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16. Abstract

For many years, various apparatus and methods have been used for the expressed purpose of measuring and certifying the mesh conformance of fine sieves - primarily those sieves used by various highway agencies for the determination of aggregate material content and consistency.

Development of an Optical Sieve Comparator was undertaken by the Arizona Department of Transportation and the Optical Science Center at the University of Arizona in an effort to determine a practical and accurate method for the measurement and certification of sieve conformance to AASHTO M-92 specifications. The described comparator has proven highly successful in principle, as well as implementation. The comparator features: (1) Measurement of a wide range of mesh sizes (3/8" to No. 400); (2) GO/NO GO sampling for spotcheck statistical certification; (3) Absolute measurement; (4) Simple calibration procedures; (5) Variable optical path distance for wide range magnification; (6) Folded optical path; (7) Visual resolution and repeatability to 1.5 microns; (8) Individual precision viewing reticles for each sieve mesh size; (9) Rapid and convenient operation.

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OPTICAL SIEVE COMPARATOR DEVELOPMENT PROJECT

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PROJECT FUNDING

Development costs for the Optical Sieve Comparator project was funded in total by the Arizona Department of Transportation. Preparation of this report was funded in part by the Federal Highway Administration.

IMPLEMENTATION STATEMENT

Development of an Optical Sieve Comparator was undertaken by the Arizona Department of Transportation and the Optical Sciences Center at the University of Arizona in an effort to determine a practical and accurate method for the measurement and certification of sieve conformance to AASHTO M-92* specifications. The described comparator has proven highly successful in principle, as well as implementation. The comparator features:

- Measurement of a wide range of mesh sizes – 3/8 inch through No. 400 sieves.
- GO/NO GO sampling for "spot check" statistical certification.
- Absolute measurement capability.
- Simple calibration procedures.
- Variable optical path distance (21.5" to 33") for wide range magnification.
- Folded optical path for a compact, portable design.
- Visual resolution and repeatability to 1.5 microns (40X lens).
- Individual, precision viewing reticles (GO/NO GO) for each sieve mesh size.
- Rapid and convenient operation.

The purpose of this report is to inform the various state and federal agencies as to Optical Sieve Comparator development and design efforts conducted by the Arizona Department of Transportation. Although development and basic design principles are presented, no attempt has been made to present actual construction detail. It is anticipated however, that upon reviewing the report, certain agencies may wish to develop and construct similar comparators for their own use. Should this be the case, those agencies are encouraged to contact and consult with the Arizona Department of Transportation, Research Division. Arrangements can be made for individual demonstration and consultation sessions at the ADOT facility, 206 South 17th Avenue, Phoenix, Arizona 85007.

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*American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing,* Part I – Specifications; M92-70, Standard Specification for Wire Cloth Sieves for Testing Purposes. NOTE: Equivalent to ASTM E-11-70.

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INTRODUCTION

For many years, various apparatus and methods have been used for the expressed purpose of measuring and certifying the mesh conformance of fine sieves – primarily those sieves used by various highway agencies for the determination of aggregate material content and consistency.

Specification standards set down by AASHTO M-92 dictates requirements for the certification of fine mesh sieves. To meet these standards, various precision measurement methods are being used and are continuously being devised. The choice of a measurement method involves several considerations, including precision, ease of operation, reliability and others. However, of vital importance is the ability to accurately certify a large number of sieves, of varying mesh size, in a relatively short period of time. In addition, this certification should be accomplished by personnel of nominal skill level.

The Manual of Highway Materials, Part I, 10th Edition, as adopted by the American Association of State Highway and Transportation Officials, describes several contemporary methods of sieve certification in the Appendix to AASHTO M-92 (pages 103-104). These methods include split-image and micrometer microscopes, various contour projection systems and the much used Moire' effect.

The micrometer microscope, although highly accurate, has the disadvantages of being not only fatiguing and tedious, but extremely time consuming when performing a statistical sample of maximum and minimum openings within the sieve cloth. Although time consuming, the microscope is highly reliable in measuring wire diameters and determining the number of wires per centimeter.

The split-image microscope is a high quality, extremely delicate device, but again, is both tedious and time consuming for sieve certification applications.

The Moire' effect, a generally used measurement method, is based on optical diffraction phenomena. This phenomena is caused by the formation of a two-dimensional grid when a precision ruled glass scale is placed onto the surface of the wire cloth. The Moire' effect, as detailed in the ASTM, E11 Appendix, paragraph A1.13, can effectively be used as a means of determining mesh count (number of wires per centimeter) and wire diameter. Interference fringes between two beams of monochromatic light (light of a single wavelength) have long been used for highly refined and precise measurement of length. When performing measurements by this method, length is determined in terms of the wavelength of the particular light source being used. Measurement order of magnitudes of 20 micro-inches are possible, although only rarely required in most laboratory work.

It is possible, however, to produce Moire' fringes with "white" light by the use of two coarse slit-and-bar gratings. These consist of glass plates on which opaque bars are ruled at regular intervals – leaving transparent slits of equal width. If two such gratings are face-to-face super-imposed with their rulings nearly parallel, and viewed on a diffused light background, sharp Moire' fringes will be observed. Appendix A provides a more detailed analytical explanation of the Moire' pattern as formed by parallel gratings of slightly different pitch.

The Moire' effect has widespread application in the technology of measurement, primarily in the science of strain analysis, the study of surface topology, and stress and strain analysis as applied to deflections in flexed structures.

Application of the Moire' effect to the measurement and certification of a large number of sieves is a legitimate approach, but, not unlike the microscope, is found to be a tedious and highly sophisticated method of measurement – requiring the use of experienced high-skill personnel.

In 1922, the National Bureau of Standards developed a projection apparatus which was intended primarily for the testing of sieves in general.* The projection system developed by the Bureau was found to be much faster and less fatiguing to the operator. They found by experience that in testing sieves for conformity to the "Standard Specification for Sieves," the most reliable results were obtained by measuring the wire diameters and determining the number of wires per centimeter. The mesh opening was then determined by the following formula:

$$D = \frac{10}{N} - W$$

where D = Average mesh opening in millimeters
N = Number of wires per centimeter
W = Average wire diameter in millimeters

Measurements were taken on any number of the warp and the shoot wires of the cloth. The cloth could also be examined for "maximum" openings. It was found that the projection system allowed measurements in a fraction of the time normally required by the various other optical systems. The NBS projection system was by definition an optical comparator, utilizing a projected image of the sieve screen onto a ground glass plate – then measuring the calibrated projected image of the openings by way of a steel rule. For a more detailed description of the NBS sieve comparator, refer to Appendix B. In addition, Appendix C offers an NBS comparator application intended for the precision measurement of the coating thickness of corrosion protected iron screw threads. It should be noted that the NBS comparators did emphasize one vital aspect – that is, its speed and accuracy of measurement was clearly of major importance when a large number of sieves (or other objects) are to be examined in a relatively short period of time. The comparator (projection) concept also allows a truly comprehensive evaluation of each sieve, consistent with AASHTO standards.

The NBS comparator was state-of-the-art in the late 1960's when the Arizona Department of Transportation undertook the challenge to research, design and build an optical comparator system specifically for the measurement and certification of the full range of sieves in use. Many features were to be considered. Of prime importance was the use of an adjustable folded mirror optical path. By folding the optical path, a large optical distance could be achieved within a small physical space. This long (adjustable) optical distance would allow the use of multiple interchangeable lens systems to accurately and conveniently cover the full range of magnification required for various sieve sizes. Also, in conjunction with the University of Arizona, a specially designed, highly efficient illumination system was constructed which would be compatible with the full range of lenses used.

In addition, special telecentric lenses were used. With these lenses, the magnification of an object remains "constant," independent of focus. This important feature allowed the focus to be optimized for a sharp image during the various sieve measurements without influencing optical calibration.

Of special interest was the requirement that the comparator be capable of not only absolute measurements over a wide range of sieve mesh openings (Number 8 through 200), but be fully adapted to perform GO/NO GO certification by the use of calibrated viewing reticles. The GO/NO GO concept, in conjunction with the Fisher Sign Test, allows the operator to rapidly scan each sieve and determine any variance from the specified tolerance as set

*Department of Commerce Bureau of Standards. *Letter Circular* LC-72 (July 26, 1922). Also see LC-584 (March 1, 1940).

down by AASHTO and ASTM. This very rapid statistical sampling allows all sieves to be certified on a regular and continuing basis.

The Optical Sieve Comparator represents the culmination of a great amount of effort, involving planning, the building of prototypes and the analysis of performance. The results have been highly successful and rewarding for all participating individuals. You will find that the ADOT Comparator has met its goals – that is, to determine and implement a practical and accurate method for the measurement and certification of sieve conformance to AASHTO M-92 specifications. As the result, the ADOT Comparator features:

- Measurement of a wide range of mesh sizes – 9.5mm to 0.075mm nominal opening size. (3/8 inch through No. 400 sieves.)*
- GO/NO GO Sampling for "spot check" statistical certification
- Absolute measurement capability
- Simple calibration methods
- A variable optical path distance (21.5 to 33 inches) for wide range magnification
- A folded optical path for a compact, portable design
- Visual resolution and repeatability to 1.5 microns (40X lens)
- Individual, precision reticles (GO/NO GO) for each sieve size
- Rapid and convenient operation

The purpose of this report is to inform the various state and federal agencies as to the Optical Sieve Comparator developments and design efforts conducted by the Arizona Department of Transportation (ADOT). Although development and fundamental design principles are presented, no attempt has been made to present actual construction detail. It is anticipated however, that upon reviewing the report, certain agencies may wish to develop and construct similar comparators for their own use. Should this be the case, those agencies are encouraged to contact and consult with the ADOT Research Division. Individual demonstrations and consultation sessions can be arranged at the ADOT facility.

*The "number" designation refers to the number of openings per linear inch, e.g., the No. 40 sieve has 40 openings per linear inch. Metric sizes are now the official method of measurement or designation.

OPTICAL SIEVE COMPARATOR
A DEVELOPMENT PROJECT

DESIGN CRITERIA

Before proceeding with basic design considerations, the ADOT research team spent many hours evaluating existing techniques that were currently in use by other highway agencies. This investigation revealed various methods – mostly including optical comparison, the micrometer microscope, the Moire' effect principle and others as previously described in the Introduction to this report. Two basic conclusions were evident – (1) Optical projection comparators were not being utilized, primarily due to the absence of commercially available systems which could be adapted to the sieve application, and (2) those techniques currently in use by most agencies were exceedingly time consuming and tedious. This being the case, it was found that agencies were very often and routinely using sieves of unknown quality.

This lack of certification is somewhat understandable when considering that the referee test for a single sieve requires that up to 300 sieve openings be measured in order to comply with AASHTO M-92 specifications. To further compound this very tedious task, ADOT experience has found that for a reliable evaluation, each single sieve opening must include four (4) vertex-to-vertex measurements around the perimeter of the opening.

With the determination that the ADOT developed apparatus would consist of an optical projection comparator, a design specification was developed with the following objectives:

1. The optical system would have a light path of variable distance (i.e., variable optical length).
2. Optical mirrors would be employed to "fold" the light path – allowing compact design and portability.
3. The system must be easily calibrated by use of visual optical methods (i.e., by use of a precision calibration viewing reticle and reference standard).
4. The system must be capable of absolute measurement of wire diameters and mesh openings.
5. A GO/NO GO system of sieve evaluation to allow rapid and comprehensive certification of all sieve sizes.
6. Must be capable of evaluating a wide range of sieve sizes – from Number 8 to Number 200.
7. Finally, the comparator system must be designed for operator convenience, with precision controls for sieve position and focus adjustment.

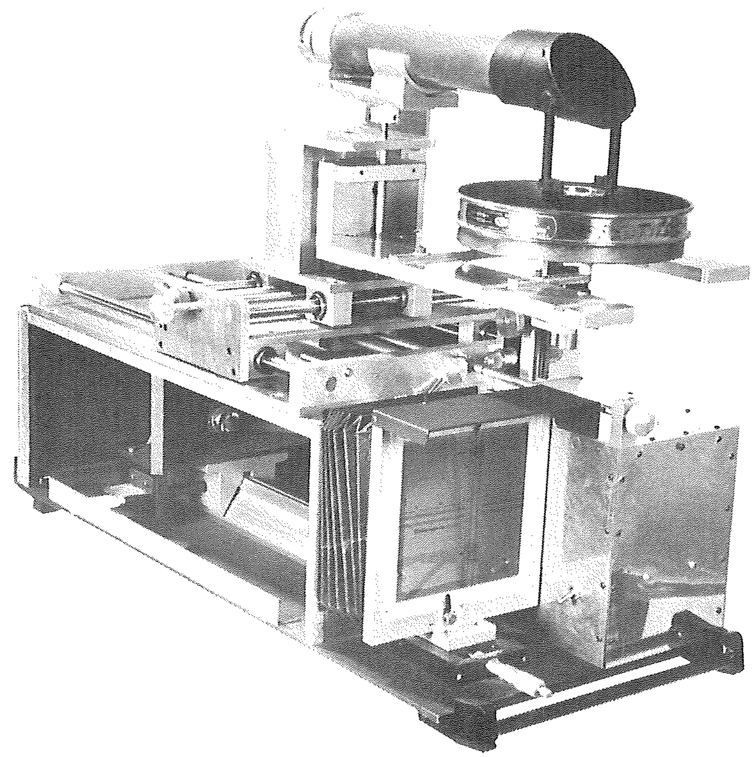


Figure 1A. Opticle Sieve Comparator

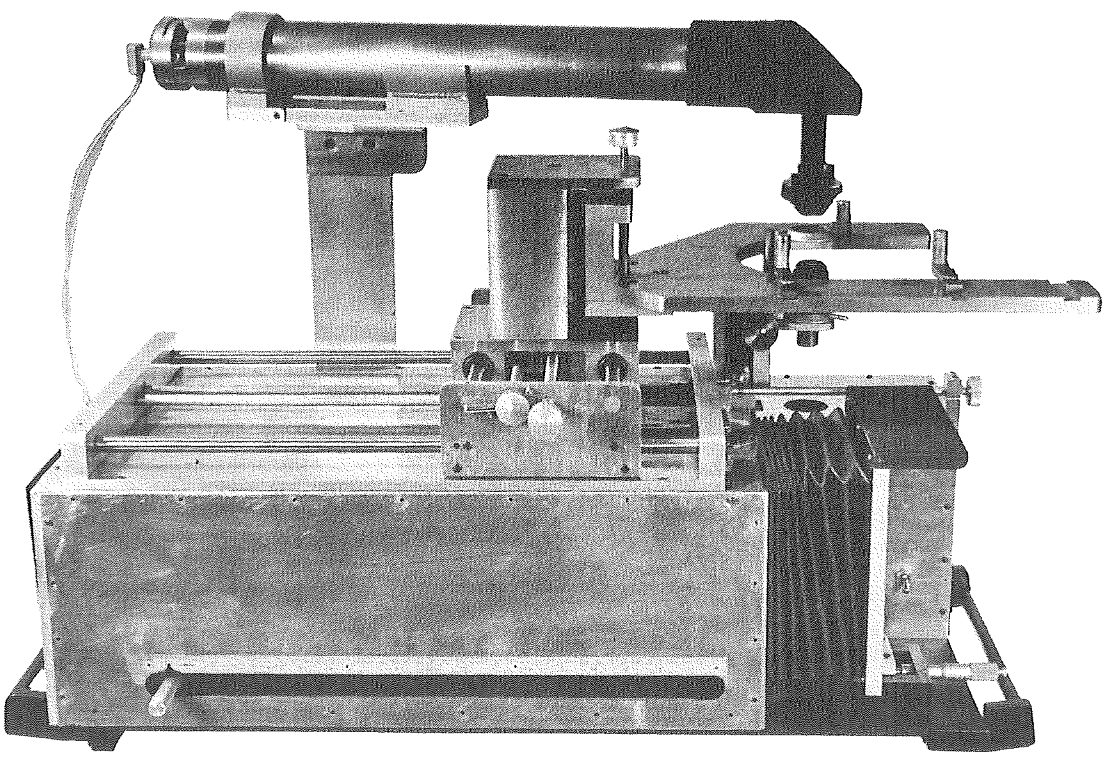


Figure 1B. Opticle Sieve Comparator

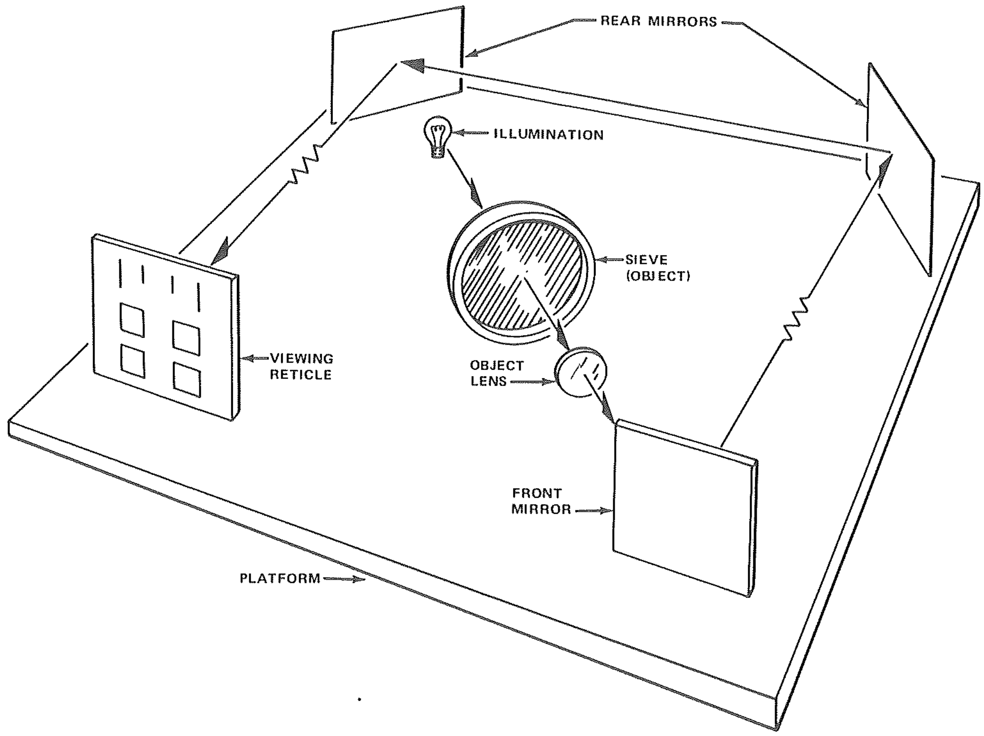


Figure 1C. Schematic of Comparator Operation

GO/NO GO TESTING

As indicated in the above objectives, a primary and very vital design function of the ADOT comparator was its ability to perform GO/NO GO evaluation of sieve sizes ranging from No. 8 to No. 200. In addition, the GO/NO GO feature must maintain precision comparable to existing optical instruments (micrometer microscopes, etc.).

In the evaluation of any sieve, the objective is the observation of mesh openings and the determination of any variance from specified tolerances as set down by AASHTO and ASTM.*

The GO/NO GO concept is a method of comparison whereby a projected image of a sieve opening is projected upon a screen which contains precision squares, each drawn according to mesh opening specifications as set down by AASHTO and ASTM (see Figures 2 and 3). The image of an opening can then be super-imposed upon each of the four squares. The square sizes correspond to tolerances as given in Table 1.

During GO/NO GO testing, the operator uses a method developed by ADOT. This method allows the operator to keep track of the test results by means of a control chart as shown in Figure 4. In this way, the results can be evaluated as testing proceeds. The actual values contained in these charts are based on the Binomial Distribution and the operator's choice of confidence level. Thus, the operator automatically performs a statistical test of hypothesis as he proceeds with the evaluation.

Testing at ADOT has shown that the above method proceeds at a rate of 2/3-minutes per opening, with a 5-minute set-up time for each sieve size.

THE COMPARATOR ASSEMBLY

Housing Assembly

The ADOT comparator, as shown in Figure 5, consists of an optical "V"-rail mounted to a stable 13 x 30 inch platform.* The V-rail assembly is enclosed within a box-like housing with a height of 8 inches. The rail platform and housing are machined of

*American Society for Testing Materials, *Annual Book of ASTM Standards,* Part 41. Ref. E-437-77, Standard Specifications for Industrial Wire Cloth and Screens; E-161-70, Standard Specifications for Electroformed Sieves (The primary standard is ASTM E-11).

*The reader who wishes to construct a duplicate comparator must deal with a mixture of both English and Metric units. Optical parts are referred in Metric units, while construction dimensions, etc. are in English units to be consistent with most machine shop standards.

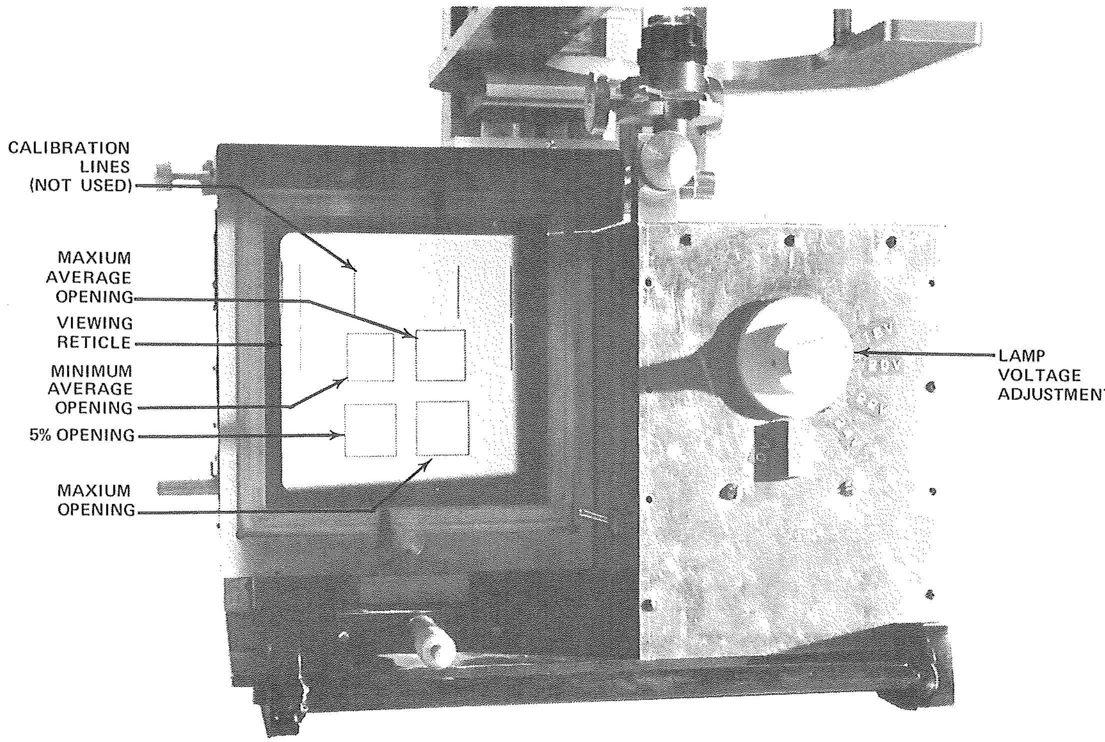


Figure 2. Viewing Reticle Pattern For Go/No Go Testing

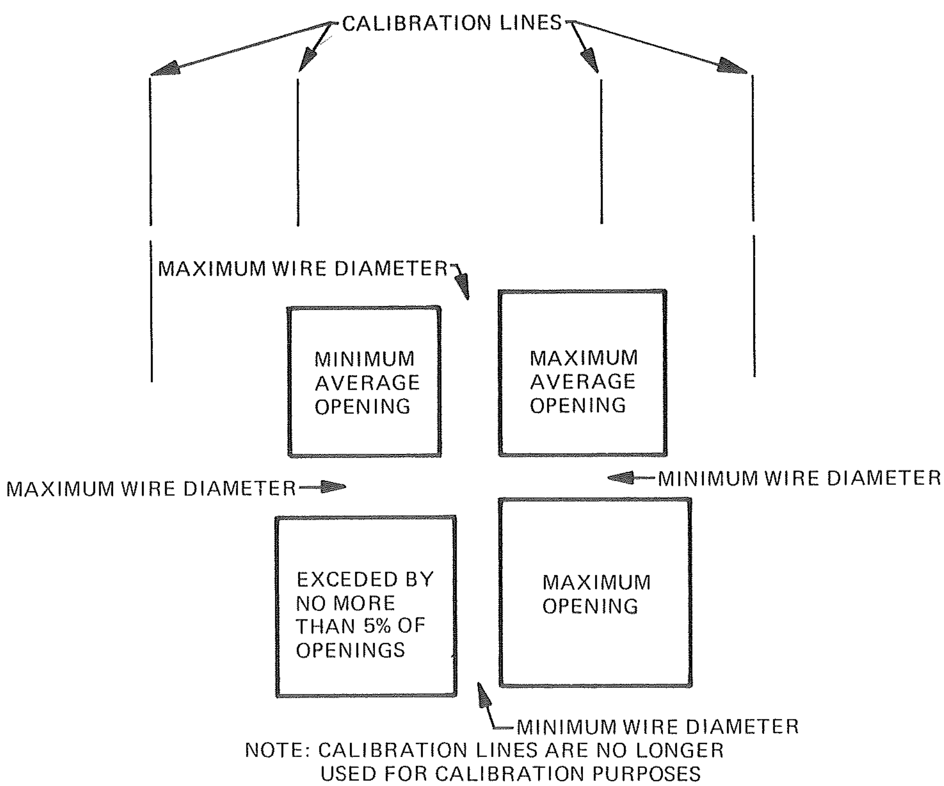


Figure 3. Sieve Evaluation Reticles

5%	59	|	7	16	28	40	53	REJECT								
LARGE		+ 9	+ 12	| 15	| 17	20	23	25	28	30	33	35	37	40	42	44
SMALL		9	12	15	17	20 / 5	23 / 6	25 / 8	28 / 9	30 / 11	33 / 13	35 / 14	37 / 16	40 / 18	42 / 19	44 / 21
TOTAL		1 ✓	2 ✓	3 ✓	4 ✓	5 ✓	6 ✓	7 ✓	8 ✓	9 ✓	10 ✓	11 ✓	12 ✓	13 ✓	14 ✓	15 ✓

Acceptance α = 0.025 for large and small sizes.
Rejection α = 0.050 for each category.

5%																
LARGE		47 / 23	49 / 24	51 / 26	54 / 28	56 / 30	58 / 31	61 / 33	35	37	39	40	42	44	45	47
SMALL		47 / 23	24	26	28	30	31	33	35	37	39	40	42	44	45	47
TOTAL		16 ✓	17 ✓	18 ✓	19 ✓	20 ✓	21 ✓	22 ✓	23	24	25	26	27	28	29	30

5%																
LARGE		49	51	53	54	56	58	60	REJECT							
SMALL		49	51	53	54	56	58	60	REJECT							
TOTAL		31	32	33	34	35	36	37	38	39	40	41	42	43	44	45

Figure 4. Sieve Evaluation Chart

heavy gauge aluminum to form a rigid structure for the mounting of all remaining optical sub-assemblies.

Object Translator Carriage Assembly

The upper surface of the housing provides mounting for the sieve (object) translator carriage and the lens mount assembly (Figure 6). The sieve carriage assembly is attached to the housing by way of two (2) precision ball-slides and a full length lead-screw. The lead-screw allows the operator to position the sieve carriage in the longitudinal ("Y") direction. This longitudinal adjustment is a "fine" adjustment with a full range of 10.5 inches. A coarse adjust lever allows the lead-screw to be disengaged for "hand" positioning the carriage over its full range (coarse adjustment).

For transverse ("X") adjustment (side-to-side), a sieve holder assembly (object table) is mounted to the carriage by way of two (2) transverse ball slides. Transverse adjustment is provided by a "fine" adjust lead-screw, having a total travel of 7.5 inches. A coarse adjust lever disengages the lead-screw, allowing the sieve holder to be "hand" positioned over the full transverse range (Figures 5 and 6).

Vertical ("Z") positioning of the sieve holder is by "fine" adjust lead-screw without disengage capability. The vertical adjustment range is 1.5 inches.

The three sieve positioning adjustments as described above, provide the following functions:

1. The longitudinal (Y) and transverse (X) adjustments are used by the operator during sieve evaluation – allowing precise positioning of individual mesh openings or wire images relative to the measurement of GO/NO GO viewing reticles.
2. The vertical (Z) adjustment is used to focus the light source (filament) on the object for maximum intensity during protection. It should be noted that the Z-adjustment is the only focusing adjustment, or adjustment at object position allowed after system calibration. This being the case, this adjustment is used only for re-focusing or maximizing light intensity during sieve evaluation.

The horseshoe shaped sieve holder (Figures 5A and 6A) serves as a mounting surface for the sieve during sieve evaluation, and as a support for the plexiglass calibration plate during system calibration. Three adjustable sieve support posts support the sieve or calibration plate during operation.

Objective Lens Mount Assembly

Also mounted to the comparator housing support surface is the lens mount assembly (Figure 7). Note that the assembly has two (2) lens mounts (upper and lower) for mounting the various objective lens, with each lens providing a different magnification range (See Table 2). The upper mount accepts the

TABLE 1
SPECIFICATION FOR MATERIALS (AASHTO M92)

Nominal Dimensions, Permissible Variations for Wire Cloth of Standard Test Sieves (U.S.A. Standard Series)					
Sieve Designation		Permissible Variation of Average Opening from the Standard Sieve Designation mm	Maximum Opening Size for not more than 5 per cent of openings mm	Maximum Individual Opening mm	Nominal Wire Diameter mm
Standard mm	Alternate				
(1)	(2)	(4)	(5)	(6)	(7)
4.75	No. 4	0.15	5.02	5.14	1.54
2.36	No. 8	0.080	2.515	2.600	1.00
2.00	No. 10	0.070	2.135	2.215	0.900
1.18	No. 16	0.045	1.270	1.330	0.650
0.850	No. 20	0.035	0.925	0.970	0.510
0.600	No. 30	0.025	0.660	0.695	0.390
0.425	No. 40	0.019	0.471	0.502	0.290
0.300	No. 50	0.014	0.337	0.363	0.215
0.150	No. 100	0.008	0.174	0.192	0.110
0.075	No. 200	0.005	0.091	0.103	0.053
0.045	No. 325	0.003	0.057	0.066	0.030
0.038	No. 400	0.003	0.048	0.057	0.025

Column (3) omitted

TABLE 2
OBJECTIVE LENSES

Objective Type	Magnification Range	Working Distance (mm)	Linear Field Of View (mm)	
X3	8-24	60	10-20	Lower Mount
X5	10-30	45	8-11	Lower Mount
X10	25-75	7	5-6	Upper Mount
X20	50-150	2	4	Upper Mount
X40	100-300	1	2	Upper Mount

Objective lenses and their performance parameters. Note change of field of view with magnification for lower power lenses.

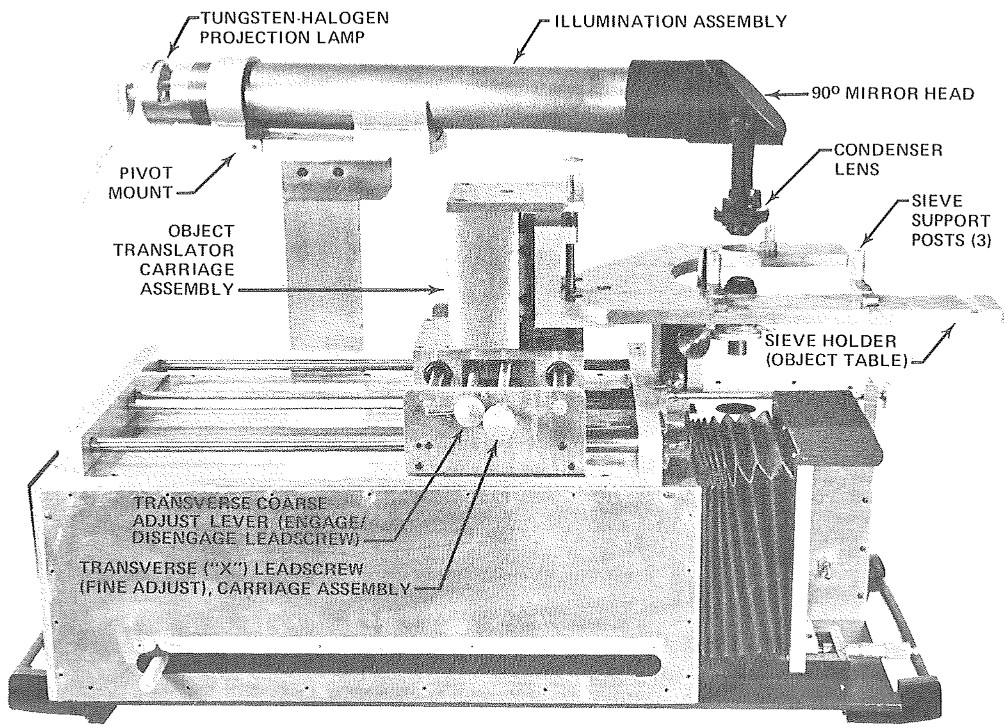


Figure 5A. ADOT Comparator — Detail View

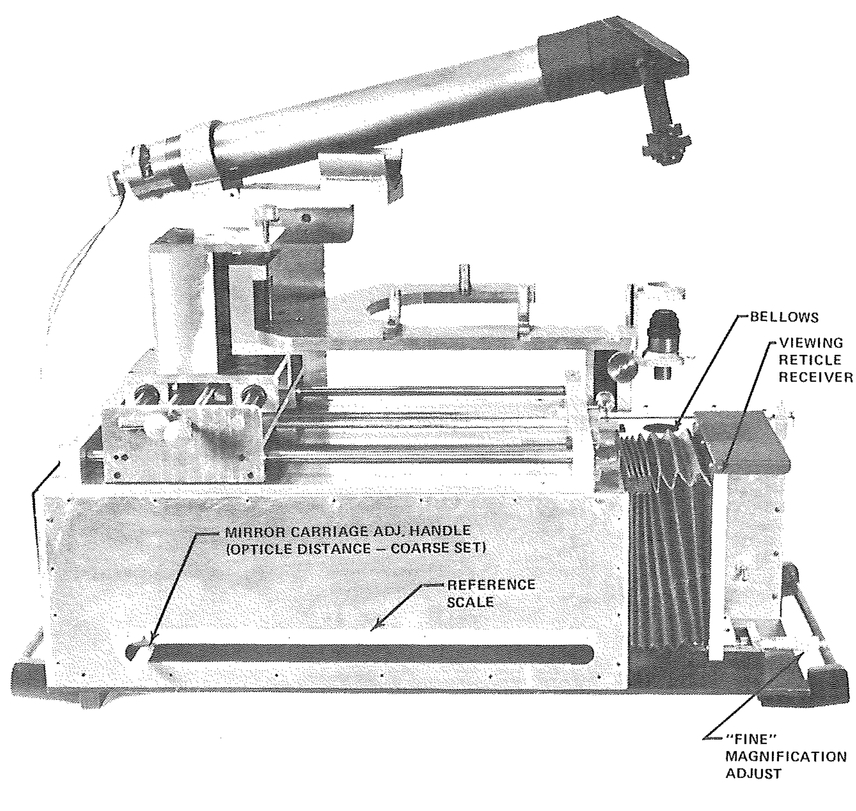


Figure 5B. ADOT Comparator — Detail View

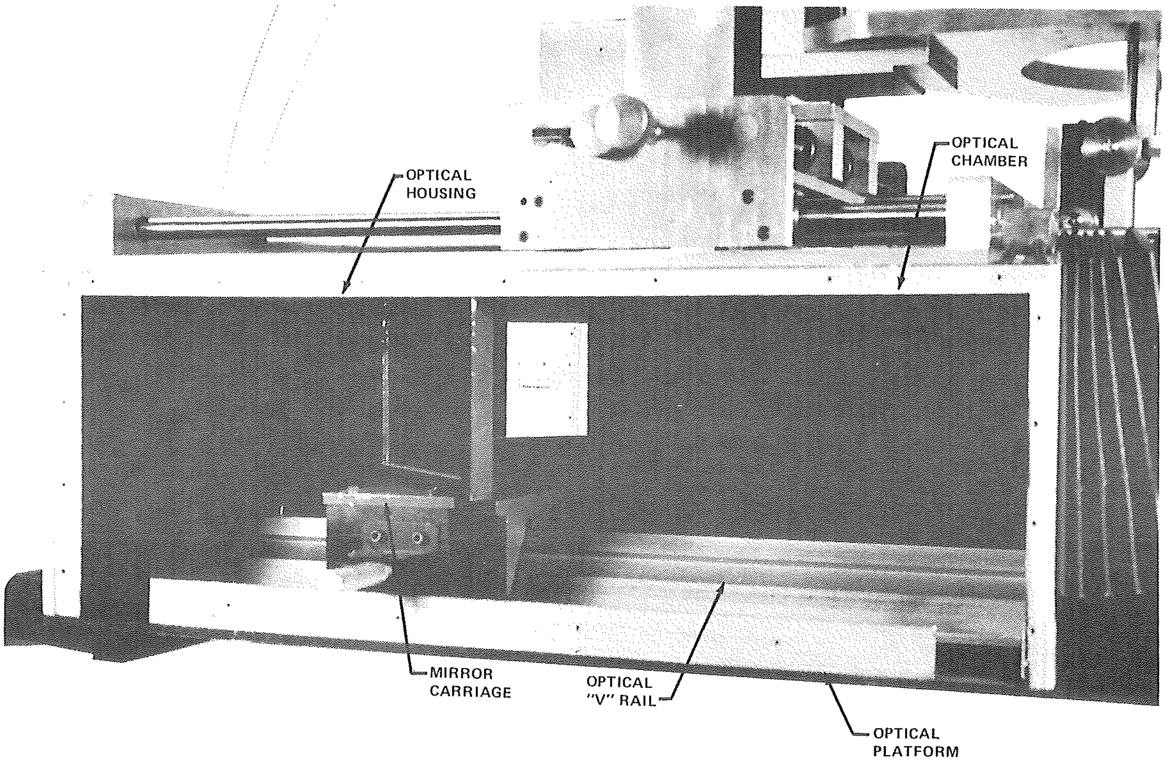


Figure 5C. ADOT Comparator – Detail View

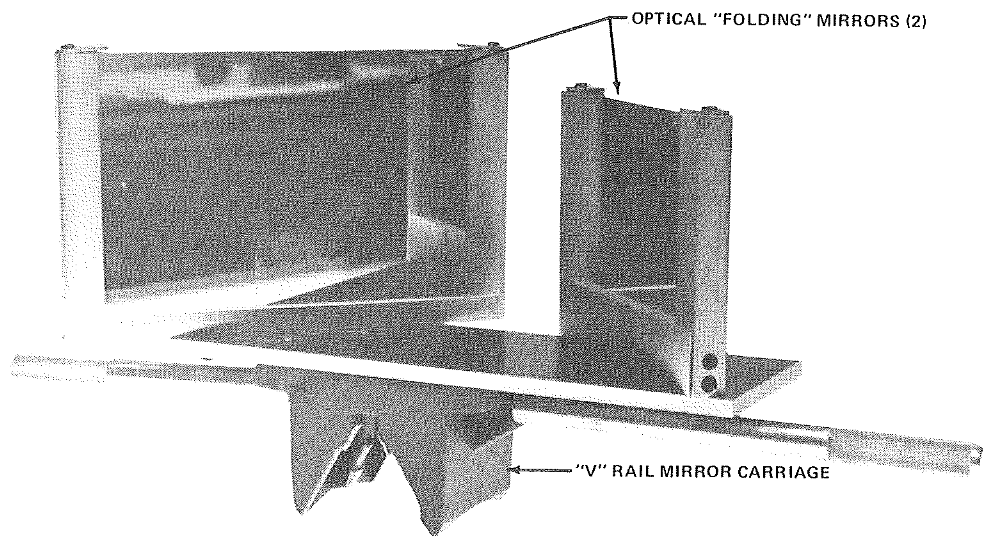


Figure 5D. ADOT Comparator – Detail View

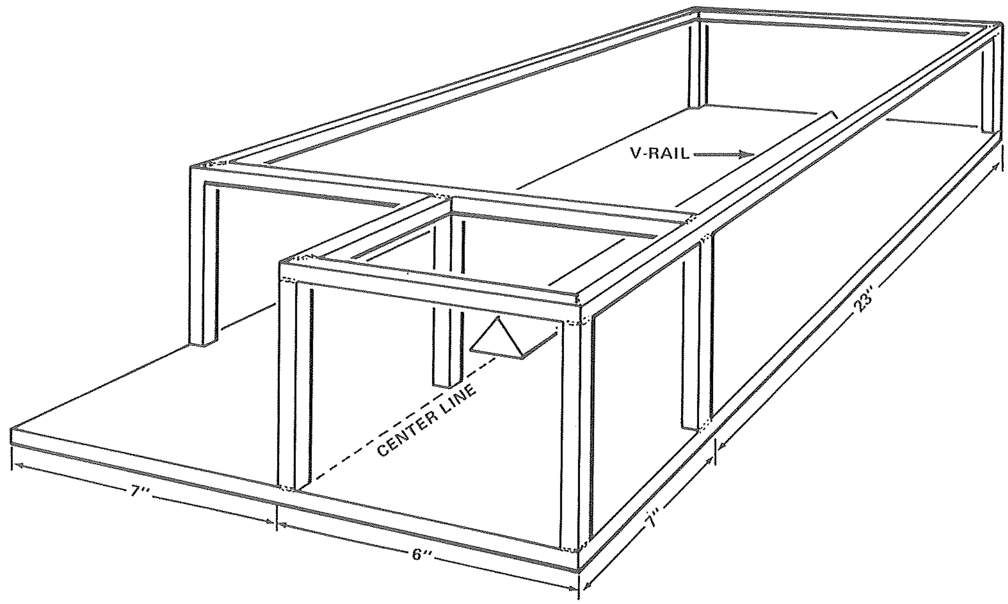


Figure 5E. Comparator Platform, V-Rail Housing

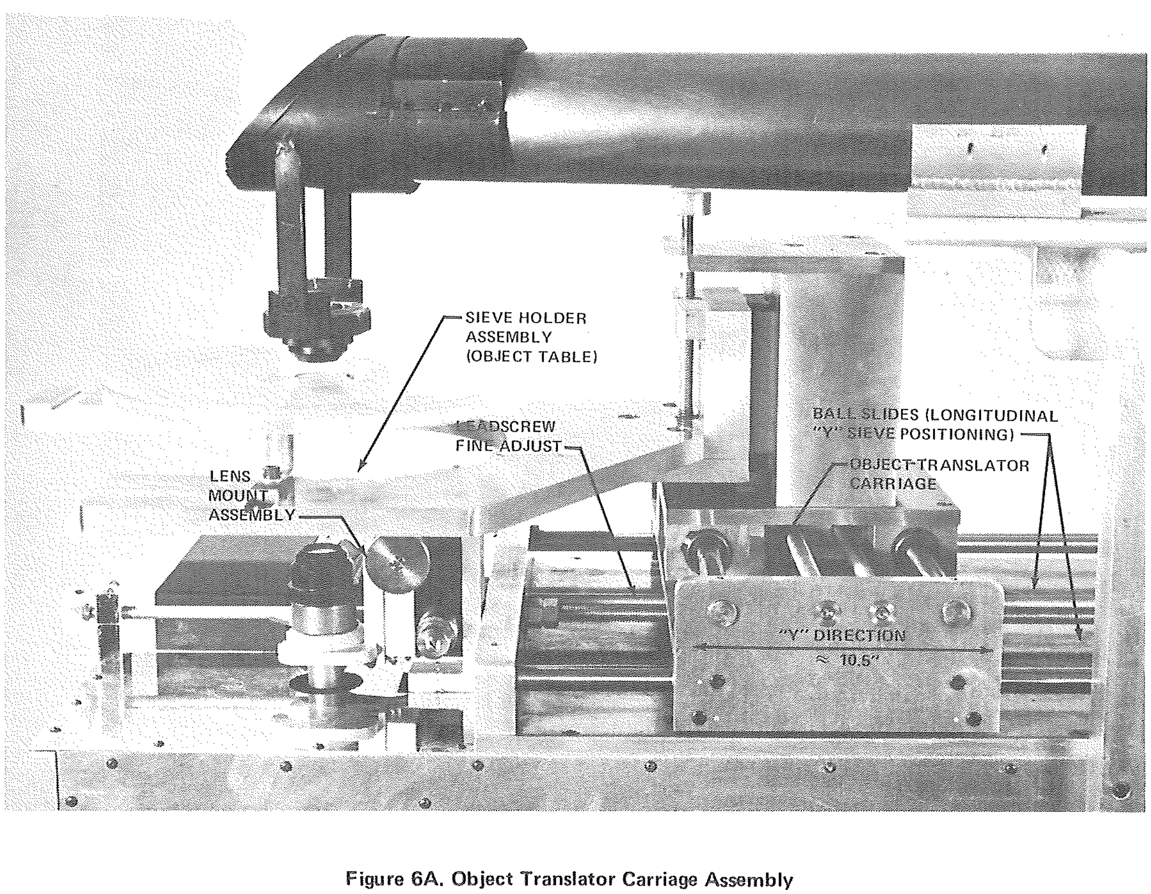


Figure 6A. Object Translator Carriage Assembly

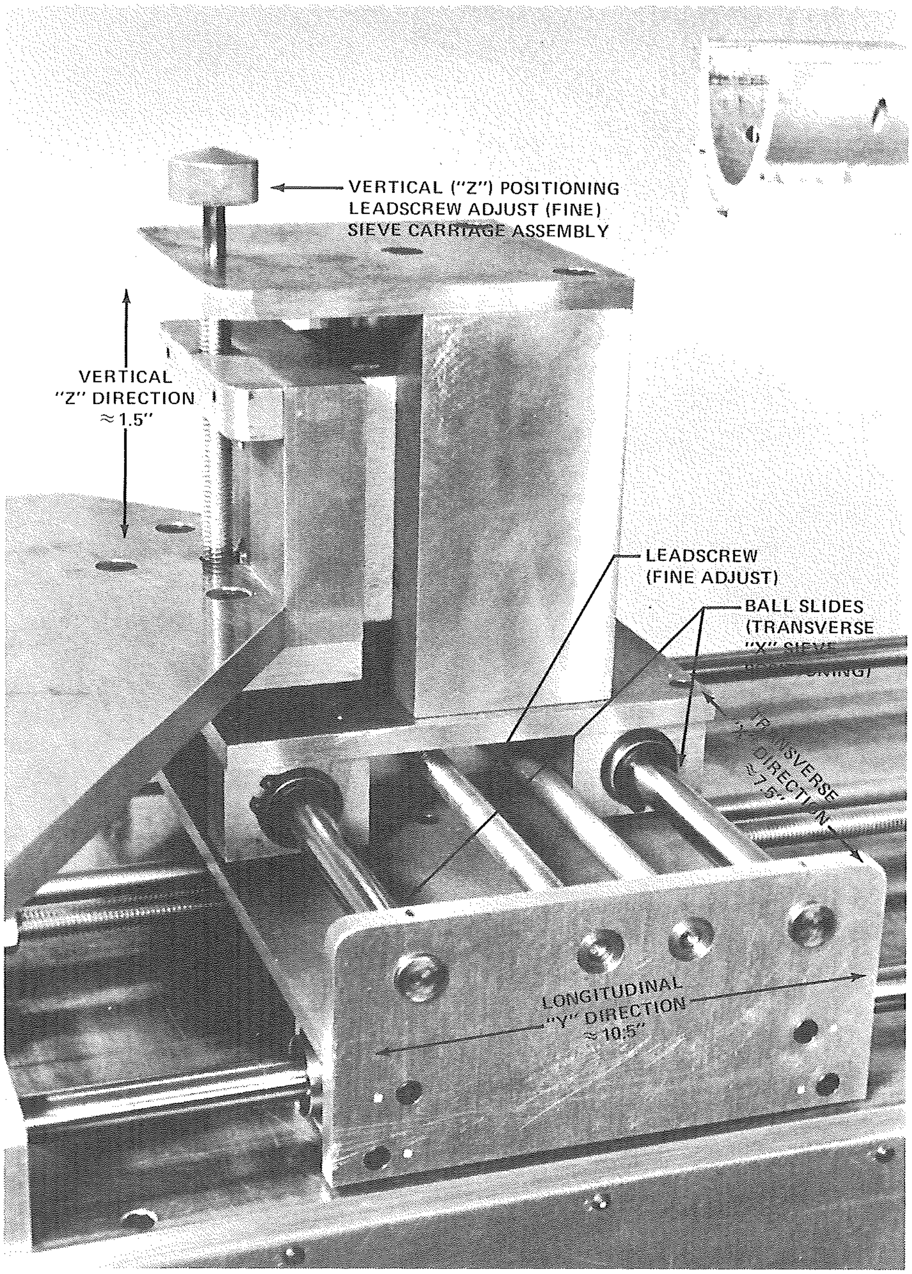


Figure 6B. Object Translator Carriage Assembly

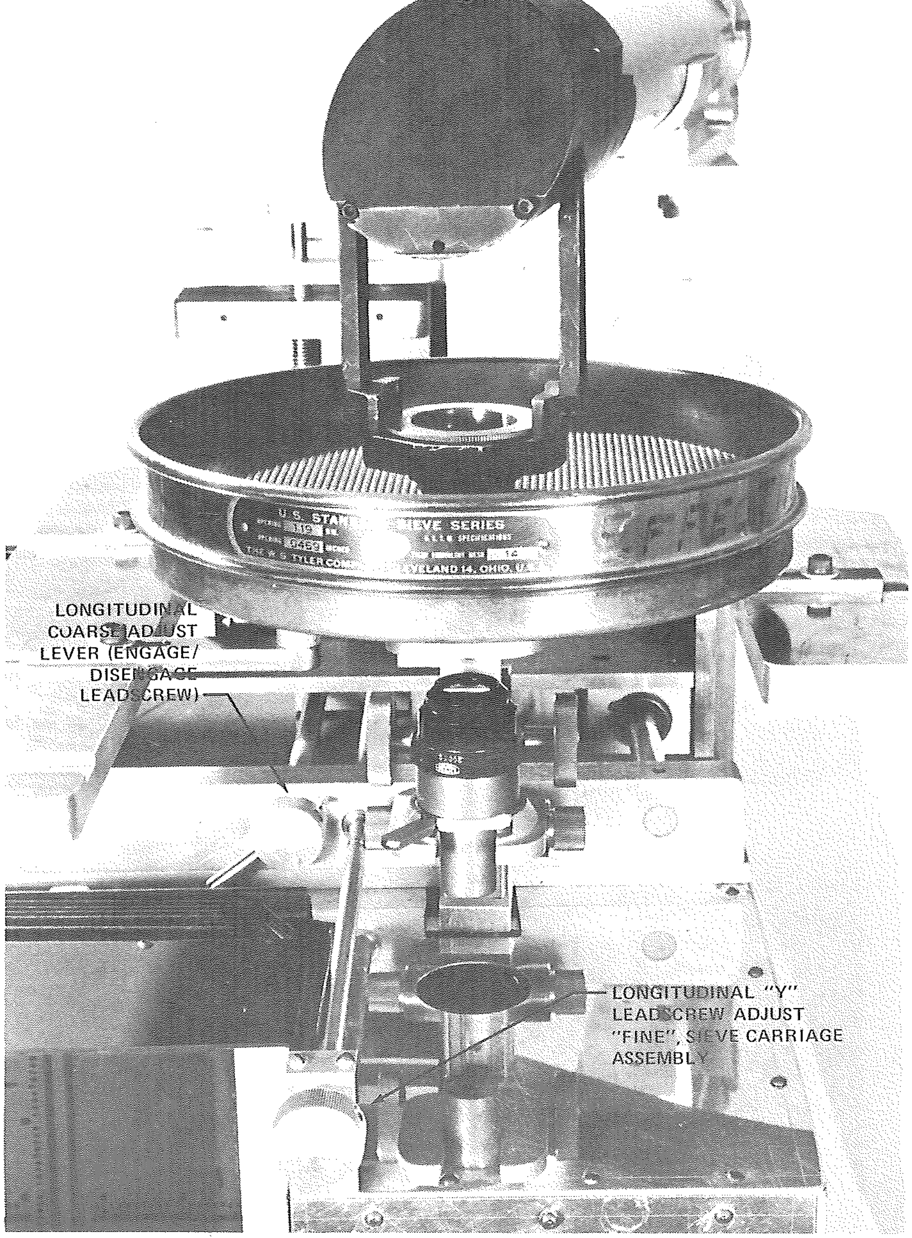


Figure 6C. Object Translator Carriage Assembly

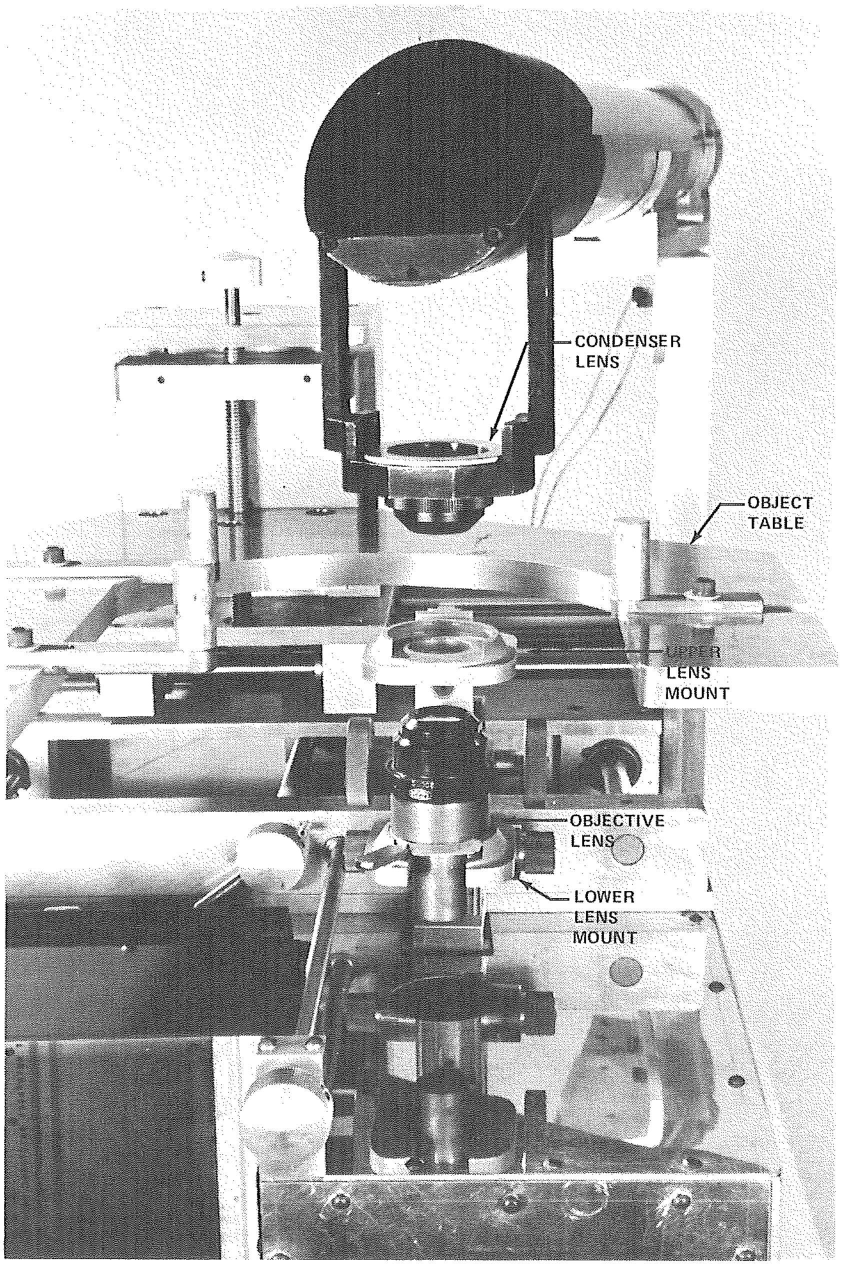


Figure 7A. Objective Lens Mount Assembly

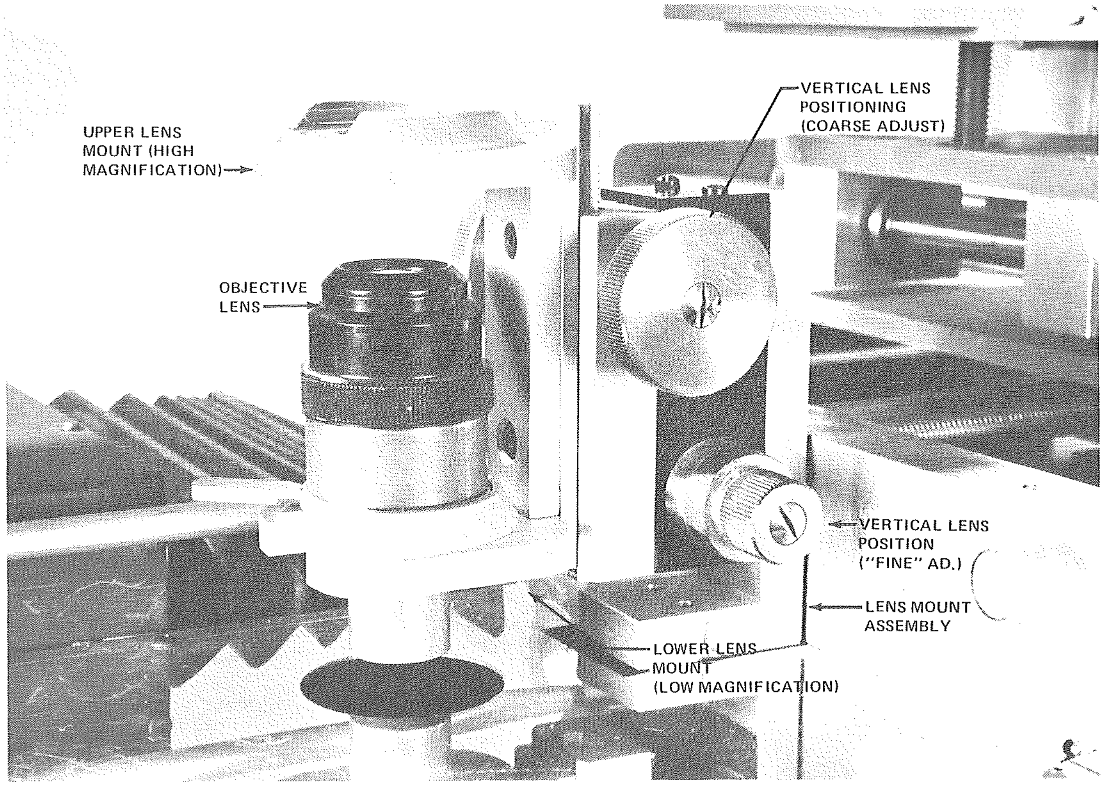


Figure 7B. Objective Lens Mount Assembly

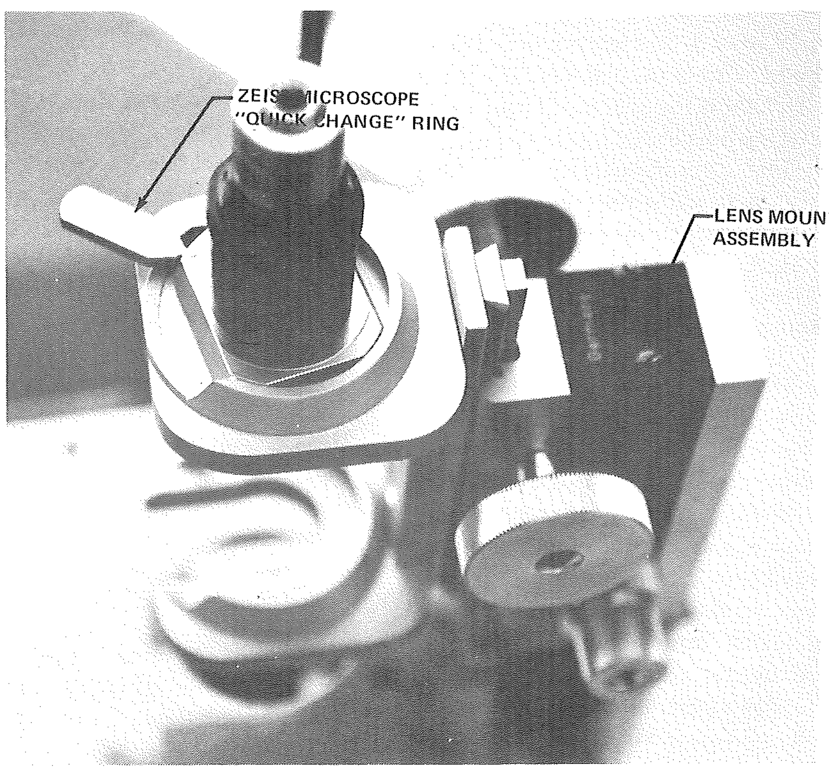


Figure 7C. Objective Lens Mount Assembly high power lens, while the lower mount is used for the lower power lens. Each lens is fitted with a standard Zeiss microscope quick-change ring, which allows convenient insertion of the lens into the lens holder. The lens mount assembly contains a coarse and fine micrometer adjustment for vertically positioning the objective lens relative to the object – thus allowing precise focusing relative to the focal length of each individual lens. It should be noted that lens mount focus adjustments are used during system calibration only. Minor focus adjustments during sieve evaluation are made by vertically adjusting the sieve holder with the "Z" adjustment.

Illumination Assembly

In order to obtain a bright image over the full magnification range of all objective lenses, a special collimated illumination system was required. The light system in use is basically a Kohler type illuminator* designed to operate with three (3) different externally mounted condensing lenses. In this way, a correct numerical aperture is maintained for a high illumination efficiency. The illumination assembly is housed in a cylinder, 50mm inside diameter and 50cm long (Figure 5A). This configuration was chosen to conform with the relay lens requirements. A General Electric Quartzline (Tungsten-Halogen projection lamp) 80 watt, 19 volt lamp is positioned at one end of the cylinder. Three (3) relay lenses are internally mounted, with a 90 degree optical mirror mounted at the other end of the cylinder. The three (3) condenser lenses allow the collimated light to be sharply focused on the object for maximum illumination. Note that the illumination assembly (cylinder) is mounted to a pivoting bracket – thus allowing the assembly to be raised out of the way for changing sieves. A more detailed explanation of the illumination assembly will be presented in the Technical Description Section of this report.

Optical Chamber Assembly

The optical chamber (Figures 5C and 5D) contains a transformer for the illumination system, a fixed 90 degree optical mirror directly beneath the objective lens mount, a 50 cm long optical V-rail and a mirror carriage onto which a pair of folding mirrors (180 degrees) are fixed. It should be noted that the V-rail and mirror carriage are standard commercially available items. The mirror carriage can be manually moved along the optical path, thus providing a "coarse" magnification adjustment.

*Leo Levi, "Applied Optics," Volume 1, John Wiley & Sons, New York, 1968, page 475.

At the front of the optical chamber is the viewing reticle receiver (Figures 5B and 8). The receiver is designed such that the various 6-inch square measurement and GO/NO GO viewing reticles can be clamped in place against a diffusion glass plate which is fixed within the receiver. The receiver is mounted to a commercially available micro-translation unit which provides "fine" magnification adjustment by moving the reticle image plane along the optical path (shortening or lengthening the optical distance). A standard photographic bellows provides a light-tight interface between the reticle receiver and the optical chamber.

Objective Lenses

The ADOT comparator uses a set of five (5) microscope objective lenses, ranging from X3 to X40 in magnification (Figure 9). An aperture stop at the back focal plane of each lens makes the system telecentric. That is, the system magnification remains constant, independent of object focus. Table 2 lists the objective lenses and their range of magnification. Also listed is the "working distance" for each lens, that is, the average distance from the face of the lens to the object surface. This distance is an important factor when access to the object surface is restricted. Note that the X3 and X5 lenses are mounted in the lower lens mount socket, while the X10, X20 and X40 lenses use the upper socket.

Calibration Plate and Reticle

System calibration is accomplished by use of a calibration object and a corresponding calibration viewing reticle (Figure 10). The calibration object is a Bausch & Lomb projection standard as used for pocket comparators. Two object standards are used with the ADOT comparator. One has 0.1 inch divisions, subdivided into 0.005 inch – the other having 1.0mm divisions, subdivided into 0.1mm.

The calibration viewing reticle (view plate) features two (2) scales (one horizontal and one vertical). See Figure 10. The scales are based on one (1) inch divisions, subdivided into 0.1, 0.025, and 0.005 inches. It should be noted that the calibration viewing reticle is *also* used for all absolute measurements during sieve evaluation.

The calibration plate is dimensioned such that the object standards are placed at the object reference plane corresponding to normal sieve measurements.

Calibration procedures will be covered in the System Calibration Section.

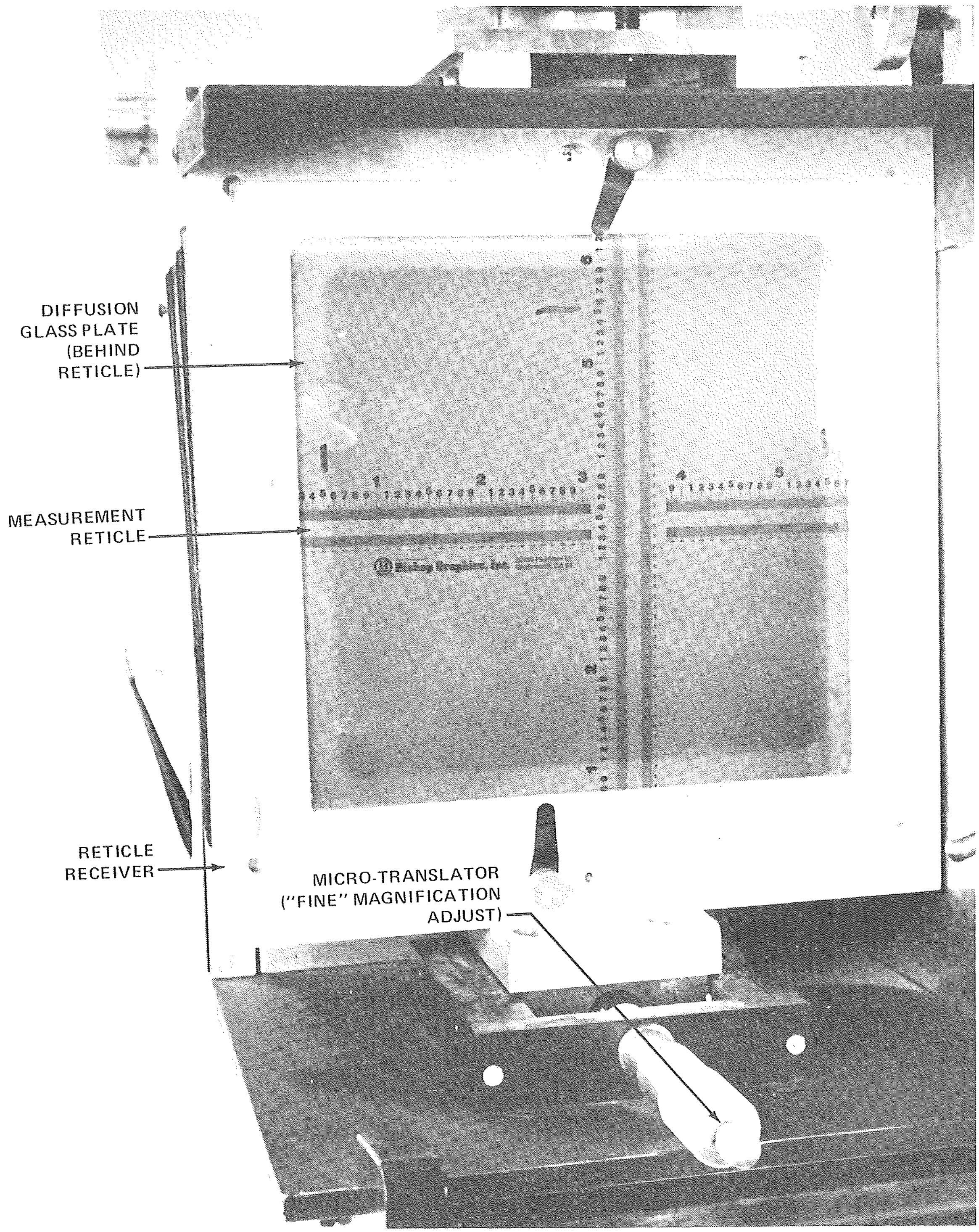


Figure 8. Viewing Reticle Receiver

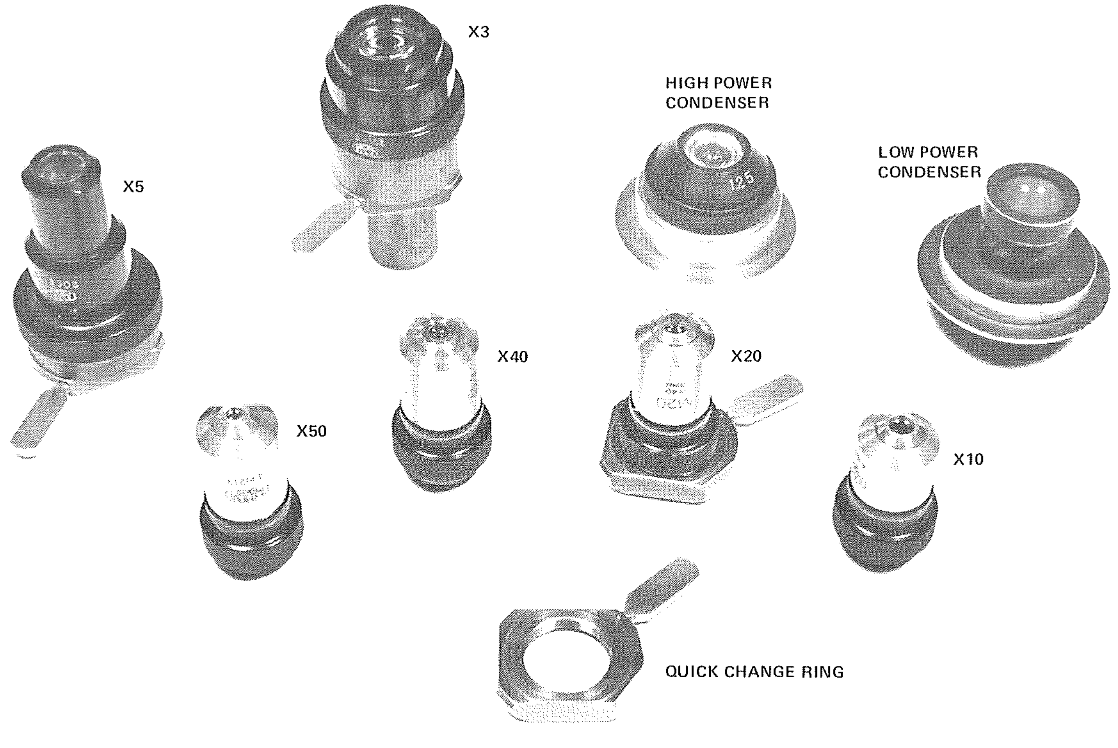


Figure 9. Objective Lens

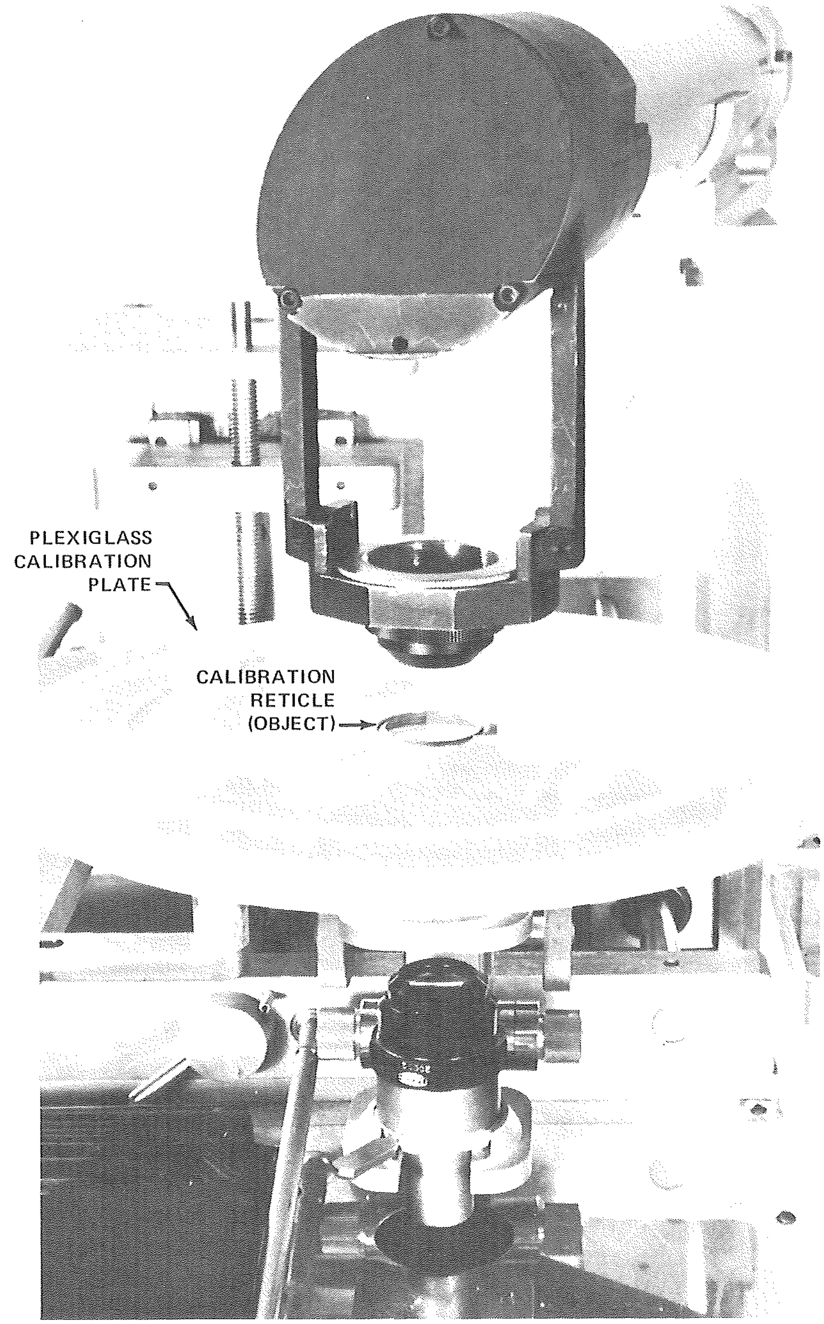


Figure 10A. Calibration Plate, and Object Reticle

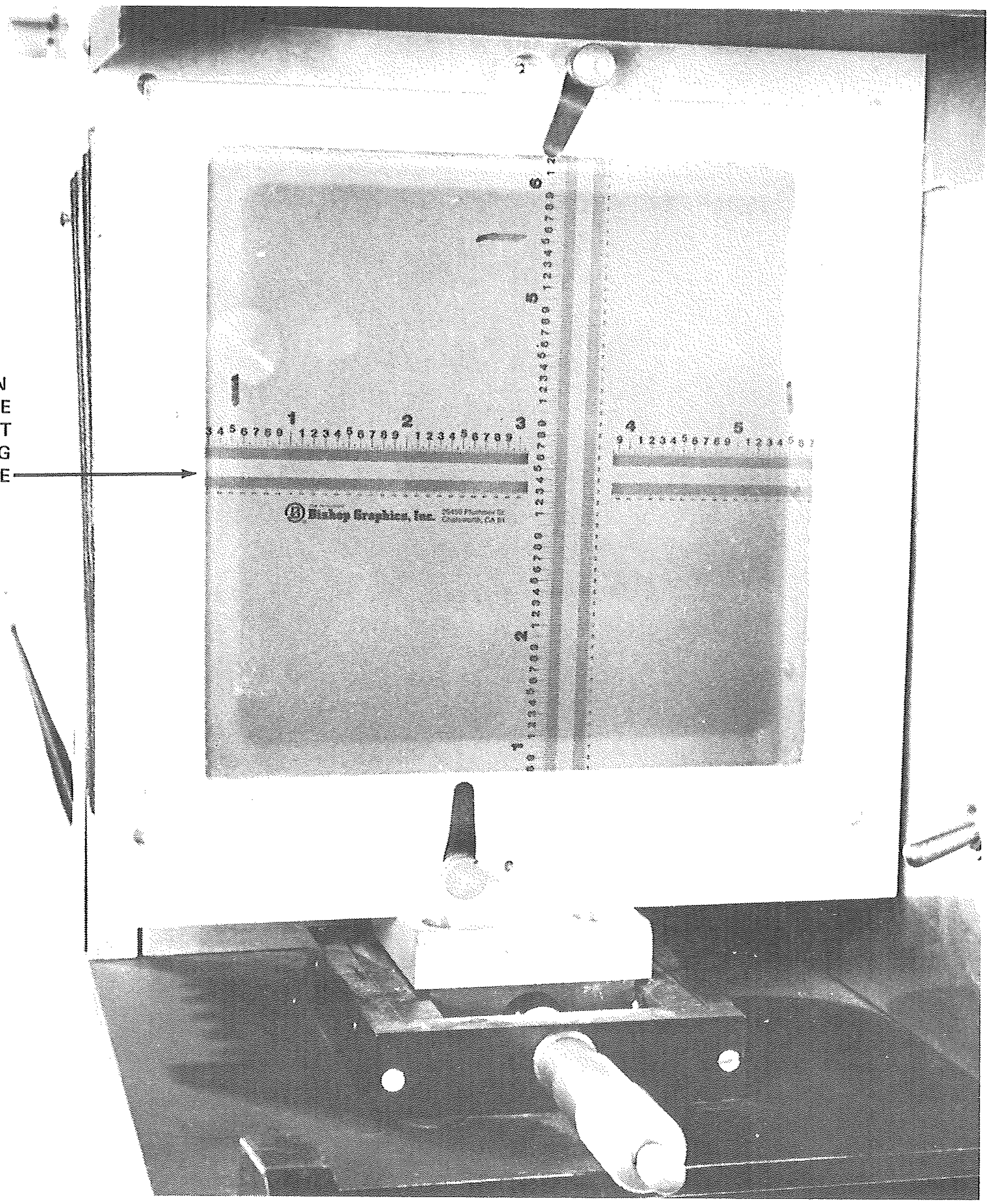


Figure 10B. Measurement Viewing Reticle

DESIGN CONSIDERATIONS

GENERAL

The object of this section is to provide the reader with a background into the design considerations involved during the comparator development program, and to provide sufficient detail to assist the reader should he consider constructing a similar comparator.

ILLUMINATION SYSTEM

Figure 11 shows a schematic of the illumination system. The object of this system is as follows:

1. It "slows down" the large numerical aperture of the quartz-halogen lamp such that a better interface is achieved with the low-power condensers used with the low-power objective lens. If this were not the case, much of the available light would be wasted.
2. To achieve (1) above, the illumination system is designed to image the halogen lamp exit pupil (i.e., its rim) onto the entrance pupil of the condensing lens.
3. Further, the illumination system is designed to image the filament of the halogen lamp onto the plane of the sieve (object plane), thus achieving maximum illumination of the sieve. In designing the illumination system, one must first consider the total light-relay distance required. That is, where will the lamp be mounted relative to the object that requires illumination. It is then necessary to know where the lamp images its filament. Knowing this distance, it is possible to calculate, using 1st-order theory, the focal lengths required of the relay lenses in order to image the filament on the sieve plane and to image the lamp rim on the entrance pupil of the objective lens. If this is not accomplished, illumination of the sieve plane would be quite poor in quality.

The illumination system consists of a light source, relay lens assembly and condenser head. See Figures 5A and 11. A quartz-halogen lamp, as used in 8mm movie projectors, serves as the light source. The lamp is located at the rear of the apparatus, with the light being relayed to the work station by a four-element relay lens assembly. This assembly was designed to interface between the fast beam of light (large cone angle) emerging from the light source (i.e., a high numerical aperture), and the two types of condensing lenses required. For high power objective lenses, a standard Abbe type condenser lens is used with interchangeable two-element condenser lenses for low power objectives. Interchanging of the condenser lenses is required in order to make the numerical aperture of the illuminating beam compatible with the objective lens – thus providing maximum illumination effeciency. The illumination assembly is mounted in a brass tube. Two 100mm focal length lenses (L_1 and L_2), used in conjugate as a single element (effective F=50mm), form the first element which is used to slow down the high numerical aperture beam from the halogen lamp. The next lens (L_3) is a 150mm focal length lens. The 50mm lens (L_1 and L_2) together with 150mm lens and the condenser lens, serves to image the halogen lamp filament onto the object plane (i.e., the plane of the sieve mesh). This insures an optimum illumination condition.

The 75mm lens (L_4) is used to image the rim of the lamp beam onto the entrance pupil of the condensing lens, while the 150mm lens (L_3) serves as a relay lens for this purpose.

Two condenser lenses are used with the ADOT Comparator – one for high power objective lenses and one for low power objectives. The high power condenser is a standard Abbe condenser with designated Numerical Aperture of 1.25. Although the NA of the lens used in air is actually about 0.9, it can be ordered by means of the designated NA.

The low power lens was specially constructed as shown in Figure 12.

The transformer originally used to power the halogen lamp was a 115 VAC unit with an 18.5 VAC secondary, capable of 80 watts continuous duty. This has been replaced by a variable output transformer (VARIAK) in conjunction with a 115/24 VAC output transformer. This allows us to increase the lamp voltage such that a 50 percent increase in illumination can be achieved for high magnification applications. With operation at this increased level, the lamp should still maintain a service life in excess of 50 percent of its rated 200 hour life, particularly since the high voltages need only be used with the higher power lenses.

This increased illumination is necessary when using the 40X or high power objective lens, since the restricted aperture stop used with these lenses (to obtain the desired working depth of field) results in considerable loss of light transfer at the higher magnifications.

Table 3 provides a list of parts used during construction of the illumination system. It should be noted that focal lengths are nominal and actual focal lengths of lenses or lens systems need to be determined using an optical bench. An alternate approach would be to use the distances given in Figure 11 and then re-adjust the lens positions to accommodate the slightly differing focal lengths. Either procedure, however, requires an optical bench.

Our choice for a lens holder consisted of a brass cylinder, approximately 500mm long by 50mm internal diameter. Cylinders with outer diameters of 50mm and appropriate lengths were inserted into the main cylinder to maintain the correct distance between lenses.

Mounts for the lamp, mirror and condensing lenses, as well as the low power condensing lens, were custom made.

OBJECTIVE LENSES

Table 4 lists the objective lenses and the range of magnification obtained with each. Also tabulated is the average distance from the face of the lens to the object surface, called the "working distance." This distance is an important factor when access to the object surface is restricted.

The lowest power lens was chosen for its wide field of view (approximately 20mm at X10.16). A stop had to be installed in order to make the lens telecentric.

All remaining magnifiers were microscope objective lenses, with the higher powered lenses (X10, X20, X40) requiring constrictions in the stops to obtain the required depth of field. Stop sizes are not necessarily optimum, since empirical methods were used in determining the stop sizes. Exceptions were the X5 and X3 lenses. The X3 lens was modified by the University of Arizona Optical Science Center, and the X5 lens stop was used as is.

There is one remaining point. When purchasing lenses, be sure they are achromatic. Planachromats may be considered superior, but are not necessary. Our wide angle lenses and the special X40 lens are Planachromats, with all remaining lenses being

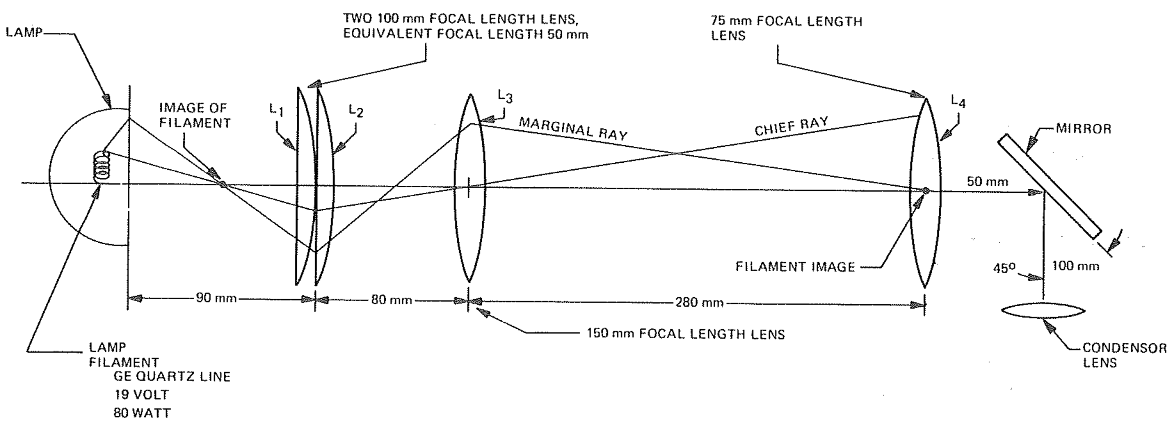


Figure 11. Illumination Relay Lens System Schematic
(Not To Scale)

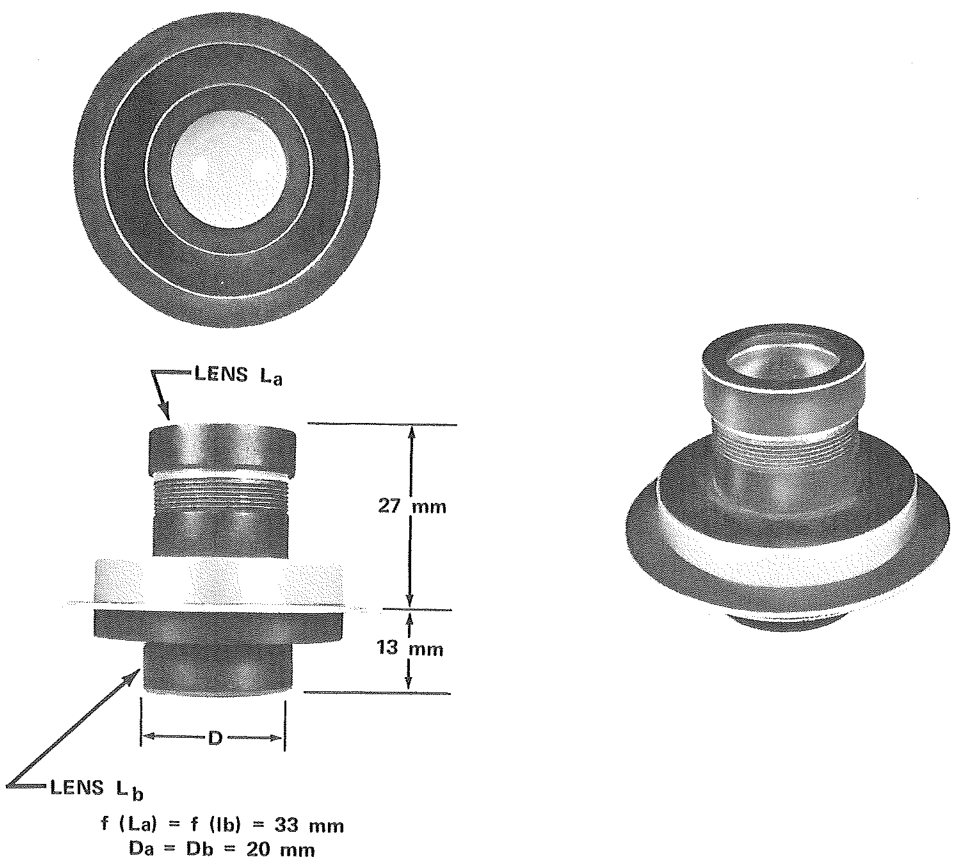


Figure 12. Low Power Condenser Lens

TABLE 3
ILLUMINATION SYSTEM
LIST OF PARTS AND SPECIFICATIONS

Electronics

1 each 115/24 VAC, 5A, 60 Hz Filament Transformer (F-83A)
1 each Variable Transformer (STACD Type 221)
1 each 19 volt, 80 watt Quartzline Halogen Lamp (GE)

Optical (Illumination System)

4 each 50mm Diameter Lenses
- 2 Plano Corvex, 100mm Focal Length
- 1 Biconvex, 150mm Focal Length
- 1 Biconvex, 75mm Focal Length

1 each Mirror, 50mm X 70mm (Rectangular or Elliptical)

Optical (Condenser Lenses)

1 each Abbe Condenser, NA 1.25
2 each Plano Convex Lenses, 20mm Diameter, 33mm Focal Length

Tolerances (Illumination System)

Spacers: 50 μm (Separation)
25 μm (Parallelism)

Note: Mirrors have some degree of play. Adjusting screws set in oval holes are used for alignment. Also, tolerances are given only where critical. Most machine shops can routinely work within the 25 μm (0.0011 inch) tolerance quoted here.

Stop Diameters

Lens	Diameter
X40	0.15
X20	0.09
X10	0.125
X5	0.375
X3	0.25

TABLE 4
OBJECTIVE LENSES

Objective Type	Magnification Range	Working Distance (mm)	Linear Field Of View (mm)
X3	8-24	60	10-20
X5	10-30	45	8-11
X10	25-75	7	5-6
X20	50-150	2	4
X40	100-300	1	2

Objective lenses and their performance parameters. Note change of field of view with magnification for lower power lenses.

TABLE 5
LENS SELECTION FOR
GO/NO GO OPERATION

Lens	Max Depth of Field Required (3 Wire Diameters)	Sieve Size	Focal Length
X3	3.15mm	No. 8	63mm
X5	2.28mm	No. 16	47mm
X10	1.45mm	No. 30	19mm
X20	0.71mm	No. 50	10mm
X40	0.18mm	No. 200	5mm

achromatic. The reason achromatic lenses are satisfactory is due to the fact that the actual field of view is restricted to a small solid angle at the center of the lens.

The special X40 lens (Planachromat) was necessary to achieve a long working distance. With a short working distance, you run the risk of scratching the lens.

All constricted stops are made as plugs to be pressed into the original lens stops (see Figure 13).

Note that original stops are difficult to remove from the lens, thus, this plug arrangement is worthwhile.

VIEWING RETICLE DESIGN

The overall reticle plate size was chosen to be six (6) inches square. This size was considered for not only sieve evaluation readability, but was well suited to the maximum and minimum optical path lengths of the comparator.

In general, design of the GO/NO GO viewing reticles is given in Figure 14. It should be noted that although the present reticle size is adequate with respect to measurement precision, the effect of visual error due to human fatigue could be reduced by a larger reticle design. ADOT has found that for a reticle size of one inch square, and an estimated visual error of 0.003 to 0.005 inches, an error of 0.3 to 0.5 percent can be expected. An error of this magnitude is well within the comparator design requirements. Note that no significant enlargement of the GO/NO GO reticle is possible when viewing the No. 200 sieve without a substantial increase in the optical path length. The relatively small reticle dimensions for the No. 200 sieve can be seen by referring to Table 6.

Note that AASHTO specifications are given in metric units, while the reticle designs were accomplished in English units. This being the case, each magnification had to perform the conversion from metric to English units, while leaving the operator with reasonable numbers to work with. Table 6 and Figure 14 illustrate this concept.

Those who wish to construct reticles of the same size can refer to Figures 14 and 15, Viewing Reticle Design. The conversion factor is simply Magnification divided by 25.4 to obtain the reticle design size from AASHTO M92 specifications.

Design Size = AASHTO Specification X Magnification
(Metric-to-Metric)
Design Size = Specification X Magnification/25.4
(Metric-to-English)

As a further example, a No. 8 sieve, with a magnification of 10.16, would have a conversion factor of 10.16/25.4, or 0.4 inches/mm.

- The smallest average opening is: 2.36mm – 0.080mm = 2.28mm.
- The reticle size on the plate would be: 2.28 in. X 0.4 in. = 0.912 in.
- The largest average reticle opening is: 2.36mm + 0.080mm = 2.44mm.
- In this case, the reticle size on the plate would be: 2.44 in. X 0.4 in. = 0.976 in.
- The 5 percent opening is: 2.515 in. X 0.4 in. = 1.006 in.
- The maximum opening is: 2.600 X 0.4 in. = 1.040 in.

Larger reticles, which have the effect of reducing visual error, should be considered during any new design. However, it should be noted that depth of field and working distance problems will limit the

TABLE 6
RETICLE SIZE VS. AASHTO SPECIFICATION (FOR NO. 200 SIEVE)

	AASHTO Specification (mm)	Size on Reticle (inches)
Smallest Average	0.070	0.70
Largest Average	0.080	0.80
5% Level	0.091	0.91
Largest Possible	0.103	1.03
Largest Wire Diameter	0.0583	0.583
Smallest Wire Diameter	0.0477	0.477

Note: Magnification is X254

maximum magnification (for woven sieves) to approximately 300. To overcome this limitation, the optical path length would have to be lengthened appreciably.

The line thickness for viewing reticle designs was found to be satisfactory (0.020 inches). Thicker lines are not recommended since evaluation is aided by being able to see the image both "inside" as well as "outside" the reticle square.

SIEVE TRANSPORT APPARATUS (Object Translator)

The object translator was designed and custom made by the ADOT Materials Division. Hardened aluminum alloys were used for the majority of all construction, except for the steel guide rails, linear bearings, translator carriage and other precision parts, which were purchased items.

The sieve X-Y-Z transport consists basically of four parts . . . a longitudinal transport carriage, a transverse transport carriage, a vertical transport carriage, and a "horse shoe" shaped sieve support platform.

The longitudinal unit consists of a 13 X 20 X ¼ inch support plate, with aluminum end plates for securing the guide rails, lead screw and clamping rod. The support plate is bolted to the optical chamber structural housing. Each end plate is 13 X 1½ X ¾ inches. The guide rods are hardened and ground stainless steel with a Rockwell hardness of 55 and a diameter of 0.4990 to 0.4995 inches. Four (4) precision linear bearings (0.5" dia., -0.0005", + 0.0") are fitted to these guide rails and secured to the longitudinal carriage by use of two bearing support blocks (1X 1¼ X 1¾ inches, each). These longitudinal bearings also serve as support for the transverse carriage.

The threaded screw rods (lead screws) are fitted to bearings set in the end plates, thus allowing continuous rotation of the lead screw for carriage position adjustment. The clamping rod has a standard bearing on one end and an eccentric bearing on the other end. The eccentric bearing allows rod rotation to perform the clamping action. A pair of aluminum blocks are used to clamp the lead screw, with the clamping rod running through these blocks. When in the clamp position, the clamping rod forces the clamping blocks to clamp the lead screw in its current position.

The transverse carriage is constructed similar to the longitudinal unit. For the transverse carriage, the base plate is 12 X 6 X ¼ inches, while the end plates are 6 X 5 X ¼ inches.

The vertical carriage consists of a base plate which is 6 X 5 X ¼ inches, on which is mounted an aluminum block of 4¾ X 4½ X 2½ inches. A top plate of

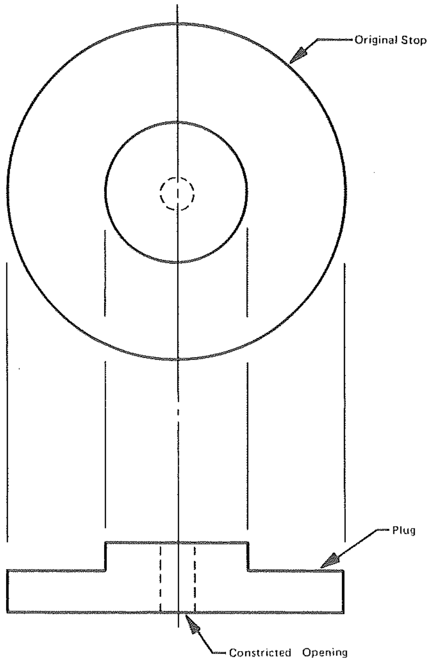


Figure 13. Constricted Stop Construction

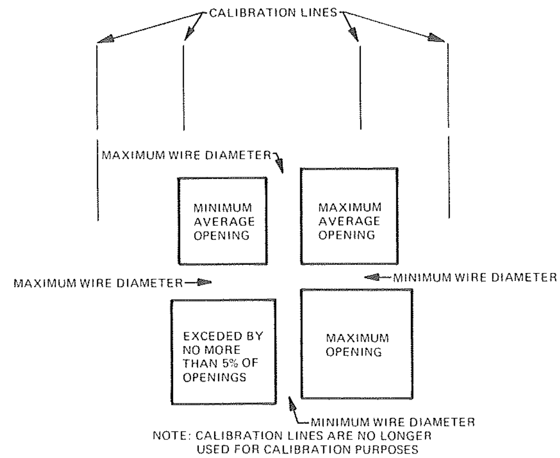
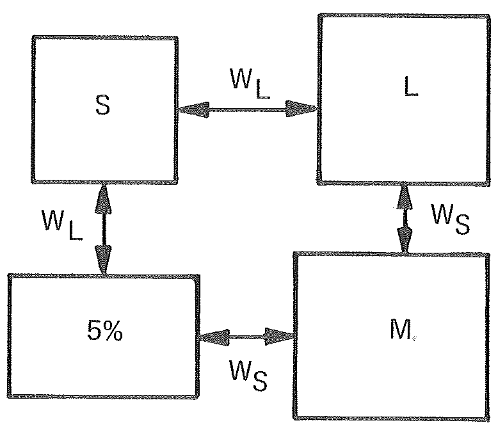


Figure 15. Sieve Evaluation Reticles

RETICLE DIMENSIONS

SIZE	SMALL (S) INCHES	LARGE (L) INCHES	5%	MAXIMUM (M) INCHES	WIRE (INCHES)	
					W_S	W_L
No. 8	0.912	0.976	1.006	1.04	0.38	0.42
No. 10	0.965	1.035	1.068	1.108	0.427	0.473
No. 16	0.908	0.98	1.016	1.064	0.494	0.546
No. 30	0.92	1.000	1.056	1.112	0.577	0.671
No. 40	0.65	0.71	0.754	0.803	0.430	0.499
No. 50	0.915	1.005	1.078	1.162	0.636	0.74
No. 100	0.909	1.011	1.114	1.229	0.651	0.757
No. 200	0.7	0.8	0.91	1.03	0.477	0.583



RETICLE LAYOUT

Figure 14. Viewing Reticle Design

4¾ X 4½ X ¼ inches, in conjunction with the base plate, serve as supports for the vertical lead screw. The vertical adjustment plate guides for the sieve holder are fixed to the vertical carriage support block.

Figure 16 shows a simple outline drawing of the X-Y-Z translator subassembly.

Miscellaneous Components

Table 7 provides a listing of various additional components used in the construction of the ADOT comparator. All listed items may be purchased from most optical supply establishments.

TABLE 7
MISCELLANEOUS COMPONENTS

1. Vertical Slide (for objective lens mount).
2. Front surfaced mirrors (¼" thick).
   a) 1 in. X 1.5 in.
   b) 2 in. X 3 in.
   c) 4 in. X 6 in.
3. Six (6) inch square optical diffusion glass (1/16" thick).
4. Triangular rail, ½ meter long.
5. Aluminum carriage for rail.
6. Micrometer translator unit, 25mm range, sensitive to 0.01mm.

OPTICAL SYSTEM DESIGN PROCEDURE

Within this section, a discussion of the optical design is presented to familiarize the reader with the optical system, as well as the process by which the various design parameters were established.

A major feature of the ADOT comparator is the fact that the comparator is constructed with a variable optical path. The reason for this construction has been qualitatively outlined elsewhere in this report. Now a more quantitative examination of this feature will be made.

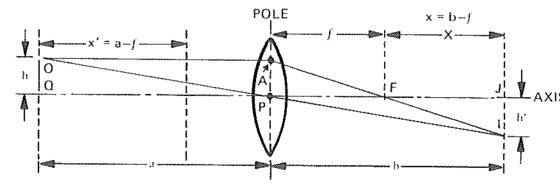
First, the focal length of a simple lens may be loosely defined as the distance, measured from the center of the lens, at which incoming rays (photons) parallel to the optic axis are made to converge. See Figure 17.

The focal length of a lens is denoted by *f*. Now if we are given a lens with focal length *f* and have an object at a distance *a* from the lens,* then the distance from the lens where the image of the object is formed is related to the Gaussian equation

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b} \qquad \text{Equation (1)}$$

This equation may be obtained as follows:

Let: F = focal point of lens
f = focal length of lens
O = object point
I = image point



where: $M = \text{magnification} = \frac{h'}{h}$

The following relations hold:

$$M = \frac{b-f}{f} = \frac{b}{f} - 1, \text{ and } M = \frac{b}{a}, \text{ thus}$$

$$\frac{b}{a} = \frac{b-f}{f}, \text{ or}$$

$$\frac{1}{a} = \frac{1}{f} - \frac{1}{b}$$

$$\text{Hence: } \frac{1}{a} + \frac{1}{b} = \frac{1}{f}$$

Another useful relation, called Newton's Lens Equation is obtained as follows:

Since $X = b-f$ and $X' = a-f$, we have

$$XX' = ab - (a+b)f + f^2$$

From $\frac{b}{a} = \frac{b-f}{f}$, we get $ab - (a+b)f \equiv 0$, thus

$$XX' = f^2 \text{ (Newton's Equation).}$$

Also note that,

$$M = \frac{b}{f} - 1 \text{ thus,}$$

$\frac{dM}{db} = \frac{1}{f}$ giving the rate of change of magnification with respect to the image distance (the Power Equation).

A warning is in order here regarding the usage of this equation. It is only a first order approximation, because it is obtained under strong assumptions. For example, the lens is assumed to have negligible thickness, and all incoming rays are confined to a small area about the center of the lens. This last consumption a-priori implies that the object has small linear dimensions compared to the lens.

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*For our purpose here we can assume the center of the lens is the geometric center. For precise definitions see *Optics* by Frances W. Sears, published by Addison Wesley, 1969.

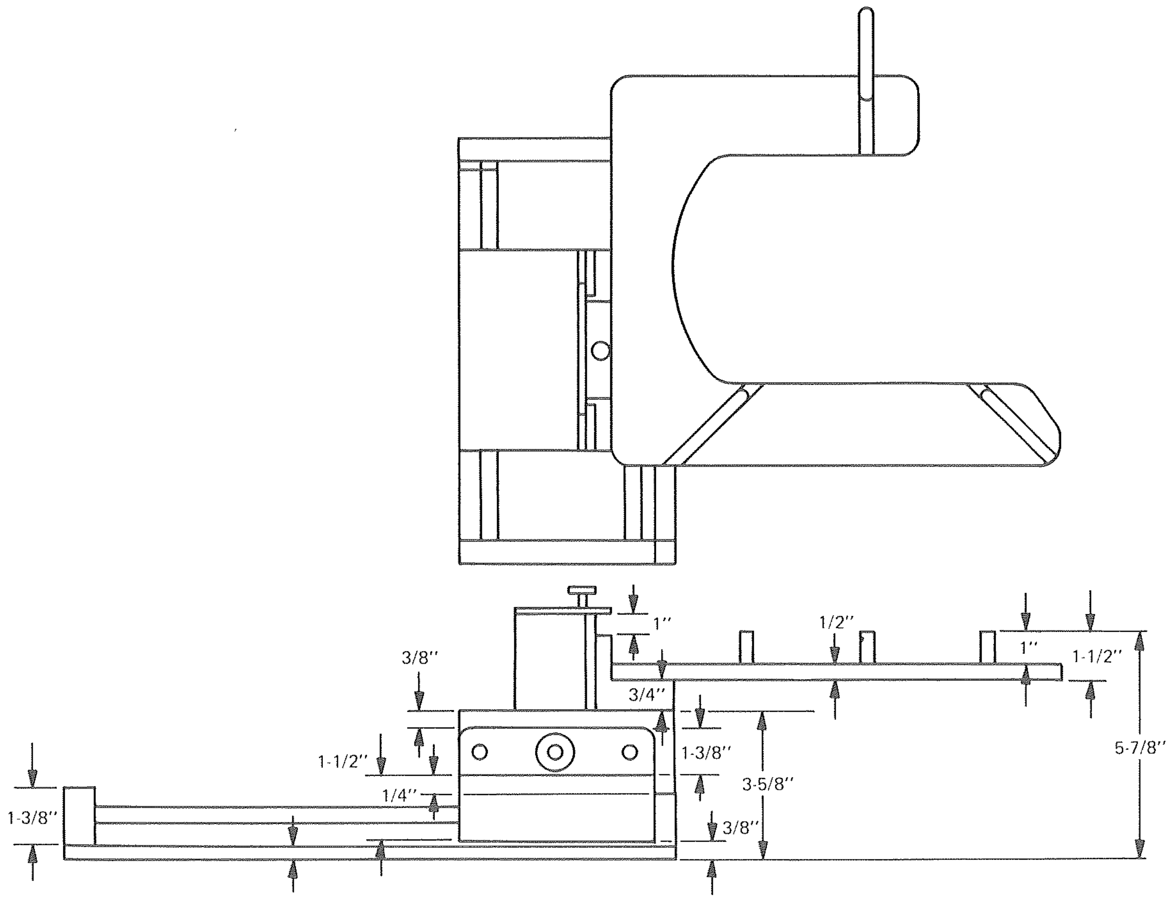


Figure 16. XYZ Translator Outline Drawing

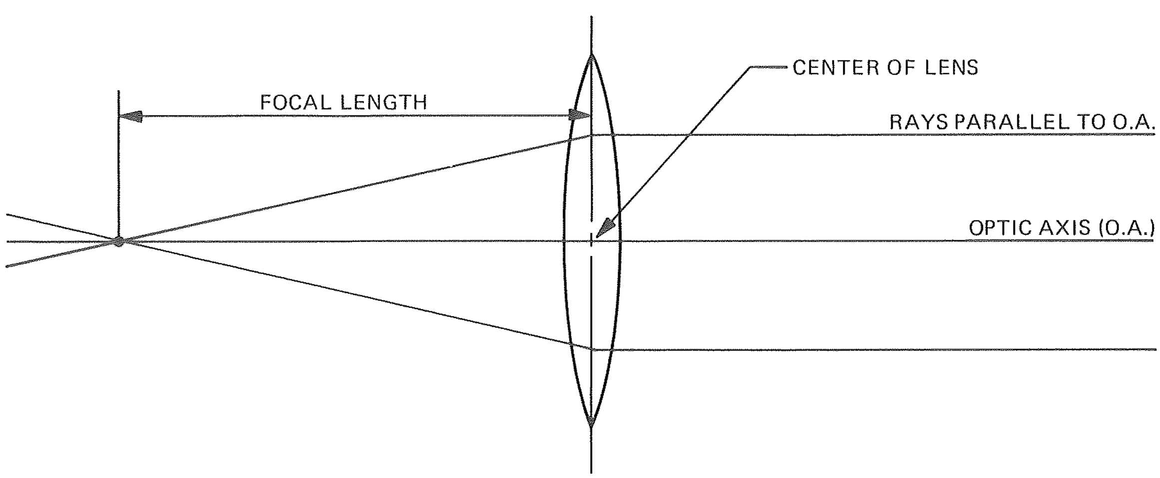


Figure 17. Simple Lens System

To obtain a more realistic result, one must solve the Eikonal Equation.* However., for good qualitative answers the above relation suffices.

Using the Gaussian equation one may easily see that for the different magnifications that are required for each sieve, various focal lengths can be used to achieve the magnification.

Assume we have an object a distance a from a lens with a focal length f. From the relation $\frac{1}{f} = \frac{1}{a} + \frac{1}{b}$, we have that $b = \frac{af}{a-f}$. This gives the approximate distance from the lens where the image will form. In passing we note that if $a-f < 0$ then the image is a virtual one. If $a-f > 0$ then the image is called a real one.

A virtual image cannot be projected onto a screen. Magnified virtual images of objects are obtained when one uses a magnifying glass to look at newsprint, etc. See Figure 19 for an example of a virtual image.

Now we have $b = af/a-f$ and in Figure 18 we see how the real image of the object is formed with a ray diagram.

Now the real inverted image is magnified and we may calculate exactly how much it is magnified as follows:

AOB is similar to BDC so noting that $\overline{OA} = h$ and $\overline{DC} = h'$ we have, since $\overline{OB} = f$ and $\overline{BD} = b - f$,

$$\frac{h}{f} = \frac{\overline{OA}}{\overline{OB}} = \frac{\overline{DC}}{\overline{BD}} = \frac{h'}{b-f}, \text{ thus} \qquad \text{Equation (2)}$$

$$h' = \frac{b-f}{fxh} = \left[\frac{b}{f-1}\right] h = \text{magnification factor.}$$

Moreover, since $\frac{h'}{b} = \frac{h}{a}$, then $\frac{h'}{h} = \frac{b}{a}$ Equation (3)

Now b is related to the optical path length of the ray so to make things simple we will call it the path length.

While remembering that Equation (1), $1/f = 1/a + 1/b$, is only an approximate one and consequently all deductions therefrom are likewise, we still may obtain much information from the above equation.

We note from Equation (3) that the larger b or longer the optical path and correspondingly the shorter the focal length f the more magnification we obtain.

Principles of Optics, by Born and Wolf, Pergammon Press, 4th Edition, 1967.

Using these equations, we are able to make a "first pass" at determining the first models' dimensions. For example, for the No. 200 sieve we required a magnification of 180-X to magnify 0.0029" to about 0.523". Hence using these equations we were able to make a judicious choice of a lens with a very short focal length, i.e., 4mm and adjusted the optical path length b so that the 180-X magnification was obtained. Clearly in this instance we could have used a lens with a focal length of say 20mm. However, to obtain an order of magnitude figure for using such a lens we will use Equation (3):

$$h' = \left[\frac{b}{f} - 1\right] h$$

We want $h' = 180h$ so $180 + 1 = b/f$, therefore

$f(180 + 1) = b$ Equation (4)

Now if $f = 20mm$ this gives b as $3520mm \sim 142$ inches. With a 4mm focal length we can look for a path length of about 28 inches.

Considerations such as these resulted in our first model design. There were many improvements which finally led to the present model. However, these were of an operational nature and did not alter the basic design concept, which was a variable optical path comparator.

In passing we give a ray diagram of a virtual image. Recall that this is the image of an object that is formed when $a - f < 0$, i.e., the object is closer to the lens than the focal point.

Note that the image is "formed" on the same side of the lens as the object. It is not inverted as a real image is, and in the case of a convex lens such as is illustrated it is magnified. This is what occurs when one uses an ordinary magnifying glass to observe an object in order to "magnify" it.

Optical Distortion

Errors affecting the comparator's read-out accuracy may be caused by the optical system. For example, in Figure 20 an illustration is given of "barrel" and "pincushion" distortion present when a lens system has a variation in magnification with respect to distance from the optic axis.

In the barrel distortion, magnification of the image decreases with distance from the optic axis of the lens system. In contrast, increasing magnification with respect to distance from the optic axis, causes the phenomena of pincushion distortion to appear.

However, with a high quality lens system as employed in the present ADOT Comparator, this type of abberation has been eliminated.

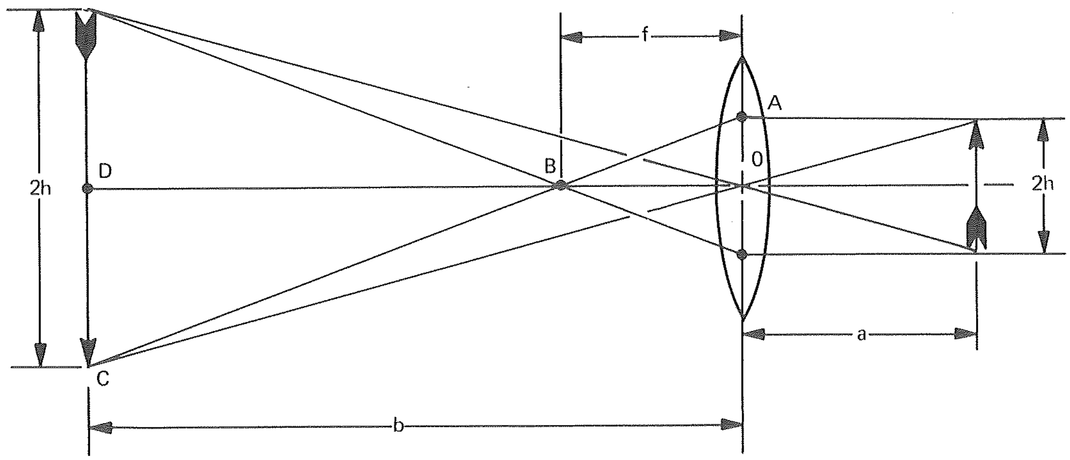


Figure 18. Real Image Formation

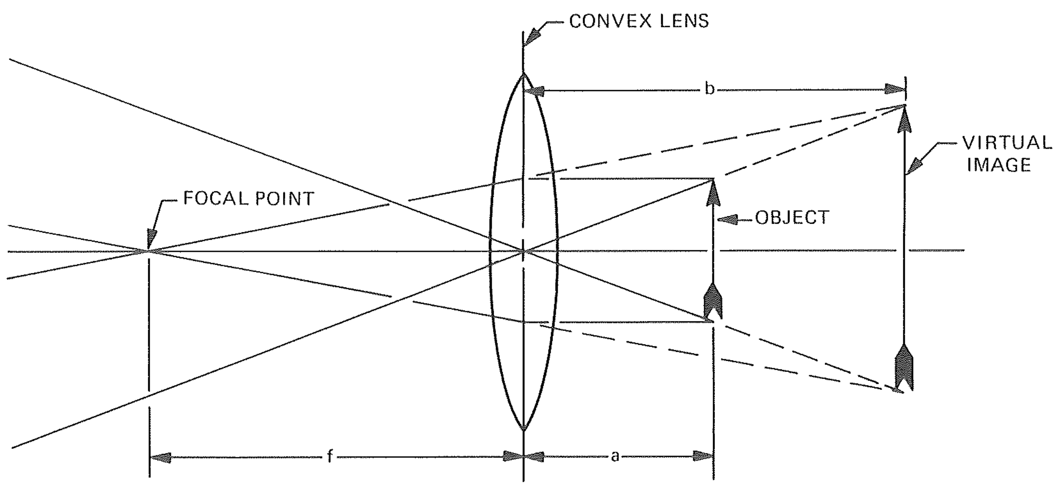


Figure 19. Example of Virtual Image

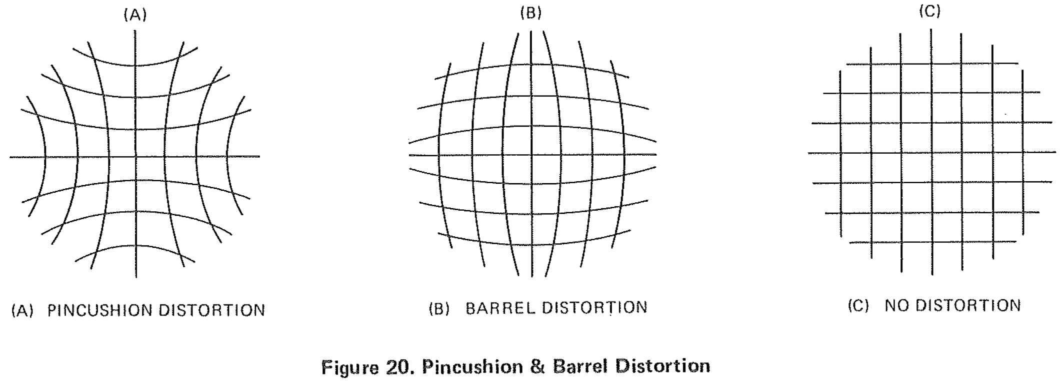


Figure 20. Pincushion & Barrel Distortion

Error Due to Mirror Misalignment

Another source of image distortion may result from misalignment of the mirrors with respect to the optic axis, or each other.

To illustrate the formation of an image with the lens and mirror system of the first model comparator, a ray diagram has been provided in Figure 21. This diagram is shown under the assumption that the mirrors are properly aligned.

Another diagram is provided in Figure 22, illustrating image formation with the mirrors aligned at arbitrary angles. It can be seen from this diagram that the image plane of the object is not coplanar to the screen. We remind the reader that these diagrams illustrate the mirror system of the first comparator mode.

To further elucidate this phenomena, a simple analysis of the problem is presented below.

The first mirror is assumed to be inclined at an angle θ to the optic axis and mirror #2 is inclined at angle δ to the optic axis.

From our analysis, we see that the plane of the image will be inclined at $2(\delta-\theta) - 90°$ to the optic axis. Thus, if we are imaging an object with a transverse linear dimension *d*, it will project onto the screen as

$$L = \frac{d}{|\text{Cos}\ [2(\delta-\theta)]|}$$

Normally we set the mirrors so that $\delta-\theta = 90°$, thus $\text{Cos}\ [2(\delta-\theta)] = 1$.

Our % error in measurement due to misalignment of the mirrors will be defined as

$$\left[\frac{L-d}{d}\right]100$$

where d is the transverse linear dimension of the image and

$$L = \frac{d}{|\text{Cos}\ [2(\delta-\theta)]|}.$$

Let $\delta-\theta = 90° + \alpha$, where α is the angle of misalignment. Then $2(\delta-\theta) = 180 + 2\alpha$, so $|\text{Cos}\ 2(\delta-\theta)| = \text{Cos}\ 2\alpha$. Hence, our % error denoted by $e(\alpha)$ can be expressed as a function of α through the equation

$$e(\alpha) = 100\left[\frac{1}{\text{Cos}\ 2\alpha} - 1\right] = 100\left[\frac{1 - \text{Cos}\ 2\alpha}{\text{Cos}\ 2\alpha}\right]$$

Now α is limited to a certain range, e.g., the mechanical design of the mirror holders limited it to a range of 0° to ±5° on the first model.

The following Figure 24 is a graph of this function and illustrates the effect of the mirror misalignment on the % error introduced.

We note that for the range of values given the cosine function is only slowly varying from the value "1," so we may approximate it as follows:

$$\text{Cos}\ x \sim 1 - \frac{x^2}{2}, \text{ where } x = 2\alpha.$$

Thus our error function becomes under this approximation

$$e(\alpha) \sim 100\left[\frac{2\alpha^2}{1 - 2\alpha^2}\right]$$

where α is measured in radians, i.e., $1° = \frac{\pi}{180}$ radians.

A note of caution is in order here, this expression is valid only for the range considered that is $-5° < \alpha < +5°$ or in radian measurement $-0.087 < \alpha < +0.087$.

From the graph of $e(\alpha)$ it is seen that it is a monotonic increasing function of α.

Now *ABC* has its three vertical angles determined and from *OCD* we see that $0 = \theta$, $C = 180° - \delta + \theta$ and since $0 + C + D = 180°$ it follows that $D = \delta - 2\theta$.

Now continuing the second reflected line down to the line parallel with the optic axis and denoting this point of intersection by E we have the following diagram, Figure 23B.

Now *DEB* has the following angles: $\angle D'$ is $180 - (\delta-2\theta)$ and angle $\angle B$ is $180°-\delta$, it follows that angle E is $2(\delta-\theta)-180°$. This angle is the angle that a ray collinear with the optic axis would be deflected by passing through the mirror system. Note that if $\theta = 45°$, as in the comparator, and $\delta = 135°$, then $E = 0$ or the ray is parallel to the optic axis.

Now that rays (1) and (2) will always maintain angles relative to this ray collinear with the optic axis of magnitude α and β, respectively. This results in the collinear ray being oriented at 90° to the plane of the image. It follows that the image plane is now included to the original optic axis at $2(\delta-\theta)-90°$.

From this simple analysis we can glean an important result. Namely, if the first mirror is inclined at angle θ and the second at angle δ so that $2(\delta-\theta)=180°$ we see that the image plane will be properly oriented to the original optic axis. This signifies the reason for choosing angle $\theta=45°$ and angle $\delta=135°$ since then $2(135-45) = 180°$. Clearly this fact also gives plenty

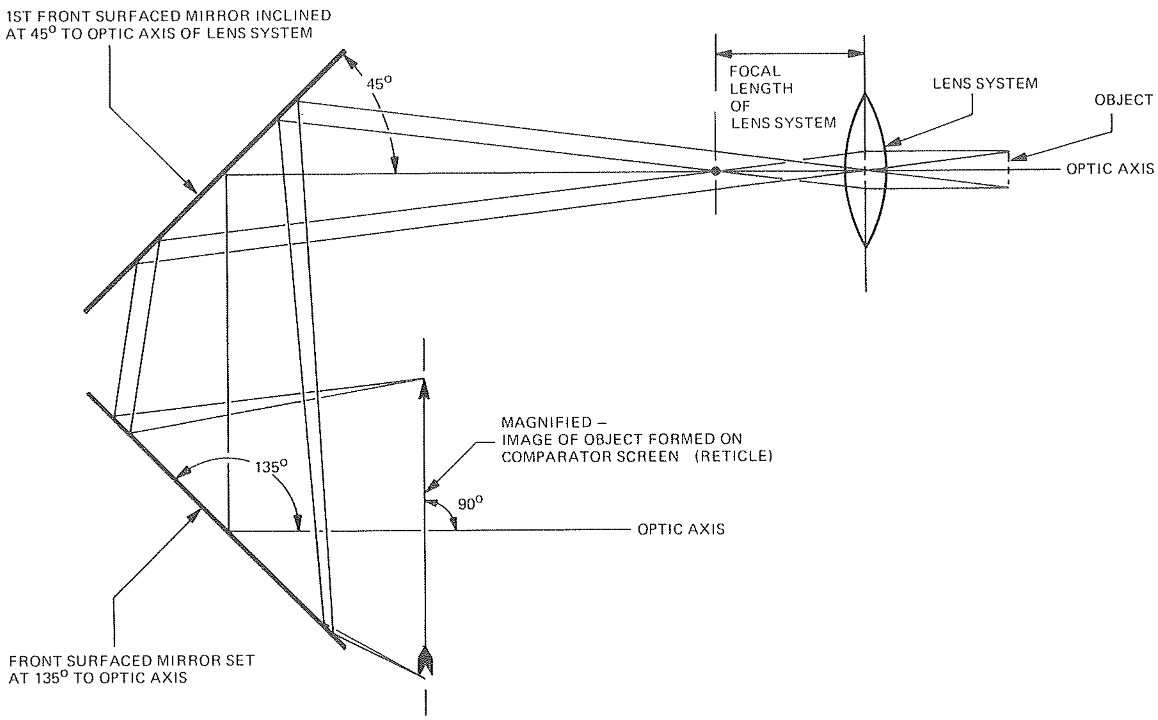


Figure 21. Image Ray Diagram (Aligned)

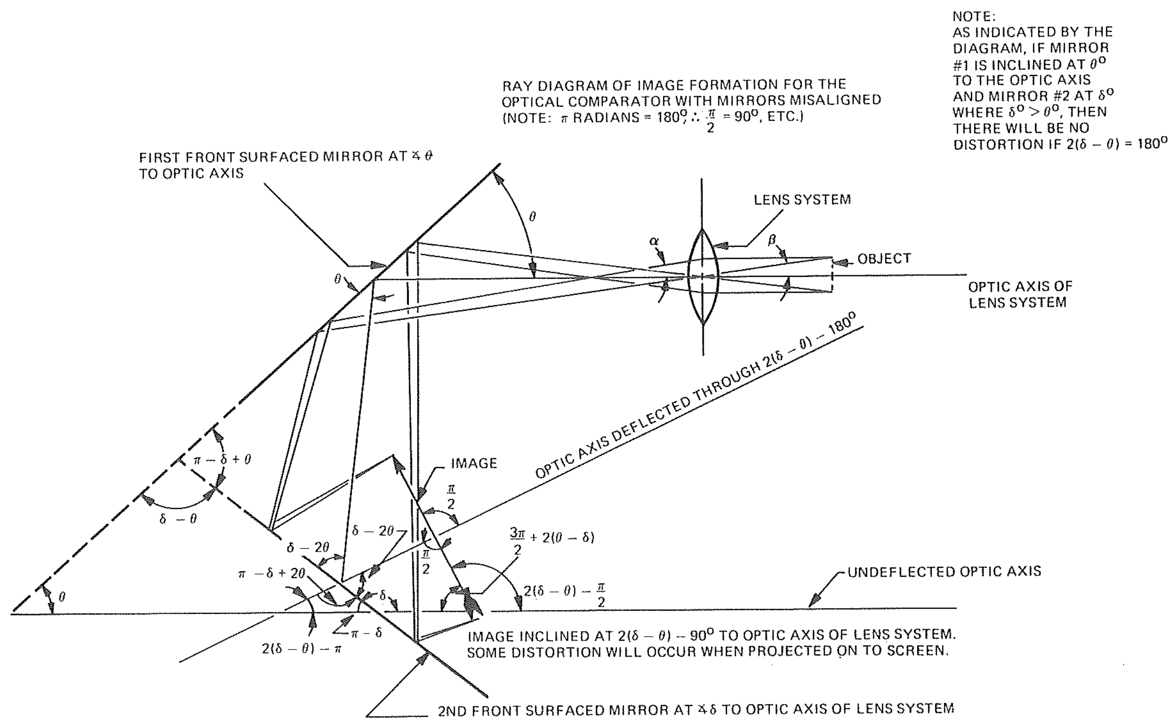


Figure 22. Image Ray Diagram (Misaligned)

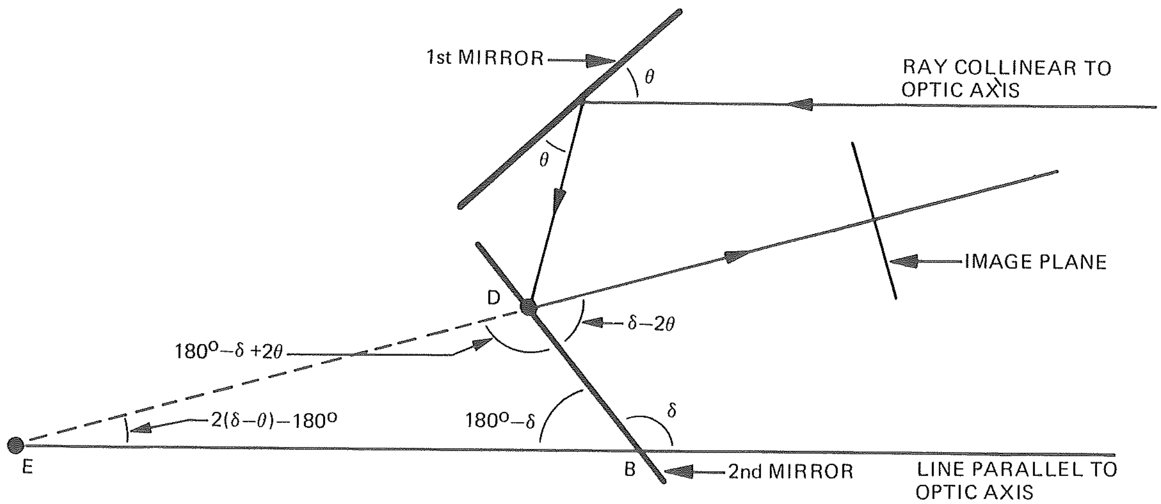


Figure 23A. Ray Diagram

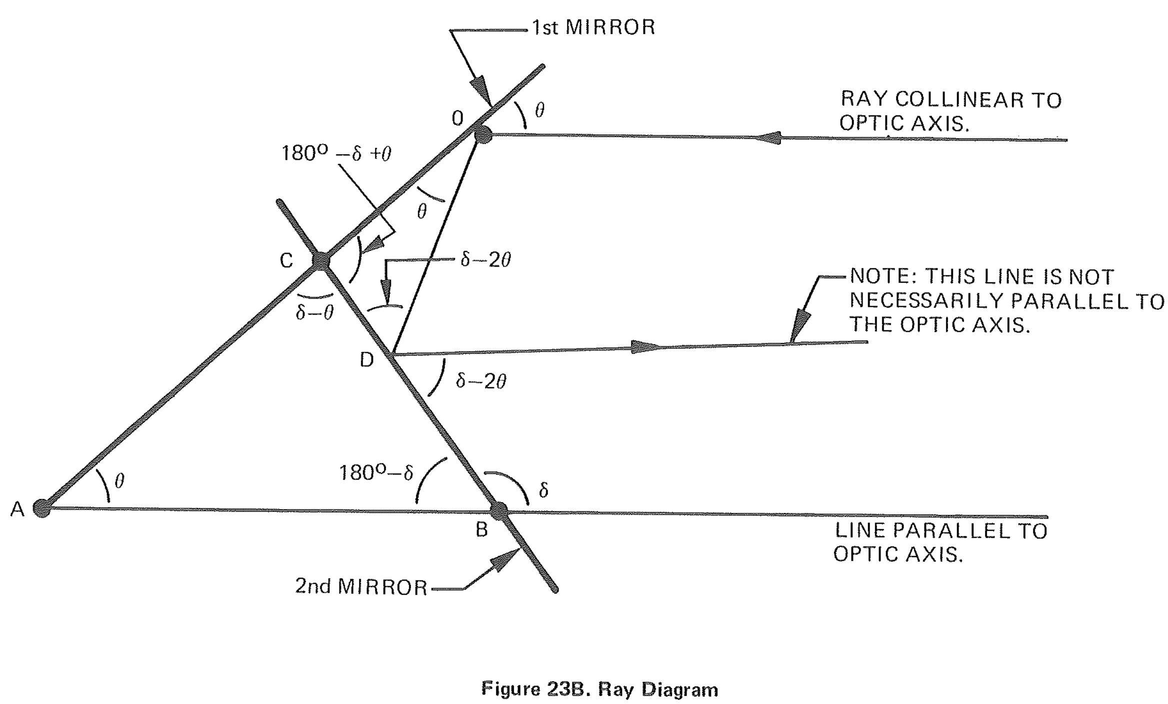


Figure 23B. Ray Diagram

of leeway to the design for if angle θ is say 43° then we need only adjust angle δ to 133° so that $2(133-43) = 180°$.

Collimating Procedure

A method of determining (and correcting) possible mirror misalignment is described below.

If a set of concentric circles, see Figure 25, is projected through the optical system, it follows that with no abberations present, the resulting image should be a set of magnified concentric circles. The slightest amount of distortion present in the image will be immediately discernible using the concentric circles, which will be imaged as ellipses of various eccentricities. The larger the eccentricity the more distortion* present in the optical system.

To collimate the comparator, we need only project a circular pattern onto a special screen or viewing reticle. This special reticle would also have a magnified version of this circle drafted upon it. By superimposing the image of the circle upon the reticle's circle, we will immediately discern any eccentricity in the image. If any such image eccentricity is present, it is easily eliminated by using the mirror adjustments provided on the instrument.

*Distortion due to mirror misalignment or reticle misalignment.

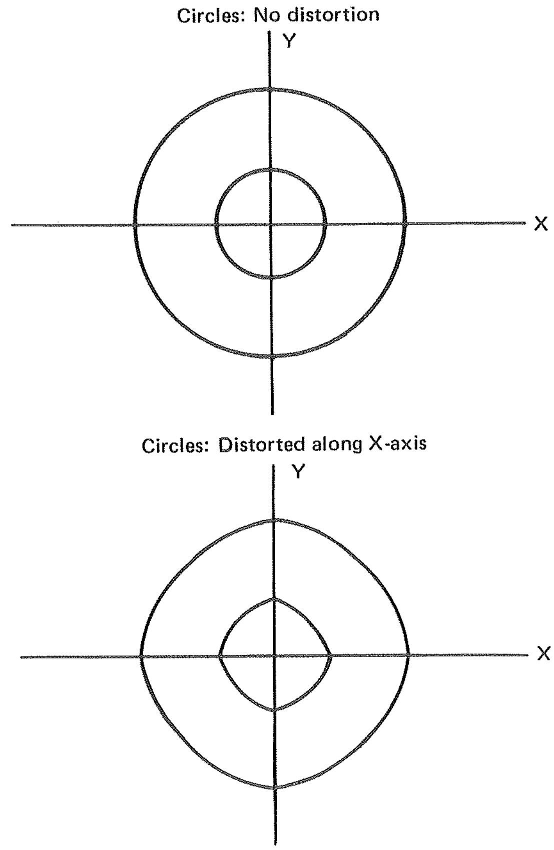


Figure 25. Collimating Circles

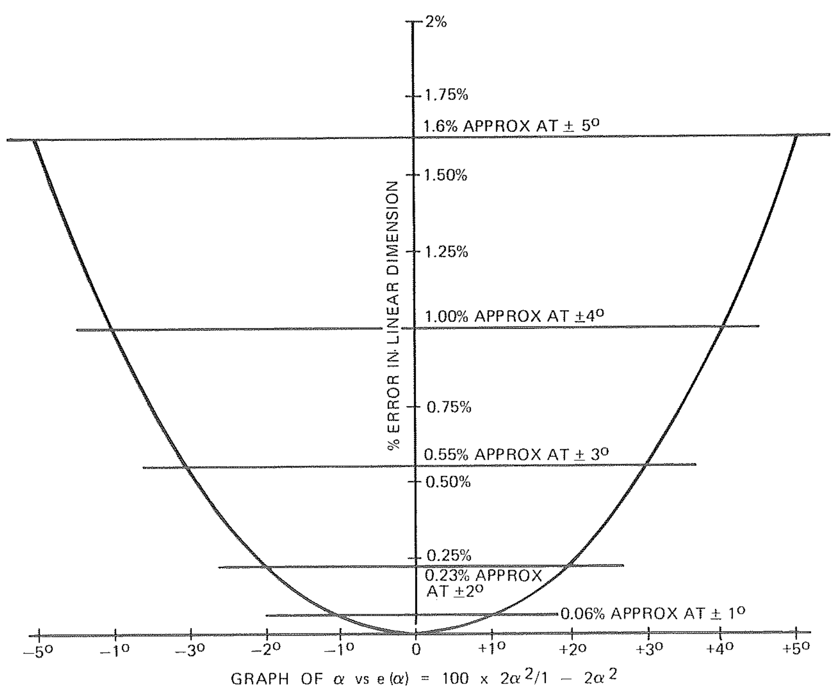


Figure 24. Mirror Misalignment vs. Percent of Error

COMPARATOR EVALUATION

The ADOT optical comparator was evaluated according to the following criteria:

1. Initial estimates were made for single operator repeatability for each lens.
2. Comparison tests were performed against well recognized measurement standards to determine relative accuracy.
3. Time tests were performed for absolute measurement as well as GO/NO GO procedures.
4. An operator's subjective evaluation of the comparator was obtained (ease of handling, object control, convenience of operation, etc.).

The results of this evaluation are detailed in this section.

REPEATABILITY TESTING

Repeatability test results are presented in Table 8, Reproducibility Standard Deviations.

In addition to performing repeated measurements of sieve openings, the operator was asked to estimate his visual resolution at the viewing reticle. Estimated values for resolution in the object plane were obtained by dividing the estimated values (Column 3, Table 8) by the corresponding magnification.

Column 4 presents the results of calculating standard deviations for the measurements of single openings. The values presented are the composite of several such calculations as accumulated from several measurement sessions for each opening. Unfortunately the standard deviation for the 40X lens were made with the previous ("old") 40X lens. However, a single test of the new LWD40 lens was performed with the No. 200 sieve, which led to the "double starred" result as shown in Table 9, Comparison Test Results.

It can be observed from Table 8 that experimental standard deviations do in fact approximate the estimated resolution. The estimated resolution is influenced by the operator's visual acuity, as well as the visual definition of the image. Visual definition is in turn determined by the depth of field characteristics of the particular lens being used. These test results thus indicate that comparator performance is equal to or better than the limitations imposed by the operator and the particular lens in use.

The extraordinarily good repeatability results for the LWD40 lens are more difficult to evaluate. Analysis of predicted resolution, using the Abbe formula, shows that a resolution of less than 0.8 microns is attainable. Furthermore, it is clear that

TABLE 8
REPRODUCIBILITY STANDARD DEVIATIONS

Col 1 Lens	Col 2 Magnification	Col 3 Estimated Values	Col 4 Experimental Values
3X	10X	10.2 microns	5.5 microns
	20	5.1	
5X	25	4.1	5.5
10X	40	5.1	
	50	4.1	3
20X	80	2.5	
	140	2.0	3.5
40X	160	1.9	
	250	1.2	1.4

multiple setting should result in larger standard deviations due to the variance inherent in calibration. This calibration variance will not show up as a result of a single setting. On the other hand, there is always a possibility that the operator "unconsciously" repeated earlier measurements, thereby reducing the variance for a single session. This effect is always a possibility, even though measurement procedures were chosen to eliminate it.

The Abbe formula states that:

$$\text{Lens Resolution} = \lambda/[NA(C) + NA(L)],$$
approximately,

where λ = wavelength of incident light,
NA(C) = numerical aperture of condenser,
NA(L) = numerical aperture of objective lens

In air, the Abbe condenser has a numerical aperture of approximately 0.9 and the objective lens (with its stop) has a numerical aperture of approximately 0.1. This being the case, a resolution in the order of the wavelength of the incident light (less than 0.8 microns) should be obtained.

The Abbe formula must be considered when reducing the diameters of the lens stops to obtain increased depth of field. Once the depth of field is sufficiently great, there is no reason to further restrict the lens stop.

COMPARISON TESTS

The ADOT optical comparator was also tested by comparing the comparator's measurement results to those obtained by means of recognized standard methods. The recognized methods used consisted of microphotography and a scanning electron microscope. An independent measurement laboratory provided the microphotography and SEM measurements.

Single openings were isolated on selected sieves, one for each of the sieve sizes: No. 8, 10, 16, 30 and 40. These openings were measured by microphotography, as well as by the optical comparator. In addition, groups of openings were isolated from pieces of sieve cloth from No. 50, 100 and 200 sieves. These groups were measured by use of the electron microscope. At this time these measurements were made, the comparator was not specifically designed to handle small pieces of sieve cloth. However, subsequent improvements were made, consisting of the introduction of "crossed rulers" (instead of a single horizontal ruler) on the measurement reticle, and the replacement of the 40X lens by the LWD40 lens. The "double starred" values in Table 9 represent measurements made after the above improvements were made.

The results of all comparison testing are shown in Table 9. Although there are occasional erratic variations, the majority of all results are remarkably

TABLE 9
COMPARISON TEST RESULTS

Sieve No.	Optical Comparator	Microphotography
8	2.399 ± 0.042 mm	2.40 ± 0.03mm
S.E.	0.002 0.002	
10	1.996 ± 0.014 mm	2.00 ± 0.01mm
S.E.	0.003 0.002	
16	1.204 ± 0.008 mm	1.21 ± 0.01mm
S.E.	0.002 0.001	
30	581 ± 21 microns	580 ± 15 microns
S.E.	1.7 3.5	
40	439 ± 15 microns	450 ± 10 microns
S.E.	2.0 2.4	
Pieces of Sieve Cloth		**Scanning Electron Microscope**
Average of 2 Openings		
50	307 ± 7 microns	307 ± 4* microns
S.E.	4.9 1.8	
Average of 4 Openings		
100	152 ± 4 microns (one axis only)	160 ± 2* microns
S.E.	3.6 2.7	
200	77.5 ± 7.5 microns (single measurement)	74.7 ± 5.8 microns
	σ0.7** 1.8**	μ78 ± 0.8*

S.E. = Standard Error
* = Error Mean
* = Standard deviation calculated independently for No. 200 measurements.

close. The largest percent difference between comparator and "standard" results was the 5 percent difference recorded at the No. 100 sieve. This particular measurement was somewhat biased since only one axis was measured. The largest valid difference was the 3.7 percent variation recorded for the No. 200 sieve openings. It should be noted that the independent laboratory did not claim better than 5 percent error (2σ) for the electron microscope.

In view of the favorable results for both repeatability and comparison testing. ADOT has gained a high level of confidence that the accuracy and repeatability of the comparator is comparable to that of the best optical instrumentation.

TIME TESTING

Rapid testing is the only method by which statistical precision becomes practical. This being the case, time testing was of particular importance. As previously indicated, absolute measurement tests consumed approximately 3.66 minutes per opening.

This rather slow pace was due, to some extent, to operator inexperience. Since the operator was equally inexperienced with the GO/NO GO procedure, the 2/3-minute per opening rate for GO/NO GO testing becomes all the more impressive.

The initial GO/NO GO test form, as developed by ADOT, was similar to that shown in Figure 26. With this form, reference was to be made to the table of Figure 26. This form has since been replaced by the form shown in Figure 27. In this case, the numbers in the squares allow the operator to terminate testing as soon as a preassigned acceptance or rejection level has been reached. In contrast, the same test as shown in Figure 26 would have resulted in acceptance after only 47 evaluations had been made.

	First Diagonal	Second Diagonal
LP		
5%	X	X
LA	X	X X X X
SA	XXXXXXXXXXXXXXXXXX	XXXXXXXXXXXXXXXXXXX
	XXXXXXXXXX	XXXXXX

No. of Measurements	Accept Larger Than Largest Average or Smaller Than Smallest Average	Reject	No. of Measurements	A	R
6	1	5	34	13	21
8	2	6	36	14	22
10	3	7	38	14	24
12	4	8	40	15	25
14	5	9	42	16	26
16	5	11	44	17	27
18	6	12	46	18	28
20	7	13	48	19	29
22	8	14	50	20	30
24	9	15	52	21	31
26	9	17	54	21	33
28	10	18	56	22	34
30	11	19	58	23	35
32	12	20	60	24	36

Accept the sieve if the number of widths smaller than the smallest average, $n-t$, is less than the appropriate number in column A and the same holds for the widths larger than $n+t$, the largest average.

Reject the sieve if the number of widths smaller than $n-t$ or the number of widths larger than $n+t$ exceeds the appropriate number in column R.

FIGURE 26. GO/NO GO TEST FORM (ORIGINAL)

5%	59	|	7	16	28	40	53	REJECT								
LARGE		+ 9	+ 12	| 15	| 17	20	23	25	28	30	33	35	37	40	42	44
SMALL		9	12	15	17	5 20	6 23	8 25	9 28	11 30	13 33	14 35	16 37	18 40	19 42	21 44
TOTAL		1 ✓	2 ✓	3 ✓	4 ✓	5 ✓	6 ✓	7 ✓	8 ✓	9 ✓	10 ✓	11 ✓	12 ✓	13 ✓	14 ✓	15 ✓

Acceptance α = 0.025 for large and small sizes.
Rejection α = 0.050 for each category.

5%																
LARGE		23 47	24 49	26 51	28 54	30 56	31 58	33 61	35	37	39	40	42	44	45	47
SMALL		23 47	24	26	28	30	31	33	35	37	39	40	42	44	45	47
TOTAL		16 ✓	17 ✓	18 ✓	19 ✓	20 ✓	21 ✓	22 ✓	23	24	25	26	27	28	29	30

5%																
LARGE		49	51	53	54	56	58	60	REJECT							
SMALL		49	51	53	54	56	58	60	REJECT							
TOTAL		31	32	33	34	35	36	37	38	39	40	41	42	43	44	45

Figure 27. Sieve Evaluation Form

Currently, ADOT is following a GO/NO GO test program which consists of checking 30 openings for the initial sieve evaluation. In this case, those sieves which are still in the undecided category, are taken back to the central testing laboratory for further evaluation as time permits. This allows a large number of sieves to be accepted or rejected during the initial evaluation, which requires only 20 minutes or less per sieve. This is a reasonable rate for production purposes.

It should be noted the GO/NO GO testing can only test for medians as opposed to averages. Although the results of testing for these two central indices do not coincide, we feel that equivalent sieve quality will result. See Appendix E for a discussion of this problem.

OPERATING CHARACTERISTICS

To say the least, extensive testing and evaluation has resulted in certain improvements to the ADOT comparator. Among these improvements are the long working distance (LWD) 40X lens, restricted stops on the higher power magnifiers, crossed rules on the measuring reticle and the variable voltage lamp transformer for increased illumination. All of the above improvements were external to the basic system and were thus implemented with few problems.

A more difficult problem to resolve was encountered during comparison testing. In theory, the comparator has the capability of locating a preselected small field by beginning with a low power magnifier and successively replacing lenses with more powerful lenses. This approach did not turn out to be practical when dealing with the small pieces of sieve cloth which were used with the SEM. The problem was with the sieve support device which was designed for 8-inch diameter sieves. The support did not lend itself to convenient vertical movement; and in addition, the illuminator assembly cannot be controlled by the operator with any facility.

Originally, the illuminating cylinder was designed for "fine" vertical movement by way of a hinge at the lamp end of the cylinder. The small displacements in vertical illumination would have caused no problems due to the telecentricity characteristics of the lenses. Unfortunately, this vertical fine tuning of the illuminator system did not survive various basic, but necessary, modifications of the sieve positioning unit. The hinge remains, but vertical movement is restricted and not easily controlled by the operator.

The primary reason for this loss of vertical illumination adjustment results from the design of the sieve vertical positioning unit which eliminates the necessary clearance for positioning the illumination system.

The lack of any control (or adjustment) of the height of the illumination cylinder, in conjunction with the relatively short adjustment range of the vertical sieve control mechanism, forces the operator to adopt a somewhat roundabout calibration procedure. As a result of this limitation, he must first adjust the object to its optimal position and then perform calibration. If the operator were to calibrate first, he could discover that the object is receiving poor illumination, or that the object cannot be brought into proper focus at all.

As an overall evaluation, the following is excerpted from an internal ADOT report as prepared by one of the research engineers.

> "...The only mechanical problems experienced during the initial design of the comparator were with the sieve positioning unit. It was found, by experience, that this unit had to be fairly massive. Attempts to construct a lightweight unit resulted in a better seismometer than comparator.
>
> The final comparator as constructed at the ADOT Annex, turned out to be entirely satisfactory. The rolling table, on which the comparator rests, is considered as a part of the system, and helps considerably in the control of vibration. Thus, with the present configuration, the operator is able to use the comparator in the presence of external vibration due to the operation of heavy equipment in the general area.
>
> It has been found that the sieve positioning controls do exhibit certain annoying features. For example, location of the vertical and transverse controls make them somewhat awkward to use, while both horizontal controls exhibit some degree of backlash. Also, the vertical sieve position control should allow a finer adjustment, to match the fineness of the "tuning" on the lens mount.
>
> Of these problems, none were considered to be of sufficient concern to interfere with good precision measurements, but the annoyance factor could lead to operator fatigue which in turn could lead to measurement errors."

EVALUATION CONCLUSIONS

ADOT tests have demonstrated that the optical comparator can be operated with a precision which is comparable to the best of available optical instrumentation, and that the present calibration standards provide the necessary accuracy.

GO/NO GO testing, in conjunction with the statistical methods developed by ADOT, results in the desired "rapidity" in sieve evaluation.

There does remain certain areas of desired improvement which fall into the category of operator convenience, etc. These improvements are not considered worthy of incorporation into the existing system, but would be considered should future comparators be constructed.

OPERATING PROCEDURES

PRELIMINARY SET-UP

Before applying power to the comparator, the following steps should be taken:

1. Select the appropriate magnification for the desired object.
2. Select the appropriate objective lens.
3. Select the appropriate condensing lens.
4. Dial the lamp intensity to "LOW" voltage (approximately 18 VAC).

WARNING: If the variable lamp transformer (VARIAC) is on "HIGH," it should be set to "LOW" before turning the lamp OFF.

Tables 10 and 11 show the various magnifications and lenses to be used for sieve evaluation. For absolute measurements, these magnifications are optional. However, the designated magnifications are *mandatory* for use in GO/NO GO procedures.

COMPARATOR SET-UP

Perform the following steps (See Figure 28):

1. Place the objective lens in the lens mount.
   a) The 3X and 5X lenses are placed in the "lower" mount.
   b) All remaining lenses utilize the "upper" mount.
2. Place the condensing lens in the condensing lens bracket.
3. Place the object (sieve) on the object stage.
4. Adjust the object stage to an intermediate vertical position, leaving room for subsequent vertical adjustment.

NOTE: When using the 20X and LWD40 lenses, keep the object "close" to the condensing lens.

POWER-ON

1. With the lamp transformer in the "LOW" position, turn power ON.
2. Adjust the lamp intensity to the desired value for reticle viewing.
3. Adjust the object vertical position for best illumination as seen at the viewing reticle.
4. Adjust the lens mount for optimum focus at the viewing reticle.

   NOTE: Steps 2, 3 and 4 will be accomplished more or less simultaneously . . . a process of converging adjustments.

5. Now that the comparator has been adjusted for a particular sieve mesh size, no further

TABLE 10
MAGNIFICATION VS. LENS (GO/NO GO TESTING)

Sieve	Magnification	Objective Lens*	Condensing Lens
No. 8	X10.16	3X	A or B (See Key)
No. 10	X12.7	3X	A or B
No. 16	X20.32	3X or 5X	A or B
No. 30	X40.64	M10	A or B or C
No. 40	X50.8	M10	C
No. 50	X81.28	M20	C
No. 100	X162.56	LWD40	D
No. 200	X254	LWD40	D
			D

Key A: No Condenser
B: Low Power Condenser, Long Side UP
C: Low Power Condenser, Long Side DOWN
D: High Power Condenser

*These are the symbols actually appearing on the lens.

TABLE 11
MAGNIFICATION VS. LENS
(ABSOLUTE MEASUREMENT)

Sieve	Magnification	Objective Lens	Condensing Lens
No. 8	X20.32	3X	A or B
No. 10	X25.4	5X	A or B or C
No. 16	X50.8	M10	C
No. 30	X50.8	M10	C
No. 40	X139.7	M20	D
No. 50	X139.7	M20	D
No. 100	X254	LWD40	D
No. 200	X254	LWD40	D
Very Small Flat Objects	X330	M50	D

adjustment will be necessary for testing subsequent sieves of the same mesh size. The only further adjustments that will be necessary will be calibration and then bringing the object table back to its optimum position for sieve evaluation.

CALIBRATION

To calibrate the optical comparator, perform the following steps:

1. Select the "Measuring" Viewing Reticle and place it in the reticle receiver (Figure 29).
2. Select the Calibration Reticle and plastic Reticle Holder (Figure 30).

   NOTE: Use the "metric" calibration reticle for all magnifications as shown in Tables 10 and 11.

3. Remove the object (sieve) from the object stage and place the Reticle Holder on the object stage. Then place the Calibration Reticle on the Reticle Holder.
4. Adjust the object stage vertical adjustment for optimum focus.

   WARNING: *DO NOT* adjust or change the position of the objective lens.

5. Calibrate the comparator by adjusting the "coarse" mirror adjustment and the "micro-fine" magnification adjustments. See Figure 5B.
6. Calibration is achieved by matching the image of the calibration reticle (metric) to appropriate lines on the measuring reticle. Correspondences are provided in Table 12.

TABLE 12
CORRESPONDENCE VS. MAGNIFICATION

Magnification	Correspondence
X10.16	1.0mm/0.4 in
X12.7	1.0mm/0.5 in
X20.32	1.0mm/0.8 in
X25.4	1.0mm/1.0 in
X40.64	1.0mm/1.6 in
X50.8	1.0mm/2.0 in
X76.2	1.0mm/3.0 in
X81.28	1.0mm/3.2 in
X139.7	0.6mm/3.3 in
X162.56	0.5mm/3.2 in
X254	0.1mm/1.0 in
X330	0.1mm/1.3 in

For further details on calibration, see the background notes at the end of this section.

Now that the comparator has been calibrated, it is ready for sieve evaluation.

DO NOT TOUCH ANY ADJUSTMENTS, EXCEPT THE OBJECT POSITIONING CONTROLS.

Note that calibration will hold true for the evaluation of all sieves of the same size (mesh); however, should the sieve size change or a lens change be required, the comparator must be set-up again and be re-calibrated.

Background Notes

System calibration is performed for each magnification setting, which in turn is determined by the particular sieve to be evaluated. Once calibration is set, all adjustments pertaining to optical distance must *not* be altered. Only adjustments pertaining to the object (sieve) position translator (X,Y,Z) are permissible once calibration has been set.

Calibration is accomplished by use of a "measuring" reticle which contains a pair of scales (horizontal and vertical), each scale being subdivided into 1.0, 0.1, 0.025 and 0.005 inch divisions. This reticle is used for absolute measurements as well as system calibration.

In combination with the measuring reticle, the operator has a choice of two "projection standards" – both being Bausch & Lomb pieces for standard pocket comparators. One projection standard has 0.1 inch divisions, subdivided into 0.005 increments, the other standard having 1mm divisions, subdivided into 0.1mm increments. Since the reticle is scaled in inches, if the metric projection standard is used a conversion factor of 25.4mm/inch is required for determining magnification. Also since sieves specifications are presented in millimeters, it is more convenient to use the millimetric Bausch & Lomb glass when sieves are to be evaluated. The millimetric glass should always be used when the GO/NO GO viewing reticles are used.

The operator calibrates by matching appropriate reference lines between the projection standard and the measurement reticle. For best results, the sides of the image lines should be matched to the sides of the reticle reference lines, with alternate sides being used for successive settings until the desired degree of calibration is achieved.

For example: If the operator desires to measure "openings" on the No. 100 or 200 sieves, he will

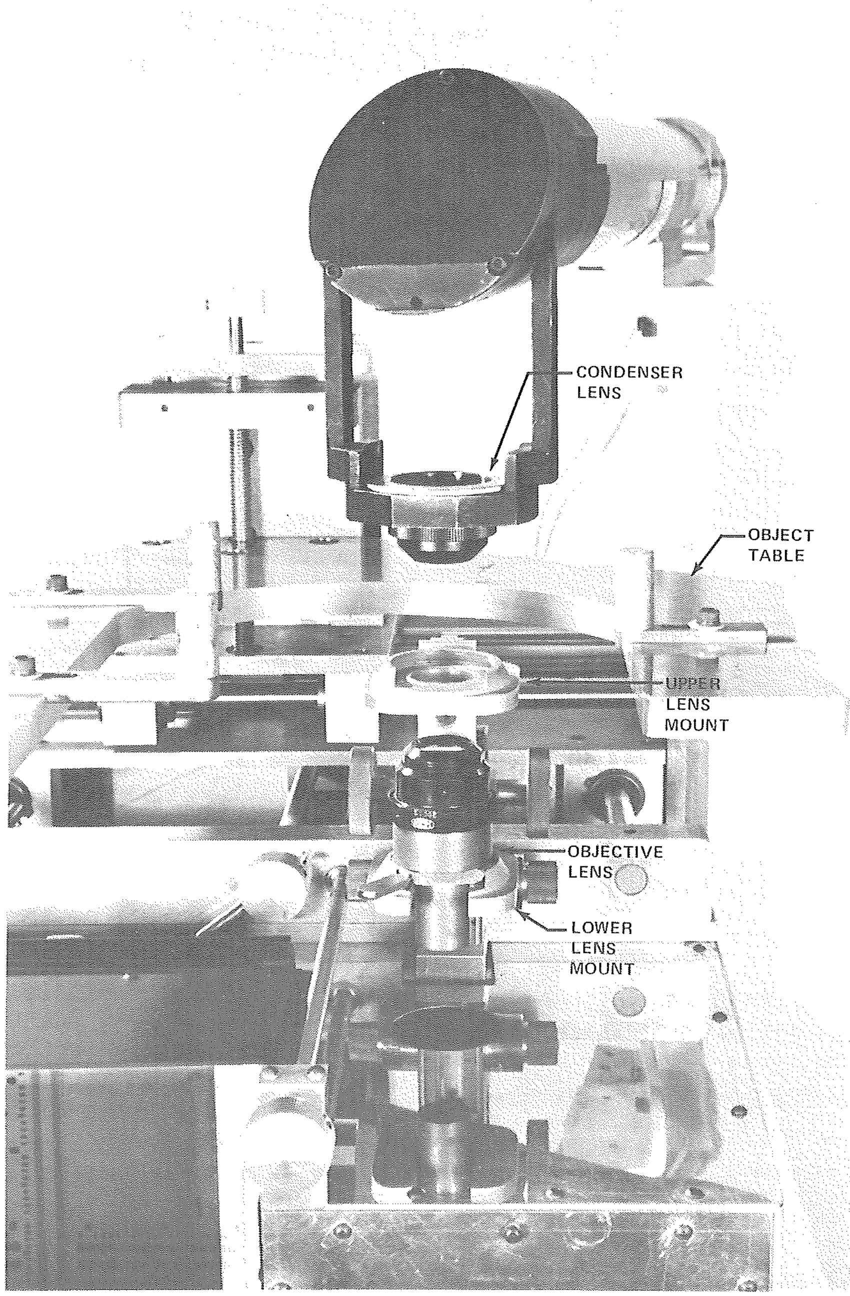


Figure 28. Lens Configuration and Mounting

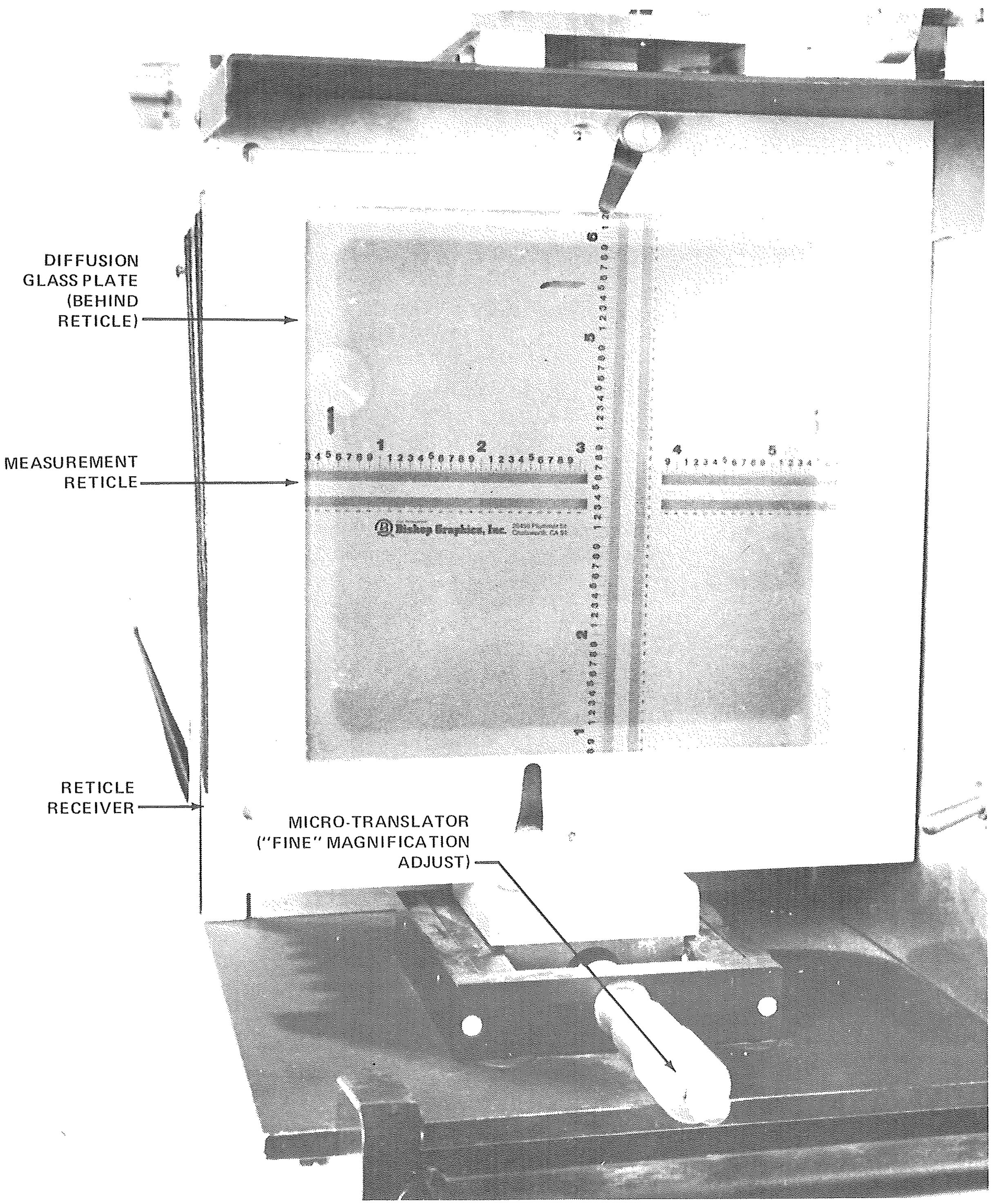


Figure 29. Measurement Reticle

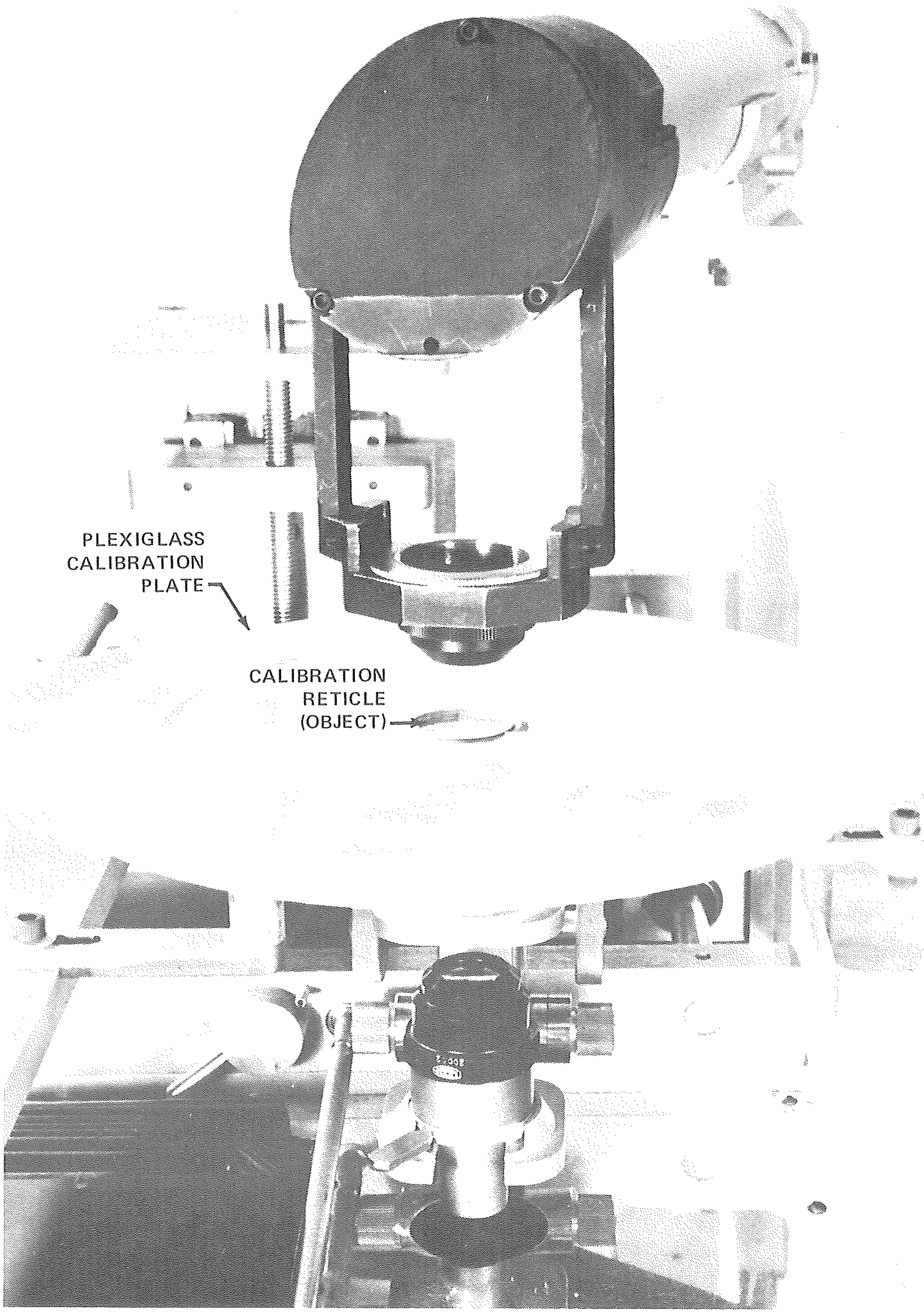


Figure 30. Calibration Reticle and Plate

choose to match four (4) of the 0.1mm divisions (image) over a field of 4 inches on the reticle – the largest possible field giving the best resolution and measurement accuracy. This calibration rate of 1 inch to 0.1mm (4 inches to 0.4mm) gives a magnification rate of 254X (i.e., 25.4 X 1" divided by 0.1mm). With this particular calibration, the No. 100 sieve will have image openings of approximately 1½ inches in width, while the No. 200 sieve would project openings of approximately ¾ inches.

Note that since the final calibration steps involve changes in the micrometer translation unit only, the precision of calibration can be increased by performing multiple calibrations and calculating averages and standard deviations of the micrometer settings.

EXAMPLE: The operator calibrates, as in the previous example, to 254 magnifications using the 40X lens. Note: See Table 7 for lens and condenser selection. Having made coarse adjustments until the image is approximately right, lock the coarse adjustments and make fine adjustments on the micrometer translation unit to keep the calibrator in focus. Four calibrations are then made which yield micrometer readings of 11.32mm, 10.37mm, 9.16mm and 8.24mm, respectively. (Note that these successive calibrations are made using the reticle receiver micrometer adjustment.) These readings yield a mean setting of

$\overline{v} = 9.77$mm and a standard deviation estimate of

$s(v) = 1.351$mm. The standard error is $\sigma\overline{v} = s(v)/\sqrt{n}$

$= 1.351/2 = 0.675$mm.

In Appendix D it is shown that one can convert variations in optical path length, to estimates of the variation in estimated object size by the relation

$$\sigma(Z) = \sigma(V)(\overline{Z}/Mf)$$

Here $f = 5.33$mm

$M = 254$ and

$Z = 0.4$mm, so

$$\overline{Z}(Z) = 1.351x0.4/254x5.33 = 4.10^{-4}\text{mm} = 0.4\ \mu\text{m}$$

Thus, we have a 95 percent confidence estimate that calibration is within (0.4)(1.96) = 0.78 μm of the correct value . . . the wavelength of visible light at the edge of the infra-red spectrum. It should be noted that the above test was actually performed by use of the ADOT comparator.

GO/NO GO PROCEDURES

For GO/NO GO evaluation, perform the following procedures:

1. Place the appropriate GO/NO GO viewing reticle in the reticle receiver (Figure 31). Note that there are reticles for each of the sieve sizes: No. 8, 10, 16, 30, 40, 50, 100 and 200.
2. GO/NO GO evaluation consists of superimposing the image of a given opening on the reticle squares. Two (2) evaluations, a horizontal and a vertical, are made for each opening.
3. The operator makes a decision. Based on the superimposed image, is the opening (in the given dimension) larger (on the average) than the given square or not (Figure 32)?
4. The operator keeps a record of his evaluations on the tally sheet (Figure 33). By placing a mark in a square in the "total" row each time an opening is evaluated. This represents two (2) evaluations, a horizontal and a vertical evaluation. In the example, we used vertical lines to represent openings which were out of specification in the vertical dimensions and horizontal lines for horizontally "out of spec" openings.
5. Start the evaluations with the maximum average opening (see Figure 32). Although the calibration lines are no longer used for calibration, they are useful in finding the appropriate openings.
6. If the evaluation reveals that the opening is larger than the square, place a mark in the LARGE ROW of the form. If the opening dimension is smaller than the square, do *not* make any mark.
7. If either opening dimension is larger than the maximum average square, move the opening to the 5% level square.
   a) If the large dimension is larger than the 5% square, place a mark in the 5% row, then move the opening to the maximum opening square. Now, if the opening dimension is larger than the square, REJECT the sieve. Otherwise, proceed with the sieve evaluation.
   b) If the largest dimension is larger than the maximum average square, but smaller than the 5% square, then make no additional marks on the form, other than the one previously made in the LARGE ROW.

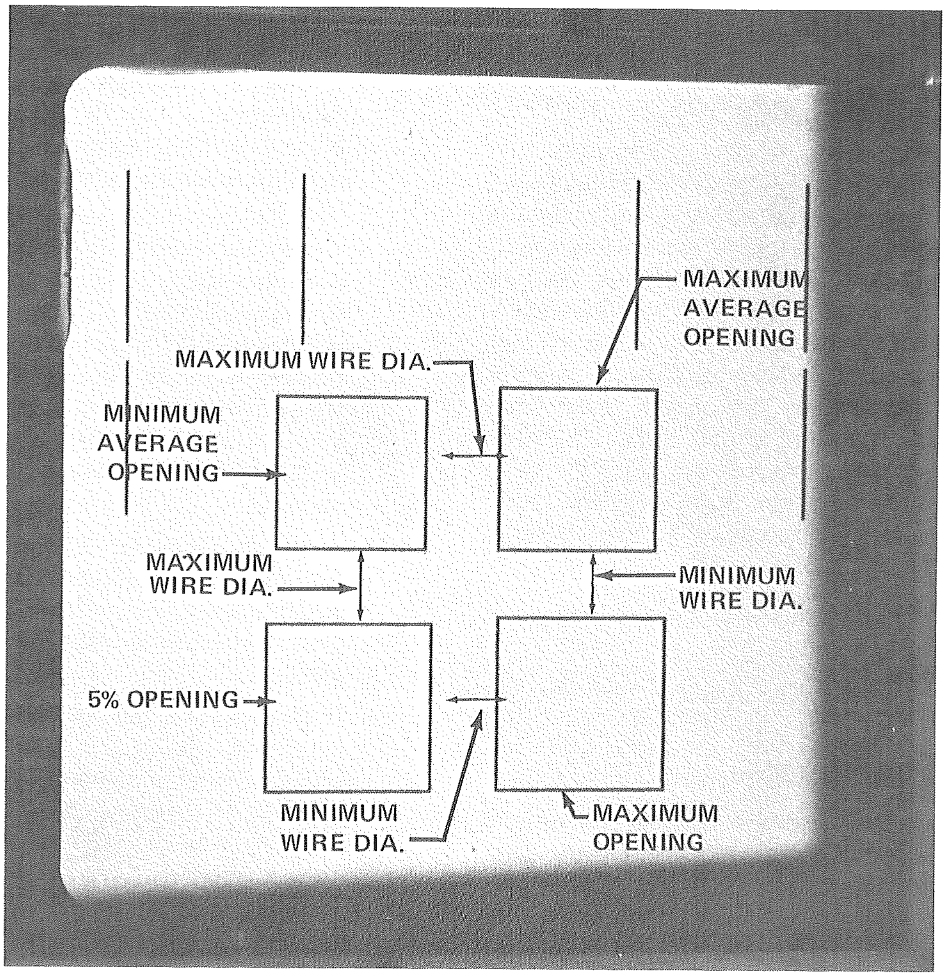


Figure 31. Go/No Go Viewing Reticle

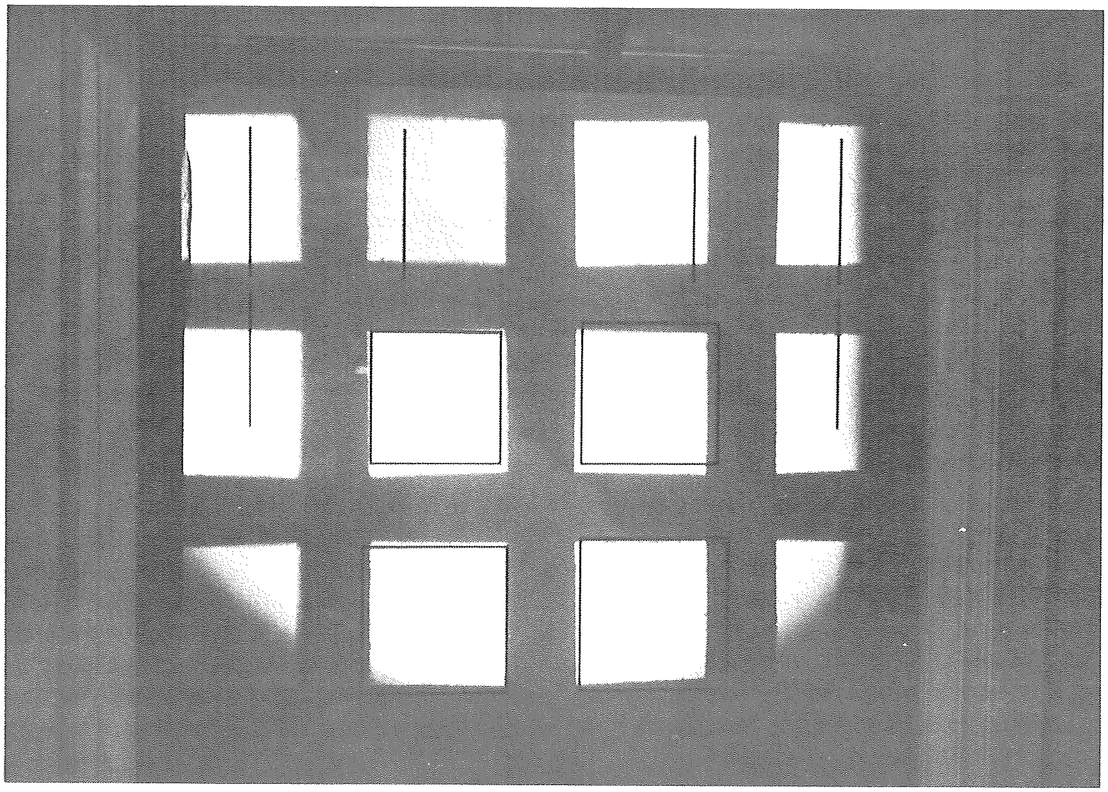


Figure 32. Projected Go/No Go Image

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
5%	59	|	7	16	28	40	53	REJECT								
LARGE		+ 9	+ 12	| 15	| 17	20	23	25	28	30	33	35	37	40	42	44
SMALL		9	12	15	17	20 / 5	23 / 6	25 / 8	28 / 9	30 / 11	33 / 13	35 / 14	37 / 16	40 / 18	42 / 19	44 / 21
TOTAL		1 ✓	2 ✓	3 ✓	4 ✓	5 ✓	6 ✓	7 ✓	8 ✓	9 ✓	10 ✓	11 ✓	12 ✓	13 ✓	14 ✓	15 ✓

Acceptance $\alpha = 0.025$ for large and small sizes.
Rejection $\alpha = 0.050$ for each category.

		16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
5%																
LARGE		47 / 23	49 / 24	51 / 26	54 / 28	56 / 30	58 / 31	61 / 33	35	37	39	40	42	44	45	47
SMALL		47 / 23	24	26	28	30	31	33	35	37	39	40	42	44	45	47
TOTAL		16 ✓	17 ✓	18 ✓	19 ✓	20 ✓	21 ✓	22 ✓	23	24	25	26	27	28	29	30

		31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
5%																
LARGE		49	51	53	54	56	58	60	REJECT							
SMALL		49	51	53	54	56	58	60	REJECT							
TOTAL		31	32	33	34	35	36	37	38	39	40	41	42	43	44	45

Figure 33. Sleve Evaluation Form

8. If an opening is smaller than the maximum average square, then move the opening to the smallest average square.
   a) If the relevant dimension is smaller than this square, place a mark in the SMALL ROW.
   b) If the opening is *not* smaller than the smallest average square, make no additional marks on the form.
9. The numbers in the box which has the last check mark in each row, tells you how to evaluate the sieve. Numbers in the upper, right-hand corner are ACCEPTANCE numbers, while numbers in the lower, left-hand corner are REJECTION numbers.
   a) If the ACCEPTANCE number in the last checked LARGE ROW, and the ACCEPTANCE number in the last checked SMALL ROW are both no larger than the TOTAL number of evaluations, then you may accept the sieve.
   b) If the REJECTION number in any category is no smaller than the total number of evaluations, the sieve is to be rejected.
10. The above sieve evaluation is to be made as the operator proceeds with his opening evaluation. If there has been no decision by the time the total number of evaluations reach GO, then the sieve is regarded as UNDECIDED and is placed aside for later statistical evaluation. Remember to keep the tally sheet with the sieve for future reference.
11. Undecided sieves may be subjected to a secondary evaluation at the testing site without resorting to further measurement. For example:
   a) The user may decide to accept sieves in this category as "backup" sieves, if the number of accepted sieves is too small.
   b) Results of the test may be re-evaluated at lower confidence levels, particularly for individual results. A quick method for calculating confidence levels is to use the normal distribution as follows:

   Set $t_L = (30 - L)/3.873$
   and $t_S = (30 - S)/3.873$

   Where L = number of large squares which have been checked
   S = number of small squares which have been checked

   The normal distribution table will provide the corresponding level of confidence.

Background Notes

Sieve evaluation should be quite simple, but it turns out to have complications due to ambiguities in the relevant ASHTO M92 specifications. These specifications consist of ASHTO M92-70 (equivalent to ASTM E 11-70). The M92 section pertaining to measurement is Section 2.3 which is quoted below:

"2.3 Wire cloth shall conform to the dimensional requirements of Table 8. The average openings (distance between parallel wires), both in the warp and shoot directions, measured separately, shall conform to the value in column 1, within the permissible variation in average opening given in column 4. The maximum individual openings shall not exceed the value given in column 6. Not more than 5 percent of the openings shall exceed the value given in column 5. The average diameter of the warp and shoot wires, taken separately, of the cloth of any sieve shall be that given in column 7, within the permissible range given in Footnote (a). All measurements of openings and wire diameters shall be made on the wire cloth mounted in the completed sieve."

Measurement difficulty occurs with the phrase "distance between parallel wires." The fact is, the wires are seldom exactly parallel. (See Figures 32 and 34). At least tentatively, we are taking measurements at the vertices to determine wire diameters. Thus, for the purpose of opening evaluation, "distance" shall be defined as the average of median distance.

The ADOT comparator is equipped with a set of precision reticle plates for GO/NO GO operations (See Figure 31). These reticles should be used for spot checks and are not adequate for referee testing. The general idea is that a few openings can be spot checked on each of a large number of sieves, with absolute measurements being taken only on those sieves which fail the spot check.

Each reticle plate is equipped with four (4) individual squares and four (4) calibration lines. It should be noted that the four (4) calibration lines are no longer used, and have been replaced by the calibration reticle procedure as discussed in the Calibration Procedures, previously presented.

It is expected that a great deal of GO/NO GO testing will be performed at district and project labs. This being the case, such testing will involve use of the GO/NO GO reticle plates which have been developed. The results of all GO/NO GO testing must be subject to review by absolute measurement testing, since GO/NO GO testing can only test for medians rather than averages. Since any absolute measurement review will most likely be conducted at a Central Laboratory, it is expected that only the rejected sieves will be reviewed. This being the case, the overall guidelines for rapid testing is that the operator should develop a high level of confidence that a sieve which is accepted is within specification.

It should be noted that in order to bring GO/NO GO testing into reasonably close conformance to referee testing, the tally should be kept on warp and shoot wires separately.

MEASUREMENT

The following measurement method should be used for referee testing (Figure 34):

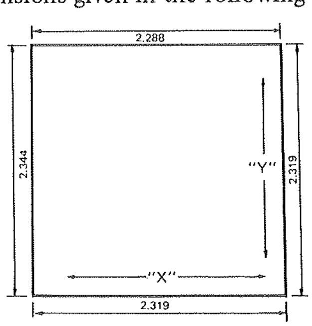
1. Place the measurement viewing reticle in the reticle holder.
2. Using the rules, measure distance by placing the image relative to the rule measurement reference.
3. Estimate values to the nearest 0.005 inches.
4. Divide the measurement value by the magnification factor.

   Example: The operator calibrates at a rate of 0.8 in/mm. He reads one dimension of a No. 8 sieve opening as 1.855 inches since it is just slightly more than 1.85 inches. His estimated opening size is therefor x = 1.855/0.8mm = 2.319mm.

   A second estimation of the same openning gives an estimated reading of 1.83 inches. This converts to 1.83/0.8 = 2.288mm.

5. In order to evaluate an opening, it is necessary to make four (4) vertex-to-vertex measurements. This is accomplished as shown in the following example:

   Example: An opening is measured by the estimation procedures and is found to have the dimensions given in the following diagram.

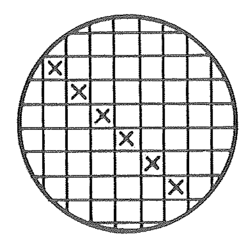


This gives two distances, x = 2.304 ± 0.16mm, y = 2.344 ± 0mm. For measurement purposes, this gives x = 2.304mm, y = 2.344mm.

6. In order to perform a referee test, it is necessary to make these measurements for a total of 300 openings according to the M92 specification section, as reprinted below. It is not, however, necessary to make the conversion from the reading on the viewing reticle to the reading for the object until all measurements have been completed.

   "A2 *Methods of Calibrating Wire-Cloth Sieves.*

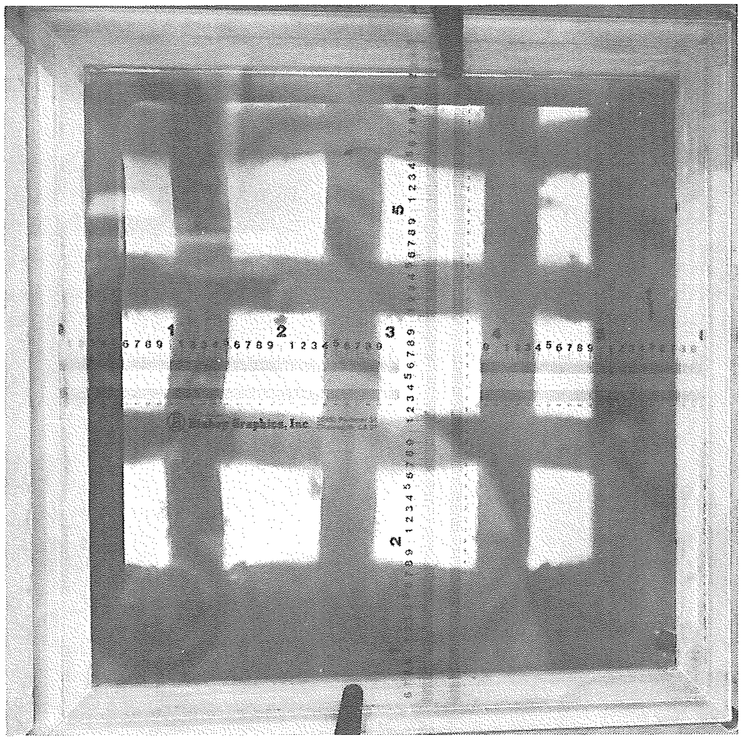
   A2.1 A wire-cloth sieve may be calibrated by plotting the frequency of occurrence of the mesh openings as indicated in the following procedure: Six fields are chosen in such a manner that one of the openings to be measured will have common wires. In each field the openings to be measured should lie in a diagonal direction across the sieve (see the Figure below). The openings of the fields should lie in a direction at right angles to those in the other three fields. Measure at least 50 openings in each field. Measure each opening between the warp wires and the shoot wires and separately tabulate and plot the readings."



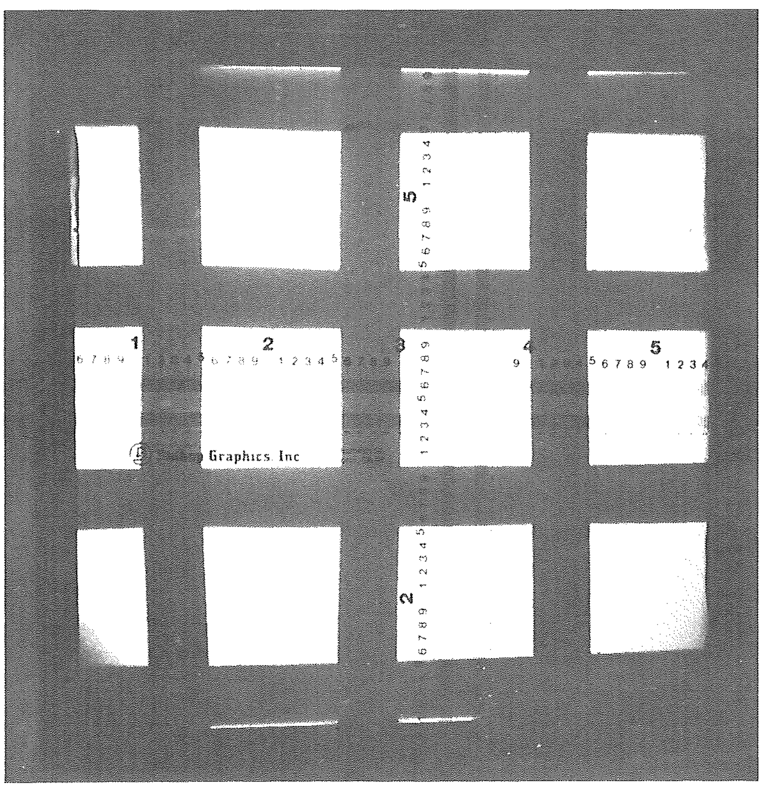
Only the indicated openings are measured.

Example: The operator measures openings according to the prescribed method (Section A.2 of AASHTO M92), keeping track of measurements as follows:

WARP (in)	SHOOT (in)
1.830	1.875
1.855	1.855
etc.	etc.



Number 200 Sieve
(X40 Lens)



Number 8 Sieve
(X3 Lens)

Figure 34. Typical Mesh Opening for Measurement

For evaluating sieves, it is only necessary to calculate the average in each category and then compare results to the converted AASHTO limits.

Example: For the No. 8 sieve with a magnification rate of X20.32 and a conversion rate of 0.8mm/inch, the AASHTO limits are as follows:

> *Note:* Converting these four (4) values to object values yields the squares of the previous example.

Sieve Size	Smallest Average (in)	Largest Average (in)	5% Level (in)	Maximum (in)
No. 8	1.824	1.952	2.012	2.080

Of course, finding an opening which is larger than the maximum permissible leads to immediate rejection of the sieve, and finding more than 15 warp or shoot diameters larger than the 5 percent level also leads to reject of the sieve. Final acceptance thus depends on average values for both warp and shoot diameters.

PRECISION MEASUREMENTS

In order to evaluate the comparator, a method of measurement was needed which was as free from operator bias as possible. Furthermore, it was felt that some method of evaluating operator precision would be useful as a training aid. These requirements are both fulfilled by the following method of measurement:

> *Note:* This method is the *only* method whereby reticle controls may be moved after calibration.

1. The measurement reticle is left in the reticle receiver.
2. Following calibration, the operator records the numerical reading on the micrometer translation unit. This value is read in millimeters.
3. Measurement is performed as described in the previous Section, Measurements, with one vital exception. By means of the micrometer, the reticle receiver is moved until the image coincides with clearly marked division lines. Then the *new* value on the micrometer is recorded.
4. The apparent measurement of the object "y," the difference between the two micrometer readings "x," the focal length "f" of the lens and the original magnification "M" are all used to calculate the actual distance "Z."
5. The formula is:

   $$z = y/(M + \Delta M) = y/(M + \frac{\Delta v}{f}) = fy/(fM + \Delta v).$$

   The operator follows the above procedure several times, as necessary, to obtain a precision statement for his measurements.

   Example: The operator uses the 3X lens at a calibrated magnification rate of 1mm to 0.8 inch (20.32X). The calibrated micrometer setting is 15.68mm. He then matches an opening width image to 1.875 inches on the viewplate at a micrometer setting of 11.68mm. Now M = 20.32, f = 62.6mm, Y = 1.875 inches = 1.875 x 25.4 = 47.625mm.

   Then $\Delta v = 11.68 - 15.68mm = -4.00mm$, and $z = y/(M + \Delta M)$ mm where $M = \Delta v/f = -.054$. $M + \Delta M = 20.32 - .64 = 47.624/20.256mm = 2.351mm$.

   An estimate of the measurement precision which is attainable is given by:

   $$\sigma(Z) = \sqrt{\sigma_c^2(Z)+\sigma_m^2(Z)}$$

   where $\sigma_m(Z)$ is the estimated standard deviation of the measurement obtained in a single setting and $\sigma_c(Z)$ is the estimated standard deviation obtained during calibration.*
6. The opening measurements used to evaluate this instrument were obtained by this method. Where it was convenient the actual measurements of a single opening obtained at various times were used to calculate precision standard deviations. For the smaller openings the above methods were used.

FOCAL LENGTH MEASUREMENTS

Occasionally it is useful to recall that the ADOT comparator is built around an optical bench. With this in mind, it is possible to measure the focal lengths of lenses by means of the Power Equation, $f = \Delta v/\Delta M$. To proceed, observe that each setting has a coarse and fine component and that differences in the coarse components are given in cm, while the fine components in mm. Thus, the focal length equation may be written as:

$$f = \Delta v/\Delta M = (20\Delta v_c+\Delta v_f)/\Delta M \text{ mm}$$

*For example, our testing suggests $\sigma_c(Z) = \sigma_m(Z) = 0.78$ μm for measurements at X254. Thus, our estimate of $\sigma(Z)$ is $\sqrt{2}$ (0.78) = 1.10 μm.

Example:

$M = 10.16, v_c = 7.5cm, v_f = 8.75mm$

$M' = 20.32, v'_c = 39.0cm, v'_f = 14.99mm$

$f = f_{3X}$

$$f = [20(39-7.5)+(14.99-8.75)]/(20.32-10.16)$$
$$= (630+6.24)/10.16$$
$$= 62.6mm$$

Calculated focal lengths for all lenses are given in Table 13.

TABLE 13
FOCAL LENGTHS OF LENSES
(FIRST MEASUREMENTS)

Lens	Focal Length (mm)
3X	62.6
5X	46.7
10X	19.3
20X	10.2
40X	5.33
50X	4.43

CONCLUDING REMARKS

Whenever an instrument is to be reviewed, the question is bound to arise: Can it be made better? The answer is obviously, yes. Various minor improvements have already been suggested, some of which would provide for ease of operation, and one (new lenses) which would improve comparator resolution. It is our opinion, however, that each of these would only result in small improvements to the overall accuracy and precision of the instrument.

The conclusion remains that the ADOT comparator is already close to optimal performance. This conclusion can be reached by referring to the Abbe equation again: Optimum Resolution = λ/N.A.* Although condenser N.A. values as large as 1.4 can be produced with microscopes using oil immersion, this is not a practical method for looking at sieves. Furthermore, the depth of field problems which are inherent with woven sieves make it unlikely that combined N.A. values much larger than 1.0 can be obtained – thus a resolution of approximately the wavelength of light is just about optimum. If 0.005 inches is taken as the best visual resolution of a typical operator, it can be concluded that magnifications much greater than 254X must be considered empty, since no additional detail can be seen. However, a magnification of 254X is readily obtained by the ADOT comparator.

In order to obtain a measuring instrument of significantly better performance, it would be necessary to abandon optics and go to much shorter wave lengths. Such instruments are many times more expensive than optical instruments, and invariably, they use high energy sources and possess inherent reliability problems.

In view of the theoretical basis and the highly satisfactory experiment results as present in this report, the ADOT Optical Sieve Comparator is considered a successful, highly accurate means for the evaluation and certification of woven sieves.

*λ/N.A. = (wavelength of incident (Light/(combined numerical aperture).

APPENDIX A

MOIRE' EFFECT

In Figure A-1, a schematic of a Moire' pattern is shown. It is assumed that two line gratings are inclined at an angle θ to each other. The Moire' pattern or fringes appear as lines inclined at an angle ϕ to the y-axis. The pitch or spacing of the test = grating, labeled by the letter K, is given as P. The spacing of the grating to be measured, labeled by L, is $P(1 + \lambda)$.*

The equation of the lines labeled by K is: $x = PK$.

Note that the lines of the grating labeled by L are rotated with respect to the x-y axis through an angle θ. This family is characterized by the equation:

$$\begin{bmatrix} \text{Cos}\,\theta & -\text{Sin}\,\theta \\ \text{Sin}\theta & \text{Cos}\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 0 \\ P(1+\lambda)L \end{bmatrix}, \text{ or}$$

$$x \text{ Sin } \theta + y \text{ Cos } \theta = P(1 + \lambda)L$$

It is also clear that the Moire' fringes have an equation given by $x \text{ Sin } \theta + y \text{ Cos } \theta = mf$, where f is the spacing of the fringes.

*λ has nothing to do with the "wavelength" of light, etc. It is obtained as follows: Clearly, if S is the spacing of the grating to be measured, then it is simply defined to be $S/P - 1 = \lambda$.

Thus the following equations describing the gratings:

(1) $y = PK$

(2) $x \text{ Sin } \theta + y \text{ Cos } \theta = P(1 + \lambda)L$

Finally, the equation describing the Moire' fringes:

(3) $x \text{ Sin}\phi + y \text{ Cos}\phi = mf$, where f is the spacing between fringes

The following is a result which follows from a more general analysis of Moire' fringes. Namely, an equation relating the indices K, L, and m. It is given by

(4) $K - L = m$

From equations (1) and (2):

(5) $x \text{ Sin } \theta + y \text{ Cos } \theta - y\,(1 + \lambda) = \left[P(1 + \lambda)L - P(1 + \lambda)K\right]$

obtained by subtracting $(1 + \lambda)$ times equation (1) from equation (2).

Now (5) represents the family of lines passing through the points of intersection of the two families representing the respective line gratings.

Thus (5) is formally equivalent to

(3) x Sin + y Cos = mf.

So, rewriting (5) as (5′),

$$y\left[\frac{\text{Cos}\theta-(1+\lambda)}{\text{Sin}\theta}\right]+\frac{\text{MP}(1+\lambda)}{\text{Sin}\theta}=-x,$$

and (3) as (3′)

$$y\left[\frac{\text{Cos}\phi}{\text{Sin}\phi}\right]+\left[\frac{\text{mf}}{\text{Sin}\phi}\right]=-x, \text{ then}$$

proceed as follows:

Since (3′) is identical to (5′), it follows that the coefficients of y and f are equal.

Therefore,

$$f=\frac{P(1+\lambda)\,\text{Sin}\phi}{\text{Sin}\theta}.$$

Moreover,

$$\frac{\text{Cos}\phi}{\text{Sin}\phi}=\frac{\text{Cos}\theta-(1+\lambda)}{\text{Sin}\theta}, \text{ or}$$

$$\frac{\text{Cos}^2\phi}{\text{Sin}^2\phi}=\left[\frac{\text{Cos}\theta-(1+\lambda)}{\text{Sin}\theta}\right]^2.$$

Now, $\text{Cos}\phi = 1 - \text{Sin}^2\phi$.

Substituting this expression for $\text{Cos}^2\phi$,

we have

$$\frac{1-\text{Sin}^2\phi}{\text{Sin}^2\phi}=\left[\frac{\text{Cos}\theta-(1+\lambda)}{\text{Sin}\theta}\right]^2, \text{ or}$$

$$\text{Sin}^2\phi=\left[1+\left[\frac{\text{Cos}\theta-(1+\lambda)}{\text{Sin}\theta}\right]^2\right]^{-1}, \text{ thus}$$

$$\text{Sin}^2\phi=\left[\frac{\text{Sin}^2\theta+\text{Cos}^2\theta-2\,\text{Cos}\theta(1+\lambda)+(1+\lambda)^2}{\text{Sin}^2\theta}\right]^{-1}.$$

Simplifying, obtain $\text{Sin}^2\phi = \text{Sin}^2\theta\,[1 - 2\,\text{Cos}\theta\,(1+\lambda) + (1+\lambda)^2]^{-1}$.

Now this may be written as $\text{Sin}^2\phi = \text{Sin}^2\theta\,[2\,(1 - \text{Cos}\theta) - 2\lambda\,(1 - \text{Cos}\theta) + \lambda^2]$.

Noting that $\text{Cos}\theta = 1 - 2\text{Sin}^2\frac{\theta}{2}$, and $\lambda^2 = \lambda^2(\text{Cos}^2\frac{\theta}{2} + \text{Sin}^2\frac{\theta}{2})$, then write

$$\text{Sin}^2\phi = \text{Sin}^2\theta\,[\lambda^2\,\text{Cos}^2\frac{\theta}{2} + \text{Sin}^2\frac{\theta}{2}\,(2+\lambda)^2]^{-1}, \text{so}$$

$$\text{Sin}\,\phi = \text{Sin}\theta\,[\lambda^2\,\text{Cos}^2\frac{\theta}{2} + \text{Sin}^2\frac{\theta}{2}\,(2+\lambda)^2]^{-1/2}.$$

Finally

$$(6)\ f=\frac{P(1+\lambda)}{\text{Sin}\theta}\,\text{Sin}\phi =$$

$$P(1+\lambda)\left[\lambda^2\text{Cos}^2\frac{\theta}{2}+\text{Sin}^2\frac{\theta}{2}\ (2+\lambda)^2\right]^{-1/2}$$

which characterizes the Moire' fringes produced by two line gratings of spacing P & P(1+λ) inclined to each at an angle θ.

Now as is normal when calibrating the No. 200 mesh sieves with a Tyler Glass gauge the angle θ is set = 0, so the equations reduce to:

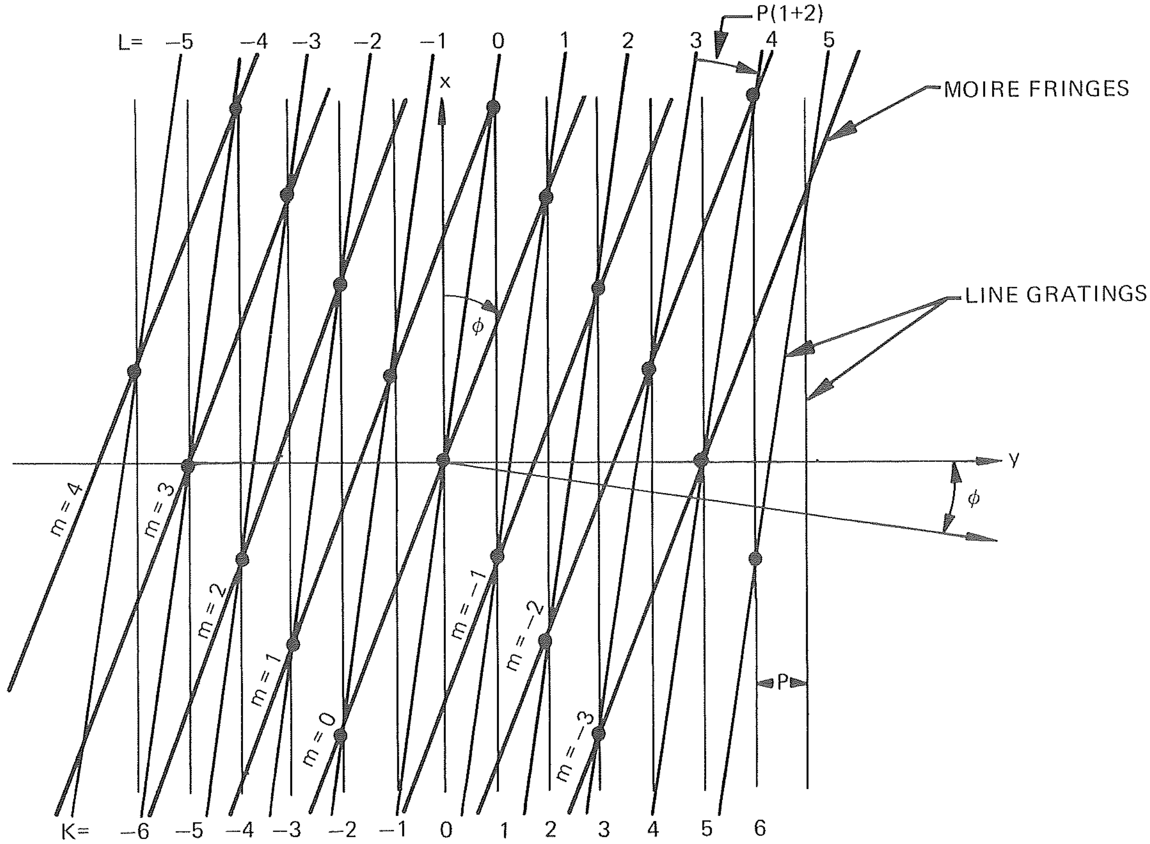
$$(8)\ f=\frac{P(1+\lambda)}{\lambda}, \text{ and}$$

$$(9)\ \text{Sin}\,\phi = \theta$$

(Note: Equation (9) is the condition for the fringes to be parallel to the gratings.)

Clearly from Equation (8) by knowing P, i.e., the pitch of the Tyler Glass guage and f which may be accurately measured, we can determine λ which then yields P(1+λ), the pitch or mesh of the screen.

However this method if employed in the calibration of sieves is more difficult than the single visual comparison method of the comparator.



Schematic of Moiré pattern formed by two line gratings angulary displaced by an angle θ.

Figure A-1.

APPENDIX B

NATIONAL BUREAU OF STANDARDS OPTICAL COMPARATOR FOR THE MEASUREMENT OF SIEVES (Circa 1922)*

Development of the NBS comparator consists of several steps:

- Construction of a suitable light-tight box of proper dimensions
- Selection of a microscope combination (lens)
- Specifying a projection screen onto which the image is cast
- Determine a measurement method which would avoid parallax
- Reduce to a minimum the color bands at the edge of the image
- A device for focusing and moving the sieve at right angles to the optical path.

The NBS system, as developed, consists of a light-tight box of about 40 centimeters square and one meter in length. A microscope is mounted at one end and a ground glass plate (2mm thick) at the other end. The illumination source is a microscope illuminator containing a concentrated filament lamp (6 volts, 108 watts), connected through a transformer to a 110 VAC source. The concentrated light passes through a lens in the end of the illuminator and is focused on the objective of the microscope. After passing through the microscope, the image is cast onto a ground glass plate which is mounted with the ground side "in." A 50 centimeter steel scale is mounted against the inner ground surface of the glass plate in such a way that the graduations of the scale may be observed through the glass. The scale position allows a direct reading on the edges of the displayed image (sieve mesh). It was found that by oiling the ground surface, visibility was greatly enhanced without diminishing the image.

A frame for holding the sieve is located on a platform and so arranges as to allow lateral motion of approximately 8 inches. Axial motion provided for focusing. Long rods, extending the full length of the apparatus, enabled the operator to move the sieve from his point of observation. Lateral motion was accomplished by means of a rack and pinion, while focusing required the use of beveled gears. A green filter is mounted to the face of the microscope. The filter relieves eye strain and virtually eliminates color band which would otherwise appear at the edges of the image.

During operation, the sieve is mounted in its holder on the focusing platform, between the illuminator and the objective lens of the microscope. Once

*Highway Materials, Part I, Pages 438-439, AASHO Publication, 1966.

focused for a sharp image, measurements are taken in millimeters by reading the position of the scale relative to where the two edges of the wire image cross the scale – a magnifying glass sometimes being required. The sieve is then moved across the field, reading being taken at several sample locations on the cloth. This procedure continues across the full sieve diameter, while simultaneously watching for uniformity of spacing and stopping to measure any excessively large openings. The sieve is then rotated 90 degrees and the process is repeated.

Absolute measurements are achieved by knowing the magnification factor of the apparatus. Magnification is determined by observing a "standard" wire of known diameter. Once the magnification is known, absolute value sieve measurements can be calculated.

By using a microscope having a tube of about 15 centimeters long and an eyepiece with a magnifying power of approximately three (3) diameters, together with a 16 millimeter objective lens, a total magnification of about 260 diameters is achieved. This magnification is found to be very satisfactory for fine-mesh sieves. Measurements to 0.2 millimeters can be made on the ground glass plate, with individual reading repeating to 0.5 millimeters or better. This results in an accuracy of better than 0.001 millimeters for the average wire diameters and width of openings.

APPENDIX C

KEINATA'S APPLICATION FOR THICKNESS MEASUREMENT*

The principle of optical comparison has long been employed as a technology to facilitate precision examination of small components. An example of such a procedure is outlined in Handbook 77, Volume III of the NBS. With this technique, determination of the coating thickness of corrosion protected iron screw threads is made. A diagram of this instrument is shown in Figure C-1.

The procedure used with this method involves the projection of a greatly magnified image of the screw threads onto the reticle, which in turn provides a coordinate system for comparison with the contour of the coated threads. Next, the coating is chemically stripped from the metal, and after carefully washing and drying the screw, a second projection is made. This latter projection shows clearly the line of demarcation of the coating on the thread. See Figure C-2.

When viewed on the linear coordinates of the reticle, an accurate determination of the thickness and distribution of the plating can be made. In this particular expose' of measurement no scale magnitudes were given. However, using appropriate magnification, one could measure in magnitudes of microns or mils.

This example further indicates the flexibility and utility of optical comparator technology.

*George Keinata, "The Measurement of Thickness," Handbook 77, Volume III, NBS, February 1, 1961, Pages 113-129.

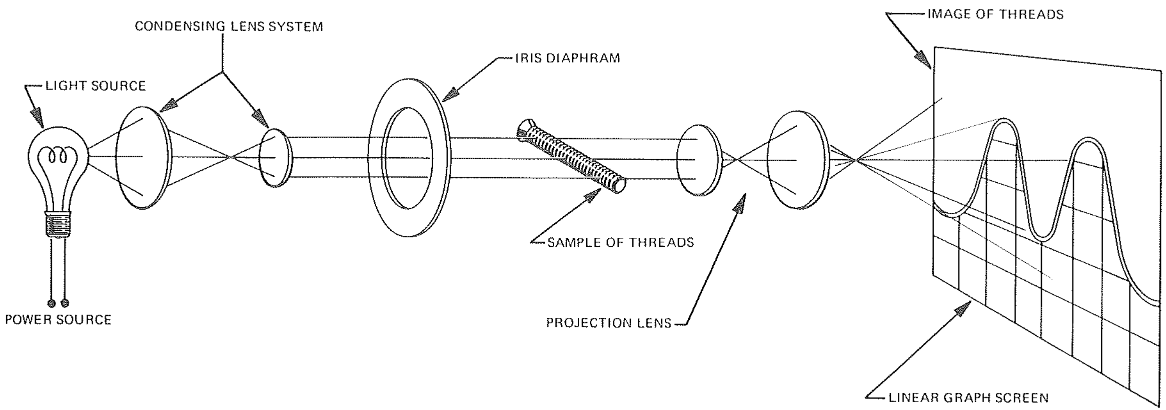


Figure C-1. Optical Contour Projector to determine Thickness of Coating On Screw Threads

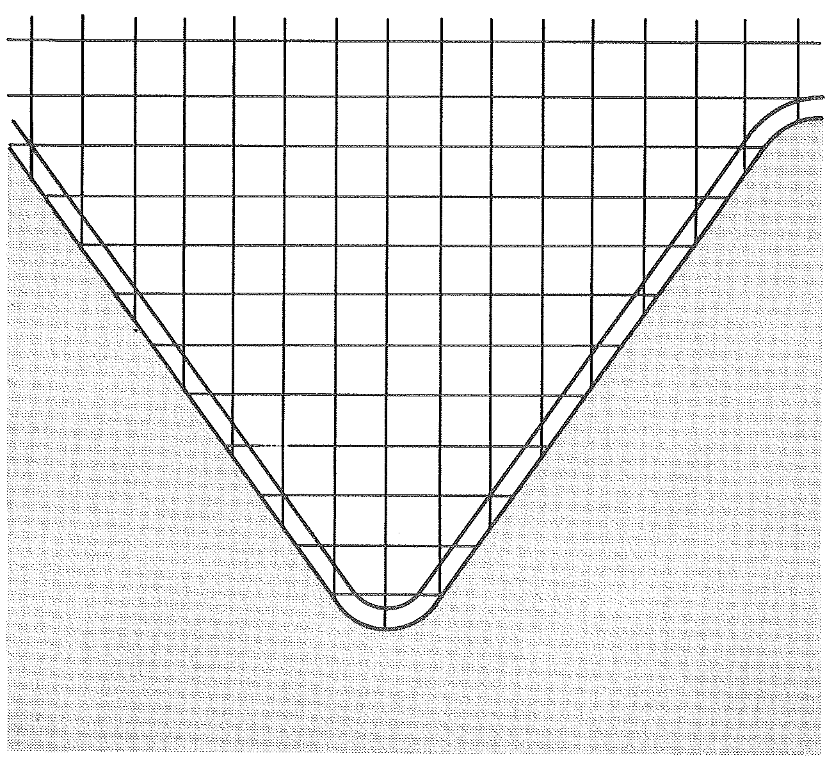
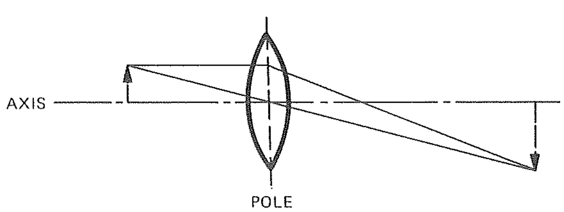


Figure C-2. Schematic of Projected Image of Screw Thread With the Half-Tone Delineating The Thickness of the Chemically Stripped Coating Superimposed Onto the Linear Graph Screen.

APPENDIX D

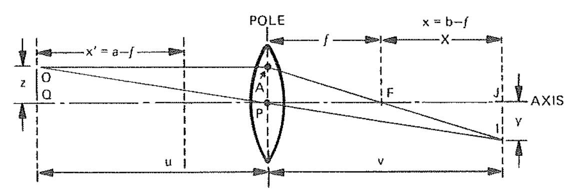
SHORT DERIVATIONS OF USEFUL OPTICAL FORMULAS

The geometric model of lens phenomena considers the image of a point through a lens as the intersection of rays through the point and the lens. It has been shown that only two rays are needed to derive the fundamental lens equations. A convenient pair is determined by a line through the given point parallel to the optical axis and the line determined by that point and the intersection of the optical axis and the pole of the lens.



In order to derive the necessary relations, we fill in this diagram with the following objects:

F = focal point of lens
f = focal distance of lens
O = object point
I = image point
p = lens pole
a = optical axis



M = magnification $= \frac{y}{z}$

The following relations then hold:

(1) $M = \frac{v-f}{f} = \frac{v}{f} - 1.$

PROOF: Since the triangle APF is similar to FJI, we have $\frac{f}{z} = \frac{v-f}{y}$ and $M = \frac{y}{z} = \frac{v-f}{f}.$

(2) $M = \frac{v}{u}.$

PROOF: The traingle OQP is similar to PIJ.

Hence $\frac{u}{z} = \frac{v}{y}$ so $\frac{v}{u} = \frac{y}{z} = M.$

(G) Gauss' Lens Equation: $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}.$

PROOF: From the first two equations, we have

$\frac{v}{u} = \frac{v}{f} - 1$ so $\frac{1}{u} = \frac{1}{f} - \frac{1}{v}$ and $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$.

(N) Newton's Lens Equation: if $x = v-f$, $x_1 = u-f$, then $xx_1 = f^2$.

PROOF: From equation (1) and (2) we have

$\frac{v-f}{u} + \frac{f}{u} = \frac{v}{u} = M = \frac{v-f}{f}$,

$\frac{v-f}{u} + \frac{f}{u} = \frac{v-f}{f}$,

$f(v-f)+f^2 = U(v-f)$,

$f^2 = (u-f)(V-f) = x_1x$.

Useful relations for our purposes are as follows:

(P) $\frac{\Delta M}{\Delta y} = \frac{1}{f}$ (the power equation).

PROOF: $M = \frac{v}{f} - 1$ and $M_1 = \frac{v1}{f} - 1$,

where $M_1 = M+\Delta M$, $v_1 = v+\Delta v$, Hence

$M+\Delta M = \frac{v+\Delta v}{f} - 1 = \frac{v}{f} - 1 + \frac{\Delta v}{f} = M + \frac{\Delta v}{f}$, and

$\Delta M = \frac{\Delta v}{f}$, so $\frac{\Delta M}{\Delta v} = \frac{1}{f}$.

(E) $\frac{\Delta M}{M} = \frac{\Delta y}{y} = \frac{\Delta z}{z}$ (error equation).

PROOF: $(M+\Delta M)z = y+\Delta y = Mz+\Delta y$, so

$\Delta Mz = \Delta y$, and

$\frac{\Delta M}{M} = \Delta M\frac{z}{y} = \frac{\Delta y}{y}$.

Now, if $(M+\Delta M)z = M(z+\Delta z)$, we have $\Delta Mz = M\Delta z$ and $\frac{\Delta M}{M} = \frac{\Delta z}{z}$.

This relation tells us that the percent error in magnification, in image size and in our estimate of object size are all equal.

A more direct error relationship follows from: $\Delta M/M = \Delta z/z$

Since $\Delta Mz = M\Delta z$ and $\Delta M = \frac{\Delta v}{f}$ we have

$\frac{v}{fz} = M\Delta z$,

$z = v \frac{z}{Mf}$, thus

$\sigma(z) = \sigma(v) \frac{z}{Mf}$.

APPENDIX E

RECOMMENDED STATISTICAL TECHNIQUES FOR SIEVE EVALUATION

The Arizona Department of Transportation's decision to use GO/NO GO methods for sieve evaluation, introduced several problems relative to the adaptation of this method to AASHTO M92/ASTM E11 specifications. It is the purpose of this Appendix to acquaint the reader with the problems, their solutions and the reasoning behind the solutions.

It should be noted that the user is in no way bound to the use of the recommended ADOT procedures or the evaluation charts as found within the text of this report.

When using the ADOT test procedures for GO/NO GO testing, all testing is regarded as statistical tests of hypothesis. This includes Referee testing as well. In all tests, the sieve is rejected if it fails at any specification level. It should also be noted that Referee testing differs from spot-checking, in that any sieve which is not rejected is automatically accepted. In spot-checking, however, a sieve may be accepted, rejected or classified as undetermined. An undetermined designation means the sieve is conditionally accepted or re-scheduled for more extensive testing.

During any test, the finding of a mesh diameter which is larger than the largest permissible opening specification is cause for certain rejection. However, for all other specifications, a null hypothesis with a confidence level is stated, and further testing is conducted to statistically accept or reject the null hypothesis.

The prepared GO/NO GO charts are based on such statistical testing. For example: Consider the null hypothesis H_0 . . . "No more than 5 percent of the opening diameters are larger than the specified value." In this case, the test is conducted at the 95 percent confidence level, and the Binomial Distribution is used to determine Acceptance/Rejection levels. Thus, if $p = 0.95$ and $q = 0.05$, then the probability of two (2) or more "larger-than-specification" diameters in seven (7) tries is

$$1 - [(.95)^7 + 7(.95)^6(.05)] < 0.045 < 0.05,$$

and the conclusion is that the sieve must be rejected. From the evaluation chart, the seven (7) in the lower left-hand corner, second column of the 5 percent row, indicates that with two (2) rejections after having evaluated seven (7) or fewer openings, the sieve would have to be rejected.

Similarly, for the Large category on the evaluation chart, the null hypothesis is H_0 . . . "No more than 50 percent of the sieve diameters are larger than the specified values." In this example case, the confidence level is 97.5 percent. The nine (9) in the upper right-hand corner of the first column of the Large row indicates that with one (1) rejection, you must have evaluated nine (9) diameters before accepting the sieve.

The Small evaluation column is used in the same way as discussed for the Large column. In addition, this chart can be used under the same procedure to evaluate wire diameters with perhaps different numbers inserted for the desired confidence levels. It should be noted that a symmetrical (or near symmetrical) distribution of opening diameters is assumed during the application of GO/NO GO testing.

When performing more than 60 evaluations, we use the Normal approximation to the Binomial Distrib tion, with $(m - np + ½)/\sqrt{npq}$ as the upper tri ordinate and $(m - p - ½)/\sqrt{npq}$ as the lower tri ordinate. Again, we replace averages with mediar such that for the largest average and smallest averag evaluations, $p = q = ½$.

When performing measurement, we again assume a underlying distribution. The user calculates the ave age, X; and the standard error, $S/\sqrt{n}$; and the est mate of the standard deviation, S. The sieve i rejected at the Small specification if U – $-t\alpha(S/\sqrt{n}) > \overline{X}$, where U is the nominal size and is the tolerance. The sieve is accepted if $\overline{X} > U - T$ $t\alpha(S\sqrt{n})$. At the Large specification, the sieve i accepted if $\overline{X} < U + T - t\alpha(S\sqrt{n})$, and rejected if $> U + T + t\alpha(S\sqrt{n})$.

APPENDIX F

ESTIMATED COMPARATOR COSTS

This Appendix provides approximate costs to assist other agencies should they wish to construct an Optical Comparator of similar design and function. These costs assume all construction and assembly is performed by outside contractors, while the purchase of optical parts is performed by the agency itself. An approximate cost breakdown is as follows:

Optical Parts	1000.00
Viewing Reticles	1500.00
Overall Construction (includes illumination system)	7300.00
Sieve Transport Unit	1000.00
Total Costs	$10,800.00