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# Guidelines for Schlieren Systems at Langley Research Center

*E. Conrad Compton and Robert C. Spencer*
*Langley Research Center, Hampton, Virginia*

July 2023

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National Aeronautics and
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Langley Research Center
Hampton, Virginia 23681-2199

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## Purpose of Special Publication

The original Langley Working Paper (LWP 448) published on July 27th, 1967, provided guidance to NASA Langley Research Center personnel on how to set up conventional path-integrated schlieren flow visualization systems and what pitfalls could be expected with such setups. The guidance and information contained in the document continues to be used for schlieren setups at NASA Langley Research Center to this day.

Thanks to Stephen B. Jones, a former NASA employee and schlieren expert, for providing a copy of this document for public dissemination.

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# LANGLEY WORKING PAPER

## GUIDELINES FOR SCHLIEREN SYSTEMS AT LRC


By

E. Conrad Compton and Robert C. Spencer

Langley Research Center
Langley Station, Hampton, Va.



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
July 27, 1967

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Prepared by
E. Conrad Compton Robert C. Spencer
E. Conrad Compton and Robert C. Spencer

Approved by R. M. Hanson
for Howard B. Edwards
Chief
Instrument Research Division

LANGLEY RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTENTS

# GUIDELINES FOR SCHLIEREN SYSTEMS AT LRC

By E. Conrad Compton

and

Robert C. Spencer

## INTRODUCTION

The most commonly used method of flow visualization in supersonic wind tunnels is the schlieren method, or method of striae. At the Langley Research Center this method is so commonly used that it has come to be regarded somewhat as merely another piece of instrumentation which is to be maintained by service people, and which is too mysteriously complicated to be touched by tunnel personnel. This should not be the case. High-quality results from a schlieren system can only be obtained by having personnel on the tunnel staff who are well-informed on the subject and who have the time and the interest to do a good job of adjustment.

This paper is a discussion in practical terms, of some of the points to be considered and the pitfalls that may be encountered in designing, setting up and using a working schlieren system. It is directed specifically toward helping specify and install a Z-type mirror system. It is hoped that the material will be of assistance to facilities throughout the Center and NASA and that users of the schlieren method will be inspired to the point of training people in the adjustment of the systems in use at their facilities.

## MECHANICS OF SCHLIEREN TECHNIQUE

The word schlieren is a German word, meaning streaks or striae. In the schlieren technique, changes in the refractive index of the flow medium are visualized as striae. This change in the refractive index is a result of density gradients in the flow medium. The disturbance or schliere may be in the form of shock waves, boundary layers, turbulence, etc. (figure 1). A schlieren system operates as follows: a point source or line of light and suitable optics are used to pass light through a tunnel test section and the light then focused to a one-to-one inverted real image of the source. At this point a knife-edge is placed such that it cuts this image causing uniform shading of the passed light. With any change in the density of the tunnel medium, light passing through a disturbance is refracted in a way to cause brighter or darker points of the schlieren display depending on whether the light from these points is refracted away from or towards the knife-edge. A focused image, i, of the schliere is found some finite distance from the imaging optics and can be determined by the lens formula.

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

where $p$ is the distance from the mirror $M_2$ to the schliere (object distance); $q$ is the distance from the image of the schliere to $M_2$. These parameters are shown in the mirror system of figure 2. The image can be projected on a screen or photographed directly; in either case the image has to be focused in the film plane of the camera or the plane of the readout system. Again the lens formula is used to select the proper focal length lens to be placed as shown in figure 2. This lens is mounted between the knife-edge holder and the screen or camera. The object for this lens is the image formed by the second mirror. The expression becomes

$$\frac{1}{p'} + \frac{1}{q'} = \frac{1}{f'}$$

where $f'$ is the focal length of the lens. The object distance is negative when the object is on the same side as the image.

## TYPES OF SCHLIEREN SYSTEMS

There are two basic types of schlieren systems; the mirror system, and the lens system. Typical examples of each are shown in figures 3 and 4. Mirror systems may be the single pass Z-shaped schlieren system, figure 3, or the multi-pass systems such as figures 5 and 6. The most commonly used system at LRC is the single pass Z-shaped schlieren system. This paper will primarily discuss this system. The double pass systems of figures 5 and 6 are occasionally used in facilities for added sensitivity. Multi-pass systems with more than two passes have been designed but have been little used at LRC.

Lens systems are used rather infrequently. Cost of large lenses, greater than 6-inch diameter, gets considerably greater than of comparable mirrors. Chromatic aberration cannot be eliminated entirely in a lens system, so that when the knife-edge is introduced at the image plane the test section image on the screen will show colors of various pastel hues, ranging from pink to green or blue from one side of the image to the other. Such variations in color do not cause nonuniform exposure of panchromatic film, so the color is not actually a serious disadvantage for black and white photography. When good achromatic telescope objectives of adequate size can be obtained, a good system can be set up and will be easy to aline. Focal ratios of the lenses should be at least f/10 or greater to minimize aberrations.

## PROPER SETUP OF SCHLIEREN COMPONENTS

### Mirror Systems

Mirrors having a focal length to diameter ratio of 8 (f/8) are a good choice for ease of alinement. Lower f/no. mirrors become progressively more difficult to aline, up to a practical limit of about f/4. The choice of supporting framework is dictated largely by need and cost. If a mobile system is needed to examine different areas of the test section a rigidly connected overhead system which rolls on tracks can be constructed. If the system is to look through only one area, a good method is to separate the system into two units which stand on opposite sides of the tunnel test section. One unit supports the light source and the first mirror and the other unit supports the second mirror and the knife-edge, with arrangements for holding the camera if desired. These stands should be fairly heavy tables of correct height, long enough to hold the light source or knife-edge at the focal length of the mirror, and wide enough to provide a stable footing. If vibration is a problem in the laboratory, antivibration pads similar to the "Isomode" pads can be installed under the support. Figure 3 gives a rough idea of the layout of a practical working system using two separate units. In setting up such a system, the mirrors, light source, and knife-edge are first placed in their approximate positions. The distance between the first mirror and the source is then adjusted until the reflected beam is parallel, with the light source at the same height as the mirror centerline. The mirror is then adjusted in the horizontal plane until the edge of the reflected beam is at a convenient offset from the source - one inch is a good figure. The entire stand is then so placed that the beam of light goes through the tunnel test section and is perpendicular to the direction of flow. The second stand, with the second mirror and knife-edge mounted in their approximate proper locations is now put in position so that the beam of parallel light is incident upon the second mirror. The second mirror is adjusted until the image of the light source is offset to the same amount as the source is offset on the other side - one inch from the edge of the beam, and at the same height as the centerline. The knife-edge is then placed at the image location and the setup is essentially complete.

### Lens System

In setting up a lens system, supporting stands can be used or in some instances the lenses can be attached to the test section window frames. Figure 7 is a photograph of a model lens schlieren system used as a training aid which shows the positioning of components. The lenses are mounted to cover the field of view and the light source is mounted at the focal distance on the optical axis of lens #1. The light emerging from the other side of the lens should be collimated, and normal to the tunnel flow. A good check for parallelism is to be sure that the light beam exactly fills the clear aperture of lens #2. The size of the beam is adjusted by moving the light source toward or away from lens #1. Lens #2 now focuses the light to a real image of the light source at its focal distance. It is at this focus that the knife-edge is placed. To minimize spherical aberrations both lenses should be mounted with their more curved surface facing each other, i.e., both facing parallel light for conventional lens design.

## Camera

There are many suitable cameras for recording schlieren images. The camera types can be divided into two general classes for the purpose of getting the desired size image in focus; (1) cameras already provided with their own lenses and needing to be adapted to a schlieren system, and (2) cameras composed chiefly of the body and film magazine, with a cone in front to hold the lens at the proper distance. The first class includes most conventional cameras and high-speed motion-picture cameras. The second class includes the large aerial cameras that are installed in the schlieren system of most LRC tunnels. In a schlieren system the light getting to the film cannot be regulated by decreasing or increasing the lens aperture. Exposure can be regulated by changing the brilliance or size of the light source, by changing exposure time, by changing the cutoff at the knife-edge, or by using neutral-density filters. Considerable exposure control also can be attained by variation of final image size, which of course is regulated by the distance of the film from the lens.

The camera may be mounted on a bracket on the same stand with the knife-edge and mirror or on a separate stand. In general it is preferable to use a bracket on the same stand with the knife-edge and mirror because the camera lens must be close enough to the knife-edge for the entire expanding cone of light to get through the lens without being vignetted. The problem can become critical with a motion picture camera, because the apertures of most 16 mm camera lenses are relatively small. A 50 mm f/2 lens, for example, will have an aperture of about one inch. The cone of light in an f/5 schlieren system will be about one inch in diameter five inches from the knife-edge, hence in order to get the light through the lens with sufficient clearance to allow for some misalinement, the front of the lens should not be much more than three inches from the knife-edge.

For proper focusing of the image of the model in a "type 1" camera, one must remember that the second mirror (or lens) is forming an image of the model, normally behind the camera lens, so that the camera sees an object "beyond infinity," i.e., it sees converging light. It is therefore necessary to insert a diverging lens into the system, to focus the image in the camera. The calculations involved in choosing such a lens are very simple, but the relationship of the mirror, the knife-edge, camera lens, and the image formed by the mirror is calculated by the lens formula. The distance of this image behind the camera lens is then determined, and a negative (diverging) lens is selected which will make the image formed by the mirror appear to be at infinity or closer. Obviously, to make that image appear at infinity, the negative lens should have a focal length equal to the distance from the lens to the image formed by the mirror. The main camera lens would then be focused at infinity. In practice it is well to select a diverging lens somewhat stronger so as to provide some focusing range. That is, the image formed by the mirror would appear to be at some finite distance from the camera lens.

Control of image size in the schlieren camera is determined just as in any camera, by the ratio between the object distance and the image distance. However, since the image is contained in an expanding cone of light, the image diameter usually is only slightly smaller than the unfocused cone of light would be. For a "type 1" camera, with a relatively large amount of glass in the optical system, there may be a considerable narrowing of the light cone. For cameras with interchangeable lenses the proper image size can usually be obtained by selecting the correct focal length lens. Fixed-focus cameras will be limited to whatever is obtainable from the lens as installed.

Setup of a "type 2" camera usually involves also the determination of the proper length of the cone on the front of the camera, to provide the desired image size at the film. This is done in steps. First the position and size of the primary image formed by the second mirror is determined, then the distance ratio necessary to obtain the desired image size on the film is found and finally the focal length necessary to focus the image at the film is calculated. A sample calculation is as follows. Assume one has a 16-inch diameter system with 90-inch focal length mirrors and with the second mirror 150 inches from the centerline of the test section. It is desired to have a 4-½ inch image at the film plane.

First, to calculate the image position;

$$\frac{1}{150} + \frac{1}{q} = \frac{1}{90}$$

$$\frac{1}{q} = \frac{1}{90} - \frac{1}{150} = \frac{60}{13500} = \frac{1}{225}$$

Thus the first image is 225 inches from the mirror. The image size will be;

$$\frac{i_1}{16} = \frac{225}{150}, \text{ or, } i_1 = 24 \text{ inches diameter}$$

Assume that the focusing lens is about 3 inches from the knife-edge, which is in turn 90 inches from the mirror. The image $i_1$ is thus 225 - (90 + 3) = 132 inches behind the objective lens. To obtain the distance of the film plane from the lens, use the ratio of the sizes, with 4.5 inches being the desired size;

$$\frac{4.5}{24} = \frac{d}{132}, \quad d = 24.75 \text{ inches}$$

To calculate the lens required;

$$\frac{1}{132} + \frac{1}{24.75} = \frac{1}{f} = \frac{107.25}{3268} = \frac{1}{30.45}$$

The calculated value is thus 30.45 inches for the required focal length. This corresponds to 1.293 diopters (where diopter = 1/f meters). If it is intended to use a simple test case lens, a power of 1.25 diopter is a standard lens power and would be used for this application, as it is the nearest to the desired lens. Design of the lens cone should always allow plus and minus two inches or so for focusing accurately.

## Sensitivity

The sensitivity of a schlieren system is the minimum detectable deviation angle of the refracted light. For the best sensitivity, the two most important requirements are: first, the smallest and brightest point source available (or a narrow line source when more light is needed), and second, the longest focal length mirrors or lenses feasible. In order to measure the sensitivity of a system, a sensitivity meter is placed in the test area of the parallel path. One such meter is shown in figure 8. The meter consists of a rotatable calibrated optical wedge mounted in a holder with an adjacent clear aperture so that the intensity of the deviated and undeviated light can be compared. This meter is calibrated for deviations from 0.1 sec. to 5 sec. of arc. A test for sensitivity is shown in figure 9, where a definite contrast in light intensity can be noted between the nonrefracted and refracted light areas. For this photograph the meter was set for 5 sec. to accentuate the contrast, however the measured sensitivity of the system was about 1.5 sec.

Another important requirement for good schlieren data is clean optics. Schlieren system optics represents a sizable investment. Optical elements such as lenses, and particularly mirrors, are extremely delicate components and are in constant need of protection from dust and foreign matter. Dust will cause damage such as scratches to the optics as well as attenuating and scattering light. All mirrors and lenses should be covered when not in use. Fingerprints are also detrimental. All optics should be handled as little as possible and then only on the edges. Any fingerprints on optical surfaces should be removed as soon as possible to prevent etching. A good technique for cleaning mirrors was suggested by James B. McDaniel in an article "Collodion Technique of Mirror Cleaning" (Applied Optics, Vol. 3, No. 1, Jan. 1964). Appendix A describes this technique.

## ABERRATIONS RESULTING FROM MISALINEMENT

Alining a Z-shaped system requires more care than setting up an on-axis lens system. Two aberrations are introduced into the mirror system because the source and knife-edge are offset from the axis. The aberration known as astigmatism causes the image of a point source to be drawn out into two lines, one vertical and one horizontal, with the location of the two separated by a short distance longitudinally. These two lines are referred to as the tangential (vertical) and the sagittal (horizontal) foci. Figure 10 is a photograph of sections of the light path about the area of the knife-edge position in a real schlieren system. It shows how astigmatism actually looks when proper positioning of the knife-edge is sought. This photograph is the result of exposures made with a screen placed at various positions along the light path, three of which show the mean focus, the tangential focus and the sagittal focus. This was a properly alined system with no aggravated conditions used to emphasize the astigmatism. The knife-edge is positioned either horizontally or vertically depending on whether vertical or the plane horizontal gradients are to be examined in the flow. The knife-edge can usually be positioned by eye so that it is parallel to the direction of the light-source image; it is then positioned longitudinally by observing the cutoff as shown on a screen. Uniform cutoff indicates exact positioning longitudinally, provided that the system is properly alined. There is no astigmatism in a properly set up lens system. The problem of knife-edge positioning is not of the same magnitude as with the Z-shaped system since there is only one correct knife-edge position.

The other aberration, known as coma, is so called because the image of a point appears to have a flare similar to the tail of a comet. Coma is readily observable as a comet-shaped image. As long as a system has coma, no uniform cutoff can be obtained. The coma is eliminated by having the offset of the source and the image of the source on opposite sides of the axis equal, and by taking care that the axis, the source, and the image are all in the same plane. Figure 11 is a photograph made just as figure 10 showing the results of coma. In the same schlieren system employed for figure 10, coma was introduced into the system by increasing the offset on the knife-edge side. This condition was exaggerated, i.e., the increase in the offset was more than is needed for detection in a schlieren picture so as to show more clearly this effect in a photograph. If an f/8 system, errors as large as 1/4 inch can probably be tolerated and will never be detectable in the final picture on the screen. However, an f/4 system is very critical and demands that errors be less than 1/8 inch, both in the offset and in being in one plane. It is easier to set up a system with the "Z" in the horizontal plane, as the source, image of the source, and axis are then at the same height. However, there is no objection other than the difficulty in alining the system, to rolling the "Z" to any desired angle.

## SCHLIEREN COMPONENTS (SUPPLIERS AND HOW TO SPECIFY)

There are a great many companies well qualified to supply either separate optical components or complete schlieren systems. Table I gives a listing of several companies that have given LRC satisfactory service in the past. This list is by no means all inclusive but it does serve as a good cross section of the optics industry capability.

## Mirrors

In specifying optical components LRC has found it important to state the purpose for which the parts are to be used. Such information enables the optician to direct his efforts toward achieving optimum results. A typical specification for a schlieren system mirror reads as follows: "Mirrors, schlieren instrument quality, first-surfaced, parabolized, made from Pyrex glass or equal; surface shall be aluminum with a protective coating of silicon monoxide and have a reflectivity of at least 85 percent throughout the visible region; shall be of good astronomical quality with smooth figure; shall be sufficiently accurate in figuring and surfacing to show uniform darkening of the field to complete cutoff when they are used in two mirror schlieren arrangements with a light source not larger than 0.030 inch in diameter." The diameter and focal length are then given, and the thickness is specified to be from 1/6th to 1/8th of the diameter. A reasonable tolerance for the focal length is about plus or minus one inch, and dimensional tolerances on the diameter and thickness may be specified as plus or minus 3/16 inch. In the case of 6-inch mirrors, it might be stated that the mirrors may be made from a standard 6-inch mirror blank. Normally specifying schlieren mirrors in terms of a fraction of a wavelength of accuracy is avoided, since a mirror may be made, say, to an accuracy of 1/10 wavelength but the 1/10 wavelength may be concentrated into a narrow band and show as a ring in the schlieren field. The terms, "smooth figure" and "astronomical quality" convey meaning to the practical optician. Unless there is definite need for a special size of mirror, the size specified should conform to one of the standard size mirror blanks. Standard blank diameters are 4, 6, 8, 10, 12, 16, and 24 inches.

## Windows

The selection and specification of windows for use with schlieren systems presents more varied problems than that of the mirrors, particularly if the wind tunnel must operate at high pressures or high temperatures or both, or if the window must be of large size. For windows up to about 15 inches diameter, intended for service where the window temperature will not exceed 150° or 200° F and the differential pressure on the window will not exceed one atmosphere, all of LRC's windows are made from selected optical crown glass which is rolled, ground and polished on a commercial plate-glass polishing line by Pittsburgh Plate Glass Co. The glass is examined by a shadowgraph method in order to select glass which is free from striae, and is then given an optical finish by the optician who supplies the window. Most of the custom opticians in this country are familiar with this approach to the problem, but occasionally an optician will base his price upon the use of conventionally-made optical glass. Obviously the price is much higher in such a case. The glass made by PPG is available in thicknesses up to and including two inches. In calculating the thickness of glass necessary to withstand the pressures in the wind tunnel, it is conventional to assume a tensile strength of 6500 pounds per square inch, with a safety factor of ten (10) which lowers the value of tensile strength to 650 pounds per square inch, for the computations. The high value for the factor of safety is necessary because of the erratic behavior of glass as regards breakage. Figures 12 and 13 are charts prepared by Pittsburgh Plate Glass Co., showing safe loads for plate glass. The strengths of most glasses are approximately the same, except for fused silica, which has a tensile strength of about 7,000 psi, or 700 psi at a safety factor of 10. For conditions not included on these charts, reference should be made to formulas in some standard work such as the book "Formulas for Stress and Strain" by Raymond J. Roark, McGraw Hill, 1966 edition. When severe conditions of pressure and thermal shock are to be encountered, two different approaches are used, depending upon the severity of the condition. For temperatures not in excess of 500°F, optical crown glass, such as used for our other windows, can be fully tempered and then given an optical finish. Such glass is four times as strong as annealed glass and is resistant to thermal shock up to a differential of about 400°F between the two faces. The optical refinishing of tempered glass should be done only by an optician familiar with the problems. So far, such windows have been supplied to LRC only by the John Unertl Optical Co., who did the early experimental refinishing. Also, if there is danger to personnel in case of breakage, the windows should be laminated from two or more thicknesses, each capable of withstanding the pressure by itself. The Unertl Company has supplied a number of such windows to LRC facilities, and they have been completely successful.

For temperatures in excess of 500°F, LRC's high-temperature tunnels have had to use the very expensive fused quartz (fused silica). It has been very difficult to secure fused silica of adequate optical homogeneity for schlieren windows. The usual procedure in procurement of this material has been to buy the rough silica from the manufacturer in the form of fine-ground discs, examine it for internal quality in a tank of index oil of the proper refractive index, and then send it to the optician for optical finishing. LRC has secured the discs from Corning Glass Works, and from Heraeus Quarzchmelze GMBH. Both companies have supplied very high quality material at different times, but the quality obtainable depends somewhat upon the good fortune of the buyer at the time.

In specifying crown glass schlieren windows, normally commercial dimensional tolerances (plus or minus 1/16 inch) are sufficient; however, a good optician can work to plus or minus 0.001 inch if it is necessary. The price would be higher, for closer tolerances. Also the glass must be schlieren quality, free from striae, finished flat to one wavelength per foot of surface and smooth to 1/10 wavelength per inch of surface. The window must be zone-free when viewed in a schlieren system having a sensitivity of 3 seconds, and the ground edges of the finish windows must be free from scratches and they must be finished at least to the finish obtainable with No. 95 aluminum oxide (9.5 microns). The later requirement is necessary because scratches, or chipped places in a rough-ground edge, provide a place for a crack to originate.

A typical set of specifications for tempered windows are: schlieren windows, laminated from two layers of tempered optical glass in accordance with a drawing. The glass shall be selected for freedom from striae, then edged with a fine-ground edge, then tempered; no edgework shall be done on the glass after tempering; the plates shall be optically refinished after tempering, with all four surfaces of each group of two discs refinished; the finished surfaces which are to be in contact with cement must be as flat as those which are to be exterior surfaces; in the refinishing process, not more than a nominal five (5) percent reduction in thickness is allowed, counting material removed from both faces. The windows are to be laminated using an optical grade cement which will not affect the performance adversely; maximum thickness of the cement after laminating shall not exceed 0.005 inch; any bands of unequal refractive index caused by strains from the tempering process must be all oriented in the same direction when each group of plates is assembled to make one window; the final windows after laminating must be flat to one wavelength per foot of surface and smooth to 1/10 wavelength per inch of surface; windows shall be zone-free when viewed in a schlieren system, having a sensitivity of 6 seconds with the exception of any strains introduced by the tempering process. Commercial dimensional tolerances of $\pm$ 1/16 inch will apply.

A typical set of specifications for fused silica windows are: schlieren windows, of schlieren grade fused silica. The windows shall be flat to one wavelength per foot of surface and smooth to 1/10 wavelength per inch of surface. The window shall be zone-free when viewed in a schlieren system having a sensitivity of 3 seconds. The ground edges of the finished windows must be free from scratches and they must be finished at least to the finish obtainable with No. 95 aluminum oxide (9.5 microns).

## Light Source

The selection of a light source depends to a great extent upon the type of work involved. If there is no need to photograph transient phenomena in the flow, a simple continuous light can be used and the schlieren field can be photographed with a camera equipped with a conventional shutter. Such snapshot-type photographs are easy to take and will be useful in most cases. A 25 watt zirconium concentrated-arc lamp is an ideal source for many purposes. It is easy to take snapshot-type pictures using this source, and it will be found that adequate exposure can be obtained at 1/150 second for a picture of 2-½ to 3 inches diameter using an f/8 schlieren system. If photographic exposures in the sub-microsecond range are required, the best light source is a spark. Such a source is inconvenient to set up, and it is usually advisable to set up two interchangeable sources, one the spark and the other one a zirconium concentrated-arc lamp. It is possible to mount both sources permanently and change from one to the other by means of a movable mirror, or by moving the two sources as a unit and providing fixed stops to locate their position accurately.

Many of LRC's facilities use a high-pressure mercury arc lamp of either the water-cooled AH-6 or the air-cooled BH-6 type. This lamp can be pulsed for short-duration flashes (approximately 10 microseconds) or burned continuously for viewing or for motion pictures. Its disadvantages are unreliability because of frequent lamp failures, and personnel danger because of the high voltage and relatively high current involved (one ampere at 1000 volts). There is no known supplier of equipment for operating the lamps on direct current or for pulsed operation, so LRC has always built these power supplies. Circuit diagrams are shown in figure 14 and figure 15.

Presently, experiments with some facility schlieren systems using a high-pressure compact xenon arc lamp as the light source are being conducted. The lamp is manufactured by Pek Labs, Inc. and Illumination Industries, Inc. The lamp is the type X-75, a 75 watt convection cooled lamp. Preliminary evaluation of the lamp has proven the lamp suitable as a schlieren source. The lamp's small arc size (.015 inch), continuous operation capability, and its readily ionized inert gas makes it ideally suited as a pulsed point source for schlieren. A power supply schematic is shown in figure 16. A published paper covering the evaluation of the lamp is available in the LRC files. It is Langley Working Paper number 301.

## Knife-Edge Holder and Positioner

For holding and positioning the knife-edge, a micropositioner which permits precise adjustments in three directions is available from Brinkmann Instruments, Inc. A small holder for the knife-edge is usually constructed to mount upon the positioner. It is possible to build a relatively simple knife-edge positioner which will work satisfactorily, although it would not be as convenient as the commercially-built equipment.

## Lenses

Consideration for lens systems should include the cost and availability of lenses for lenses over 6 inches in diameter. Any good telescope objectives up to and including 6 inches in diameter will suffice and can be obtained from Edmund Scientific Co., and A. Jaegers, Inc. A suggestion for the procurement of schlieren lenses over 6 inches in diameter would be to talk to prospective optical bidders about the requirements and cost involved. Lens systems above 6 inches diameter become increasingly impractical because of rapidly increasing cost and aberrations.

# SPECIALIZED USES OF SCHLIEREN

## Reflecting Knife-Edge

Often it is required that the schliere be both photographed and monitored. Usually in this case, the camera is mounted such as to receive the image direct and a flat mirror is pivoted for intercepting the beam and reflecting the image on to a screen for monitoring. However, there are instances when simultaneous photographing and monitoring of the image is desired. This can be done with a reflective knife-edge, figure 17. A rectangular piece of front surface mirror stock ½" x 1" which is tapered about 60° from the back side to a very sharp edge on the front is used as the knife-edge. It is mounted with the silvered side facing the second mirror or lens and canted such that it reflects that portion of the image which is usually cut off by the knife-edge in any desired direction. The camera and screen can thus be placed as wanted. There are many configurations using both the reflecting knife-edge and the folding flat mirror to permit the use of several types of cameras, etc., with one schlieren system.

## Color Schlieren Using Filters

Color schlieren is often used for publicity and display. One way of obtaining color schlieren is with the use of a color knife-edge. This is done with color filters placed at the knife-edge position, figure 18. Normally only two filters are used, a no. 58 (green) and a no. 25 (red), placed edge to edge on a microscope slide and taped into place. This knife-edge is placed so that the junction bisects the light source image thus producing a yellowish background with flow disturbances showing as red or green depending on whether the image is refracted by the schliere into the red or green areas of the knife-edge. A problem with this system is obtaining a coplanar surface of the two filters to eliminate scattered light within the schlieren image. However, a carefully constructed color knife-edge will produce some very impressive results.

Another knife-edge configuration is the tricolored with a narrow strip of a yellow filter bounded by red and green. Here the coplanar problem is magnified. Also there is the problem in getting the width of the yellow band uniform across its length and exactly the same as the image width so that in a static state there is a uniform yellow background; here the slightest angle deviation of light resulting from the schliere is detectable as either a red or green trace on the yellow background. Since this system has no advantages over the two-filter system and is more difficult to implement, it is not normally used.

## Color Schlieren Using a Prism

The best appearing color effects in a schlieren system are obtained when the effective source is a tiny spectrum formed by passing white light through a prism, and the "knife-edge" is a small adjustable slit. This configuration is shown in figure 19.

A point source of white light (the 25 watt zirconium arc is excellent; a mercury light is poor because it is deficient in red) is first collimated by a good achromatic lens (a 6 x 30 binocular objective is suitable) and then passed through a relatively small-angle prism. The most suitable prism is best determined by experiment, but it is important that dispersion be kept fairly small. Somewhere in the neighborhood of 15 or 20 diopters in prism power is probably suitable.[1] The crown glass wedge type prisms (42 mm square) sold by Bausch and Lomb are well suited. A 15 diopter prism gives an angular deviation of $8^{\circ}\ 32'$. The light is refocused by a second achromat, and the tiny spectrum that is formed becomes the effective light source and goes at the focus of the first mirror. In setting up it is well to put the original light source, the collimating lens, prism and focusing lens all on one support which can then be positioned so that the spectrum is at the focus of the mirror.

The system is now arranged in the conventional form, with the second mirror reimaging the source (the spectrum) at the place where the knife-edge would be. At this location a precision adjustable slit is placed, with the axis of the slit perpendicular to the direction of dispersion induced by the prism. If the dispersion is horizontal, the slit will be vertical. If the power of the prism has been properly chosen, and the slit is of the proper width, the slit can be positioned at one position so that only, say, the yellow goes through. Then a deflection in one direction shifts red into the slit, and a deflection in the other direction will shift green or blue. Usually it is found that the center band will be a combination of yellow and green, so that the background is yellow-green, and the other colors are blue and red. When a white light is used and the system alined, the colors lend themselves well to good color schlieren. The alinement problem often discourages the use of this system. This system is not often used because the relatively high blue dispersion reduces the "blue shift" sensitivity compared to the "red shift", and because of the alinement problem.

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1. The deviation, b, of a prism such as these is given by the formula

$\text{Tan } b = \dfrac{\Delta}{100}$, where $\Delta$ is the prism power in diopters. The angle, a, between the surfaces necessary to produce a given prism power is

$\text{Tan } a = \dfrac{\sin b}{N_D - \cos b}$ where $N_D$ is the refractive index of the glass.

## Lasers as a Schlieren System Light Source

Lasers, either of the solid state or gas variety, appear to offer a new approach to the problems of light sources for schlieren and shadowgraph work. The monochromatic, highly parallel laser light can be focused to a point which approaches the theoretical Airy disc in size. The concentration of energy makes it possible to have large quantities of light available for photography even when the source is exceedingly small. Also, in cases where the working fluid is self-luminous it is feasible to use filters which will pass only the laser light.

In practice, there are difficulties to be overcome in applying lasers as light sources, and the prospective user must be prepared to go to great pains in order to attain good results. In using such an exceedingly small source, the great increase in sensitivity immediately leads to need for optical components of very high quality. Also the difficulties from thermals in the room air are increased proportionately, and adequate mechanical stability of the supporting structure becomes exceedingly hard to attain. It certainly is possible to obtain a good schlieren system using a laser as the source, but the user must be prepared to start from the very beginning and design the building and the system for the maximum attainable stability; the best optics obtainable will be none too good, and the light path should be evacuated for best results.

## CONCLUDING REMARKS

This paper represents an attempt to put into condensed form and easily understood language, the fundamentals of knowledge needed for specifying, setting up, and operating a schlieren system. The list of component suppliers, and to a certain extent the specification for mirrors and windows, can easily become out of date. It is believed, however, that the material is good for a period from 5 to 10 years.



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R.C.S.

## APPENDIX A

### Collodion Technique of Mirror Cleaning

A new technique for cleaning mirrors is now being utilized whereby the mirror can be cleaned in its holder and on the job. It minimizes handling of and possibility of damage to the mirror while providing a cleaner job than with the water and detergent method. The technique consists of applying a film of collodion to the mirror surface and peeling of the collodion and entrapped dirt. The only equipment necessary is collodion, a soft camel's-hair brush, and cheesecloth. Only U.S.P. collodion (cellulose nitrate in ether-ethanol solution) should be used. So-called "flexible" collodion with a camphor plasticizer will not work because it adheres to the mirror and cannot be lifted off. The ether solvent is dangerously flammable and is an anesthetic therefore standard safety measures should be taken. It is advisable to try this technique first on a surplus mirror or a piece of glass in order to become acquainted with the steps involved.

To clean the mirror in place paint a thin, even film of collodion over the entire surface of the mirror using the camel's-hair brush. It may be desirable to scrub the mirror lightly with collodion using the brush. Application of two or three thin coats of collodion should be sufficient. Allow a few minutes for each coat to harden so as to support the following coat without running. Place a piece of cheesecloth somewhat larger than the mirror over the mirror surface. Put enough layers of collodion over the cheesecloth to allow it to flow through to the other coats on the mirror and make a solid seal over the whole area. When the collodion is sufficiently dry, peel off the cheesecloth and collodion with a gentle even pull. The process may be repeated if necessary.

TABLE I.- SCHLIEREN COMPONENT VENDORS

| SCHLIEREN COMPONENT | COMPANY |
|---|---|
| Complete schlieren systems. All optics. | Jones and Hargbol Optical Corp.<br>5 Forest St.<br>Arlington, Mass. 02174 |
| " | John Unertl Optical Co.<br>3551 East Street<br>Pittsburgh, Pa.<br>Attn: Mr. John Unertl, Jr. |
| " | Itek Corp.<br>10 Maguire Rd.<br>Lexington, Mass. 02173 |
| " | Goerz Optical Co., Inc.<br>461 Doughty Blvd.<br>Inwood, L.I., N.Y. 11696<br>Attn: Mr. Kenneth L. Kemp |
| " | Ferson Optical Co.<br>Oceans Springs, Miss. |
| " | Optics for Industry<br>1929 N. Buffum St.<br>Milwaukee, Wis. |
| " | Perkin-Elmer Corp.<br>Maine Ave.<br>Norwalk, Conn. 06852 |

TABLE I.- SCHLIEREN COMPONENT VENDORS - Continued

| | |
|---|---|
| Complete schlieren systems. All optics. | Davidson Optronics, Inc.<br>2223 Ramona Blvd.<br>W. Covins, Calif. 91792<br>Attn: Mr. Don E. Davidson |
| Glass for windows | Pittsburgh Plate Glass Co.<br>1 Gateway Center<br>Pittsburgh, Pa. 15222 |
| Antivibration pads. | M. B. Electronics<br>Division of Textron<br>Ind., Inc.<br>New Haven, Conn. |
| Fused silica, Vycor.<br>Massive cast glass windows. | Corning Glass Works<br>Corning, New York |
| Fused silica | Heraeus Quarzchmelze<br>GMBH<br>Hanau, West Germany |
| Zirconium arc lamps, etc. | Sylvania Electric Products Corp.<br>1740 Broadway<br>New York, N.Y. 10019 |
| Zirconium arc lamps and power supplies. | George W. Gates & Co.<br>Hamstead Turnpike & Lucille Ave.<br>Franklin Sq., L.I., N.Y.<br>Attn: Mr. Schultz |

TABLE I.- SCHLIEREN COMPONENT VENDORS - Continued

| | |
|---|---|
| BH-6 Lamps<br>AH-6 Lamps | General Electric Co.<br>Outdoor Lighting Dept.<br>Hendersonville, N.C. |
| BH-6 Lamps<br>AH-6 Lamps<br>Xenon compact arc lamps and power supplies | PEK Laboratories, Inc.<br>825 East Evelyn Ave.<br>Sunnyvale, Calif. |
| Xenon compact arc and power supplies. | Illumination industries, Inc.<br>Sunnyvale, California. |
| Achromatic lenses, prisms, general optical supplies, war surplus. | A. Jaegers, Inc.<br>691 Merrick Rd.<br>Lynbrook, N.Y. |
| Flatwork, windows, and prisms. | Gaertner Scientific Corp.<br>1201 Wrightwood Ave.<br>Chicago, Ill. |

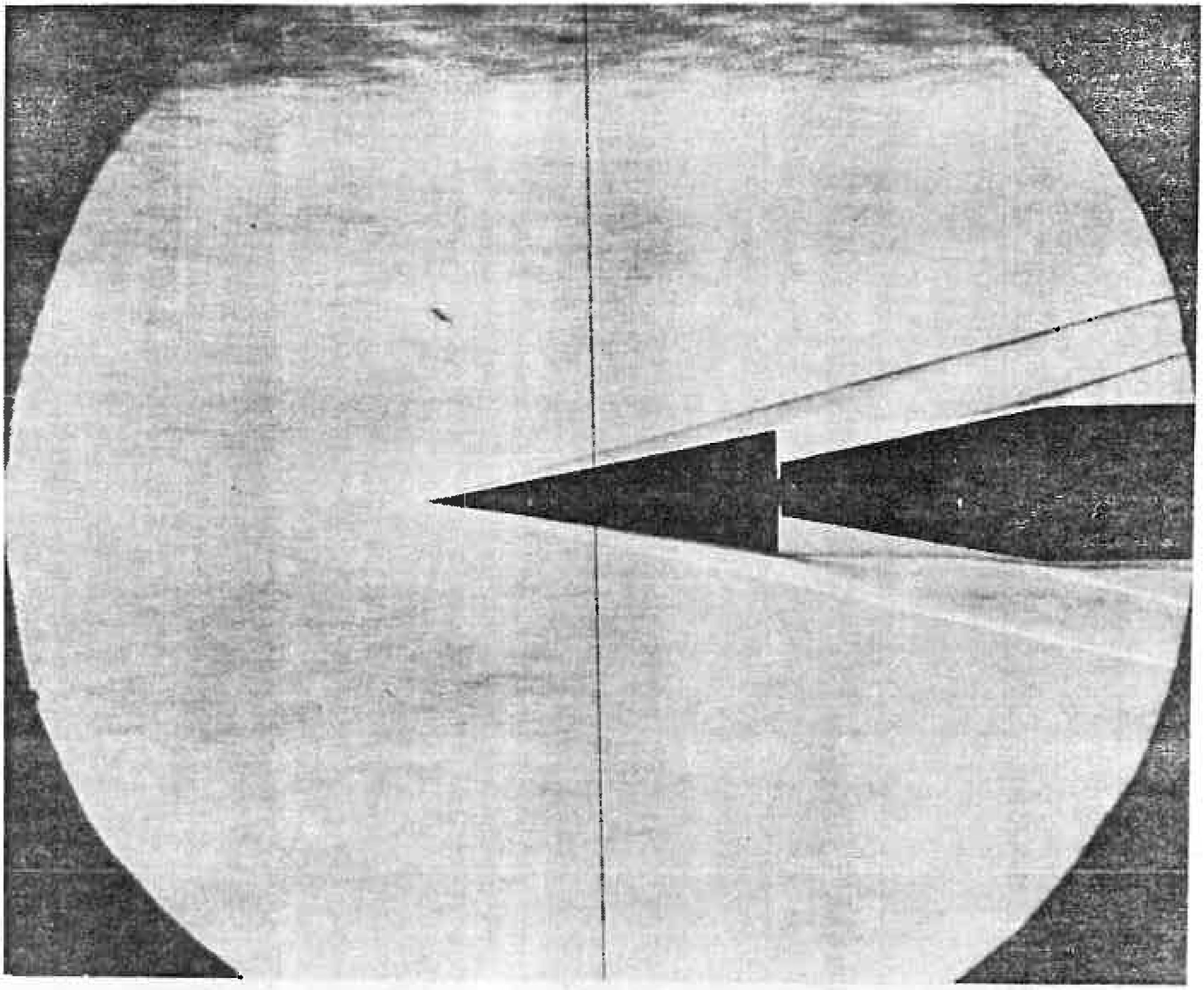

Figure 1. - Schlieren Photograph of a Wind Tunnel Model

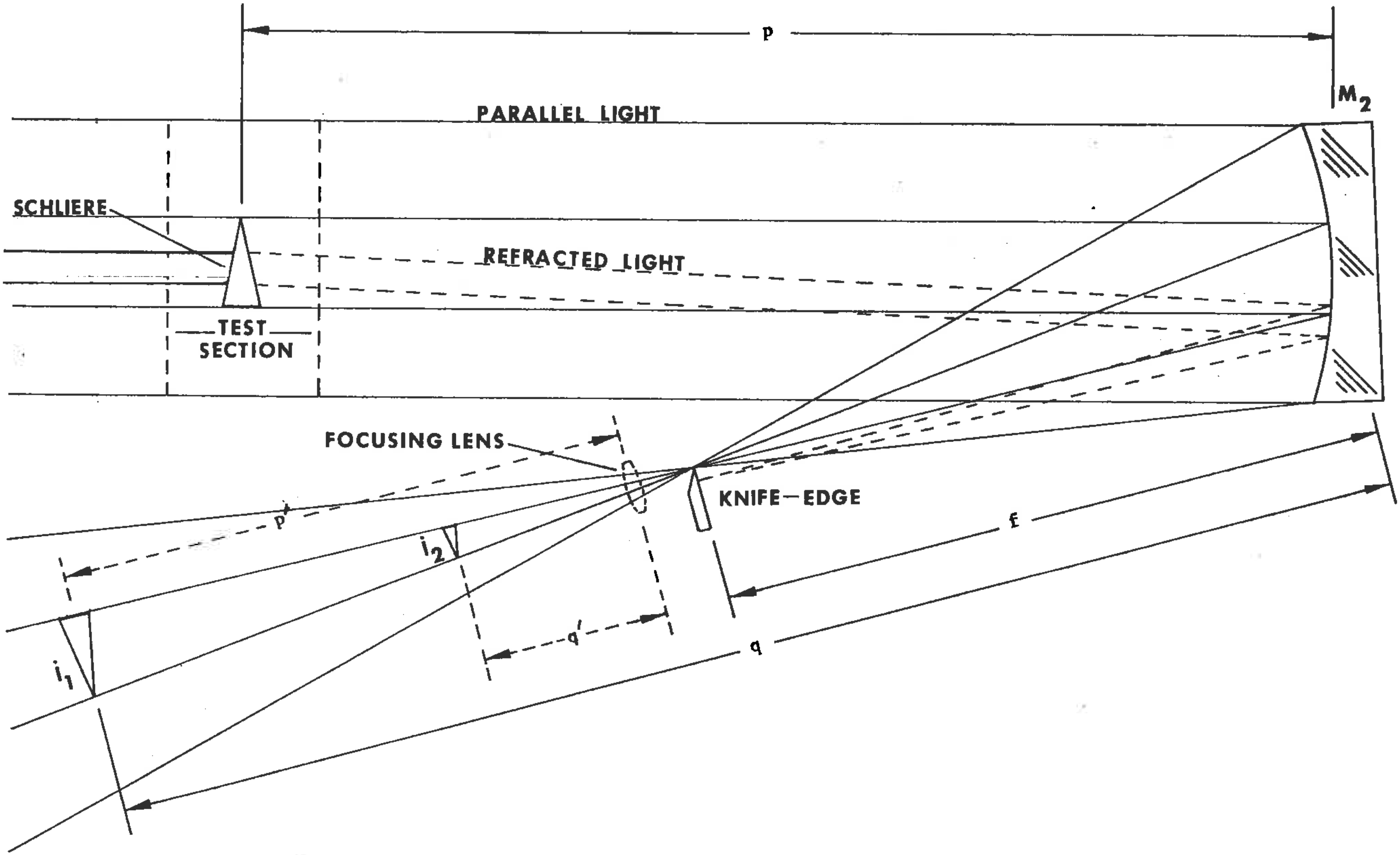


Figure 2. - Typical Off-Axis Schlieren System
Showing Image Positions

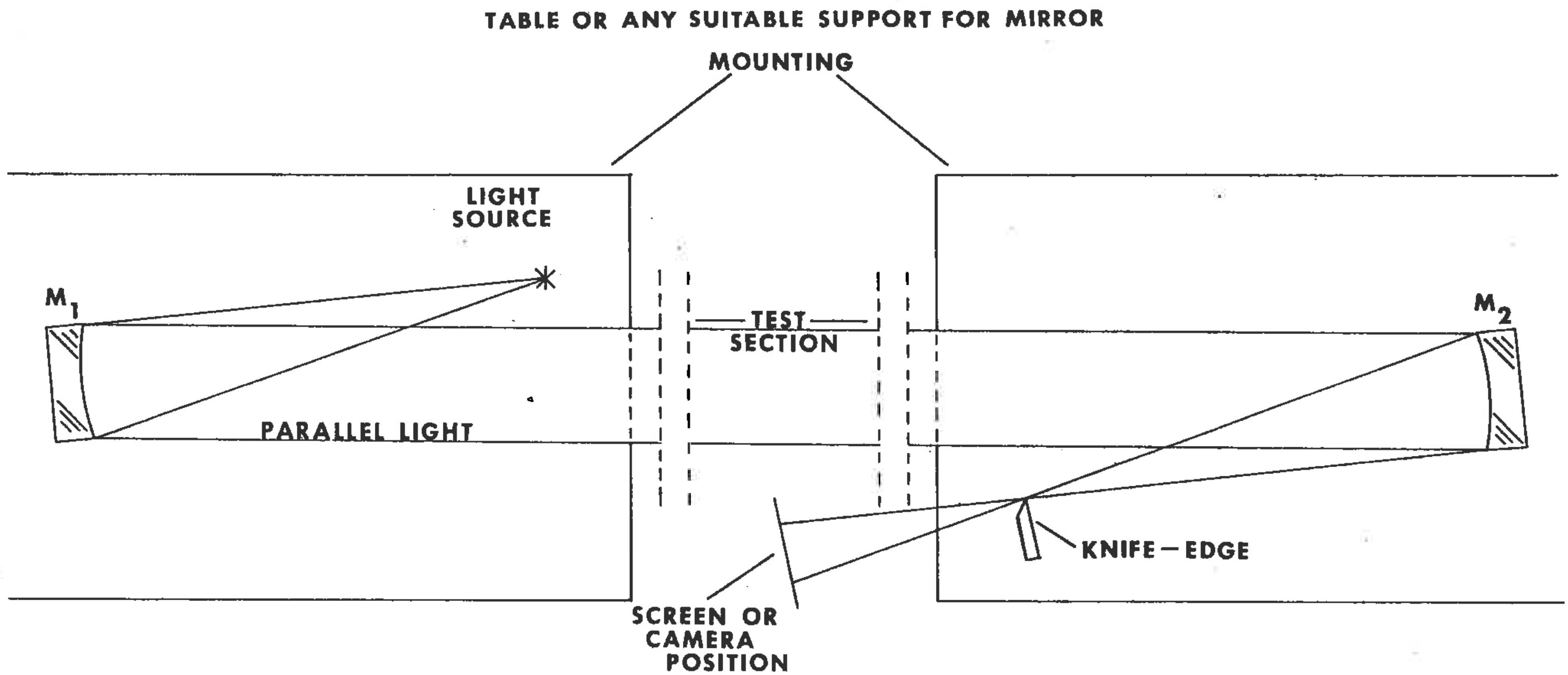


Figure 3. - Typical Off-Axis Schlieren System (Top View)

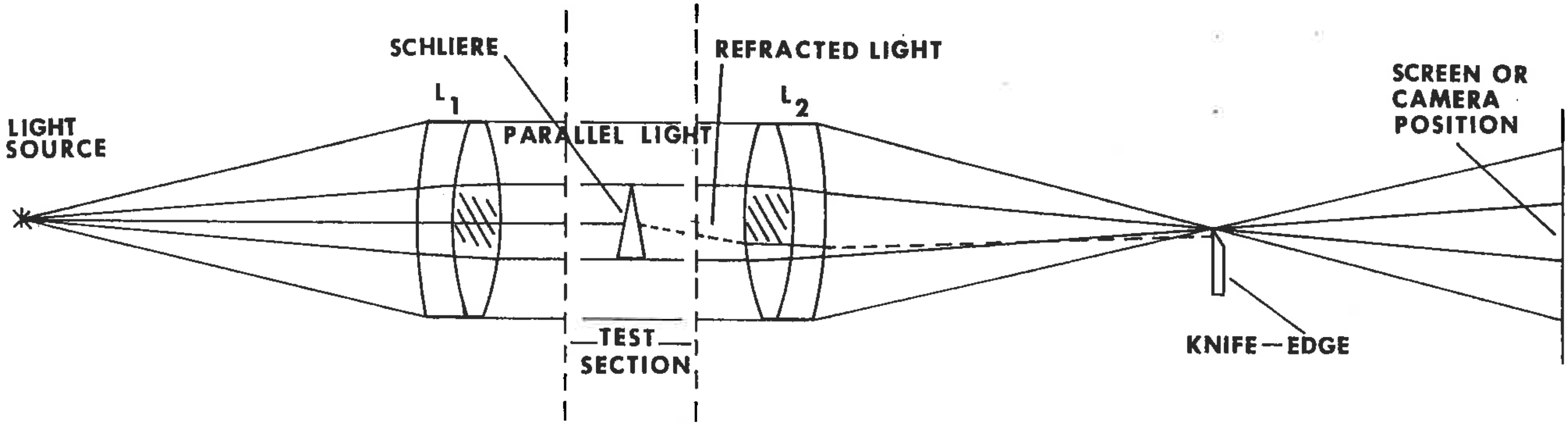


Figure 4. - Diagram of A Lens Schlieren System

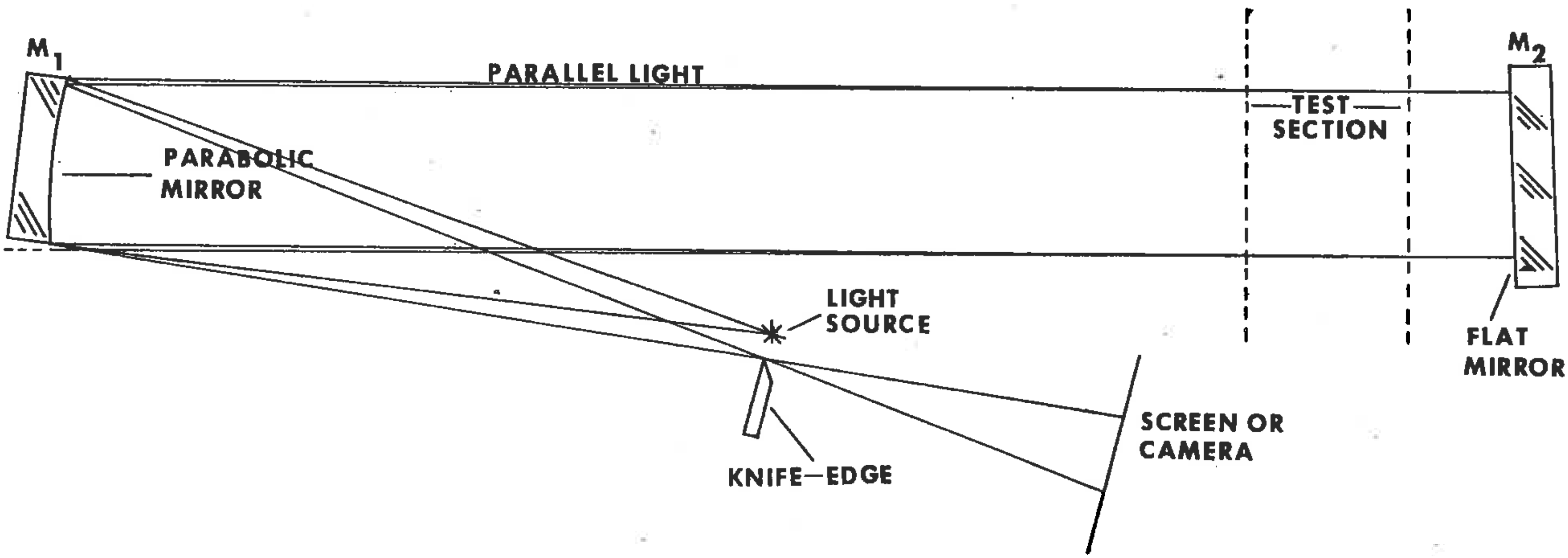


Figure 5. - Double-Pass Schlieren System Using Parallel Light

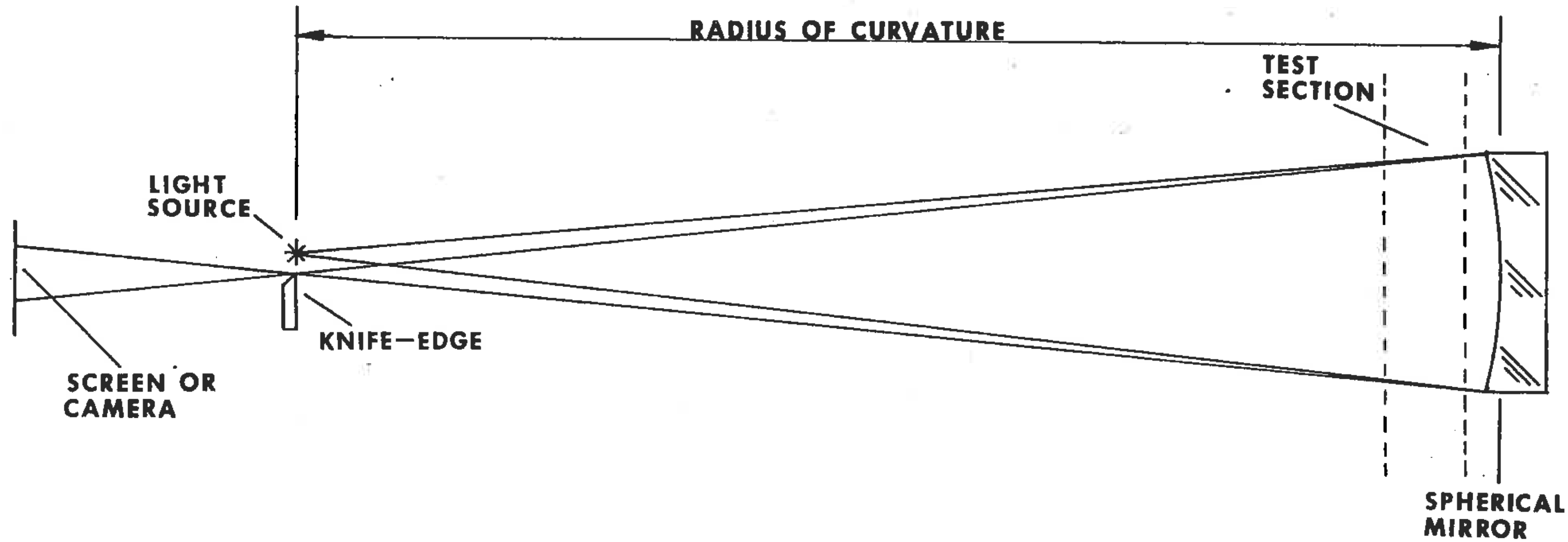


Figure 6. - Double-Pass Schlieren System
with Non-Parallel Light

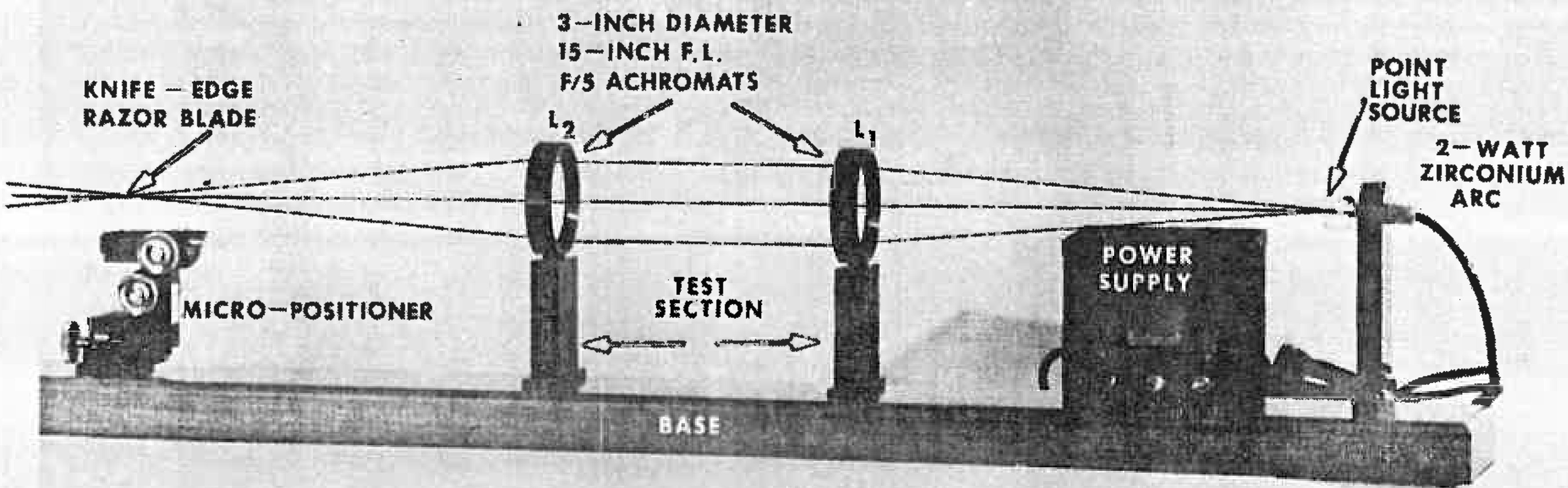


Figure 7. - Training Model of a Lens Schlieren System

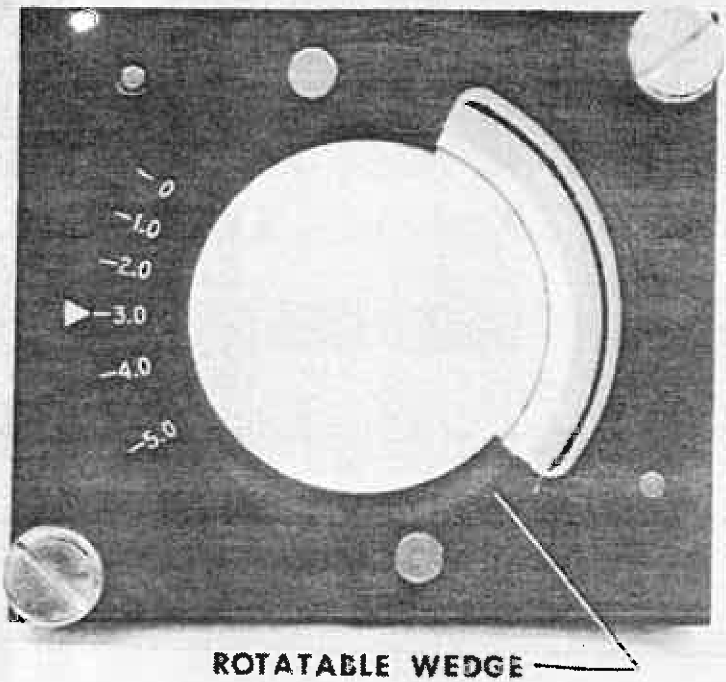


Figure 8. - Schlieren Sensitivity Meter

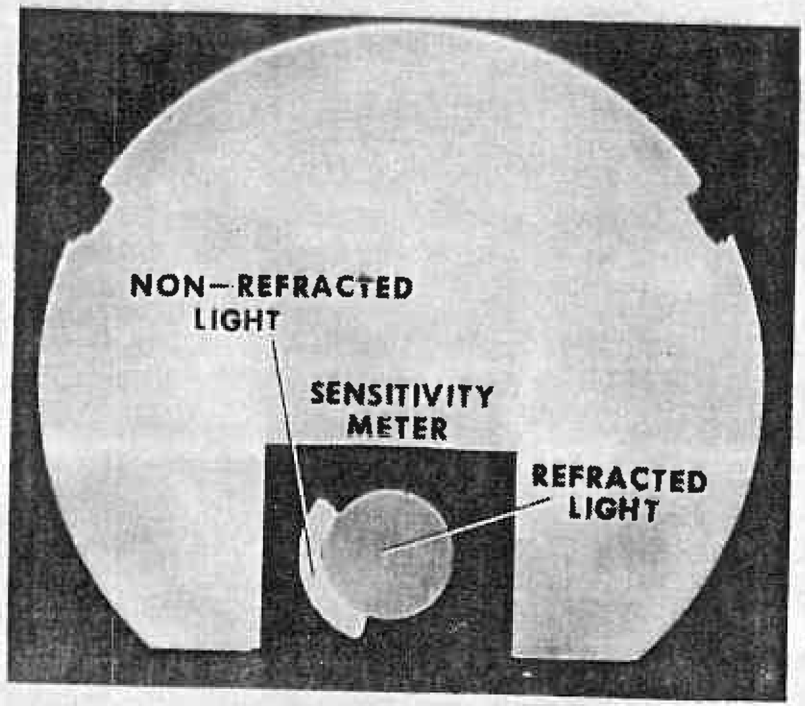


Figure 9. - Schlieren Photograph of the Sensitivity Meter Set for 5 Sec. of Arc Deviation

NASA
L-67-2064

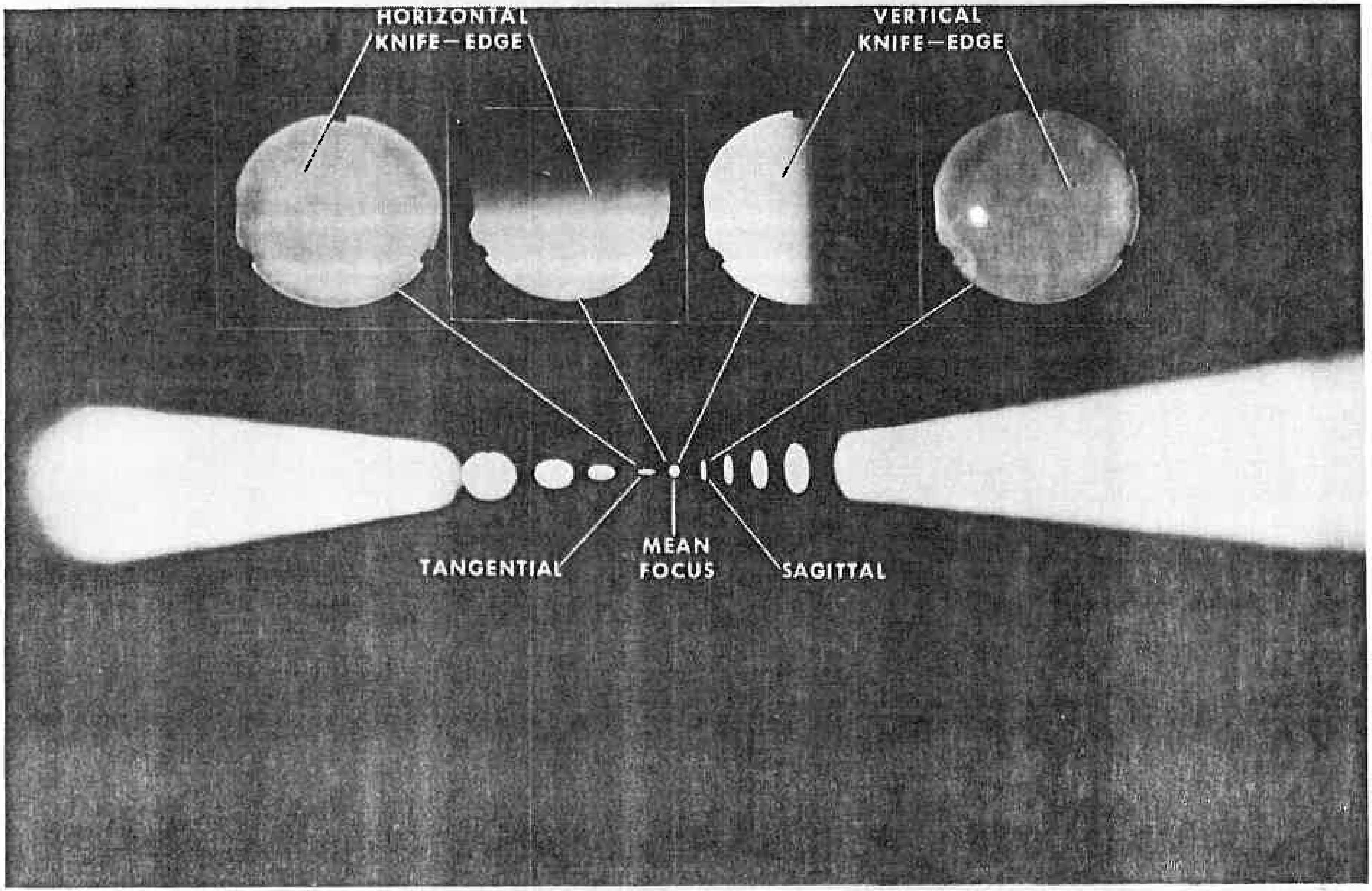


Figure 19. - Astigmatic Images Formed by an Off-Axis Mirror Schlieren System

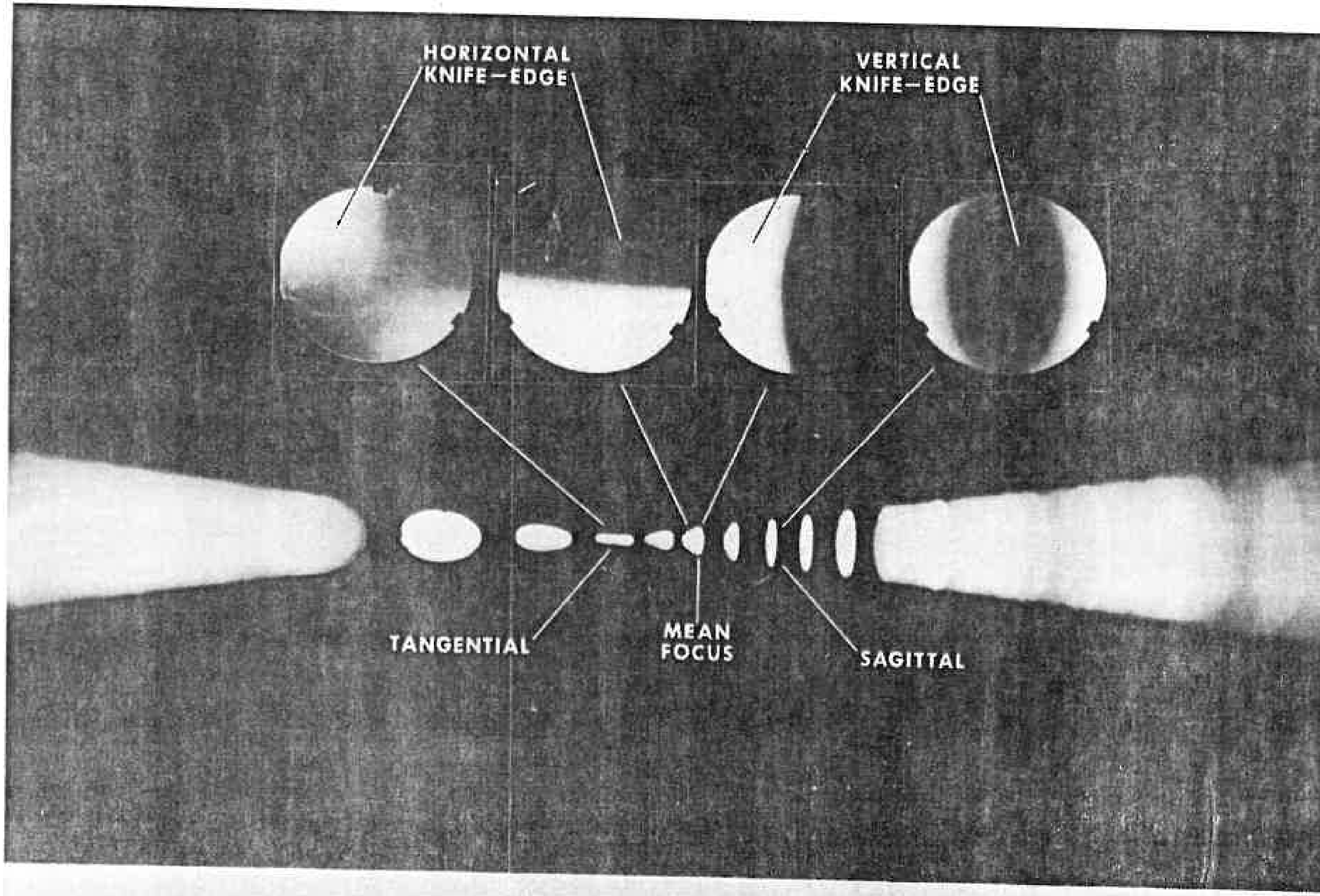


Figure 11. - Comatic Images Formed by a Misaligned Off-Axis Mirror System

# SAFE LOADS FOR PLATE GLASS AND WINDOW GLASS

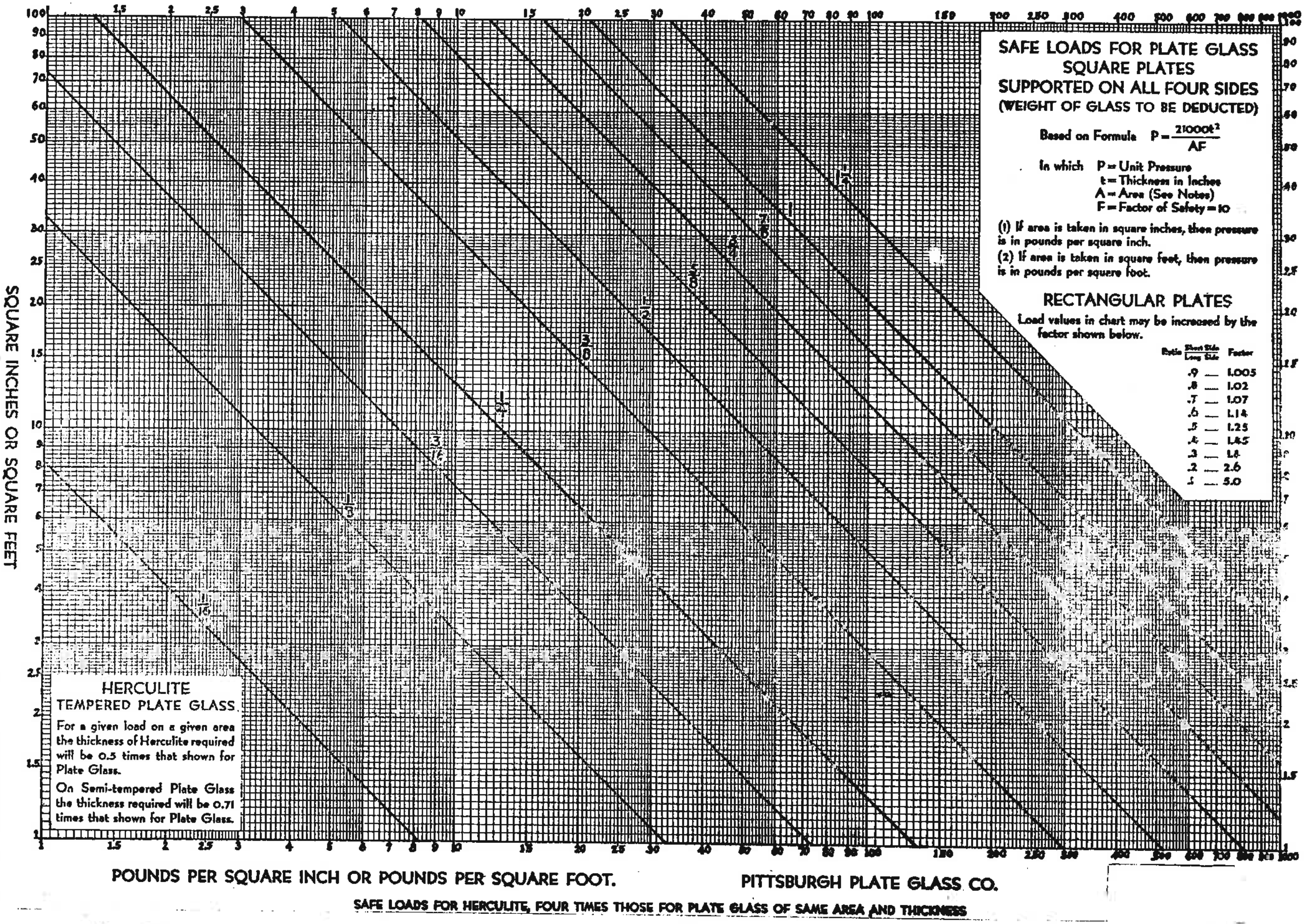


**Figure 12. - Safe Loads for Rectangular G[illegible] Windows Uniformly Loaded**

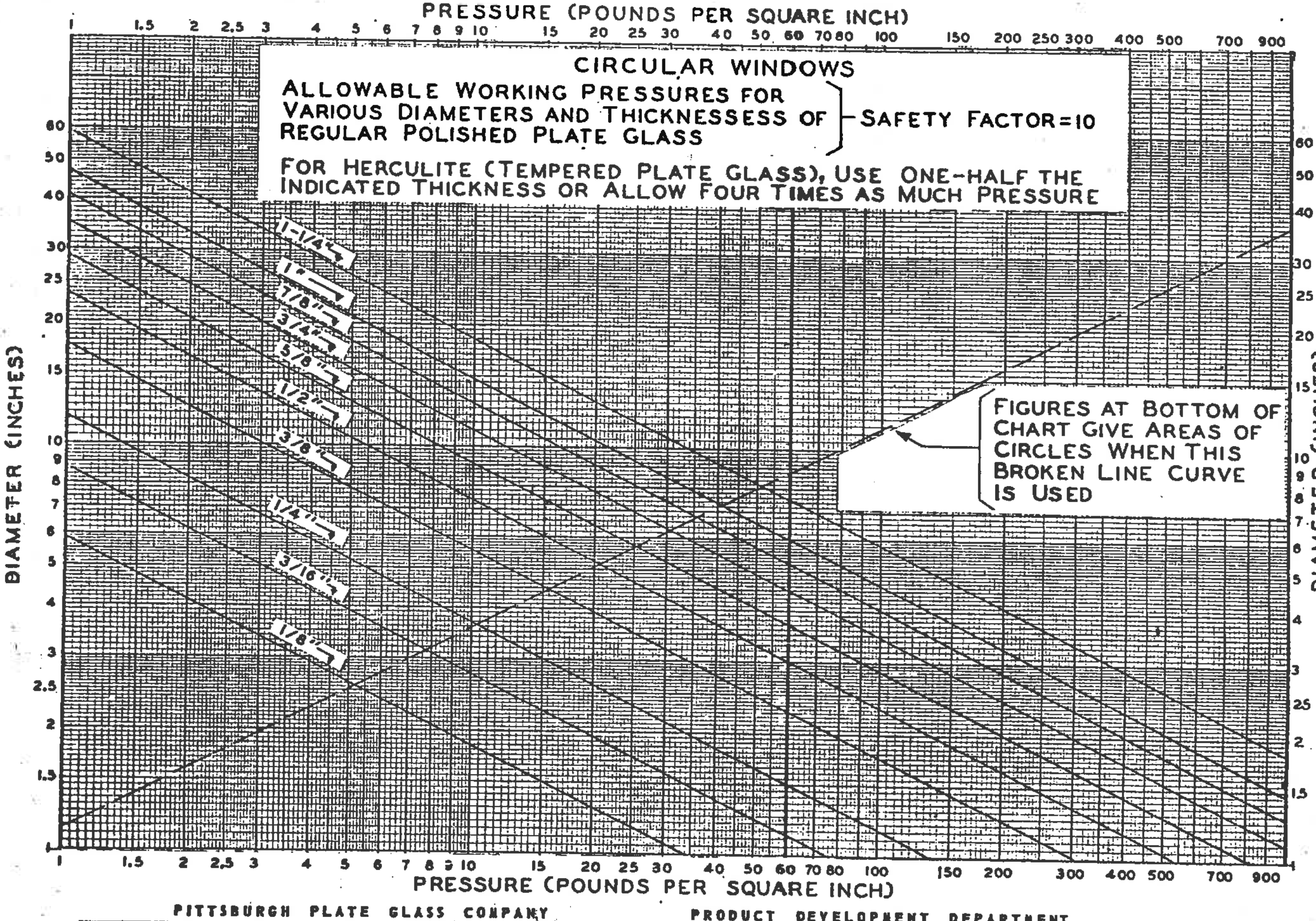


Figure 13. - Safe Loads for Circular Glass Windows Uniformly Loaded

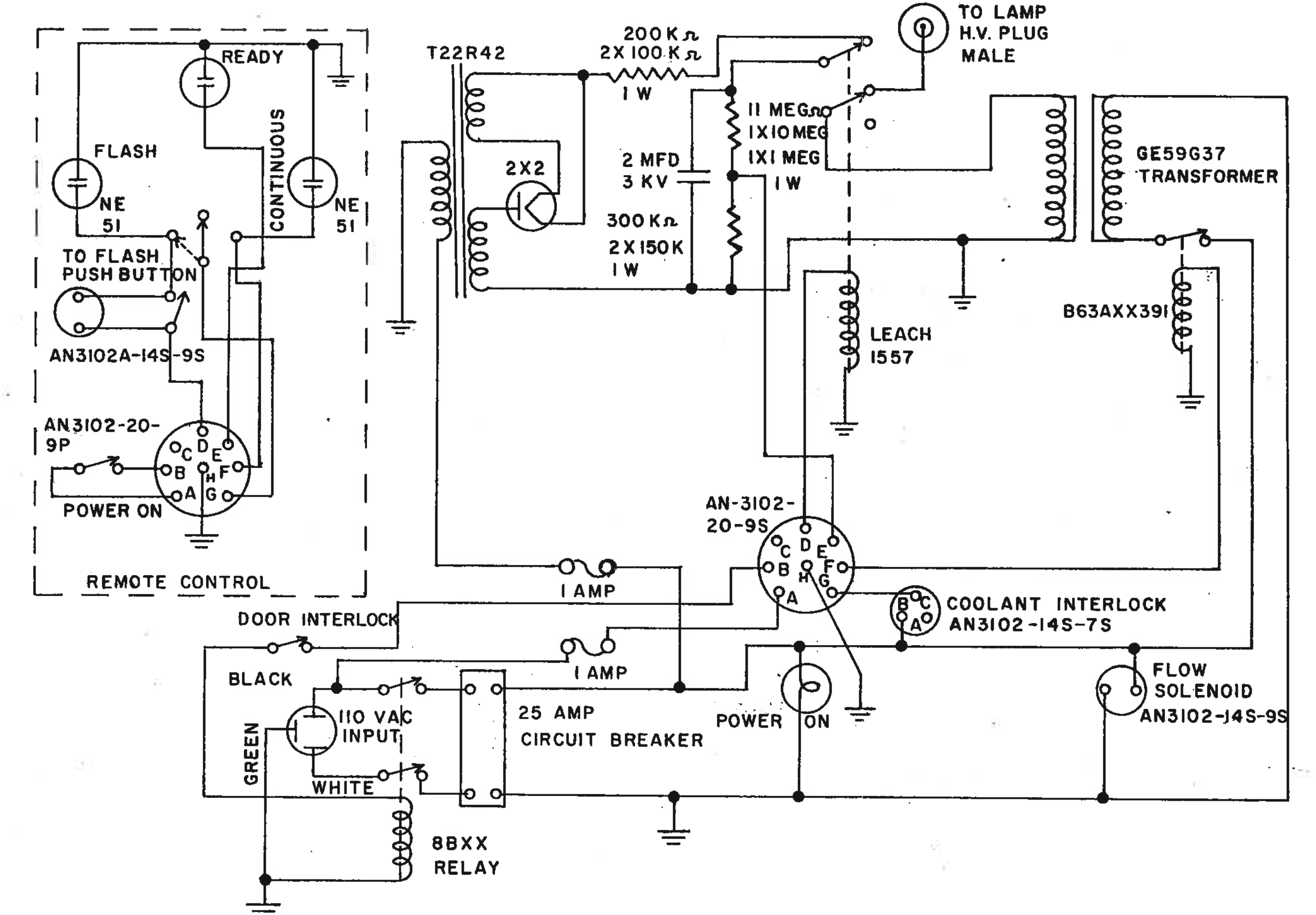


FIGURE 14. – H-6 A.C. & PULSE POWER SUPPLY DIAGRAM

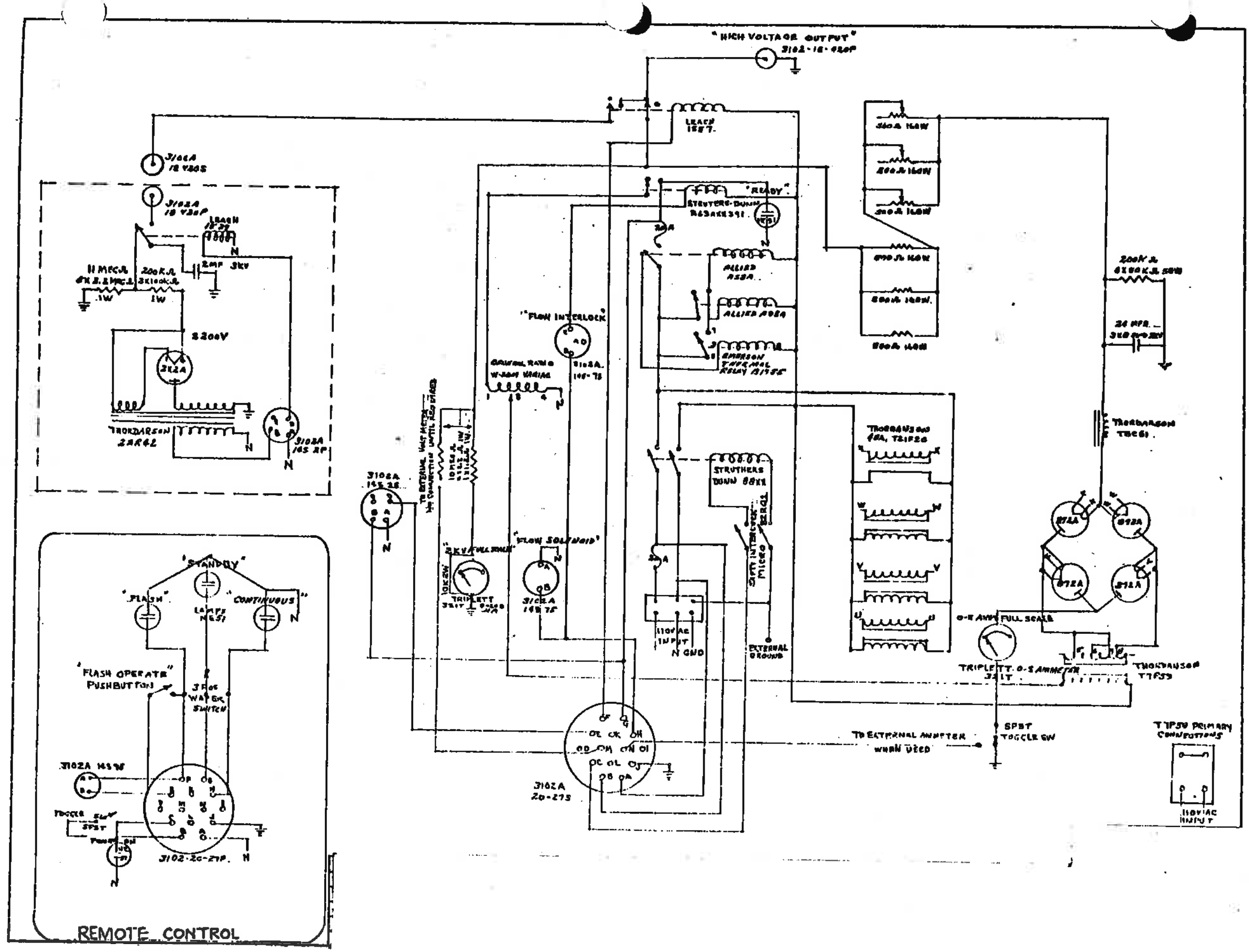


FIGURE 15.— H–6 D.C. AND PULSE POWER SUPPLY DIAGRAM

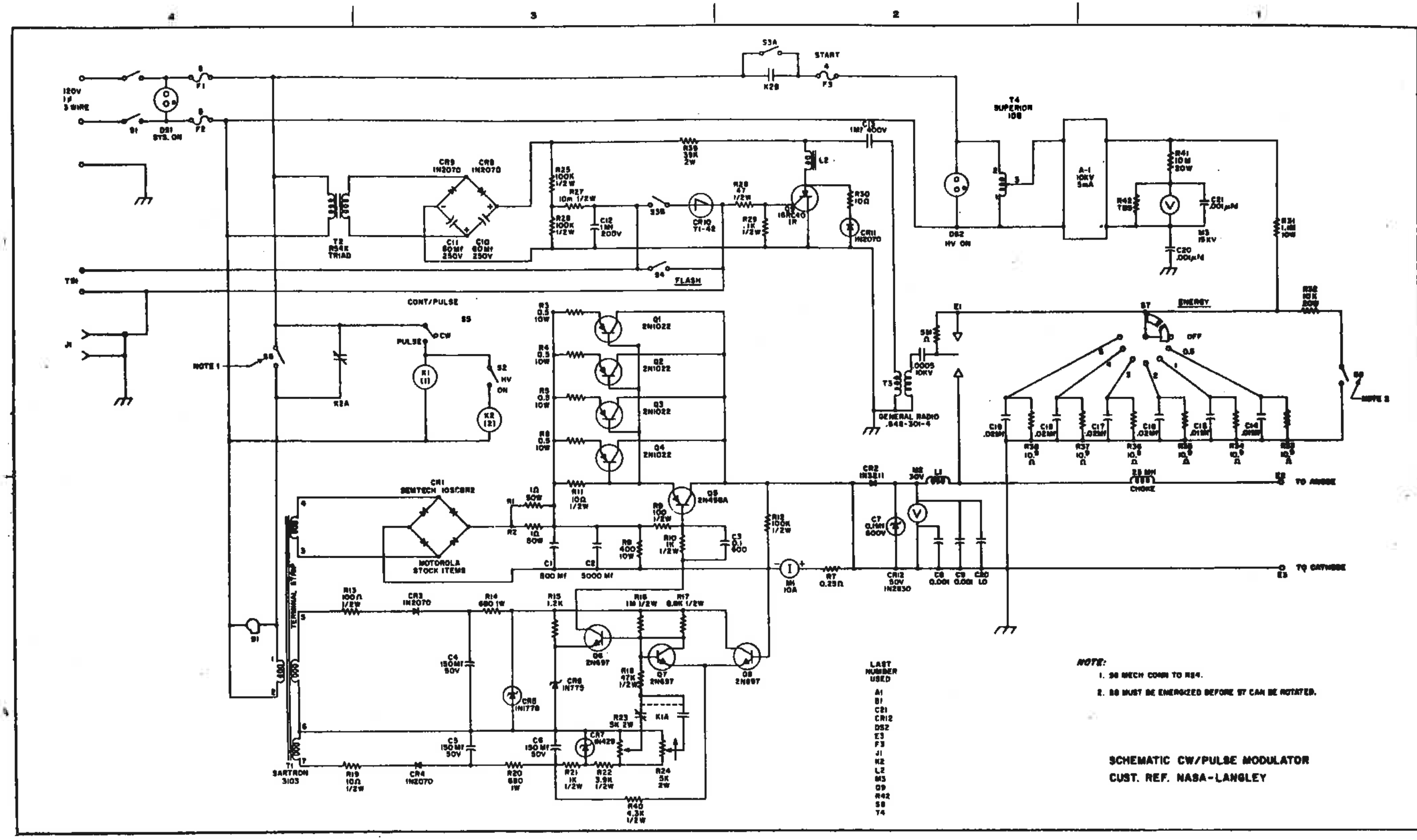


FIGURE 16. — X–75 XENON D.C. AND PULSE POWER SUPPLY DIAGRAM

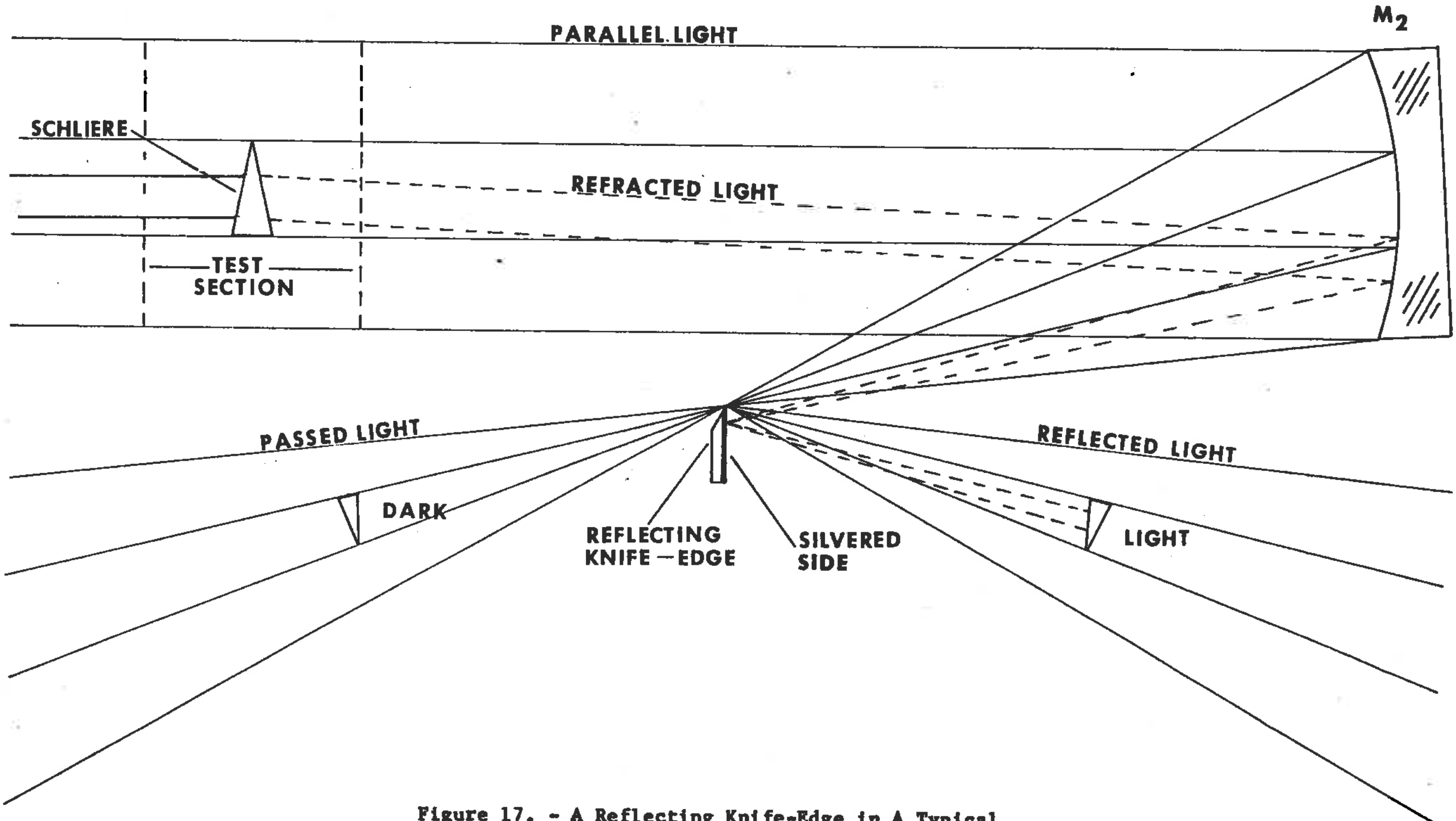


Figure 17. - A Reflecting Knife-Edge in A Typical Off-Axis Schlieren System

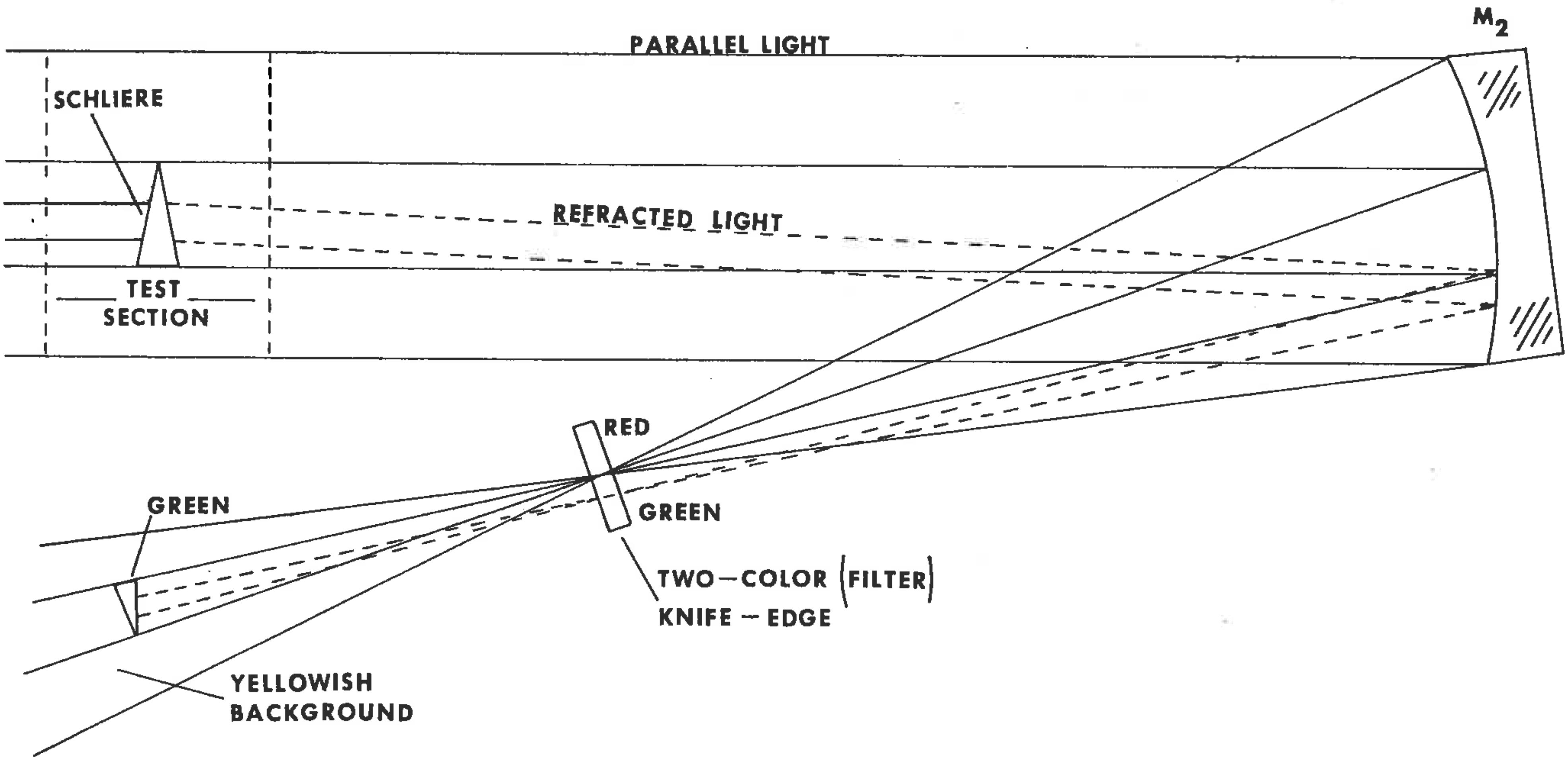


Figure 18. - Color Schlieren Using A Two-Color Filter Knife-Edge

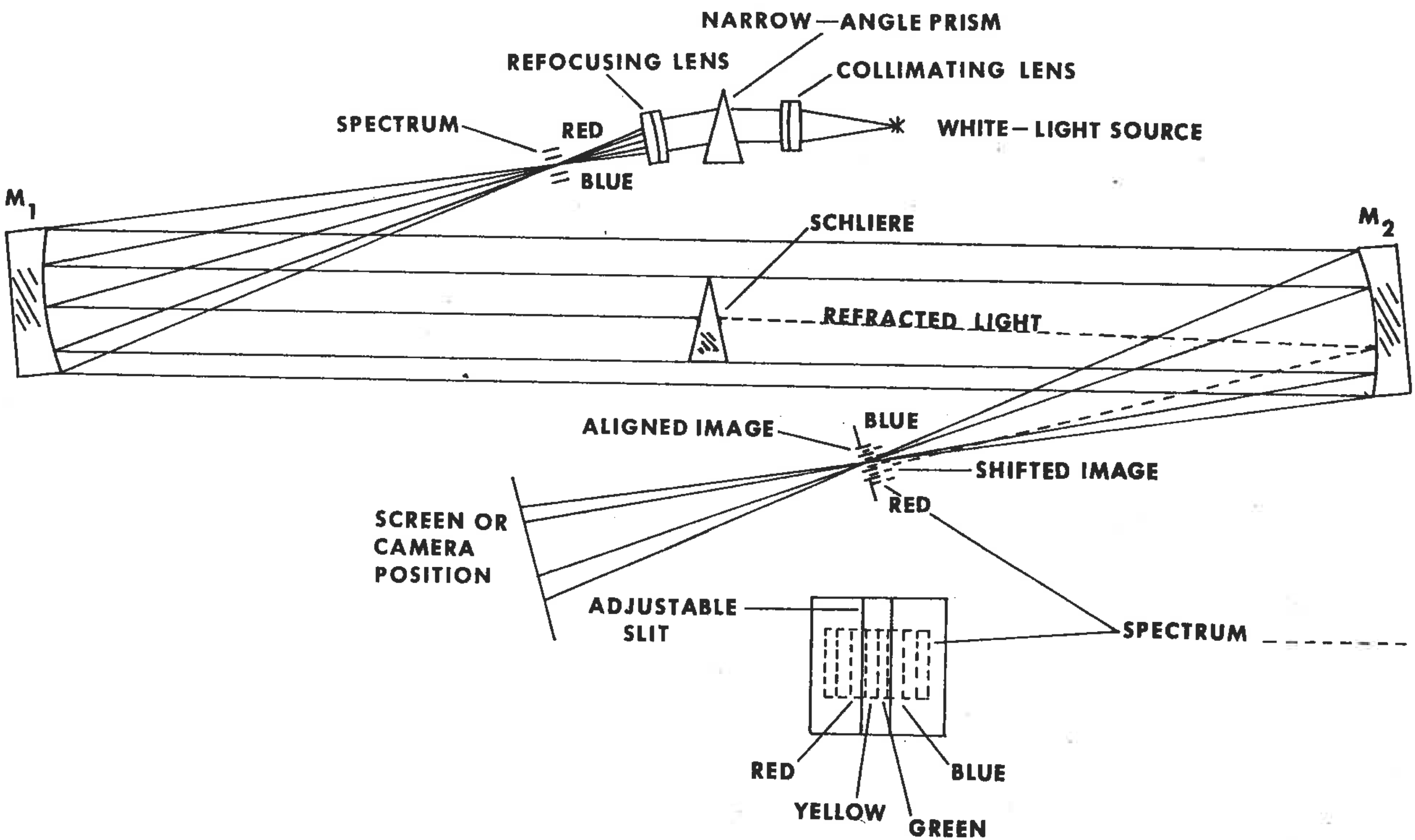


Figure 19. - Color Schlieren Using A Prism (Wedge)