory. The cost of a bowl mirror was several thousand dollars and they were expendable due to oil polymerization problems.

2. The mirror bar array with its hand-made guards was a beautiful and expensive piece of optical and mechanical craftmanship. Each mirror was individually adjustable for tilt and the alignment of the assembly was excellent. The cost of such an item is in terms of thousands of dollars.

3. Oil collecting on the mirror bars and field lens was a frequent cause of trouble. In many ways, the bars would be better outside the vacuum.

4. The projection lens is special and rather expensive. It cannot be replaced by a lens of shorter focal length.

5. Aberrations of the spherical mirror bowl necessitate guards on the mirror bars which reduce the efficiency of the system.

6. The source non-uniformity, the design of the condensers and a number of minor factors contribute to a marginal screen illumination uniformity.

7. The large mirror bar array makes the position of the field lens ambiguous. Either the source image cannot be on the bars as it ideally should be, or the field lens cannot lie in the image plane as it should. A compromise is required and this results in some loss of control of marginal rays and some reduction of efficiency and uniformity.

8. The large number of bars breaks up the aperture of the projection lens and limits its resolution by diffraction, though this cannot be considered as a defect because the diffraction effects are not visible on the screen.

Efficiency

These figures are based entirely on our estimates since we have never measured the efficiency of a single Gretener part. They are based on our most optimistic guesses as to materials and quality of surface treatment. The efficiency is diagrammed in Figure 35 which is a straightened and idealized layout.

a. Source output 100%, or 60,000 lumens according to the Osram bulletin.

b. Source energy collected by the first condenser, based on a collection angle of 96 degrees, estimated to be 21%. The spherical lamp reflector if properly adjusted increases this 40% with a new lamp. Total collection therefore amounts to 29.4%.

c. Transmission of two fused silica condensers low-reflection coated 90%.

d. Transmitted by aperture plate calculated on a basis of a uniformly illuminated circle 5% larger than the minimum circumscribed circle around the raster rectangle, 60%.

e. Reflected by dichroic mirror 94%.

f. Transmitted by silica field lens, one side coated 92.5%.

g. Reflected by mirror bars 90%.

h. Reflected by mirror bowl 90%.

i. Modulation efficiency 30%.

j. Intercepted by guards and guard bands 20%.

k. Transmitted by window, one side coated 93%.

l. Transmitted by projection lens 85%.

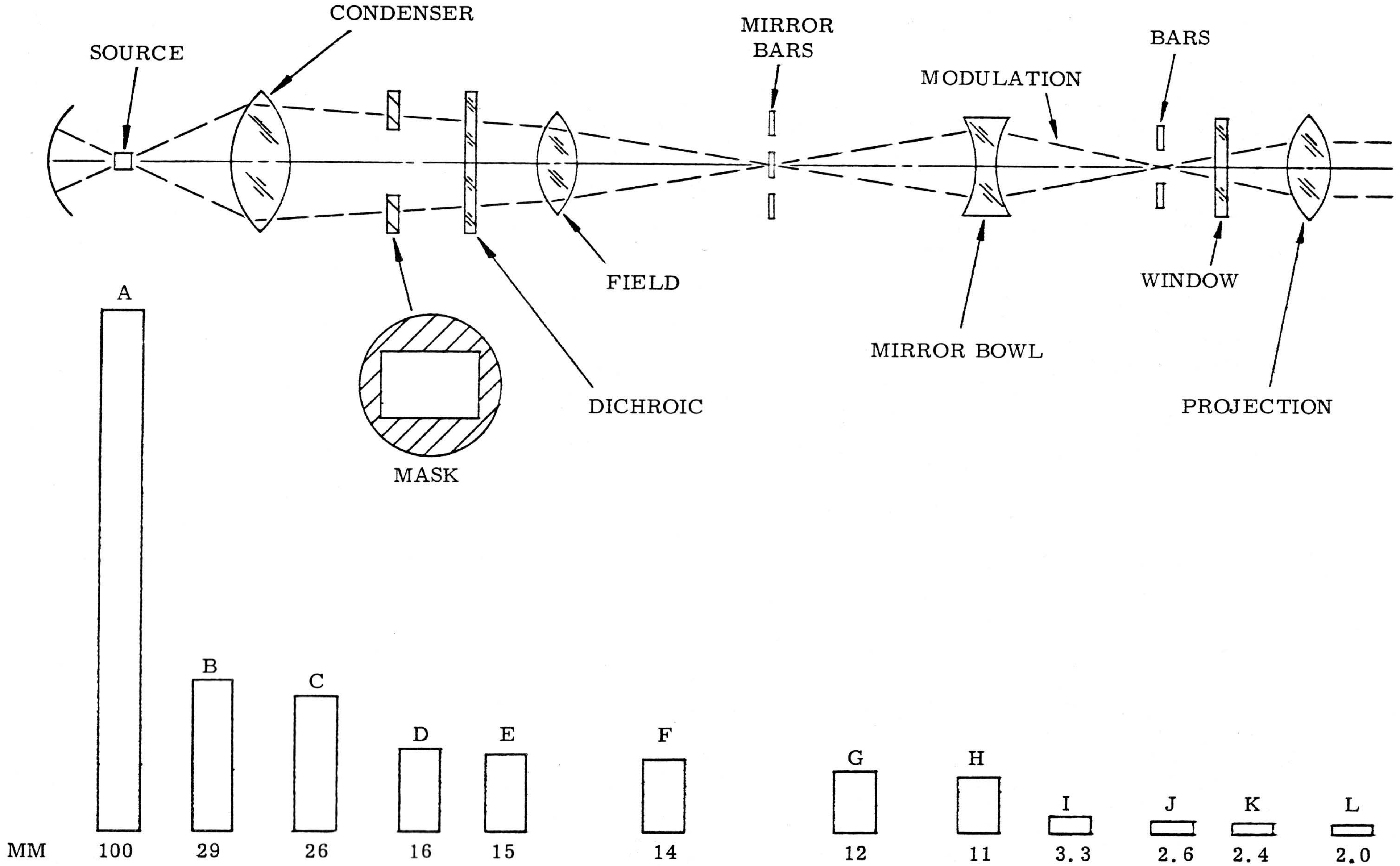


FIG. 35 EFFICIENCY GRETENER PROJECTOR

The calculated highlight efficiency is therefore estimated to be 2.0% and multiplied by the source output this should result in 1200 screen lumens. The measured screen lumens for a projector which may have had a weak lamp or a poorly adjusted lamp reflector was about 1000 lumens.

FIRST G-E LIGHT-VALVE PROJECTOR

Because we had no experience with a schlieren projector, did not completely trust the information in the Eidophor literature and had no means for estimating the refractive angles that could be obtained in the new fluids we planned to use, it was decided to build a laboratory model of simplified construction to learn more about the process.

General

The laboratory projector was designed by Herb Lavin of Syracuse, T.P.O., and was aimed chiefly at the elimination of the expensive optical features of the Gretener design. It was also hoped to provide a wider angle of projection, interchangeable projection lenses, and fewer parts in the vacuum system. Expensive features of the Gretener design were the mirror bowl and the mirror bar assembly. It was planned to use a flat transparent raster plate in place of the bowl and this would incidentally allow the use of normal flat-field lenses for projection. Instead of the spherical mirror schlieren optics it was intended to use conventional schlieren lenses, which because of their larger field would allow the use of a simpler bar system and eliminate the oddly shaped guards on the Gretener bars.

The optical layout of this "one-bar" system is shown in Figures 36 and 37. The first source was a 1000 watt tungsten projection lamp, the condensers were two elements from a slide projector, the raster plate was a glass disc coated with a semi-transparent metal film. The schlieren lens was a condenser and the objective was a slide projection lens. The stop was a sheet metal disc supported on a wire.

Figure 38 shows the actual layout of the projector. This instrument had several good features which we regretted having to abandon later:

1. It was built entirely from low-cost commercially available optics.

2. The raster was on the back (side toward the lamp) of the raster plate which allowed almost unlimited space for the electron gun.

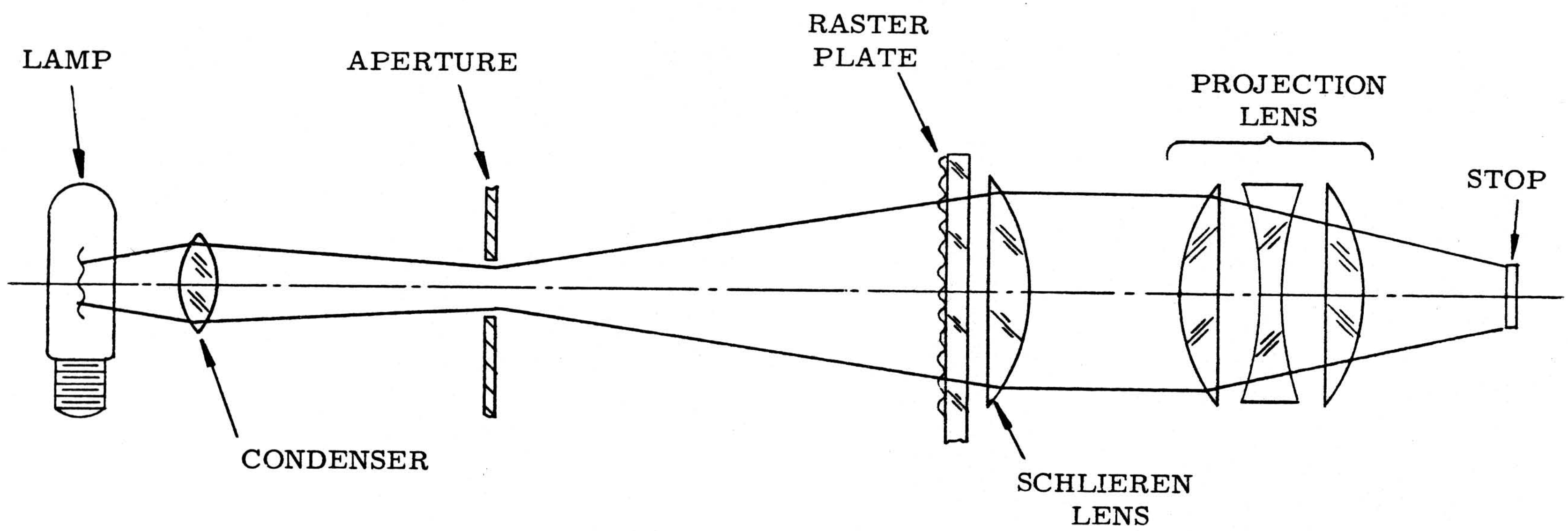


FIG. 36 OPTICAL LAYOUT

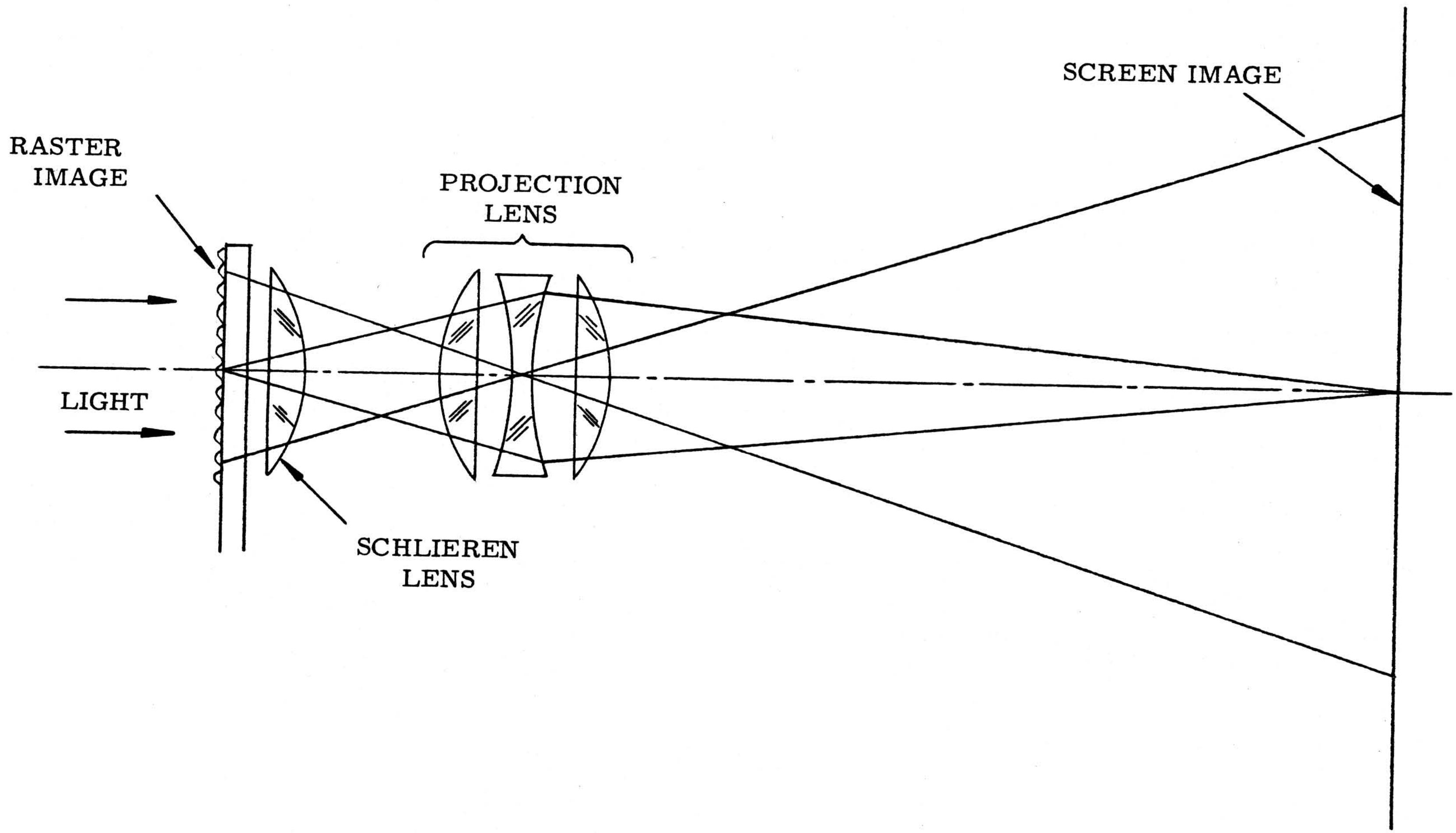


FIG. 37 OPTICAL LAYOUT

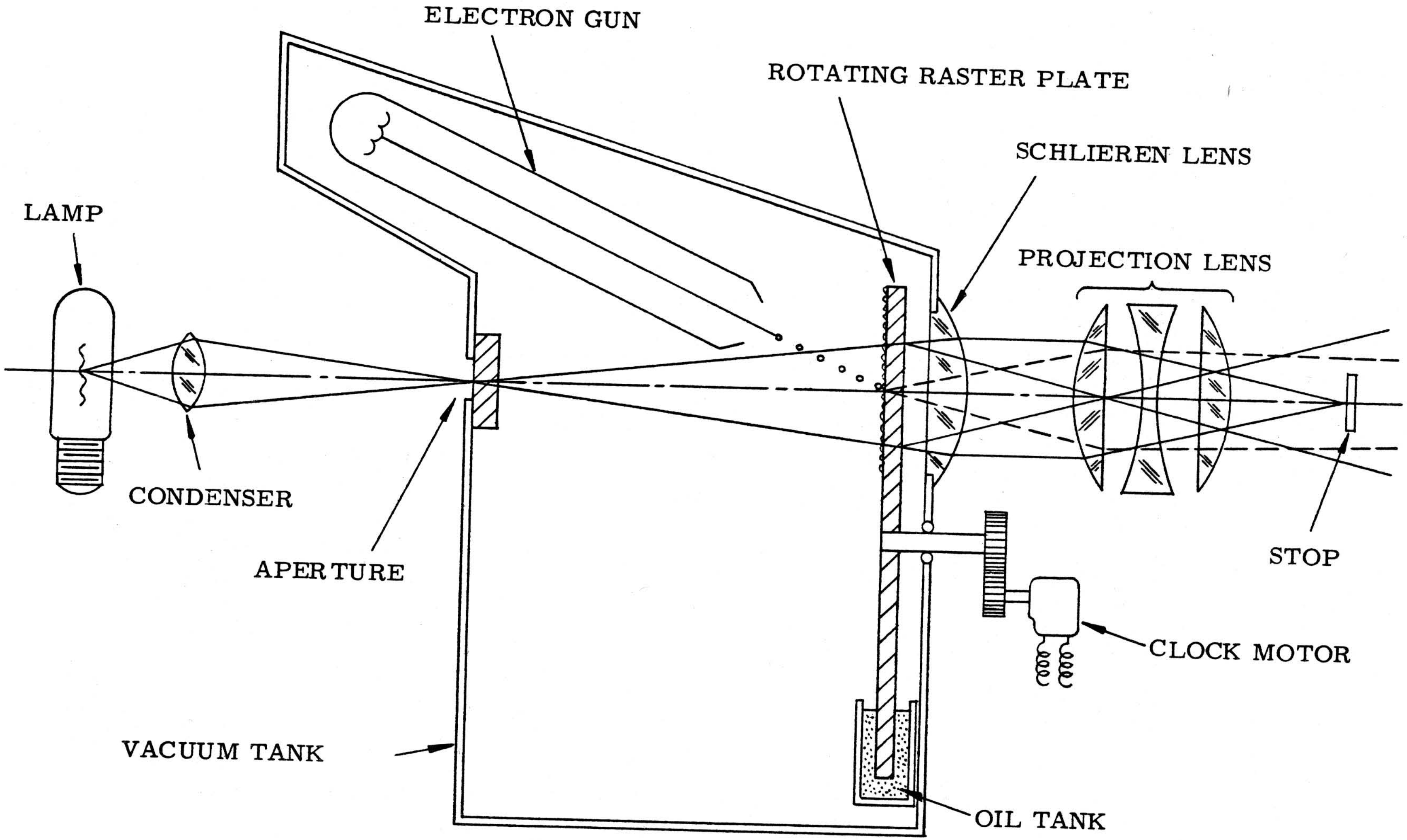


FIG. 38 PROJECTOR LAYOUT

3. With the stop in front of the projection lens, it was possible to use a lens of almost any focal length if it were large enough to cover the raster.

While a great deal was learned from this instrument, its bad features soon became apparent:

1. A very small amount of the source energy entered the first aperture. With this single bar system the aperture cannot be very large and due to the separation between the aperture and raster, the illumination angle cannot be very large. Using a tungsten lamp with a 10 mm. square source there was no advantage to magnify the source image, it was already too large and hence the collection angle could not be greater than the raster illumination angle. The layout in Figure 36 is not to scale on this point. The actual collection angle was only 18 degrees and of the 28,000 lumens emitted by the source only 560 entered the system. A considerable improvement was the substitution of a 2 kw Osram xenon lamp which has a source size of 2 x 4 mm. and permitted about four times source image magnification and an increase of the collection angle at the source to about 70 degrees which allowed about 6000 of the 65,000 lamp lumens to enter the system. The optical diagrams are hybrid drawings as they show the Osram collection system and a tungsten source.

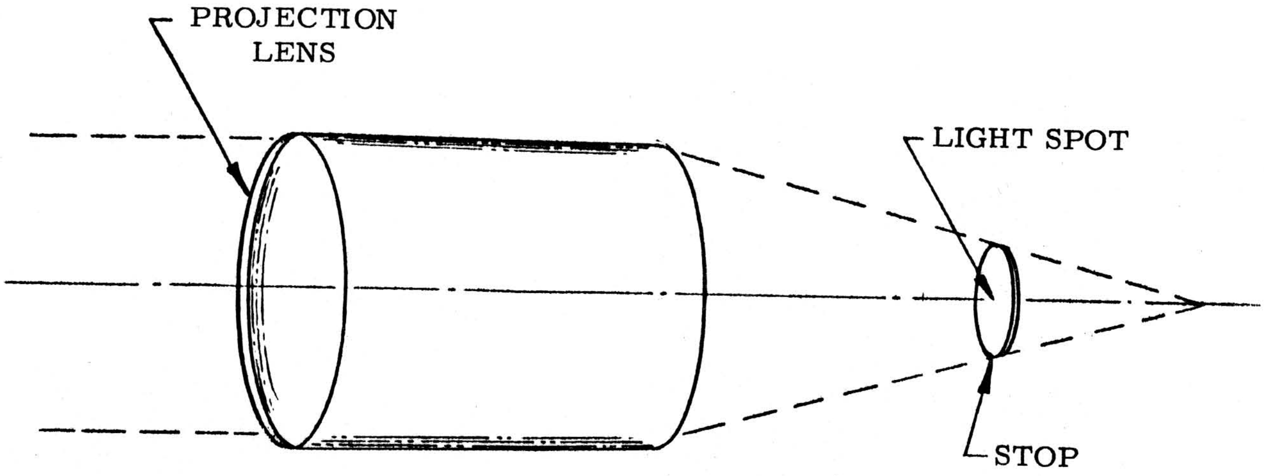
2. The raster plate when coated with chromium with a thickness which had 100,000 ohms resistance showed a light transmission of only about 65 percent. Metals are light absorbers and it was early decided to try transparent dielectric coatings such as tin oxide. The coating should have a resistance of less than 1000 ohms measured radially, should not be affected by the oil and resist scratching. When examined with a dark field microscope, it should be free of defects larger than 5 - 20 microns and must contain no electrical breaks.

3. The simple schlieren lens shown in Figure 36 is not adequate to form a well-defined image of the aperture on the stop. As designed, the schlieren lens shown was only half the schlieren optics, the projection lens did double duty as the other half. A bad feature

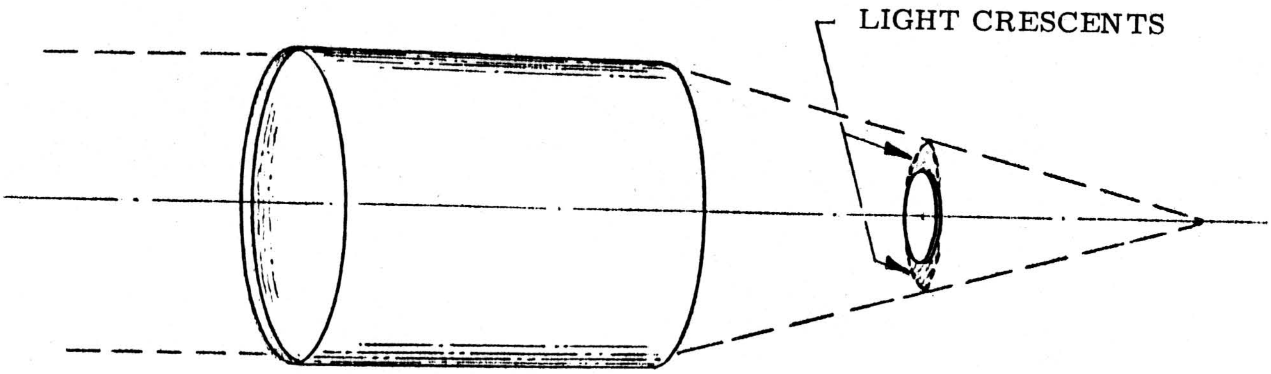
of the schlieren lens in this position is that it adds field curvature to the projection lens. Since it is a positive lens, thicker at the center than at the edge the greater thickness of glass at the center puts backward field curvature into the image rays. Unfortunately, this type of field curvature is difficult to correct in a projection lens, especially if the lens has a high aperture. While it is true that a properly designed achromat used as the first schlieren lens would have improved the definition of the aperture image on the stop, there appears to be no easy solution to the image curvature, astigmatism and other off-axis aberrations which the schlieren lens would contribute to the projected image. This does not mean the optical problem is impossible, but the straightforward solution was to place the schlieren lens on the other side of the raster plate. This new position of the lens obstructed the electron gun and meant placing the raster on the front of the plate and moving the position of the electron gun. This is somewhat awkward because the long electron gun now protrudes from the front of the projector and in this position it limits the size of the projection lens and requires that the lens be a distance from the raster that will clear the electron beam.

4. While it is true that all of the projection lens was filled with light, this was because it was acting as the second schlieren lens. When considered as a projection lens, the only areas that were used were two crescent shaped spots above and below the stop. This is shown in Figure 39. The nominal aperture of the projection lens was f/2.8 to perform as a schlieren lens, but the effective aperture as a projection lens was about f/12, though when considering resolution it is necessary to take into account the height, length and shape of the aperture elements. The resolution loss from this cause was minor compared to the major loss due to field curvature and astigmatism introduced by the schlieren lens which was between it and the raster.

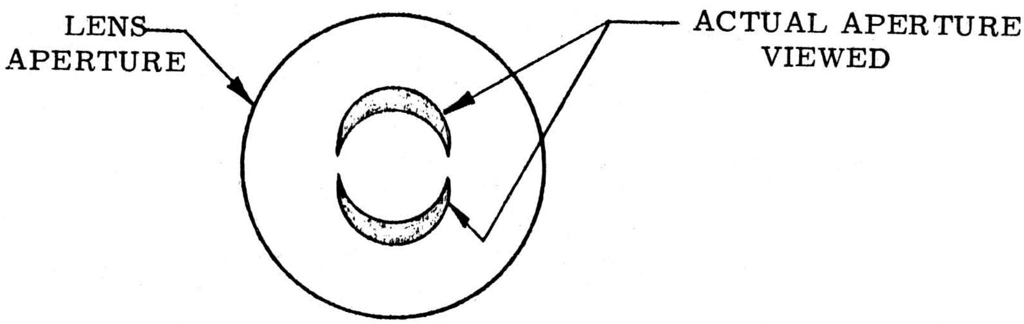
5. A very bad feature of this laboratory model projector was the poor dark-field caused by internal reflections in the projector



a. UNDEVIATED RAYS (DARK FIELD)



b. MAXIMUM DEVIATION OF RAYS (BRIGHT SCREEN)



c. ACTUAL LENS APERTURE

FIG. 39 ONE BAR SYSTEM

lens. Even though the lens was the simplest three element construction available, had excellent low-reflection coating and was clean, the dark-field contained a high level of stray light. This came from two causes, reflections of the undeviated rays in the lens before they struck the stop, and rays which reflected from the stop and re-reflected in the lens. Each of these will be discussed briefly:

a. The undeviated rays (dark-field condition) are assumed to be all directed toward the stop. However, the six lens surfaces, even with the best coating will each reflect from one-half to one and a half percent of the light depending on the refractive index of the glass. These reflected rays are changed in angle as if they were reflected from concave and convex spherical mirrors. Some of this reflected light is re-reflected by the lens elements and the schlieren lens and since these rays are now on uncontrolled paths they miss the stop and fall on the screen. In a bright-field projector these re-reflections are practically undetectable, but in a dark-field system it is necessary to make a calculation to indicate how serious they can be. Assuming that 1000 lumens of light entered the projection lens in Figure 38, then the reflected light from the six surfaces might amount to 10 percent or 100 lumens. Reflections from the two surfaces which are convex toward the light will spread out and be largely lost. Perhaps 80 percent of the reflected light or 80 lumens are available for re-reflection which including the schlieren lens will amount to about 10 percent or 8 lumens. Again, the light reflected from surfaces that are strongly convex to the beam will be largely lost, but a considerable amount of the remainder, perhaps 6.5 lumens will fall on the screen. If the refractive efficiency of the fluid is 30 percent then .3 of 1000 lumens less reflection and absorption losses can fall on the screen for a bright-field. This amounts to a bright-field of 225 lumens and the contrast ratio between 225 and 6.5 is only 35 to 1. A good motion picture projection will have a contrast of 250 to 1 and it was our goal to equal or exceed this value in the G-E light-valve projector. This feature of internal reflections has made us very cautious of multiple element schlieren lenses in spite of their advantages. It is likely that an air-spaced lens design can be produced in which all the surfaces were so shaped that their reflections were thrown out of the system, but we preferred cemented elements.

b. The undeviated rays in the dark-field condition fall on the blackened stop and are reflected back into the lens where they are re-reflected by the lens elements onto the screen. The best black surface when new and clean reflects about 2 percent. Actually a value as low as 4 percent is difficult to maintain. If 850 lumens of light were transmitted by the lens and 4 percent or 34 lumens were reflected by the stop, this light would re-enter the lens and about 13 percent of this would be re-reflected by the projection lens and schlieren lens. This would amount to perhaps 4 lumens of stray light on the screen. This light would be spotty because it would be in the form of out-of-focus images of the stop and would appear as vague discs of light of different sizes. While it might be possible to reduce the reflection from the stop by more sophisticated treatment such as making the side toward the light a mirrored cone, our conclusion based on this and other compromises was that the best place for the stop or cut-off was on the other side of the projection lens.

6. A fundamental weakness of the system that is not too apparent from the layout is that the projection lens which has a fairly high aperture, is being used for two dissimilar purposes and with two dissimilar sets of conjugates. As a projection lens it images the raster on the screen and therefore has a short rear conjugate and a long front conjugate. As one half of the schlieren lens it has an infinite rear conjugate and a short front conjugate. It is difficult to correct a fast lens for two sets of conjugates. This may seem unreasonable in view of the fact that fast photographic lenses are used with the front conjugate varying from infinity to 20 focal lengths, but these same lenses will perform very poorly if reserved. The projection lens is operating with normal conjugates

when considered as a projection lens, but with reversed conjugates when considered as a schlieren lens. It was our decision to separate the functions, though the decision was based on several other considerations such as the change of stop location.

FIRST COMMERCIAL G-E PROJECTOR

This projector was designed January 1959 and the first unit completed in May. While there were many electronic and material differences between this and previous models this report is concerned only with the optical features.

General

The intention of this design was to produce an optical system as simple as possible with provisions for a wider angle of projection, interchangeable lenses and if possible more illumination on the screen and better uniformity than the Gretener model while using the same light source. The optical development was carried out jointly by Herb Lavin of Syracuse, T.P.O. and G.E.L. with assistance from optical companies as mentioned. The schematic optical layout is shown in Figure 40 and the actual layout of the parts in Figure 41.

Light collected from the source by a very high aperture condenser and mirror is reflected from a dichroic mirror which is transparent to most of the infrared and then focused on the mirror bars which are staggered so they are separated as seen from the raster plate. The cones of light from the luminous points of the source image fill the schlieren lens. Only an axial bundle is shown but magnification of the source by the condenser causes its image to fall on all the bars. The field lens superimposes the cones of light from all three mirror bars on the schlieren lens. The schlieren lens images the luminous mirror bars on the opaque output bars. When the fluid layer is modulated by the electron gun to refract the rays, they pass between the bars and enter the projection lens to form an image of the raster on the screen.

Illumination System

Figure 42 shows the arrangement of this unit. The collection angle of the condenser was designed to be 100 degrees which according to the polar distribution of the lamp is just about all that is worthwhile to collect in a vertical meridian. This is also about the maximum that can be handled by a simple lens condensing system. The magnification is 4.3 X so that the geometrical size of the source

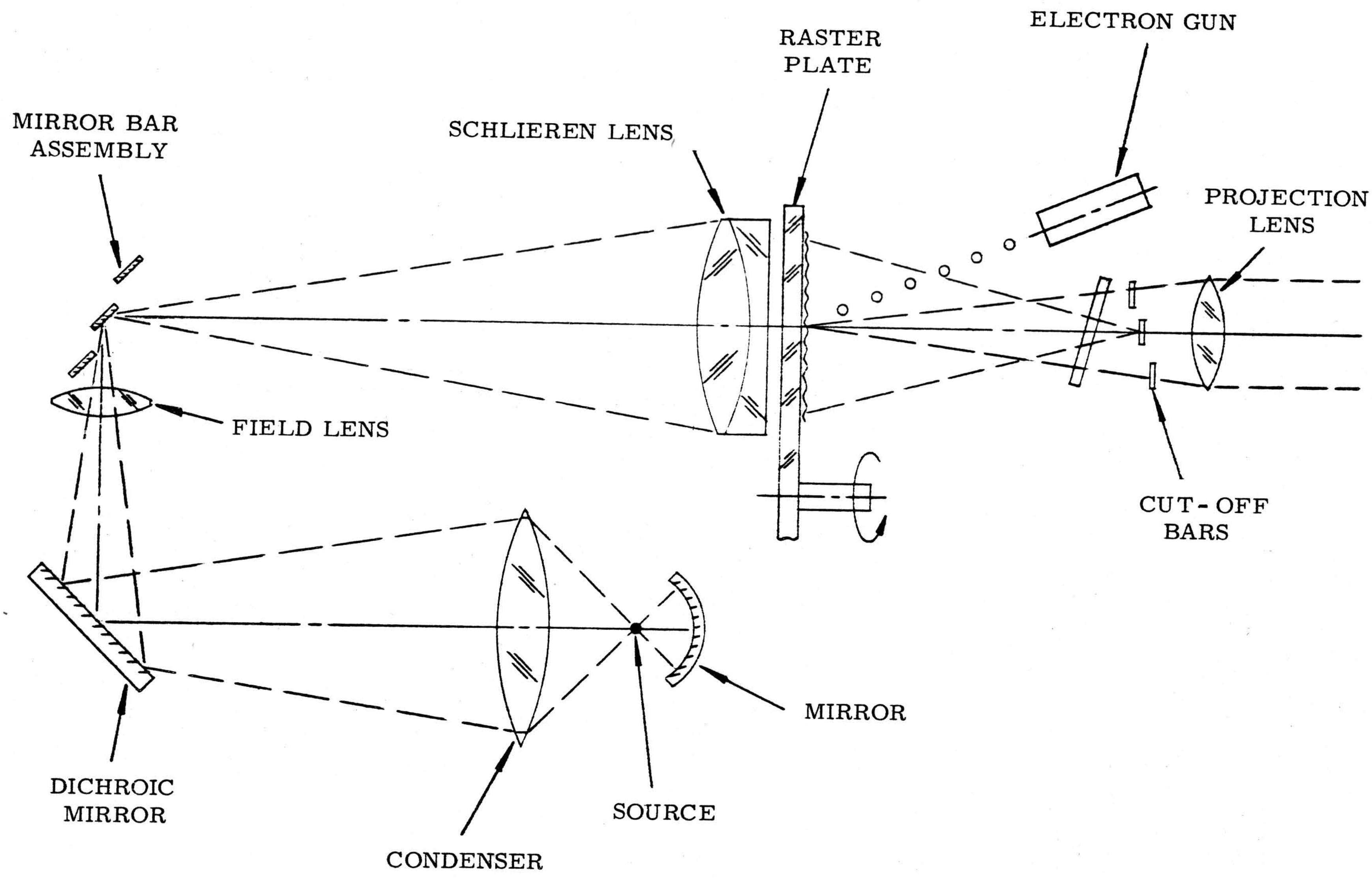


FIG. 40 OPTICAL SCHEMATIC

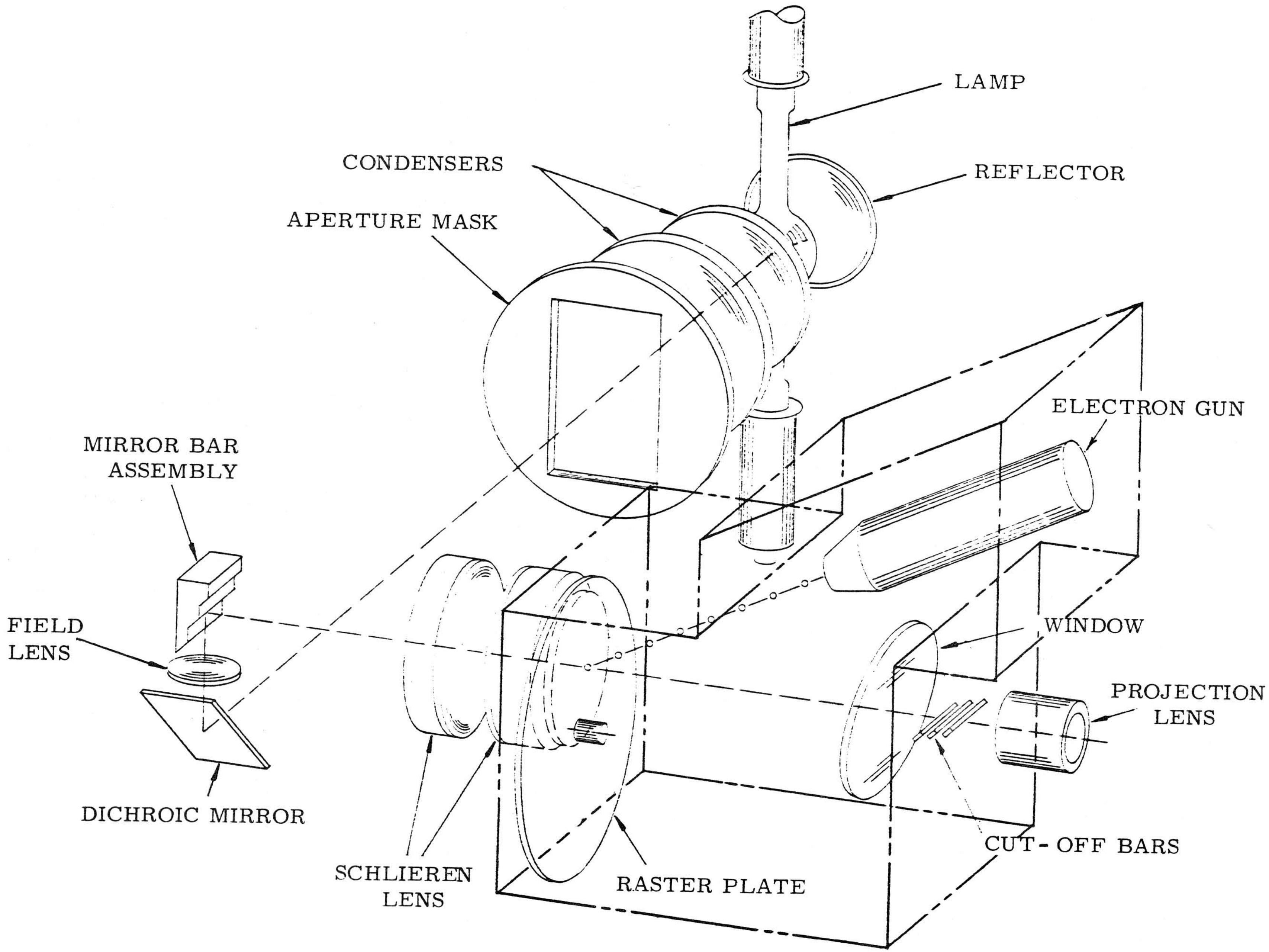


FIG. 41 FIRST G.E. COMMERCIAL PROJECTOR

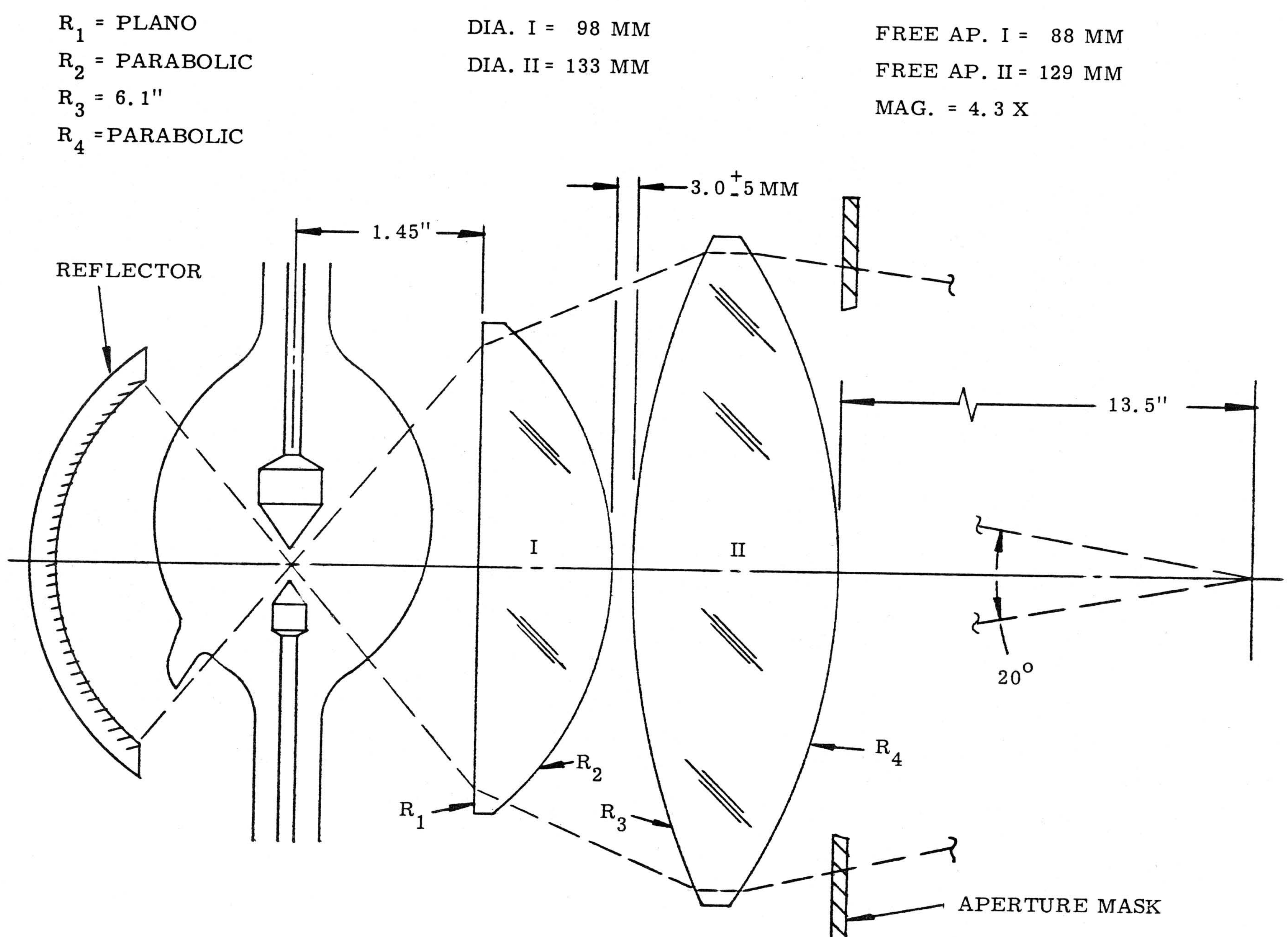


FIG. 42 BAUSCH & LOMB CONDENSERS

image should have been 3/8 by 3/4 inch. Since it was our intention to limit the condenser to two elements and it was felt that better control of spherical aberration could be obtained with two aspheric surfaces, we proposed a design consisting of two convex paraboloids which in spite of their high aperture have no spherical aberration for one set of conjugates. The Bausch & Lomb Optical Company was the only facility known to have equipment for making such lenses and so this job was given to them. The cost of such special condensers is considerable if only a few are made. The cost of the design was about $3000 and the cost of one pair of lenses $700.

When tested with a point source, the condensers proved to be nearly free of spherical aberration, but being made of Pyrex glass they showed considerable chromatism.

In general, aspheric surfaces due to their non-axial asymmetry to oblique rays show worse off-axis aberrations than spherical lenses and even the 4 mm. arc source shows at its ends considerable flare - a name given to any unidentified aberration.

Aspheric lenses are also more sensitive to decentering from the optical axis than spherical lenses so this feature was tested to determine the required alignment accuracy. It was found that either of the condensers could be decentered by one sixteenth of an inch or given a tilt to the axis of up to two degrees without appreciable effect.

The separation was specified as 3 mm. ± .5 mm. We found that if this figure were exceeded, there would either be light lost between the condensers or more flare to the image. The flare in these lenses took the form of "butterflies", a fairly well known type in which the source image is the "body" and the two flare circles appear at the sides as wings.

The condensers were made of Pyrex glass to resist thermal shock and this glass is not particularly transparent in thick lenses and its refractive index is so low that low-reflection coating is not very effective. The small element (not coated) had an average white light transmission on the axis of 88 percent, the larger coated lens, 87 percent.

An experimental attempt was made to account for the losses in the condensers with results as follows:

	Percent
Light falling on first surface	100
Transmission (axial)	79
Light in source image (measured)	73
Light lost in flare (difference)	6

The actual size of the source image due to aberration was about .6 by 1.1 inches.

The collection efficiency, defined as the fraction of total source flux collected by the condenser was calculated two ways:

a. A point source radiating uniformly over a 100 degree zone of a sphere was assumed. The condenser acceptance was calculated as the percentage of the surface which was within an inscribed circle having the same height as the zone as shown in Figure 43a. The calculated efficiency was 23.3 percent.

b. A point source radiating in the vertical meridian according to the polar distribution curve in the Osram bulletin and uniformly in the horizontal meridian. This is diagrammed in 43b. The calculated efficiency was 23.2 percent.

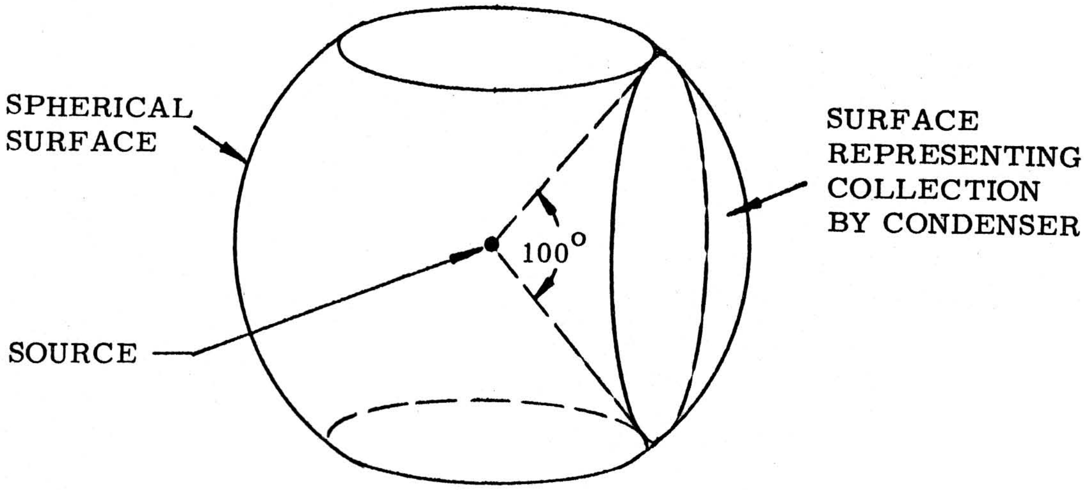
The reflector was aluminized glass with a reflectivity close to 90 percent. If correctly located it should increase the light collection 40 percent or a total collection of 32.5 percent. This is practically one-third of the entire lamp output and is very good for a lens system.

Aperture Mask

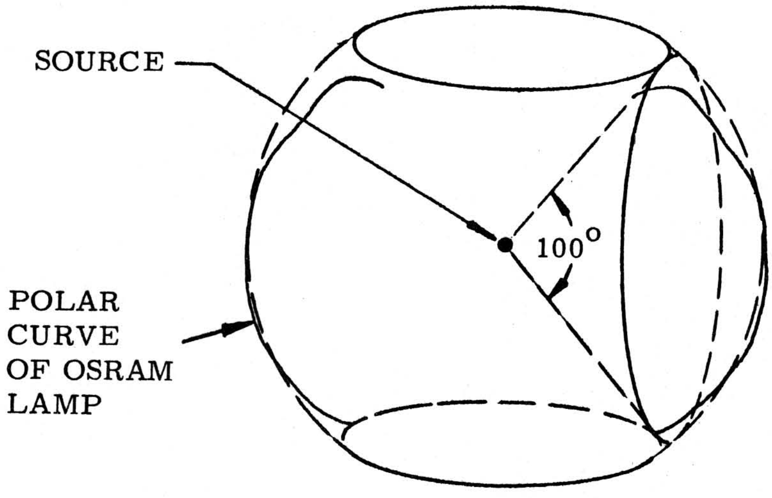
Without this mask the round condensers would form a round spot of light on the raster plate. Since a rectangular image is to be projected, the light outside the rectangle is not needed and will become a source for stray light in the vacuum system. The aperture mask is made a size which when imaged by the field lens on the raster plate, the illuminated area will be the size and shape of the raster image.

Dichroic Mirror

A Fish-Schurman mirror was used. The best of these had about 94 percent reflectivity for white light and a 70 percent transmission of infrared out to 4 microns.



a. UNIFORM POINT SOURCE



b. OSRAM SOURCE

FIG. 43 COLLECTION EFFICIENCY

Field Lens

The field lens images the aperture mask on the raster and also controls the marginal rays from the source image so they largely fall on the schlieren lens. Without it the edges of the picture are very poorly illuminated. The lens is biconvex with a focal length of about 6 inches. Several lenses of the same power but with different shape were tried and the only effect that could be seen was that certain curves caused a poor dark-field. Apparently this is the first element that must be considered from this viewpoint. It seems that the lower convex surface can become a concave spherical mirror for rays returning through the system and these rays are focused somewhere that they can pass between the bars.

Some field lenses have cracked from the heat caused by the intense source image focused on them and as result some Pyrex and silica lenses have been used.

The chromatism of the field lens causes a pink ring around the raster which is sometimes noticeable. An achromatic field lens would prevent this but we hesitated a long time before subjecting an achromat to this severe heat exposure.

Mirror Bar Assembly

Figure 44 shows a unit made from three strips of glass each with one end ground and polished at an angle and mirrored. The "risers" between the steps are painted black. As seen from the source it should appear a solid mirror, as seen from the raster it consists of mirrored strips separated by equal black bars. The source image falling on the assembly is an oval. The deficiencies of mirror bar assemblies will be discussed later. It was originally thought that this would prove a very simple and inexpensive device, in fact the first unit cost only $30 and performed fairly well, but to obtain the highest performance requires a unit that costs about $500.

Schlieren Optics "Jaegers" Lenses

The first set of achromatic schlieren lenses for these projectors was made by the A. Jaegers Optical Company. One lens is shown in

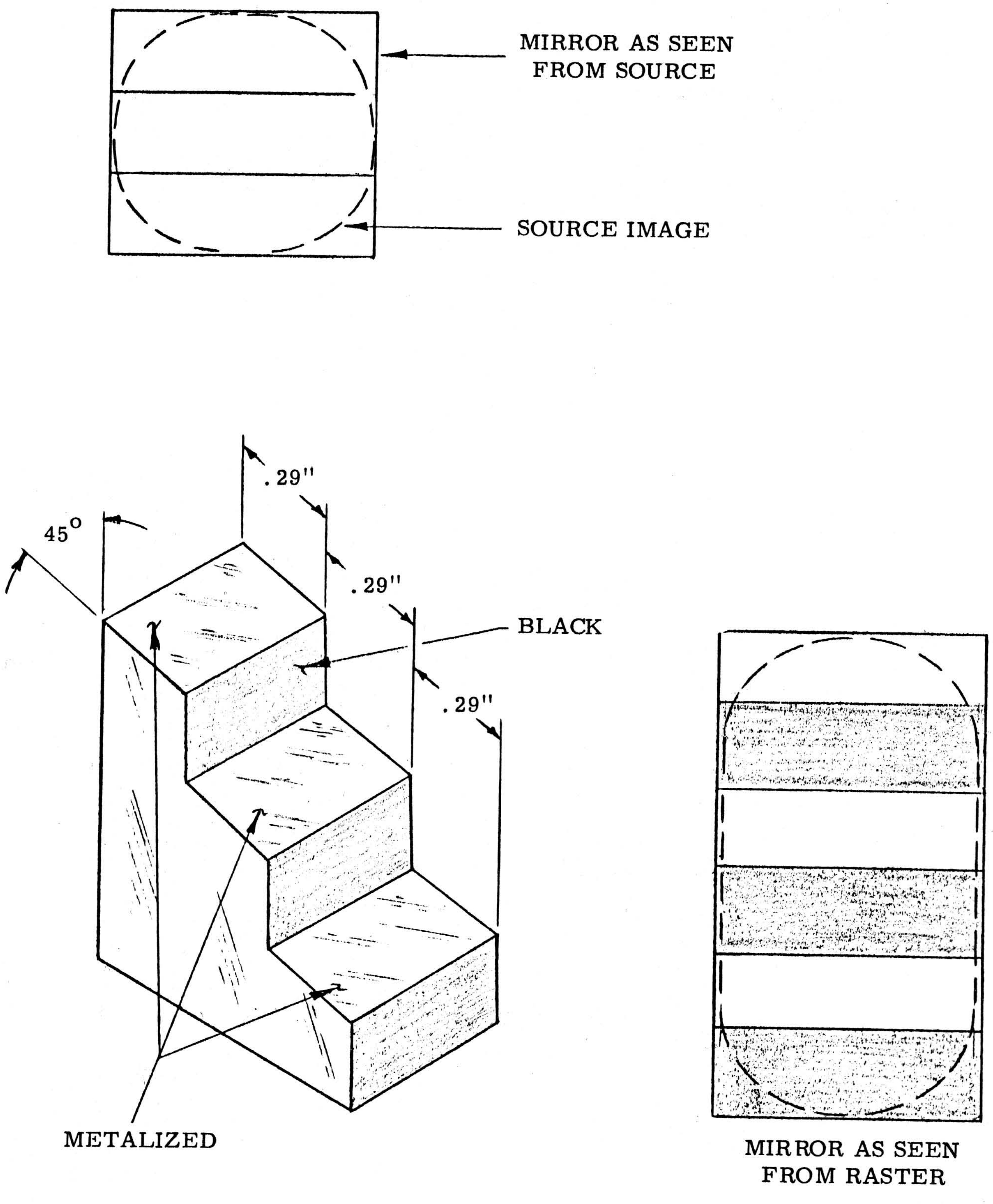


FIG. 44 MIRROR BAR ARRAY

Figure 45. These lenses are often referred to as the "Jaegers" lenses and have been used extensively as the schlieren optics for thermoplastic film projectors. The two lenses form a symmetrical pair 3.12 inches in diameter and 6.9 inches focal length. The back focus or working distance is 6 inches. The speed of the lenses if f/2.2 which is extremely fast for a good achromat. The optical design is rather unusual in that it allows good spherical and chromatic correction and fair oblique correction to 7 degrees off-axis by the use of an unusual pair of glasses. A symmetrical pair has the advantage that the two lenses are less expensive because they are identical and the tooling cost is less than for a pair of different lenses. These lenses were designed for a raster size of 1-1/2 by 2 inches and when it was decided to go to a larger raster and to "immerse" the interface between the second schlieren lens and the raster plate, the Jaegers lenses had to be abandoned.

American Optical Schlieren Lenses

The second set of schlieren lenses were designed and made by the American Optical Company and are shown in Figure 46. These achromats form an unsymmetrical pair having a ratio of conjugates of nearly 2 to 1. The actual magnification of the bar image is .54X. The second surface of the second lens is flat so that it can be immersed in the control layer fluid and "cemented" to the back of the flat raster plate. The reason for this was that it proved to be impossible to keep the fluid off the back of the raster plate and the vacuum window which in this case was also the second schlieren lens. This fluid tended to form in droplets and showed in the projected picture. Also reflections between the flat surfaces of the raster plate and the window were extremely bad for the dark-field.

Assuming 1000 lumens of light at the raster plate, there will be 5 percent reflected from the first surface (low-reflection coating is not effective in an oil-vapor atmosphere) and perhaps 10 percent from the second surface of the raster plate which has the conductive coating. The total reflected light amounts to

R_1	20."	AXIAL THICKNESS 1.15"
R_2	3.0	EDGE THICKNESS .85"
R_3	3.7	EQUIVALENT FOCAL LENGTH 175.5 MM or 6.9"

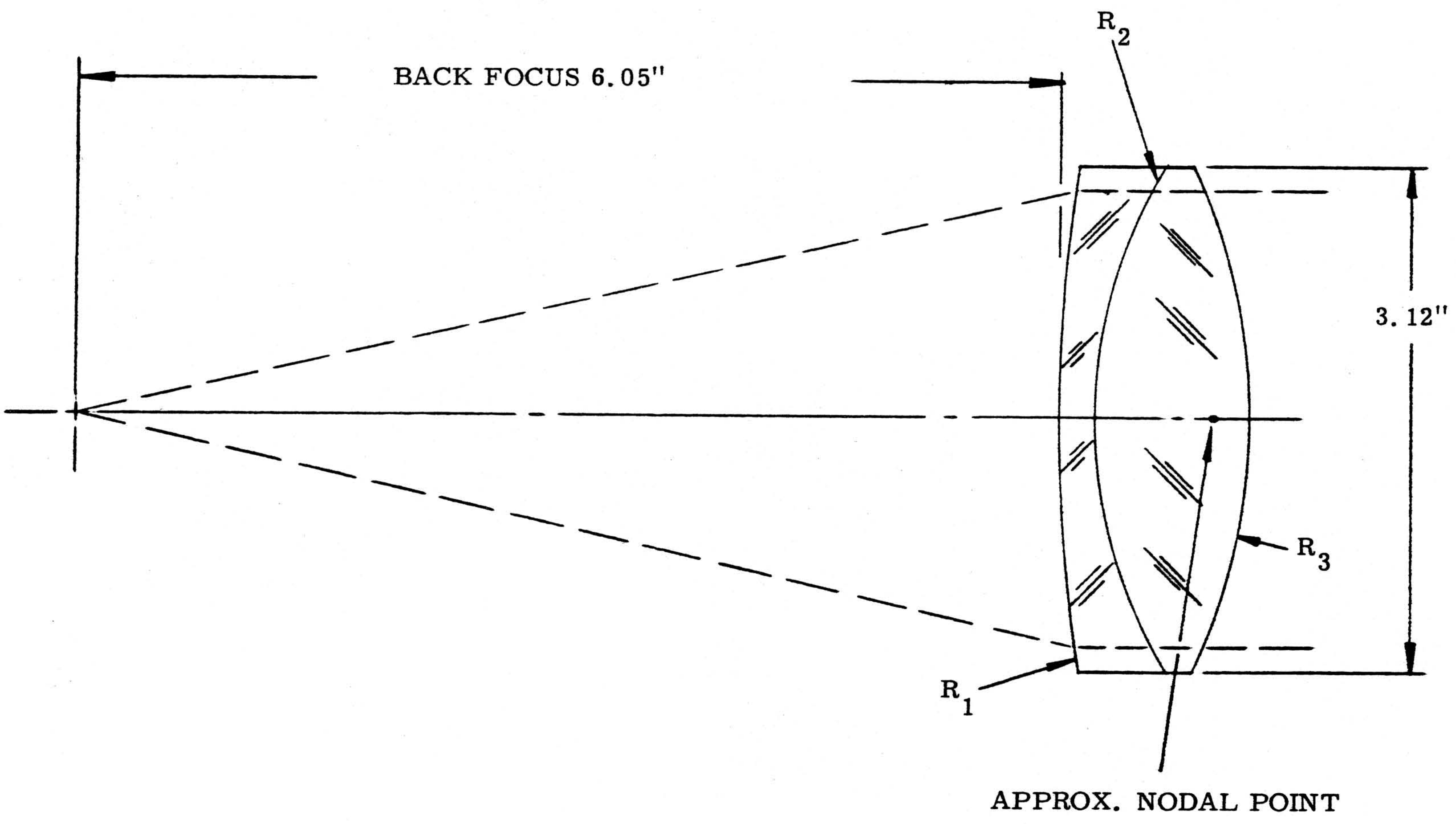


FIG. 45 "JAEGERS" SCHLIEREN LENS

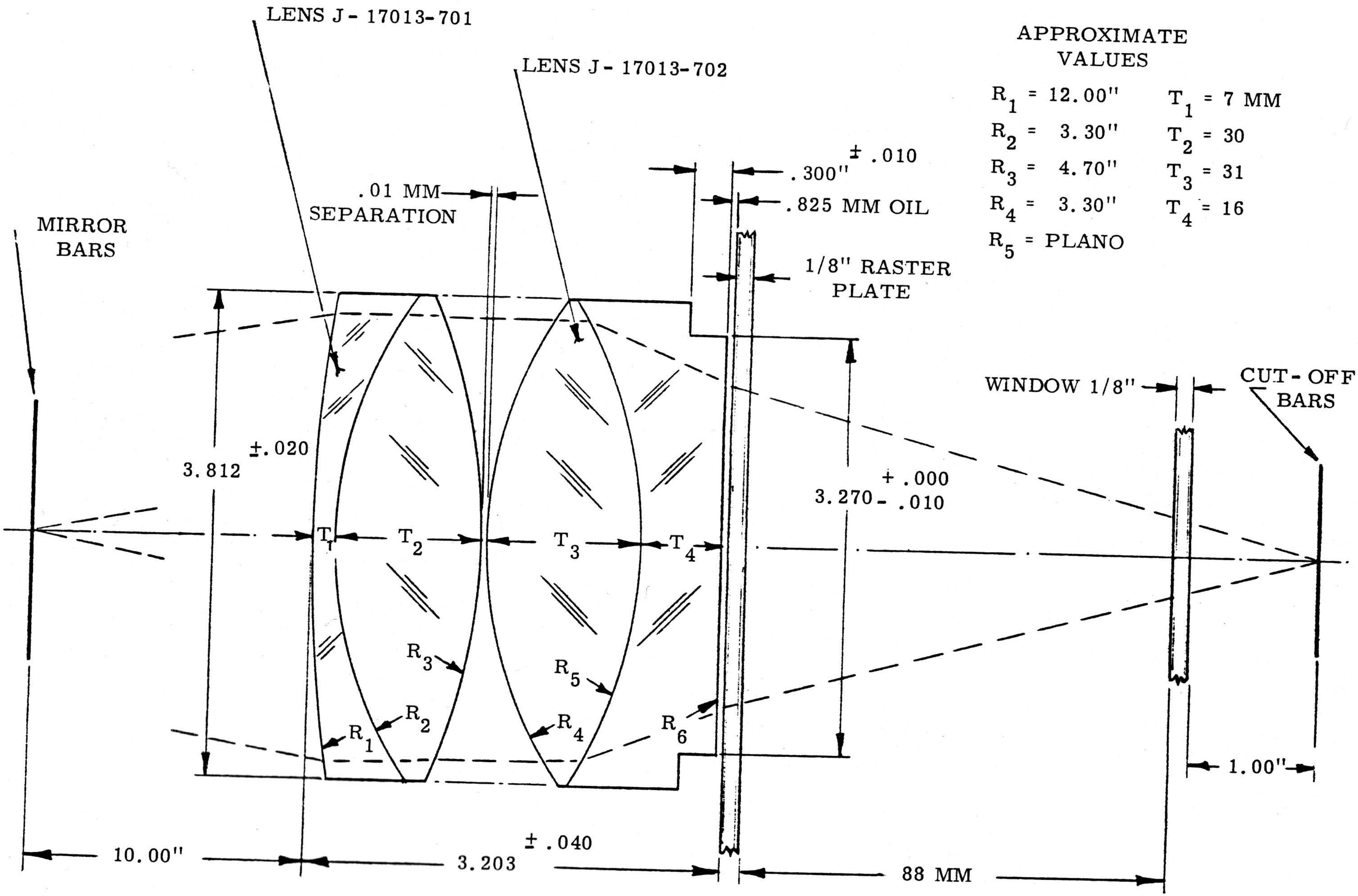


FIG. 46 AMERICAN OPTICAL SCHLIEREN LENSES

150 lumens. If 5 percent of this reflects from the schlieren lens or window, this is 7.5 lumens that can largely miss the bars and fall on the screen. The angles of the rays and the thickness of the glass are such that the rays are displaced enough after reflection to fall in the spaces between the bars. If the oil efficiency is 30 percent then the bright-screen illumination (neglecting other losses) can be only 300 lumens and the 7.5 lumens on the dark screen will limit the contrast from this cause alone to 40 to 1.

It was therefore decided to "immerse" the interface which optically is equivalent to cementing or filling the space with an liquid of practically the same refractive index as the lens and raster plate. This virtually eliminates the effects of raster plate reflections.

The shoulder on the second schlieren lens is to fit an "0" ring which forms the vacuum seal.

The design of the lenses includes the refractive effects of the raster plate and front vacuum window though actually their effect is so small that the difference in performance of the lenses with and without the two glass plates is negligible.

The measured axial transmission of the first pair of schlieren lenses was 87.5 percent.

The chromatism between red and green is .7 mm. and between red and blue, .9 mm.

There was little astigmatism or coma below 3 degrees off-axis. Since the bar mirror was intended to subtend only this angle, it was well inside the limit of good performance.

The two schlieren lenses produce a curved image of the mirror bars. The calculated radius was 127 mm. which is close to the measured value. Over a 28 mm. bar the sagitta of the curve was .32 mm. which is less than the calculated depth of focus of .6 mm. or .02".

The lenses allow some flexibility of the conjugates with consequent changes in magnification. The conjugate of the first lens can be increased from the nominal 10 inches to 12 or shortened to 9 without serious effects. The free aperture at the raster plate is 3 inches.

In all schlieren optics every effort must be made to prevent unwanted refractions, reflections, and diffusion of the light or it will be impossible to obtain a dark-field. Specifically, this means that the glass must be free from striae (variation in refractive index) which will cause unwanted refractions and free of microscopic bubbles which will scatter light. The surfaces must be shaped so that they do not act as reflectors for light returning through the system and the optical surfaces must be polished so that they are unusually free from pits and scratches which when illuminated can become sources of scattered light. The low-reflection coating should be efficient and all surfaces of the lenses must be clean. A single fingerprint or a "normal" accumulation of dust will cause a serious increase of the light in the dark-field.

The Jaegers and American Optical lenses have met these requirements very well for small fields.

Raster Plate

The raster plate is a glass disc having some means such as a central shaft to drive it. Both sides become coated with fluid and capillary attraction causes the fluid to fill the space between the plate and the flat surface of the second schlieren lens. The front of the raster plate has a conductive coating to carry off the electron charge. This coating should be durable, unaffected by the fluid, colorless, as transparent as possible, have a moderately good conductivity and be free of defects.

Metal coatings are inherently inefficient. Some metals such as evaporated chromium or rhodium can be very durable, defect-free and reasonably colorless but they are light absorbers and reflectors and to obtain a satisfactory conductivity with them requires a deposit that has poor light transmission - perhaps 50 percent. The reason for this low transmission is partly the inherent optical property of metals and partly the phenomenon of agglomeration. When metal is evaporated on glass, the atoms do not simply build up a film of uniform thickness. Instead what appears to happen is that the hot "atoms" of metal skid around on the glass until they find an irregularity or another metal atom. This is supposedly due to the difference in the work function between metals and glass. As the evaporation proceeds the adhered atoms become centers for the growth of islands or very thin irregular, but generally rounded masses of metal. Few of the islands touch and hence there is no conductivity due to the state of agglomeration. Eventually, the islands grow so large by the accumulation of metal that they touch and the coating at this time is more or less continuous, but full of holes that have not filled in. Such a film has a conductivity that depends primarily on its thickness and the specific conductivity of the metal. After further deposition the holes are mostly filled and subsequently the film simply increases in thickness though there is a strong tendency for some holes to persist. All of this action takes place on a sub-visible scale, but has been observed taking place under an electron microscope. The theory of agglomeration accounts for the strange electrical behavior of evaporated metal films. The conductance does not increase uniformly with the weight of metal deposited but remains near zero until a certain critical amount of metal has been accumulated and thereafter rapidly increases.

The best known non-metallic conductive coating is tin oxide which shows good features of high transparency, good conductivity and fair durability. Unfortunately, the process used to apply it appears to pit the surface of the glass and the coating is usually filled with many small defects which when illuminated in a dark-field system shine like a galaxy of stars. It is quite common for tin oxide films to have small electrical breaks in them. The fluid layer resting on these isolated sections does not lose its charge and tends to form a "permanent" luminous defect in the picture. Since the charge on these defects does not decay as does the charge in the rest of the image, these defects are likely to become the brightest and most eye-catching objects in the picture field. Needless to say small breaks in a virtually invisible film are nearly impossible to detect visually even under the microscope.

A promising solution to the problem is a de-agglomerated intermetallic coating. An example is gold-bismuth or gold-indium. Bismuth is scarcely a metal and has a work function similar to glass. It can be evaporated in thin layers without agglomeration and then oxidized to transparent bismuth oxide. When metallic gold, our best electrical conductor is evaporated on this oxide, it does not agglomerate but forms a thin uniform layer of high conductivity. Afterwards the film is heated and apparently the nearly transparent intermetallic compound gold-bismuth is formed. For greater durability this can be overcoated with other materials, preferably more bismuth oxide. The films so produced are practically fused onto the glass and are durable. Their color is slightly greenish but not noticeably so, and they can have a resistance as low as 10 ohms with a light transmission of 85 percent. For raster plates a resistance of several hundred or thousand ohms is allowable if it results in better light transmission.

Unexpectedly, silicone oil has been found to dissolve and remove some conductive coatings.

Our original raster plates were Pyrex discs sprayed with tin oxide and if purchased would have cost less than $5 each. The present optical glass gold-indium discs cost more than $300 each.

The raster plate should be reasonably free from striae which can become apparent in a schlieren system and diffusion which will cause scattered light and loss of dark-field. The conductive coating must not be a source of light diffusion and should be free of defects and electrical breaks.

Window

The vacuum window need not be low-reflection coated on the vacuum side because of the oil vapor atmosphere, but even if coated, the two surfaces when normal to the optical axis would send undesirable reflections back to the raster plate which would reflect back through the bars. Bowing the window is some help, but adds unwanted spherical aberration to the projected raster image.

Tilting the window appears to be the best solution. A ray trace shows that at least 15 degrees of tilt is required and an aberration analysis shows that so long as the glass is thin it has little effect on the image. The glass could be thick as .26 inches and tilted as much as 20 degrees before detectable astigmatism is produced. The only noticeable effect of window tilt is to displace the optical axis downward .27 mm. Again, the window should show no diffusion, should be well-polished and kept clean to produce a dark-field.

Output Bars

As mentioned earlier the output bars are conjugate to the mirror bars and magnified .54 times. Flat metal strips have been used, but it should be remembered that in the dark-field condition all the energy in the optical system is focused on these relatively small bars. Without the dichroic mirror they would become red hot and even with the mirror thin metal sections may become so hot that they warp out of shape and become unsoldered.

Even the best black finish reflects considerable light and if the bars are flat strips, this light returns to the raster plate where some of it can be reflected again onto the screen. One solution is to use "V" shaped bars which due to their thick section are better heat conductors and their tilted surfaces reflect light out of the system. A typical array is shown in Figure 47.

The widths of the bars are nominally their "geometrical" size plus a guard band of at least .002 inch on each edge to allow for aberration and to provide some tolerance for adjustment. Actually, the bar widths are best determined by trial and error. Too narrow bars will make a dark-field impossible and too wide bars will reduce efficiency and cause loss of gray scale. Some guard bands are inevitable in the present design and their effect on the gray scale is compensated by an electronic "gamma correction" circuit.

The mirror bars are staggered along the optical axis and hence their images will not lie in a single plane. Calculation shows that the variation of axial focus of the bar images is greater than the depth of focus of the schlieren lenses. There are two ways this can be accommodated, either a plate with flat bars which is tilted to compensate for the angle of tilt of the mirror bar array or a set of staggered bars.

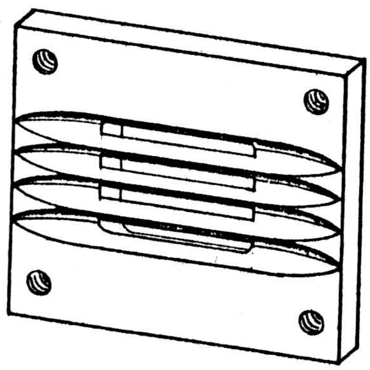


FIG. 47 "V" BAR PLATE

Projection Lens

Probably the worst optical feature of this design is the way parts are crowded around the projection lens. The vacuum window, output bars and projection lens are all very close together and right under the electron gun. The size and angle of the gun limits the size of the bar assembly and the diameter of the lens. It also prohibits the use of short wide angle lenses. The reason for this crowding is that the window and bars must clear the electron beam and should be as far from the raster as possible. The bars should be as close to the lens as practical to prevent them from showing on the screen and the total space available is equal to the back focus of the projection lens. An f/4.5 lens of the usual Tessar construction has a back focus equal to about 85 percent of its focal length. The focal length of the lens is determined by the raster size, the screen size and the projection distance, and for this application a 135 mm. (5.3 inch) lens was required. The back focus could be expected to be about 4.6 inches. The minimum size of the lens is that which will cover the bar assembly and in the original design an f/4.5 lens was adequate. This is shown in Figure 48.

A standard projection lens was not used because the normal triplet design when used at the required 27 degree projection angle showed curvature of field and lateral chromatism. The standard Petzval designs are very long and do not have sufficient back focus, therefore, a Wollensak Raptar enlarging lens, actually a variation of the Tessar was used. Since this lens has a very simple construction, the axial light transmission is 91 percent. The image quality and freedom from distortion is excellent. As purchased, the lens contains an iris which was not needed and which added to the diameter, the lens were remounted to fit into the limited space below the electron gun.

The problem of increasing the back focus was given some consideration. If a weak negative lens is placed in front of a positive lens, it increases the focal length slightly and moves the nodal point of the combination backward and hence increases the back

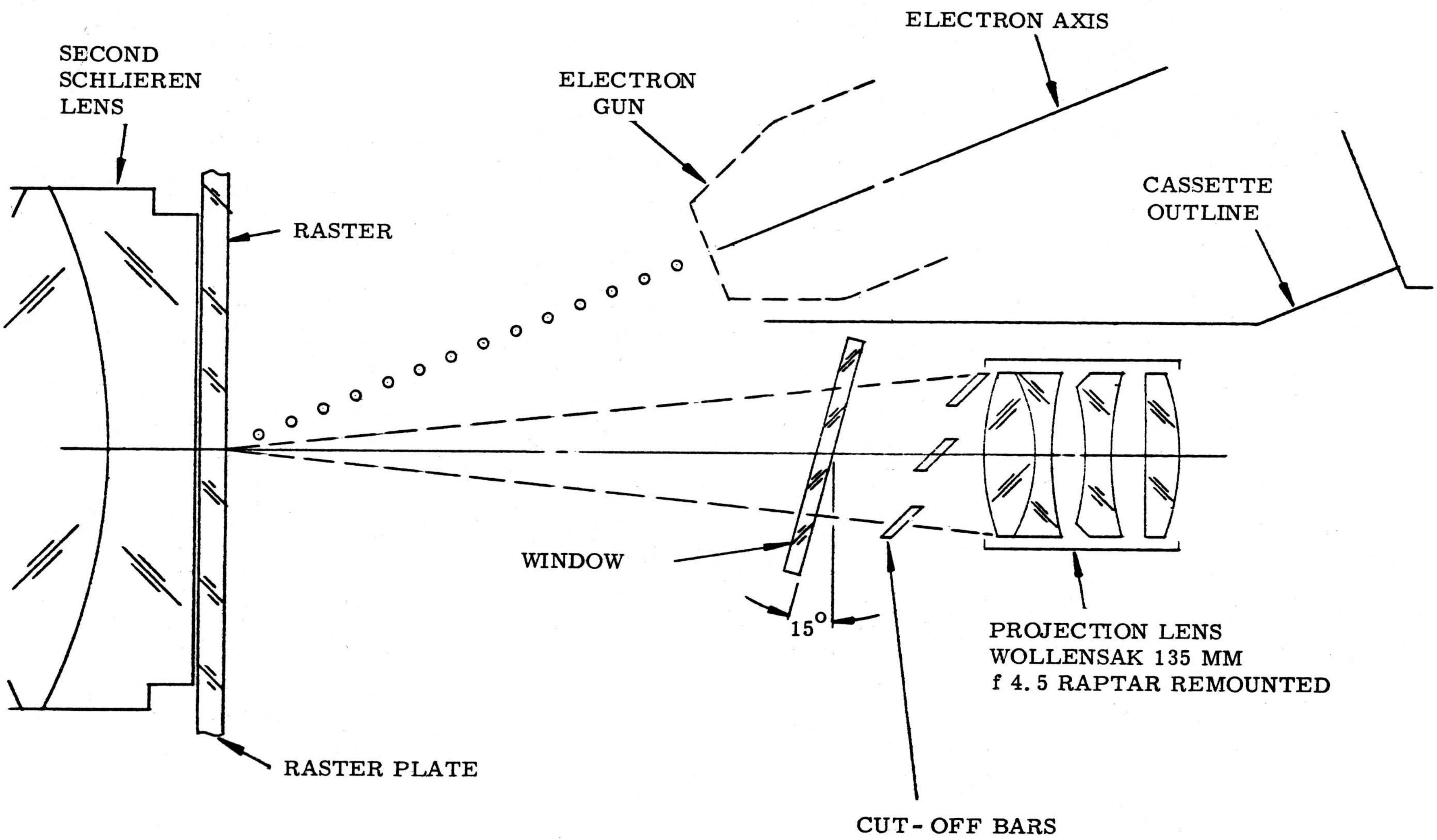


FIG. 48 G.E. PROJECTOR - ORIGINAL LENS

focus. In general this principle can be used to alter slightly the focal length or nodal point in either direction, but there is a limit to the strength of the added lens that can be used before it will contribute visible aberration of its own, mainly distortion and curvature of field. There is also an optimum shape for these lenses and this shape and the power of the lenses turns out to be the same as the "flat base" spectacle lenses. The following combinations were found usable:

Added Lens	Back Focus of Combination	E.F.L. of Combination
None	4.70"	5.31"
-.12 Diopter	4.78	5.44
-.25 "	4.88	5.47
-.37 "	5.00	5.52

If still more back focus is required, one solution is a "reversed telephoto" lens which is an objective designed to have a back focus greater than its focal length. Most of such lenses have some distortion and if this is appreciable it may be objectionable in the picture or may cause trouble from double-imaging.

If a wider angle of projection is required, another solution is to use a wide-angle attachment which is a sort of Galilean telescope turned backwards. It is possible by this means to double the projection angle.

These devices can even be added to "wide angle" lenses so long as the final projection angle does not exceed 90 degrees. Attachments of this type are on the market. A small one for lenses up to about 1-1/2 inches in diameter is the "Buhl Superwide Attachment", another for lenses up to about 2-1/2 inches in diameter is the "Vicom". Since these devices are afocal they can be used with any projection lens. Our tests have shown no visible loss of resolution and only about 10 percent loss of light.

Another report titled "Evaluation of Screen Materials", 60GL128, discusses the unusual properties of these attachments and reversed telephoto lenses. One of their desirable features is that they produce less vignetting (reduction of the light at the edges of the image) than normal lenses and it is even possible to design them to produce no vignetting over a 120 degree projection angle.

RE-DESIGNED G-E PROJECTOR

General

After completion and test of the first projector designed according to the previous section, it became apparent that the optical design left a good deal to be desired. The screen illumination was less than anticipated, not as uniform as we would have liked and showed some color effects due to chromatism. To eliminate these shortcomings required a number of replacements. The design and manufacture of the replacement parts were done by the Wollensak Optical Company.

Condenser

The design of the Gretener condenser was based on utmost simplicity, two spherical lenses of minimum size made of fused silica, a combination that resulted in considerable uncorrected spherical aberration and some chromatism. The screen illumination uniformity was none too good, but probably the optimum that could be obtained with so few spherical lenses and the residual aberrations contributed considerably to the source image flare.

The intention in the previous G-E design was to eliminate spherical aberration by the use of aspheric surfaces. The G-E projector required a smaller source image than the Gretener and it was our intention to produce as small and well defined an image as possible. When the design showed the condenser lenses to be quite large, the use of silica seemed impractical so they were made of Pyrex which has a higher dispersion. It was known that the off-axis aberrations of fast aspheric lenses is greater than comparable spherical lenses but it was believed that the small source would not prove troublesome. Actually, since these condensers have a focal length only slightly over an inch and the extreme point on the source is just slightly over 2 mm. off-axis, the field of the condenser needs to cover only 9 degrees total angle. When the lenses were tested, they proved to be free from spherical aberration, but had a considerable amount of flare which produced a larger image than intended. Also the aspheric condensers were very critical as to focus, a slight misadjustment could result in either a dark or bright center to the screen illumination. The chromatism was worse than the Gretener system and in the final comparison it appeared that our rather expensive design had accomplished little if anything over the relatively simple Gretener design. While the Gretener condenser showed spherical aberration and slight chromatism, the G-E design showed bad off-axis aberration and worse chromatism. Both were equally undesirable, though in different ways and the Gretener was superior in transmission to the thick Pyrex lenses we used. Though the G-E condenser had a higher collection angle at the source, it seemed that we lost in flare all that we gained though this point was never examined in detail.

The solution to these problems was a more complicated design based on spherical surfaces and known as the "achromatic aplanatic" condenser as shown in Figure 49. This arrangement is well known and its performance could be predicted since it is fully corrected for fields as large as the source. Actually, the condenser is designed in conjunction with the field lens to be described later, and though it is much more complex than the original G-E lens, it puts more light in the source image and because all the important aberrations are fully corrected on and off-axis it is able to produce a nearly perfectly uniform illumination at the condenser exit pupil. In the original design the exit pupil was unfortunately inside the second condenser lens making it impractical to place the aperture plate in its most desirable location and any other location can be expected to produce some vignetting of marginal rays. Also it is a poor feature to have the exit pupil on or close to a strongly convex surface as it was in the original design and doubly bad when this convex surface is aspheric. With the aplanatic design, it was possible to place the exit pupil about an inch outside the condenser and to make the final surface concave which favored marginal rays. This is an excellent feature because even though the condenser aperture was uniformly illuminated, the distribution of light on the screen would be modified by the vignetting of the schlieren and projection lenses. Favoring marginal rays at this point is the best way to assure good edge illumination on the screen.

R_1 = 1.40"	R_5 = 2.90"	R_9 = 2.40"	T_1 = .77"	T_3 = .77"
R_2 = 3.00"	R_6 = 4.80"	R_{10} = 3.70"	T_2 = .80"	T_4 = 1.45"
R_3 = 1.55"	R_7 = 8.50"	E.F.L. = 1.579"		T_5 = .30"

CONDENSER MAGNIFICATION = 10.26 X

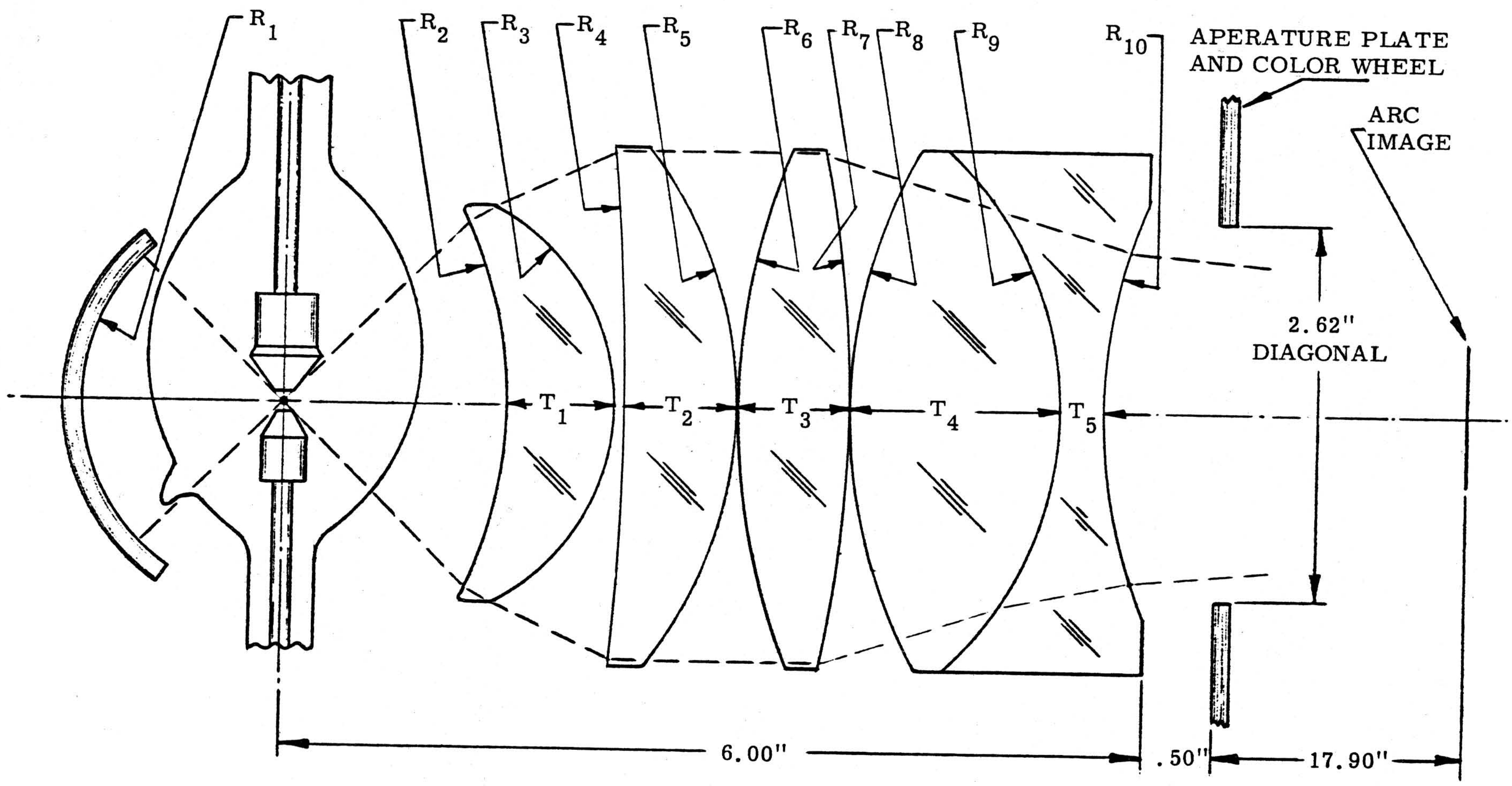


FIG. 49 WOLLENSAK CONDENSER

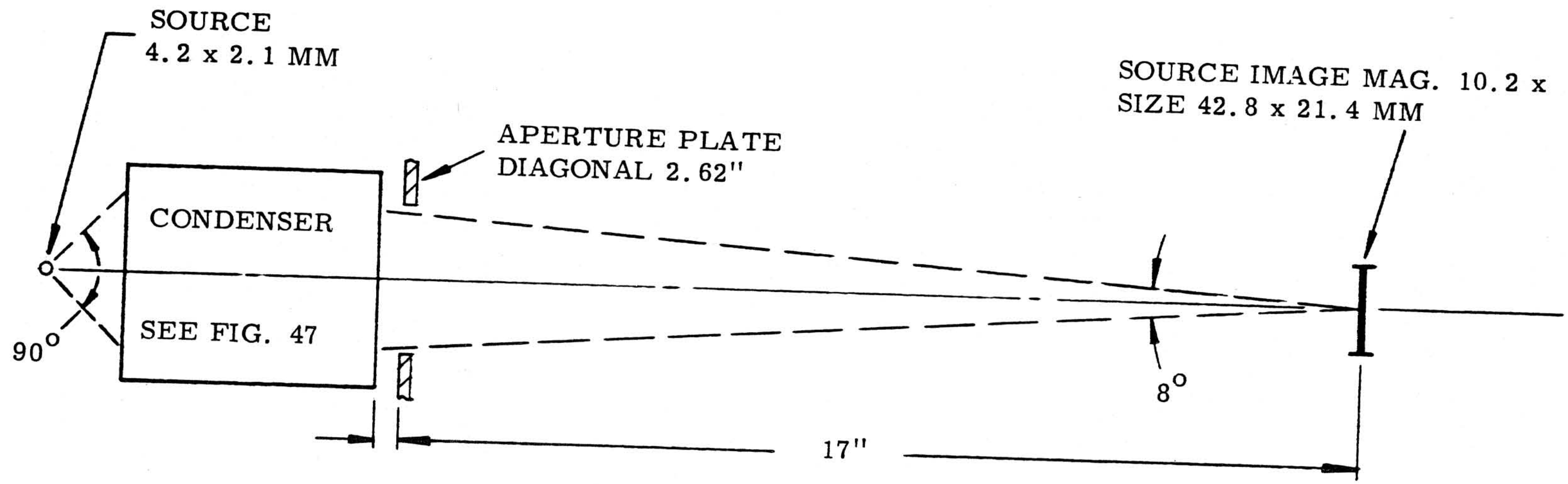
Field Lens

The field lens in this device is intended to control the marginal rays and uniformly illuminate the raster by forming on it an image of the condenser aperture. As shown in a previous calculation, these requirements are nearly always somewhat in conflict and the designer has the choice of maximum illumination, best uniformity or some compromise. The ideal solution is to rearrange the whole illumination system slightly so that the rear aperture of the condenser is well outside the lenses, displace the field lens from the source image and divide the source image magnification between the two lenses. This has been done in the re-designed system and is diagrammed in Figure 50.

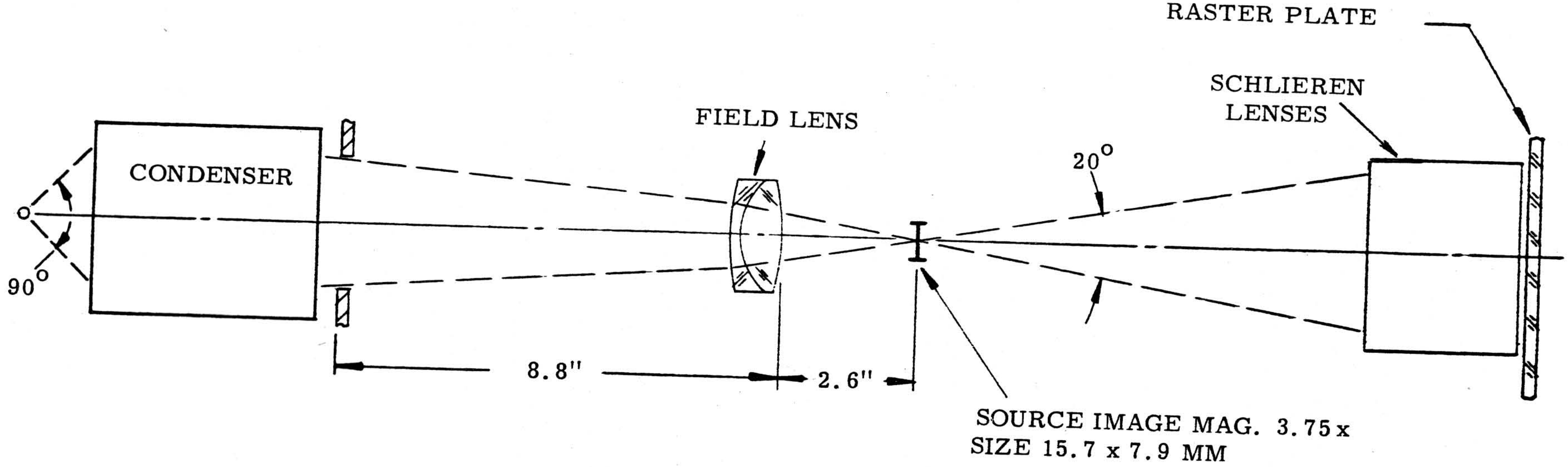
If the large number of possible ray paths that could be drawn to illustrate the various actions of the field lens were all drawn on one diagram it would be confusing, therefore, the situation has been broken down into four diagrams which indicates different aspects of the same layout. Figure 50a shows the condenser, the aperture plate which contains a rectangular hole, the shape of the raster image and the condenser focus. Alone the condenser would magnify the source 10.2 X and produce an illumination angle of only 8 degrees.

Figure 50b shows the effect of the addition of the new achromatic field lens, not at the source image, but at some distance from it. This lens has a diameter of 58 mm., an axial thickness of 26 mm. and a focal length of 5.33 inches. In this position it decreases the source image magnification of the condenser 2.73 X, shortens the second conjugate and increases the illumination angle to 20 degrees required to fill the schlieren lenses. The source image is now only 15.7 by 7.9 mm. and easily fits on the mirror bar assembly.

The field lens is achromatic to eliminate the chromatic fringe around the raster image. The fact that it is fairly close to the source image and gets quite hot has caused some difficulty. Necessarily, an achromatic lens must be made of two different glasses which nearly always have different thermal expansion coefficients.



a. LAYOUT OF CONDENSER ONLY



b. LAYOUT OF CONDENSER AND FIELD LENS

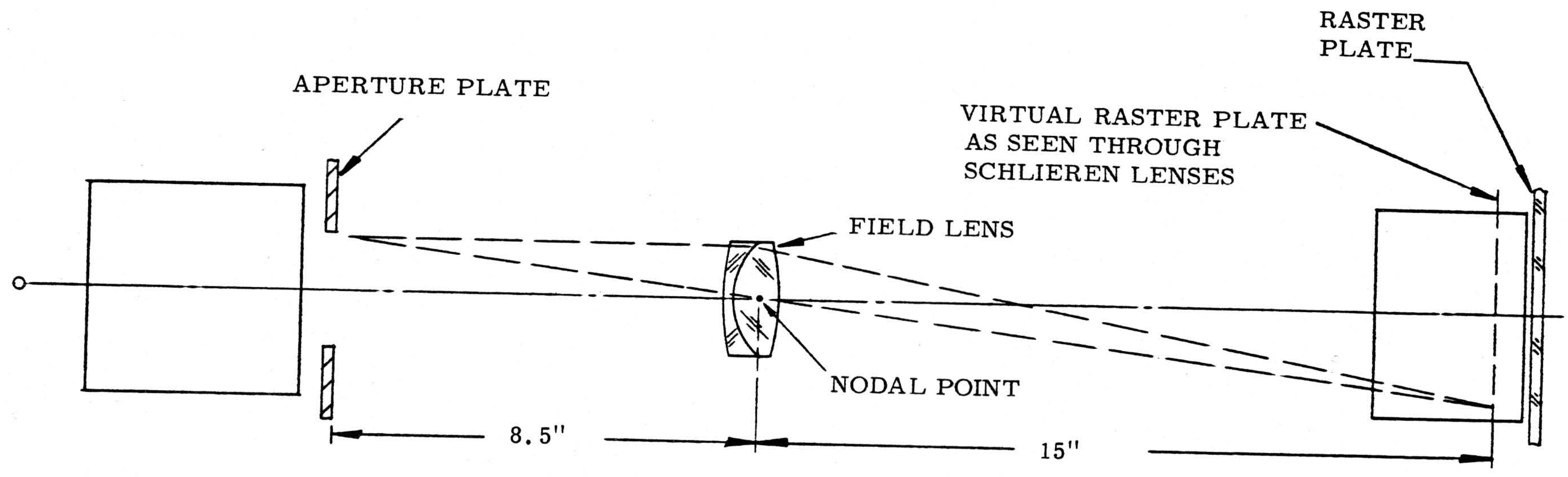
FIG. 50 USE OF FIELD LENS TO REDUCE SOURCE IMAGE SIZE

The two elements cannot be cemented firmly because differential expansion would place one of the elements under tension, a type of stress that is likely to result in fracture in glass, or if nothing else it would place terrific shear forces on the cement joint. It is common therefore to cement such lenses with a liquid cement which is polymerized only at the edges to form an elastic bond. Exposure to high temperatures cause the cements to further polymerize so that they are no longer liquid and to shrink so that they draw in bubbles of air from the edge. Continued thermal cycling causes failure of the cement which may become crazed or opaque. This application is the severest service for a cemented lens we know of and it may require a new cement or a new means for mounting the lens before an entirely satisfactory solution is found.

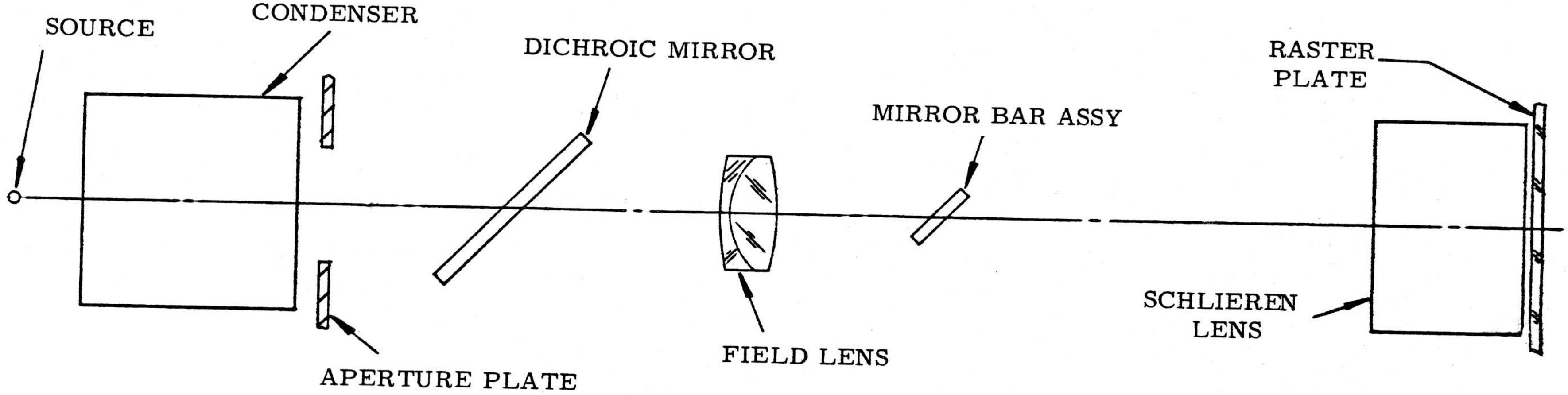
Figure 51a shows that the field lens has precisely the correct focal length of 5.33 inches to image the aperture plate on the virtual raster plate. Virtual in this case refers to the effective axial distance to the raster plate as taken by the rays through the two schlieren lenses, and is about .40 inches less than the actual distance. The rays shown in 51a are a chief ray through the nodal point and one marginal ray. The corresponding marginal ray on the other side of the lens aperture is missing because it does not exist in the condenser, nor could it be reflected in the mirror bar as shown in the next diagram.

An even better means than the aperture mask to eliminate scattered light around the raster image is to evaporate an opaque mask on the flat final surface of the second schlieren lens.

Figure 51b is a straightened one-third scale layout of the re-designed system from source to raster plate and the location of the dichroic mirror and mirror bar assembly are shown. Actually the light path is folded and twisted at the dichroic mirror and folded again at the mirror bars so that the spatial arrangement of the parts is still the same as Figure 41. It can be seen that marginal rays from the top of the aperture plate through the lower half of the field lens would not be permitted by the small size of the mirror bars.



a. APERTURE IMAGED ON VIRTUAL RASTER PLATE



b. LAYOUT OF COMPONENTS

FIG. 51 ACTUAL LAYOUT

At first glance it might appear that all that has been accomplished in the re-designed illuminating system is to replace three simple lenses with seven complex lenses, but in terms of performance the change has eliminated several undesirable compromises which together double the screen illumination of the Gretener projector, increases the edge illumination from .50 to about .80 and disposes of the color effects on the screen.

Mirror Bar Assembly

The original mirror bars as shown in Figure 44 proved to be difficult to make and inefficient. The fabrication difficulty was in the assembly of the glass strips so that all the mirror surfaces were in parallel planes and in grinding and polishing the ends so that they were free of chips. Each of these strips has a fragile 45 degree edge which tends to flake off or become rounded in the grinding and polishing operations. This can be prevented by temporarily cementing the strips to other pieces of glass called "fences" which support and protect the edge. We did not specify chip-free edges on the first bars and while the completed assembly appeared very satisfactory to the eye, its efficiency was disappointing. Examination under the microscope showed that the barely visible chips along the edges of the mirrors caused a loss of more than 10 percent of the effective area.

Another source of inefficiency was the loss of light caused by angled rays striking the vertical black "risers" between the bars. The cone of rays from the condenser has an included angle of 20 degrees, therefore, there will be rays as much as 10 degrees off-axis and some of these will strike the risers and be lost. Unfortunately, they are not completely lost because the black paint reflects some light so that the black bars are not truly black and detract from the dark-field. A rather laborious calculation has shown that the light lost from this cause is about 10 percent of the source image illumination.

Considered as a whole, the original mirror bars were the source of the following estimated losses:

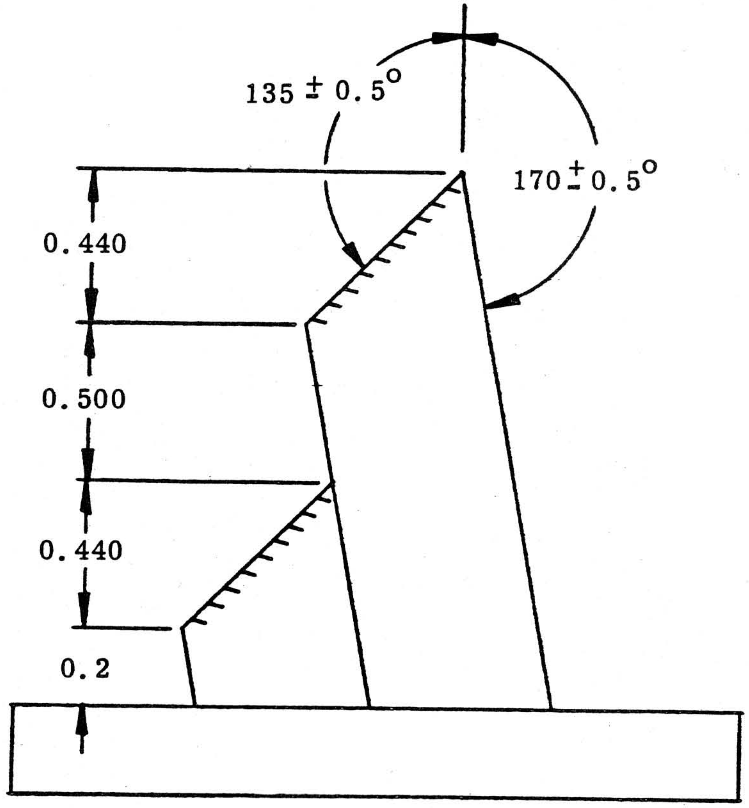
a.	Too small to intercept source image flare	10 percent
b.	Reflectivity loss	15 "
c.	Chips on edges of mirrors	10 "
d.	Intercepted by risers	10 "
		45 percent

The sum of these losses makes the mirror bar assembly no more efficient than a plain set of opaque bars, or in other words we had spent considerable money to build a part which accomplished nothing that could not have been done as well by a flat strip of metal, and in addition had introduced stray light reflected from the risers and complicated the output bar assembly by requiring staggered bars.

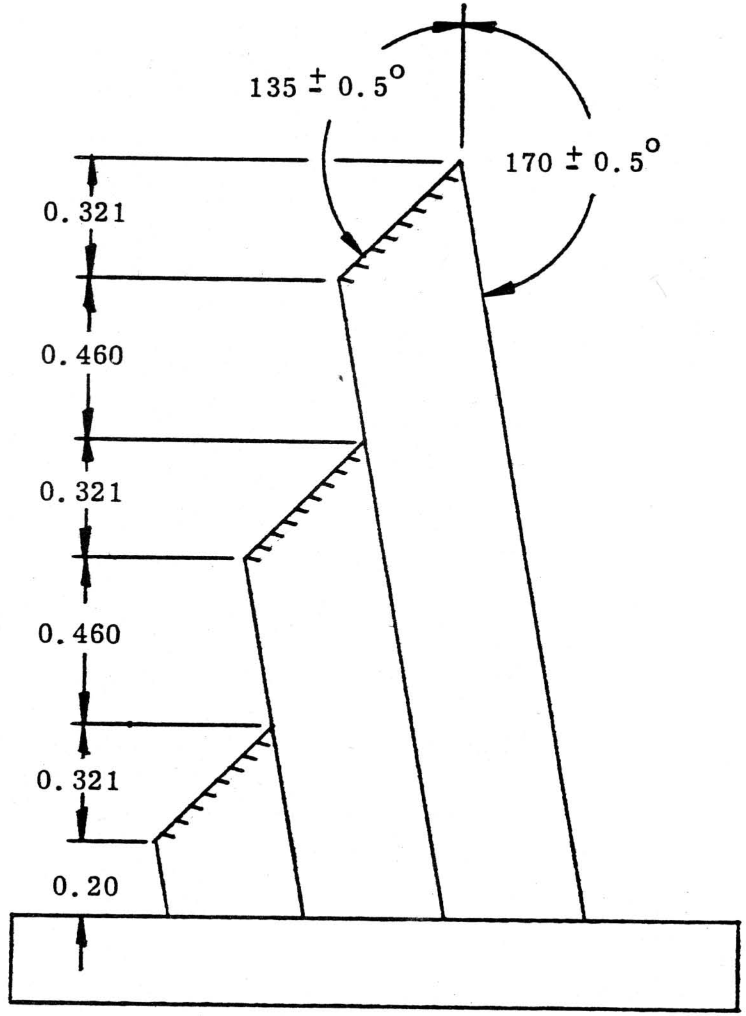
A re-designed bar mirror is shown in Figure 52a which is intended for an angle ψ (psi) of 2.5 degrees. The whole assembly is effectively tilted backward so that angled rays from the condensers cannot strike the risers, yet the mirror bars remain at 45 degrees. "Fencing" the edges to prevent chips, better reflective coatings and re-design of the condenser to reduce flare has greatly improved the efficiency.

The angle psi is defined as the maximum deviation of a ray refracted in the control layer and is the same as the full-range sensitivity of the schlieren system. As mentioned under System Design, this angle is the starting point for the optical design of the entire system, but it can be altered within limits by changing the number of bars. Figure 52b shows a mirror bar assembly designed for an angle psi of 1.84 degrees.

The angle psi depends on the deformation of the fluid surface produced by electrostatic forces, or if the surface is regarded as a sine wave, it depends on the slope of the sine wave where it crosses its zero axis and the refractive index of the oil. The refractive index of the Eidophor hydrocarbon oil was 1.47 and the G-E methyl-phenyl siloxane oil 1.53. In a prism with a refractive index of approximately 1.5 the deviation angle is one-half the prism vertex angle, therefore an angle psi of 2.5 degrees represents



(a)



(b)

FIG. 52 BAR MIRROR

a vertex angle in the fluid prisms of about 5 degrees. In the Gretener projector the light made two passes through the oil film and in this case the effect is doubled and psi is equal to the prism vertex angle. An analysis of the Gretener projector shows that it was designed for an angle psi of only about one-half a degree. In a laboratory model G-E projector we have been able to obtain 5 degrees and even higher angles are attained in thermoplastic film.

The G-E silicone oil has a reciprocal dispersion of 34.5, a fairly high value and equal to a flint glass. It is normal for liquids to have low refractivity and high dispersion as compared to glass. In some ways this is an unfavorable combination of properties and we have calculated that the dispersion should be visible as rainbow colored bands between the projected images of the raster lines. In fact, some such effect is visible on close observation, but it is largely diffused by the cyclic inversion phenomenon of interlaced scan.

Schlieren Lenses

The same schlieren lenses were used in the re-designed projector as the original models. Since both bar plates were made larger, the lenses are used at a greater angle off-axis than originally intended. Two other changes were made. An opaque mask the size of the raster was evaporated on the flat surface to the second lens to keep all stray light out of the vacuum system. A thick lens-like bead of fluid forms around the edges of the picture and if this is illuminated, it may refract unwanted stray light. The strongly convex surfaces of both schlieren lenses are made of a low index glass which does not take ordinary low-reflection coating very efficiently. The internal reflection was reduced and the transmission of the lenses increased by more efficient multiple-layer low-reflection coating.

Projection Lens

The Tessar-type lens used in the original design had barely enough back focus to clear the cut-off bars and the lens was so short that the projected beam just cleared the obstructions on the lower part of the electron gun. The diameter of the lens was just adequate to cover the original set of output bars. Later when the mirror bars were made larger to utilize a larger portion of the source image, the light spot at the rear of the projection lens became larger than the rear lens and light was lost at this point.

There were no suitable larger lenses on the market, faster lenses tend to be thicker and have less back focus for the same focal length and a lens with less back focus could not be used. The best solution was to design a special reversed telephoto lens with large rear elements and low distortion as shown in Figure 53. This design consists basically of a lens plus a wide angle attachment. The three rear elements make up a Tessar-type lens and the front two elements form a low power Galilean telescope with the negative lens forward. If the three rear elements were used alone, their nodal point (point from which the focal length is measured) would be in the space between R_3 and R_4. The addition of the two front elements moves the nodal point back to the center of the rear-most lens, a distance of about .6 inch. This means that the lens as a whole has about .6 inch more back focus than we would normally expect for a lens of this focal length. The elements are made as large as space will permit and the length of the lens is approximately 7.2 inches compared to the original 1.2 inches which is a help in keeping the projected light from interfering with the electron gun.

A longer focal length lens is also provided as shown in Figure 54. This lens is of fairly normal design but specially constructed to fit the available space.

<u>Efficiency of Redesigned G-E Projector</u>

These figures are based partly on measured values and partly on estimate. The efficiency is diagrammed in Figure 55.

a. Source 100% or 60,000 lumens.

b. Source energy collected by first condenser and lamp reflector 31%.

c. Transmission of condenser 85%.

d. Transmission of aperture plate 67%.

e. Reflected by dichroic mirror 94%.

f. Transmission of field lens 96%.

$R_1 = 2.5$, $R_2 = 1.10$, $R_3 = 7.00$, $R_4 = 1.33$, $R_5 = 2.9$, $R_6 =$ PLANO

$R_7 = 1.7$, $R_8 = 6.7$, $R_9 =$ PLANO, $R_{10} = 4.65$, $R_{11} = 3.65$, $R_{12} =$ PLANO

$T_1 = .55$, $T_2 = .16$, $T_3 = .12$, $T_4 = .31$, $T_5 = .20$

$T_6 = .13$, $T_7 = .23$

E.F.L. = 5.55"

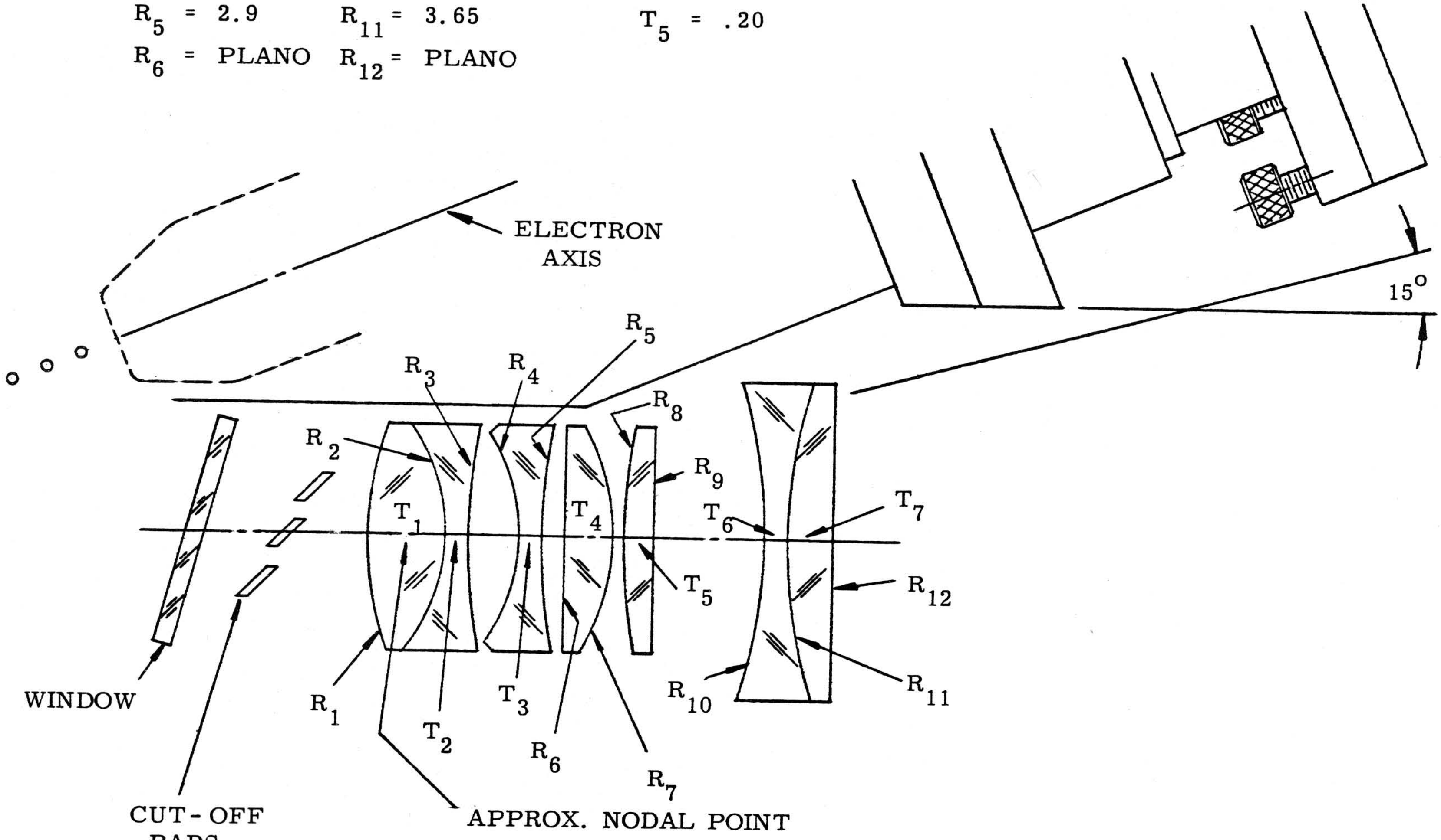


FIG. 53 WOLLENSAK 5 1/2" LENS

R_1 = 4.50"	R_6 = 6.2"	T_1 = .63"	T_5 = .15"	E.F.L. = 7.77"
R_2 = 3.7	R_7 = 2.45	T_2 = .15	T_6 = .50	
R_3 = 4.2	R_8 = 4.00	T_3 = .28		
R_4 = 2.6	R_9 = 8.00	T_4 = .56		
R_5 = 5.00	R_{10} = 3.6			

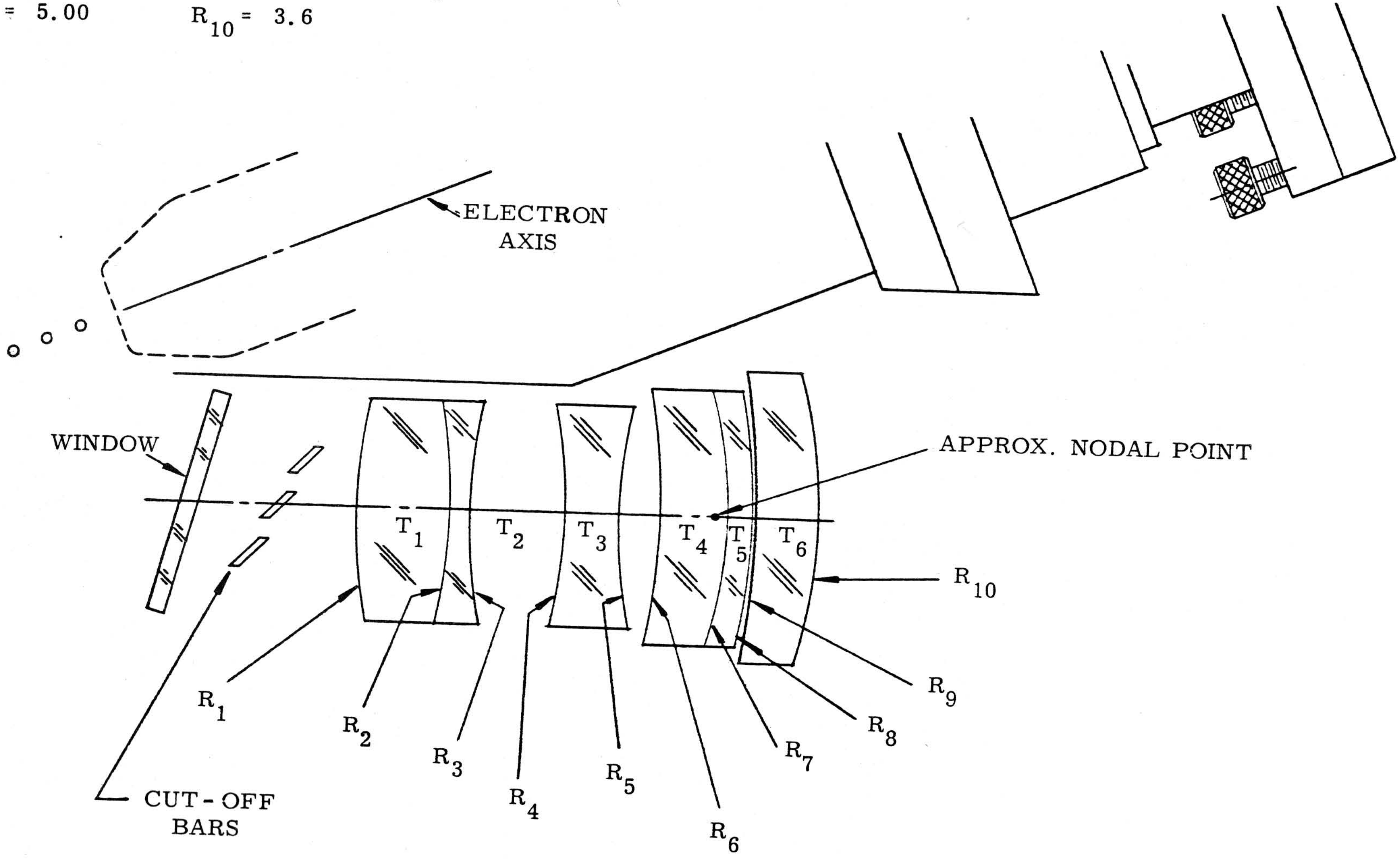


FIG. 54 WOLLENSAK 7.8" LENS

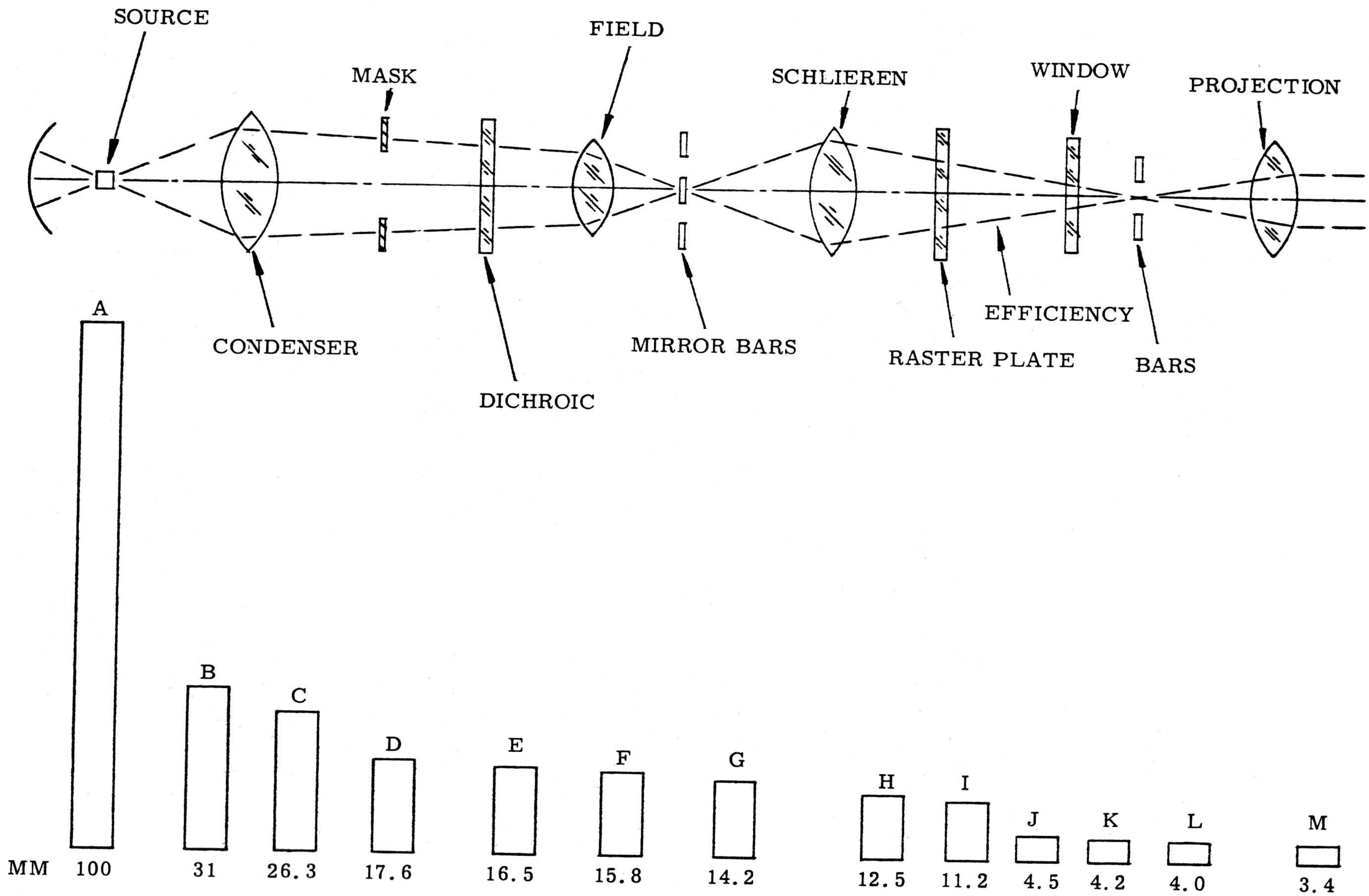


FIG. 55 EFFICIENCY G.E. PROJECTOR

g. Efficiency of mirror bar assembly 90%.

h. Transmission of schlieren lenses, one surface "cemented" to raster plate 88%.

i. Transmission of raster plate, one side "cemented" to schlieren lens 90%.

j. Modulation efficiency 40%.

k. Transmission of window, one side coated 94%.

l. Intercepted by guard bands 5%.

m. Transmission projection lens 85%.

The total as calculated above is 3.4% and multiplied by the source output this should result in 2040 screen lumens. Measurements show about 2000 screen lumens which indicates that some of the estimates must be slightly high.

GAS CONVECTION VISUALIZER

General

This name was given to a schlieren device to make visible the convection of gas in an operating incandescent lamp. Most incandescent lamps are filled with an inert gas, usually nitrogen at less than atmospheric pressure. In projection lamps it is necessary to make the enclosure small and the problem of lamp blackening becomes serious. In the typical tubular projection lamp used in a vertical position with external air cooling, evidence is that rising currents of hot gas above the filament carry off evaporated tungsten and deposit it on the first cool surface they strike, which is the portion of the glass envelope near the filament. From an optical point of view this is undesirable because it causes loss of light transmission at the point where it is most needed. It can also be bad from a structual standpoint as the envelope is usually made of lime glass with a low softening temperature and the accumulation of evaporated metal may increase the energy absorption to the point where the glass softens and a "bubble" forms.

The usual means to prevent this is to divert the blackening to another area by means of deflectors or baffles which change the course of the normal gas convection. The design of these deflectors has been based on common sense, a knowledge of heat transfer, analogy to convection in similarly shaped vessels and experience. The devices in use appear to be satisfactory, but it was desired to actually observe the gas convection to determine if the deflectors performed as it was thought they did.

Past History

This is the most difficult schlieren problem we have heard of and a literature search found references to two attempts to solve it without success, and one writer who claimed it was impossible.

The Problem

The serious optical problems are listed below:

1. The filling gas has a low refractive index and a small variation of refractive index with temperature; at this low pressure the refractive gradients will be very small.

2. The lamp enclosure or bulb is blown and variations in the glass thickness cause very strong refractive schlieren effects, hundreds of times stronger than the anticipated gas schlieren.

3. The cylindrical or spherical shape of the enclosure causes it to act like a lens, which while weak for ordinary purposes is very strong in a schlieren system. Each type and size of lamp acts as a lens of different power. Tubular lamps act as cylindrical lenses and introduce strong astigmatism into the optical system.

4. Irregularities in the enclosure defocus the source image or images greatly reducing the sensitivity of the system.

5. At thermal equilibrium the hot gas rises and cooler gas falls, the temperature gradients are small and the condition of laminar flow makes the convection nearly invisible. There will be none of the sharp boundaries usually seen in schlieren pictures.

6. The light from the hot filament may be a hundred or a thousand times stronger than the schlieren source and this will obliterate the dark-field and hence the schlieren images.

7. Even if direct rays from the filament can be stopped with shields, there is so much unavoidable scattered light caused by reflections from the inside of the enclosure and filament supports that the schlieren image is washed out.

Solution

The reasoning toward the optical solution was followed in the same steps as shown above:

1. A calculation showed that if there were no difficulties that only a moderate degree of sensitivity would be required to make visible the difference between the ascending hot gas stream and the descending cooler gas. A full range sensitivity of four minutes of angle was considered to be adequate based on the estimated temperature and refractive index of nitrogen.

2. The very strong schlieren in the lamp enclosure was considered as poor "windows" and the system was designed as a sharp-focusing multiple-source schlieren system. The multiple sources would send light through the glass at many different angles and the

effects of the schlieren in the glass would average out. Sharp-focusing would allow the photographic lens to focus on the desired gas convection column while throwing the defects in the glass out of focus. It was estimated that at least 60 round apertures or 20 slits would be required to performing the averaging. To limit the depth of field would require a fairly fast long-focus lens. The lens chosen showed a depth of field of about one-quarter of an inch.

3. The cylindrical lens effect of tubular lamps and the spherical lens effect of globular lamps would be compensated by suitable lenses of the opposite power. Perfect compensation did not seem necessary.

4. The irregularities in the enclosure which acted to defocus the source images would also reduce the geometrical sensitivity of the system. A check of this feature made by focusing a point source through a typical lamp bulb showed an image about .050 inch in diameter. Estimating that this represented at least a five times loss in sensitivity, it was decided that the geometrical sensitivity would have to be increased at least five times over the estimate in (1) above. The new value for full range sensitivity was 50 seconds of angle.

5. The thermal equilibrium and laminar flow problem were difficult to estimate. In a normal room atmosphere or a wind tunnel, it is fairly easy to detect heated gas currents because they mix with cool air in a turbulent fashion and create sharp schlieren boundaries. In the "stagnant" atmosphere of a lamp, the schlieren can be expected to be much less visible. To test this feature a Calrod heater connected to a Variac was placed in an ordinary Toepler system. At a fairly low temperature it produced distinct schlieren when the hot air from the heater mixed with the cool room air. The very slight movement of the room air due to the air-conditioning was seen to be partly responsible for the distinctness of the images. When the circulation was stopped, the schlieren became thin nearly straight lines and were less easy to see. When the heater was surrounded by a transparent chimney duplicating the

conditions inside a lamp, the flow became so laminar that it was nearly invisible. It was estimated that a further increase in sensitivity to perhaps 10 seconds would be necessary to make this flow visible. This value represents a very sensitive system that could not easily be made with small or short focal length optics.

6 & 7. Light from the filament would have to be removed by a combination of baffling and filtering. The light from the hot filament is "blackbody" radiation which for tungsten has its peak energy in the infrared. The fall-off of energy on the Planck curve is greatest on the short wavelength side, therefore a blue or ultraviolet schlieren source could be relatively stronger than the filament in these wavelengths. If the remainder of the filament energy could be removed by a filter, the schlieren source should be able to overpower the small amount of light coming through the filter.

Equipment

The apparatus finally used with successful results is shown diagrammed in Figure 56. The schlieren optics consist of a pair of 12 inch diameter f/8 paraboloids of very high quality used off-axis as in Figure 26.

The source is an Osram 100 watt type HBO high pressure mercury lamp. Any concentrated mercury arc would work as well and a 200 watt or larger lamp would provide a brighter image. The reason for using this spectral source is that a large percentage of the output, approximately 6 watts, is in the green emission line at 5461 angstroms and perhaps 4 watts in the blue 4358 line. A 1000 watt tungsten lamp would have only about .002 watts in a band from 5465 to 5457 angstroms and .0004 watts in a band from 4362 to 4354 angstroms. Calculations of this type were easily made with the G-E Radiation Slide Rule. There are interference filters made which transmit these bands and practically nothing else. It was possible to calculate that the light passing through the green filter from the schlieren source would be 200 times as strong as the stray light from the filament and in the blue the ratio would be perhaps 800 times.

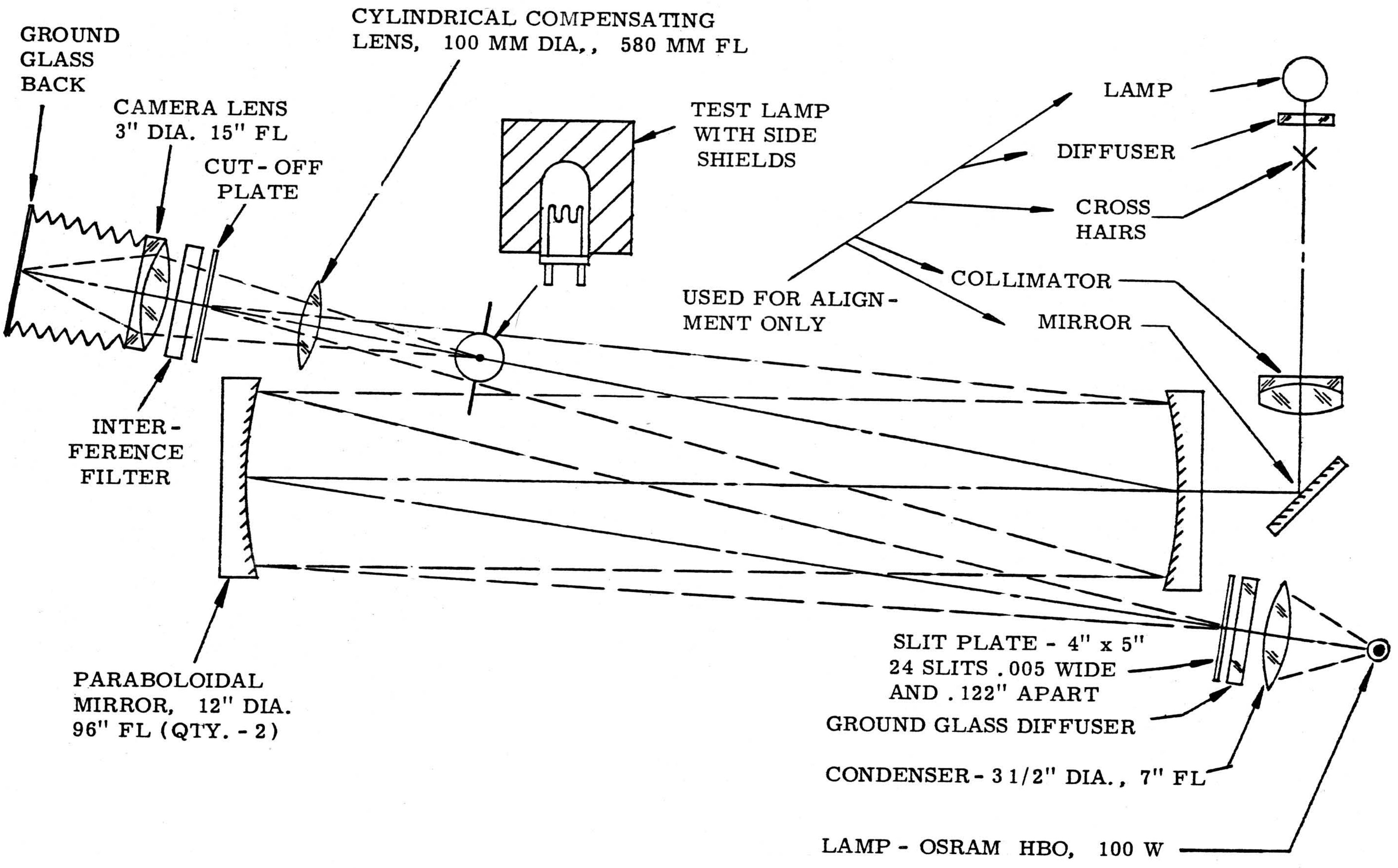


FIG. 56 GAS CONNECTION SCHLIEREN APPARATUS

The input slit plate consists of a photographic negative, black except for 24 narrow parallel transparent slits. The slit plate could have been made by ruling the lines in a opaque metal film on glass or any of several ways. The actual means used was as follows:

a. A metal plate 6 by 10 inches was drilled with a row of holes along each of the long sides. The holes were spaced one-quarter inch apart. The holes were tapped and headless screws placed in them so the end extended about a half inch above the plate, a total of 80 screws was used.

b. Using these screws as posts, .006 inch tungsten wire was wound back and forth to produce a grid of parallel wires one-quarter inch apart. The threads on the screws kept the wires from slipping on the posts. The grid of wires was about one-eighth inch above the metal plate.

c. In the darkroom a 4 by 5 inch Kodak high resolution plate was slid under the wire grid and the assembly placed under the light of an enlarger. The focused light cast sharp shadows on the wires on the emulsion. After processing, the exposed portion was opaque and the shadows nearly clear. To make them completely clear the plate was treated with Farmer's Reducer until a magnifier showed the lines to be "clean". The resulting clear lines were about .005" wide due to the effects of diffraction and image spread.

The illumination system consists of the source and a condenser. Any condenser at least 3 inches in diameter should do, but a short focal length of about 6 inches is preferred. The purpose of this lens is to collimate the source rays so they will pass through the slits in the aperture plate. As seen from the first schlieren mirror all the slits should appear fully illuminated. To improve the illumination angle, a ground glass diffuser is placed just behind the aperture plate with the polished side in contact with the plate.

The schlieren mirrors had to be set up with considerable care to be certain that the slit plate was exactly at the focus of the first mirror. To do this a long focal length collimator was placed as shown in Figure 56, before the second schlieren mirror was installed and the slit plate was moved back and forth until the luminous cross projected by the collimator was in exact focus on its surface. When the second schlieren mirror was installed, the cut-off plate holder was placed so that the two off-axis angles were equal and as small as possible. A ground glass focusing screen was placed in the cut-off plate holder and the image of the illuminated slits located. The focusing screen was removed and the images of the slits examined with a microscope and seen to be extremely good. The images of the .005 inch slits measured about .008 inch wide which is about the theoretical minimum at f/8 allowing for diffraction effects. Since the focal length of the mirrors is nearly 100 inches and the illuminated diameter of the slit plate only 3 inches, the slit plate subtends a field angle of only about 5 minutes. The image of the slits appeared to be equally good over this entire field. Anyone unfamiliar with setting up a high-sensitivity schlieren system should consult the articles by Barnes in the Jour. Opt. Soc. of Am., 1945, p. 497.

The lamp to be tested is inserted in the converging beam as shown. In this case the lamp was the most difficult example that could be found, a 3 kilowatt, 220 volt projection-type searchlight lamp with a zig-zag filament and the strongest schlieren in the glass we had ever seen. Sheet metal shields are placed around the lamp where they do not obstruct the schlieren system light path. Their purpose is to keep the level of room illumination down so that the schlieren image can be seen on the ground glass camera back and also to prevent light in the schlieren system from passing around the lamp.

A precision plate holder was made for the cut-off plate. A ground glass focusing screen was placed in it and the image of the slit-plate as seen through the unlighted lamp was observed with a magnifier and brought to the best focus. It was seen that the entire slit-plate pattern was distorted by the cylindrical lens effect of the tubular lamp and since the cylindrical power introduced considerable astigmatism, vertical and horizontal lines came to focus in different planes.

Using a set of cylindrical spectacle lenses of graded powers, they were tried one at a time in the beam until the horizontal and vertical foci were coincident. Any one of three different lenses appeared to be satisfactory and since the depth of focus of the schlieren system is considerable, the exact focal length is not critical. While spectacle lenses which have a nominal diameter of two inches would be large enough for any of the smaller lamps, a larger lens of the same focal length was required to cover the field of this very large lamp.

With the aid of a magnifier the best focus of the image of the slit-plate as seen through the lamp was obtained on the ground glass in the position which the cut-off plate would later occupy. The slit images were fuzzy, much wider than they had been without the lamp and irregular due to the refractive effects in the lamp enclosure.

A shutter was placed over the slit plate to shut off the light and a high resolution plate inserted in the holder and the shutter opened long enough to expose the plate. The plate was processed to show opaque black lines representing images of the slits on a nearly transparent background. The processed plate was replaced in the plate holder so that it returned to the exact position in which it was exposed. The opaque lines then act as cut-off bars for the multiple-slit schlieren system. Fine adjustment allowed the bars to be displaced slightly for the best dark-field.

Directly behind the cut-off plate is the interference filter which removes practically all the light except that of one of the spectral lines of the schlieren source. The green filter gave the best light for visual observation, but for photography the blue filter gave better contrast.

The photographic lens used to image this large lamp on 6 by 9 cm. film was a single achromat which had the required aperture ratio to give the desired shallow depth of field and the necessary focal length. For smaller lamps photographic lenses with shutters would be better.

Results

The schlieren image was weak but visible. When the 3 kilowatt lamp filament was turned on, it could be seen in the picture as faintly luminous. The following gas convection phenomena were observed:

1. A sharp boundary of hot gas, the Langmuir sheath surrounds the filament as soon as it is turned on even at reduced voltage. This layer is less than one millimeter thick.

2. The thickness of the boundary layer does not change noticeably as the lamp voltage and filament temperature are increased.

3. The boundary layer persists as long as the filament retains any heat.

4. A rising column of hot gas forms around the filament and appears to cling to it. At the top of the filament it forms a smooth rising column which is virtually featureless.

5. In the case of a "V" shaped filament with the point of the "V" upwards, the two columns which cling to the filament members join at the point of the "V" to form a single column.

6. In a vertical tubular lamp with a rounded top, the hot gas columns strike the center of the top and start down the sides. It has not been possible to follow them very far on the downward passage.

7. An angled deflector made of screen or perforated metal when placed in the rising column of heated gas acts as if it were solid. The gas behaves as if it were extremely viscous and would rather be deflected than go through the holes.

8. An inverted funnel of screen wire having a mesh similar to fly screen forces all the streams of heated gas to pass through the opening in the center. No gas could be seen escaping through the mesh. The concentrated column of rising hot gas strikes the top of the lamp, spreads out and follows the surface of the bulb downward.

9. When the shields were removed from the outside of the bulb, it could be seen that a very sharp boundary layer of heated air forms on the lamp envelope within two seconds after the lamp is turned on and persists until the lamp is completely cooled.

10. A rising hollow cylinder of clinging hot air surrounds the lamp. This appears to be about one-quarter inch thick. At the top of the lamp the cylinder constricts to form a thinner column.

11. When the lamp is first turned on, most of the enclosed gas is cold and the rising column of hot gas is easily visible, but within a short time all the enclosed gas is fairly hot and the gradient becomes less distinct. By the time the lamp has reached thermal equilibrium, the schlieren effects may disappear entirely unless the sensitivity is high. To test the correctness of this explanation for the fading of the phenomenon, a lamp was operated until thermal balance had been established and then turned off. In this case no schlieren rising from the still-hot filament could be seen though the boundary layer was present. After complete cooling the experiment was repeated except that the lamp was operated only a few seconds and then turned off. In this case schlieren could be seen rising from the hot filament for a considerable time because the hot gas was mixing with the relatively cool gas in the lamp.

<u>Improvements</u>

Since the convection currents are largely vertical, the slits were arranged vertically to obtain the best sensitivity in this direction. A slit system has sensitivity in only one direction. In a later experiment the slits were made horizontal and very little of the gas convection could be seen.

A crude compound lens consisting of 16 cylindrical glass strips ground from glass rod were placed behind the slits in the aperture plate. Their purpose was to focus the collimated light from the condenser into lines so that more energy would pass through the slits. In the original setup the slits were .005 inch wide separated by a space of about .23 inch. This allows only about 5 percent of the incident light to pass the slits and the rest is wasted. Further it had been found necessary to diffuse the light with a ground glass in order to fill the schlieren mirror with light. The addition of the crude cylinder lenses made the diffuser unnecessary and increased the light through the slits 50 times as judged by the decrease in exposure time to make a cut-off plate. This refinement is not the only way to increase the illumination. A larger source of the same brightness which, because of its size would be less perfectly collimated would therefore illuminate the slits at the angle necessary to fill the schlieren optics, or a better condenser system which collected a larger angle of light from the source could illuminate the slits with the required illumination angle. Either of these solutions might be simpler than the problem of precisely positioning 16 lenses behind their respective slits.

At one time it was felt that an omnidirectional system using round apertures as the sources instead of slits would be preferable. A source-plate containing 60 small regularly spaced round holes was difficult to make and it transmitted much less light than the slit-plate. In this case it was absolutely necessary to use a compound lens to illuminate the apertures. The lens was a Zeiss "Honeycomb" condenser from their Ikosol lamphouse and consists of 163 spherical lenses molded into a single glass plate. Actually, the plate was larger than necessary for this experiment and only 60 of the lens elements were used. Each of these lenses focused a spot of light which illuminated one of the holes in the aperture plate. Alignment of the 60 holes with the images of the composite lenses proved to be an exasperating experience. When operated in the omnidirectional mode, the schlieren images were no better than those given by the slit-plate. It was concluded that for this job the omnidirectional circular-aperture system offers no advantages over the simpler slit system. The fabrication of the one of the circular-aperture plates is described in detail in the first part of this report under "Condensing Systems for Compound Lens Illuminators".

<u>Limitations of the Method</u>

The lens effect of the lamp glass must be compensated by a different lens for each size and shape of lamp.

The cut-off plate is made to compensate for the schlieren in a particular lamp bulb at a particular orientation. The lamp cannot be moved in any direction without requiring a new cut-off plate.

At least this is true with very large lamps with strong refractive errors in the bulb. It is possible that in the case of small lamps with thinner and better glass that one cut-off plate may suffice for many lamps. This can be determined only by experiment. However, the problem of making cut-off plates is not serious. The actual time to expose, process and install a cut-off plate is only about five minutes if darkroom facilities are available. The plates can be used wet just as they come from processing.

Further Information

There is an unissued report by the writer titled "Optical Artifacts in Multiple-Source Schlieren Systems" which includes photographs of various kinds of aperture plates as seen through lamp enclosures and the optical defects in the Zeiss honeycomb lens. The report does not show any pictures of gas convection, only the defects in the system.

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GENERAL ELECTRIC

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SCHENECTADY, NEW YORK

TECHNICAL INFORMATION SERIES

AUTHOR	SUBJECT CLASSIFICATION	NO. / DATE
J.M. Holeman	Optics	NO. 60GL197 DATE 10/12/60

TITLE

Unusual Applications of the Schlieren Principle

ABSTRACT

This report describes the optical details of:

1. Classical and modern types of schlieren equipment to study air flow and shock wave phenomena.
2. Evolution of the schlieren projector.
3. A thermoplastic film projector. (Cont'd Below)

G.E. CLASS	REPRODUCIBLE COPY FILED AT LIBRARY OF GENERAL ENGINEERING LABORATORY SCHENECTADY, NEW YORK	NO. PAGES
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4. The Gretener Eidophor T.V. projector.
5. Three models of General Electric light-valve projectors.
6. A gas convection visualizer to allow mapping of the convection currents in a gas-filled incandescent lamp.

Conclusions

None

INFORMATION PREPARED FOR D. Garrett, T.V. Receiver Dev. Engrg.

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